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A COMPARISON OF WIND-TUNNEL AND FULL-SCALE WIND PRESSURE MEASUREMENTS ON LOW-RISE STRUCTURES*

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Summary

Comparisons are made between wind pressures measured on two low-rise experimental buildings and pressures measured on wind-tunnel models of those buildings. For the experimental building at Aylesbury, U.K., comparisons are made between the full-scale pressures obtained by the Building Research Establishment and those of model tests at 1:500 scale carried out by the University of Western Ontario, Canada (U.W.O.) and at 1:50 scale by Virginia Polytechnic Institute and State University (V.P.I.S.U.). The second experimental building, constructed by V.P.I.S.U. at Price's Fork, VA, provided information on wall pressures which are compared with those obtained from a 1:24 scale model tested in the wind tunnel at V.P.I.S.U.

By using pressure coefficients based on the mean velocity in the approach flow at the level of the pressure measurement, it is shown that there is little difference between mean or fluctuating pressure coefficients obtained from a model at 1:500 scale, in a carefully simulated boundary layer, and those from a model at 1:50 scale. Scaling in the latter case did not allow careful simulation of the mean velocity profile, but did provide a suitable level of turbulence and a turbulence integral scale at least as large as the largest model dimension. Use of large model-scales has the advantage that relatively small details of construction can be included.

On the basis of the full-scale/model comparisons it is shown that the non-stationary character of the natural wind has a significant effect on the mean, r.m.s. and peak pressure coefficients. Under non-stationary wind conditions the full-scale extreme peak coefficients may be as much as 5 times the wind-tunnel values.

Local pressure coefficients can be modeled adequately for low-rise structures located on level sites (Aylesbury) with relatively uniform upstream terrain, provided the turbulence intensity and turbulence integral scale are properly simulated. For structures located on sloping sites and with complex upstream terrain (Price's Fork experimental building), the modeling of the mesoscale terrain features may be very important. The complex terrain is responsible for increased turbulence intensities of the horizontal velocity components as a result of increased low-frequency spectral energy.

1. Introduction

Research dealing with wind loading of low-rise structures has been responsible for the rapid advances in this field during the past decade. For reasons

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*Paper presented at the 4th Colloquium on Industrial Aerodynamics (Building Aerodynamics), Aachen, June 19—20, 1980 of economy and simplicity most of this research has concentrated on the development of wind-loading specifications based on data acquired from wind-tunnel model tests. Only a small number of experimental studies have addressed themselves to the problem of the reliability of wind-tunnel results in comparison with full scale.

Reliable full-scale wind pressure data on low-rise structures have recently become available and it is now possible to check the validity of the different wind-tunnel techniques used, by comparing wind pressure measurements from full-scale experiments and corresponding model tests. Because of the different modeling techniques used with short test-section and long test-section wind tunnels and because of differences in measuring equipment and data analysis, a direct comparison of results obtained at various laboratories is valuable.

These comparisons are important for wind-load data on low-rise buildings since exact modeling of the atmospheric flow near the surface is difficult to obtain at small geometric scales. The geometric modeling of the length scales of turbulent flow and of the low-rise structures at the same scale ratio requires the use of scales in the region of 1:500. Such scales dictate extremely small models, making it difficult to model structural detail. For example, pressure taps of diameter 0.5—1 mm represent holes of 0.25—0.5 m in full scale and cannot be associated with point measurements.

In this paper, model-scale pressure data obtained in wind tunnels at V.P.I.S.U. (scale 1:50 [1]) and U.W.O. (scale 1:500 [2,3]) are compared with pressure data obtained from a full-scale experimental building at Aylesbury, U.K. by the Building Research Establishment [4,5]. In addition, full-scale/model comparisons of wall pressure data obtained from the Price's Fork experimental building located near the V.P.I.S.U. campus are presented (scale 1:24 [1]). Other studies have dealt with the Aylesbury full-scale/model comparison, notably those by Holmes and Best [6] and by Greenway and Wood [7]. However, the Aylesbury model results presented in an unpublished report from U.W.O. [3] are more complete and in a format which allows detailed comparison.

2. Experimental procedures and data analysis

2.1 Full-scale: Aylesbury

The experiments associated with the full-scale pressure and wind measurements at Aylesbury are described in detail in refs. 4 and 5. The experimental building is located near the edge of a housing development with near flat rural terrain in the direction of the prevailing winds. It is for winds from these directions that pressure measurements were made and these are used for the comparison. Wind measurements were made with cup-vane instrumentation mounted on a 10-m mast. Pressure measurements were made with pressure transducers having a frequency response accurate to 10 Hz. The recorded pressure-data were digitized at 32 Hz and analyzed for mean, r.m.s., maximum and minimum values for record lengths of 17 min.

2.2 *Full-scale: Price's Fork*

An experimental building with a 30°-pitch roof, plan dimensions of 4.9 by 4.1 m, and a side-wall height of 2.4 m has been erected at an exposed site at the V.P.I.S.U. Price's Fork Research Center [1]. The entire structure is located on a turntable, enabling data to be acquired from any wind-approach angle. Flow measurements were made with four sets of Gill propeller anemometers and cup-vane instruments all mounted on an 18-m mast. Wall pressure measurements were made with pressure transducer units whose frequency response was flat to 5 Hz. The recorded full-scale wind and pressure data were digitized at a rate of 1 Hz, and analyzed for mean, r.m.s., maximum and minimum values for a record length of ~25 min.

2.3 *Aylesbury model: U.W.O.*

Wall and roof pressure measurements on a 1:500 scale model of the Aylesbury experimental building were made in the boundary-layer wind tunnel at the University of Western Ontario [2,3]. Thick boundary layers were developed, without any artificial stimulation, over four different floor-roughness exposures. Mean velocity and turbulence-intensity profiles were measured. The flow generated over roughness exposure no. 2, consisting of nylon cloth with local trees and hedges modeled upstream from the model as far as a full-scale distance of 500 m, showed the best agreement with the full-scale wind environment. Only pressure data associated with this roughness exposure are used for comparison purposes in this paper. The recorded pressure signals were low-pass filtered at 120 Hz, sampled at 1000 Hz, and analyzed for mean, r.m.s., maximum and minimum values for a record length of 1 min.

2.4 *Aylesbury and Price's Fork models: V.P.I.S.U.*

Wall and roof pressure measurements on a 1:50 scale model of the Aylesbury experimental building (roof pitch 22.5°) and wall pressure measurements on a 1:24 scale model of the Price's Fork experimental building were made in the V.P.I.S.U. wind tunnel [1]. The spire roughness method was used for the development of a thick, turbulent shear layer. No attempts were made to model the upstream roughness, or to simulate the model flow to either the Aylesbury or Price's Fork wind environment. The pressure data were sampled at 120 Hz and analyzed for mean, r.m.s., maximum and minimum values for a record length of 6 s.

2.5 *Pressure coefficients*

From extensive wind-tunnel pressure measurements made on rectangular-shaped models [8], it has been found that local pressure coefficients, based on the undisturbed velocity in the approach flow at heights corresponding to the locations of the pressure measurements, are nearly independent of the properties of the upstream flow. For all wind-tunnel and full-scale pressure data in this paper, mean, r.m.s., minimum and maximum pressure coefficients are referenced to undisturbed local velocity conditions at the height of the pressure measurement.

Based on the pressure measurements of ref. 8, it can be expected that when local pressure coefficients are used, their dependence on the shape of the mean velocity profile is negligible. Consequently it can be assumed that exact simulation of the mean velocity profile and exact geometric scaling of the roughness length can be relaxed. However, it is believed that simulation of the turbulence intensity of the approach flow at the height of the pressure measurement is essential. The problem of geometric scaling of the turbulence integral scale is not fully resolved. A previous experiment [9] indicates that exact geometric scaling of the turbulence integral scale can be relaxed, provided that this scale in the shear layer where the models are located is larger or at least as large as the major model dimension.

3. Results and Discussion

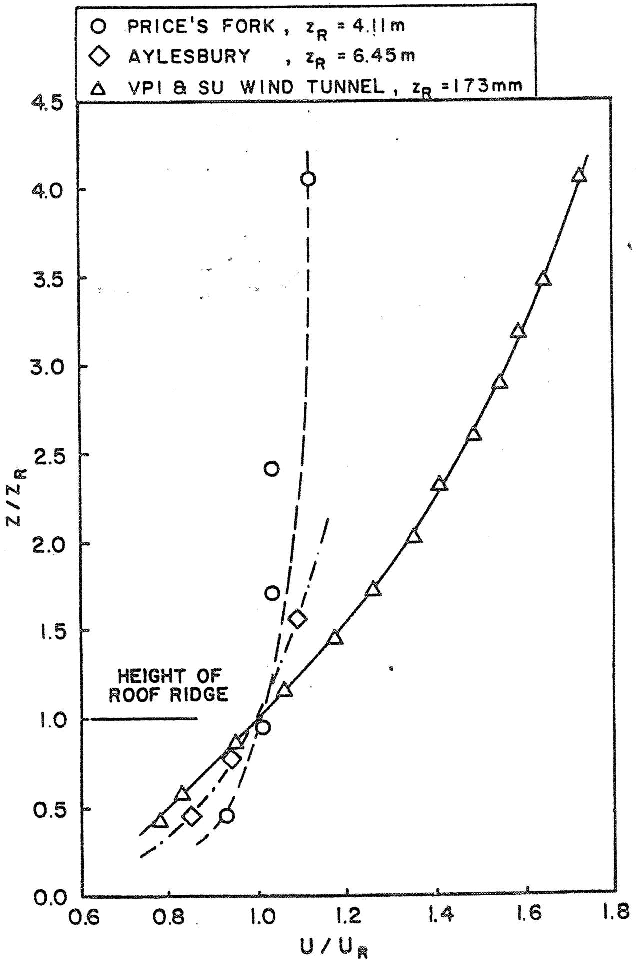
3.1 Flow parameters

Full-scale (Price's Fork and Aylesbury) and wind-tunnel profiles of mean velocity and longitudinal turbulence are presented in Figs. 1 and 2. The mean and r.m.s. velocities are normalized with the mean velocity corresponding to the height of the roof ridge. The wind-tunnel profiles shown in these figures are normalized with the undisturbed mean velocity, U_R, corresponding to the height of the roof ridge, z_R, of the Price's Fork model. Consequently, the normalized height and velocity data for the Price's Fork model in Figs. 1 and 2 require multiplication by factors of 1.33 and 1.12 respectively in order to match the wind-tunnel data for the Aylesbury model. The difference in velocity profiles is appreciable; specifically, the Price's Fork profile is nearly uniform with height. This is the result of the flow acceleration near the surface as a result of the gradual increase in terrain elevation upwind of the experimental site. The full-scale and model longitudinal turbulence-intensity profiles are of the same order up to heights of $z/z_R = 1.7$. In Table 1, full-scale/model comparison is made of the turbulence intensities and normalized turbulence integral scales at roof-ridge height. These results show that geometric

TABLE 1

Turbulence parameters at roof-ridge level, $z/z_R = 1$

Location	Results	σ_u/U_R (%)	σ_v/U_R (%)	σ_w/U_R (%)	L_u^x/z_R	L_v^x/z_R	L_w^x/z_R
Price's Fork	Full-scale	21.6	23.5	9.0	22	28	2.5
	Model V.P.I.S.U.	24.8	16.4	14.6	1.53	0.49	0.47
Aylesbury	Full-scale	24.3	—	—	—	—	—
	Model V.P.I.S.U.	25.3	17.7	15.8	1.90	0.63	0.57



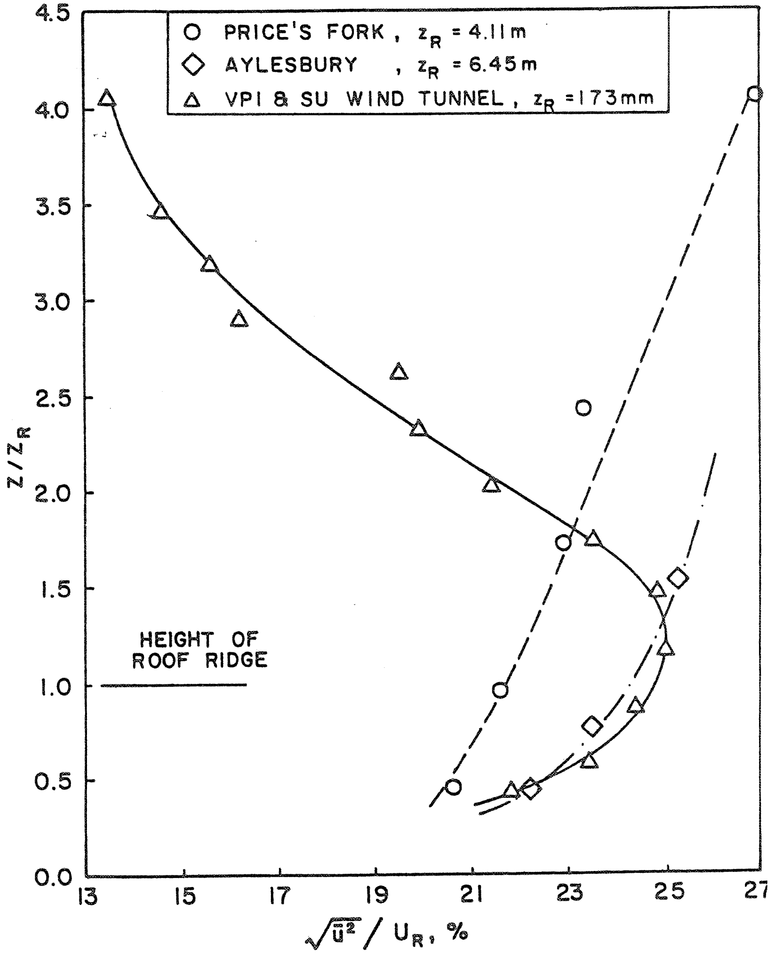


Fig. 1 (left). Comparison of mean velocity profiles.

Fig. 2 (right). Comparison of r.m.s. values of the streamwise turbulence components.

scaling of the turbulence integral scales is not achieved but that the wind-tunnel scales of the turbulence components are at least as large as the major model dimension.

3.2 Local pressure coefficients

Detailed full-scale/model comparisons of local pressure coefficients representing the mean, r.m.s. and peaks of the pressure records are shown in Figs. 3—14. These comparisons include wall and roof pressure coefficients of the Aylesbury experimental building, and wall pressure coefficients of the Price's Fork experimental building.

3.2.1 Local mean pressure coefficients (Figs. 3—5)

Full-scale mean pressure coefficients for walls are simulated quite satisfactorily in both the V.P.I.S.U. and U.W.O. wind-tunnel tests. For roof pressures the variability of the measured mean pressure coefficients for both full scale and model is much greater and consequently the full-scale/model comparison is not as good. Discrepancies between full scale and model can be created as a result of non-stationarities such as low-frequency components and individual gusts, as is the case for the marked records for the wind direction near 240° (Fig. 5, Table 2).

TABLE 2

Full-scale/model comparison of Price's Fork wall pressure coefficients ($\theta \simeq 240°$) and velocity data

	Full-scale records				V.P.I.S.U. Wind tunnel
	T9-2320	T9-2580	T9-2795	T9-3035	
β (degrees)[a]	307	302	299	296	—
U_{10} (m s^{-1})	7.6	6.7	5.6	5.2	16.4
σ_u/U_{10} (%)	26.0	36.0	35.0	39.0	13.5
U_{MAX} (m s^{-1})	14.6	15.5	11.6	14.3	—
U_{MIN} (m s^{-1})	2.7	1.5	1.2	1.8	—
η, pos. peak	+3.57	+3.59	+3.10	+4.4	—
Wall					
θ (degrees)[b]	247	244	238	236	240
C_{PMEAN}	-0.76	-1.01	-0.89	-0.91	-0.72
C_{PRMS}	0.39	0.64	0.60	0.75	0.20
C_{PMAX}	+0.36	+0.21	+0.11	0.00	-0.19
C_{PMIN}	-2.25	-6.59	-3.66	-5.58	-1.41
η, neg. peak	-3.74	-8.72	-4.62	-6.23	-3.45

[a] β = wind direction. [b] θ = relative angle of wind with respect to building.

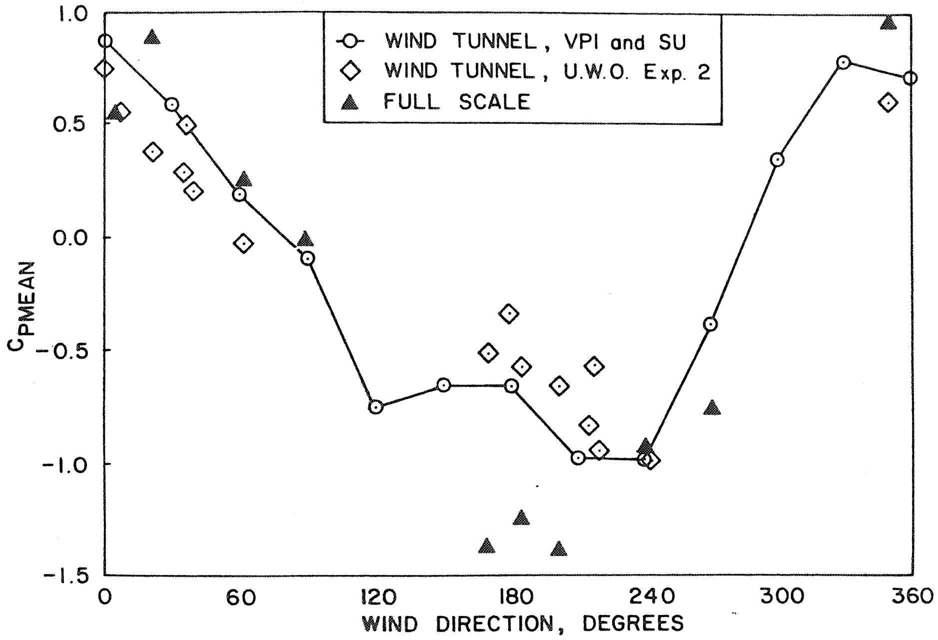


Fig. 3. Comparison of mean pressure coefficients for wall locations 3WW2—3EW2, Aylesbury experimental building; α = 22.5°.

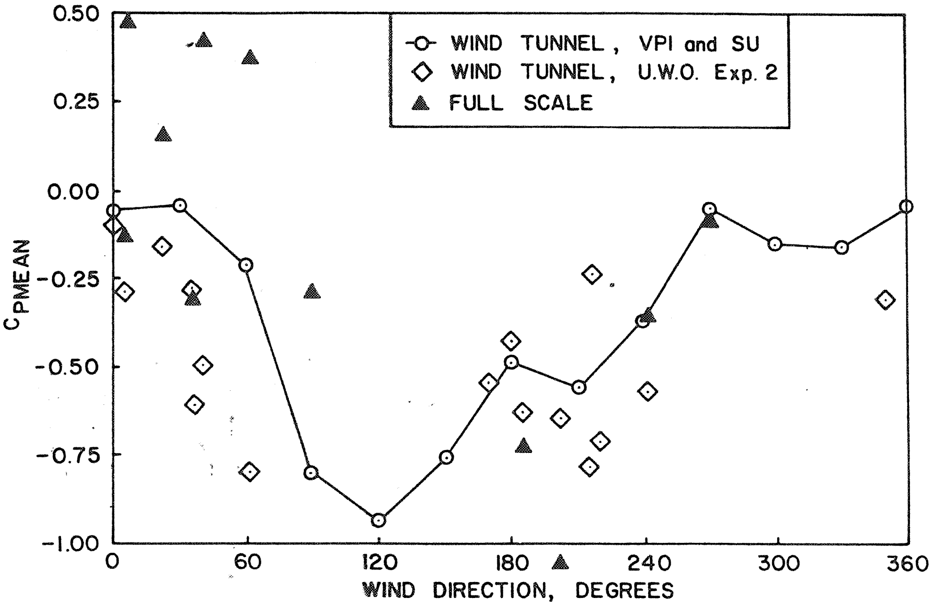


Fig. 4. Comparison of mean pressure coefficients for roof locations WR3B—ER2E, Aylesbury experimental building; α = 22.5°.

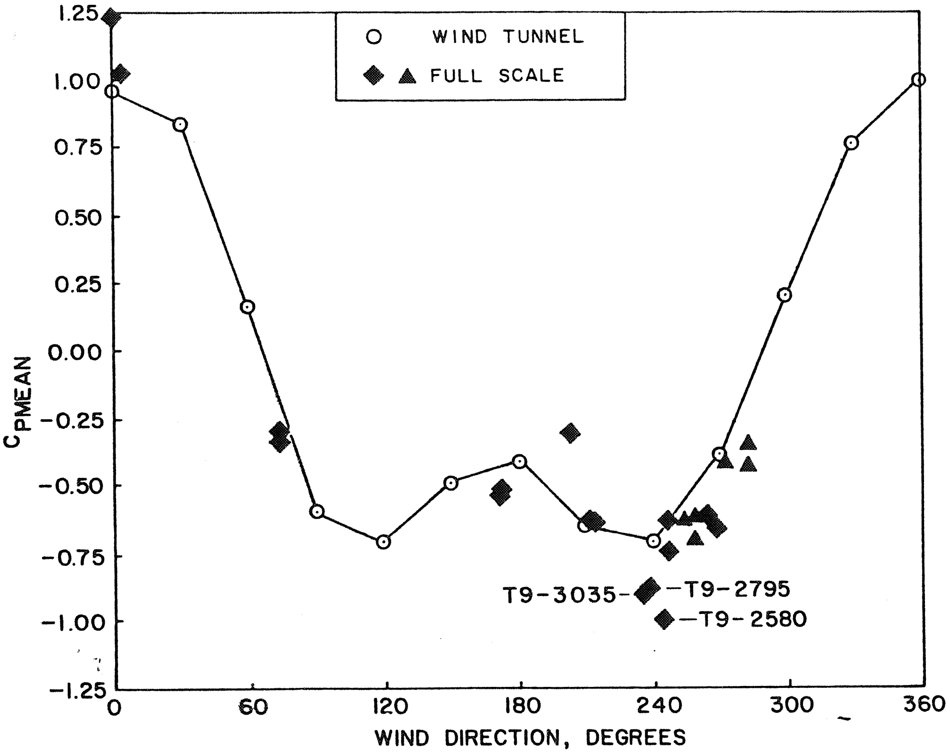


Fig. 5. Comparison of mean pressure coefficients for the wall of the Price's Fork experimental building.

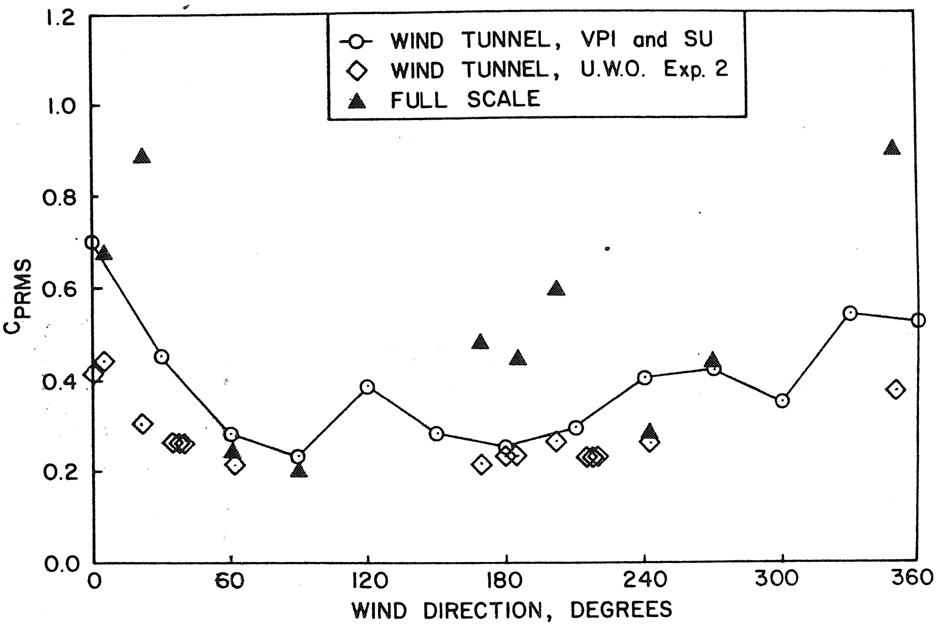


Fig. 6. Comparison of r.m.s. pressure coefficients for wall locations 3WW2—3EW2, Aylesbury experimental building; α = 22.5°.

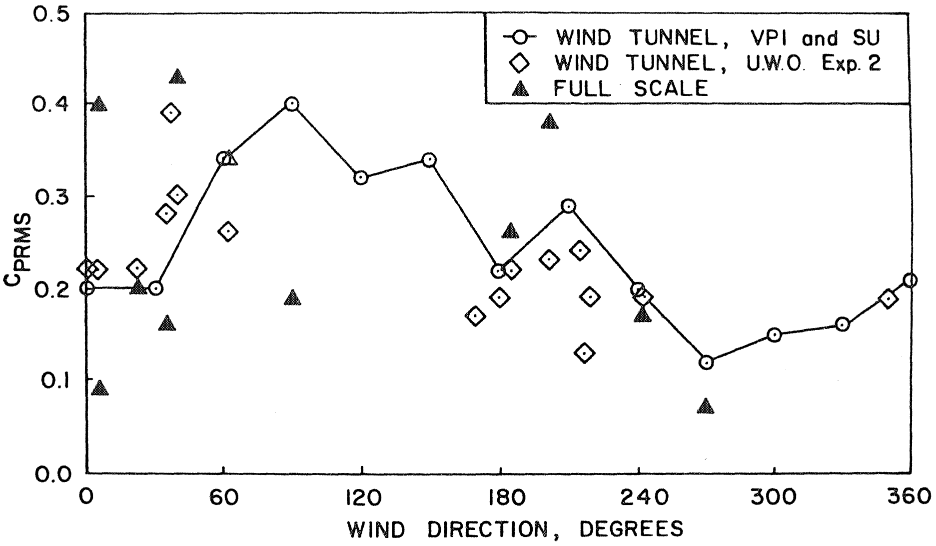


Fig. 7. Comparison of r.m.s. pressure coefficients for roof locations WR3B—ER2E, Aylesbury experimental building; $\alpha = 22.5°$.

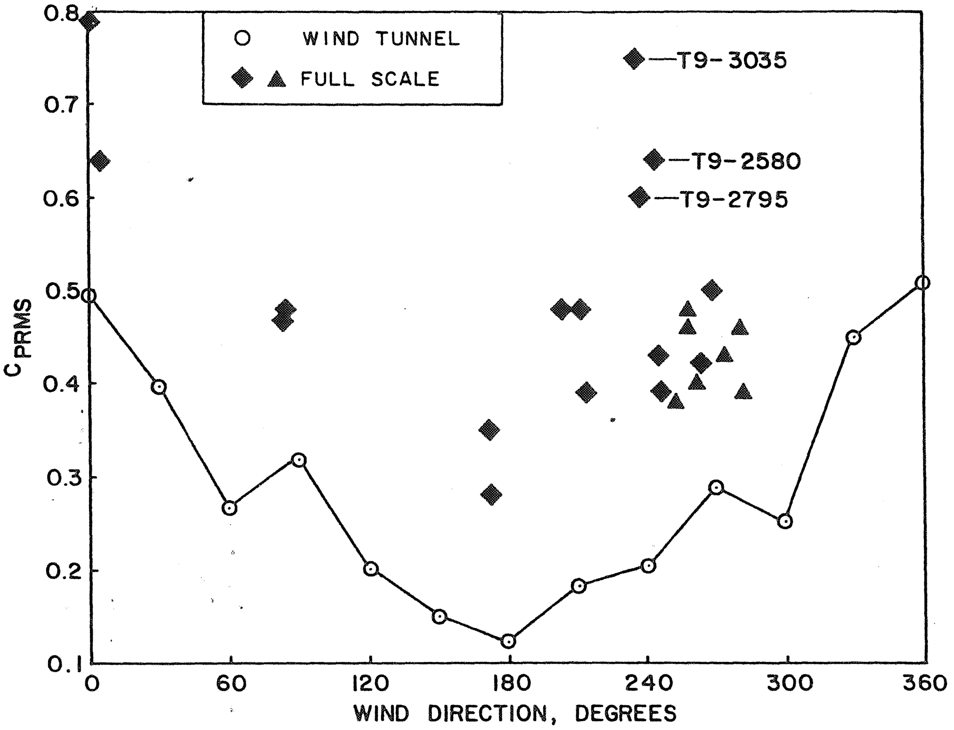


Fig. 8. Comparison of r.m.s. pressure coefficients for the wall of the Price's Fork experimental building.

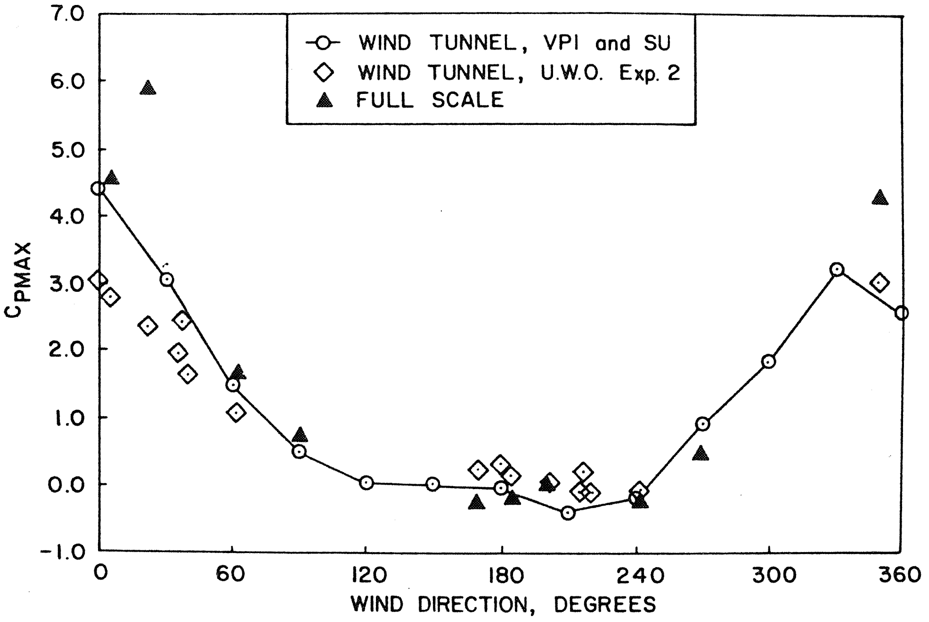


Fig. 9. Comparison of maximum pressure coefficients for wall locations 3WW2—3EW2, Aylesbury experimental building; $\alpha = 22.5°$.

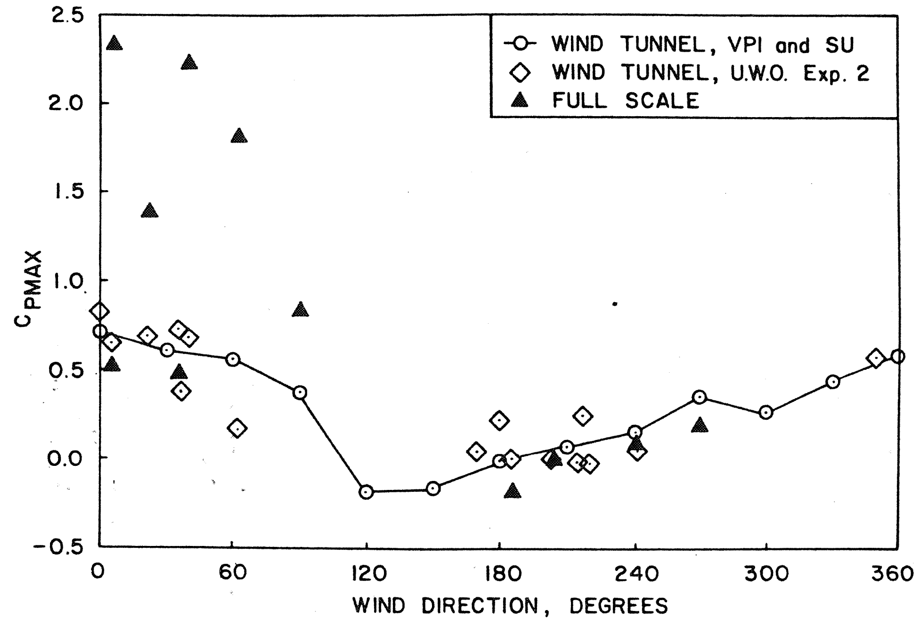


Fig. 10. Comparison of maximum pressure coefficients for roof locations WR3B—ER2E, Aylesbury experimental building; $\alpha = 22.5°$.

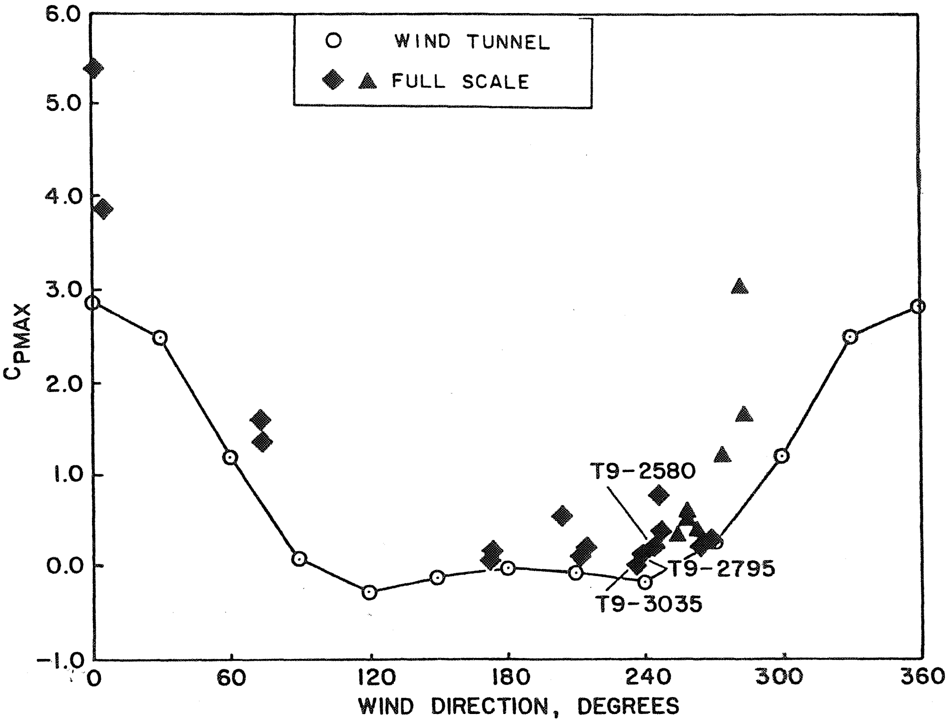


Fig. 11. Comparison of maximum pressure coefficients for the wall of the Price's Fork experimental building.

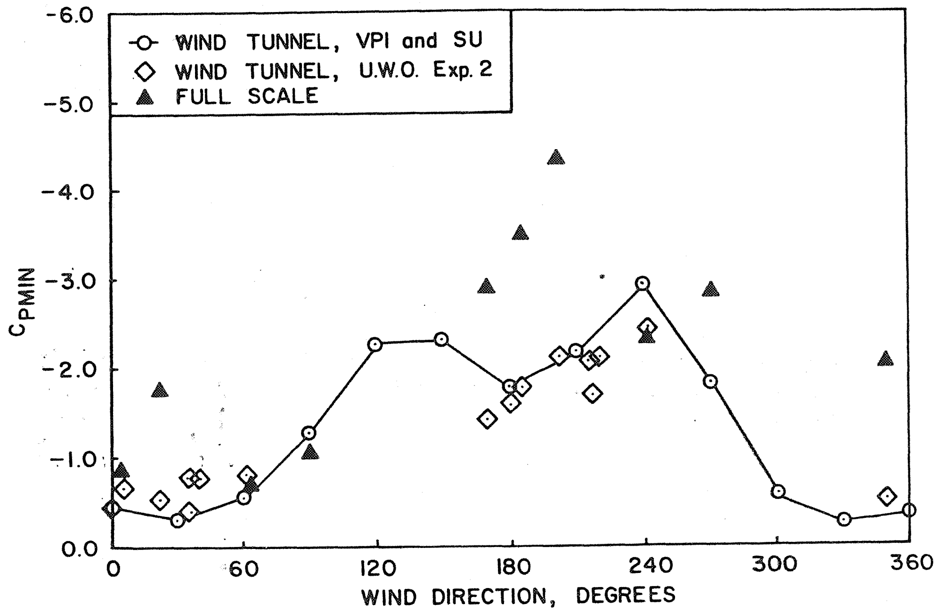


Fig. 12. Comparison of minimum pressure coefficients for wall locations 3WW2—3EW2, Aylesbury experimental building; α = 22.5°.

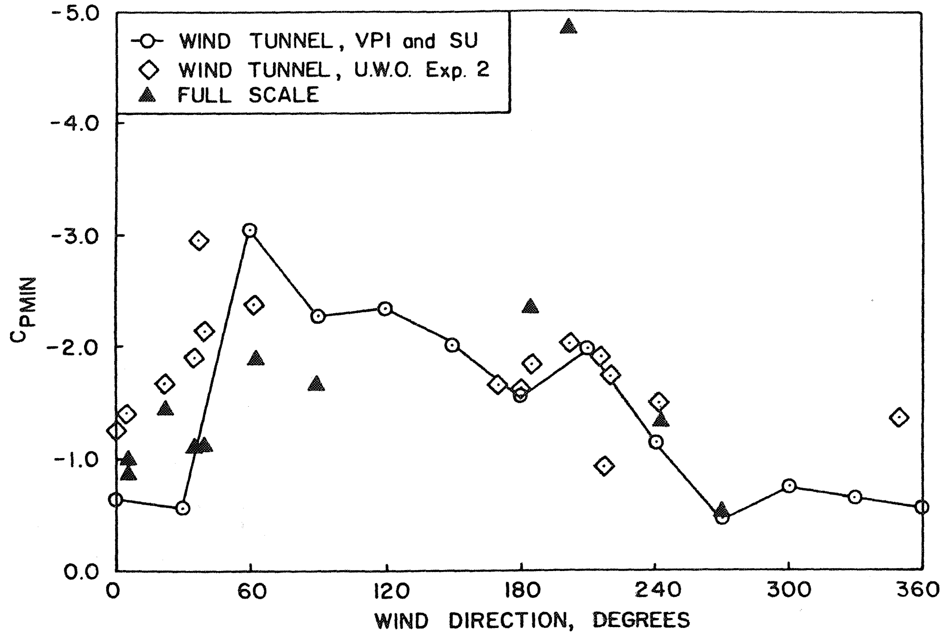


Fig. 13. Comparison of minimum pressure coefficients for roof locations WR3B—ER2E, Aylesbury experimental building; α = 22.5°.

3.2.2 Local r.m.s. pressure coefficients (Figs. 6—8)

The comparison of the wall r.m.s. pressure coefficients between V.P.I.S.U. and U.W.O. is very good. Greater variability is evident for the r.m.s. pressure coefficients for the roof. Full-scale/model comparison of the Aylesbury roof and wall r.m.s. pressure coefficients is fair. However, for Price's Fork the full-scale values of the wall r.m.s. pressure coefficients are systematically about twice as large as the model results. Again, full-scale values of C_{PRMS} are greatly influenced by non-stationarities in the approach flow (Fig. 8, Table 2).

3.2.3 Local maximum pressure coefficients (Figs. 9—11)

Comparison of the values of C_{PMAX} for either wall or roof locations from both V.P.I.S.U. and U.W.O. model tests is excellent. The full-scale/model comparison is quite good for wake regions (120° $< \theta <$ 240°), but for wind directions in the sector 300° $< \theta <$ 60°, the full-scale values of C_{PMAX} seem to be systematically higher.

3.2.4 Local minimum pressure coefficients (Figs. 12—14)

Excellent agreement exists between the values of C_{PMIN} for both model tests. In wake regions the full-scale values of C_{PMIN} are larger than the corresponding model values for both Aylesbury and Price's Fork. For upstream wind directions the agreement between full-scale and model values of C_{PMIN} is better. Non-stationarities in the data records affect the values of C_{PMIN} in wake regions (Fig. 14, Table 2).

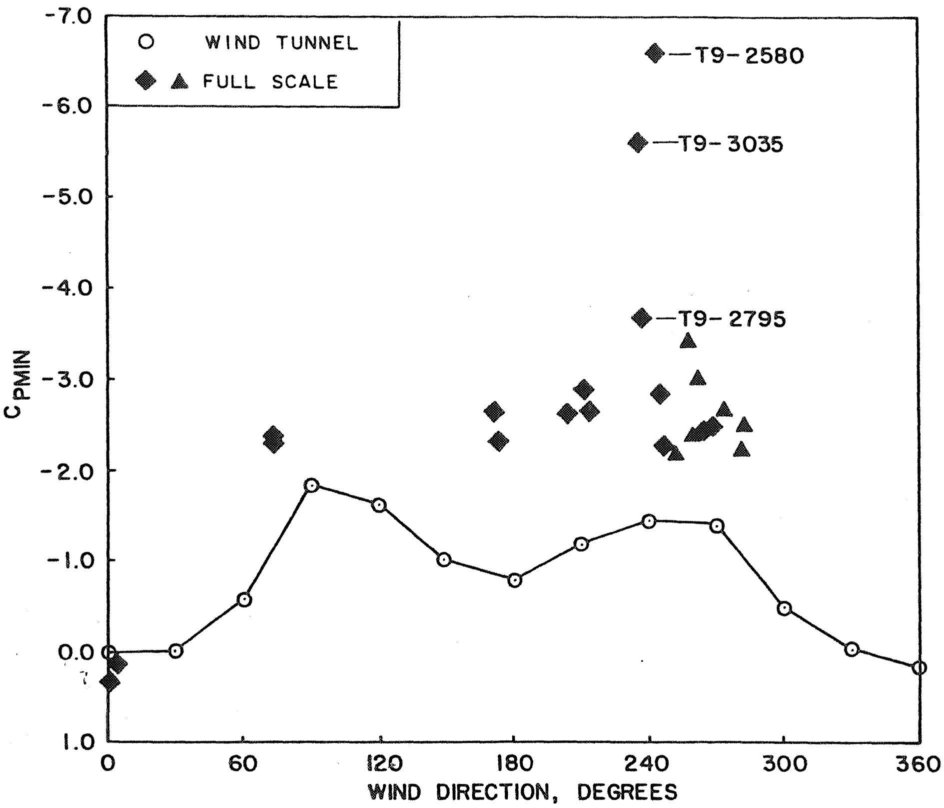


Fig. 14. Comparison of minimum pressure coefficients for the wall of the Price's Fork experimental building.

3.2.5 The effect of non-stationarities

The velocity time-histories of the three data records marked on Figs. 5, 8, 11 and 14 (Price's Fork data) show a non-stationary character in the form of low-frequency fluctuations and short-duration gusts [1]. The non-stationary nature of the three data records (T9-2580, T9-2795 and T9-3035) is supported by the fact that their turbulence intensities and their values of C_{PRMS} and C_{PMIN} are larger than those for the more stationary record, T9-2320 (Table 2). Agreement for the mean pressure coefficients between full scale and model is excellent for the stationary record but for the non-stationary records C_{PMEAN} is 25—50% larger than the model value. For the stationary record, C_{PRMS} is approximately twice the model value, and for the three non-stationary records, C_{PRMS} is about three to four times as large as the model value. Similar observations can be made for the peak pressure coefficients.

The full-scale/model comparison of the Price's Fork wall pressure record shows the following trends;

	Wake regions	*Stagnation regions*
C_{PMEAN}:	Full-scale more negative than model, both negative	Full-scale larger than model, both positive
C_{PRMS}:	Full-scale larger than model and stationary full-scale records	Full-scale larger than model
C_{PMIN}:	Full-scale more negative than model and stationary full-scale records	Full-scale and model approximately equal
C_{PMAX}:	Full-scale and model approximately equal	Full-scale larger than model

With these general observations for the Price's Fork wall pressure coefficients as reference, the Aylesbury wall data can be analyzed and the following observations made. All pressure coefficients associated with records A31B and A35F (see Table 3 for the corresponding wind directions) show an excellent agreement with model results. For record A32, the pressure coefficients from tap 3WW2 match the model results extremely well, while for the tap 3EW2 appreciable deviations exist between full-scale and model results.

TABLE 3

Aylesbury records used for comparison of pressure coefficients [4,5]

Record	Wind direction, θ (degrees)	
	Location 3WW2 or WR3B	Location 3EW2 or ER2E
A5	040	—
A7	005	—
A11	035	—
A25B	350	170
A31B	090	270
A32	005	185
A35F	062	242
A38G	022	202

For records A25B and A38G the deviations of the pressure coefficients for tap 3WW2 (stagnation region) and for tap 3EW2 (wake region) occur in the same fashion as those in the Price's Fork non-stationary records. From these observations one can draw the conclusion that records A31B and A35F appear to be stationary and records A38G and A25B appear to be non-stationary, and also that record A32 is stationary but that tap 3EW2 during this run was probably not functioning properly.

With these observations as reference, the corresponding full-scale pressure coefficients for the roof pressure taps WR3B and ER2E indicate the following. For records A31B and A35F the pressure coefficients obtained from tap ER2E match the model data extremely well. Relatively large full-scale/model discrepancies exist for the pressure coefficients of tap WR3B for the same records. For record A32, tap WR3B, only the r.m.s. pressure coefficient deviates from the model value, while for tap ER2E the full-scale/model agreement is good. For record A38G large full-scale/model discrepancies exist for both taps. For records A5, A7 and A11, pressure coefficients are only available for tap WR3B. The pressure coefficients from this tap for records A5 and A7 deviate considerably from the model values, similarly to those in wall stagnation regions. On the other hand the full-scale/model agreement of the pressure coefficients for tap WR3B for run A11 is excellent. These observations seem to indicate that certain records, e.g. A31B, A35F and A11, are stationary, and other records, e.g. A5, A7, A25B and A38G, are non-stationary. Additional full-scale/model discrepancies may exist as a result of improper functioning of equipment.

Observations of the Price's Fork wall data seem to indicate that differences in full-scale/model pressure coefficients exist as a result of non-stationarities in the data records (T9-2580, T9-2795 and T9-3035, Figs. 5, 8, 11 and 14, Table 2). Differences in full-scale/model mean pressure coefficients exist only for the three non-stationary records (Fig. 5). For those data records for Price's Fork which do not exhibit a non-stationary character, a second difference in r.m.s. pressure coefficients (Fig. 8) and maximum and minimum pressure coefficients (Figs. 11 and 13) can be observed for all wind directions. For the Aylesbury records A31B and A35F, no systematic full-scale/model differences in r.m.s., maximum and minimum pressure coefficients exist for any wind direction.

The terrain at the Price's Fork site may be classified as complex — with rolling upstream terrain and a mountain ridge 6 km upstream for the reported wind directions. Turbulence measurements made at Rock Springs, PA with similar upstream terrain [10,11] indicate clearly that the turbulence intensity of the horizontal components does not vary only with roughness length (z_0), but that complex terrain introduces additional turbulent energy in the low-frequency range. These low-frequency fluctuations cannot easily be simulated in the wind tunnel at the present time. Consequently it is believed that the differences in the Price's Fork full-scale/model comparisons of C_{PRMS}, C_{PMAX}, C_{PMIN}, are due mainly to the inadequate modeling of the effect of complex terrain on the horizontal wind fluctuations.

4. Conclusions

4.1 Aylesbury model studies at V.P.I.S.U. and U.W.O.

In spite of the different flow-modeling techniques used in the two laboratories, excellent agreement exists for any of the local pressure coefficients.

The use of local pressure coefficients is preferable to use of pressure coefficients based on a reference velocity at 10-m height unless extreme care is taken in duplicating the mean velocity profile in the wind tunnel.

4.2 Price's Fork: full-scale/model comparison

Full-scale/model differences exist as the result of non-stationary data records.

Additional differences between full-scale and model values of C_{PRMS}, C_{PMAX} and C_{PMIN} are thought to be the result of inadequate modeling of the mesoscale features of the upstream terrain.

Full-scale/model differences of the pressure coefficients for wake and stagnation regions seem to occur in a predictable manner.

4.3 Aylesbury: full-scale/model comparison

For some records the agreement between full scale and model is excellent, for other records differences exist which are similar to those observed for the Price's Fork wall data under non-stationary wind conditions.

Evidence exists that discrepancies may also exist as a result of malfunctioning of the full-scale test equipment for certain data records.

4.4 General conclusions

As a result of the comparison of the full-scale experiments at Aylesbury and Price's Fork with the model tests at Virginia Polytechnic Institute and State University and the University of Western Ontario, it is concluded that model mean, r.m.s. and peak pressure coefficients are likely to be in agreement with full-scale results if:

(1) local pressure coefficients are used;

(2) the streamwise turbulence intensity is modeled adequately up to an elevation of at least two building-heights;

(3) the streamwise turbulence integral scale is at least as large as the largest model dimension;

(4) mountain ridges, rolling upstream terrain, and changes in nearby surface elevation are modeled adequately;

(5) the full-scale data records do not exhibit non-stationary character such as low-frequency components and/or short-duration gusts.

It is possible that data reduction techniques may be developed for the full-scale records in order to take into account non-stationary effects. Also, improved wind-tunnel modeling techniques should be established to include the effects of mesoscale terrain features on the horizontal velocity components. Such developments may help to resolve the full-scale/model comparison of local pressure coefficients. It is also possible that some of the differences between model and full scale in the wake regions could be caused by Reynolds-number effects. Sufficient data do not exist to examine these possible causes, but further studies to address these issues might be considered.

References

1 H.W. Tieleman, R.E. Akins and P.R. Sparks, An investigation of wind loads on solar collectors, College of Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, Dept. Eng. Mech. Sci., VPI-E-80-1, January 1980 (available from Natl. Tech. Inf. Serv. as PB 80158744).

2 L. Apperley, D. Surry, T. Stathopoulos and A.G. Davenport, Comparative measurements of wind pressure on a model of the full-scale experimental house at Aylesbury, England, J. Ind. Aerodyn., 4 (1979) 207—228.

3 D. Surry, Measurement of wind pressure on a model of a two-storey building, unpublished report, Boundary-Layer Wind Tunnel Laboratory, University of Western Ontario, London, Ont., Canada (private communication).

4 K.J. Eaton and J.R. Mayne, The measurement of wind pressures on two-storey houses at Aylesbury, J. Ind. Aerodyn., 1 (1975) 67—109.

5 K.J. Eaton, J.R. Mayne and N.J. Cook, Windloads on low-rise buildings — effects of roof geometry, Build. Res. Establ. (U.K.), Curr. Pap. CP1/76, January 1976.

6 J.D. Holmes and R.J. Best, Pressure measurements on wind tunnel models of the Aylesbury experimental house, Wind Eng., 2 (1978) 203—220.

7 M.E. Greenway and C.J. Wood, Wind tunnel pressure measurements on the Aylesbury low-rise housing estate, Department of Engineering Science, University of Oxford, Rep., 1213/1977, 1271/1978 and 1272/1978.

8 R.E. Akins, Wind pressures on buildings, Ph.D. Dissertation, Colorado State University, Fall 1976 (available from University Microfilms, Ann Arbor, MI).

9 H.W. Tieleman and T.A. Reinhold, Wind tunnel model investigation for basic dwelling geometries, College of Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, Dept. Eng. Mech. Sci., VPI-E-76-8, 1976.

10 H.A. Panofsky, C.A. Egolf and R. Lipschutz, On characteristics of wind direction fluctuations in the surface layer, Boundary-Layer Meteorol., 15 (1978) 439—446.

11 H.A. Panofsky, M. Vilardo and R. Lipschutz, Terrain effects on wind fluctuations, Proc. 5th Int. Conf. on Wind Engineering, Colorado State University, Fort Collins, CO, 1979, Vol. 1, Pergamon, 1980, pp. 173—179.