FULL-SCALE TESTING OF ROOFING PERFORMANCE

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Recent experiences with Hurricane Hugo (September 1989) drew attention to the need for better roofing performance in high winds. Much of the damage to residential and light commercial buildings was attributed to roofing damage and subsequent damage from wind and rain to building contents. A cooperative research program between Texas Tech University and Colorado State University is addressing roofing performance in one of the eight tasks being considered.

At Texas Tech University a 30 x 45 ft. (9.2 x 13.7 m) metal building is mounted on a circular track so that it can be rotated to any angle of attack relative to wind direction. The building is instrumented with the latest technology in pressure and force measuring transducers. One of the primary objectives of the project is to obtain full-scale measurements of roof pressures that can be compared with model measurements in a wind tunnel. The performance of single-ply, mechanically-attached and loose-laid ballasted roofs is being studied on the full-scale building. A preliminary study of paver blow-off is also underway. The pavers are scaled to blow off at wind speeds in the 30-35 mph (13.4—15.6 m/s) range. Such speeds are not uncommon at the test site.

Information gained from this study is useful in understanding the full-scale behavior of roofing systems. The information will be used to validate wind tunnel results and to evaluate the effectiveness of proposed dynamic performance tests.

INTRODUCTION

Hurricane Hugo, which struck the coast of South Carolina on September 23, 1989, confirmed that some proprietary roofing systems in use today are incapable of resisting hurricane winds. Damage investigations after the storm revealed that the majority of wind-related property damage was caused by failure of roofing systems and subsequent damage to building interiors by wind and rain.[1]

Roof damage was extensive, despite the fact that wind speed measurements during the storm in the Charleston, South Carolina vicinity were less than design wind speeds specified by the jurisdictional building code (SBCCI, 1986). Figure 1 shows measured and design wind speeds at selected locations. Wind speeds are fastest-mile at 10m height in open terrain exposure. A variety of roofing systems in use experienced various degrees of damage, including asphalt and metal shingles, clay tile, metal, built-up, and single-ply roofs. Causes of failure were attributed to:

- Insufficient design attention.
- Insufficient strength of the roofing material.
- Inadequate fastening (incorrect size, type or spacing).
- Improper installation.
- Poor maintenance.

In many cases, a lack of understanding of the dynamic loading by the roof designer or contractor contributed to the failure. Windstorm damage prior to Hugo, as well as the Hugo experience, points to the need for additional research. Even before Hugo, a number of organizations within the U.S. roofing industry recognized the need for additional research. Two workshops were organized to exchange information and to hear discussions on topics dealing with wind effects on roofs. The Proceedings of the Second Workshop recognized several important issues:

- There is no comprehensive understanding in the industry of the dynamics of wind phenomena.
- There is inadequate field data on the wind's effect on roof performance.
- The correlation between field performance and laboratory testing is poor.
- Procedures for laboratory testing and field testing are inadequate for many roofing systems.[2]

The need for full-scale measurements was evident even before the workshops focused on the roofing problems. A study of roofing performance in both full-scale and in the wind tunnel was identified as one of eight tasks in the Cooperative Program in Wind Engineering (CPWE) between Colorado State University and Texas Tech University. The five-year program is sponsored by the National Science Foundation. This paper presents preliminary results of full-scale measurements of wind pressures on the roof of a building with simple geometry in an open terrain exposure. The full-scale pressure data will be used as bench marks for comparing pressures measured in wind tunnel tests. The characteristics of the full-scale pressures also will be useful in developing and evaluating dynamic tests for mechanically-attached single-ply roofing systems.

The Wind Engineering Research Building (WERB), located on the campus of Texas Tech University in Lubbock, Texas, is being used to obtain roof pressures produced by the natural wind. This paper describes the test facility and a planned series of experiments to measure wind pressures on the building roof with and without a single-ply roofing membrane in place. A preliminary study of paver blow-off is also described.

BACKGROUND

A small number of full-scale tests have been conducted in the field to assess wind pressures on surfaces of low-rise buildings. Probably the best known of these is the measurement of wind pressures on an experimental building at Aylesbury in the United Kingdom.[3] Analysis of the data at a later date revealed uncertainties in the collected field data.[4,5] Marshall measured wind pressures on a residential building in Montana,[6] on small buildings in the Philippines[7] and on a mobile home in Gaithersburg, Maryland.[8] Analysis of field and wind tunnel data for the mobile home indicated that high frequency pressure responses in the field are not always evident in the wind tunnel tests.[9,10] None of these projects had simultaneous and coordinated testing in the field and in the wind tunnel. This lack of coordination prevented adjustment of field instrumentation for reference pressure and a check on wind tunnel simulation of the boundary layer wind. The Silsoe Building in the United Kingdom is another example of a building constructed for the purpose of full-scale measurements.[11]

The field experiment project at Texas Tech University provides an opportunity to compare wind pressures obtained in field measurements with those measured in the wind tunnel. The comparison permits adjustment of instruments in field work, assessment of scale effects in the wind tunnel, repetition of measurements at critical locations, and calibration of wind tunnel pressure measurements.

If reasonable correlations are obtained between full-scale and wind tunnel measurements of pressure on buildings with simple geometry, then confidence can be built on wind tunnel measurements of more complex low-rise structures. The complex structures are more easily tested in the wind tunnel than in full scale.

TEST FACILITY

The WERB is designed to obtain a reliable data base of wind pressures on low-rise building surfaces, including roofs. To accomplish this objective, a facility consisting of a 30 x 45 ft. by 13 ft. (9.2 x 13.7 m by 4.0 m) high metal building and a 160 ft. (48.8 m) high meteorological tower were constructed at a location on the Texas Tech University campus where the terrain is flat and open (see Figure 2). The building is supported on a circular track so that it can be rotated to a desired angle of attack of the wind. The building surface is penetrated with pressure taps to record surface pressures using differential pressure transducers. Pressures can be measured both above and below roof membranes and pavers. Extreme care is taken to provide a stable reference pressure for the differential transducers. For additional details of the WERB, see Reference 12.

The meteorological tower is located near the building. The tower is instrumented at different levels above ground: wind speed is measured at 13, 33, 70 and 160 ft. (4.0, 10.0, 21.3, 48.8 m) above ground; wind direction sensors are located at 33 and 160 ft. (10 and 48.8 m); temperature sensors are at 30 and 160 ft. (9.2 and 48.8 m); relative humidity and barometric pressure gages are located at 13 ft. (4 m) above ground. These instruments provide sufficient information to assess wind profile, wind turbulence level, air density, stability of the atmosphere and ground roughness.

The data acquisition system consists of a microcomputer, an A/D converter and optical disk drives. The computer is located in a controlled environment inside the test building. The computer is programmed to trigger and collect data automatically when high winds occur. The system is capable of taking readings at a rate of 1200 Hz. Approximately 60 channels are available for meteorological and wind pressure data collection. Typically, data is collected at 10 Hz for periods of 15 minutes.

WIND PRESSURE MEASUREMENTS

The WERB has smooth sheet metal cladding on its walls and roof. For this study, nine pressure taps were installed in one corner of the roof. Wind pressure measurements have been collected over a period of 11 months, whenever the one-minute average wind speed reached 25 mph (11.2 m/s) or more. Typical records run 15 minutes in duration. In some cases, the building is rotated to a desired angle of attack. In others, when the system triggers automatically, the angle of attack is dependent on wind direction and building orientation prior to the storm. A systematic procedure is established to identify and screen each 15-minute record. Tests for anomalies are made to assure transducers are operating properly and that no rain water has collected in the pressure tubes. Data are displayed in a number of different formats, examples of which are shown later. The massive amount of data is being analyzed at this time.

Meteorological measurements from the meteorological tower are recorded simultaneously with the pressure measurements. The records are first screened for anomalies and then are processed by an established procedure that normally includes a calculation of the wind profile, turbulence intensity and a time history plot of wind speed at one or more levels. Records at 13 ft., which is building height, are usually of the most interest. Wind speed and wind direction (angle of attack) are checked for stationarity. A total of 287 15-minute records have been recorded between July 13, 1989 and May 20, 1990.

TEST RESULTS

Time histories of wind speed, wind direction and wind pressure at Tap 50501 are shown in Figure 3.

The variation of mean pressure coefficient with angle of attack from Tap No. 50501 is displayed in Figure 4. The averaging time for the mean pressure coefficient is 15 minutes. The tap is located five feet from the roof corner and one foot from the edge (see Figure 4).

The wind pressure characteristics are equivalent to the pressures on the top surface of a single-ply membrane roof. Later, a single-ply roof with pavers will be installed over one-fourth of the roof surface and pressure taps will be used to measure pressures underneath the membrane and underneath the pavers. Plans also include instrumentation of selected pavers to determine net uplift and overturning moments acting on a single paver.

PAVER BLOW-OFF

Several researchers have attempted to model paver blow-off in the wind tunnel.[13,14] As part of the CPWE project, a small experiment to correlate paver blow-off in full-scale and wind tunnel was devised. Because wind speeds in excess of 75 mph (33.5 m/s) would be needed in full-scale to blow off actual pavers weighing approximately 10 psf, the full-scale pavers are modeled by reducing their weight through dimensional analysis so they will blow off in 25-30 mph (11.2-13.4 m/s) wind. The modeling is accomplished by using 24 x 18 in. (610 x 457 mm) plywood boards that are 3/8 in. (9.5 mm) thick. The model pavers will be replaced in one corner of the roof and will be restrained by weights that can be quickly removed. As the wind speed approaches approximately 20 mph (8.9 m/s), the building will be oriented so the angle of attack is approximately 180. Wind uplift pressures near the corner should be low in this orientation. The weights will be removed and the building will be rotated to an angle of attack of 225 (45 relative to corner). Wind speed and direction will be monitored and a video camcorder will record the blow-off. A time clock will be used to correlate video with wind speed measurements. At the time of this writing (July 1990), the experiment is in place awaiting an overdue windy day in Lubbock, Texas.

CONCLUSIONS

A full-scale test facility is in place to measure wind pressures on mechanically-attached and paver-ballasted single-ply roofing systems. The building is designed to produce a reliable data base of wind pressure measurements. Instrumentation has been carefully designed, calibrated and maintained to produce reliable results that can be used to compare with similar tests in the wind tunnel.

Almost 300 15-minute records have been collected to date. Angles of attack of the wind range from 180° to 270°. The data are being processed and archived for use by researchers in the future who wish to compare or calibrate wind tunnel measurements and to devise or evaluate standard dynamic testing procedures for mechanically attached single-ply roofing systems.

ACKNOWLEDGEMENTS

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REFERENCES

1 McDonald, J.R. and Smith, T.L., 1990: "Performance of Roofing Systems in Hurricane Hugo," IDR Doc. 91D, Institute for Disaster Research, Texas Tech University, Lubbock, Texas.

2 Courville, G.E. and Gillis, P.S. (Ed.), 1990: Proceedings of the Roof Wind Uplift Testing Workshop, CONF-891173, Oak Ridge National Laboratory, Oak Ridge, Tenn.

3 Eaton, J.K. and Mayne, J.R., 1975: "The Measurement of Wind Pressures on a Two-Storey House at Aylesbury," Journal of Industrial Aerodynamics, Vol. 1, No. 1, pp. 67-109.

4 Holmes, J.D., 1983: "Wind Loads on Low-Rise Buildings—A Review," CSIRO, Division of Building Research," Highett, Victoria, Australia.

5 Vickery, P.J., 1984: "Wind Loads on the Aylesbury Experimental House: A Comparison Between Full-Scale and Two Different Scale Models," Master of Engineering Science Degree, Faculty of Graduate Studies, The University of Western Ontario, London, Canada, 443 pp.

6 Marshall, R.D., 1974: "A Study of Wind Pressures on a Single-Family Dwelling in Model and Full Scale," NBS Technical Note 852, National Bureau of Standards, Washington, D.C.

7 Marshall, R.D., Simiu, E., Ettal, S.G., Kowalski, J.G. and Kliment, S.A., 1977: "Building to Resist the Effect of Wind," NBS Building Science Series 100, Vol. 1-5, National Bureau of Standards, Washington, D.C.

8 Marshall, R.D., 1977: "The Measurement of Wind Loads on Full-Scale Mobile Homes," NBSIR 77-1289, National Bureau of Standards, Washington, D.C.

9 Marshall, R.D. and Reinhold, T.A., 1982: "Discussion of Effective Wind Load on Flat Roofs by T. Stathopoulos, D. Surry and A.G. Davenport," Journal of the Structural Division, Vol. 108, No. ST2, ASCE, New York, N.Y., pp. 495-498.

10 Johnson, G.L. and Surry, D., 1985: "Wind Tunnel Tests of a Mobile Home and Comparison with Full-Scale Data," Proceedings of the Fifth U.S. National Conference on Wind Engineering, Texas Tech University, Lubbock, Texas, pp. 3B:49-56.

11 Hoxey, R.P., 1989: "Structural Response of Portal Framed Building Under Wind Load," Proceedings of 8th Colloquium on Industrial Aerodynamics, Fluid Mechanics Laboratory, Fachhochschule, Aachen, Germany.

12 Levitan, M.L., Mehta, K.C., Chok, C.V. and Millsaps, D.L., 1989: "An Overview of Texas Tech's Wind Engineering Field Research Laboratory," Proc., Sixth U.S. Conference on Wind Engineering, A. Kareem, Ed. (Houston, Texas, March 8-10, 1989), University of Houston, Houston, Texas.

13 Okada, H. and Okabe, M., 1989: "Wind Tunnel Tests on Wind Forces on Roof Blocks Setting on Roof of Existing Buildings," Proceedings of 8th Colloquium on Industrial Aerodynamics, Fluid Mechanics Laboratory, Fachhochschule, Aachen, Germany.

14 Bienkiewicz, B. and Meroney, R.N. 1985: "Wind Tunnel Study of Westile Ballast Paver," Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colo.

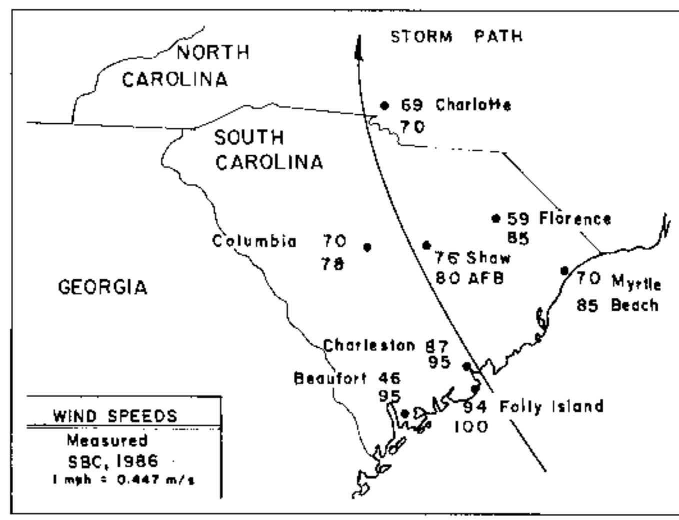

Figure 1 Map of South Carolina showing measured and Standard Building Code (1986) design wind speeds (fastest-mile winds).

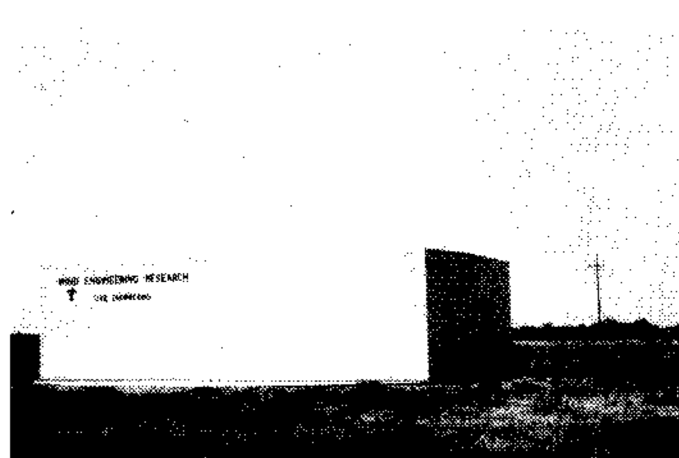

Figure 2 Texas Tech University Wind Engineering Research Building (WERB).

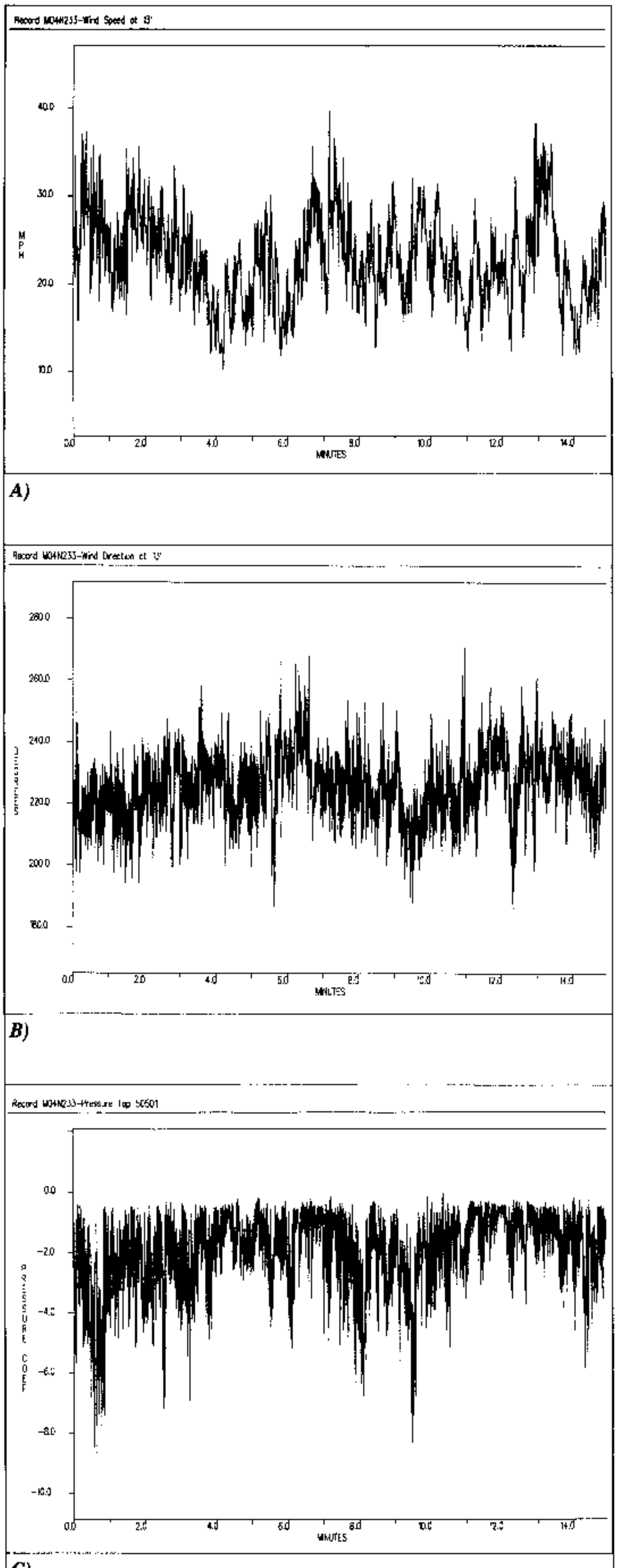

Figure 3 *Time Histories. a) wind speed b) wind direction c) wind pressure.*

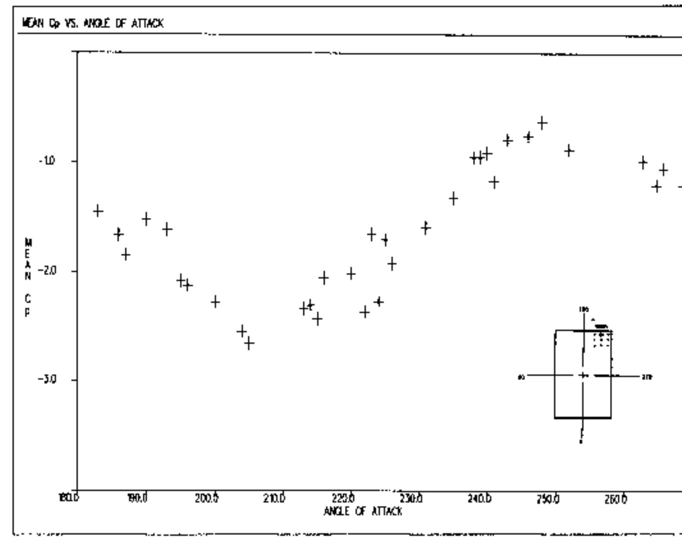

Figure 4 *Mean Cp vs. angle of attack (15-minute records).*