

**APPLICATIONS OF WIND TUNNELS TO INVESTIGATIONS OF
WIND EFFECTS ON ROOFS AND ROOF COVERINGS**

by

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Paper presented at

Session on Wind Loading on Structures
1986 Spring ASCE Annual Meeting
7 April 1986
Seattle, Washington

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ABSTRACT:

Wind blown debris from roofs result in major building damage and failure during severe wind storms. Typically roofs are only 2% of a building cost, but their failure represents about 25% of the hazard related lawsuits. The response of different types of roofing systems to wind loads induced by high wind speeds can be investigated in wind tunnels. This paper reviews fluid model experiments which have identified the primary failure mechanisms of roofs covered by various combinations of single-ply membranes, tiles, pavers, insulation boards and gravels. New data are presented on the uplift performance of pavers with overlap joints, the advantages of paver clips, and the influence of exposure and parapet height on paver movement.

1.0 INTRODUCTION:

Roofs are subject to forces of nature such as the sun, wind, rain, snow and hail. The sun can cause ultraviolet damage to the surface; whereas wind, snow and hail can cause loss of containment and permit penetration of rain and cold. In addition roofs must resist the ravages of fire, and accidental puncture, abrasion and vandalism by man. Thus, the ideal roof should be light, fire resistant, ultraviolet light safe, and walkable. It should resist wind-induced failure, and its structure should permit routine inspection.

Man has ingeniously used many surfaces for roofs ranging from earth to ice, but most new, commercial flat-roofed buildings today have built-up roofs (BUR), single-ply-membrane roofs (SPM), modified bitumen roofs (MB), or liquid-applied systems (LAS). Characteristics of metal membrane roofs are not included in this review. Built-up roofs are made from layers of felt, asphalt tar, and stones laid over

a support deck. Proponents for other systems claim these traditional roofs are not cost effective and require the most roof-top work, use expensive oil-asphalt products, split and blister under thermal shock, and require costly double layers of insulation to meet increased insulation standards. Nonetheless, BUR retain 42% of the roofing market ⁶.

Single-ply roofs now share 34% of the roof market. They are made from prefabricated layers of insulation or insulation boards, a single-ply elastomeric plastic or rubber membrane, and a top ballast of gravel or paving blocks. Still newer, and occupying a 15% market share is the modified bitumen membrane composed of one or more prefabricated plies of fiberglass or polyester, each ply coated on both sides with a polymer filled bitumen. The MB membranes are affixed to the roof either by torch or hot-applied bitumen. The remaining 9% of the roof market belongs to liquid-applied systems such as polyurethane foams.

Roof ballast materials dislodged during wind storms caused major damage to windows and building cladding during the 1983 Hurricane Alicia in Houston.⁹ Although most damage was associated with loose pea gravel from BUR roofs, roofing manufacturers and code officials became concerned about the integrity of all ballasted roofs. Since 1972 wind tunnel experiments have been performed on the behavior of ballasted roofs. The present paper reviews past wind-tunnel experiments reported by various researchers. It also describes a recent wind-tunnel study of a ballasted roof failure conducted by the authors. Section 1.1 reviews the character of ballast on BUR and SPM roofs, section 1.2 reviews the results from previous fluid model experiments. Section 2.0 summarizes similarity requirements for fluid

modeling of roof ballast systems; whereas, sections 3.0 and 4.0 report paver behavior for overlapping and edge clipped pavers under different wind exposures and parapet heights. Incorporation of fluid model results into code statements is provided in section 5.0.

1.1 Ballast Characteristics

BUR typically are constructed from crushed rock, slag, or pea gravel about 3/8 inch diameter. Most of this material is adhered together with bitumen. SPM are ballasted with loose stone or gravel no smaller than 3/4 inch or even larger concrete pavers or tiles. SPM manufacturers conventionally lay large insulation boards over a supportive deck. Next, an elastomeric membrane is stretched from roof edge to roof edge, and then ballast is loose laid over the membrane. Sometimes the membrane is placed beneath the insulation. The membrane is glued or mechanically fastened to the underlying surface, or, alternatively, sealed just at the edges of the roof.

Gravel ballast on SPM roofs are usually round river stones ranging from 1 to 3 in. (25.4 to 76.2 mm) diameter. Crushed stones, slag, or other sharp edges stones are not allowed because of abrasion to the membrane. Gravel ballast typically weighs between 10 to 25 lb/sf (479 to 1198 N/sq m), and layer thickness varies from 1 to 5 in. (25.4 to 127.0 mm). Paving stones are usually square or rectangular pavers cast to provide drainage on the underside. Sometimes they include interlocking edges or other special (usually patented) features. Paver weights range from 11 to 25 lb/sf, and their sizes range from 12 x 12 x 2 in. (0.30 x 0.30 x 0.05 m) to 24 x 24 x 3 in. (0.61 x 0.61 x 0.075 m) and larger. In some cases pavers are prefabricated with insulation bound to the under-side in sizes up to 4

x 8 ft (1.22 x 2.44 m) sheets.

1.2 Fluid Modeling Experiments

Wind-tunnel modeling of gravel ballast failures have been performed by Durgin et al. (1972) using lead shot, and by Kind and Wardlaw (1976), Kind (1974, 1977, 1985), and Kramer et al. (1979) using natural gravel.^{10,11,12,14,18} They studied gravels with equivalent sizes ranging from 1.5 to 2.8 in. (38 to 75 mm). The upper wind speed limit for gravel to resist scour at building orientations of 45° was found to be between 50 to 60 mph (22 to 27 m/s) at a 30 ft (10 m) elevation. Replacing corner regions with ballast pavers in a gravel/paver composite arrangement allowed speeds to increase to over 100 mph (45 m/s) before significant scour occurred. Kind (1985) determined that model gravel as small as 0.004 in. (0.1 mm) can be used in model experiments; thus, useful results are possible from fluid modeling for scale ratios as large as 1:120.¹²

Ballast paver experiments have been performed by Kind et al. (1974, 1982, 1984) and Bienkiewicz and Meroney (1985).^{2,10,13,16} Tests included pavers with and without overlapping, pavers with and without taped or fixed joints, parapets of heights varying from 0 to 36 in (0 to 0.91 m), and effects of water pooling. Kind et al. also studied larger insulation boards and membrane behavior under the ballast.

Membrane experiments have been made by Durgin and Allan (1981) and Kramer et al. (1979).^{5,18} Durgin and Allan examined lift forces on mechanical tie-downs on an unballasted roof; whereas, Kramer et al. examined the effects of membrane damage on unballasted roofs with suction pressures maintained on the bottom membrane surface.

2.0 SIMILITUDE REQUIREMENTS FOR FLUID MODELING OF ROOF BALLAST SYSTEMS

Dimensional analysis and similarity considerations indicate that similitude for fluid modeling of roof ballast systems will be achieved if the wind approaching the model simulates the natural wind, if all model dimensions are correctly scaled, and if the Reynolds number, UL/ν ; the Froude number, U^2/gL ; and density ratios of air and ballast materials have the same numerical values in both the model and prototype situations. It is impossible to match both the Reynolds and Froude numbers in a fluid model experiment, but fortunately it is well established that flows over sharp edged building shapes are independent of Reynolds numbers for moderately high wind speeds.

In the case of thin objects such as insulation boards or pavers scaling of the density ratio can be relaxed and replaced by the similarity requirement that the weight per unit area ratios be the same for model and prototype, or $(\rho t)_m/(\rho t)_p = L_m/L_p$, where ρ is paver density, t denotes paver thickness, and the subscripts m and p denote model and prototype respectively. The adjustment of model paver thickness and density permits the use of convenient modeling materials to represent both the prototype concrete paver and/or foam insulation boards.

The remaining similarity requirement--the Froude number--is satisfied when the wind speed scale, λ_v , and the geometrical scale, λ_L , are related as:

$$\lambda_v = (U_m/U_p) = \lambda_L^{1/2} = (L_m/L_p)^{1/2}.$$

This relation can be used to compute the prototype wind speed corresponding to a given wind tunnel speed.

3.0 WIND EFFECTS ON ROOF BALLAST SYSTEMS

Wind accelerating over a roof top produces low pressure patterns which can combine with internal building pressures to produce a net local uplift on a roof element. Roof pressures are a function of building height, exposure, building orientation, parapet heights, and other roof top features such as elevator housings, stairwell covers, and cooling towers. Very little full scale information is available on roof pressures; hence, the flow situation is understood primarily from wind-tunnel measurements.^{3,8,12,17,20}

3.1 Features of the Roof Pressure Field

Maximum negative values of pressure coefficient, $C_p = (p-p_o)/(\rho U^2/2)$, occur for a rectangular building when its corners are aligned at a 45° angle to the approach wind. In this case twin vortex "tornadoes" form which produce minimum pressures near the building edges in the region of the upwind corner. Minimum mean C_p values lie between -3 and -4 for an unparapeted building. Ballast movement actually occurs as a result of short period gusts which exceed the mean wind speed, and consequently produce local maximums in lift pressure. Very little information is available about such pressure fluctuations, their size, their persistence, and how they relate to the gusty approach wind. First expectations might be that a building parapet should increase sheltering and reduce roof loads. Wind-tunnel measurements made by Stathopoulos (1982), and Stathopoulos and Baskaran (1985) suggest that small parapets may, in fact, actually increase roof loads over pavers substantially.^{19,20} In general parapets do reduce the maximum suction on the roof edges, but they slightly increase the magnitude of suction on the interior areas of

the roof. Yet roof corner suction actually increase significantly for low parapet heights [0 to 6 in. (0 to 152 mm)], and low parapets spread suction minimums over larger areas; thus increasing the likelihood that uplift exceeds paver or ballast weight. As parapet height increases true sheltering occurs, and the region where ballast uplift occurs moves downwind from the corner.

3.2 Response of Ballast to Pressure Fields

Ballast gravel is usually blown toward low pressure regions and away from the corner diagonal. Once the ballast is removed from the single-ply membrane, it may balloon, ripple, or tear. Often the gravel accumulates against the back face of the upwind parapet, or the gravel is actually caught up into the low pressure regions and catapulted off the roof.

For loose laid ballast systems the pressure field communicates to regions beneath the pavers by means of the cracks between the ballast. The region beneath the paver responds almost instantaneously to changes in pressure above; however, the pressure tends to vary linearly between the joints. Since the pressure above the paver can have a minimum over mid-paver, the result is a net up-lift. This pressure difference can become large enough to lift the ballast materials off the roof.

Initial failure of roof pavers occurs about four feet downwind of the corner next to the parapet wall. The paver rotates about its roof-edge side, moves upwind, and then tumbles downwind in the windflow coming over the building edge. Once one paver is missing the remaining pavers shuffle into the low pressure region and also displace toward the parapet. If one edge of the paver is interlocked

beneath another block on the edge away from the wall, then the paver resists movement at lower wind speeds, and it is finally dislodged at much higher wind speeds.

3.3 Wind-tunnel Experiments on Interlocking and Edge Clipped Ballast Pavers

The performance of interlocking pavers and pavers with edge clips was evaluated during a wind-tunnel study conducted at the Fluid Dynamics and Diffusion Laboratory, Colorado State University. The study was conducted in the Industrial Aerodynamics Wind Tunnel, which is of recirculating type with a test section 6 x 6 ft (2 x 2 m) and 60 ft long (18 m). Model blockage effects can be resolved with an adjustable test-section ceiling. Simulated atmospheric boundary conditions are created by placing flow modifying spires at the entrance to the test section and a uniform fetch of roughness elements on the floor upwind of the model.

Model Building and Pavers - Model pavers were placed in various configurations on a roof of a model building chosen to simulate flow conditions on a typical flat roof. The building model with a typical parapet and model pavers is shown in Figures 1 and 2. The model at a scale of 1:15 represented a 15 ft (4.6 m) tall prototype building with a 22 ft square (6.7 m) flat roof. The size of the model was limited by the size of the wind-tunnel test section, and by the desire to maintain blockage below 5%. The model was configured with parapets of various heights. Model ballast pavers were made of plexiglass and dimensioned as noted in Figure 1b. An equivalent full scale paver which weighed 11 1/2 lb/sf (570 N/sq m) would have dimensions of 11 3/4 x 16 1/2 x 1 5/16 in. (0.358 x 0.419 x 0.033 m).

All experiments were performed for the critical 45° building orientation. Kind and Wardlaw (1982) indicated that the roof flow field is mainly dependent on the speed of the approaching wind at rooftop level.¹⁶ It was assumed that characteristics of the rooftop flow were only minimally dependent on building height to boundary layer depth ratio. A series of pretests performed over a zero-height-parapet building revealed that ballast movement correlated with rooftop wind speed for powerlaw exponents ranging from 0.1 to 0.3.

A modified configuration of the staggered pavers was also investigated to simulate the effects of mechanical metal clips attached between pavers in high-uplift regions. The pavers were arranged in a staggered pattern as noted in Figure 3, and then the outer pavers along roof edge AB were connected together by circular adhesive paper tabs attached to the upper and lower surfaces of the two adjacent pavers.

Flow Conditions - Two representative approach flow configurations were simulated. One of the configurations represented conditions typical for flow over open or rural country (Uniform Building Code - Exposure C, ANSI A58.1-1982 - Exposure C). The other situation modeled flow over built-up or urban terrain (Uniform Building Code - Exposure A, ANSI A58.1-1982 - Exposure A).^{1,7} The turbulent boundary layer generated by the spires, barrier and surface roughness was about 40 in. (1.0 m) deep at the model location. Figure 4 depicts the mean velocity and turbulent intensity profiles achieved at that location. Such velocity profiles are frequently described by an empirical power-law relationship, $U/U_{ref} = (z/z_{ref})^{\alpha}$. The model power law

coefficients, α , for the two cases are 0.14 and 0.37 for Exposures C and A respectively.

Test Procedure - During the wind-tunnel experiments the pavers were placed on the roof of the building model in a desired arrangement. Wind speed in the tunnel was gradually increased, and the behavior of the pavers was observed. Wind speed was measured by a pitot-static tube mounted at rooftop level of the model building. When a paver failure (dislocation) was observed, the wind-tunnel speed was recorded. The prototype wind speed, corresponding to the measured mean wind speed at paver failure was called the failure wind speed at roof height, and it was denoted by V_D . The paver failure wind speed, V_D , was averaged over several separate replications of each flow condition, paver configuration, and parapet height. It should be noted in passing that since the wind speed approaching the building model is turbulent, the paver failure is a random event initiated by peak velocities (greater than the mean), which are of sufficient spatial distribution and temporal duration to cause the paver or pavers to uplift.

4.0 RESULTS FROM FLUID MODEL EXPERIMENTS

The paver failure wind speed is summarized in Table 1 for three wind exposures, two paver configurations and five parapet heights. The failure wind speed depends on the paver configuration. It is higher for the modified configuration (staggered pavers with edge clips) than for the original configuration (unstaggered pavers without edge clips) The difference between the failure wind speed for the two configurations decreases as the parapet height increases. For parapet heights above 18 in. (0.46 m) failure wind speeds have the same

magnitude for the two configurations; however, it is entirely possible that the building depth to parapet height has become the limiting factor in the experiments.

4.1 Failure Mode of Ballast Pavers - Original Configuration

Failure wind speed at rooftop is plotted in Figure 5 as a function of the parapet height. The failure wind speed is higher for Exposure C than Exposure A. This suggests that an increase in turbulence level results in a decrease in the mean wind speed associated with the paver failure. The effects of the parapet height are similar for both exposure conditions. A relatively low height parapet (up to about 6 in.) causes a decrease in the failure wind speed, V_D ; whereas a parapet of greater height results in an increase in the failure wind speed. The failure mode of the pavers is very consistent. Failure was initiated when one or two pavers located in positions 1,4 or 1,5 as shown in Figure 6 dislodged. Then nearby pavers shuffled or vibrated sideways into this region, rotated toward the parapet and also dislodged. Eventually a large number of pavers in the roughly triangular region downwind from these positions also failed.

4.2 Failure Mode of Ballast Pavers - Staggered and Edge Clipped

Failure wind speed at rooftop for the modified configuration is plotted in Figure 7 as a function of the parapet height. Paver failure occurred at higher wind speed for the modified configuration. The character of the failure of the pavers arranged in the modified configuration also differed from the original configuration. Failure initiated near positions (1,4) or (1,5), but the failure was more

$$C_e(z) = \begin{cases} -1.11 \times 10^{-5} z^2 + 6.33 \times 10^{-3} z + 1.078, & z \leq 120 \text{ ft} \\ 1.433 + 2.22 \times 10^{-3} z, & z > 120 \text{ ft} \end{cases}$$

Exposure B:

$$C_e(z) = \begin{cases} -1.11 \times 10^{-5} z^2 + 6.33 \times 10^{-3} z + 0.558, & z \leq 120 \text{ ft} \\ 0.983 + 2.22 \times 10^{-3} z, & z > 120 \text{ ft.} \end{cases}$$

Given that $C_e(H) = C_H^2$, then the maximum permissible building height, H, can be calculated from Equation (1) for any exposure, design wind speed, and parapet height from Figures 5 or 7 for the paver geometries studied. Table 2 presents the result of such calculations for the UBC code. Situations resulting in building heights less than 10 ft high have been set to zero height.

5.2 Design Considerations Using ANSI Standard A58.1-1982.

The paver failure condition can be written in terms of the wind/load parameters specified by ANSI as $C_H^2 = K_z(H) G_z(H)$, where K_z is a pressure exposure coefficient and G_z is a gust response factor.¹ The pressure coefficient and the gust response factor are defined by ANSI as

$$K_z = \begin{cases} 2.58(z/z_g)^{2/\alpha}, & \text{for } z \geq 15 \text{ ft} \\ 2.58(15/z_g)^{2/\alpha}, & \text{for } z < 15 \text{ ft} \end{cases}$$

and

$$G_z = 0.65 + 0.35 T_z,$$

where

z = height (ft),

z_g = gradient wind height (ft),

α = velocity power law coefficient,

$T_z = 2.35 D_o^{1/2} / (z/30)^{1/\alpha}$, and

D_o = surface drag coefficient.

sudden, and more pavers were dislodged simultaneously. As noted in Figure 8, sometimes almost half of the roof tiles failed together after the edge clipped pavers buckled and displaced.

5.0 DESIGN CONSIDERATIONS FOR BALLAST INSTALLATION

The mean wind speed at the rooftop level at which paver failure occurs or failure wind speed, V_D , can be used to establish rough design criteria for the use of ballast pavers on roofs of typical low-rise buildings located within uniform surroundings as defined in codes and standards. A design wind speed, V_m , is specified by codes and standards as the mean wind speed at a height of 30 ft (10 m) above the ground. The peak wind speed used in design codes, V_H , at rooftop height H is related to the design wind speed by

$$V_H = C_H V_m, \quad \text{Eq (1)}$$

where C_H is a correction factor for variation in the mean wind speed and gustiness with height. It is proposed that a conservative condition for the paver failure for a building of height H would be $V_H = V_D$, ie. the peak velocity at rooftop would be assumed equal to the mean velocity at rooftop height during paver failure. Since the ratio V_H/V_D may reasonably be expected to be greater than 1.25, the approach involves a reasonable level margin of safety.

5.1 Design Considerations Using Uniform Building Code

The Uniform Building Code recommends a coefficient, $C_e(z)$, to correct for combined effects of height, exposure, and gust factor (Table No. 23-G, UBC (1982)).⁷ This factor may be approximated by the expressions,

The gradient height, z_g , the power law coefficient, α , and the surface drag coefficient, D_o , are specified by ANSI and summarized in Table 3. The numerical values computed for maximum permissible building height, H , are summarized in Table 4 for two paver configurations, three wind exposures, five parapet heights, and different values of the design wind speed.

5.3 Comparison of Results Obtained from UBC and ANSI Codes

The maximum building height for a 12 inch parapet computed using UBC (Section 5.1) and ANSI (Section 5.2) is compared for the wind exposures C and B in Figures 9 and 10 for the original and modified paver configurations. Maximum building heights, computed using the two approaches, are similar for the wind Exposure C, but the use of the UBC code leads to more conservative results for the wind Exposure B. The present study confirms observations made by Kind and Wardlaw (1979, 1982) that failure wind speed is dependent on wind exposure and associated turbulence intensity, parapet height, paver orientation, and the presence of paver interlocks.^{15,16}

6.0 CONCLUSIONS

The results of this study indicate that wind effects on and failure of ballast pavers are of a complicated nature; nonetheless, several observations and conclusions can be provided:

- a. The failure wind speed at rooftop is affected by wind exposure and parapet height.
- b. As the level of turbulence in the approach wind increases, the failure wind speed decreases.
- c. Low height parapets cause a reduction in the failure wind speed when compared with the failure speed for the zero height parapet.
- d. Moderate height parapetes result in an increase in the failure wind speed.
- e. Failure wind speeds are higher for staggered and edge clipped

- pavers than for unstaggered pavers without edge clips.
- f. Paver height and exposure affect the two paver configurations similarly.
 - g. The design methodology proposed results in conservative values for the maximum heights of buildings employing similar prototype pavers installed in similar wind field environments.
 - h. The results of this study are in agreement with the results of studies performed by other researchers.

REFERENCES:

1. American National Standards Institute (1982), Minimum Design Loads for Buildings and Other Structures, ANSI A58.1-1982, New York, NY.
2. Bienkiewicz, B. and R.N. Meroney (1985), "Wind-Tunnel Study of Westile Ballast Paver," Civil Engineering Report CER85-86BB-RNM13, Colorado State University, Fort Collins, CO, 98 pp.
3. Chien, N.; Feng, Y.; Wang, H.; and Siao, T.T. (1951), "Wind Tunnel Studies of Pressure Distribution on Elementary Building Forms," Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City.
4. Durgin, F.H., O'Neill, T.O., and Debout, B. (1972) ROOF LIFT OFF TESTS OF THE TROCAL ROOF SYSTEM FOR DYNAMIT NOBEL OF AMERICA, Wright Brothers Wind Tunnel TR 1062, Mass. Inst of Technology, Cambridge, 45 pp.
5. Durgin, F.H., and Allan, J. (1981), A WIND TUNNEL STUDY OF THE PRESSURE AND TIE-DOWN LOAD ON A TYPICAL MEMBRANE ROOF, Wright Brothers Memorial Wind Tunnel WBWT-TR-1135, Mass. Inst. of Technology, Cambridge, 83 pp.
6. Godfrey, K.A. (1986), "ROOF MEMBRANES: New Systems, New Problems," Civil Engineering/ASCE, Vol.56, pp. 76-79.
7. International Conference of Building Officials (1982), Uniform Building Code, Whittier, CA.
8. Jensen, M. and Franck, N. (1963), Model-Scale Tests in Turbulent Wind, Part I: Phenomena Dependent on the Wind Speed, Danish Technical Press, Copenhagen, 97 pp.
9. Kareem, A. (ed.) (1984), "Hurricane Alicia: One Year Later, Proceedings of", ASCE, Galveston, Texas, 16-17 August, 1984, 333 pp.
10. Kind, R.J. (1974), WIND TUNNEL TESTS ON SOME BUILDING MODELS TO MEASURE WIND SPEEDS AT WHICH GRAVEL IS BLOWN OFF ROOFTOPS, National Research Council Canada, National Aeronautical Establishment, Ottawa, LTR-LA-162, 32 pp.
11. Kind, R.J. (1977), FURTHER WIND TUNNEL TESTS ON BUILDING MODELS TO MEASURE WIND SPEEDS AT WHICH GRAVEL IS BLOW OFF ROOFTOPS, National Research Council Canada, National Aeronautical Establishment, Ottawa, LTR-LA-189, 17 pp.
12. Kind, R.J. (1985), MEASUREMENT IN SMALL WIND TUNNELS OF WIND SPEEDS FOR GRAVEL SCOUR AND BLOWOFF FROM ROOFTOPS, Proceedings of 6th Colloquium on Industrial Aerodynamics, Aachen, BRD, June 1985, pp. 197-212

13. Kind, R.J. Savage, M.G., and Wardlaw, R.L. (1984), FURTHER MODEL STUDIES OF THE WIND RESISTANCE OF TWO LOOSE-LAID ROOF-INSULATION SYSTEMS (HIGH-RISE BUILDINGS), National Research Council Canada, National Aeronautical Establishment, Ottawa, LTR-LA-269, 57 pp.
14. Kind, R.J. and Wardlaw, R.L. (1976), DESIGN OF ROOFTOPS AGAINST GRAVEL BLOW-OFF, National Research Council Canada, National Aeronautical Establishment, Ottawa, NRC No. 15544, 33 pp.
15. Kind, R.J. and Wardlaw, R.L. (1979), MODEL STUDIES OF THE WIND RESISTANCE OF TWO LOOSE-LAID ROOF-INSULATION SYSTEMS, National Research Council Canada, National Aeronautical Establishment, Ottawa, LTR-LA-234, 47 pp.
16. Kind, R.J. and Wardlaw, R.L. (1982), FAILURE MECHANISMS OF LOOSE-LAID ROOF-INSULATION SYSTEMS, Journal of Wind Engineering and Industrial Aerodynamics, Vol. **9**, pp. 325-341
17. Kramer, C. (1985), WIND EFFECTS ON ROOFS AND ROOF COVERINGS, Proceedings of the 5th U.S. National Conference on Wind Engineering, 6-8 November 1985, Lubbock, Texas, pp. 17-33
18. Kramer, C., Gerhardt, H.J., and Kuster, H.W. (1979), ON THE WIND-LOADING MECHANISM OF ROOFING ELEMENTS, Journal of Industrial Aerodynamics, Vol. **4**, pp. 415-427.
19. Stathopoulos, T. (1982), WIND PRESSURES ON LOW BUILDINGS WITH PARAPETS, Journal of the Structural Division, ASCE, Vol. **108**, ST12, pp. 2723-2736
20. Stathopoulos, T. and Baskaran, A. (1985), THE EFFECTS OF PARAPETS ON WIND-INDUCED ROOF PRESSURE COEFFICIENTS, Proceedings of the 5th U.S. National Conference on Wind Engineering, 6-8 November 1985, Lubbock, Texas, pp. 3A-29 to 3A-36

Table 1. Failure Wind Speed at Roof Height

ORIGINAL CONFIGURATION

Wind	Parapet Height (in.)				
	0	2	6	12	18
Exposure	0	2	6	12	18
A‡	70	65.7	66	82.1	108.4
B‡‡	72	67.9	67.7	87.9	122.2
C‡	74	70	69.3	93.6	136

MODIFIED CONFIGURATION

Wind	Parapet Height (in.)				
	0	2	6	12	18
Exposure	0	2	6	12	18
A‡	98.9	88.2	82.4	87.2	101.2
B‡‡	107.4	96.3	93.1	100.8	117.6
C‡	115.8	104.3	103.7	114.4	133.9

‡ Measured in Wind Tunnel

‡‡ Interpolated between values for Exposures A and C

Table 2a. Maximum Building Height (ft) Estimated Using UBC --
Modified Configuration, Exposure C and B

Exposure	C					B				
	Parapet Height (in.)					Parapet Height (in.)				
	0	2	6	12	18	0	2	6	12	18
60	1032	716	700	992	1598	1235	918	903	1195	1801
70	587	355	343	558	1003	790	557	546	760	1205
80	298	126	121	276	616	501	66	48	97	819
90	114	45	43	104	352	61	11	0	29	554
100	45	0	0	39	155	12	0	0	0	53
110	0	0	0	0	73	0	0	0	0	10
120	0	0	0	0	28	0	0	0	0	0

Table 2b. Maximum Building Height (ft) Estimated Using UBC --
Original Configuration, Exposure C and B

Exposure	C					B				
	Parapet Height (in.)					Parapet Height (in.)				
	0	2	6	12	18	0	2	6	12	18
60	82	49	44	451	1669	64	34	33	653	1872
70	0	0	0	160	1055	0	0	0	94	1258
80	0	0	0	50	656	0	0	0	21	859
90	0	0	0	0	383	0	0	0	0	586
100	0	0	0	0	177	0	0	0	0	76
110	0	0	0	0	83	0	0	0	0	26
120	0	0	0	0	35	0	0	0	0	0

Table 3. Wind Exposure Characteristics Specified by ANSI Standard

Exposure	Power Law Exponent α	Gradient Height z_g (ft)	Surface Drag Coefficient D_o
A	3	1500	0.025
B	4.5	1200	0.010
C	7	900	0.005
D	10	700	0.003

$$n = \frac{1}{\alpha}$$

Table 4a. Maximum Building Height (ft) Estimated Using ANSI Standard -- Original Configuration, Exposure A, B and C

Exposure	C					B					A				
	Parapet Height (in.)					Parapet Height (in.)					Parapet Height (in.)				
	0	2	6	12	18	0	2	6	12	18	0	2	6	12	18
60	82	50	45	651	14809	216	153	150	677	4092	489	389	385	1044	3446
70	20	12	11	169	4172	86	60	59	281	1786	267	210	208	583	1987
80	0	0	0	51	1359	38	26	26	128	856	155	121	120	347	1220
90	0	0	0	17	495	18	12	12	63	441	95	74	73	216	785
100	0	0	0	6	197	0	0	0	33	240	60	46	46	140	525
110	0	0	0	3	84	0	0	0	18	137	39	30	30	94	362
120	0	0	0	1	38	0	0	0	10	81	27	20	20	65	256

Table 4b. Maximum Building Height (ft) Estimated Using ANSI Standard -- Modified Configuration, Exposure A, B and C

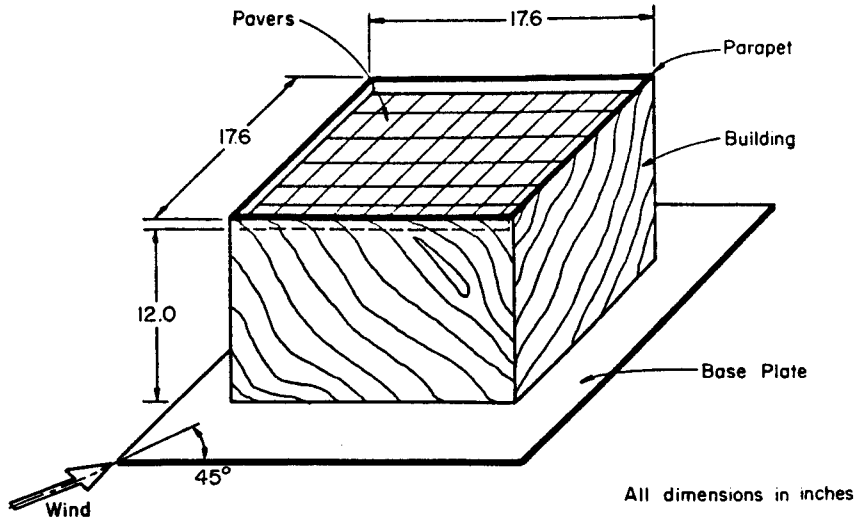
Exposure	C					B					A				
	Parapet Height (in.)					Parapet Height (in.)					Parapet Height (in.)				
	0	2	6	12	18	0	2	6	12	18	0	2	6	12	18
60	3947	1641	1563	3567	13047	2046	1126	934	1448	3335	2175	1463	1292	1729	3008
70	1077	438	416	971	3665	877	475	391	615	1448	1240	825	726	979	1729
80	340	135	128	306	1190	413	220	180	287	690	752	495	434	591	1058
90	120	47	44	108	432	209	110	89	144	354	479	312	273	374	679
100	46	18	17	41	171	112	58	47	76	192	317	204	178	246	452
110	19	0	0	17	73	63	32	26	43	109	216	138	120	167	311
120	0	0	0	0	33	37	18	15	25	64	151	96	83	116	219

LIST OF FIGURES:

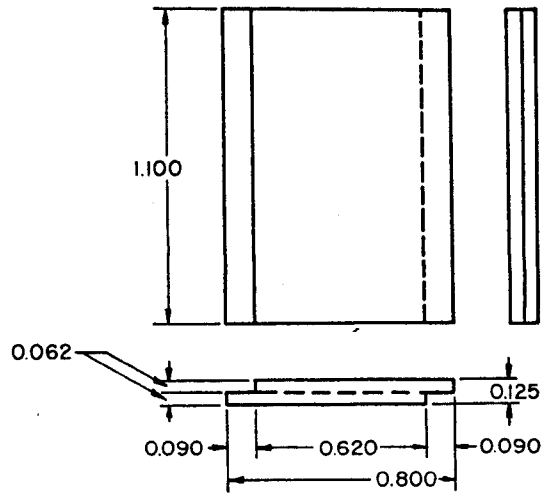
1. Experimental Details: a) Building Model; b) Paver Model.
2. Boundary Layer Generators and Model Building.
- 3a. Details of Paver Layout -- Original Configuration.
- 3b. Details of Paver Layout -- Modified Configuration.
4. Mean Wind Speed and Turbulence Intensity Profiles -- Exposure A and C.
5. Failure Wind Speed at Roof Height -- Original Configuration.
6. Three Typical Realizations of Paver Failure -- Original Configuration with Zero Height Parapet.
7. Failure Wind Speed at Roof Height -- Modified Paver Configuration.
8. Three Typical Realizations of Paver Failure -- Modified Configuration with Zero Height Parapet.
9. Maximum Building Height Estimated Using UBC and ANSI Standard -- Original Configuration with 12 inch (0.3 m) Parapet, Exposures B and C.
10. Maximum Building Height Estimated Using UBC and ANSI Standard -- Modified Configuration with 12 inch (0.3 m) Parapet, Exposures B and C.

LIST OF TABLES:

1. Failure Wind Speed at Roof Height
- 2a. Maximum Building Height (ft) Estimated Using UBC -- Original Configuration, Exposure C and B.
- 2b. Maximum Building Height (ft) Estimated Using UBC -- Modified Configuration, Exposure C and B.
3. Wind Exposure Characteristics Specified by ANSI Standards.
- 4a. Maximum Building Height (ft) Estimated Using ANSI Standard -- Original Configuration, Exposure A, B, and C.
- 4b. Maximum Building Height (ft) Estimated Using ANSI Standard -- Modified Configuration, Exposure A, B, and C.



Paver Model
 Figure 1a. Building Model



All dimensions in inches

Figure 1b. Paver Model

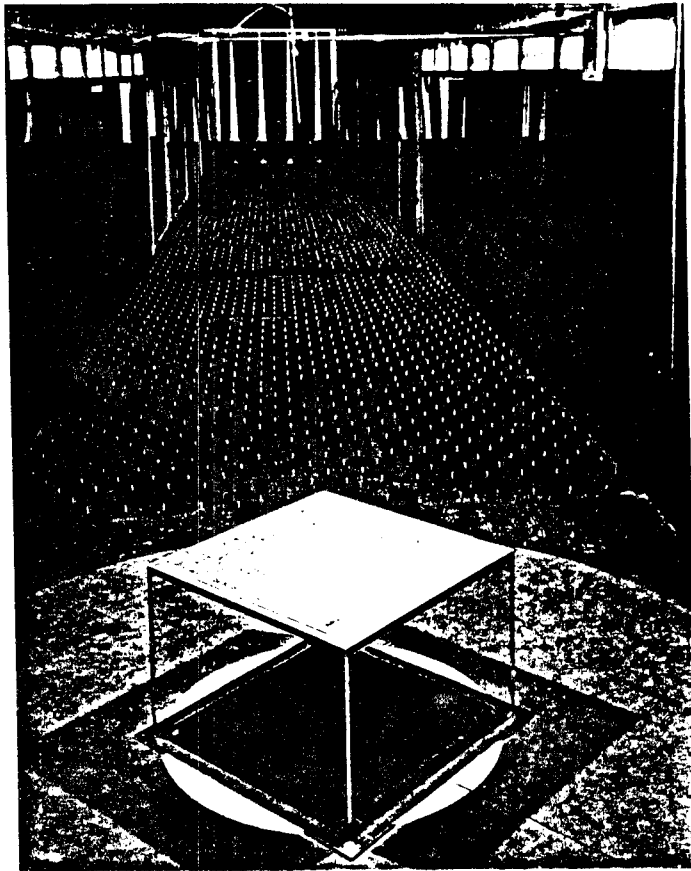


Figure 2. Boundary Layer Generators and Model Building

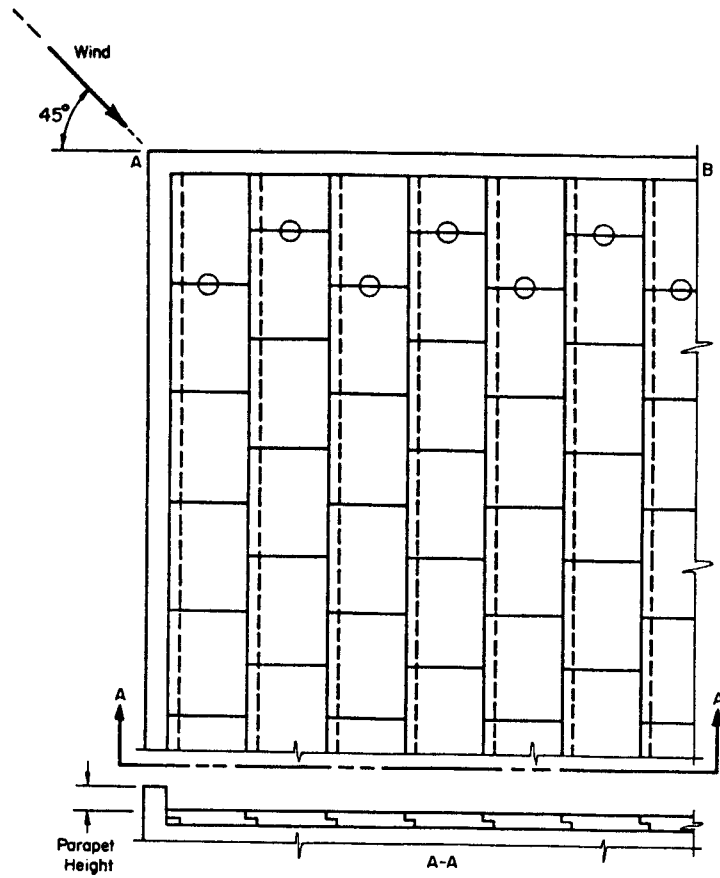


Figure 3b. Details of Paver Layout - Modified Configuration

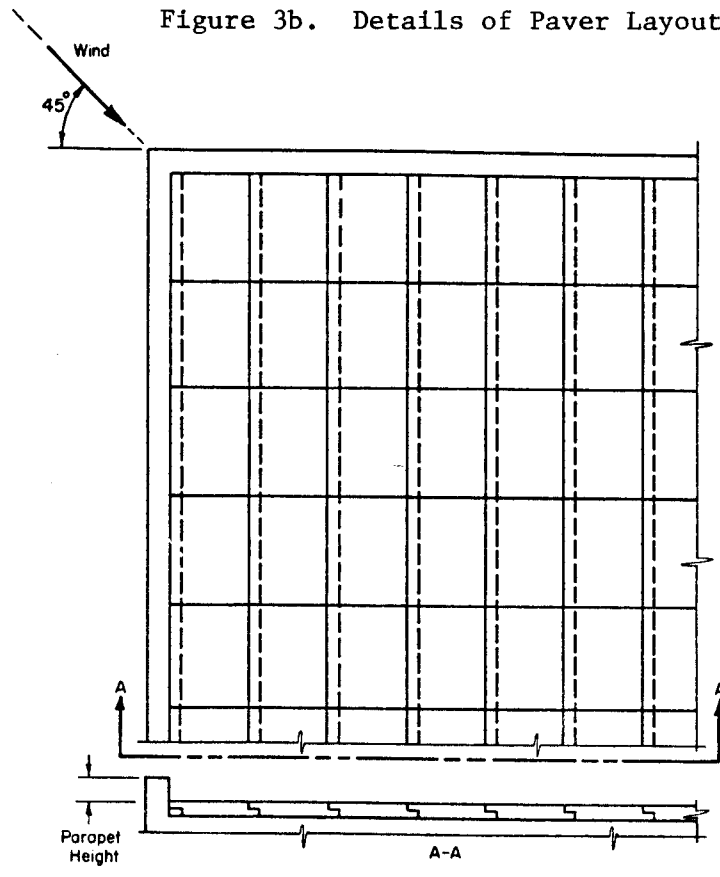


Figure 3a. Details of Paver Layout -- Original Configuration

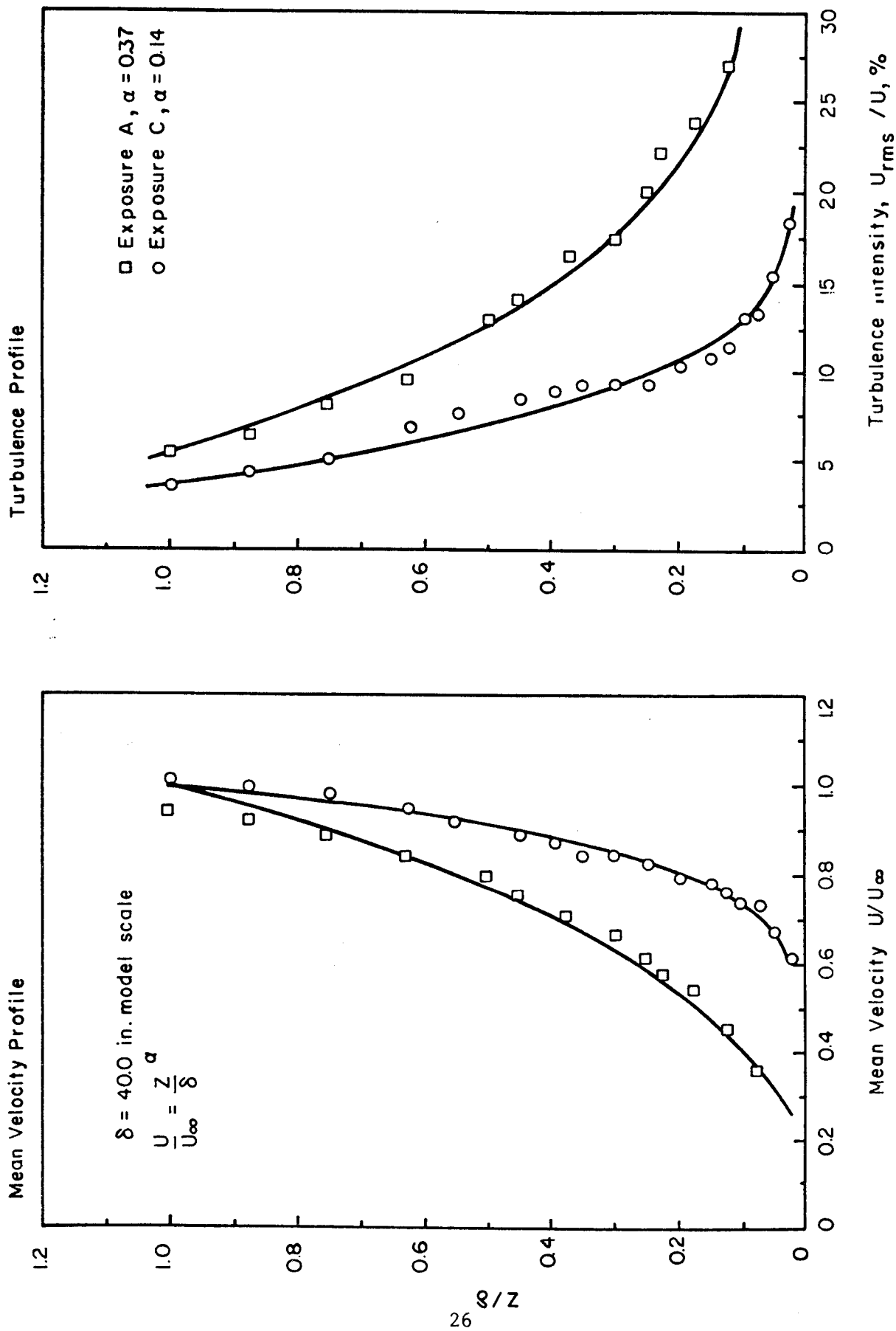


Figure 4. Mean Wind Speed and Turbulence Intensity Profiles -- Exposure A & C.

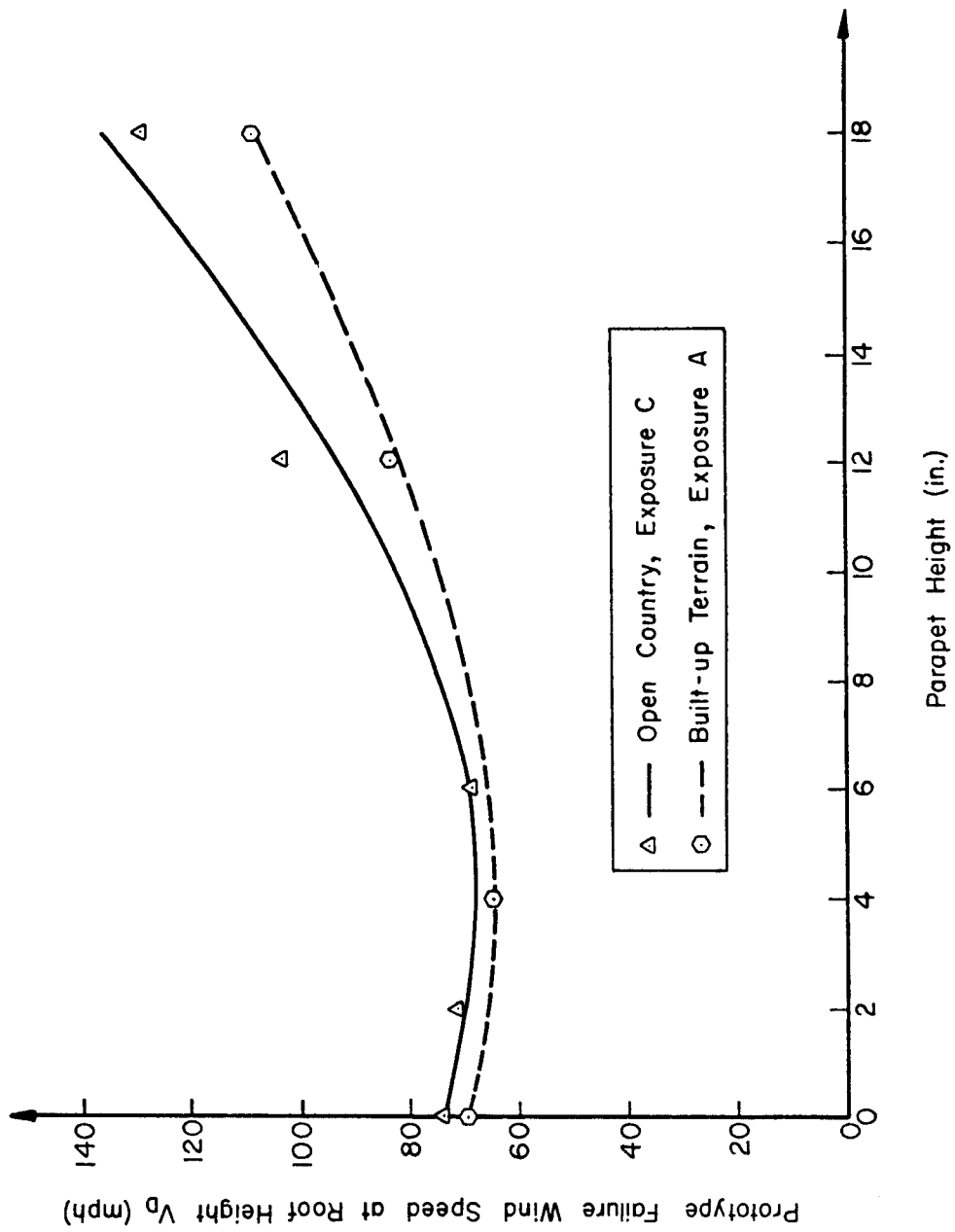
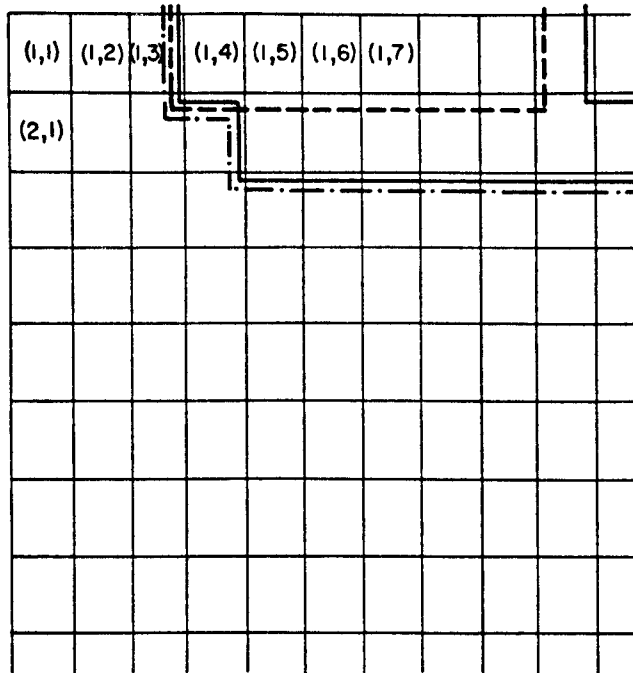
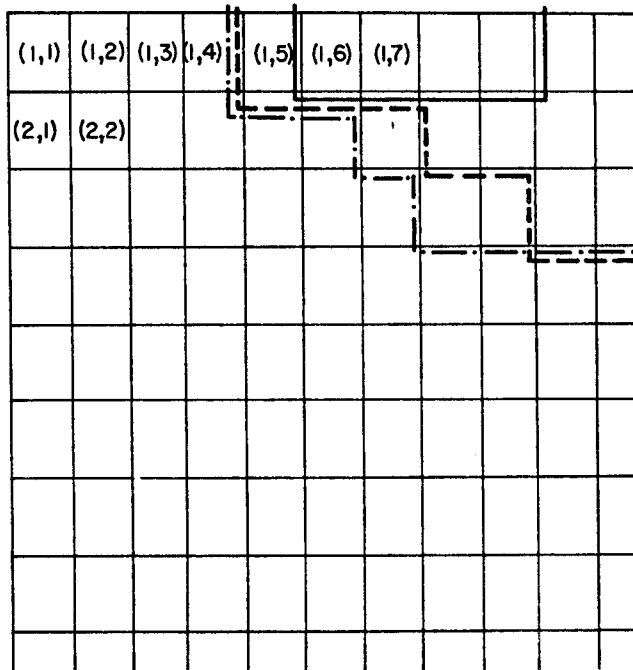


Figure 5. Failure Wind Speed at Roof Height -- Original Configuration



Exposure C



Exposure A

Figure 6. Three Typical Realizations of Paver Failure -- Original Configuration with Zero Height Parapet.

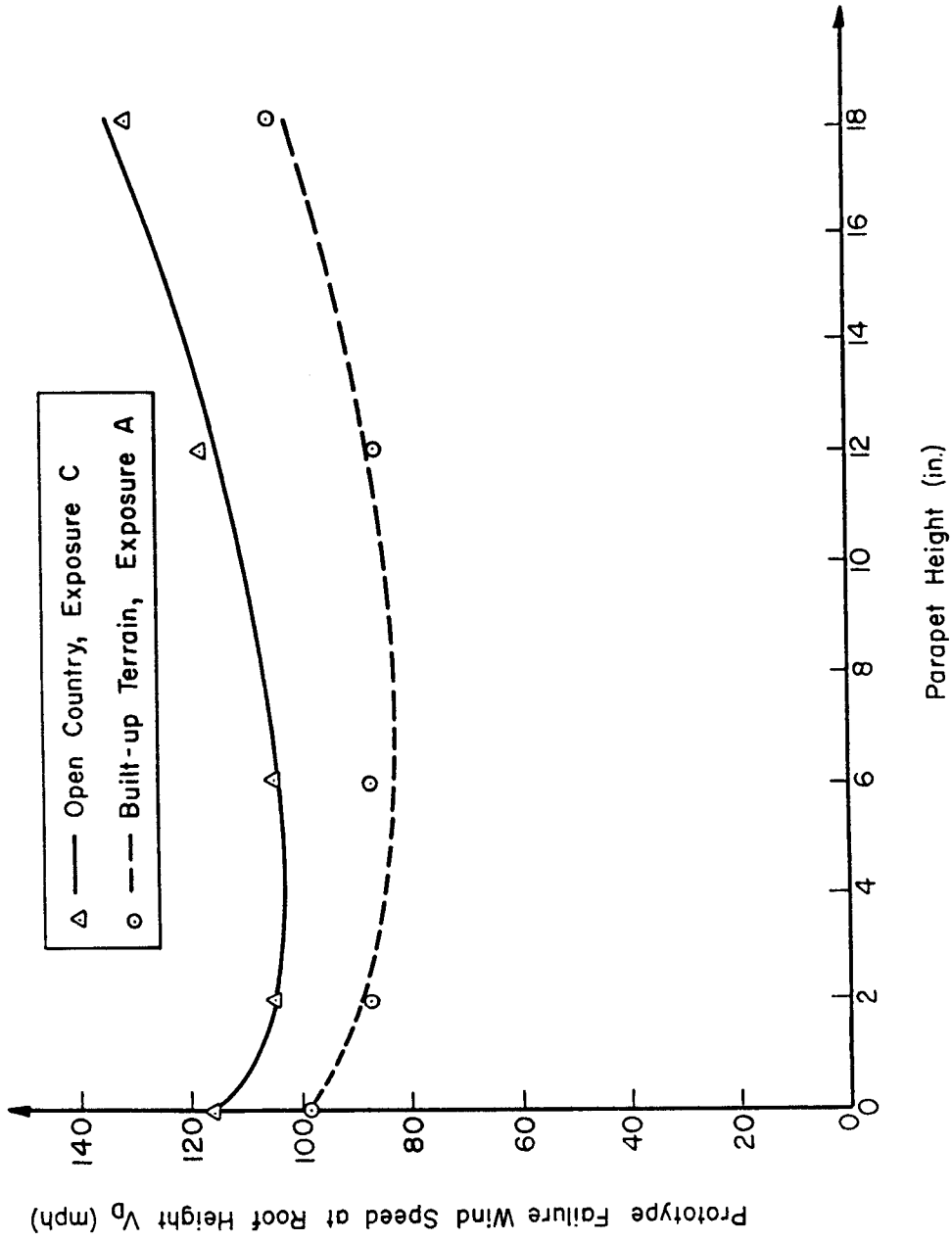
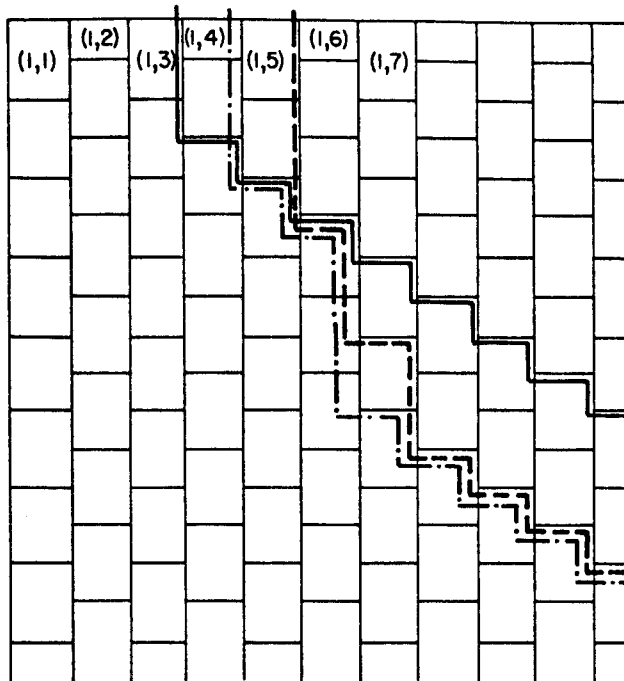
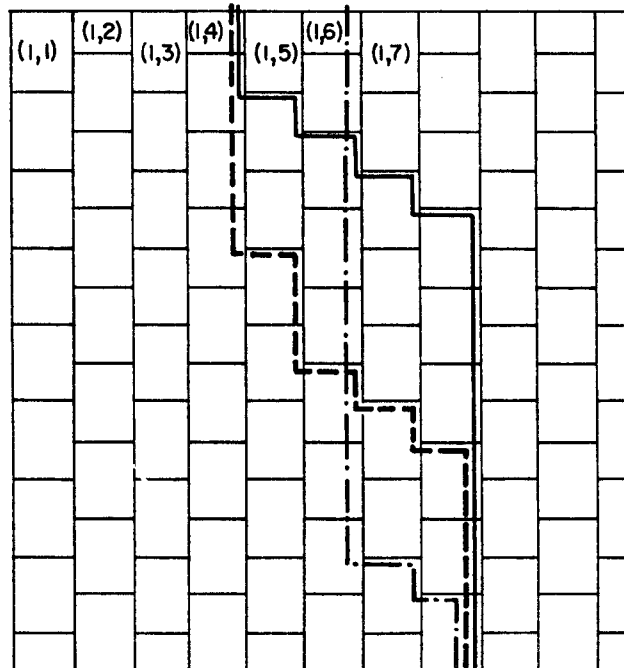


Figure 7. Failure Wind Speed at Roof Height -- Modified Paver Configuration



Exposure C



Exposure A

Figure 8. Three Typical Realizations of Paver Failure -- Modified Configuration with Zero Height Parapet.

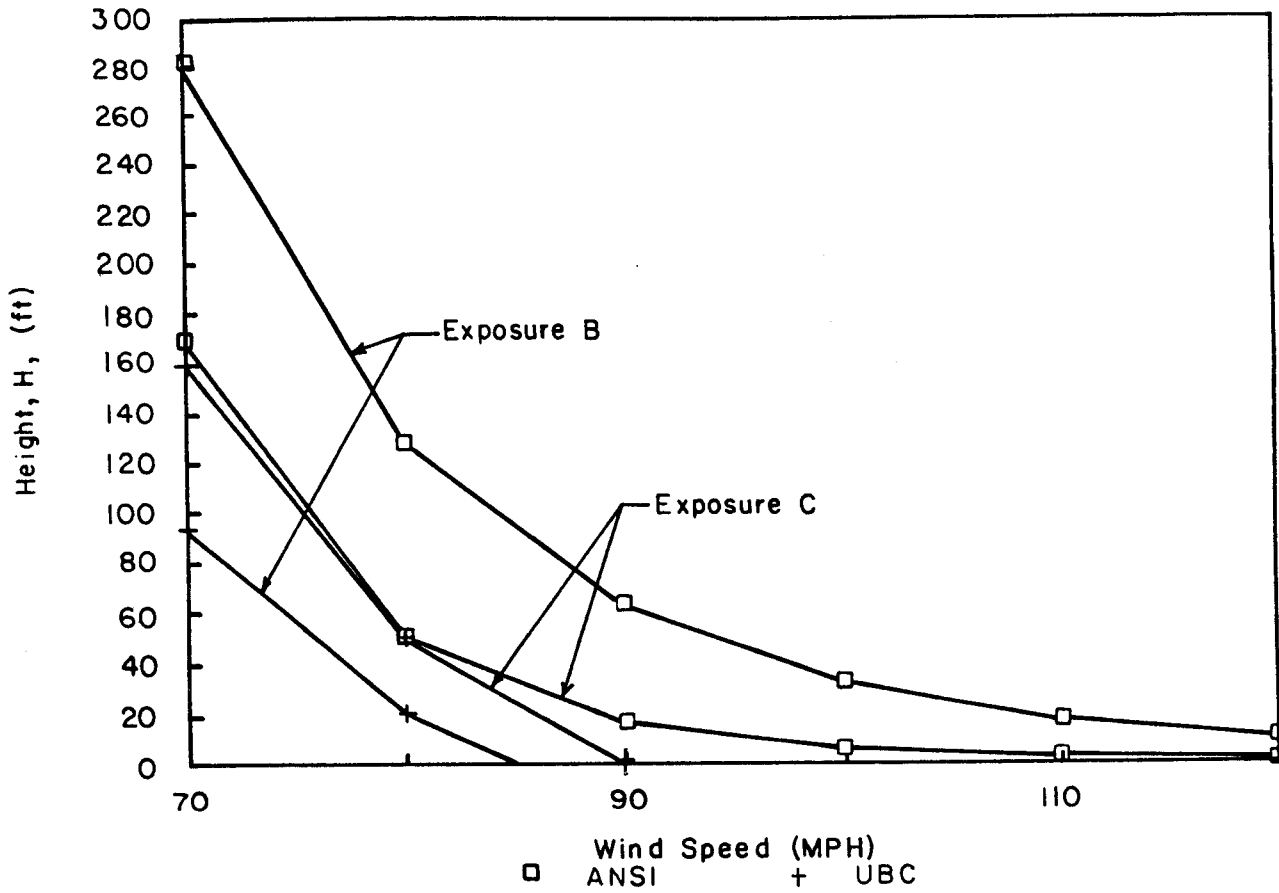


Figure 9. Maximum Building Height Estimated Using UBC and ANSI Standard -- Original Configuration with 12 in. Parapet, Exposure B.

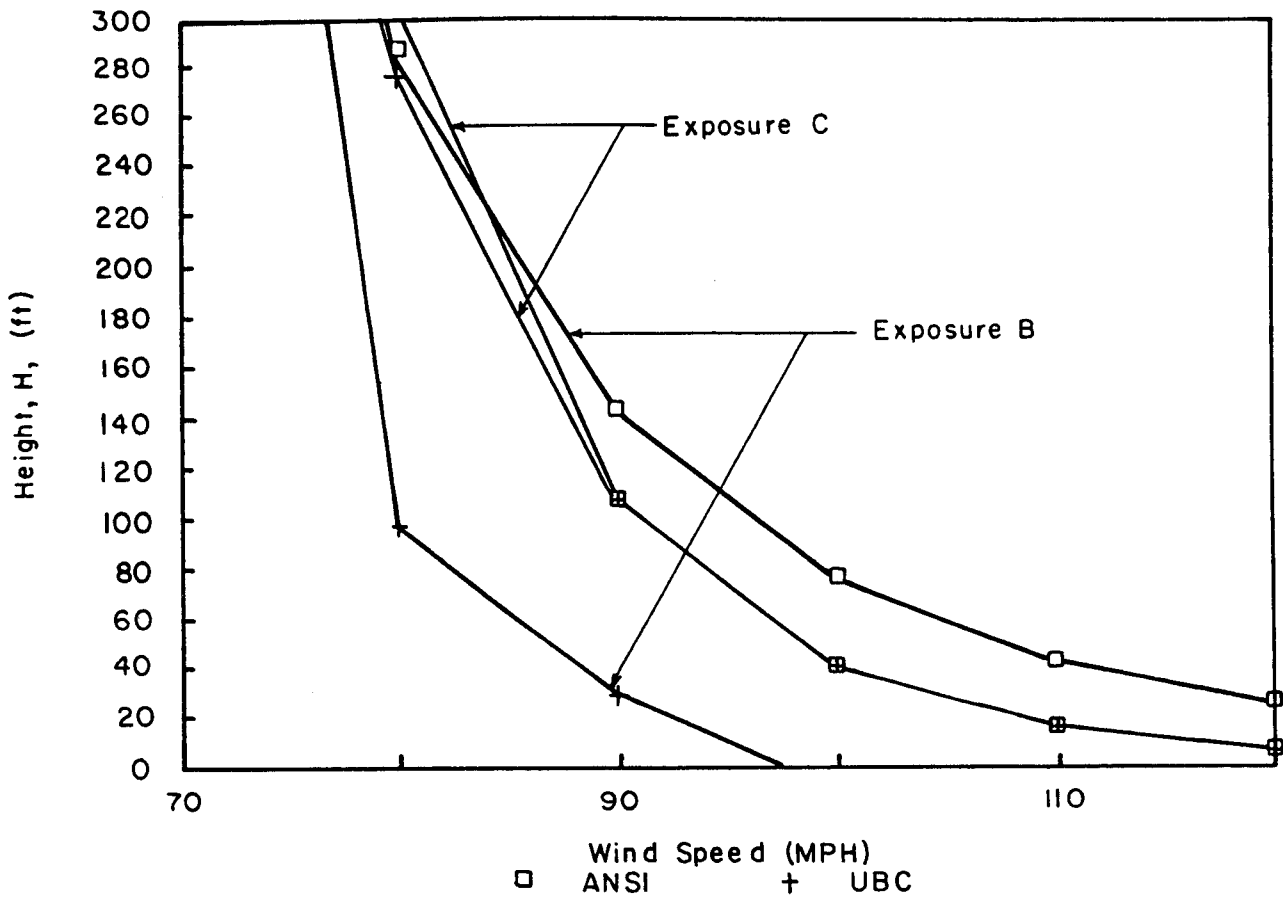


Figure 10. Maximum Building Height Estimated Using UBC and ANSI Standard -- Modified Configuration With 12 in. Parapet, Exposure C.