WIND-TUNNEL STUDY
OF ROOFBLOK BALLAST BLOCK FOR HIGH WINDS

by

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1.0 INTRODUCTION

Recent developments in roofing technology resulted in the introduction of single-ply membranes held in place by ballast. Different ballast types are used in various configurations. The basic ballast systems consists of: (a) loose laid well-rounded stones; (b) standard paving blocks; (c) a composite tongue and groove board; and (d) lightweight tapered interlocking ballast blocks. Design of such systems requires analysis of wind effects for a given configuration. Recent studies conducted by Phalen (1-4) indicated that the ballast system (d), consisting of interlocking blocks, exhibits much better performance in adverse wind conditions (strong winds) than the systems (a) through (c). Partial and ultimate failure of that system occurred at the wind speed 75 and 107 mph, respectively, i.e. at the speeds much higher than failure wind speeds for the remaining systems. Phalen (2) based his conclusions on full scale testing of the interlocking blocks and on wind-tunnel data reported by Kind (5), and Kind and Wardlaw (6). His results were incorporated by Roofblok Limited to formulate design criteria for the Roofblok System (7), and to establish design guidelines issued by the International Conference of Building Officials (8).

Studies reported by Phalen (3) indicated that the interlocking mechanism of lightweight blocks (d) plays an important role in preventing failure of the system at wind speeds higher than the design wind speed. Recently, a design application has arisen to use a ballast paver system in Dade County, Florida, where design wind speeds up to 157 mph may occur at roof top, Saffir, (10). Phalen (9) has suggested that the Roofblok system with an appropriate adhesive applied on all four block edges should withstand high lifting forces.

The report presents the results of wind-tunnel modeling of wind effects (including partial/ultimate failure) of a system consisting of ballast blocks manufactured by Roofblok Limited. Considered were adhered and nonadhered blocks in several configurations. The experimental study is described first. Then the results are presented and discussed. The representative experiments are documented on two VCR tapes which accompany the report.

2.0 EXPERIMENTAL CONFIGURATION

2.1 Wind Tunnel

The study was conducted in the Industrial Aerodynamics Wind Tunnel located at the Fluid Dynamics and Diffusion Laboratory, Colorado State University. Location of the wind tunnel in the laboratory is shown in Figure 1. The wind tunnel is depicted in Figure 2. The wind tunnel is of recirculating type, and the facility has a test section 6 ft wide and 60 ft long. Model blockage effects can be resolved with a test-section ceiling adjustable from 5 ft to 7 ft. Air flow in the tunnel is generated by a 16-blade axial fan driven by a single-speed 75 hp-induction motor. The air speed is controlled by varying the pitch of the fan blades. The speed range of the flow in the tunnel can be continuously adjusted from 0 to approximately 80 fps. The flow enters the test section through a 4:1 contraction which produces uniform cross-section flow and background turbulence of low levels (turbulence intensity of approximately 0.5 percent). Simulated atmospheric boundary conditions are created by placing flow tripping devices at the entrance to the test section and a uniform fetch of roughness elements on the floor.

2.2 Model

A series of experiments involving models of the Roofblok Ballast Block were designed and conducted in the Industrial Aerodynamics Wind Tunnel. The experiments were to provide information about the failure mode and the failure wind speed of the prototype blocks.

The prototype Roofblok Ballast Block is shown in Figure 3. A 1:15 geometrical scale model shown in Figure 4 was used in the study. The wind-induced motion of the block model must be kinematically similar to that of the prototype block. This requires that the mass ratio (mass of air/mass of block) must be the same for the model and for the prototype. If the block geometry is properly scaled, this requirement implies that the average mass density (mass per unit volume) of the prototype and the model blocks should be the same, or

$$\lambda_{\sigma} = 1 \qquad (1)$$

where

$$\lambda_{\sigma} = \frac{\sigma_m}{\sigma_p}$$

σ_m = mass density of model paver, and

σ_p = mass density of prototype paver.

To satisfy this requirement, the model block was made of plexiglass. The resulting mass density scale differed by 4% from the desired value of unity, Eq. (1).

Model blocks were placed in various configurations on a roof of a model building shown in Figure 5. The building shown was used to simulate flow conditions on a typical flat roof with ballast blocks. Only one building model of a square plan and a fixed height was employed in the study. The model represented a 15 ft. tall prototype building with a 22 ft. square flat roof. The size of the model was limited by the size of the wind-tunnel test section and by flow perturbations caused by blockage effects. Blockage effects caused by the presence of the model were eliminated by adjustments of the wind-tunnel roof. The roof of building model was configured with the edge block attachment shown in Figure 6.

2.3 Flow Conditions

The wind-tunnel study was conducted in one approach flow. The configuration tested represented conditions typical for flow over open or rural country (Uniform Building Code [7] -- Exposure C, ANSI A58.1-1982 [8] -- Exposure C).

The turbulent boundary layer was generated using flow tripping devices (spires and a barrier) placed at the entrance to the wind-tunnel test section combined with a uniform fetch of roughness elements located upstream of the model. A 47 inch deep boundary layer was generated.

The mean velocity and turbulence intensity profiles for the flow are shown in Figure 7. The velocity profile is frequently described by an empirical power-law relationship, $U/U_{ref} = (Z/Z_{ref})^n$. The model power law coefficient n for the tested case was approximately 0.14.

2.4 Test Conditions

Wind-tunnel model tests must satisfy certain similarity criteria in order to be representative of prototype conditions. The model tested has to be dynamically similar to that of the prototype. Dynamic similarity considerations for the paver model were discussed in Section 2.2. The approach flow also needs to be dynamically scaled. This will be achieved if the wind approaching the model has the same value (for the main nondimensional flow parameters) as the prototype flow. In the present study the main flow parameters are represented by

$$\text{Reynolds Number } \frac{UL}{v} \text{ , and} \tag{2}$$

$$\text{Froude Number} = \frac{U}{\sqrt{Lg}} \text{ ,} \tag{3}$$

where

U = reference wind speed,

L = reference length,

v = kinematic viscosity of air, and

g = gravitational acceleration.

The Reynolds number represents the ratio of inertial to viscous forces in the flow, whereas the Froude number relates the inertial lift forces of the air to the weight of the pavers. It is impossible to match both the Reynolds and Froude numbers for the present case. However, it is well established that flows over sharp edged objects are independent of Reynolds numbers for moderately high Reynolds numbers. As a result, the Reynolds number similarity is often relaxed and it was relaxed during the present study. The remaining similarity requirement (3) -- Froude Number -- is satisfied when the wind speed scale λ_V and the geometrical scale λ_L are related as follows

$$\lambda_V = \lambda_L^{1/2} . \tag{4}$$

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

Wind-tunnel studies conducted in boundary-layer flows require proper scaling of the prototype boundary layer. At the 1:15 geometrical scale used during the present study, proper scaling of the prototype boundary layer (more than a thousand feet deep) was impossible. Kind and Wardlaw [12,13], indicated that the flow pattern over the upwind corner of the building rooftop is mainly dependent on the speed of the approaching wind at rooftop level. Hence, only the lower part of the boundary layer was modeled. It was assumed that characteristics of the flow at rooftop level were dominant. Since the boundary layer depth was not properly scaled in the study, the wind-tunnel flow was expected to be deficient in low frequency (large-scale) gusts. This lack of large-scale, low-frequency gusts was not expected to influence the aerodynamics of the relatively small pavers.

Earlier studies by Kind and Wardlaw [12] established that most paver failures occur near the upwind corner of a roof, and that the most critical wind direction for such failures is along the bisector of the upwind corner, as indicated in Figure 8. This critical wind direction was examined in the present study, and the model was tested in the configuration shown in Figure 9.

2.5 Test Procedure

The wind-tunnel experiments were conducted according to the following procedure. The blocks were placed on the roof of a building model in a desired arrangement. Wind speed in the tunnel was gradually increased, and the behavior of the blocks was observed. Wind speed was measured by a pitot-static tube mounted in the tunnel at rooftop level of the model building. The tube was connected to an electronic manometer, and the transducer output voltage was monitored by a minicomputer on line. When a paver failure (dislocation) was observed, the wind-tunnel speed was maintained constant and the mean wind speed was recorded. The prototype wind speed, corresponding to the measured mean wind speed, is called throughout this report the failure wind speed at roof height, and it is denoted V_R. This speed was measured for various ballast block configurations. The roof failure - - ballast block dislodging - - was recorded on VCR 0.5 inch television tape.

2.6 Tested Configurations

The building model was placed in the wind-tunnel as shown in Figure 9. The paver configuration was chosen to model an arrangement for the typical roof corner layout shown in Figure 10. The configuration is depicted in more detail in Figure 11. Figure 12 shows the paver configuration employed during initial wind-tunnel tests. Seventy-five percent of the roof was covered with the pavers, while the remaining 25% was covered with a plate fastened to the roof. The entire area of the roof, see Figure 13, was covered with pavers during the final series of the wind-tunnel tests.

Three configurations of the interlocking scheme, configurations A,B, and C, shown in Figure 14 were tested. During the initial series of tests the pavers themselves were not interconnected. The final series of tests included experiments with some of the pavers interconnected in two rows close to the parapet and along the bisector, see Figure 15. A strip of 0.25 in. scotch tape was used to interconnect the pavers. The resulting configuration was denoted CM1 (Configuration C, Modification 1). The same method was used to interconnect all the pavers, tested during the final series of tests, see Figure 16. The second configuration was denoted CM2 (Configuration C, Modification 2). Configurations CM1 and CM2 used a paver pattern defined as scheme C shown in Figure 12.

3.0 RESULTS

3.1 Initial Tests

A series of preliminary experiments were conducted to test the effects of packing of model Roofblok Ballast Blocks on the failure wind speed. The model blocks were placed on the roof of the model building in configuration A (see Figure 14) according to the pattern arrangement shown in Figures 11 and 12. The blocks were tested in three packing modes: tight, moderate and loose. The tight packing mode was achieved by placing blocks as close to each other as possible and applying some lateral force to the blocks while placing them on roof. Blocks in loose packing mode were positioned with some visible clearance spacing between them (1/32 inch). The moderate packing represented an intermediate level between tight and loose packing. The results of the experiments are presented in Table 1 (Tests 1 through 9). The failure wind speed is the mean wind speed at which ballast blocks were dislodged as measured at the roof level. The data in Table 1 was used to compute the average failure wind speed for different packing modes, shown in Table 2. It can be seen that the degree of the ballast block packing affects the failure wind speed by as much as 15%. It is expected that the prototype ballast blocks are arranged in moderate to tight packing. It follows from Table 2 that such packing can be achieved during wind-tunnel testing (moderate to tight packing) with a packing control leading to an error (in the failure wind speed) lower than 10%.

The effects of the interlocking scheme was tested next, see tests 9 through 11, Table 1. These tests were of a preliminary nature and the packing control was not always consistent. The tests were recorded on a 0.5-inch VCR tape (Tape 1). The configurations A, B, and C are defined in Figure 14. It was concluded that the edge metal fixture along the roof periphery becomes an effective part of the interlocking system, provided that the fixture is of sufficient stiffness and no gap between the edge blocks and the fixture is allowed. When the interlocking was not fully effective, the ballast block failure occurred at locations typical for other ballast systems, reported by Bienkiewicz and Meroney [11] and Kind and Wardlaw [13].

3.2 Final Tests

Final tests were conducted for the ballast configuration C, CM1 and CM2 described in Section 2.6. The results are presented in Table 3 and on VCR tape, Tape 2. Tests over configuration C resulted in a prototype failure wind speed at roof level of 92.2 mph. As can be seen on the tape, the failure was initiated with blocks (5,1) and (6,1). Blocks are identified on Figure 17. The failure progressed and included blocks in column 1 (starting with block (5,1), column 2 (starting with block (7,2), column 3 (starting with block (7,3) and column 4 (starting with block (7,4).

Tests over configuration CM1, see Figure 15, resulted in a failure wind speed of 100.9 mph. This failure (shown also on Tape 2) included non-interconnected blocks (see Figure 15) in columns 2 and 3.

Configuration CM2, (see Figure 16), did not fail at all up to a wind speed of 213 mph. This prototype speed corresponded to the maximum wind speed obtainable in the wind tunnel used. In order to achieve such a high wind speed, the wind tunnel ceiling was lowered and the spires (used to initiate early turbulent stirring) were removed from the wind tunnel. As a result, the flow turbulence characteristics were somewhat reduced. However, the flow changes were not expected to alter dramatically the performance of the ballast blocks. The final tests were recorded on Tape 2 as Run 1 (Conf. C), Run 2 (Conf. CM1), and Runs 3 and 4 (Conf. CM2). Run 3 consisted of several tests (Tests 1 through 3) corresponding to wind-tunnel modifications made to increase the maximum speed obtainable in wind-tunnel.

4.0 CONCLUSIONS AND REMARKS

4.1 Conclusions

A. The data presented showed the effects of the degree of packing and of the interlocking system on the ballast block performance. Variations in the controlled packing of the model ballast blocks result in uncertainty for the failure prototype wind speed predictions of lower than 10%.

B. The Roofblok interlocking system was very effective in increasing the failure wind speed.

C. The failure wind speed increased by approximately 23% when two rows of the edge blocks and blocks along the diagonal near the upwind corner of the roof were interconnected by using 0.25-in. wide scotch tape.

D. Blocks completely interconnected with a 0.25- in. wide scotch tape did not fail at prototype wind speeds lower than the maximum rooftop speed tested of 213 mph.

4.2 Remarks

In the present study the performance of model Roofblok Ballast Blocks were examined in various configurations. The wind-tunnel experiments were designed to reproduce a prototype roof failure. It is believed that the data obtained for non-interconnected blocks reproduces the aerodynamic behavior of the corresponding prototype block system.

The aerodynamic performance of prototype blocks held together with adhesives was also examined. Strips of 0.25-in. scotch tape were used to interconnect adjacent model blocks to represent the presence of adhesives between prototype blocks. Such a modeling technique should result in somewhat conservative results for block configurations CM1 and CM2.

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TABLES

Table 1. Experimental Results -- Initial Tests

TEST	CONF	PROTOTYPE FAILURE WIND [MPH]	TAPED RUNS (VCR)			COMMENTS	
			TAPE NR	RUN NR	VCR COUNTER	BALLAST PACKING	BALLAST FAILURE
1	A	79.5	-	-	-	Moderate	
2	A	77.7	-	-	-	Moderate	
3	A	69.2	-	-	-	Loose	
4	A	70.1	-	-	-	Loose	
5	A	78.2	-	-	-	Moderate	
6	A	76.2	-	-	-	Moderate	
7	A	81.8	-	-	-	Tight	
8	A	74.2	-	-	-	Moderate	
9	A	88.6	1	2	48-167	Very Tight	
10	C	90.5	1	Last	468-1180	Moderate	Initial Failure
		108.6					Final Failure
11	B	113.6	1	3	167-468	Loose	

Table 2. Summary of Data for Initial Tests

BALLAST PACKING	PROTOTYPE FAILURE WIND SPEED [MPH]	FAILURE WIND SPEED RATIO
Very Tight	89	1.16
Tight	82	1.06
Moderate	77	1.00
Loose	70	0.87

Table 3. Experimental Results -- Final Tests

CONF	TEST	PROTOTYPE FAILURE WIND SPEED [MPH]	TAPED RUNS		
			TAPE NR	RUN NR	VCR COUNTER
C	1	92.2	2	1	23-459
CM1	1	100.9	2	2	459-730
CM2	1	160.7	2	3	730-1213
	2	181.	2	3	1213-1556
	3	181.	2	3	1556-1637
	1	213.	2	4	1637-1750

FIGURES

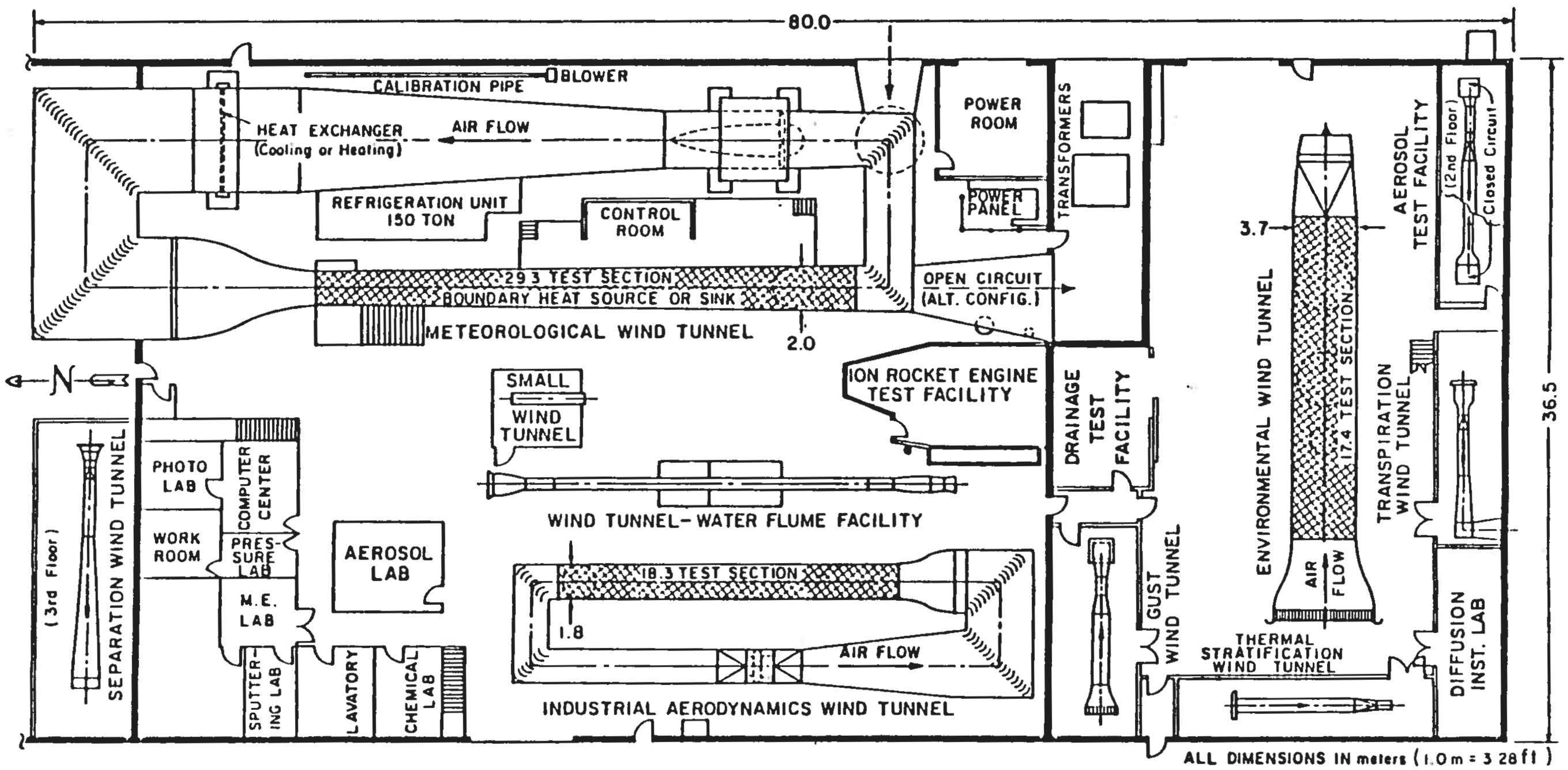


Figure 1. Fluid Dynamics and Diffusion Laboratory, Colorado State University

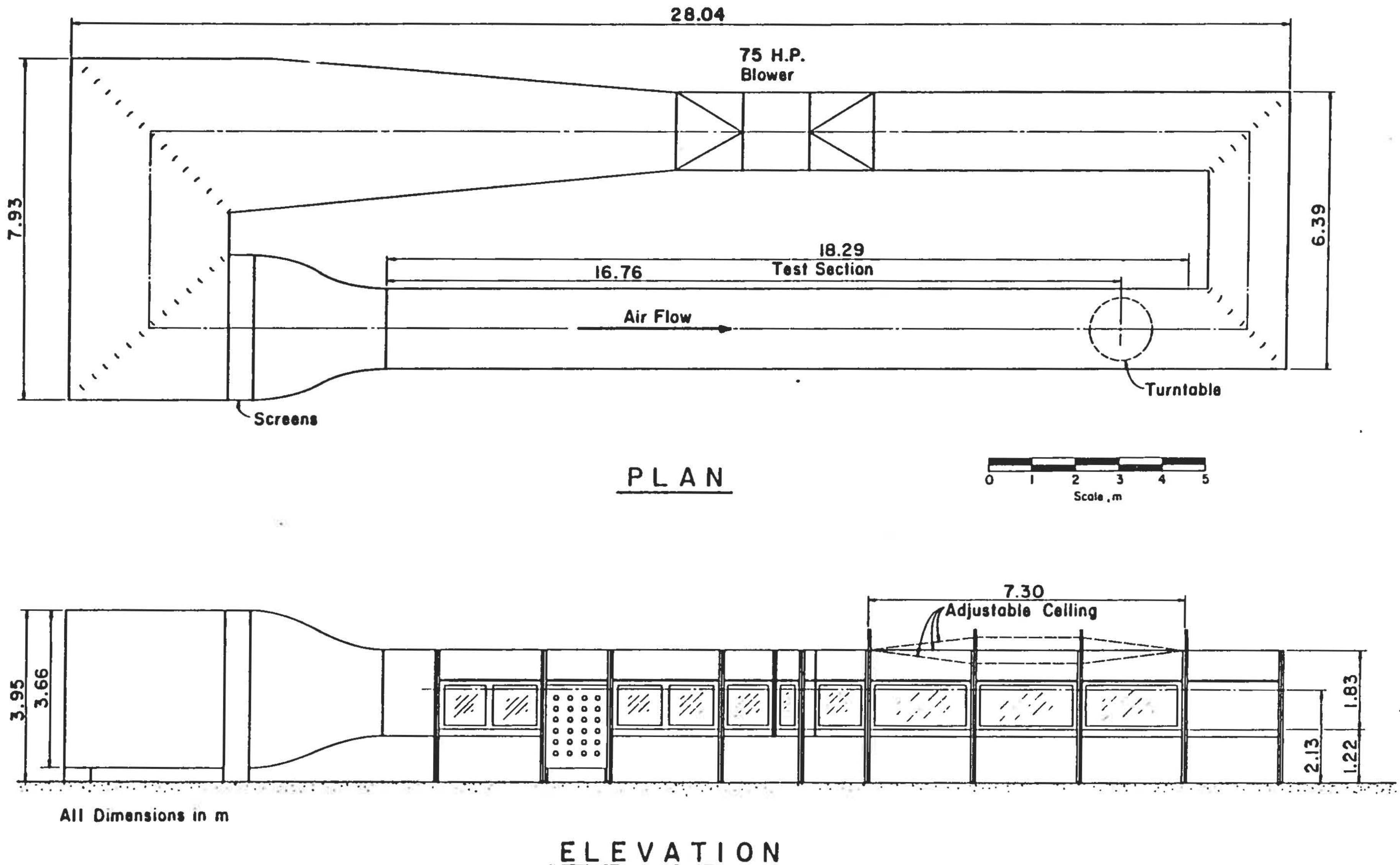


Figure 2. Industrial Aerodynamics Wind Tunnel

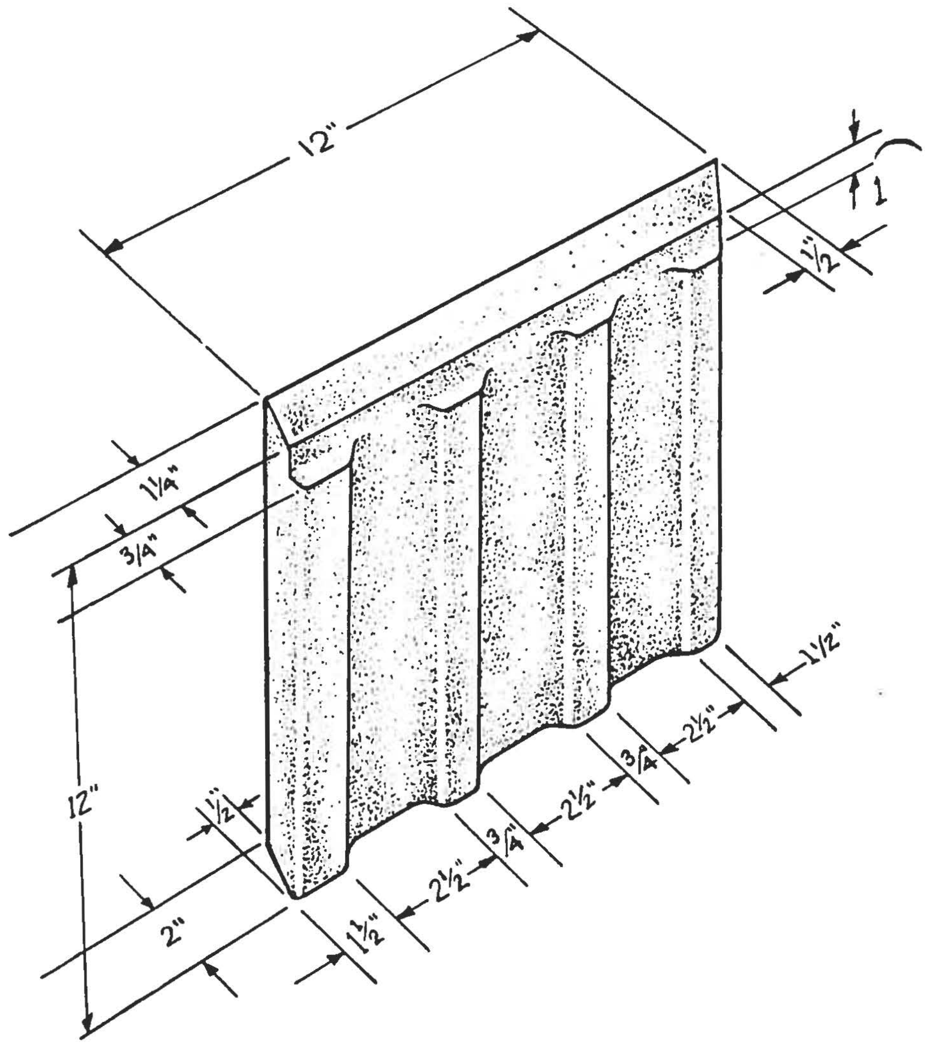


Figure 3. Roofblok Ballast Block

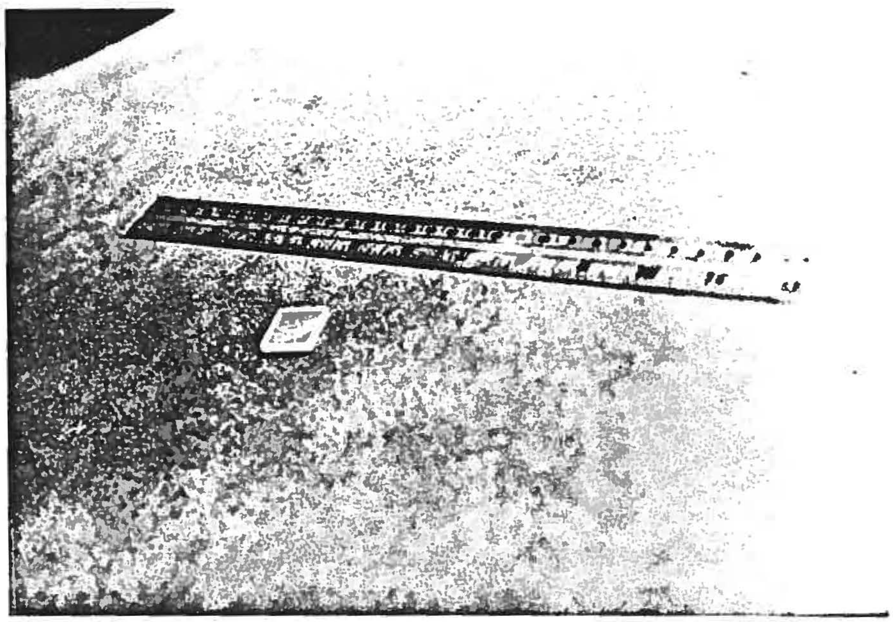


Figure 4. Model of Roofblok Ballast Block

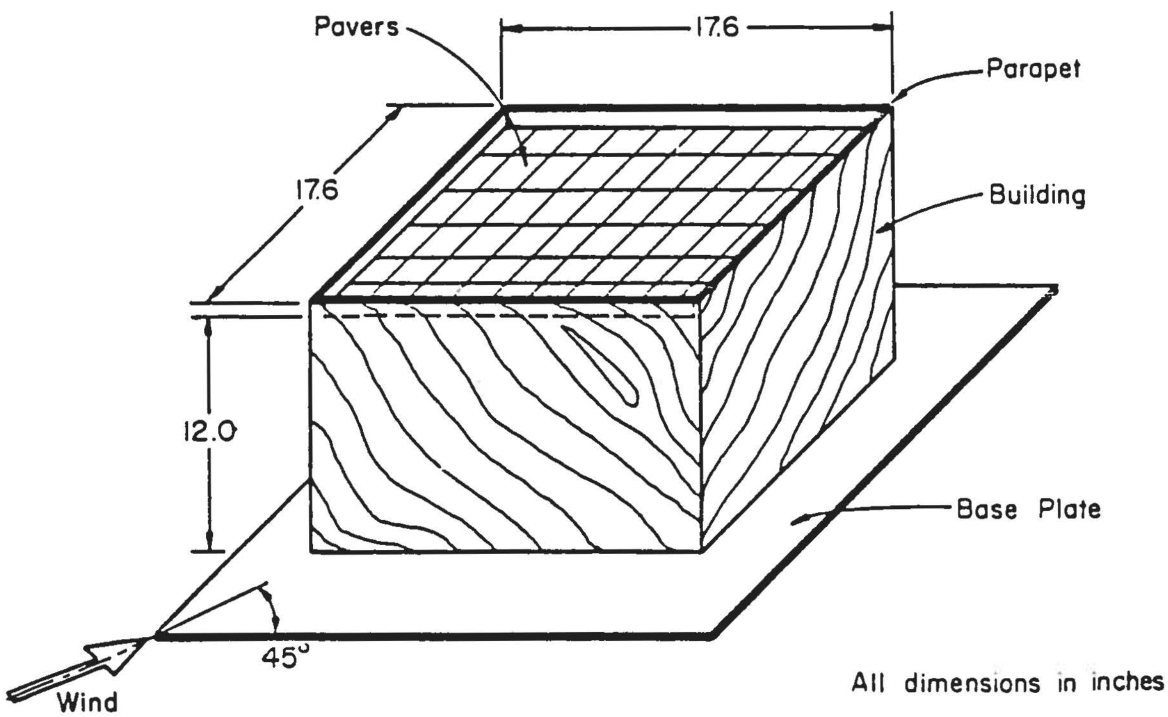


Figure 5. Building Model

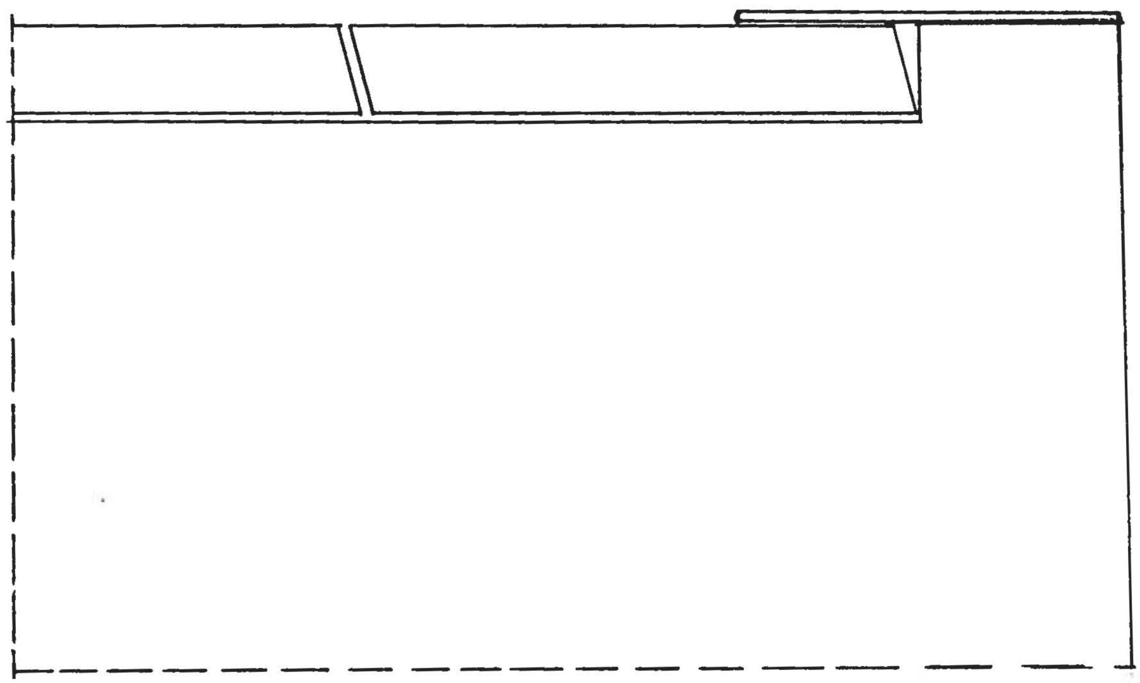


Figure 6. Roofblok Interlock System

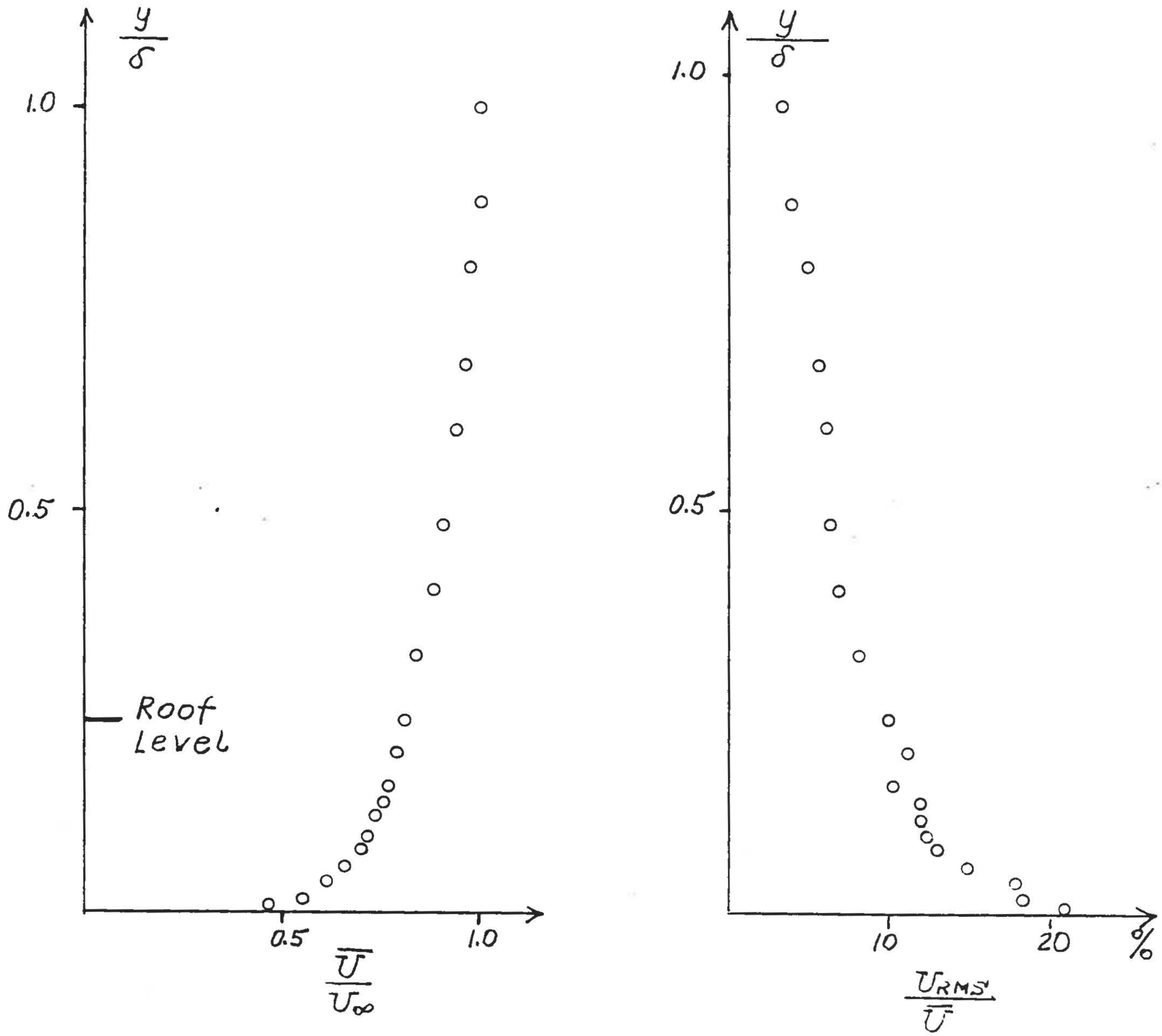


Figure 7. Mean Wind Speed and Turbulence Intensity Profiles

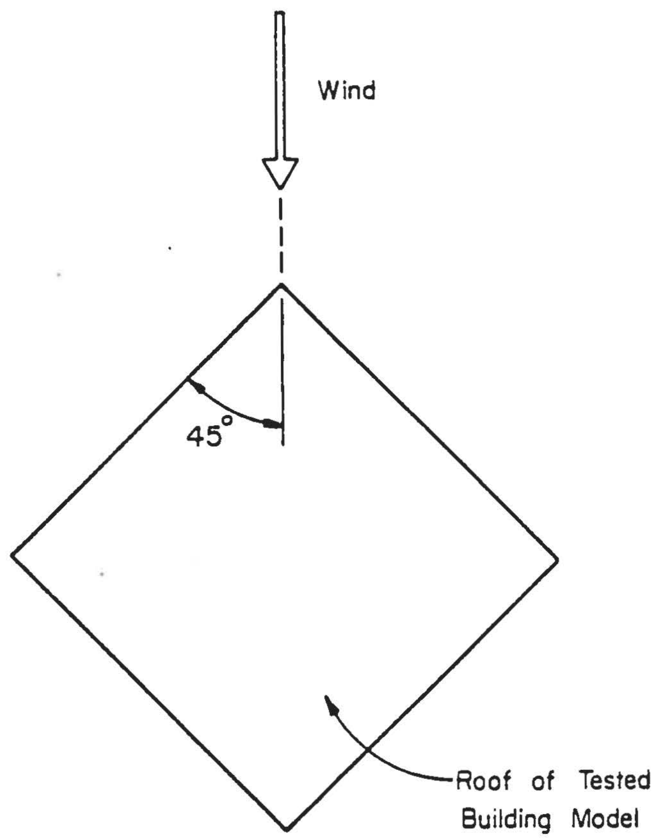
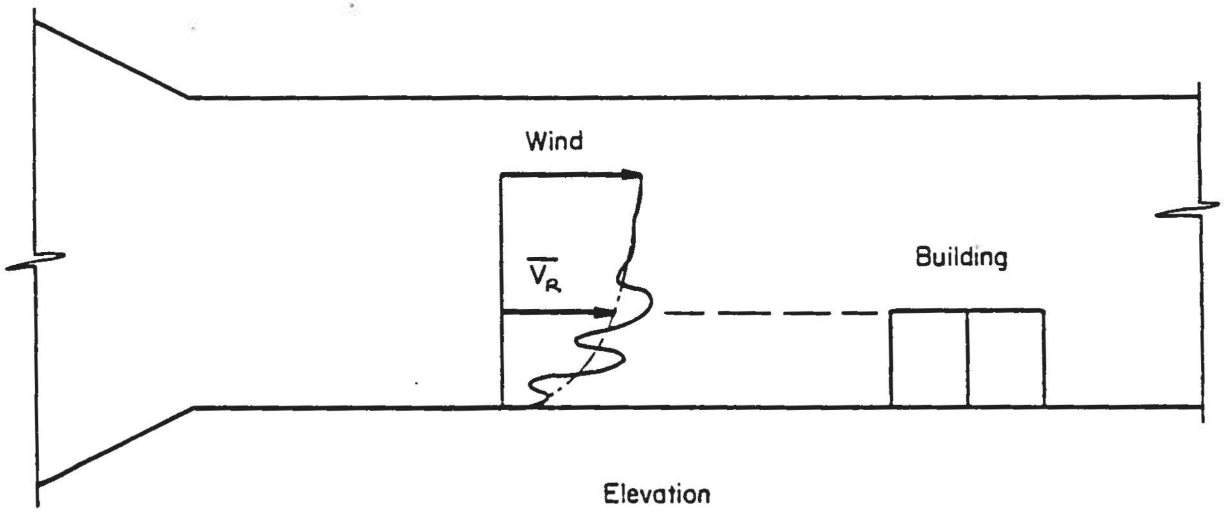
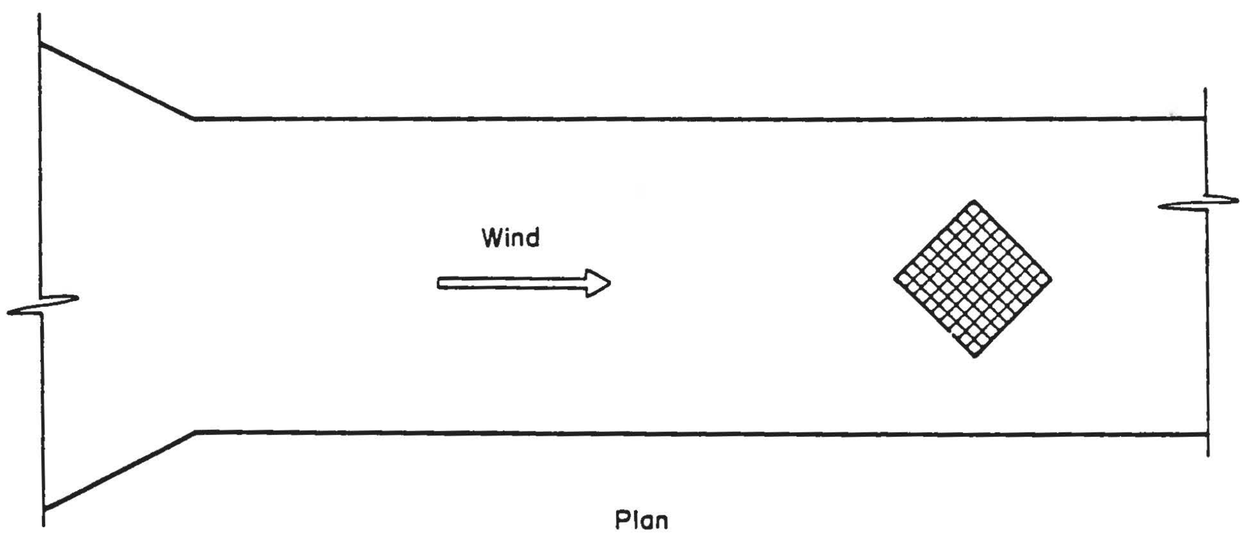


Figure 8. Tested Wind Direction



Elevation



Plan

Figure 9. Tested Experimental Configuration

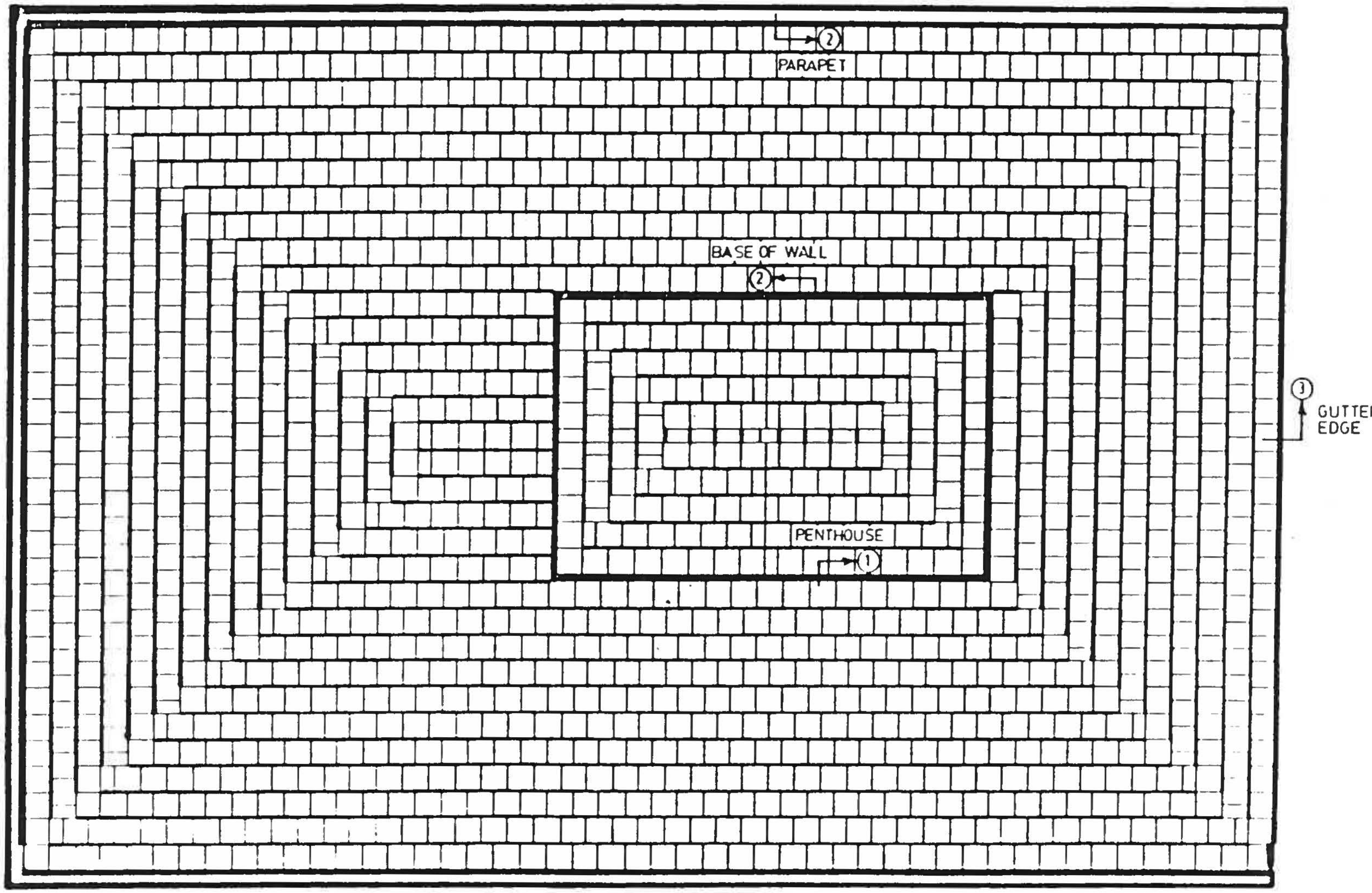


Figure 10. Roofblok Layout Plan

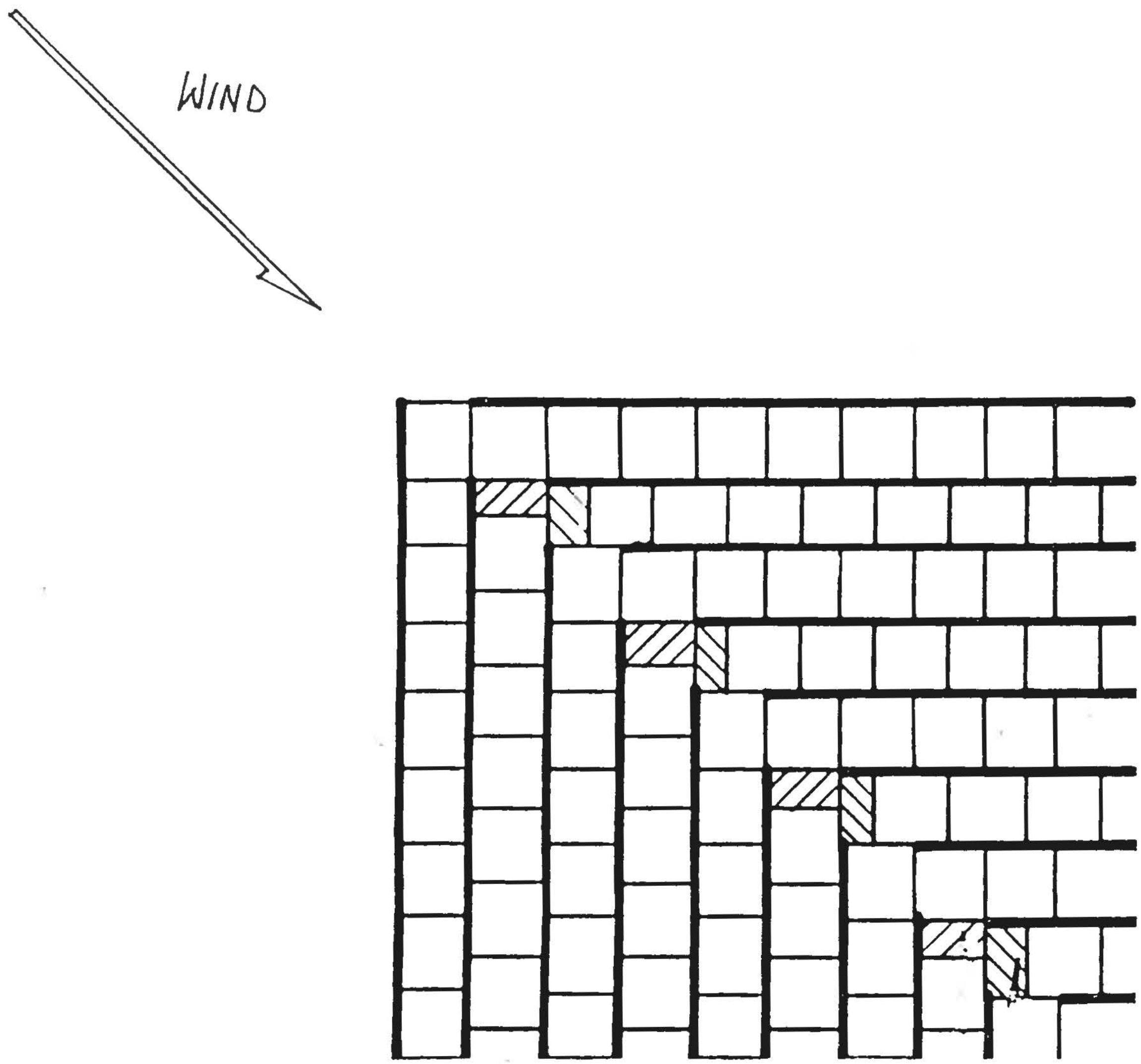


Figure 11. Details of Ballast Block Layout

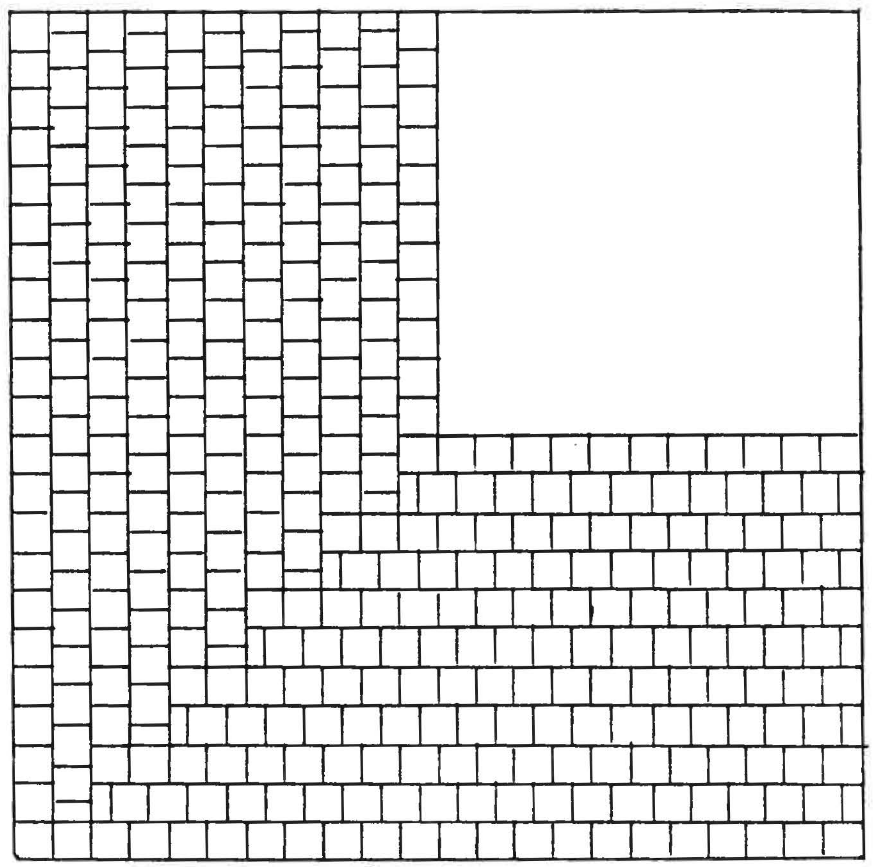


Figure 12. Ballast Block Layout Tested -- Initial Tests

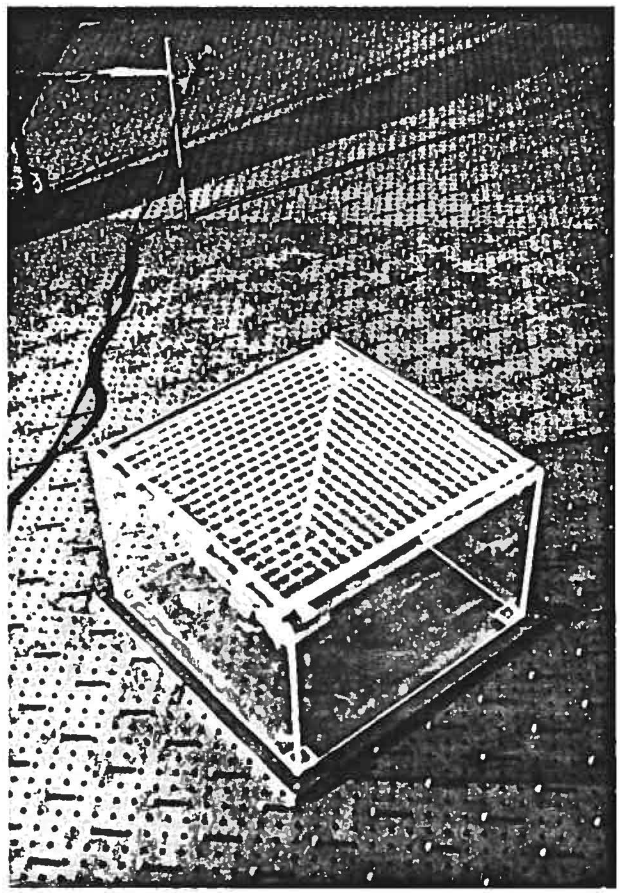


Figure 13. Model inside Wind Tunnel

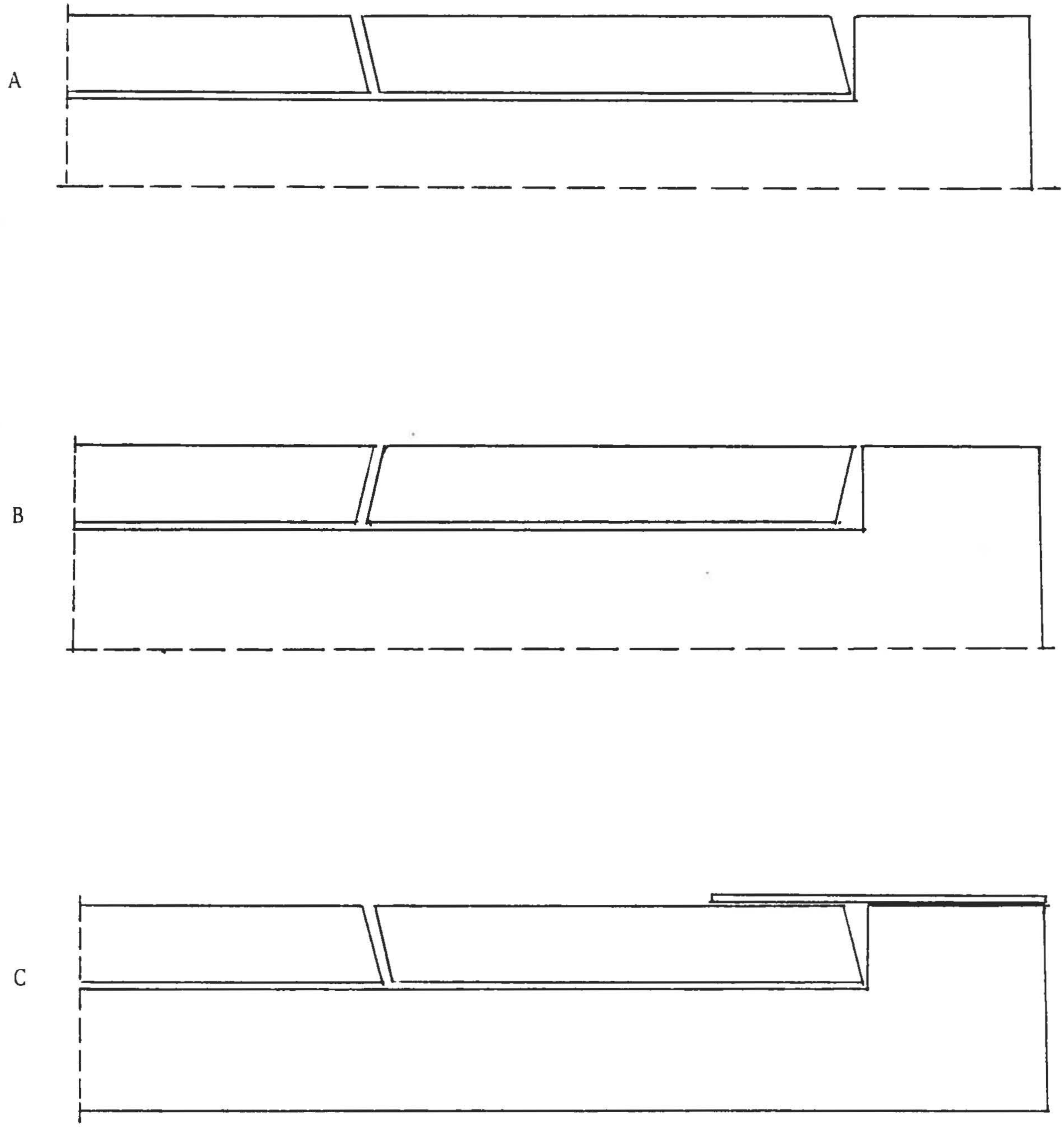


Figure 14. Interlock Configurations Tested

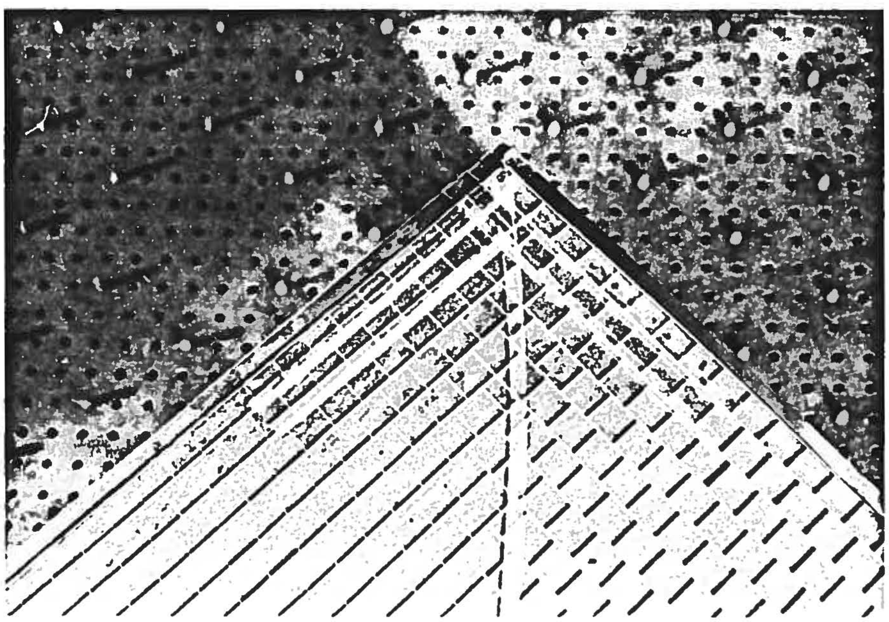


Figure 15. Final Tests -- Configuration CM1

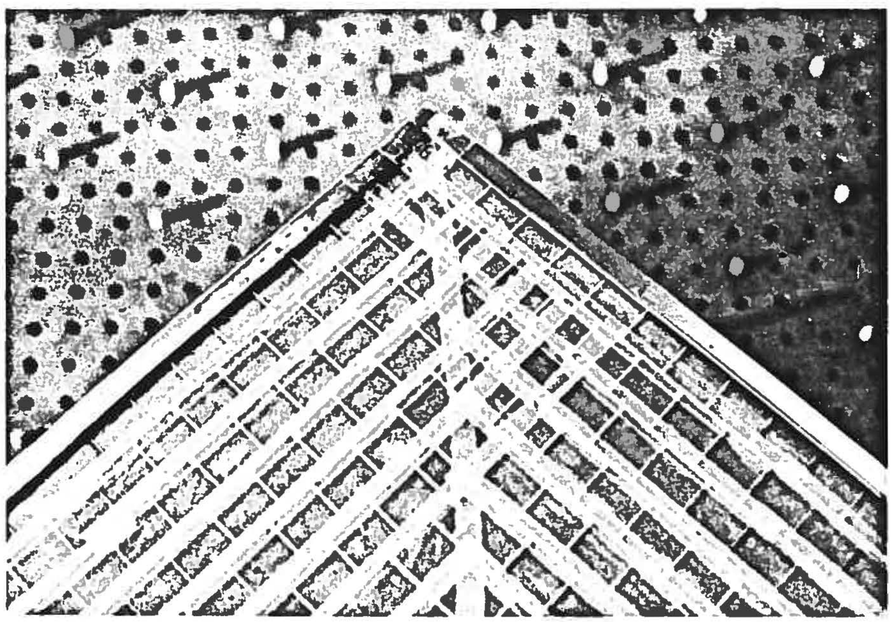


Figure 16. Final Tests -- Configuration CM2

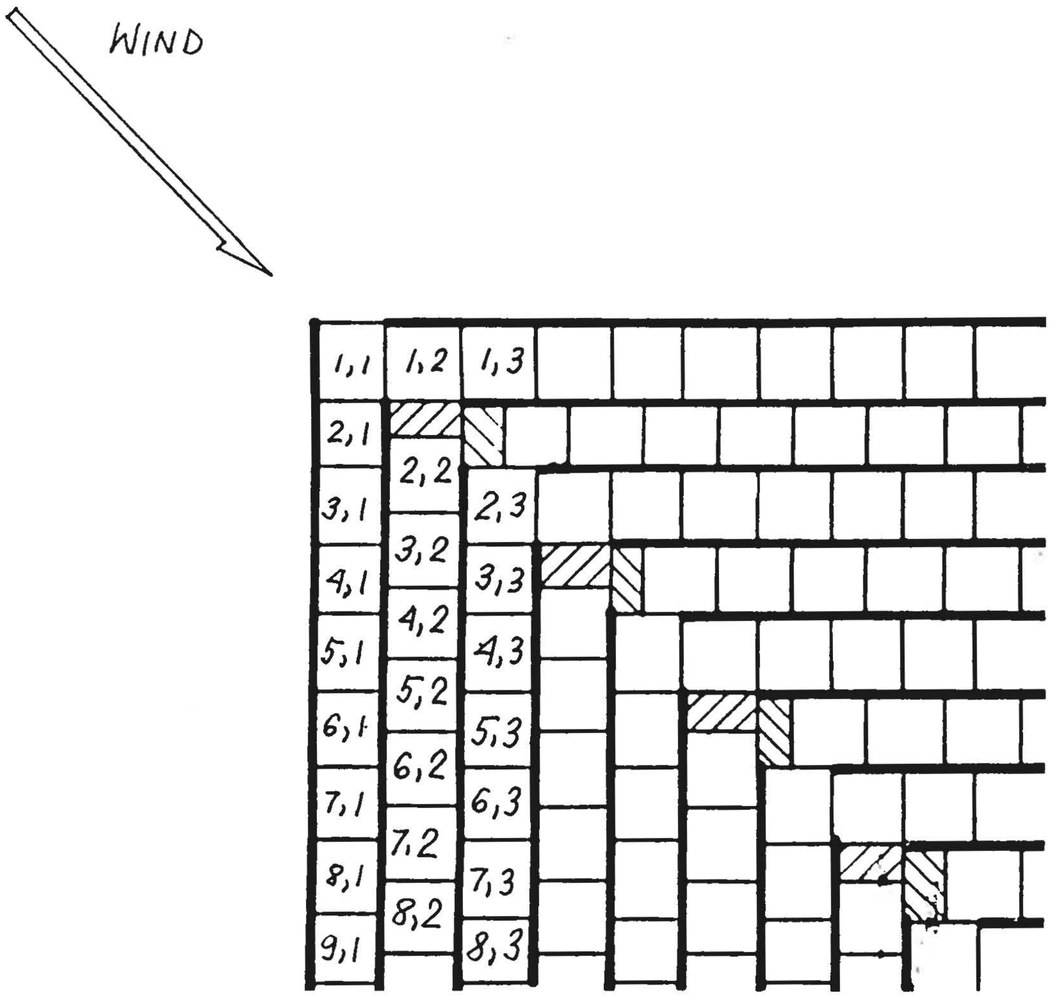


Figure 17. Identification of Ballast Blocks