WIND EFFECTS ON TALL BUILDINGS

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ABSTRACT

Wind interacts with earth-bound buildings to produce both static and dynamic effects on the building. These include stressing of the primary frame through overall action of wind pressures, local loading of cladding panels and glass lights, and oscillation of tall buildings at their natural frequency through the phenomena of vortex shedding and galloping. On the other hand, buildings can modify the wind and cause an unpleasant or dangerous environment for pedestrians. All of the foregoing effects increase in intensity as building heights increase and are increased by the distributions of turbulence and mean wind, geometry of the building and surrounding structures, upwind surface roughness and topography and local climatological factors.

The development of special meteorological wind tunnels during the last ten years has made simulation of natural winds associated with pressure gradients on a synoptic scale possible. This capability has enabled wind effects on tall buildings to be obtained by direct measurement on small-scale physical models and provides a reliable source of data for the design of even taller buildings of the future. However, neither a method to obtain design data nor adequate design methods have been developed which will give assurance that a tall building will not be damaged seriously by intense small-scale atmospheric disturbances such as a tornado.

NOMENCLATURE

$C_{\overline{p}}$ = local coefficient of mean pressure

$C_{p'}$ = local coefficient of the rms pressure fluctuation

K = wave number

$f(k)$ = spectral distribution of turbulent energy--longitudinal fluctuations

f_s = natural frequency of structure

f_v = frequency of eddy shedding

H = height of structure

M_b = moment of wind forces about base of structure

$\overline{p}$ = mean pressure

$\Delta p'_{max}$ = maximum of instantaneous pressure difference--$(p-p_o)_{max}$

Δp_{rms} = root-mean-square of instantaneous pressure difference

U = mean wind speed

S = Strouhal number

W = width of structure

z = vertical coordinate

z_o = roughness height

δ = boundary-layer thickness

δ_s = logarithmic decrement of structural damping

ε = turbulent-energy dissipation per unit mass

ρ = mass density

ν = kinematic viscosity

Ω = angular velocity of coordinate system

Subscripts:

$()_a$ -- refers to air

$()_g$ -- refers to gradient wind elevation

$()_o$ -- refers to reference quantity

$()_s$ -- refers to structure

INTRODUCTION

Efforts to determine wind pressures on buildings by measurements on small-scale models placed in a wind tunnel date back at least to 1893 when Irminger made some aerodynamic experiments in Copenhagen. The results of this early work and later studies are reported by Irminger and Nøkkentred (1) in 1930. In 1933, Dryden and Hill (2) reported their measurements of pressures on a model of the Empire State Building which was tested in a wind tunnel of the National Bureau of Standards. Buildings in these studies and in many subsequent wind-tunnel tests were subjected to "winds" of essentially uniform velocity and no attempt was made to simulate the characteristics of natural winds. The need to use a thick turbulent boundary layer with upwind surface roughness scaled down to the same scale as the building for obtaining realistic pressure distributions was clearly established by Jensen (3) in 1958.

The first wind tunnel designed specifically for simulating natural winds resulting from large scale pressure systems was reported by Cermak (4) in 1958. Characteristic features of these natural winds are so well simulated by the boundary-layer flow of the long-test-section wind tunnel that it provides an ideal laboratory facility for investigation of wind effects on buildings. Reviews of the way in which wind tunnels of this type are used to obtain quantitative data on wind effects have been published by Davenport and Isyumov (5), Cermak (6), and Cermak and Sadeh (7). This approach has not been satisfactorily extended to provide wind-effect data for severe local storms such as thunderstorms and tornadic winds.

The characteristics of winds to which most buildings are subjected are strongly dependent upon the geometry of upwind and surrounding structures. Therefore, the examples of modeling referred to in this paper are those in which the structure under investigation is embedded in a scale model of the city where the structure is to be built. While this procedure permits simulation of locally generated contributions to the wind characteristics, basic wind information for the specific locality--probability of occurrence of strong winds having specified strength and the relative duration of these winds from particular directions--must be obtained from U.S. Weather Service records. Evaluation of climatological records is essential for the design of a realistic and economical model study which will lead to safe behavior of tall buildings in strong winds.

The purpose of this paper is to describe primary wind effects on tall buildings and the modeling concepts and techniques currently in use for determination of these effects on tall buildings. Careful consideration of wind effects on tall buildings is necessary because modern buildings are constructed in ways to make them more susceptible to wind damage. Greater flexibility, smaller damping, thinner cladding and larger glass lights coupled with taller structures or buildings of greater spatial extent all contribute to major wind-loading effects.

Only the wind effects of most common concern to the structural engineer and architect are discussed in this paper. These include the following:

1. Integrated effects of wind pressures--mean and fluctuating forces and moments.
2. Local pressure fluctuations.
3. Dynamic response of tall buildings--gust action, excitation by vortex shedding and galloping.
4. Building induced environmental modifications.

SIMULATION OF NATURAL WINDS

Since most of our basic knowledge of wind effects on structures has been derived from investigations on small scale models placed in a wind tunnel boundary layer, a brief discussion of techniques for simulation of natural winds is in order. The requirements for simulation of natural winds by means of boundary-layer flow in wind tunnels have been discussed by Cermak (8). In the study of wind effects on buildings, strong winds are of primary concern. For these winds thermal stratification of the atmosphere near the surface is destroyed by intense mixing and the problem becomes one of simulating neutral atmospheric flows which correspond to isothermal flow in the wind tunnel. Basic requirements for simulating natural winds of this type are:

1. Undistorted scaling of boundary geometry--including topographic features and buildings.
2. Reynolds number $(U_o W/\nu)$ equality.
3. Rossby number $(U_o/W\Omega_o)$ equality.
4. Kinematic similarity of approach flow--distributions of mean velocity and turbulence characteristics.

For most cases the exact requirement of equal Reynolds number and equal Rossby number must be compromised. Geometrical scaling of 1:500 is very common; therefore, unless a compressed-air wind tunnel or a facility using a fluid such as Freon is used, the laboratory Reynolds number will be smaller than for the prototype. This relaxation of Reynolds number equality has been found to not be a deterrent to modeling since the flow around sharp-edged buildings becomes invariant with this parameter well below the range of Reynolds number achieved in the laboratory. Large wind tunnels cannot be rotated easily; therefore, the Rossby number requirement has been relaxed also. Rotation of the earth causes the mean wind to change direction with height but only by amounts of two to five degrees over height of 1000 ft in the case of internal boundary layers developed by strong winds over rough boundaries such as cities. Studies to determine if wind-direction changes of this magnitude can affect the aerodynamic stability of tall buildings are needed.

Kinematic similarity of the approach flow can be achieved if an adequate wind tunnel is used. A wind tunnel suitable for modeling wind loading of structures must be capable of developing a turbulent-boundary layer thickness δ from 1-2 times as great as the height H of the modeled structure. If this can be accomplished and the ratio of upwind surface roughness z_0 to structure height H is equal for model and prototype, Jensen (3) demonstrated by measurements on both a model and prototype box-like structure that the pressure distributions are similar. Using these criteria for sharp-edged structures leads to a desired test-section length of from 75-100 ft when studies are to be made on tall buildings approximately 1000 ft high modeled on scales of from 1:600 to 1:400. An additional requirement is for the pressure to be essentially constant along the test-section length as it is in the atmosphere. This requirement may be met by providing adjustment of the cross-sectional area of the test section--usually accomplished through use of a flexible ceiling which can be raised several feet from the position of parallelism with the floor.

A wind tunnel built for this purpose which was completed in 1963 is shown in Fig. 1. It has been used to determine wind loading on several tall structures such as the New York World Trade Center Towers, the Bank of America World Headquarters Building, the Standard Oil (Indiana) Building and several others. It has also been used to study thermally stratified flow over modeled topographic features and urban complexes. In this tunnel, boundary layers up to 4 ft in thickness at wind speeds near 100 mph can be developed at the downstream position of the test section where the models are normally located.

In 1966 an excellent facility for wind-load studies was completed at the University of Western Ontario. This open-return tunnel has a test section 8 ft square and 100 ft long. Boundary layers up to 4 ft in thickness can be developed over a floor roughened to represent an extensive urban complex. A wind study of the United States Steel Building was made in this wind tunnel by Davenport and Isyumov (9).

A second wind tunnel for studies of structural and environmental aerodynamics was completed at Colorado State University in 1969. This facility shown in Figs. 2 and 3 has a test section 12 ft wide by 8 ft high with a flexible ceiling for pressure adjustment. The motivation for designing a tunnel with greater width of the working section was to permit more extensive building groups to be modeled without reduction of scale below 1:400 or 1:500. In this tunnel, with a limited test-section length of 56 ft some structural studies require augmentation of the naturally developed boundary layer through the use of vortex generators, tripping fences and/or grids of variable spacing at the test section entrance. Recent studies by Counihan (10) confirm that artificial thickening of the boundary layer is possible without serious distortion of the turbulence field if sufficient length of test section is available between the stimulator and the model. As building heights increase (2000 - 4000 ft) larger wind tunnels will be needed to obtain optimum scaling.

Using a 30 ft V/STOL wind tunnel of the National Aeronautical Establishment (Canada), Standen, Dalgliesh, and Templin (11) studied pressures on a 1:400 scale model of the Canadian Imperial Bank of Commerce Building. They compared mean pressures with a boundary layer developed over a long (60 ft) rough boundary and a boundary layer stimulated by 4 ft-high vortex generators with measurements taken on the full-scale structure. The authors concluded that both flows gave acceptable results for the small-scale model.

Several comparisons of mean velocity and turbulence data are presented to give some appreciation for the wind-tunnel capabilities. Unfortunately, field data for the case of interest, strong wind over city centers, are not available with the result that field data obtained at sites of lesser roughness must be used for comparison.

Mean velocity distributions obtained in the Bank of America World Headquarters Building model study (12) and the United States Steel Building model study (9) are shown in Fig. 4. A velocity profile for the conditions of neutral stability from a tower on the outskirts of Philadelphia reported by Slade (13) is also presented on the nondimensional plot. These profiles are in satisfactory agreement with the power-law distribution recommended by Davenport (14). The profiles for extremely rough surfaces such as the center of cities with tall buildings ($U \alpha z^{0.4}$) and for surfaces corresponding to suburban areas ($U \alpha z^{0.28}$) provide a good bracket for simulated profiles in the long-test-section wind tunnels.

An example of how laboratory and natural turbulence power spectra compare is given by Fig. 5 taken from a study by Sandborn and Marshall (15). The wind-tunnel data were obtained in the Colorado State University meterological wind tunnel over a smooth boundary 69 ft from the test-section entrance 1 ft above the surface in a boundary layer 2 ft thick. Excellent agreement is found for high wave numbers (high frequency) turbulence down to a wave number of 1 cycle/ft for the simulated flow. Comparable data are now available for the boundary roughness conditions shown in Fig. 6. For this type of roughness the agreement is extended down to a substantially lower wave number of approximately 0.1 cycle/ft. It is extremely important that all major upwind buildings be represented in the model since the wakes produced by them will add energy to the spectrum at wave lengths comparable to the dimensions of the structure. The primary deficiency in the simulated turbulence spectrum is the inability, using existing facilities and techniques to simulate the meso-scale wave lengths ranging upward from about 5 miles. This is not a serious limitation but must be recognized when attempting to compare wind-tunnel derived mean force and moment coefficients with those obtained from measurements on prototype structures.

INTEGRAL MEAN AND FLUCTUATING FORCES AND MOMENTS

Wind pressures on the outer surface of a building vary strongly with both position and time. A minimum requirement of the primary structural frame is that neither overstressing of the members nor excessive deflection will result when subjected to a system of mean forces and moments obtained by integrating time averaged pressures for the design mean wind speed over the entire building surface. Of course, the instantaneous surface integral of forces and moments produced by surface pressures will fluctuate from the mean value even if the mean wind velocity were to remain constant. This is caused by turbulence of the wind (an effect which is described in this section) and by interaction of the wind with the structure to produce vortices and/or lateral focus similar to lift on an airfoil (dynamic effects of vortex shedding and galloping are discussed in a subsequent section).

Mean Forces and Moments

The usual procedure for determination of mean forces and moments is to measure mean pressure differences at a large number of points (piezometer taps) distributed over the building surface. Figure 6 shows the Atlantic-Richfield Plaza Building rigid model used by Sadeh, Cermak and Hsi (16) to make these measurements. The reference pressure is ordinarily taken as the pressure measured by the side ports of a pitot-static tube located in the undisturbed flow directly above the model building. From these measurements mean pressure coefficients

$$C_{\overline{p}} = \frac{\overline{p} - \overline{p}_g}{\rho\, U_g^2/2}$$

are calculated for each point. For sharp-edged structures this coefficient is a constant at a particular point and for a particular wind direction. The advantage of using a dimensionless coefficient of this form is that it yields, upon integration over the building surface, force and moment coefficients also independent of the actual wind speed used in the model study. For example, the overturning moment (about the base of a structure) may be expressed as follows:

$$C_{M_b} = \frac{M_b}{W\, H^2\, (\rho U_g^2)/2}$$

For tall prismatic structures this coefficient ranges between 0.2 and 0.4 depending upon the building shape, the wind direction, roughness characteristics of the upwind approach and local topography. Worthy of note is the fact that M_b varies as the square of the building height H .

Fluctuating Overturning Moments

Information on the instantaneous values of the fluctuating overturning moment and forces are useful in efforts to determine how the random gust loading may influence fatigue life of the structure and maximum stresses. This information cannot be obtained through measurement of the instantaneous surface pressures because they vary greatly with respect to location and time. Therefore, a direct measurement which reflects the instantaneous integrated effect of the entire surface pressure distribution at any instant becomes necessary. Figure 7 shows an arrangement used by Sadeh, Cermak and Hsi (16) to measure the instantaneous overturning moment about the weak axis of the Atlantic-Richfield Plaza Building model. The dynamometer with a rigidly attached tower had a natural frequency of 200 Hz. The fluctuations of overturning moment depend strongly on turbulence structure of the oncoming flow as shown in Fig. 8. These data reveal that a tall building centrally located within a complex of other buildings is subjected to large fluctuations in wind loading. For the model with roughness as indicated in Fig. 6 the peak moment fluctuations were approximately 35% of the mean value. It must be remembered that this result is for a "static" structure and that peak moment fluctuations can exceed the value quoted by large amounts when the structure is dynamically excited.

LOCAL PRESSURE FLUCTUATIONS ON EXTERIOR SURFACES

The magnitude of peak local pressure fluctuation on the outer "skin" of a building can exceed the velocity pressure for the local mean wind $\rho U^2/2$ by factors of two to approximately five. Such large differences can lead to fatigue failure of exterior panels, rupture of panel anchors, glass breakage, and driving of rain through construction joints. Breakage of glass can result in much property damage and loss of life caused by falling glass and other debris and the possibility of persons being ejected from the open window space.

High values of local pressure fluctuations were found by Cermak (18) and by Ostrowski, Marshall and Cermak (17) to be caused by one or more of the following mechanisms:

1. action of gusts arriving at the structure in the approaching winds,
2. reattachment on the structure of flows which have separated because of sharp edges, corners, or other architectural features and
3. local vortex shedding from an exterior architectural feature.

Measurements to detect these effects must be made by pressure transducers having good frequency response up to 200 Hz. The best approach is to use a strain-gage type pressure transducer mounted on the interior wall of the model which is directly connected to the piezometer tap. The pressure fluctuations can be observed on an oscilloscope or recorded on magnetic tape for statistical analysis.

Large pressure fluctuations resulting from reattachment of separated flow were observed on a 1:100 scale model of the Standard Oil Company (Indiana) Building (19) now under construction in Chicago. Figure 9 shows a cross section of the 1100 ft building. The most severe pressure fluctuations were found to occur at a re-entrant corner where flow separating at one edge of the corner reattached at the opposite edge. Figure 10 reveals maxima for point C6 at $\alpha = -17^\circ$ and 5°. The flow pattern at $\alpha = -17^\circ$ is shown in Fig. 10. For $\alpha = 5^\circ$ the basic flow pattern looks similar. In both cases a well-defined rotary flow occurs in the re-entrant corner.

An effort was made to estimate the maximum pressure fluctuations $(\Delta p')_{max}$ from Visicorder recordings of the pressure fluctuations. The observations yielded values of $\Delta p'_{max}$ approximately equal to $4\Delta p_{rms}$; however, in some instances this factor has been found to reach values of approximately eight when exterior geometry is highly irregular.

An appreciation for the magnitude of the maximum pressure fluctuations $\Delta p'_{max}$ is obtained by comparing their magnitude with the mean pressure for a particular wind speed. If the point C6 is considered for a wind angle of $\alpha = -17°$ for which $C_{\overline{p}} \simeq -2$ and $C_p' \simeq 0.4$, a wind speed of $U_g = 100$ mph would produce the following pressures:

$$\overline{p}_{C6} - \overline{p}_o \simeq -50 \text{ psf}$$

and

$$(\Delta p'_{C6})_{max} \simeq \pm\ 40 \text{ psf}$$

Thus, an instantaneous pressure at C6 resulting from the mean wind and the separation induced maximum pressure fluctuation can attain the sum of these two values or -90 psf.

The use of smaller windows and/or installation of tempered glass provide adequate design flexibility to provide protection against glass breakage.

DYNAMIC RESPONSE

Modeling of dynamic effects produced by wind loading introduces requirements for similarity in addition to those already stated. Whitbread (2) has discussed the requirements for elastic similarity in some detail. For tall buildings in which only the fundamental mode of motion is simulated, a commonly used approximation, the additional dimensionless parameters for which equality is required in the scale model and prototype may be summarized as follows:

1) Frequency ratio: $\dfrac{(f_s)_x}{(f_s)_y} = \dfrac{\text{Natural frequency about x-axis}}{\text{Natural frequency about y-axis}}$

2) Logarithmic decrement: $\delta_s = \dfrac{\text{Energy dissipation/cycle}}{\text{Total energy of oscillation}}$

3) Density ratio: $\dfrac{\rho_s}{\rho_a} = \dfrac{\text{Average mass density of structure}}{\text{Mass density of air}}$

4) Reduced velocity: $\dfrac{U}{f_s W} = \dfrac{\text{Mean velocity of wind}}{\text{Reference oscillation velocity}}$

A common procedure is to mount the model on a gimbals fixed to an inertial platform placed beneath the wind-tunnel floor. Two pairs of mutually perpendicualr springs attached to a rod rigidly fixed to the structural shell and passing below the gimbals provides the elastic forces which can be designed to provide the desired natural frequencies. Strain gages attached to the spring mounts can be used to give a voltage output proportional to sway amplitude. Adjustable magnetic damping is provided conveniently by attaching to the support rod a metal plate which passes between the poles of an electromagnet. Variation of current through the magnet permits control of δ_s through a wide range of values. An arrangement similar to that used by Whitbread and Scruton (21) is sketched in Fig. 12.

When air at atmospheric pressure is used for the modeling fluid the density-ratio requirement results in the necessity for the average mass density of the model to equal the prototype value. An average specific weight for tall buildings of about 10 lb/ft^3 requires that the stiff central core of the model be covered with a thin shell of light material to reproduce the structural form. A soft wood about 1/16 - 1/8 in. thick can satisfy this requirement. The selection of a natural frequency f_s for the model is guided by the requirement that the reduced velocity be equal for model and prototype. For example, if testing wind speeds are to be limited to one-fifth of the atmospheric wind speeds and the length scaling is 1:500, natural frequencies of the model must then be 100 times the prototype value. Hence, a prototype structure with a natural frequency of 0.1 Hz would require a model frequency of 10 Hz.

Tall buildings may be set in motion by winds through several mechanisms which can act separately or in combination. These aerodynamic effects may be isolated as follows:

1. gust impingement upon the structure (buffeting),
2. vortex shedding from the structure and
3. energy transfer from mean wind to structure through action of lateral wind force in direction of building motion (galloping).

Gust Action

Gust action produces the type of moment fluctuations shown in Fig. 8 which in turn produce deflection fluctuations. A distinction between different types of gusts may be made according to their organization in space and time. Gusts of random size and frequency of occurrence are present as turbulence in the boundary layer. However, gusts of rather constant size and frequency of occurrence may appear as a result of vortex shedding from an upwind tall building. The latter form can be particularly distressing if the frequency of occurrence is near the natural frequency of the structure upon which they act. Wind-tunnel studies are essential for identifying the existence of oscillations driven by quasi-periodic wakes from upwind buildings.

Vortex Shedding

The same vortex shedding which produces nearly periodic wakes (Kármán vortex trails) produces periodic force on the structure from which they are shed. For uniform flow over a long cylinder of square cross section the frequency of vortex shedding f_v is related to the wind speed U and the width of the structure W by a constant value of the Strouhal number S equal to about 0.14 (Ref. 12, p. 28); i.e.,

$$S = \frac{f_v W}{U} \simeq 0.14$$

Although lateral oscillations at the natural frequency of the structure f_s are excited by this mechanism over a wide range of f_v as U varies, major problems arise if $f_v \simeq f_s$. Fortunately, as shown by the measurements of Whithead and Scruton (21) excitation by vortex shedding is greatly reduced when the structure is subjected to a highly turbulent shear flow such as that found in the center of cities. Figure 13 illustrates the dramatic disappearance of the resonance peak at a wind speed of about 130 mph. Apparently, the intense large-scale turbulence disorganizes the vortex and reduces correlation of vortex-generated pressure differences over the building height. The loss of strong vortex-shedding excitation observed here was for a building approximately 1500 ft high, a height equal to the nominal thickness of the atmospheric boundary layer. As building heights increase to 2000 - 4000 ft strong vortex-shedding excitation should be expected because of nearly uniform flow over the upper part of the structure.

Galloping

The most subtle and dangerous driving force leading to building oscillation lateral to the mean wind arises from negative aerodynamic damping. This phenomena of transfer of energy from the mean wind to the structure as the direction of oscillatory motion becomes correlated with the direction of resultant lateral aerodynamic forces is termed galloping. Unfortunately, whereas winds of high turbulence and mean shear reduces vortex-shedding excitation the opposite occurs for excitation by negative aerodynamic damping. This behavior which is clearly shown in Fig. 13 presents one of the most serious problems of wind loading on high-rise buildings. At this time, the best means of insuring against excessive amplitude of oscillation is to provide adequate structural damping. Determination of the structural damping necessary to keep the amplitude within prescribed limits for a specific building can be accomplished with greatest reliability through a systematic model study in which δ_s, the reduced velocity and wind direction are treated as independent variables. Figure 13 illustrates the effectiveness of an increase in δ_s on the control of oscillation amplitudes.

Reduction of Dynamic Effects

Excessive deflections resulting from dynamic excitation can cause external architectural features to fail, interfere with elevator operation, cause severe human discomfort and can lead to possible catastrophic failure in extreme cases. These effects which identify some of the most obvious concerns present some of the most serious difficulties in the design of buildings which may reach heights of 2000 to 4000 ft. At this time, the control of oscillation amplitudes (usually at frequencies corresponding to the natural frequencies of the structure) is obtained by providing for adequate damping. For future building, modification of architectural details for reduction of aerodynamic excitation may provide a more direct approach to this problem.

Augmentation of damping in a building presents a challenge for the structural engineer which must be met through the use of concepts new in structural engineering. This problem has been solved in a practical and efficient manner by Robertson (22) through the use of secondary connections in the form of a steel-plate viscoelastic-material sandwich between floor trusses and columns. Ten thousand of these connections were built into each tower of the New York World Trade Center Towers to provide the necessary level of damping as determined by the wind-tunnel measurements.

Several modifications of building geometry and architectural detailing appear promising for the reduction of aerodynamic excitation. Three of these possibilities suggested by Cermak (23) are shown in Fig. 14. The vertical porous plates at corners and the horizontal rings would present a penalty in the form of increased mean overturning moment while the air-duct system would result in a reduction of available floor space. The effectiveness and feasibility of these and other structural modifications must be determined by future research which has been initiated by the author through support of the National Science Foundation.

BUILDING INDUCED ENVIRONMENTAL MODIFICATIONS

Tall buildings invariably induce a strong downward flow on the upwind face. This produces a gusty environment for pedestrians which is difficult to eliminate. As pointed out in a recent paper by Melbourne and Joubert (22) the addition of horizontal surfaces such as projecting canopies or plaza roofs is necessary to cope with this problem. The wind-tunnel model measurements are essential for the design of effective and economical structural appendages and dense plantings of bushes and trees. A rough guide for avoidance of injury to pedestrians is to limit occurrence of 50 mi/hr gusts at street level to once each year or less.

CONCLUDING REMARKS

Resultant mean forces and moments are imposed upon tall buildings by wind which must be transmitted to the foundation by the structural frame. For tall buildings the overturning moment exceeds the moment of gravitational forces on the building; therefore, exterior columns are subjected to stress reversals. With information on statistics of the fluctuating mean overturning moment and statistics of mean wind speeds for different wind directions the cycling rate may be determined on an annual basis and fatigue life estimated.

Peak fluctuating wind pressures on cladding and glass windows reach destructive levels near corners of tall buildings. As buildings increase in height, window glass should be reduced in area and tempered glass should be installed in an effort to reduce property damage and injury to occupants and pedestrians.

Aerodynamic excitation of building oscillations presents ever increasing problems as building heights increase. Augmentation of inherent structural damping can be increased by installation of viscoelastic dampers for buildings of current maximum heights -- 1500 ft. As heights increase to the 2000 - 4000 ft range modification of building geometry in a manner which will minimize vortex shedding and galloping must be considered. If effective geometrical modifications can be established through basic research in this area and added damping is designed into the building, buildings twice the height of those now existing can be constructed for safe and comfortable service to man.

Investigations of wind effects on buildings by means of small-scale models subjected to boundary-layer flow in a wind tunnel currently provide indispensable data for both the design engineer and architect. The same techniques can provide knowledge which will enable development of innovative architectural details for reduction of aerodynamics excitation in tall buildings. However, great care must be taken to simulate the natural characteristic lengths of wind motion at a scale comparable to the building scale. This approach, while satisfactory for strong winds generated by large-scale pressure systems, has not been developed to study wind effects produced by thunderstorms and tornados.

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24. Melbourne, W.H. and P.N. Joubert, "Problems of Wind Flow at the Base of Tall Buildings," Preprint of *Proceedings, Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, September 1971, Paper I.11, pp. 105-114.

25. Conference on Wind Loads on Structures, Sponsored by the National Science Foundation, The California Institute of Technology, Pasadena, California, December 1970.

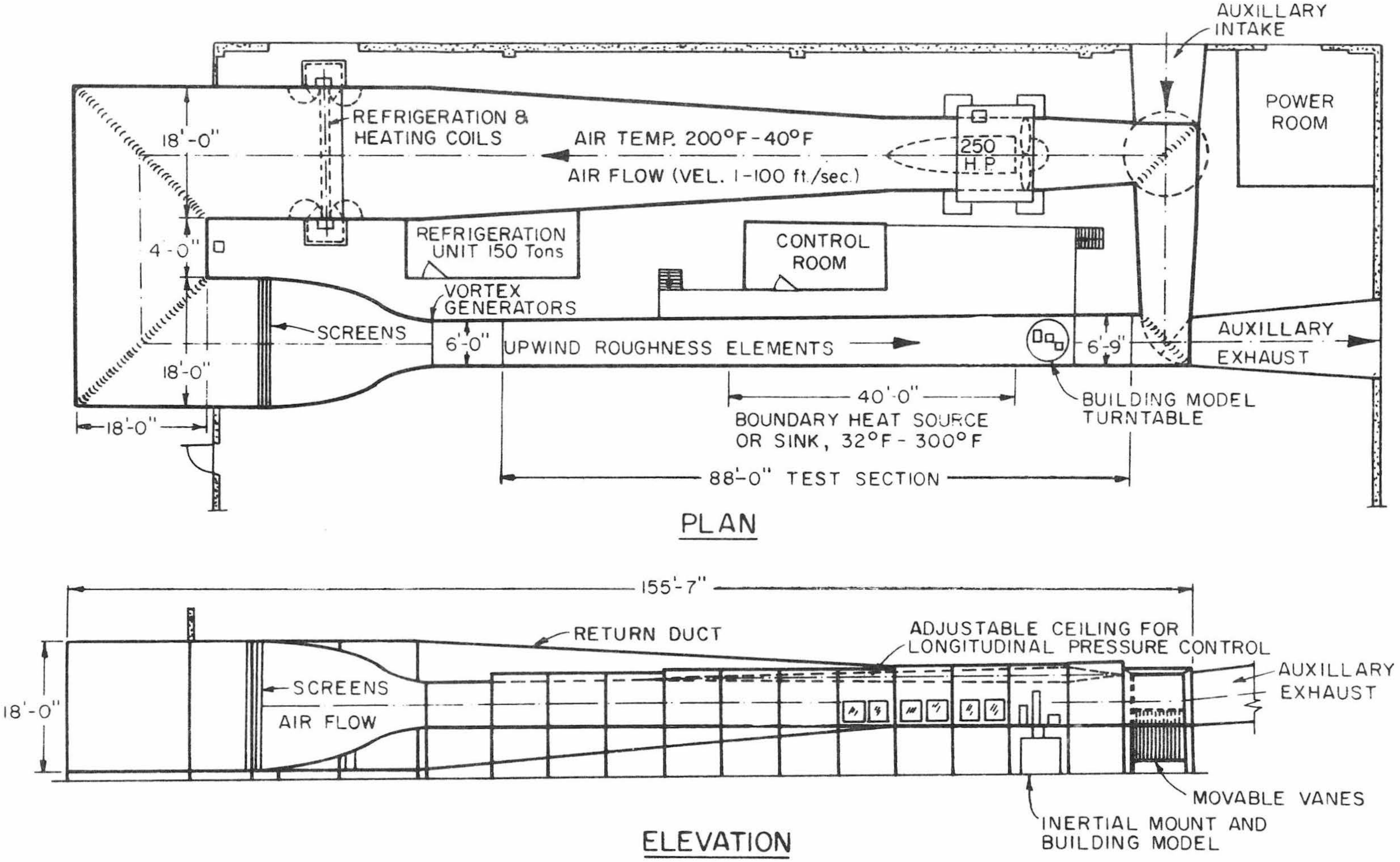


Figure 1. **METEOROLOGICAL WIND TUNNEL (Completed in 1963) FLUID DYNAMICS & DIFFUSION LABORATORY COLORADO STATE UNIVERSITY**

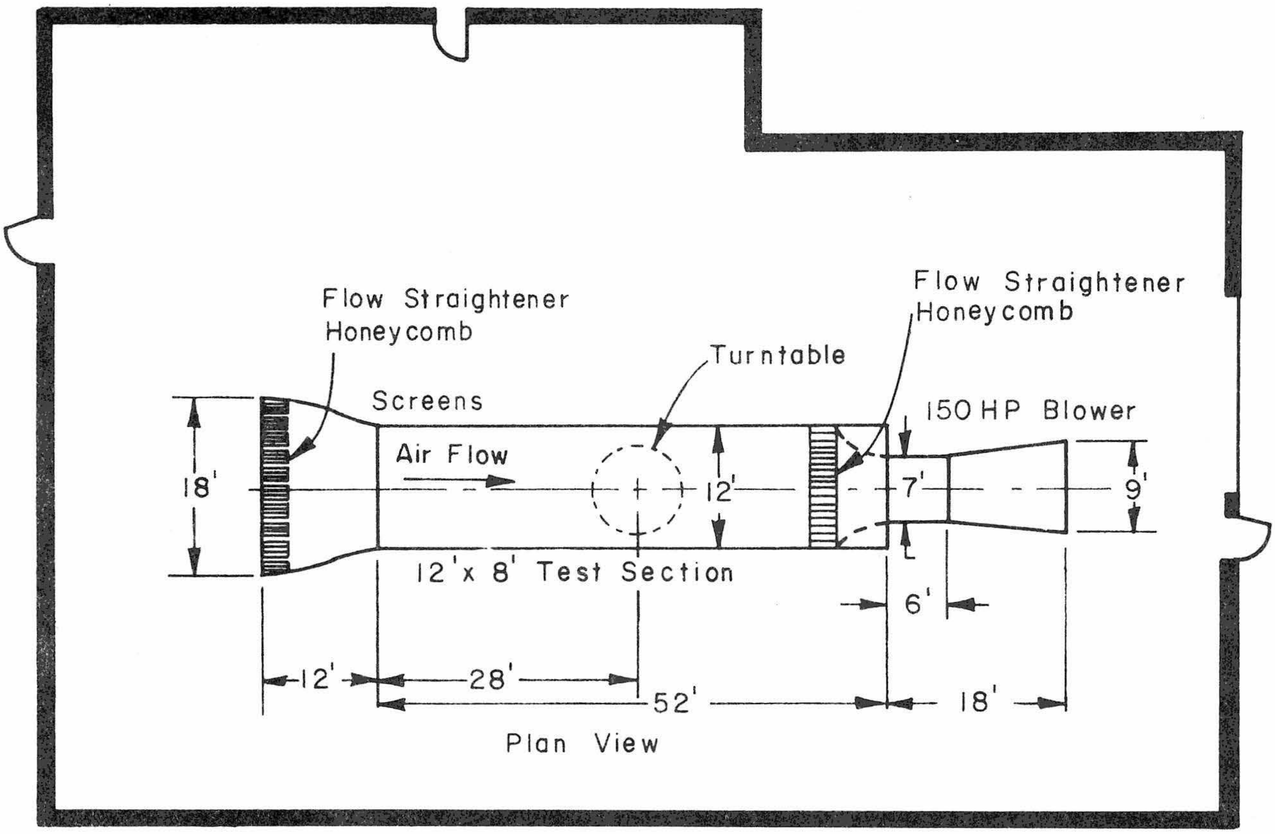


Figure 2. Environmental Wind Tunnel — Fluid Dynamics and Diffusion Laboratory, Colorado State University.

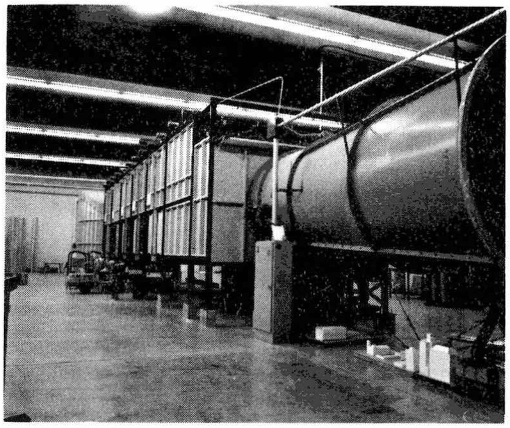


Figure 3. Exterior of Environmental Wind Tunnel.

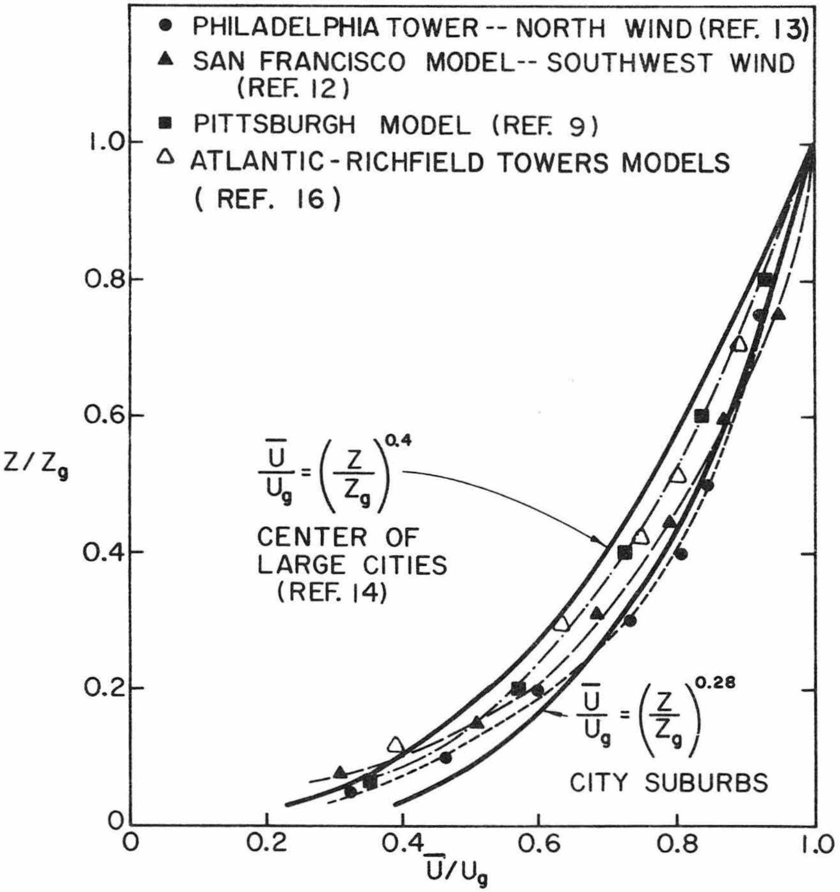


Figure 4. Comparison of simulated and natural mean wind profiles.

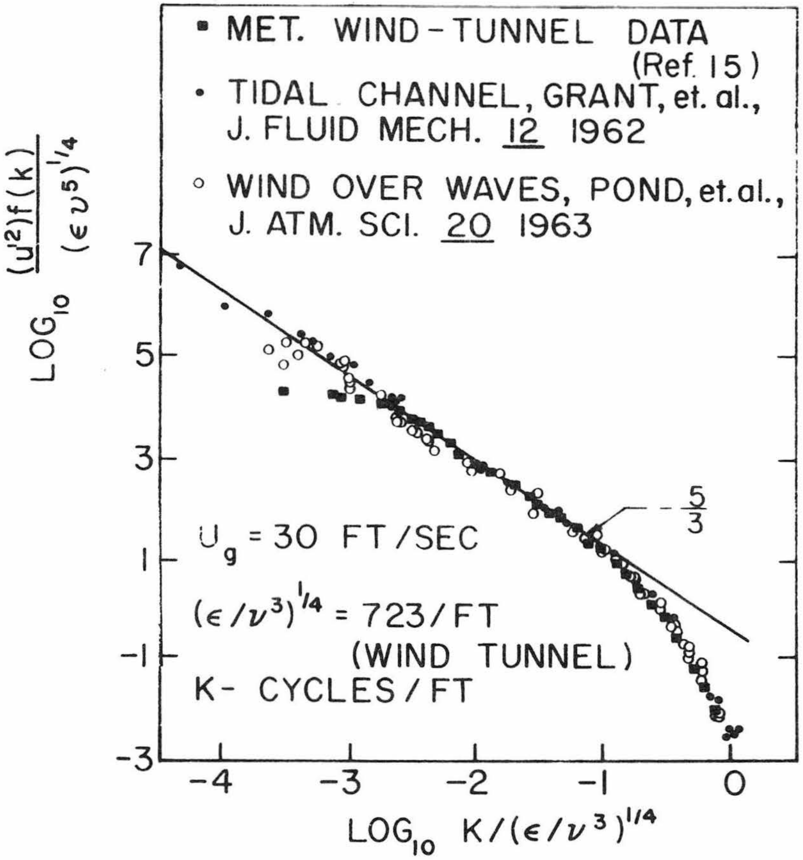


Figure 5. Comparison of simulated and natural longitudinal turbulence spectra.

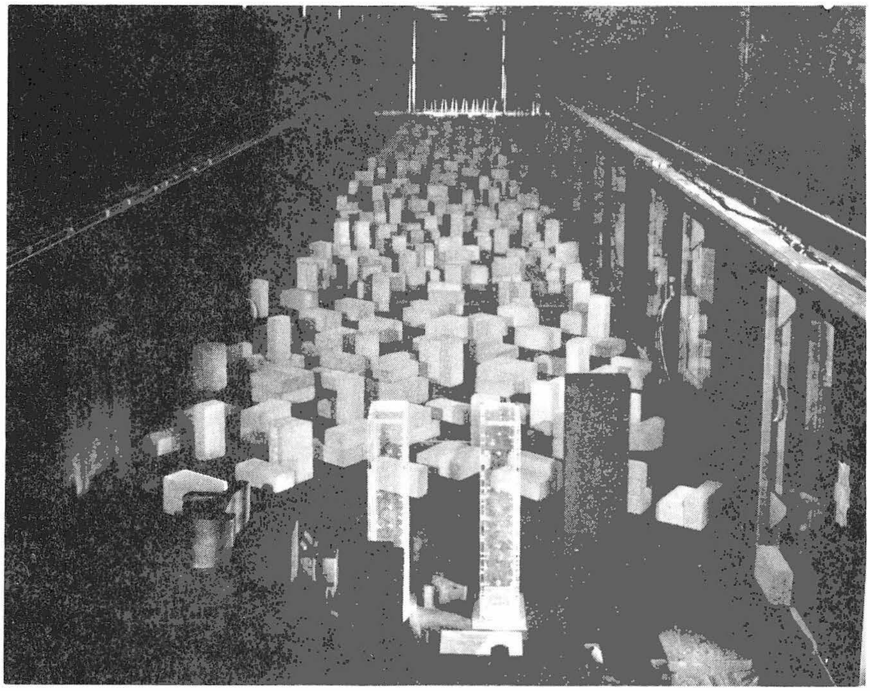


Figure 6. Atlantic-Richfield Plaza Buildings, Los Angeles (1:384 scale)

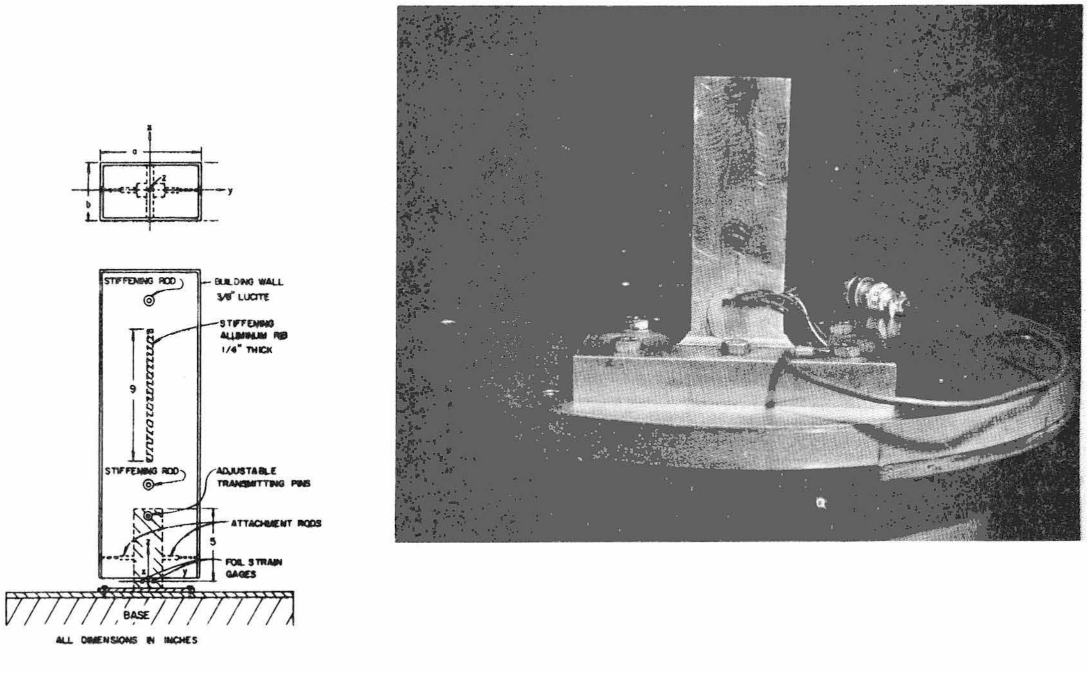


Figure 7. Moment-measuring dynamometer (Ref. 16)

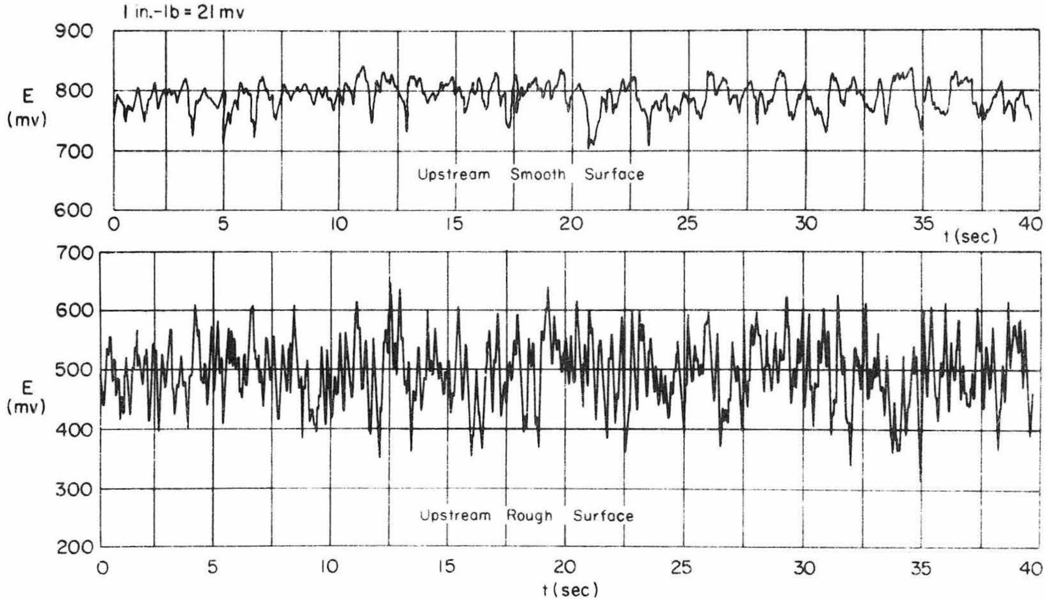


Figure 8. Total overturning moment variation: (a) without upstream roughness, (b) with upstream roughness (Ref. 16)

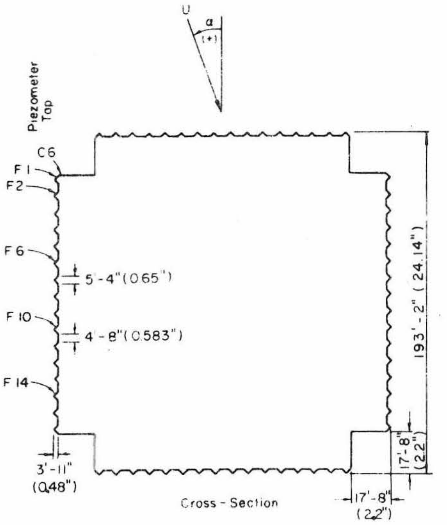


Figure 9. Standard Oil Company (Indiana) Building (Ref. 19)

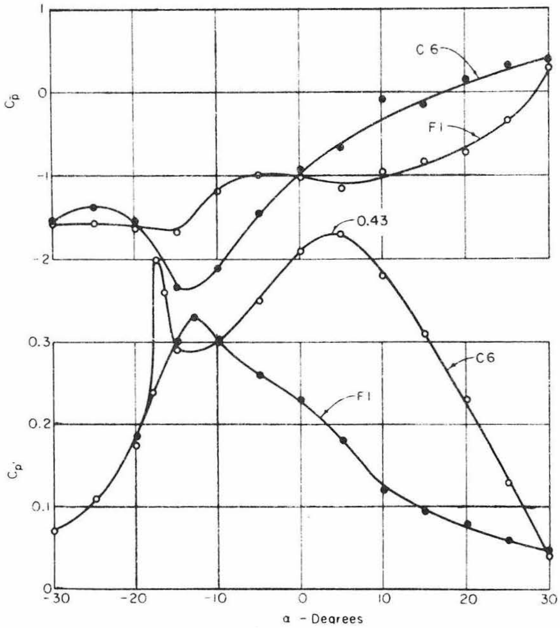


Figure 10. Mean and RMS pressure coefficients for points C_6 and F_1 —Standard Oil Building (Ref. 19)

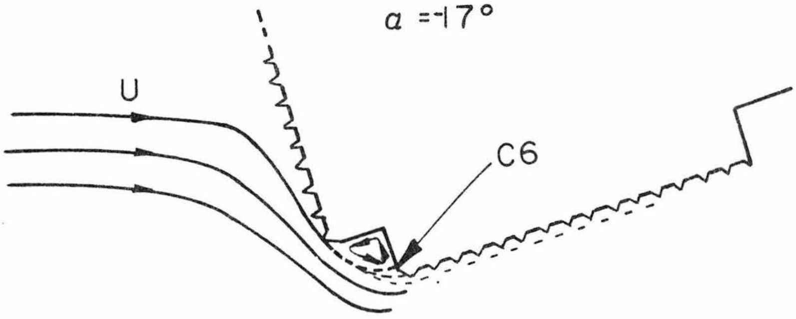


Figure 11. Streamlines near Standard Oil Company (Indiana) Building for α = -17° (Ref. 19)

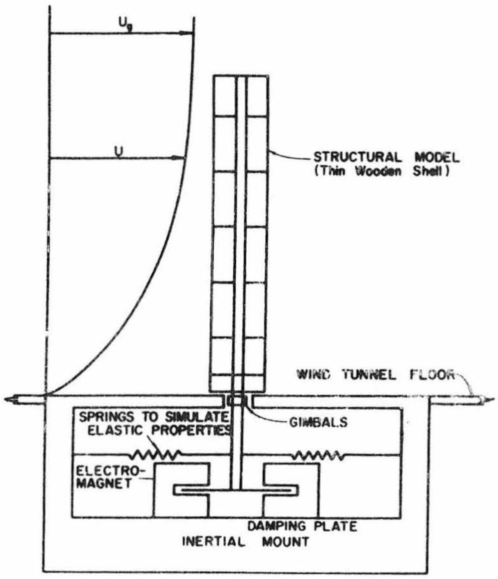


Figure 12. Typical design for dynamic modeling of a tall building

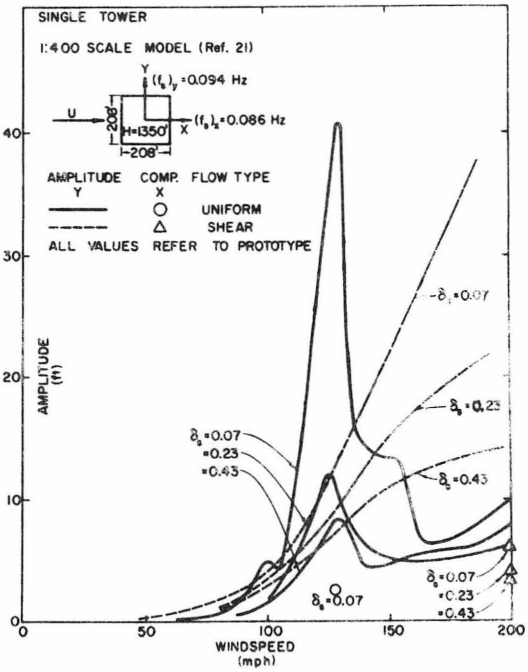
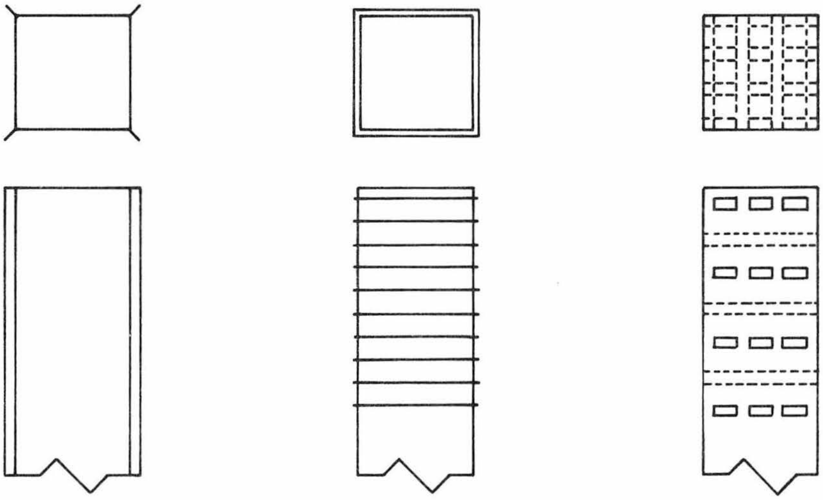


Figure 13. Comparison of dynamic response for a square high-rise building in uniform and shear flow with varying structural damping (Ref. 21)



a.) Vertical Porous Corner Plates

b.) Horizontal Ring Plates

c.) Air Passages

(schematic-- relative dimensions are not to scale)

Figure 14. Innovative building modifications for possible reduction of wind excited oscillations