EGN-5439 Design of Tall Buildings

Lecture 05

Loads

Outline

- ***Gravity Loading***
  - ***Comparison of Live Load Magnitudes***
  - ***Methods of Live Load Reduction***
  - ***Impact Gravity Loading***
  - ***Construction Loads***

- ***Wind Loading***
  - ***Simple Static Approach***
  - ***Dynamic Methods***

- ***Seismic Loading***
  - ***Equivalent Lateral Force Procedure***
  - ***Modal Analysis Procedure***

Introduction.

The effect of loads in a tall building is very different from a low-rise building.

The accumulation of gravity loads over a large number of stories will produce very high column and shear wall loads, at least an order of magnitude above low to mid-rise buildings. The maximum live gravity loads however, can be approximated from previous buildings.

Wind loads act over large building surfaces with much higher intensities and with a longer moment arm about the base. These effects are augmented with slender and un-symmetrical buildings. Wind loads are random and difficult to measure. They are even more difficult to predict.

In seismic zones, the inertial loads that ensue from the shaking ground may exceed wind loads. Therefore, inertial loading becomes the dominant influence upon the building's shape and cost.

Building Codes tend to be empirical. They are hard to compare with each other because their rational basis differ, primarily due to local experiences. (Take for example, the experiences of Miami-Dade County versus the rest of the State of Florida).

With the exception of dead loading, the loads on a building cannot be assessed accurately.

- **Maximum gravity live loads can be anticipated approximately from previous field observations.**
- **Wind and seismic loadings are random in nature, more difficult to measure from past events, and even more difficult to predict with confidence.**
- **Probabilistic theory has helped to rationalize the approaches to estimating wind and seismic loading.**
- **There are a variety of approaches to the estimation of loading in the different Codes of Practice, and most are empirical.**

Gravity Loading.

- **Dead loading is calculated from the designed member sizes. This generates only minor inaccuracies.**

- **Live loading is specified as the intensity of a uniformly distributed live load, according to the use of the space.**
  - **In certain situations, such as in parking areas, offices, and plant rooms, the floors should be considered for the alternative worst possibility of specified concentrated loads.**
  - **The magnitudes of live loading specified in the Codes (UBC, FBC, ACI) are estimates based on a combination of experience and the results of field surveys. The differences between live load magnitudes in the Codes of different countries indicate a lack of consistency sufficient to raise questions about their accuracy.**
  - **Live load reductions may be allowed to account for the improbability of total loading being applied simultaneously over larger areas.**

Dead loads are calculated just as in a low-rise building, via the tributary areas to the supporting beams and slabs. The member sizes and the material unit weights are used to estimate the assumed initial member sizes. Later, actual sizes and unit weights are used to provide accurate loads during the refined analysis cycle of the design process.

Live loads are assumptions. The intensities are chosen with the intended use in mind, such as offices, residential, balconies, corridors, garages, etc. The worst possibility will form the basis for the specified concentrated loads.

Different codes show a lack of uniformity in the selection of distributed floor loads. Many engineers are concerned that this is an indication of the lack of accuracy of these Codes. Some consider these intensities as conservative (for example, corridor loads = 80 psf), whereas others have pointed out that load capacity experiments have shown that some intensities are underestimating the real possible maximum values.

Finally, the effect of impact loading as a gravity live load is assumed to impose a load 2X of the static load at the point of application (from mechanics of materials theory). For example, an elevator that is accelerating upwards or is brought to rest on its way down will impose an impact load upon the cable support system, etc.

A Comparison of Live Load Magnitudes

	United States (ANSI A58.1-1972)		Great Britain (CP3-CH.V PT.1:1967)		Japan (AIJ Standard)	
	kPa	psf	kPa	psf	kPa	psf
Office buildings						
Offices	2.4	50	2.5	52	2.9	61
Corridors	3.8	80	2.5	52		
Lobbies	4.8	100	2.5	52	2.9	61
Residential						
Apartments	1.9	40	1.5	31	1.8	37
Hotel	1.9	40	2.0	42	1.8	37
Corridors	3.8	80	"		1.8	37
Public rooms	4.8	100	2.0	42	3.5	74

Methods of Live Load Reduction

- **The rationale behind live load reduction is that although at some time a small area may be subjected to the full intensity of live load, it is improbable that the whole of a large area will be subjected simultaneously to the full live load.**

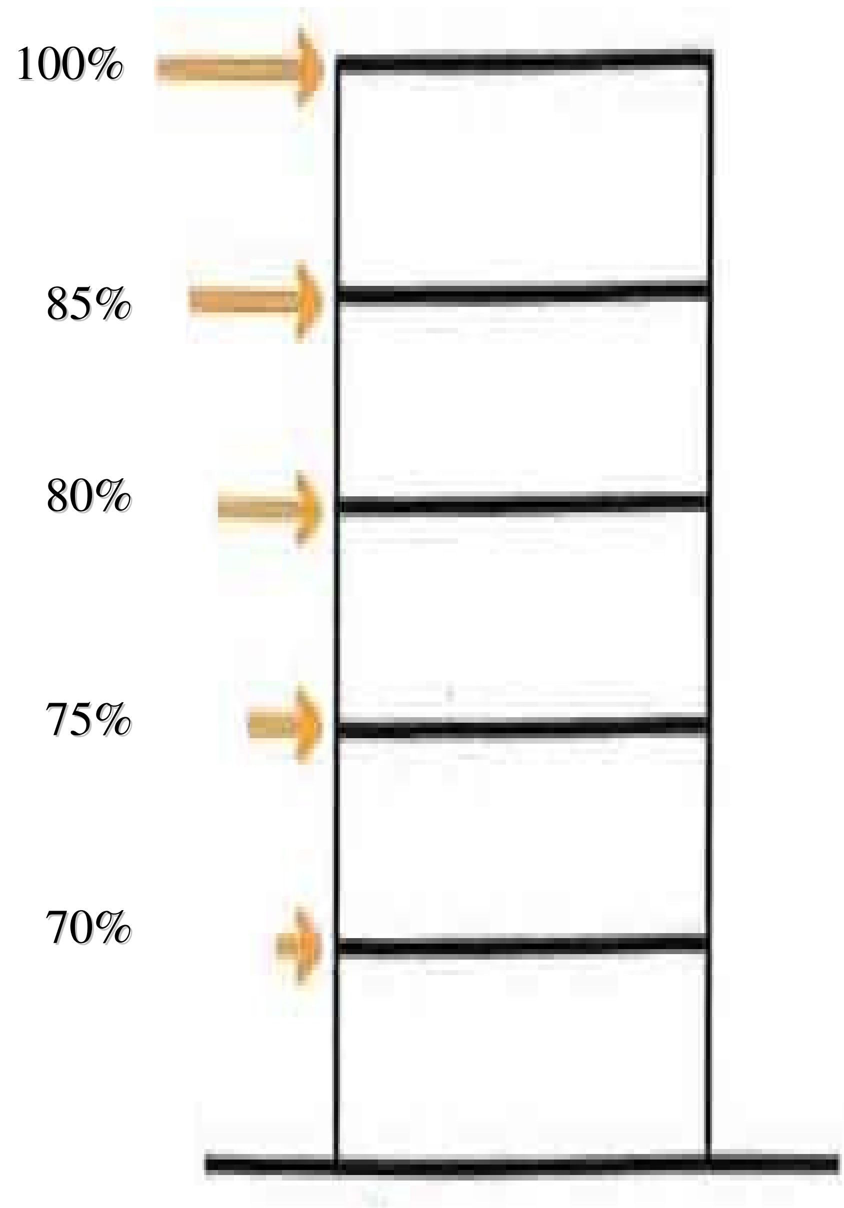
- **It is reasonable to design the girders and columns supporting a large area for less than the full live load.**

- **Different methods of live load reduction allow for the girders, columns, and walls to be designed for a reduced proportion of the live load with an increased amount of supported area.**
  - **An upper limit is usually placed on the reduction in order to retain an adequate margin of safety.**

Live Load Reduction Example 1

- **Simple percentages may be specified for the reductions and for the limiting amount.**

- **For example, the supporting members may be designed for 100% of the live load on the roof, 85% of that on the top floor, and further reductions of 5% for each successive floor down to a minimum of 50% of the live load.**



Live Load Reduction Example 2

- **A tributary area formula may be given, allowing a more refined definition of the reduction, with the limit built into the formula.**

- **For example, the supporting members may be designed for a live load equal to the basic live load multiplied by a factor,**

$$\left[0.3+\frac{10}{\sqrt{A}}\right]$$

where *A* is the accumulated area in square feet.

Live Load Reduction Example 3

- An even more sophisticated formula-type method may define the maximum reduction in terms of the dead-to-live load ratio. For example, it may be specified that the maximum percentage reduction shall not exceed,

$$\left[\frac{100\left(\boldsymbol{D}+\boldsymbol{L}\right)}{4.33\boldsymbol{L}}\right]$$

where *D* and *L* are the intensities of dead and live loading, respectively.

This particular limit is intended to ensure that if the full live load should occur over the full tributary area, the element would not be stressed to the yield point.

Impact Gravity Loading

- **Impact loading occurs as a gravity live load in the case of an elevator being accelerated upward or brought to a rest on its way down.**
- **An increase of 100% of the static elevator load has usually given satisfactory performance.**

Construction Loads

- **Construction loads are often claimed to be the *most severe loads* that a building has to withstand during its life-cycle.**
- **More failures occur in buildings under construction than in those that are complete.**
- **Typically, the construction load that has to be supported is the weight of the floor forms and a newly placed slab, which in total *may equal twice the floor dead load*.**
  - **This load is supported by shores that transfer it to the 3 or 4 floors shored below.**
  - **With the possibility of as little as a 3 day cycle per story, and concrete pumping which requires a more liquid mix, the problem is more severe.**
  - **The newly released slab, rather than supporting the construction loads, is in need of support itself.**
- **Climbing cranes are another common construction load.**

In general, construction loads are the most severe loads placed upon a building. Most failures occur in buildings under construction. For that reason, buildings that have "survived" the construction process will rarely fail structurally, unless of course, they are subjected to unusually high wind or seismic loads not considered during the design.

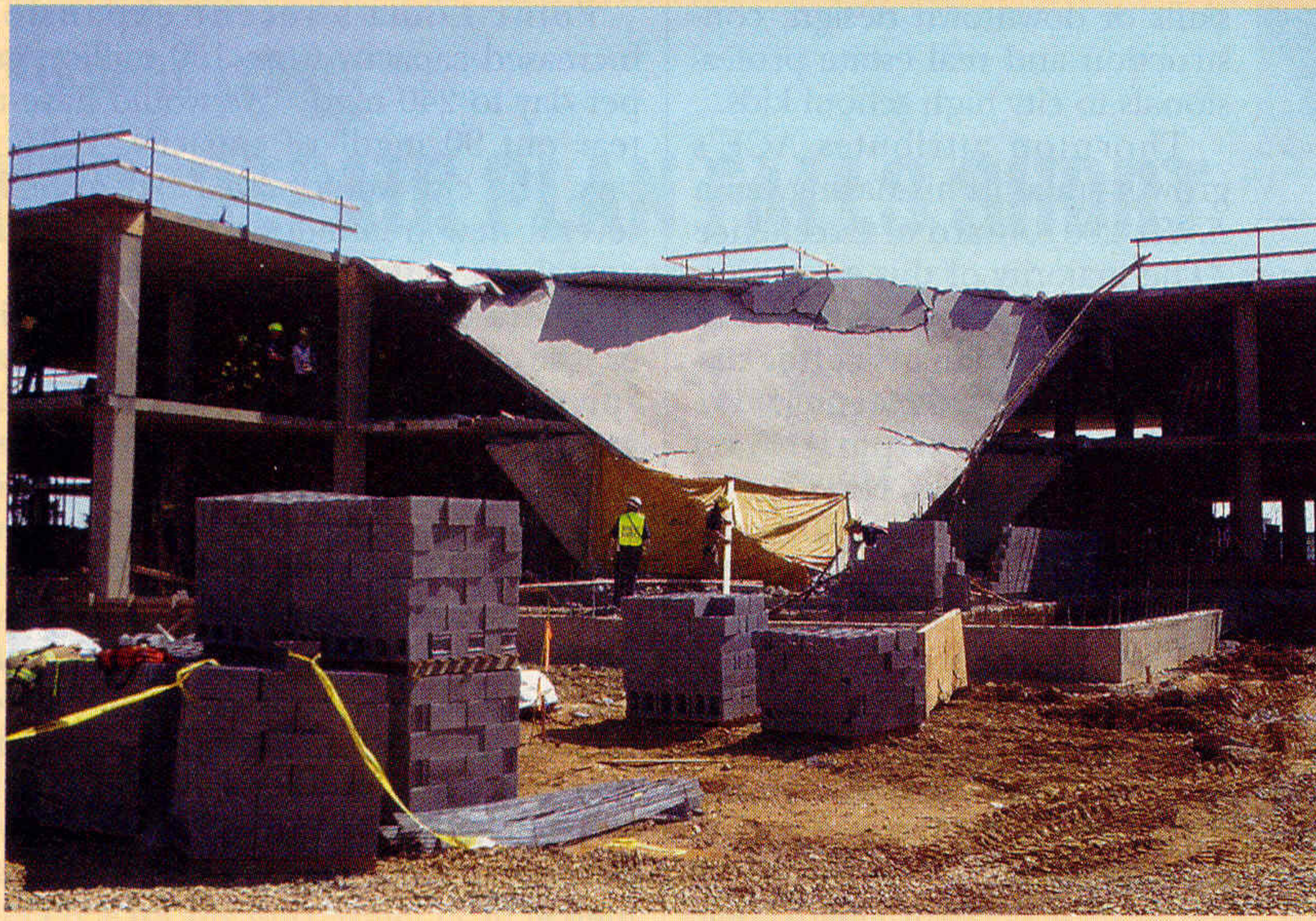
Common construction methods will cast a floor every week. Shoring for that floor will be in place for about four weeks, in order to permit the concrete to attain a 28-day strength. That means that shoring is left in place for the four levels below the active level. Many experienced shell-subcontractors can reduce the new floor cycle from 7 down to 3 days, especially using concrete pumping. The combination of a more liquid mix (higher slump) and faster cycles means that some levels immediately below may be loaded beyond their early strengths. In addition, new construction equipment, such as climbing cranes and pumps that are secured to the freshly placed floors may require additional shoring to several lower levels.

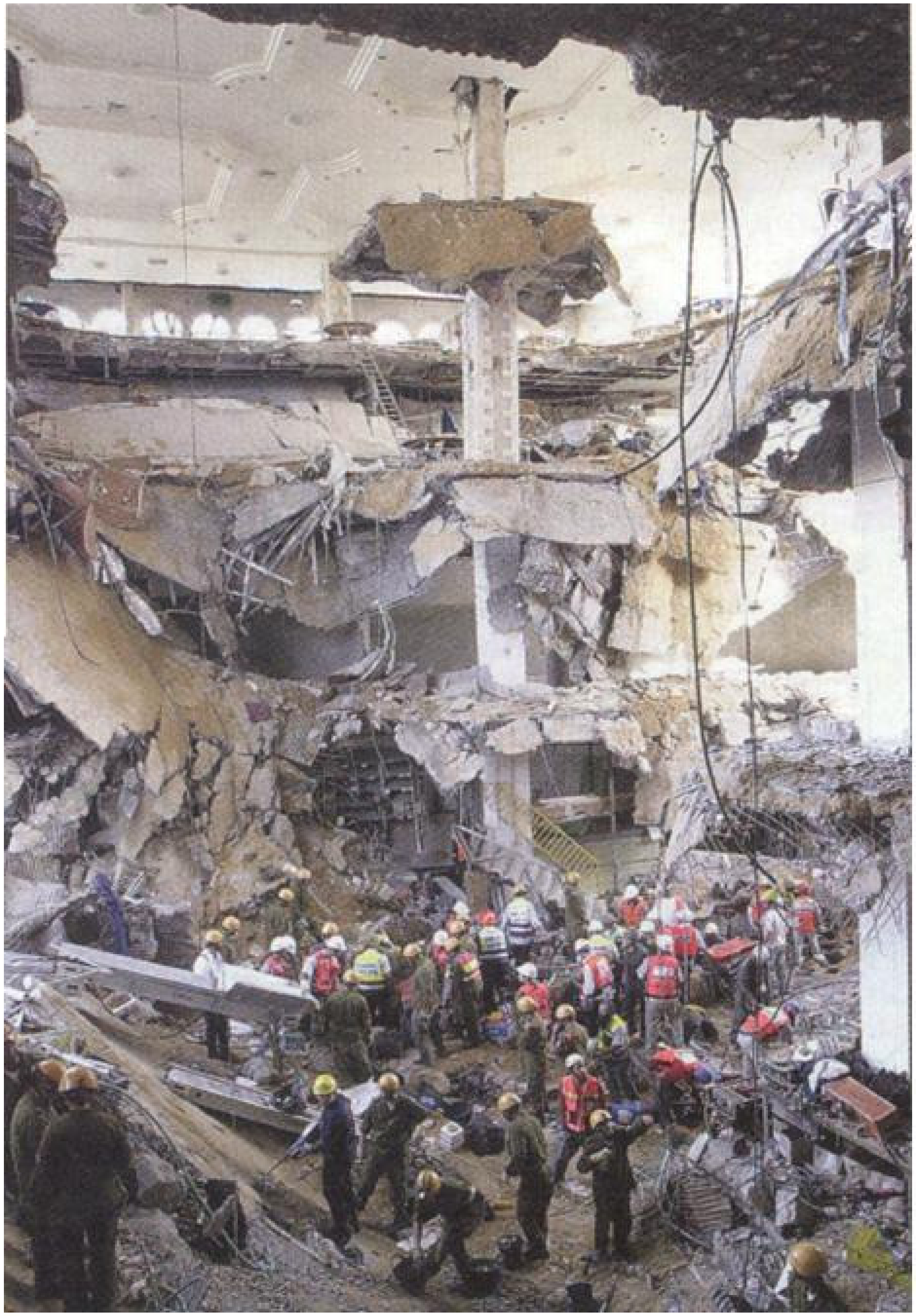
The State of Florida has recognized these construction sequence dangers, and require hi-rise projects to use a special structural engineer, called a "threshold inspector", to supervise and approve the construction process until the structure is finished.

Fatal Collapse

OFFICIALS PROBE APRIL 11 FAILURE AT CONCRETE JOB

Virginia Occupational Safety and Health is investigating a fatal April 11 construction accident at a storage facility in Newington, Va., just outside Washington, D.C. One worker was killed and another injured when a portion of the three-story concrete frame, with post-tensioned slabs, collapsed.





Banquet hall collapse in Jerusalem on 24 May 2001.

Collapse killed 24 and injured hundreds.

Police have arrested 10 people associated with the 15-year old structure, including the owner, engineer and contractor.

(ENR 4 June 2001).

This formwork collapse lead to the destruction of one bay of the Westin Hotel slab in Charlotte, NC. The collapsed slab was of standard design, 21 ft by 21 ft bay, 7-inches thick and using #7 and #11 rebars. The form was plywood and metal pans (ENR 13 Aug 2001).

Wind Loading

- **Wind loading affects the design of buildings 10 stories and higher.**

- **Structures have become lighter and more prone to deflect and sway under wind loading.**

- **There are several Code methods:**

  - **The first method is a *static approach*, assuming the building to be a fixed rigid body, which is appropriate for tall buildings of unexceptional height, slenderness or susceptibility to vibration in the wind.**

  - **Subsequent *dynamic methods* are needed for exceptional buildings, such as those described in the *Uniform Building Code* (*UBC*) as those of height greater than 400 feet or of height greater than five times their width ($H / W > 5$).**

Modern tall building designers are increasingly using lighter concretes, cladding and partitions. The consequence is that the increased efficiency and lightness of the structure has also increased the hi-rise's flexibility (lateral deflections). Increased understanding of the effects of gust forces and their dynamic interaction with the hi-rise has lead to several methods of analysis.

1) *The Uniform Building Code* is a static approach that assumes the building to be a fixed rigid body in the wind. This method is appropriate for mid-sized buildings of common height, that are not particularly slender nor susceptible to vibrations while loaded under high winds.

2) *ANSI / ASCE-7*, which is also known as "Minimum Design Loads for Buildings and Other Structures". This method differentiates between the building as a whole and the individual structural components and cladding.

3) *Dynamic Method* is used for very tall buildings (greater than 400 feet, or 120 m), or slender (their height is greater than five times their width), or highly susceptible to vibrations under wind loads (sensitive to wind-excited oscillations).

4) *Wind tunnels tests* are discussed as an experimental comparison with these analytical methods.

SHATTERED GLASS rained on Houston when Hurricane Alicia struck in 1983.

Over 160,000 windows were shattered.

1) The Static Approach: The Uniform Building Code Method.

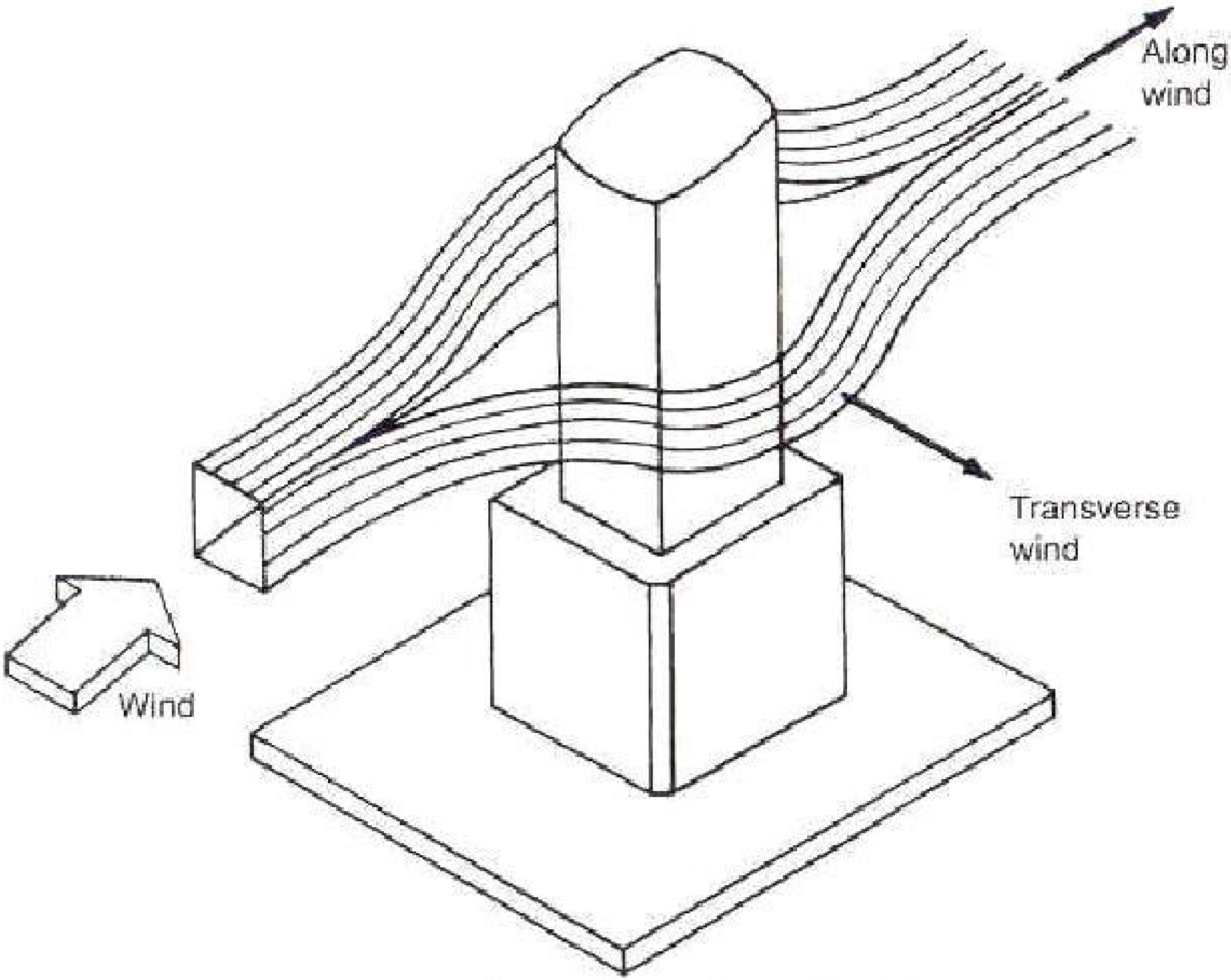
The ***UBC*** method reduces all the dynamics into an equivalent “static” loading, that takes into account the effects of gusting and extreme local pressures over the faces of the building, and the effects of location and the importance of the building to the community.

The design wind pressure p is obtained from the formula,

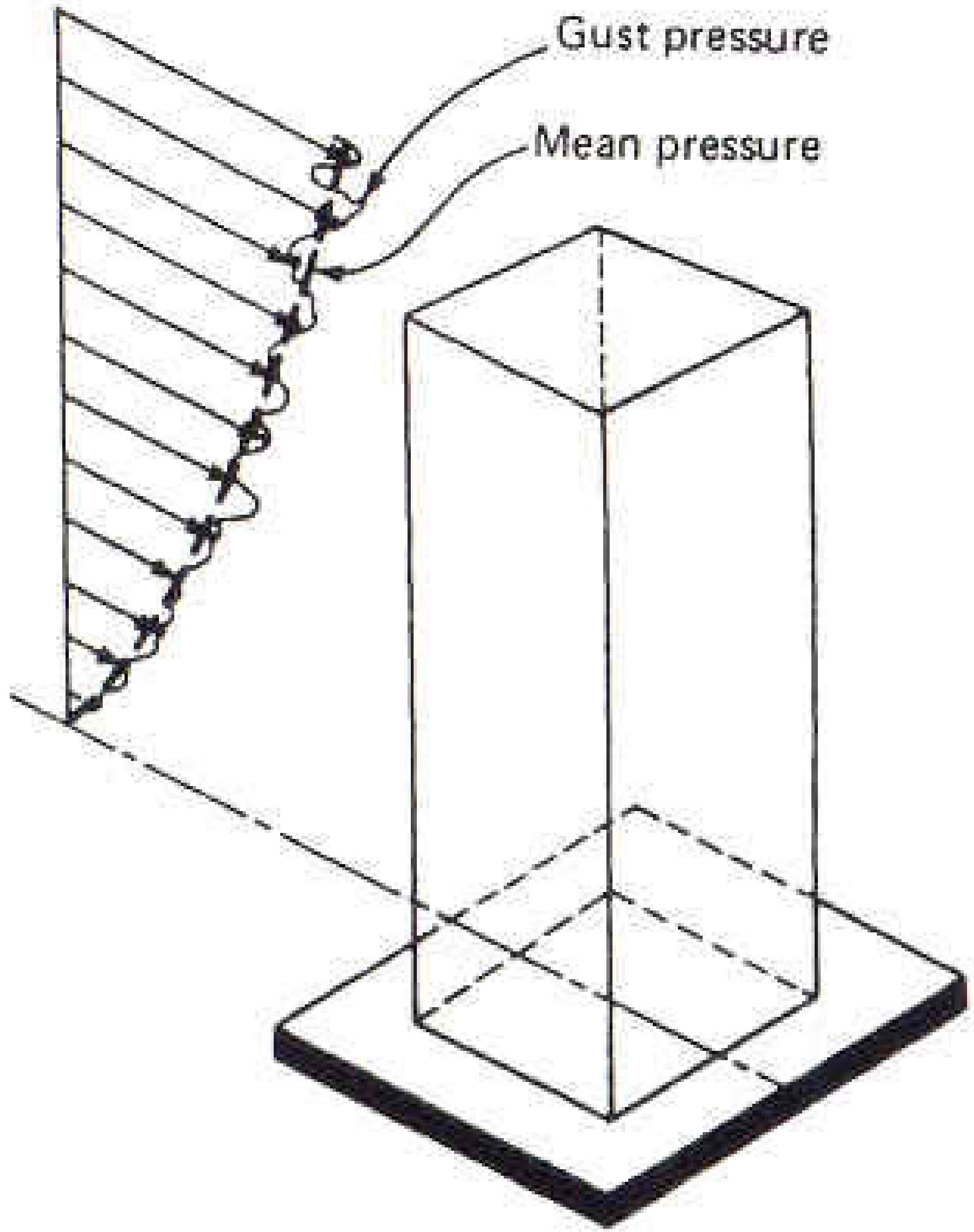
$$p = C_e \, C_q \, q_s \, I$$

where C_e is a coefficient that accounts for the combined effects of height, exposure and gusting (see table on the next slide). C_q is a coefficient that allows for higher pressures for wall and roof elements; for example, C_q has a value of 1.4 when using the projected area method of calculating the wind loading for structures over 40 ft in height, whereas it has a local value of 2.0 at wall corners. The pressure q_s is a wind stagnation pressure for a minimum basic 50-year wind speed at a height of 30 ft above ground, as given for different regions of the United States in a wind speed contour map. Where local records indicate a greater than the basic value, use the local value (such as in Miami-Dade County). The importance factor I is taken as 1.15 for post-disaster buildings and 1.00 for all other buildings.

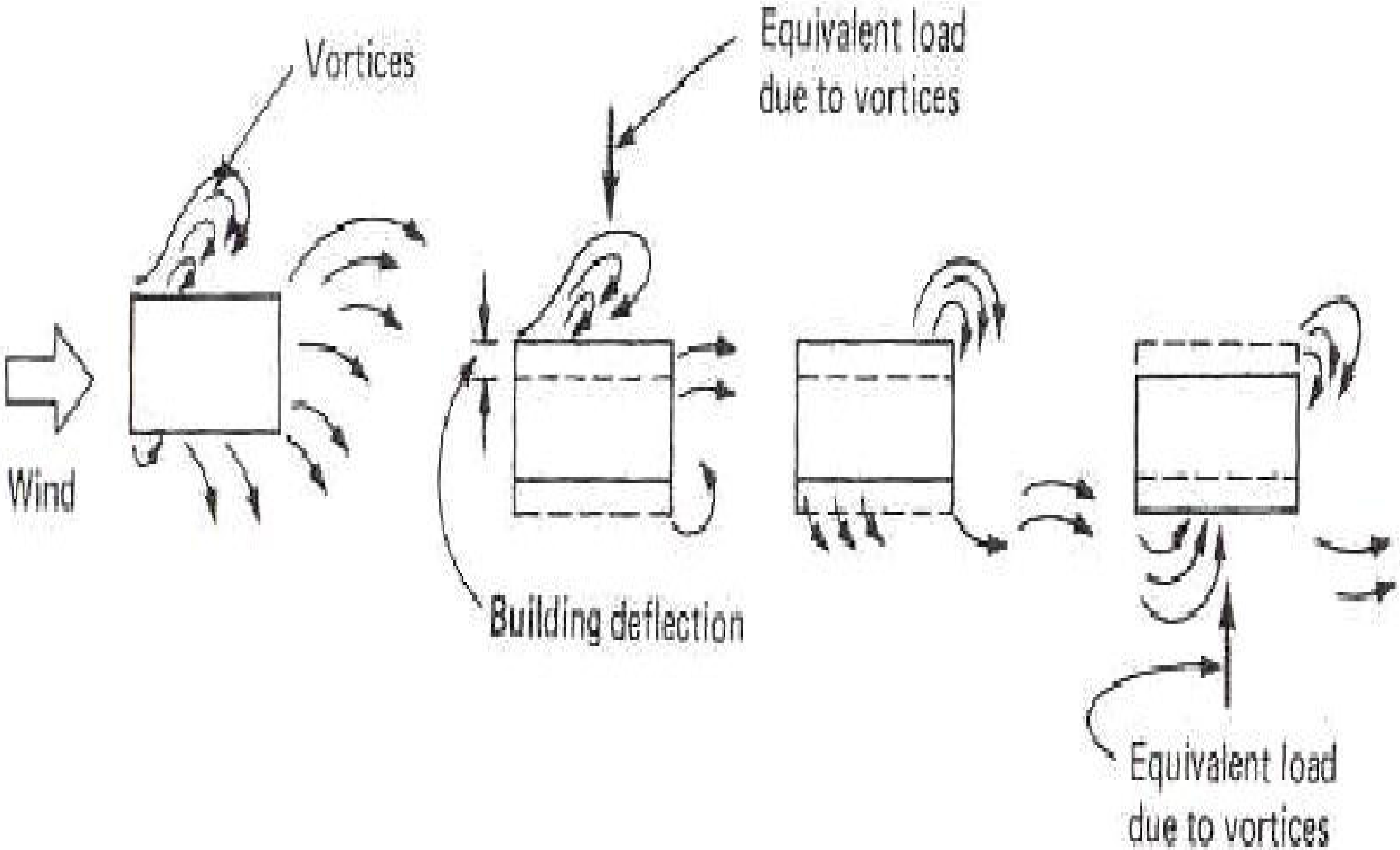
2D Flow of wind around a building.



Gusting Components



Karman Vortex Shedding



The pressure q_s manifesting on the surface of a building due to a mass of air with density ρ, moving at a velocity v is given by the Bernoulli's equation:

$$q_s = \tfrac{1}{2}\rho v^2$$

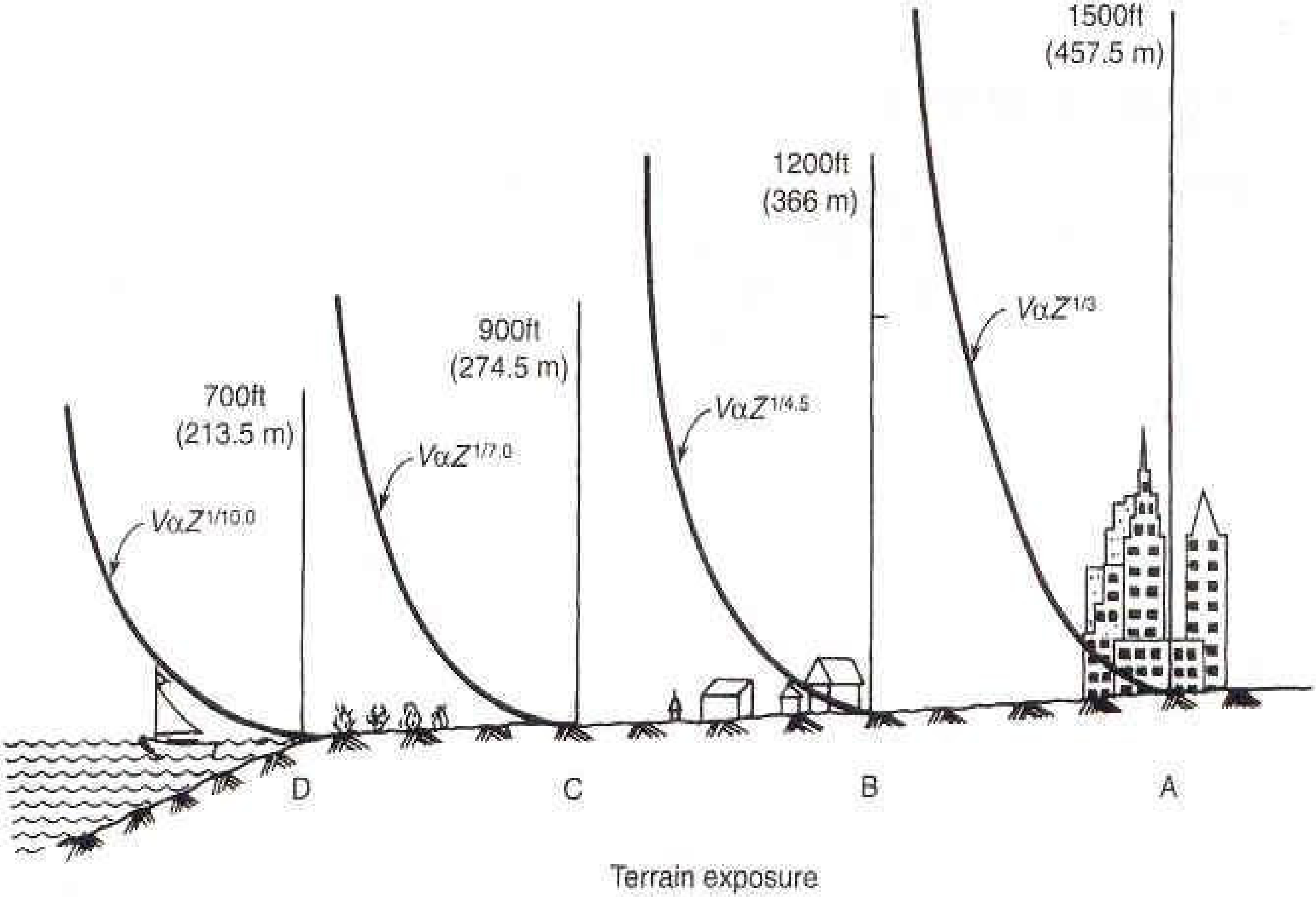
The density of air ρ is 0.0765 pcf, for conditions of standard atmosphere, temperature (59 °F), and barometric pressure (29.92 in. of mercury).

Since velocity given in the wind map is in mph,

$$q_s = \frac{1}{2}\left[\frac{0.0765\ \text{pcf}}{32.2\ \text{ft/s}^2}\right]\left[\frac{5280\ \text{ft}}{\text{mile}} \times \frac{1\ \text{hr}}{3600\ \text{s}}\right] v^2$$

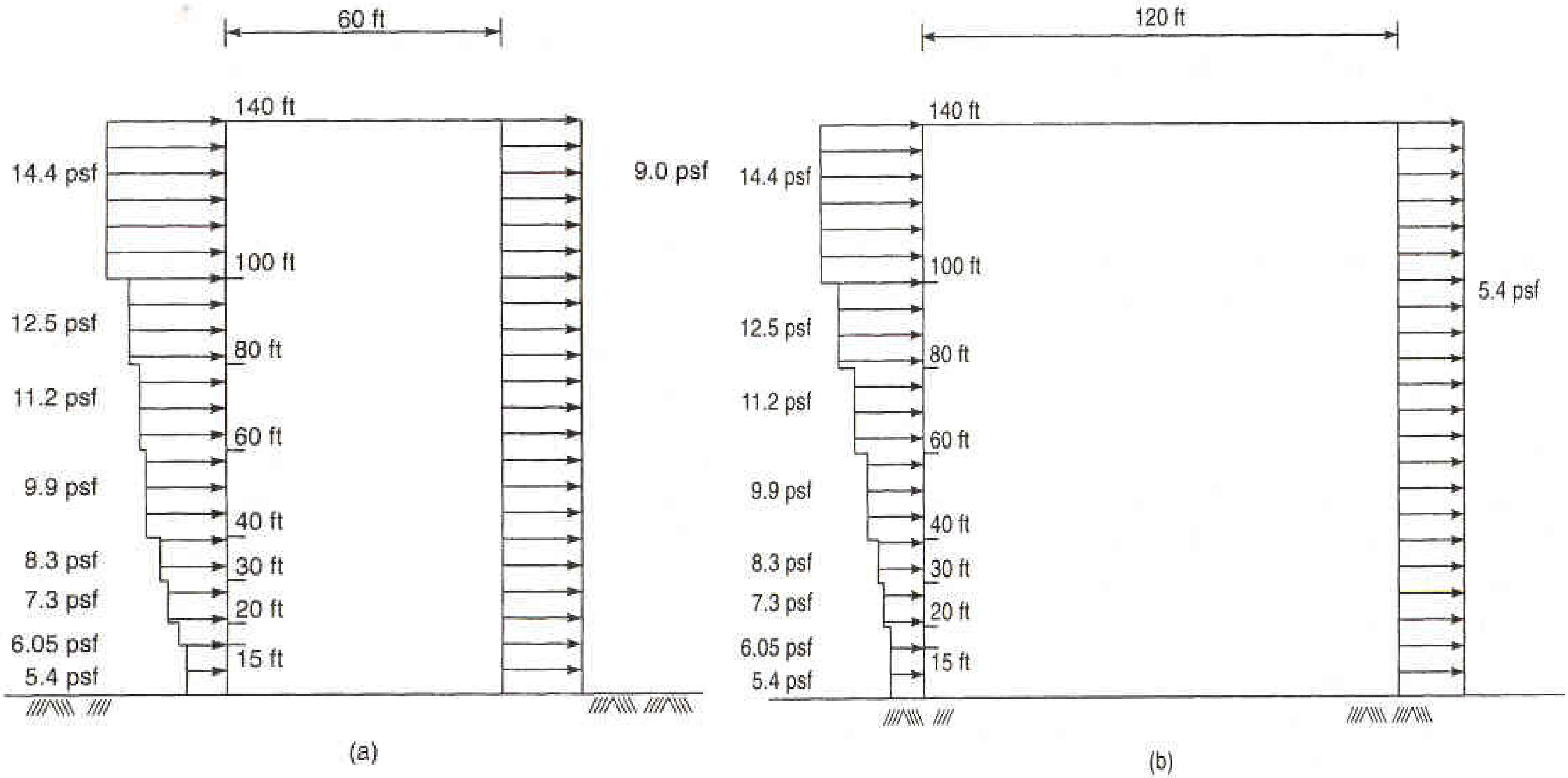
$$q_s = 0.00256V^2$$

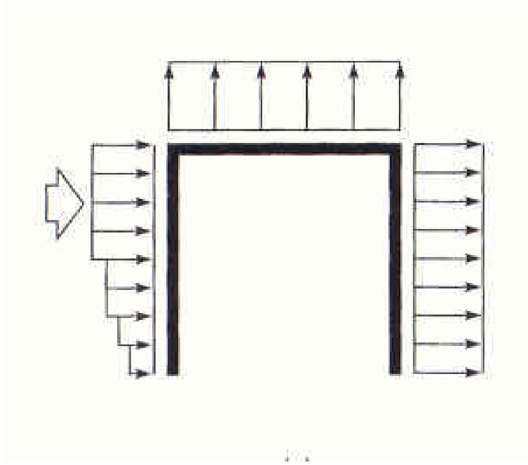
For instance, if the wind speed is 80 mph, $q_s = 0.00256 \times 80^2 =$ 16.38 psf which the UBC rounds off to 16.4 psf (Table 2.10). Note the UBC does not consider the effect of reduced air density at sites located at higher altitudes.



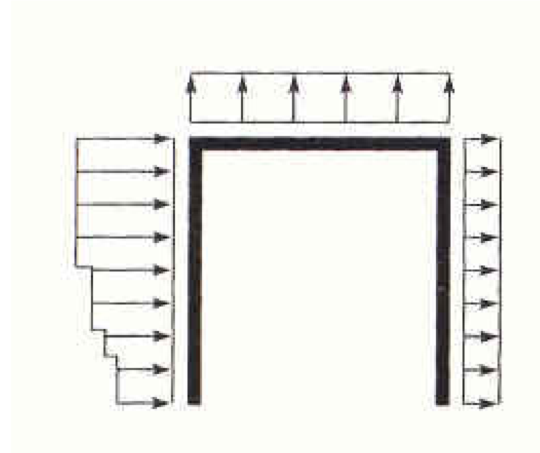
Variation of wind velocity with height.

Pressure Profiles

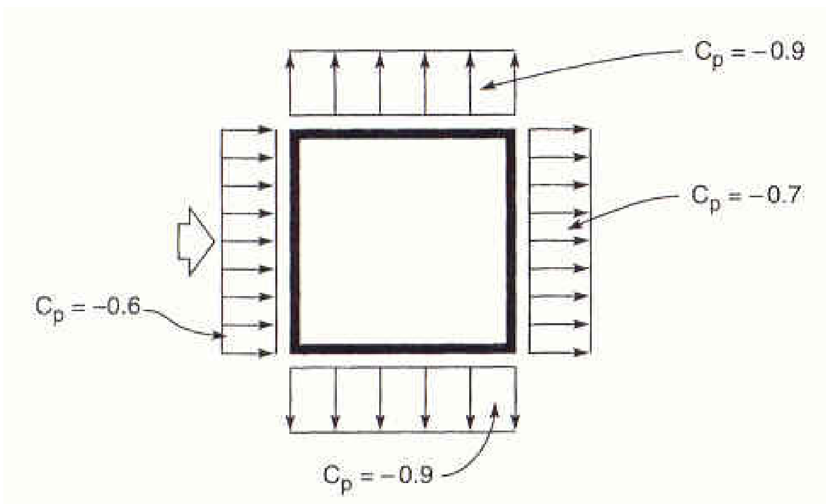




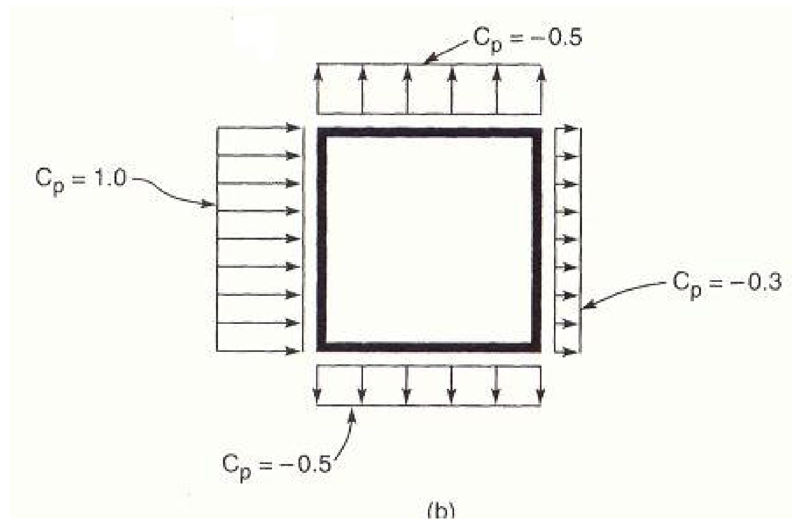
Elevation: Positive internal pressure.



Elevation: Negative internal pressure.



Plan: Positive internal pressure.



Plan: Negative internal pressure.

The ANSI / ASCE-7 Static Analysis

A simple relationship between wind buffeting a building, and the corresponding pressures or suction induced on the surface of the building is given in the form of a chain equation:

[wind pressure] = [reference velocity pressure]
× [dynamic gust response factor]
× [aerodynamic shape factor]

$$p_z = q_z \times GRF \times C_p \tag{2.13}$$

where

p_z = design wind pressure or suction, in psf, at height z above ground level

q_z = velocity pressure, in psf, determined at height z above ground level

GRF = Dynamic Response Factor, dimensionless, which magnifies the mean wind load to include the effect of: (i) random wind gusts; (ii) fluctuating forces induced by the motion of the structure itself through the wind

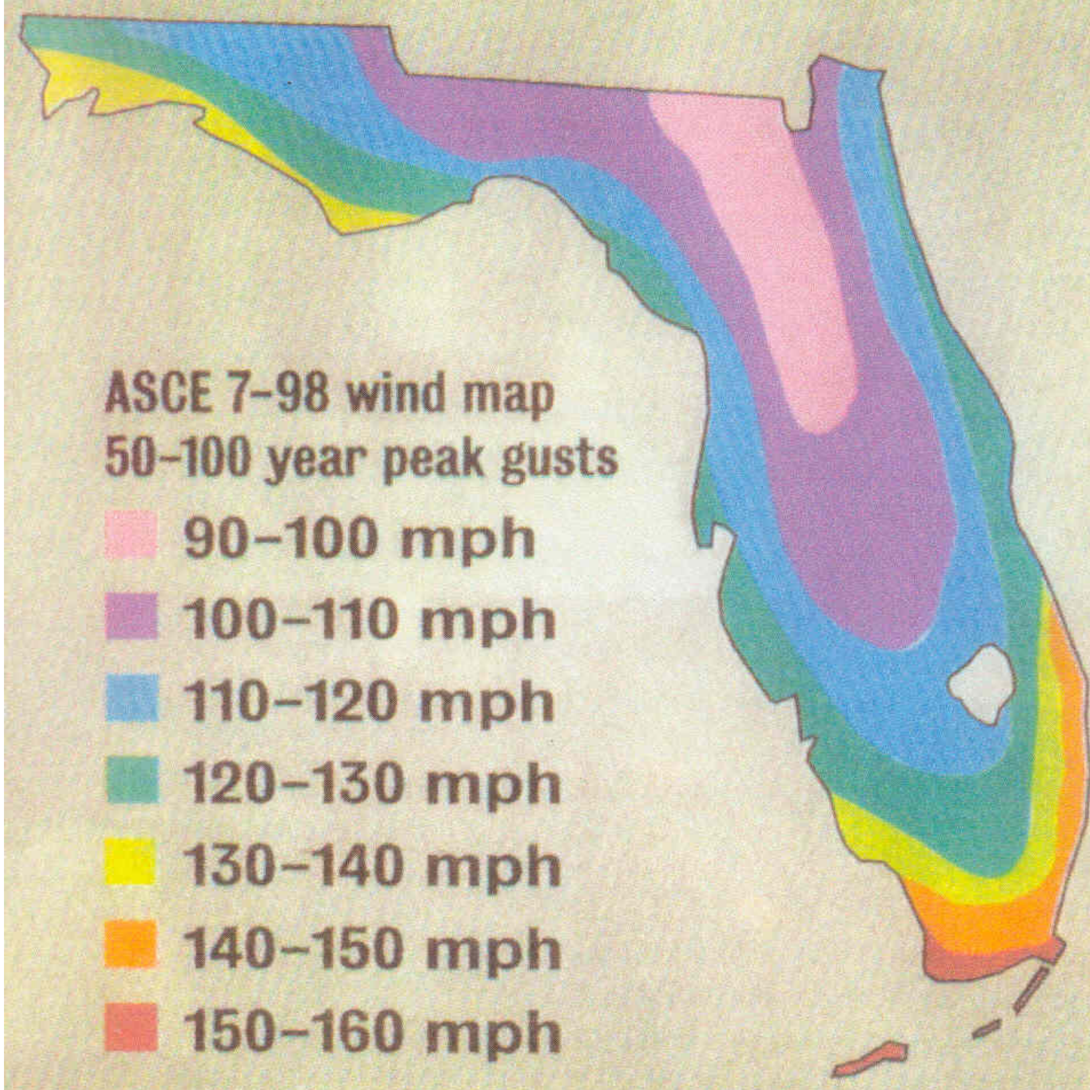
C_p = pressure coefficient which varies with height acting as pressure (positive load) on windward face, and as suction (negative load) on non-windward faces and roof

The velocity pressure, q_z, is given by the equation

$$q_z = 0.00256 K_z (IV)^2 \tag{2.14}$$

$$q_h = 0.00256 K_h (IV)^2 \tag{2.15}$$

HURRICANE RISK MAP



Source: Florida Building Commission

Dynamic Methods

- **If the structure is exceptionally slender and/or tall, or located in extremely severe exposure conditions, the effective wind loading on the building may be increased by dynamic interaction between the motion of the building and the gusting of the wind.**

- **The best method of assessing such effects is by wind tunnel tests.**

Wind Tunnel Experimental Method

- **Building models are constructed to scales from 1/100 to 1/1000 depending on the size of building and wind tunnel, with 1/400 being the most common.**

- **Tall buildings exhibit a combination of shear and bending behaviour that has a sway mode comprising a flexurally shaped lower region and a relatively linear upper region.**

  - **This is represented by a rigid model with a flexurally sprung base.**
  - **It is not necessary for the model to represent the distribution of mass in the building, but only its moment of inertia about the base.**

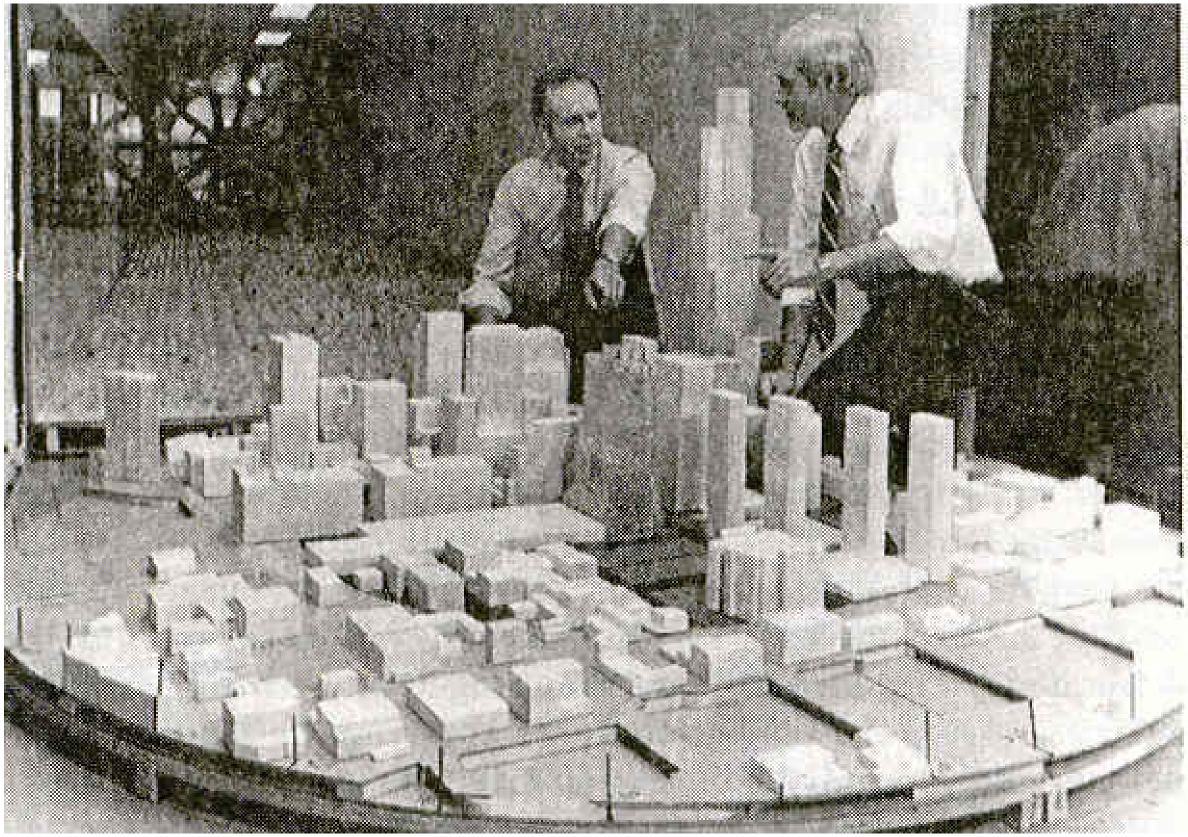
- **Wind pressure measurements are made by flush surface pressure taps on the faces of the models, and pressure transducers are used to obtain the localised pressures on the cladding.**

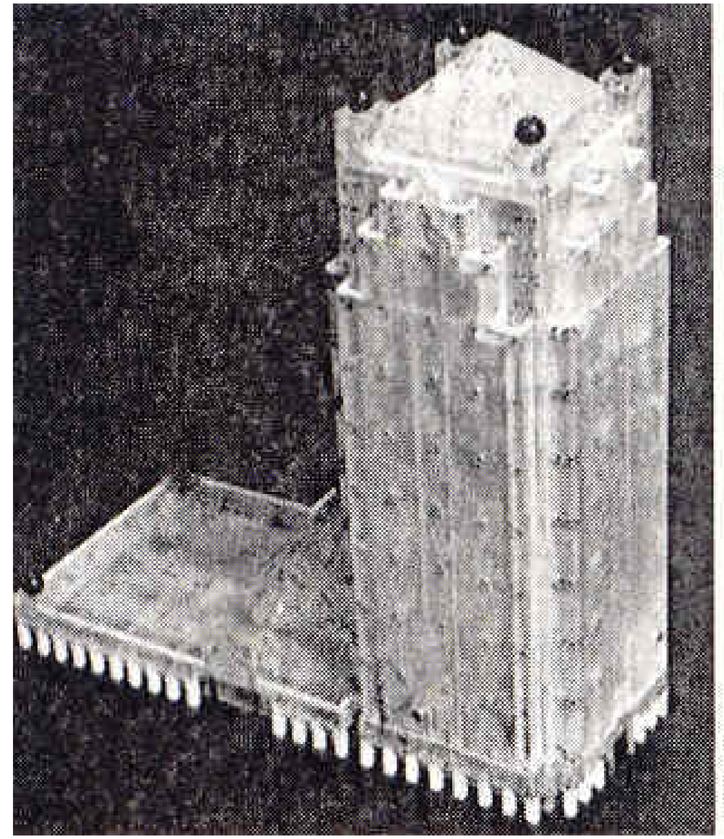
Objectives of Wind Tunnel Tests:

1. Determine the design lateral loads.
2. Predict the response of the building under the influence of wind loading.
3. Establish the boundary layer profile and turbulence intensities.
4. Find the intensity and duration of extreme winds.
5. Find the influence upon and from nearby existing and proposed buildings.
6. Find the drag, vortex shedding and wind separation from the building surface.
7. Find the building's dynamic response.
8. Find the loads on cladding and glass.
9. Find the near-zone effects (that is, the stability of vehicles and pedestrians).
10. Establish what is the motion tolerance (occupant's discomfort).
11. Determine the buffeting created to downstream structures.
12. Determine the possible damage to structures from flying gravel.
13. Determine the increase potential of moisture penetration.
14. Determine the effect of snow accumulation.
15. Determine the effect upon the structure from pollution.

Find the most favorable shape that minimizes:

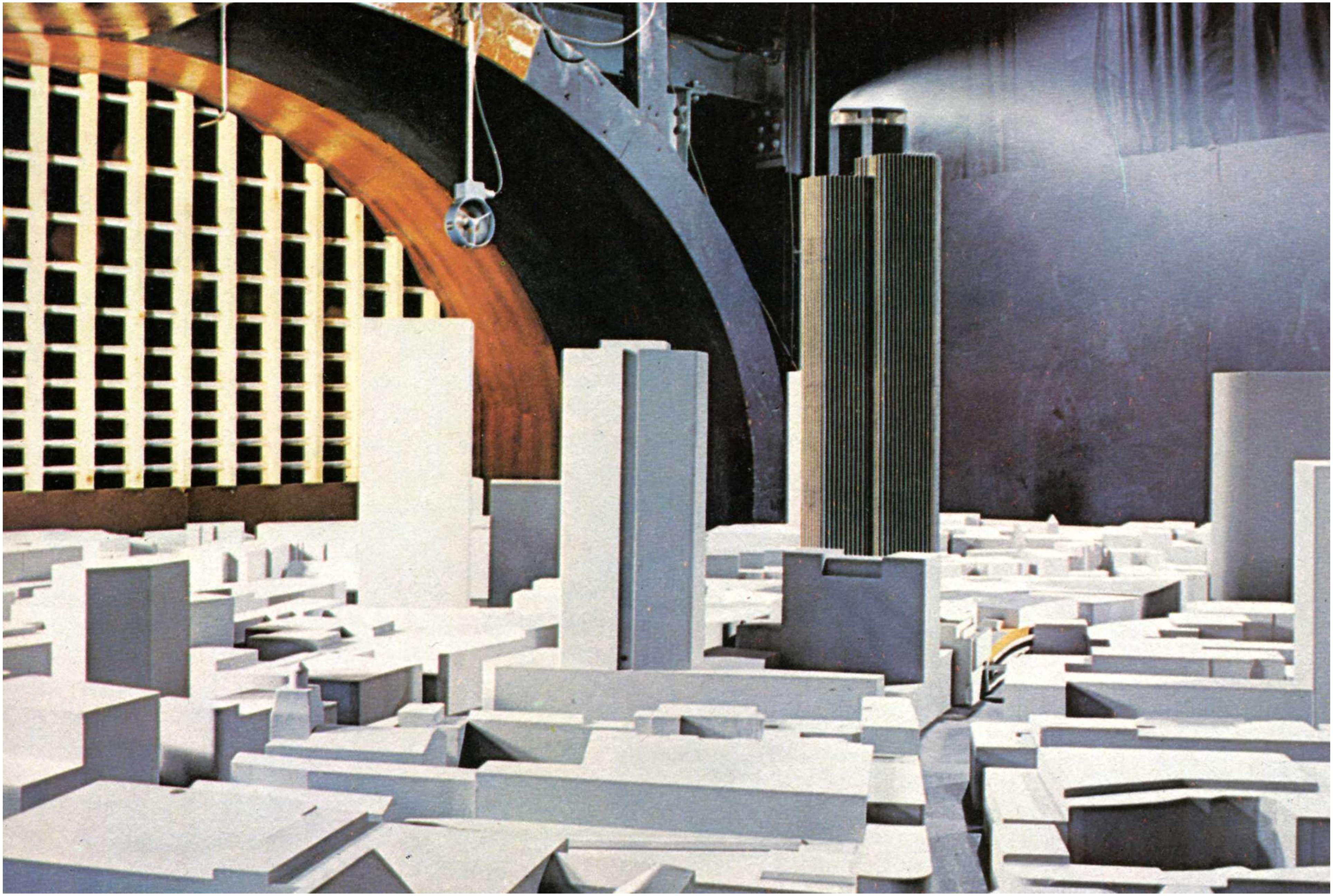
16. The intensity and scale of the pressure fluctuations on exterior panels and glass.
17. The floor-by-floor shear forces.



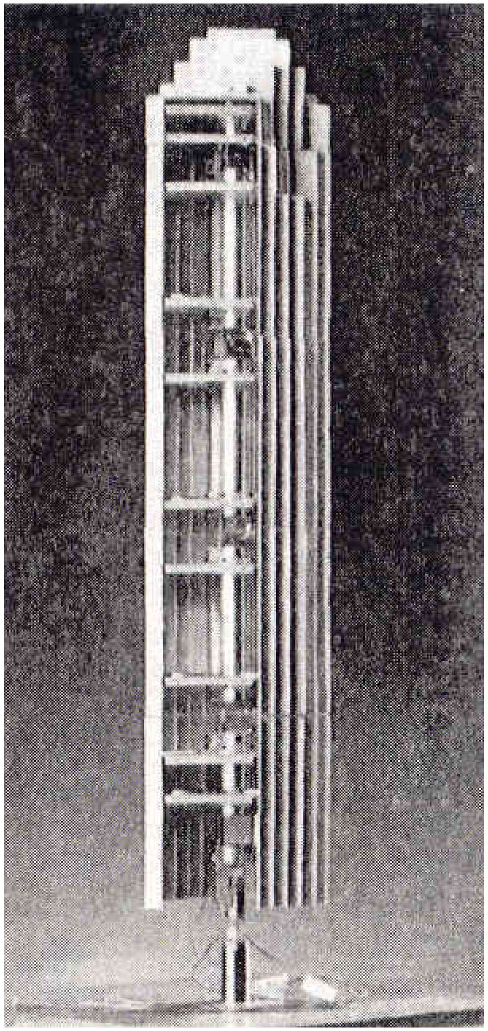


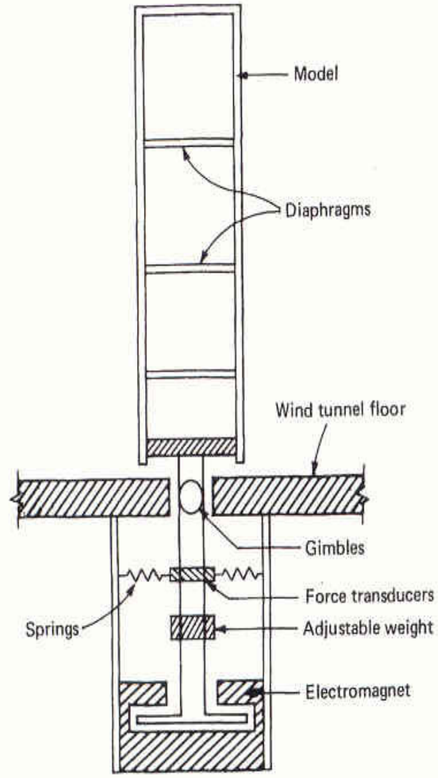
At left is a model of the scaled buildings surrounding the pressure model (between the engineers). Notice the round table that supports the cluster. It is used to rotate the models in order to study different angles of incidence for the wind.

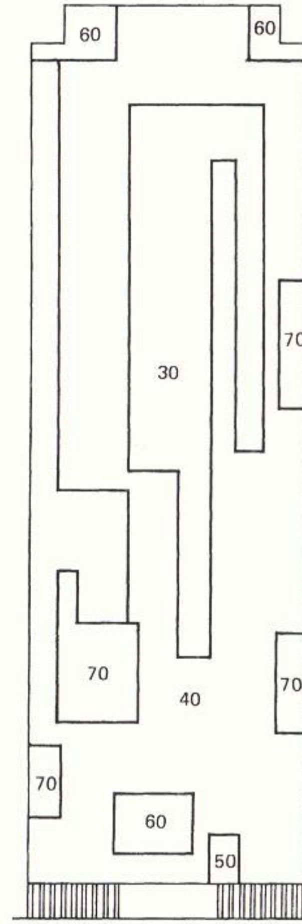
At right is a close-up of the model with many pressure ports visible on each surface (Rowan, Williams, Davis and Irwin, Inc.).



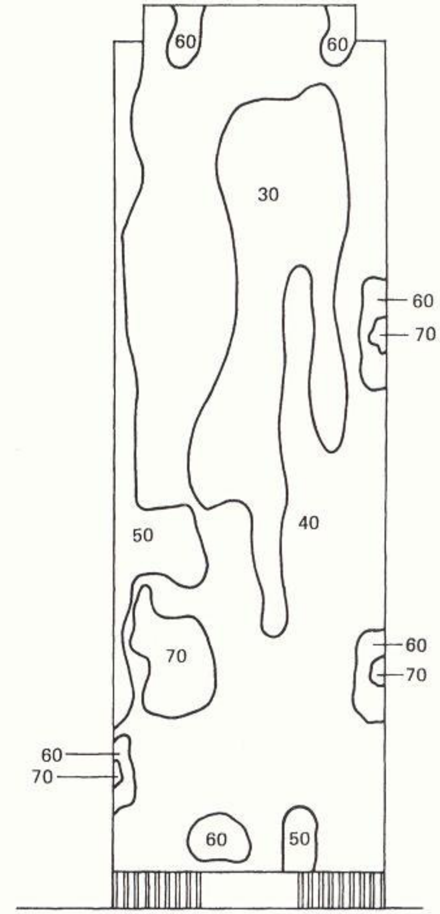
A model of a 600 m tall building is being tested to determine the wind loadings at different parts of the structure, resonance and the effects upon its surroundings.







Block pressure diagram, in psf.



Pressure Countours in psf.

At left is shown a rigid aero-elastic model from RWDI, and to the right of it is the diagram showing the gimbal assembly below the table to rotate the model. A typical scale for these models is 1:400 for a 50-story building. The model is rotated and measured at 10° to 20° angle intervals, and may have 500 to 800 tiny pressure taps. The results of these pressure measurements is shown as isobars the extreme right figure, which is also shown as the block pressure diagram.

Wind Tunnel Laboratories in North America.

1. Cermak, Peterka and Peterson (CPP Wind).

1415 Blue Spruce Drive #3, Fort Collins, Colorado 80524
Attention: Mr. Leighton Cochran.
Telephone 970-221-3371 / www.cppwind.com

2. Rowan, Williams, Davis and Irwin, Inc. (RWDI).

650 Woodlawn Road West, Guelph, Ontario, Canada N1K 1B8.
Attention: Dr. Peter Irwin.
Telephone 519-823-1311 / www.rwdi.com

3. Boundary Layer Wind Tunnel Laboratory.

University of Western Ontario, Faculty of Engineering,
London, Ontario, Canada N6A 5B9.
Attention: Mr. Erik Ito.
Telephone: 519-661-3338 / www.blwtl.uwo.ca

Seismic Loading.

- **Earthquake loading consists of the inertial forces of the building mass that result from the shaking of its foundation by a seismic disturbance.**

- **Earthquake resistant design concentrates particularly on the translational inertia forces, whose effects on a building are more significant than the vertical or rotational shaking components.**

- **The design philosophy strives that buildings should:**
  - ***Resist minor earthquakes without damage.***
  - ***Resist moderate earthquakes without structural damage but accepting the probability of nonstructural damage.***
  - ***Resist average earthquakes with the probability of structural as well as nonstructural damage, but without collapse.***

- **Two approaches are used to estimate seismic loading which take into account the properties of the structure and the past record of earthquakes in the region.**
  - ***Equivalent Lateral Force Procedure.***
  - ***Modal Analysis.***


The Mexico City earthquake of
1985 caused $4 billion of
damage in just three minutes.

Seismic: Equivalent Lateral Force Procedure

- **This procedure uses a simple estimate of the structure's fundamental period and the anticipated maximum ground acceleration together with other relevant factors to determine a maximum base shear.**

- **Horizontal loading equivalent to this shear is then distributed in some prescribed manner throughout the height of the building to allow a static analysis of the structure.**
  - **The resulting forces are non-conservative.**

- **This method is simple and rapid and is recommended for:**
  - **Unexceptionally high buildings with unexceptional structural arrangements.**
  - **Preliminary analysis for exceptional buildings.**

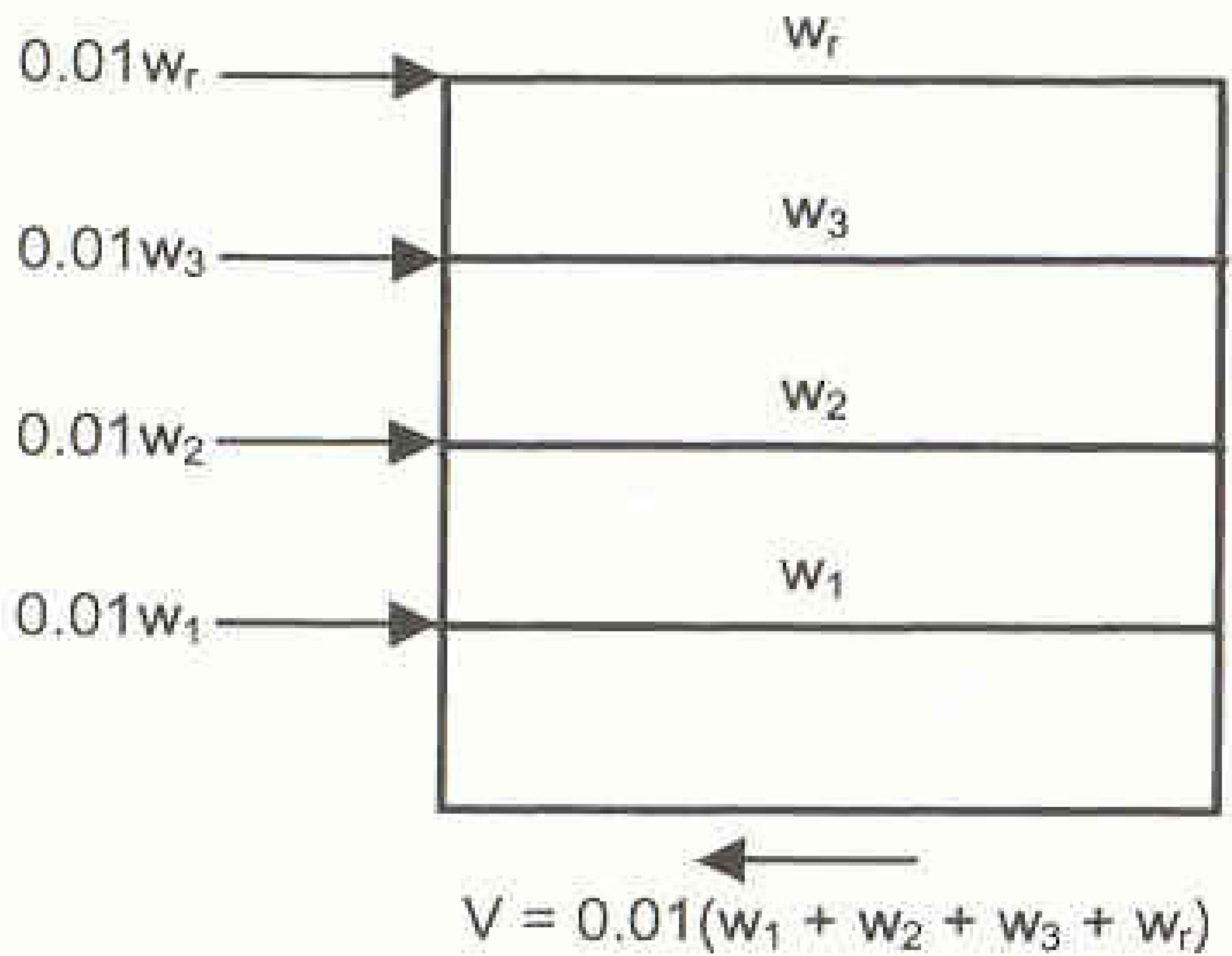
The *UBC* equivalent lateral force procedure:

- **The structure must resist a total lateral load *V*, assumed to act non-concurrently in orthogonal directions parallel to the main axes of the structure.**
- ***V* is calculated from the formula**

$$V = \frac{ZIC}{R_W} W \quad \text{in which} \quad C = \frac{1.25S}{T^{2/3}}$$

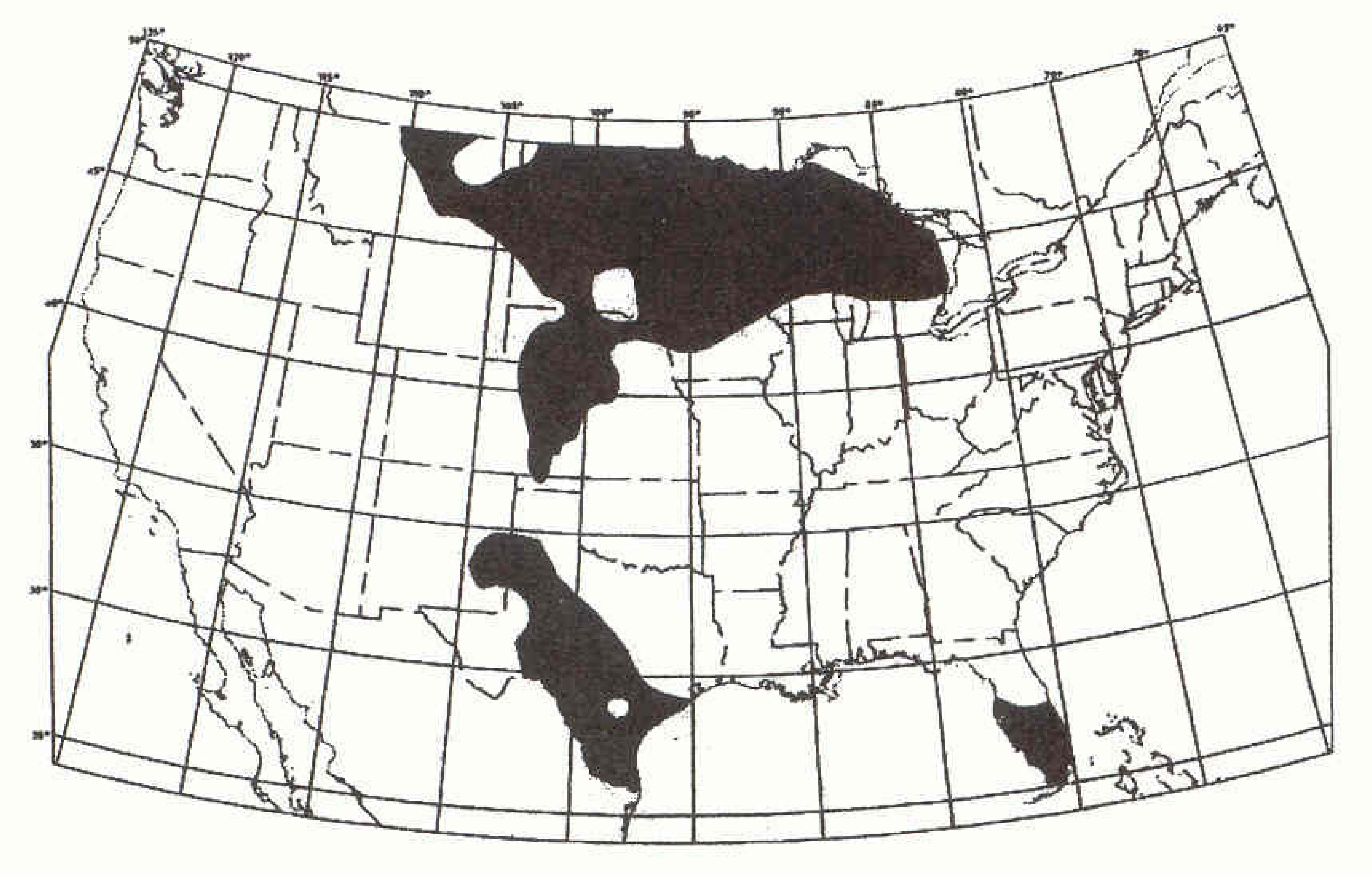
  - **This assumes that the structure will undergo inelastic deformation during a major earthquake;**
  - **This takes into account the seismicity of the area, the dead load, the structural type, response of the structure, interaction of the structure with the ground, and the importance of the structure;**
  - **The zone coefficient Z corresponds to the effective peak ground acceleration from a contour map with 5 levels;**
  - **The product of Z and C represents an acceleration response spectrum envelope having a 10% probability of being exceeded in 50 years.**

- **The importance factor *I* is concerned with the number of people in the building at risk, and the postdisaster importance of the building and *C* represents the response of the structure to the acceleration spectrum.**
    - **The curve given by the *C* equation is a simplified multimode acceleration response spectrum normalized to an effective peak ground acceleration of one.**
    - **It is a function of the fundamental period of the structure *T*, and the site coefficient *S*, to adjust for the site soil conditions. *UBC* has designated 4 soil types.**
    - ***C* is limited to a maximum of 2.75 to provide numbers where soil evaluation is not practical.**
- **The structural system factor R_w is a measure of the ability of the structural system to sustain cyclic inelastic deformations without collapse.**
- ***W* is the total dead load of the building.**
- ***V* gives the magnitude of the total base shear that must be distributed over the height of the structure for the equivalent static analysis.**


0.01wr
0.01w3
0.01w2
0.01w1
wr
w3
w2
w1
V = 0.01(w1 + w2 + w3 + wr)

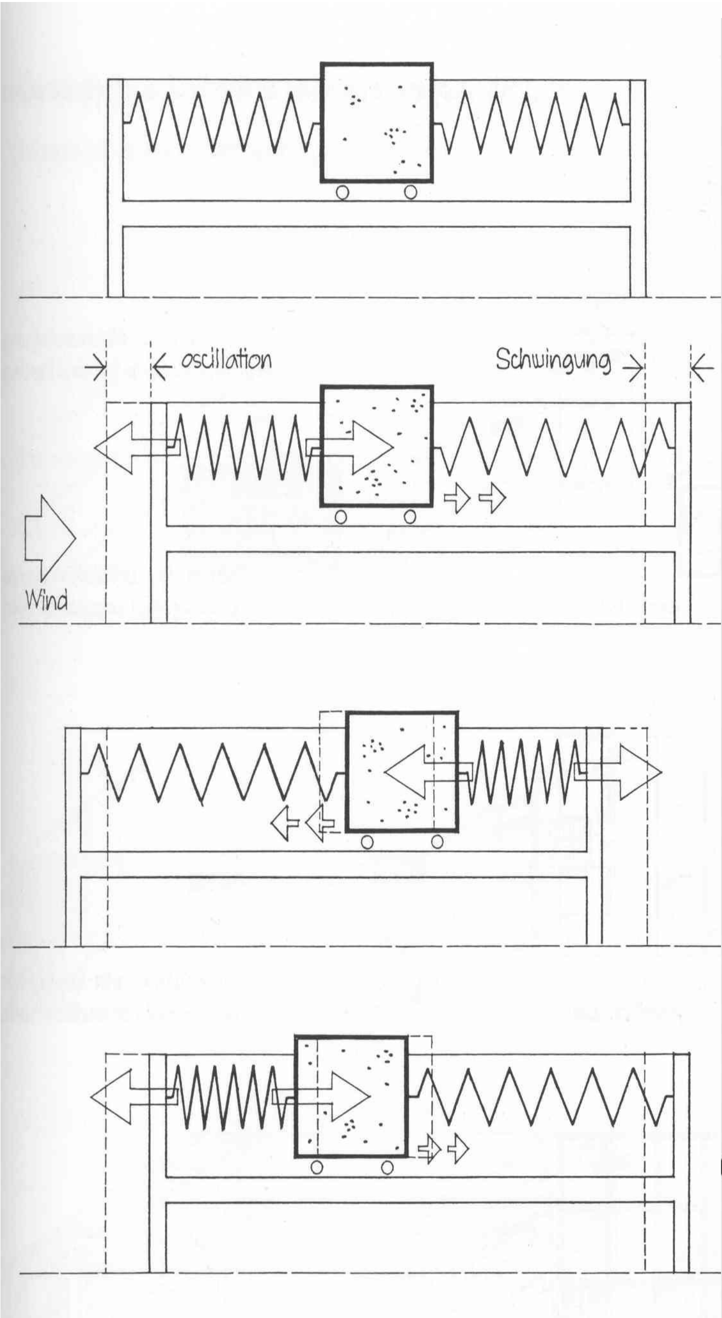
Seismic: Modal Analysis.

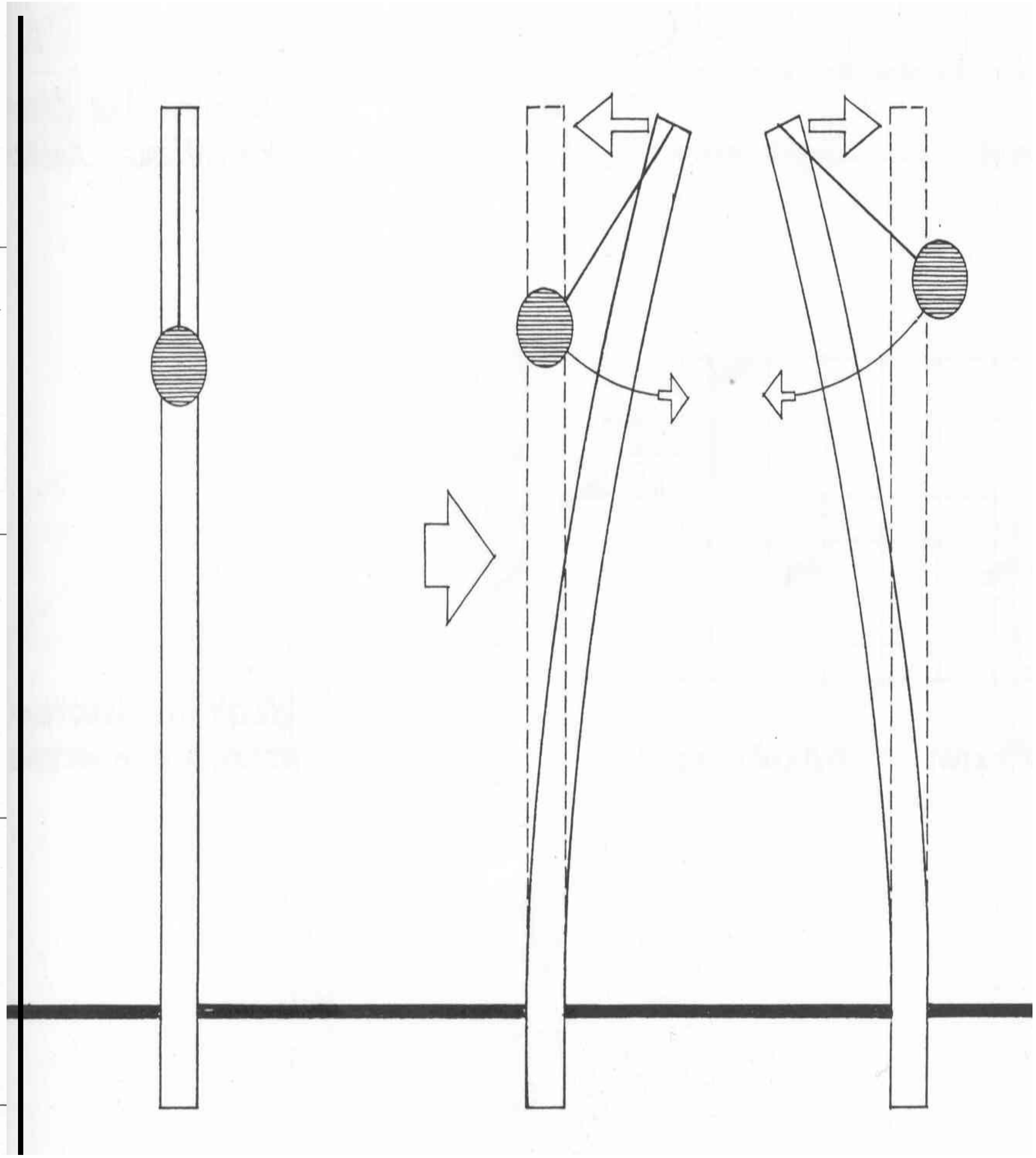
- **In this procedure, the modal frequencies of the structure are analyzed and then used in conjunction with earthquake design spectra to estimate the maximum modal responses.**
- **These are then combined to find the maximum values of the responses.**
- **This procedure is more complex and longer than the equivalent lateral force procedure, but it is more accurate as well as accounting for the nonlinear behaviour of the structure.**
- **In a modal analysis, a lumped mass model of the building with horizontal degrees of freedom at each floor is analyzed to determine the modal shapes and modal frequencies of vibration.**
- **The results are used in conjunction with an earthquake design response spectrum, and estimates the modal damping to determine the probable maximum response of the structure from the combined effect of its various modes of oscillation.**
- **This method is applicable to linear elastic systems. Consequently, the results are an approximation.**

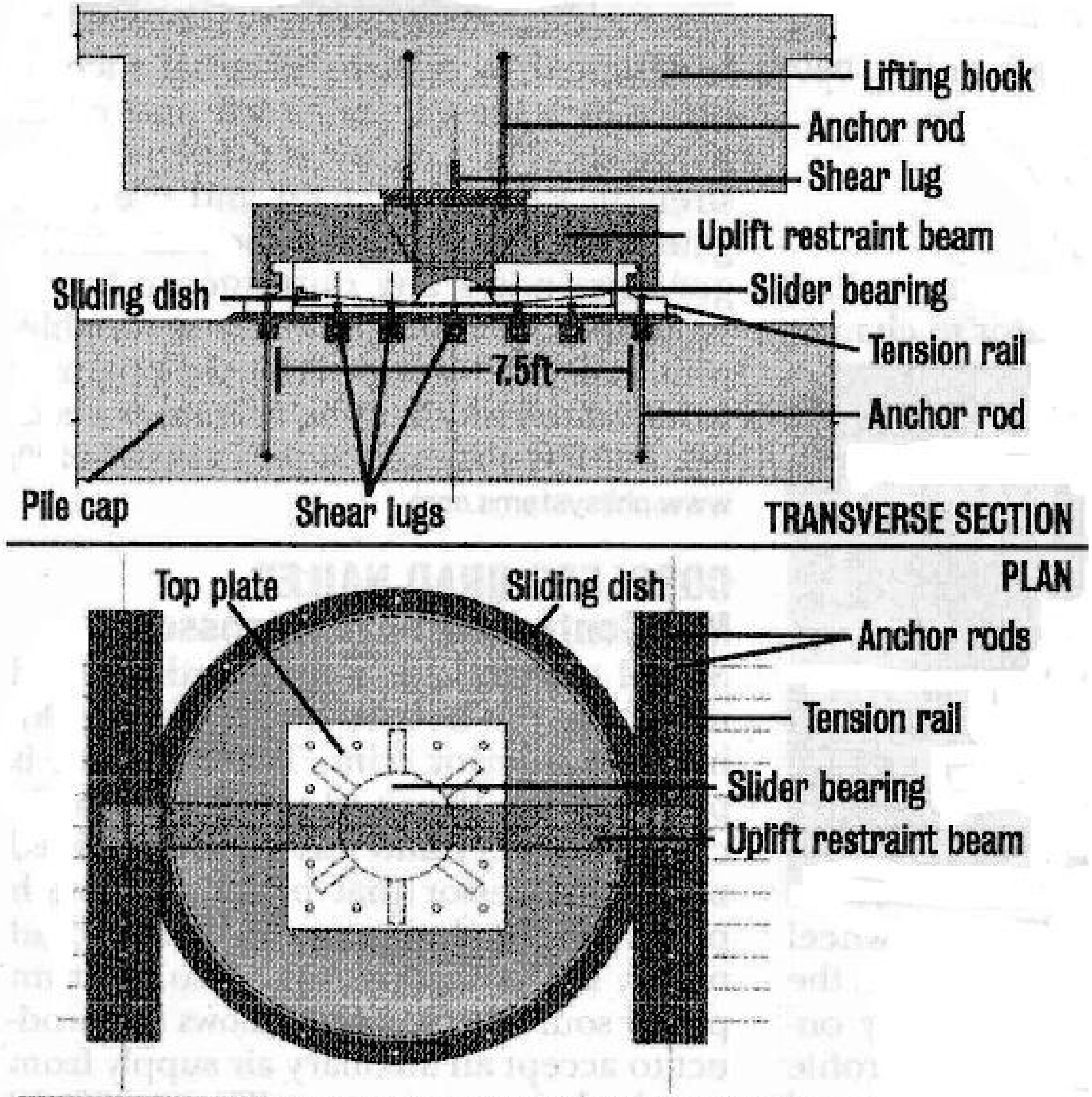


Non-seismic zones in the United States.

Mechanical Dampers







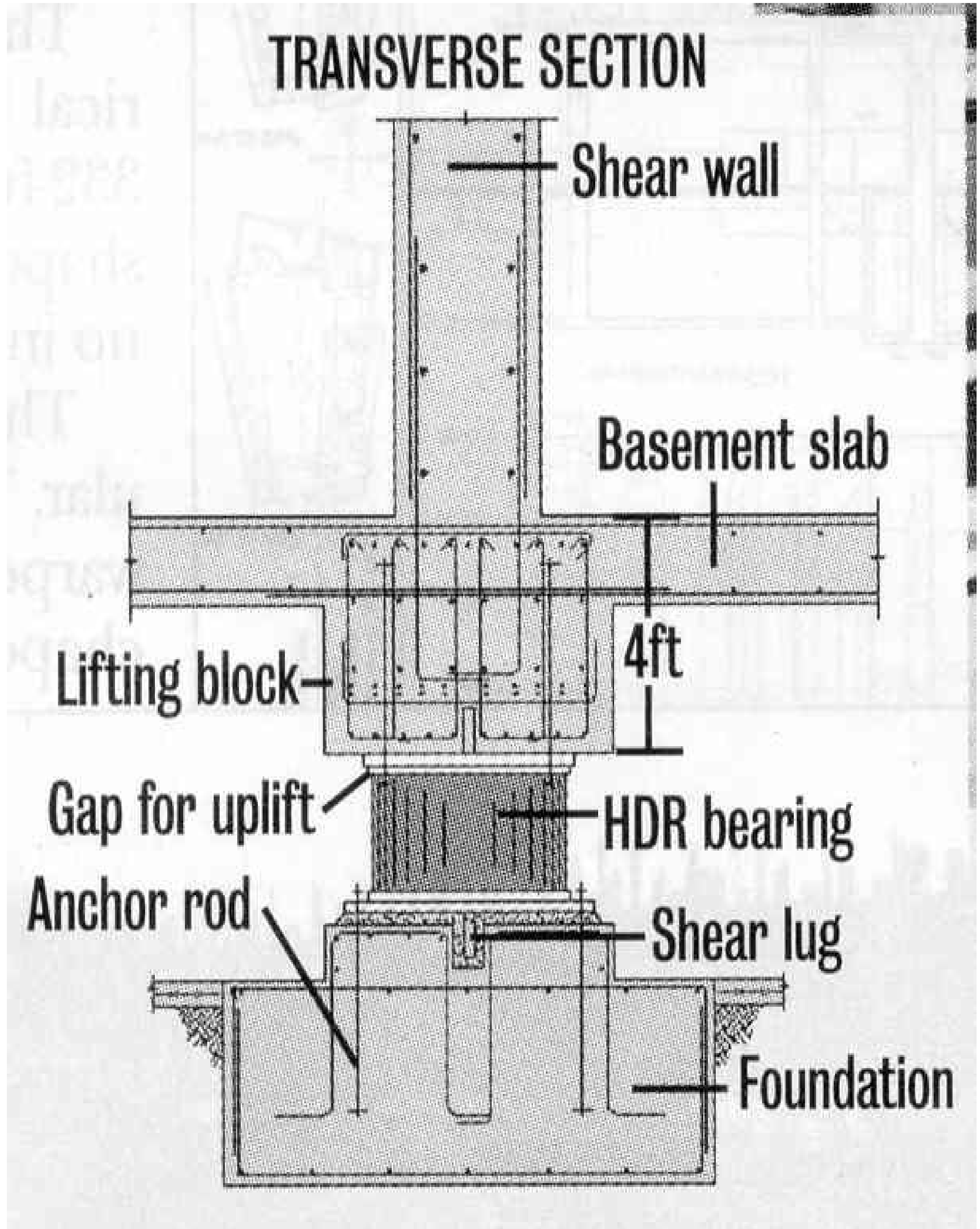
FRICTION PENDULUM SLIDERS Bearings for the tall, slender bell tower had to resist uplift.

Above. The $250-million Torre Mayor project reaches a height of 225 m and is the tallest building in Mexico and Latin America.

Left and below. Supplemental dampers reduce building sway inter-story drift.

An engineer checks the load in a jack that has lifted the foundation grade beam of Los Angeles' City Hall in order to retrofit the 452-ft tall building (32 story) with seismic base isolators (ENR 25 June 2001).


Concrete walls
156ft
Bearings


TRANSVERSE SECTION
Shear wall
Basement slab
4ft
Lifting block
Gap for uplift
HDR bearing
Anchor rod
Shear lug
Foundation

Load Combinations and the φ factors.

AISC's Manual of Steel Construction (Third Edition) provides the following load combinations, to choose the one that provides the largest loads:

1. ***1.4 D***
2. ***1.2 D + 1.6 L + 0.5 (L_r or S or R)***
3. ***1.2 D + 1.6 L (L_r or S or R) + (0.5 L or 0.8 W)***
4. ***1.2 D + 1.6 W + 0.5 L + 0.5 (L_r or S or R)***
5. ***1.2 D ± 1.0 E + 0.5 L + 0.2 S***
6. ***0.9 D ± (1.6 W or 1.0 E)***

Flexure without axial load φ = 0.90
Axial tension and axial tension with flexure φ = 0.90
Axial compression with flexure (with spiral reinforcement) φ = 0.75
Axial compression with flexure (with ties) φ = 0.70
Shear and torsion φ = 0.85
Compression buckling φ = 0.85

Example. **The axial forces on a building column from the code-specified loads have been calculated as 200 kips of dead load, 150 kips (reduced) floor live load, 25 kips from the roof (L_r or S or R), 100 kips from wind, and 40 kips from earthquake. Determine the required strength of the column.**

1. $1.4D = 1.4(200) = 280$

2. $1.2D + 1.6L + 0.5L_r = 1.2(200) + 1.6(150) + 0.5(25) = 493$

3a $1.2D + 1.6L_r + 0.5L = 1.2(200) + 1.6(25) + 0.5(150) = 355$

3b $1.2D + 1.6L_r + 0.8W = 1.2(200) + 1.6(25) + 0.8(100) = 360$

4. $1.2D + 1.3W + 0.5L + 0.5L_r = 1.2(200) + 1.3(100) + 0.5(150) + 0.5(25) = 458$

5a $1.2D + 1.5E + 0.5L = 1.2(200) + 1.5(40) + 0.5(150) = 375$

5b $1.2D + 1.5E + 0.2L_r = 1.2(200) + 1.5(40) + 0.2(25) = 305$

6a $0.9D - 1.3W = 0.9(200) - 1.3(100) = 50$

6b $0.9D - 1.5E = 0.9(200) - 1.5(40) = 120$

The required strength for the column is 493 kips, based on the second load combination.

References.

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Cherry Blossoms