<u>Buildings at Risk: Wind Design Basics for Practicing Architects</u>, AIA, 1998

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Wind Impacts on Buildings

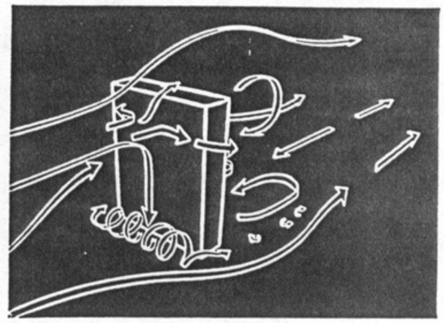

Figure 3.1: Flow of air around a high-rise building.

3.1 WIND FORCES

Buildings are continually subjected to wind forces. Generally, these wind forces are at levels that the structure is capable of resisting, whether that capability is based on an engineered design using building code-specified wind loads, or, as is the case with most residential construction, it is based on standard construction practices that have developed over time. Periodically, structures are subjected to wind forces that cause damage. In some instances, the damage is due to wind loads exceeding design criteria. In most cases, the damage results from a weakness in the building itself.[1]

Damaging Winds

Damaging wind forces usually are associated with extreme weather phenomena, such as tornadoes, hurricanes, or thunderstorms. Maps indicating wind speeds for 50-year mean return periods have been used in building codes to establish wind loads for building design. The maps and other factors in design standards take into account the varying wind loads experienced in different environments, i.e. near the coast, inland, open terrain and urban environment. Building codes and standards generally use gust and other factors that are applied to the basic wind speed to account for the dynamic effects of wind.

In practice, the actual wind loads on a building rarely exceed the design wind load. Even in cases where design-level winds are somewhat exceeded, a well-designed and constructed building should sustain relatively little damage to the structural frame.[2] The building envelope (roof, walls, and openings) is another story. Breaches to the envelope have been observed to be the major cause of damage in high wind events, and envelope systems have sustained considerable damage even at wind speeds below design levels.

Many buildings would suffer severe damage if struck directly by a moderate to strong tornado. This damage results not only from the extreme

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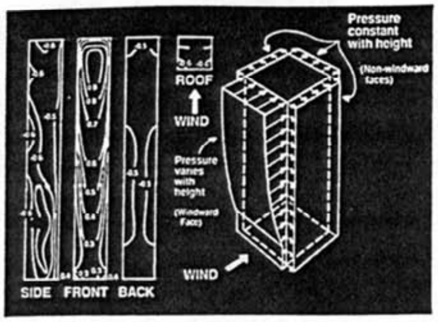

Figure 3.2: Wind tunnel analysis of the World Trade Center buildings and code approach.

wind speeds, but from the dynamically changing wind directions and the impact of wind-borne debris. Similarly, structures along the coast in the path of a hurricane may be simultaneously subjected to the severe forces of both wind and water, the greatest magnitude of each occurring at approximately the same time. The wind velocoties in a hurricane may exceed design levels and may subject the building to high winds first from one direction and then the other.[3]

Wind Loads

Wind loads on buildings can be calculated using the formula contained in the *American Society of Civil Engineers (ASCE 7-95) Standard for Minimum Design Loads for Buildings and Other Structures*. The wind load is an expression of the formula:

$$p = qGC$$
$$q = 0.00256 K_z K_{zt} V^2 I$$

where:

p = design pressure in psf
q = velocity pressure in psf
0.00256 = constant for mass density of air and appropriate conversion constants so that V may be given in mph
K_z = velocity pressure exposure coefficient
K_{zt} = topographic factor
V = basic 3-second peak gust wind speed in mph
I = importance factor, defines the level of risk depending on occupancy
G = gust effect factor, which considers spatial size of gust relative to the size of buildings, gust frequency relative to natural frequency and damping of structure, basic reference design speed, and terrain exposure
C = mean pressure coefficient (combining internal and external coefficients)

Use of this formula by an architect is relatively rare, as most wind load analysis is conducted by engineers and specialists. However, it is important for architects to be familiar with the formula so that they understand the impact of wind on the building's design and can discuss it with the engineer. Regardless of who performs the wind load calculations, it is imperative that loads be determined for the building envelope as well as the structure.

Vibration

Wind-induced structural vibration can be a concern in specialty structures such as tensile roofs, bridges, and other unusual configurations.

Buffeting vibration is produced by the unsteady loading of a building due to turbulence (velocity fluctuations in magnitude and direction) in the approaching free flow wind field. If the turbulence is generated by an upwind neighboring structure or obstacle, the unsteady loading is called wake buffeting or interference. The World Trade Center Twin Towers in New York City (Figure 3.2) and the John Hancock building in Boston are examples of buildings that experience the latter type.

Most building codes (e.g. ASCE 7) treat the along-wind vibration but do not address across-wind or torsional buffeting vibration.

The flow behind a long cylinder held perpendicular to wind is characterized by the periodic shedding of vortices (whirling air flows). Vortex shedding creates periodic lateral forces that can cause vibration of slender structures such as towers and tall buildings. Although vortex shedding is most noticeable for cylindrical buildings, it also happens to a lesser degree to tall buildings of other shapes.[4]

Figure 3.3: Vortex shedding.

Vortex-shedding vibration takes place when the wind speed is such that the shedding frequency becomes approximately equal to the natural frequency of the cylinder—a condition that causes resonance. When resonance takes place, further increase in wind speed by a few percent will not alter the shedding frequency. This phenomenon is called "lock-in." Because the structure vibrates excessively only in the lock-in range, having a wind speed either below or above the lock-in range will not cause serious vibration. If the shedding frequency is the same as the natural period of the building, it can have a load impact on the structure, pulling the building back and forth in an across-wind direction.[5] (Figures 3.3 and 3.4)

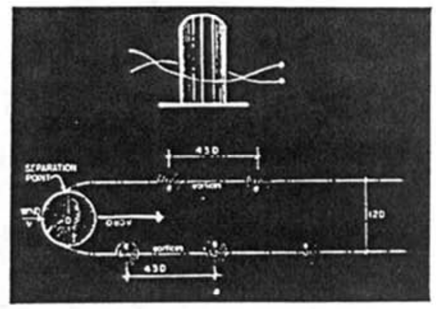

Figure 3.4: The Karman Vortex Phenomenon.

Classical flutter (or simply flutter) is a two-degrees-of-freedom vibration involving simultaneous lateral (across-wind translational) and torsional (rotational) vibrations. It occurs in structures that have approximately the same magnitude of natural frequencies for both the translational and the rotational modes. Similar to galloping and torsional divergence, flutter is produced by aerodynamic instability completely unrelated to vortex shedding.[6]

Damage Mechanisms

The four primary damage mechanisms associated with severe windstorms involve:

(1) aerodynamic pressures created by flow of air around a structure;
(2) induced internal pressure fluctuations due to a breach in the building envelope;
(3) impact forces created by wind-borne debris; and
(4) pressures created by rapid atmospheric pressure fluctuations (associated primarily with tornadoes).

Examinations of building damage caused by various types of windstorms suggest that most winds produce damage due to a combination of aerodynamic pressures and internal pressure fluctuations and, for hurricanes and tornadoes, debris impacts. Atmospheric pressure fluctuations have little or no effect on the performance of ordinary structures because most ordinary structures have sufficient building envelope permeability (or venting) to allow equalization of pressures induced by atmospheric pressure changes. In airtight structures such as nuclear containment vessels, atmospheric pressure changes can impose significant loading to the building envelope.[7]

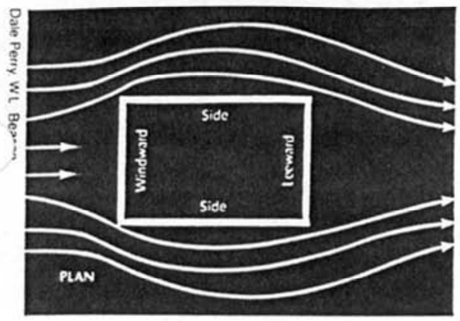

Figure 3.5: Building in wind flow.

Wind pressures acting on buildings are distributed loads that are assumed to act normal to the building surface. Positive wind pressures act toward the surface of the building element and negative pressures (suction) act away from the building surface. The fundamental characteristics of wind pressures are described below based on the building component affected and the orientation of the building in the wind environment.[8]

As winds increase, pressure against objects is added at a non-linear rate. Pressure force against a wall mounts with the square of the wind speed so that a three-fold increase in wind speed, for example, results in a nine-fold increase in pressure. A 25 mph wind causes about 1.6 pounds of pressure per square foot. Therefore a 4x8 sheet of plywood will be pushed by a force of about 50 pounds. In 75 mph winds, that force becomes 450 pounds, and at 125 mph, it becomes 1,250 pounds.[9]

3.2 AERODYNAMIC PRESSURE IMPACTS

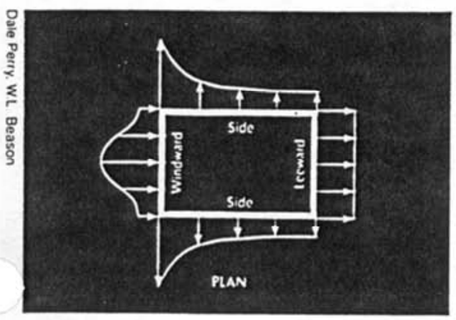

Figure 3.6: Relative wind pressure on walls.

Impacts on Walls

Figure 3.5 presents a plan view of a simple rectangular building that is submerged in a wind flow as shown. Each wall of the structure is identified as a windward, side, or leeward wall depending upon its location with respect to the direction of wind flow. The windward wall is the wall facing the wind; the leeward wall is on the side opposite to the windward wall; and the side walls are parallel to the wind flow.[10]

Because the windward wall is perpendicular to the wind flow, the wind impinges directly on the windward wall producing positive pressures (Figure 3.6). As the wind flows around the windward corners, the local wind speed increases and the flow lines have a tendency to separate from the corner of the building. This causes the side walls to be subjected to negative pressures as shown. In addition, the turbulence and flow separations that occur at the windward corners of the building induce high negative pressures for short distances along the side walls. The leeward wall is also subjected to negative wind pressures that tend to be relatively uniformly distributed.[11]

Impacts on Roofs

Wind creates a greater load on the roof covering than on any other element of a building. When a FEMA team investigated wind damage to buildings in Florida in the wake of Hurricane Andrew, their field observations concluded that the loss of roof covering was the most pervasive type of damage to buildings in southern Dade County. To varying degrees, all of the different roof types observed suffered damage due to the failure of the method of attachment and/or material, inadequate design, inadequate workmanship, or debris impact. Similar damage has been observed in the aftermath of other windstorms (Figure 3.7).