## Windborne Debris

A common experience during severe windstorms such as tornadoes, hurricanes, and severe thunderstorms is the occurrence of flying debris of all types. If these objects are able to remain airborne long enough, they can impact downwind buildings, sometimes causing injury or loss of life, as well as increasing the property damage beyond that produced by direct wind forces (Fig. 3.6). A common occurrence is the breaching of building envelopes, following which high internal wind velocities and pressures are created. A well-documented "chain reaction" effect can occur, in which debris from upwind buildings breach the windward walls of downwind buildings during a hurricane; high internal pressures occur followed by failure of roof and sidewall elements, thus generating more debris, and the process continues downwind.

### *Debris Sources and Flight Speeds*

Since the force of gravity always acts and will eventually cause an item of debris to strike the ground, the most common flying objects are those removed from the upper parts of buildings, especially roofs of buildings. These include roof cladding such as shingles or tiles, roofing components such as the classic "2 by 4" (actually about 40 by 90 mm or 1.5 in. by 3.5 in.) wooden members, and gravel from the roofs of high-rise buildings (this system is not recommended in high wind areas).


*Fig. 3.6: Windborne debris can often generate dangerous missiles.*

Smaller, lighter objects will start to fly at lower wind speeds and travel faster and farther than larger, heavy objects. Figure 3.7 shows three types of debris shapes, with different flying characteristics. The 'compact' types (perhaps represented by a piece of roof gravel), generally do not experience any lifting forces from the wind, and tend to fall downwards while being projected forward by wind forces. The plate type, representative of a roof shingle, for example, can experience lifting forces and will often fly faster and for longer than compact objects. The flight trajectories of plates are quite dependent on their angle to the wind at the start of their flight. Rod objects, represented by roofing members, for example, will usually have complicated flights with rolling and tumbling being present.

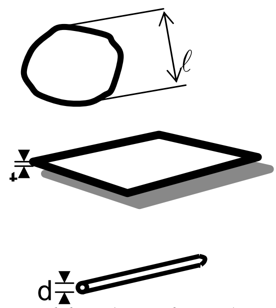


*Fig. 3.7: Types of windborne debris (top to bottom): compact; plate; rod.
From Holmes 2007, page 20; reproduced with permission from Taylor and Francis.*

The horizontal flight speed of windborne debris should not exceed the wind speed, although this can be approached if the object is allowed to fly for long enough.

***Debris Impact***

Modern building codes and standards recognize windborne debris as an additional cladding load. ASCE 7 and the International Building Code (IBC 2003) define regions wherein designs for windborne debris are required. Generally, these regions are areas susceptible to hurricanes. Windborne debris loads are divided into large missiles and small missiles. Large missiles are specified for the lower 9 m (30 ft.) of a building façade, while small missiles apply up to a specified height (60 ft. or 18 m in ASCE 7) or for the full height of a building. The most common large missile is the classic “2 by 4” (actually about 40 mm by 90 mm or 1.5 in. by 3.5 in.) timber weighing 9 lbs. or 4 kg (representing a class of large objects) impacting at 15 m/s (50 ft./sec.). The most common small missile is a 2 g steel ball (representing roof gravel) impacting at 40 m/s (130 ft./sec.). ASTM E 1996 is a commonly referenced specification for windborne debris loads on high-rise buildings.

*Fig. 3.8: A failed beachside deck canopy and adjacent roof segment becomes a source of many sizes of debris for downwind buildings.*

# Chapter 4

# Structural Loads

Wind pressures primarily act at right angles to the surface exposed to the airflow, so that for vertical walls on high and low-rise buildings, the forces are horizontal. On a flat roof, the wind forces act vertically. For a roof pitched at say 30 degrees to the horizontal, the wind force acts at 30 degrees to the vertical (Fig. 4.1).

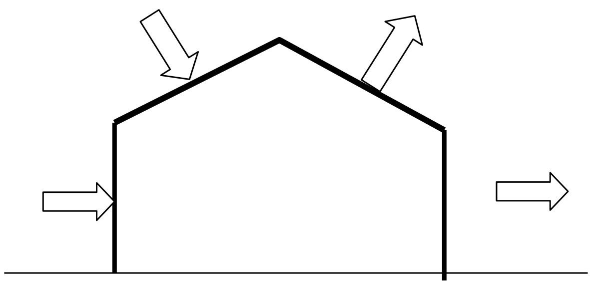

*Fig. 4.1: Directions of wind forces.*

When a tall building experiences vibration due to the wind loads, the structure sees apparent forces due to the mass times the acceleration of the structure at each floor level, for that part of its response. These apparent forces are known as inertial forces and are similar to those acting on a building responding to earthquakes. For the sway and torsional motions of a tall building, these forces act horizontally.

**Building Response**

From a structural design perspective, the most important aspects of building responses to wind are wind-induced loads and wind-induced building motions. The former are normally considered for the structural safety and the latter normally for the structural serviceability.

For a typical building the important wind loads are applied in horizontal directions and include alongwind loads, crosswind loads and torsional loads, which cause responses as shown in Figure 4.2. For structures with large roofs, such as arenas or stadiums, the important wind loads should include lift or down-force which is applied in the vertical direction on the roofs, as shown in Figure 4.3. Each of these loads consists of a static component (i.e., mean component) and a dynamic component (i.e., time-varying component). The classification of the wind loads is illustrated in Figure 4.4.

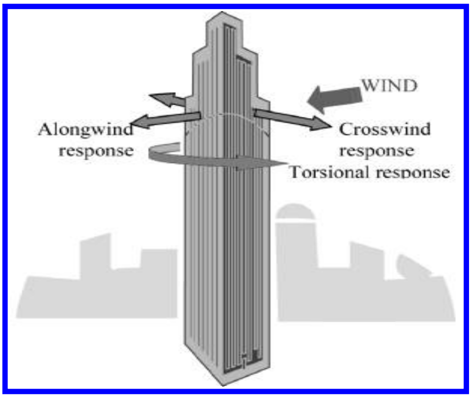


*Figure 4.2: Alongwind, crosswind and torsional responses of a typical tall building.*

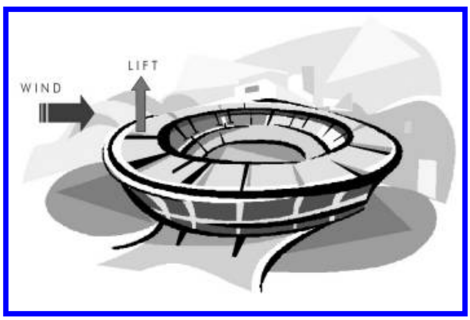


*Figure 4.3: Stadium roofs have other wind concerns.*

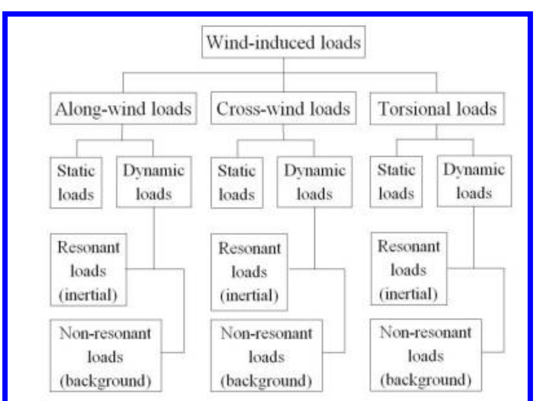


*Figure 4.4: Classification of wind loads on a building.*

The static wind loads are the results of mean wind pressure and are sensitive to the building geometry. For tall buildings, static wind loads are often dominant in alongwind direction. Crosswind static loads can be significant for some buildings with special shapes. Examples of these shapes include triangles and some unsymmetric curved sections. If the resultant force of the static wind pressures (including alongwind and crosswind) is away from the center of stiffness, a static torsional loading will be created. A typical example is the building with an "L" shape floor plan, where the torsional arm can be about 30% of the building width (Xie and Irwin, 2000). Buildings with unsymmetric step elevations can also cause high torsional loads.

Various types of wind excitation can induce the dynamic loads. The basic dynamic loads are due to unsteady wind pressures. These unsteady wind pressures can be caused by wind turbulence in the approaching wind, or by flow separations off the building surface. If the building motions are not significant, these dynamic loads can be assumed to be independent of the building's dynamic properties (quasi-static theory). These dynamic loads are called "background loads" or "non-resonant loads" and due directly to the wind pressures on the building surfaces. For a tall building or a large flexible structure, the background loads by themselves may not be very large because the unsteady wind pressures are not well correlated over the entire building surface. However, for these flexible structures the unsteady wind pressures can also excite the building structure into motion and this causes inertial loads, as the building mass accelerates during the motion. These inertial loads are generally called resonant loads because they occur at the building's natural frequencies only, and they are greatly magnified relative to the direct pressure loads coming from the wind at those frequencies.

Buffeting response causes the most common inertial loads. Buffeting is a random vibration of the structure excited by a broadband unsteady wind loading caused by wind turbulence. Buffeting will excite a building's sway and torsional modes of vibration and cause horizontal loads as well as torsional moments. Buffeting-induced dynamic loads increase with increases of wind speed and wind turbulence level. All buildings will experience some degree of buffeting responses. A typical spectrum of wind-induced base overturning moment is illustrated in Figure 4.5, which shows the background loads and the resonant loads caused by the buffeting response.

Some buildings or structures may experience vortex-induced oscillations. Vortex-induced oscillation originates from the alternate and regular shedding of vortices from both sides of the structure. This shedding of vortices generates rhythmic fluctuating forces on the structure in the crosswind direction. The frequency of the vortex shedding increases with increasing wind speed. If the frequency of the vortex shedding is close to one of the structure's natural frequencies at certain wind speed, large oscillations may occur due to resonance effects. Once vortex-induced oscillations are established, the vortex shedding frequency can become locked onto the structure's natural frequency even if the wind speed varies slightly from the original speed that initiated the motion. Wind turbulence tends to break up the regular shedding of vortices. Therefore, vortex-induced oscillations are most critical when structures are exposed to an open terrain where the turbulence level is relatively low. A structure by a lake or estuary may experience even lower turbulence levels due to the thermal stability effects of warm air flowing over cool water. Vortex-induced oscillations may cause large dynamic loads and severe building motions at a relatively low wind speed. Therefore, not only structural strength, but also serviceability and structural fatigue need to be carefully examined if there are potential vortex oscillation problems. Generally, vortex-induced oscillations should be minimized.

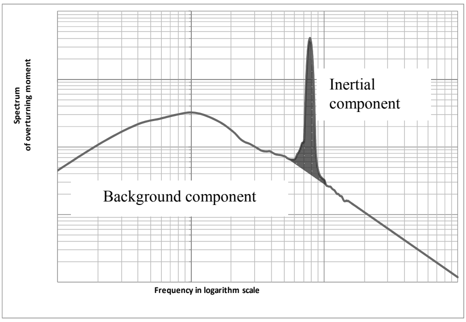


*Figure 4.5: Typical tall building base moment response spectrum.*

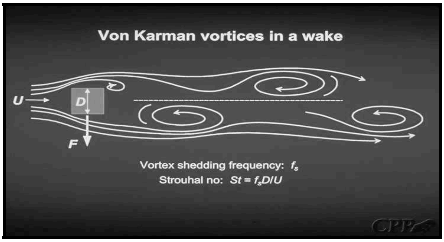


*Figure 4.6: The alternate shedding of vortices off the side of a building creates forces that act perpendicular to the wind flow - a crosswind response.*

If a building is located downstream of another tall building or a large structure, it is possible that the study building will be excited by the wake of the upwind building. Different from the buffeting case, the wake turbulence normally has a narrow band spectrum (i.e., the energy of the wake turbulence is concentrated over a narrow range of frequencies). If the outstanding frequency of the wake turbulence is close to one of the study building's natural frequencies, the study building may experience large resonance loads as well as motions. Upwind structures or topographic features may also cause localized accelerated flow acting on the study building and result in high response. This phenomenon is often referred as a "channeling effect."

Although divergent aerodynamic instability, such as galloping or flutter, has not been recorded for buildings, it has occurred on some lightweight structures such as sign structures, roof top spires and bridges. Galloping and flutter are self-excited aerodynamic instabilities that can grow to very large amplitudes and cause structural failure. The onset of galloping instability can be regarded as the wind speed at which aerodynamic forces cause the total system damping value, comprising structural damping and aerodynamic damping (which may be negative in unstable cases), to be less than zero. The higher the wind speed is above this critical speed, the more quickly the oscillations will grow to failure. Many readers will have seen the film sequence of the Tacoma Narrows bridge failure in the 1940s as an example of this mechanism (Tacoma Fire Department 1940). Therefore, it needs to be confirmed that the critical wind speed is much higher than the wind speeds expected at the site during the life of the structure.

The key parameters that affect wind-induced building response include:

1. The building's geometry and dimensions. Generally, a streamlined shape tends to experience lower wind loads. Open balconies, especially those around building corners, may be helpful in reducing wind-induced building response.
2. The building's mass and stiffness. Generally, heavier and stiffer buildings tend to be less sensitive to wind excitation than lighter and more flexible buildings.
3. The building's structural damping level. The wind-induced dynamic response of buildings will be decreased with increased structural damping level. In practice the damping inherent in the building's structural system is not readily controlled and estimates of the damping can only be made approximately based on empirical data. However, supplementary damping devices, such as tuned mass dampers (TMD), tuned liquid dampers (TLD), viscous dampers and active damping systems, can be effective and economic ways to reduce the wind-induced structural response.
4. The building's exposure to wind. Generally, a building will experience higher wind-induced response in an open terrain than in a built-up terrain. Problems with vortex-induced oscillations are mostly associated with open terrains. However, exceptions may exist if the surrounding buildings in a built-up area cause channeling effects and create accelerated flow, or induce wake buffeting loading on the study building.
5. The building's orientation. If a building's orientation is so designed that its most sensitive direction to wind excitation is away from the prevailing strong wind direction at the site, the probability of large wind-induced response will be reduced.

**Strategies to Resist Wind**

The following sections describe various design strategies for resisting or minimizing wind forces and response. The first of these describes aerodynamic strategies, which range from choosing a favorable roof such as a hipped or conical roof, to the use of desirable cross-section or corner chamfers on a tall building to reduce the wind forces to the vibration response produced by wind forces.

Other sections discuss structural strategies to resist wind forces and the directions in which the forces on a building act in strong winds. For a tall building, these forces are primarily horizontal, and the structural resistance is provided by systems such as cross bracing and shear walls.

On an inclined roof, the forces act at right angles to the roof surface, and thus have a strong component acting vertically. On a low-rise building, it is important to resist the vertical ‘uplift’ forces applied by the wind with a continuous load path down to the foundation. The roof is often the part of a low building that fails first in severe windstorms.

When the vibrations of tall buildings produced by wind are over the limits regarded as acceptable for human comfort (Chapter 5), they can be reduced by the use of special damping systems, such as tuned mass dampers or viscoelastic dampers. Devices like these, which have been installed in buildings, are described under structural strategies.

Section on storm shelters describes a social strategy to combat the effects of severe wind storms—namely the use of in-house or community storm shelters. This strategy assumes that many existing building structures will fail in severe windstorms, but the safety of residents can be assured by the use of storm shelters of high structural strength and resistance. This section describes the special design requirements of these structures.

***Aerodynamic Strategies***

Whether for a super-tall building or a domestic home, wind loads are greatly influenced by the shape of the design—the architecture. Good aerodynamic choices will result in reduced wind loads. For example, hips roofs on a home generally experience lower uplift pressures during an extreme wind event than gable roofs. They are simply more aerodynamically friendly.

The application of aerodynamics to architectural shape becomes even more important as a building becomes taller. The wind loads typically control tall building design. Varying the shape of the building with height will decorrelate the vortex shedding and so the crosswind response of a tall building. A residential building with protruding corner balconies will have a similar effect, and also reduce local cladding loads. Some taller buildings have open “refuge floors” (Fig. 4.7) for fire-safety reasons, but the aerodynamic impact is to allow flow through the building to reduce the magnitude of the negative pressure behind it. Dynamic loads on tall chimneys are often countered by installing helical strakes on the chimney. Even long suspension bridge decks commonly have fairings (triangular leading edges along both sides of the bridge deck) along their length to improve aerodynamic performance. In summary, using aerodynamic building shapes with strategic corner details, varying the shape with height, or using refuge floors to diminish the wind-induced structural loads will result in a better tall building design.

Cladding pressures may also be ameliorated with strategic design features. Corner balconies, as noted above, will reduce the design cladding pressures. Roof pressures may be reduced by the use of porous parapets or perimeter spoilers as shown in Figure 4.8. Even placing a new building within a complex cityscape of similar structures will be aerodynamically advantageous.

*Fig. 4.7: Tall buildings resist the wind by architectural shape and structural system – Two International Finance Centre, or 2IFC, (420 m) in Hong Kong, China.*

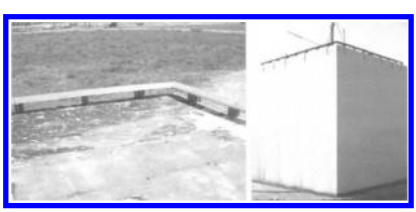

*Fig. 4.8: Roof-corner vortex formation and roof-edge flow separation may be controlled by roof-edge spoilers. The diminshed roof pressures are substantially smaller.*

***Structural Strategies***

While all structures in the wind must be designed to resist both lateral forces and uplift forces, which of these requirements is more important for a particular building is generally a function of the structure's aspect ratio, or relative height to width, as well as its shape. The design of a broad, low building with a relatively large roof area in proportion to its height, must give attention to resisting the uplift forces on the roof surface, with careful detailing of the connections to create a continuous load path to anchor the structure to the foundation. In contrast, a tall structure on a relatively narrow base must be designed with primary concern for lateral force resistance and overturning.

The use of shear walls is a time-honored, traditional way of resisting lateral wind loads on buildings. Solid masonry bearing walls provided resistance to lateral shear forces in times predating the development of the modern building materials steel and concrete. Shear walls in today's multi-story office and apartment buildings are typically created by forming one or more tall, rigid structural "boxes" wrapped around centrally-located elevators, stairs and/or lobbies. Such a structure is called a central core, and its action is to resist the tendency under the lateral force of the wind for a floor to shear or slide relative to the one below. For shear walls to be most effective they should be continuous throughout the height of the building and have as few openings as possible. A minimum of two shear walls orthogonal to one another is necessary to provide resistance to lateral wind forces, since the wind may come from any direction. Shear walls may be staggered within a vertical plane when required for interior spatial arrangements, but this is not ideal.

Reinforced concrete or braced or rigid steel framing may be used to form shear walls in multi-story buildings. Braced steel frames have diagonal members in the vertical shear walls which act in tension or compression to resist the tendency for side-to-side lateral movement of one floor relative to another. Rigid steel frames use moment-resistant connections instead of diagonals to withstand lateral forces. Moment connections are generally less efficient than diagonal members in resisting shear, but they create less difficulty when it comes to placing doors, windows or other openings in shear walls. Buildings may be designed with a combination system, using braced frames in one direction and moment frames in the perpendicular direction.

As tall buildings reach greater heights, they require structural systems with greater stiffness to increase their resistance to wind-induced lateral motion. In "tube" structures, the major wind-resisting structural system is located in or near the perimeter walls of a tall building, rather than around an internal core. As such, the wind-resisting structure becomes a factor in the architectural expression of the building. Tube structures, while inherently very efficient in use of material, must accommodate the competing demands of rigidity and continuity of structure on the one hand, and the occupants' need for multiple entrances at ground level and desire for large windows, on the other. Among the best-known expressions of tube structures in tall buildings are the closely-spaced columns of the former New York World Trade Center towers, the diagonally-braced façade of Chicago's John Hancock Building and the nine bundled