Chapter 5

Aerodynamics of Buildings and Structures

1. Flow Around Buildings

1.1 The atmospheric boundary layer

Wind near the ground is slowed by surface roughness, so the mean speed grows with height over a layer a few hundred metres to a few kilometres deep. Two models are commonly used for the mean profile.

Logarithmic law (neutral atmosphere, z above the roughness sublayer):

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \quad \kappa \approx 0.4$$

Power law (simple engineering approximation):

$$U(z) = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Here u_* is the friction velocity, z0 the aerodynamic roughness length and α the profile exponent. Typical values are given below. They are indicative and should be replaced by the values in the applicable code or site survey.

Terrain type	Roughness length (z_0) (m)	Power-law exponent (α)	Typical turbulence intensity near 10 m
Open sea, flat coast	0.0002–0.005	0.10–0.12	≈ 10%
Open country, few obstacles	0.03–0.05	0.14–0.16	≈ 15–20%
Suburban, low-rise buildings	0.3–0.5	0.22–0.28	≈ 20–30%
Dense city centre	1–2	0.30–0.40	≈ 30–40%

The turbulence intensity $I_u = \frac{\sigma_u}{\overline{U}}$ expresses gustiness. It matters as much as the mean speed because peak loads and pedestrian discomfort are driven by gusts.

1.2 Flow features around an isolated bluff body

For a prismatic building facing the wind, the following features appear (they can be sketched on a plan and an elevation view):

- **Stagnation zone** on the windward face, at roughly 60 – 70 % of the building height, where pressure is highest.
- **Downwash**: the flow below the stagnation point goes down the face, accelerates around the base and creates strong ground-level winds.

- **Horseshoe vortex** wrapping around the base, formed by the boundary layer rolling up ahead of the building.
- **Separation** at the windward edges of the roof and sidewalls, producing shear layers.
- **Recirculation zone and wake** behind and on top of the building, with low pressure and slow, turbulent flow. The cavity behind a cube extends roughly 1 – 3 building heights downwind, and the wake persists much farther.
- **Conical (delta-wing) vortices** along the roof edges under oblique wind. They cause the largest suction on roof corners.

Because separation is fixed by the sharp edges, the mean flow pattern of an angular building is almost independent of Reynolds number once Re is high (Reynolds-number independence). Rounded shapes do not have this property: their separation point moves with Re, so wind tunnel tests must be interpreted with care.

1.3 Vortex shedding

Behind a bluff body, vortices are shed alternately from each side at a frequency f that follows the Strouhal relation:

$$St = \frac{fD}{U}$$

For square and rectangular sections, St is about 0.1 – 0.15, and for circular sections about 0.2 in the subcritical range. Shedding creates an across-wind force at frequency f. If f approaches a natural frequency of the structure (chimneys, towers, slender masts, cables), resonance occurs. The critical wind speed is $U_{cr}=\frac{f_n D}{St}$

1.4 Groups of buildings and pedestrian-level wind

Buildings interact. The main effects are:

- **Channelling and Venturi effect** between two buildings that converge, accelerating the flow.
- **Sheltering** of a low building in the wake of a taller one, which cuts its loads and its natural ventilation driving pressure.
- **Wake buffeting**: a downwind tower is hit by the turbulent wake of an upwind tower, which increases dynamic response.
- **Street canyons**: for an aspect ratio H/W below about 0.3 the buildings act as isolated roughness elements. Between about 0.3 and 0.7 wake interference appears. Above

about 0.7 the flow skims over the top and a stable vortex fills the canyon, trapping pollutants.

Pedestrian comfort is judged by comparing the speed exceeded for a small fraction of the time (often 5 % or 1 % of hours) with thresholds for the intended activity. The thresholds below follow the general logic of the Lawson and NEN 8100 criteria. Use them as orientation only, since each guideline fixes its own exceedance probabilities.

Activity	Approximate wind speed (m/s)	Comment
Sitting (cafés, terraces)	4	Light objects or papers may be disturbed, depending on gusts.
Standing (entrances, bus stops)	6	Hair and clothing may be noticeably disturbed.
Strolling (pavements, parks)	8	Walking is generally possible, but comfort depends on gustiness.
Walking fast (roads, car parks)	10	May be uncomfortable; less suitable for areas where people linger.
Potentially hazardous conditions	Above 15	Strong winds can affect balance, particularly for vulnerable people.

1.5 Methods of study

1. Boundary-Layer Wind Tunnel Testing

A boundary-layer wind tunnel is a laboratory facility used to reproduce wind flow around buildings using small-scale physical models.

Strengths:

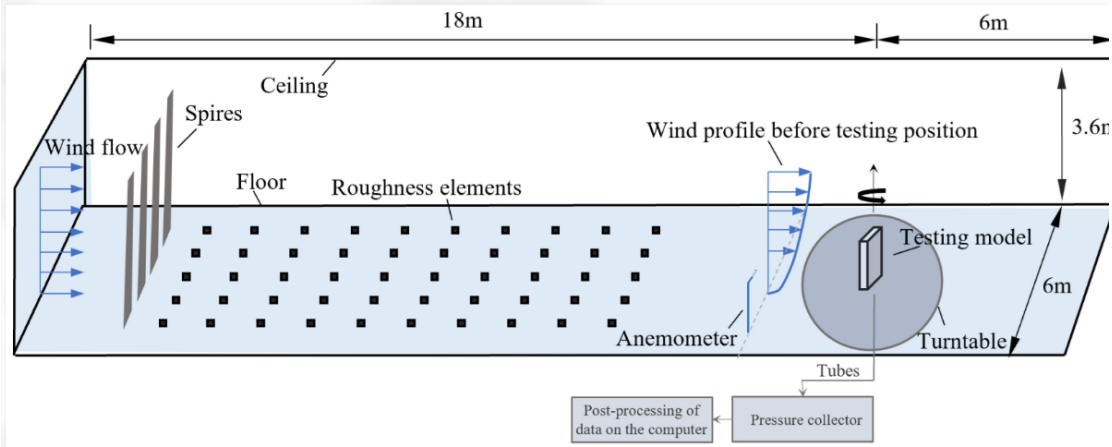
- ✓ Long record of validation: This method has been used extensively and its results have been compared with real measurements.
- ✓ Peak pressures and forces: Sensors can measure the maximum wind pressure on walls and roofs and the forces acting on a structure.
- ✓ Complex geometry: It can represent complicated buildings and the influence of surrounding buildings.

Limits:

- ✓ Scale effects: A small model cannot perfectly reproduce all the characteristics of real atmospheric wind flow.
- ✓ Cost and delay: Preparing models, conducting experiments and analysing results can be expensive and time-consuming.

✓ Limited configurations: Testing different wind directions or building designs requires additional experiments.

Example: A physical model of a tall building is placed in a wind tunnel to determine which parts of its roof experience the highest wind pressure.



2. Computational Fluid Dynamics (CFD: RANS and LES)

CFD uses numerical methods and computers to solve the governing equations of fluid motion and simulate how wind flows around buildings.

Two common approaches are:

- RANS (Reynolds-Averaged Navier–Stokes): Calculates the average flow and models the effects of turbulence. It is generally less computationally expensive.
- LES (Large Eddy Simulation): Resolves large turbulent eddies directly while modelling smaller ones. It provides more detailed information about unsteady turbulent flow but requires much more computational power.

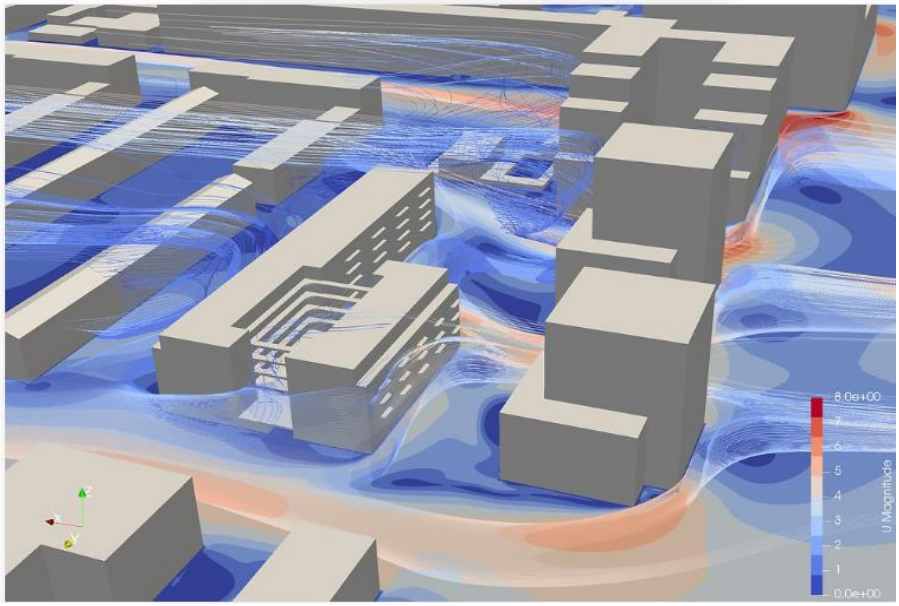
Strengths:

✓ Full flow field: Provides velocity, pressure and turbulence information throughout the computational domain, not just at sensor locations.
✓ Fast parametric studies: Allows researchers to investigate different building shapes, wind directions and inlet velocities without constructing new physical models.
✓ Temperature and pollutant transport: Can simulate heat transfer and the dispersion of pollutants, provided the relevant physical models are included.

Limits:

- ✓ RANS prediction errors: Some turbulence models may incorrectly predict flow separation, recirculation regions and wake length behind buildings.
- ✓ High computational cost of LES: Detailed turbulent simulations require fine meshes and small time steps.
- ✓ Sensitivity to simulation settings: Results depend on the inlet wind profile, mesh quality, boundary conditions, turbulence model and numerical settings.

Example: A researcher uses OpenFOAM to calculate wind velocity and pressure around a building and identify areas where strong winds or recirculation occur.



3. Full-scale measurement

Full-scale measurement involves collecting wind data directly from real buildings or at actual outdoor sites using instruments such as anemometers and pressure sensors.

Strengths:

- ✓ Real conditions: Measurements include actual atmospheric turbulence, weather conditions and interactions with the surrounding environment.
- ✓ No physical model required: Researchers do not need to build a scaled model or reproduce the flow numerically.

Limits:

- ✓ Uncontrolled wind: Wind speed, direction and atmospheric stability change naturally, making experiments difficult to repeat under identical conditions.

- ✓ Few measurement points: Instruments can only measure at the locations where they are installed, so they cannot easily provide a complete flow field.
- ✓ High cost: Installing, maintaining and operating instruments over long periods can be expensive.

Example: Researchers install anemometers on a real building to measure wind speed at different heights and compare the observations with CFD predictions.



. Summary comparison

Method	Main advantage	Main limitation
Boundary-layer wind tunnel	Reliable experimental data on pressures and forces	Cost, scale effects and limited test configurations
CFD (RANS, LES)	Detailed flow field and flexible design studies	Accuracy depends on models and simulation settings
Full-scale measurement	Direct observations under real atmospheric conditions	Difficult to control conditions and limited spatial coverage

2. Aerodynamic Pressures and Thermal Comfort

2.1 Wind pressure and the pressure coefficient

Pressure on a surface is expressed through a dimensionless coefficient built on the dynamic pressure at a reference height (usually the building height H or the eaves):

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_{ref}^2}$$

so that the wind pressure on the surface is $p_w = C_p \cdot \frac{1}{2}\rho U_{ref}^2$

. Positive Cp means pressure and negative means suction. With ρ = 1.2 kg/m³, a 25 m/s wind gives a dynamic pressure of 375 Pa.

Typical mean values for a rectangular low-rise building with wind normal to a wall are shown below. They vary with height-to-width ratio, roof shape and surroundings, so real design uses code tables or wind tunnel data.

Surface	Typical mean C_p	Remark
Windward wall	+0.6 to +0.8	Maximum near 60 – 70 % of H.
Leeward wall	−0.3 to −0.5	Wake suction, fairly uniform.
Side walls	−0.5 to −0.7	Higher suction near the windward edge.
Flat roof	−0.7 to −1.2	Local values reach −2 or more at edges and corners.

2.2 Net loads, internal pressure and peaks

The load on a wall or roof element is the difference between external and internal pressure:

$$\Delta p = (C_{pe} - C_{pi}) \cdot \frac{1}{2}\rho U_{ref}^2$$

A dominant opening on the windward side raises Cpi toward +0.7 to +0.8 and can nearly double the uplift on a roof. For this reason doors and windows must be treated as part of the structural design in storms.

Design must consider **peak** values, not means. Pressure fluctuates strongly, and small cladding panels see higher peak suctions than a whole facade because turbulence is correlated only over limited areas. Codes such as EN 1991-1-4 and ASCE 7 therefore define peak velocity pressure that includes turbulence, for example:

$$q_p(z) = [1 + 7I_v(z)] \cdot \frac{1}{2}\rho v_m^2(z)$$

2.3 Dynamic and aeroelastic effects

- **Buffeting**: response to turbulence in the approach flow or in the wake of upstream buildings.
- **Vortex-induced vibration**: lock-in near the Strouhal critical speed (section 1.3).
- **Galloping**: instability of non-circular sections (for example rectangular prisms or ice-coated cables) whose aerodynamic force changes with the angle of attack.
- **Flutter**: coupled bending-torsion instability, the classical failure mode of long-span bridge decks (Tacoma Narrows, 1940).

Typical countermeasures are shape modification (chamfered or rounded corners, tapering, setbacks, openings through the building), added damping (tuned mass dampers) and stiffening.

2.4 Thermal comfort

Thermal comfort depends on air temperature, mean radiant temperature, air speed, humidity, clothing (clo) and metabolic rate (met). Two families of models are used:

- **PMV/PPD (Fanger, ISO 7730 and ASHRAE 55)** for air-conditioned spaces. PMV is a seven-point vote from −3 (cold) to +3 (hot), and PPD is the predicted percentage of dissatisfied people, which never falls below about 5 %. A common target is $|PMV| \leq 0.5$ (PPD ≈ 10 %).
- **Adaptive models (ASHRAE 55, EN 16798-1)** for naturally ventilated buildings. The comfortable operative temperature moves with the running mean outdoor temperature, because occupants adapt through clothing, behaviour and expectation.

Air movement is the link between aerodynamics and comfort. Moving air increases convective and evaporative heat loss from the skin. Elevated air speeds of roughly 0.5 – 1.0 m/s can offset about 1 – 3 °C of operative temperature in warm conditions, which is the physical basis of comfort ventilation and of ceiling fans. Standards limit the benefit, and above about 1 m/s in offices papers start to move and occupants complain.

Outside, the wind also governs convective heat exchange with facades. A common correlation for surface convective coefficient is $h_c \approx 5.8 + 3.9\ v$ (W/m²K) for v below about 5 m/s, so wind strongly increases the heat loss of an exposed wall in winter and its night cooling in summer. In cold climates the same speed produces the wind-chill effect on pedestrians, and indices such as UTCI combine wind, temperature, humidity and radiation for outdoor comfort.

3. Bioclimatic Design Strategies

Bioclimatic design uses the local climate (sun, wind, humidity, temperature swing) to reach comfort with minimal energy. Aerodynamics enters at three scales: the urban and site scale, the building scale and the component scale.

3.1 Site and urban scale

- **Read the wind data**: use a wind rose (direction and speed frequency) for the season when ventilation is needed and the season when protection is needed. Use hourly data, not just annual means.
- **Orientation**: align the long facade and the main openings to catch the summer breeze at about 20 – 45° of incidence (cross ventilation tolerates oblique wind) while keeping solar protection on east and west faces.
- **Spacing and layout**: staggered rows let wind reach downwind buildings, while parallel rows separated by less than about 6 – 8 building heights leave the second row in a stagnant wake.
- **Windbreaks and shelterbelts**: porous barriers with a porosity near 30 – 50 % shelter the lee for about 10 – 20 barrier heights, while solid barriers produce a short, intense sheltered zone followed by strong turbulence.
- **Vegetation and water** reduce air temperature by evapotranspiration and add shade, which improves outdoor comfort.

3.2 Building scale

- **Compact form** in cold climates (small surface-to-volume ratio) and **elongated, narrow plans** in warm climates (more facade area for cross ventilation, with depth below about 5 times the floor height).
- **Courtyards and atria** work as thermal and ventilation regulators, drawing air by stack effect and giving shade.
- **Corner treatment**: chamfered, rounded or recessed corners, podiums and canopies reduce downwash and corner acceleration at pedestrian level, and cut local suction on the cladding.
- **Tall buildings**: tapering, twisting, setbacks or through-openings disrupt vortex shedding and reduce across-wind response.
- **Raised buildings (pilotis)** allow ventilation under the building, but concentrate acceleration and need wind comfort checks.

- **Envelope**: thermal mass with night ventilation, reflective roofs and shaded openings reduce the cooling load that ventilation must remove.

3.3 Passive components that use aerodynamics

Component	Principle	Best climate
Wind catcher / wind tower (malqaf, badgir)	Opening faces the wind (positive pressure), air goes down the shaft; exhaust on the leeward side. Can be combined with water evaporation or earth cooling.	Hot-arid
Solar chimney	Sun heats an exhaust shaft, increasing buoyancy and extraction even when there is no wind.	Hot, sunny; useful in calm periods
Earth-air tunnel	Air passes through buried pipes and is cooled in summer or pre-heated in winter.	Hot-arid, continental
Cross ventilation openings	Openings on opposite or adjacent faces use the C_p difference to drive flow.	Hot-humid, temperate summers
Night purge ventilation	Cool night air is flushed through exposed thermal mass.	Large day-night swing (arid, semi-arid)

3.4 Choosing strategies by climate

Climate	Wind objective	Typical measures
Hot-arid	Moderate use; avoid hot, dusty wind in the day.	Compact fabric, courtyards, narrow shaded streets, wind towers, night ventilation, high thermal mass.
Hot-humid	Maximise air movement.	Open plans, elongated form, large shaded openings, raised floor, high ceilings.
Temperate /	Seasonal control.	Operable openings, cross ventilation

Climate	Wind objective	Typical measures
Mediterranean		in summer, windbreaks against winter wind, night cooling.
Cold	Minimise wind exposure and infiltration.	Compact form, airtight envelope, windbreaks on the prevailing winter side, sheltered entrances.

4. Impact on Natural Ventilation

4.1 Driving forces

Natural ventilation is driven by two pressure differences:

Wind-driven: the difference of C_p between openings. For two openings in a space, the airflow rate is:

$$Q_w = C_d \cdot A_{eff} \cdot U_{ref} \cdot \sqrt{C_{p1} - C_{p2}}$$

Buoyancy-driven (stack effect): warm indoor air rises and leaves through upper openings while cooler air enters through lower ones. With a vertical distance h between openings and an indoor-outdoor temperature difference ΔT (absolute temperature T):

$$Q_s = C_d \cdot A_{eff} \cdot \sqrt{\frac{2gh\Delta T}{T}}$$

Here C_d ≈ 0.6 – 0.65 is the discharge coefficient of a sharp-edged opening. When wind and buoyancy act together, a common approximation adds the two pressures (or, as a simplified rule, combines the flows as Q ≈ √(Q_w² + Q_s²)). Wind can assist or oppose the stack effect depending on the opening layout.

For openings in series (air passes through both) and in parallel (air passes through either), the effective area is:

$$\frac{1}{A_{eff}^2} = \frac{1}{A_1^2} + \frac{1}{A_2^2}$$

4.2 Ventilation configurations

Configuration	Driving mechanism	Rule of thumb for effective depth

Configuration	Driving mechanism	Rule of thumb for effective depth
Single-sided, one opening	Turbulent fluctuations and pulsating flow; weak.	Up to about 2 times the floor-to-ceiling height.
Single-sided, two openings at different heights	Stack effect plus wind.	Up to about 2.5 times the floor-to-ceiling height.
Cross ventilation	C_p difference between facades; strongest.	Up to about 5 times the floor-to-ceiling height.
Stack / chimney / atrium	Buoyancy; independent of wind.	Depends on shaft height and temperature difference.

4.3 How building aerodynamics changes ventilation

- **Neighbouring buildings** change the C_p values, and a sheltered building may lose most of its wind-driven flow. The C_p must be taken for the actual surroundings and not for an isolated building.
- **Wind direction** matters: a ΔC_p that is large for normal wind can drop to almost zero, or reverse sign, for oblique wind.
- **Local wind speed**, not the weather station value, must be used. It is reduced by the boundary layer profile and by sheltering.
- **Turbulence** causes fluctuating flow, which may add substantially to single-sided ventilation.
- **Constraints** include noise, air pollution, security, rain ingress, insects and excessive speed, which may require louvres, transfer ducts or hybrid (mixed-mode) systems.