Fundamental studies of wind flow near buildings

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Introduction

The wind flow around a building affects people in or near the building in the following ways, some of which are facetiously illustrated in *Figure 1.*

Comfort of Pedestrians

High winds and gusty winds are regarded as unpleasant by most people, and sufficiently high winds have blown pedestrians over. Since buildings produce the largest relative increases or decreases in wind speed at ground level, pedestrians feel the full extent of these changes in wind speed. For this reason, the effect of buildings on the comfort of people near the building can range from dangerous, when people can even be knocked over and fatally injured (Penwarden, 1973) and inconvenient, when clothes are blown about and eyes irritated (Hunt & Poulton, 1972), to beneficial, when people are sheltered from the approaching wind (Jensen 1954). A difficulty for the designer when he is concerned with pedestrian comfort in windy conditions is that there is no systematic data on people's response to the wind. Nevertheless, casual observations have led to some criteria being proposed. A wind of 5m/sec is considered to be annoying, and 10m/sec to be disagreeable (Penwarden, 1973). Lawson (1973) suggests that a site should be regarded as intolerable if 10m/sec. is exceeded more than about 2% of the time. This uncertainty will partly be resolved by the results of experiments sponsored by the Building Research Establishment (B R E, 1974) which I am undertaking with Dr. E. C. Poulton of the Medical Research Council with about 500 subjects in a large wind tunnel at the National Physical Laboratory.

It is worth noting that in other countries criteria may be quite different. In Southern Russia high winds near buildings are regarded as pleasantly cooling, and in the north they usefully blow away the snow. It has been proposed that in Australia winds are acceptable if they only blow people over (about 20m/sec is required) once a year! (Melbourne and Joubert, 1971).

Dispersion of Smoke and Fumes

Most buildings produce their own pollution in the form of exhausts from heating and ventilation plants, kitchen, and incinerators. They also experience air

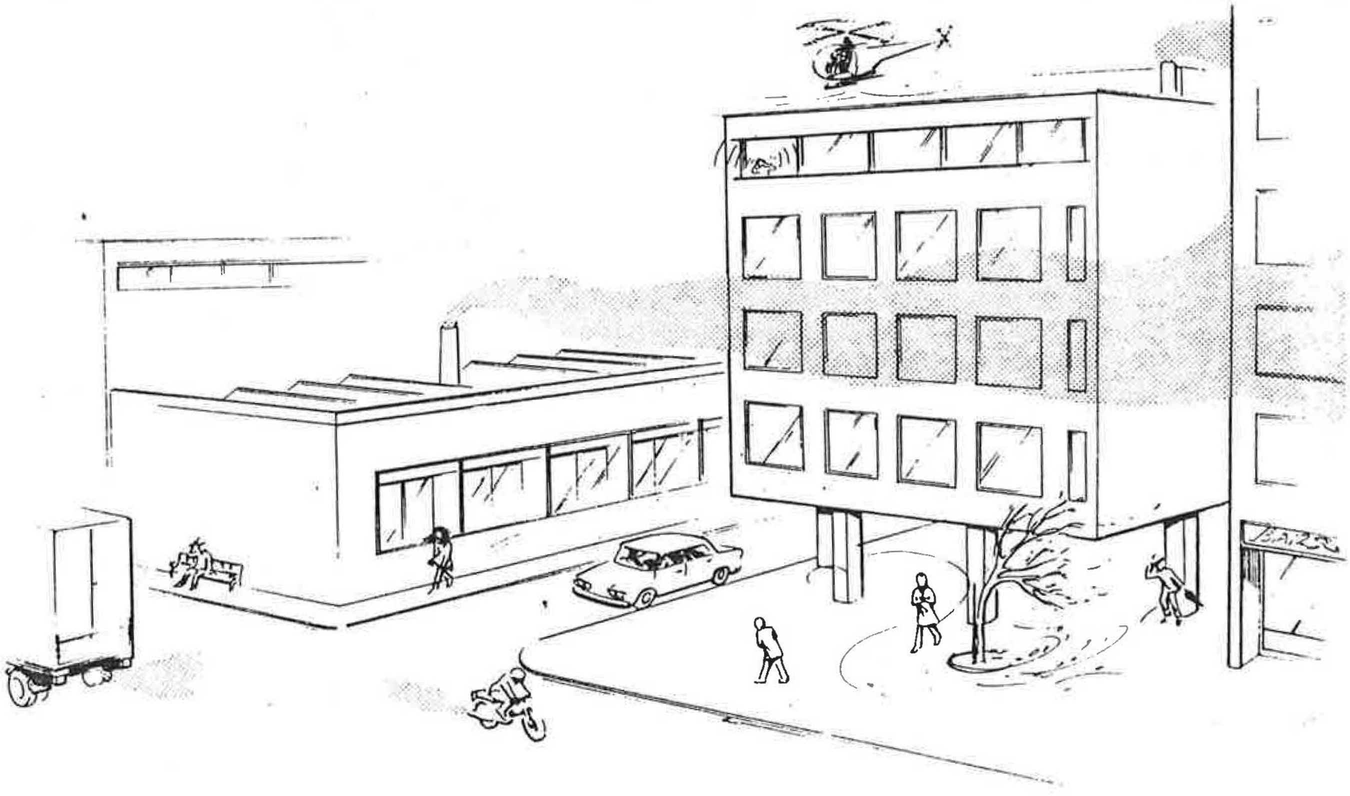


Figure 1. The wind environment problem.

pollution which is created elsewhere, e.g. by traffic. The wind around the building can help or hinder the dispersion of these airborne pollutants and therefore is crucially important in determining the concentrations of air pollution experienced by people in or near the buildings (Halitsky, 1968). Adequate dispersion of smoke is also vitally important for reducing fire risks. In general, high winds at ground level help the dispersion of air pollution produced by vehicles, so that, if vehicles and pedestrians have to use the same thoroughfare, the need to reduce air pollution and the need to improve pedestrian comfort can conflict.

Wind-created Noise

Certain types of building, for example the library at the University of Warwick, enable the wind to produce an unacceptably loud noise inside the building.

Landing of Aircraft and Helicopters

In the lee of a building the wind speed is reduced and the gustiness increased. This makes the landing of aircraft and helicopters near buildings difficult and dangerous, which is why pilots and civil aviation authorities are becoming concerned about buildings around airports. *(Nancoo, 1974).*

Note that the pressure on the building is related to the wind flow round it, and the distribution of pressure on the building determines its overall structural load and the load on individual cladding elements, and affects the performance of heating and ventilating systems. The wind flow near a building affects the surface movement of rain, which in turn affects the penetration of rain into the building and the discolouring of the building's exterior surfaces. These problems are outside the scope of this paper.

The importance of these effects of the wind round a building shows that the way in which the shape and size of a building or group of buildings forces the wind to flow round it or through it is as much a part of the functioning of the building as its heating, ventilating or lighting. Consequently, it may be as important for the architect and planner to be able to predict the wind flow near buildings, as to predict any other aspect of its performance.

The Study of Architectural Aerodynamics

Architectural aerodynamics is the study of wind flow around and wind loads on buildings with the object of understanding and eventually predicting these flows. With regard to the wind flow, the first practical object of this study, both theoretically and experimentally, should be to develop simple models of the flow round a single building and groups of buildings which will enable the architect to estimate the wind condition around his proposed building. It is essential that these models be intelligible and that the predictions of the model be easy to apply. This requires presenting the models by means of diagrams of the flow streamlines and physical concepts such as pressure, and presenting the predictions in brief tables or simple mathematical formulae which can be evaluated by slide rule or desk calculator. Only if such models are developed are wind conditions likely always to be incorporated at an early stage by all architects.

At present, guide-lines do exist (Lawson, 1968, and BRE 1973) which, although incomplete, should, if followed, eliminate some of the designs which produce poor wind conditions. Examples of buildings which have been erected in the last 10 years which produce unpleasant ground level wind conditions have been described in a Building Research Station Digest (1972). In some cases architects have been careful to investigate by means of wind tunnel tests the wind conditions in a number of possible designs before deciding which to choose (White, 1968; Taylor, 1971).

However, such experimental investigations are costly and, if they became widespread, or worse still mandatory, there would soon be an acute shortage of wind tunnels and aerodynamicists. For this reason what is needed are simple prediction methods and 'alarm signals' to tell the architect when he should seek aerodynamic advice.

The second practical objective of architectural aerodynamics is to enable the architect to obtain detailed and sufficiently accurate predictions about any proposed design. This may be necessary for the final detailed design, especially for tall buildings; for example, the best kind of door opening is determined by local pressures, or the position of heating plant exhausts can best be chosen when the wind flow is known. This may in future be possible with the use of computers alone. But the results of attempts that have been made so far in the USA by Djuric & Thomas (1971) and Hirt & Cook (1972) using the largest available computers to compute flow round tall rectangular buildings are not at all representative of actual wind conditions. For some years to come the second stage in the analysis of wind conditions, if it is necessary, must be experimental using wind tunnel tests.

As well as describing the aims of the study of architectural aerodynamics, a brief description of the *methods* is also appropriate. The basis of the theoretical approach is the dynamical equations of fluid motion. Because these consist of three non-linear partial differential equations of second order, a type of equation to which there are no general solutions, these equations can only be solved analytically for a few idealised situations. In principle, there is no reason why computers should not solve these equations. But at the moment there are no computers large enough to use these equations to solve a problem of any practical relevance. In fact, no direct computer solution has even been developed for any turbulent flow, such as the natural wind. Consequently, in turbulent flows simplifying assumptions have to be made. Then some useful progress is possible, which will be described in the next section.

To obtain detailed information even about a uniform steady flow round a building, or indeed round an ideal shape such as a circular cylinder, then experiments are needed which are usually performed in wind tunnels. To simulate in a wind tunnel the natural wind flowing round a building, the approaching wind also has to be simulated correctly, i.e. both the increase of the wind speed with height and the turbulence must be modelled correctly. *(A recent meeting was held to discuss the available techniques and the limitations of wind tunnel simulations (Fernholz and Hunt, 1975)).* Two simulation methods in use in the UK are those developed by Counihan (1969) and Cook (1973). There is a problem in deciding in how much detail the wind need be simulated when so little is known about the sensitivity of people to wind conditions. To help in understanding the complex flows round buildings, research experiments have been and are being undertaken, variously in steady uniform flows, uniform flows with turbulence added, and shear flow with small amounts of turbulence. In conjunction with theory, such basic experiments have enabled conceptual models to be developed for flows round basic building shapes.

Some Results of Fundamental Studies

Application

When a specialist in building aerodynamics attempts to predict the wind conditions near a building or a group of buildings, he usually compares the building or the group to some simple building shape or group of buildings the flow round which has been studied before. Taking into account the differences between these paradigm flows and the actual flow, an approximate prediction can be made. As already mentioned, it is to be hoped that this approach can eventually be systematised sufficiently to enable architects to use it.

In this section, we describe flows round a few of these simple building shapes or groups of building shapes for various conditions of the approaching flow. Where space does not permit a full description, references are given.

The Two-dimensional Cylinder

The best understood flow around an obstacle in the study of fluid mechanics is probably that around a cylinder in the shape of an aerofoil cross section, but this knowledge has little application to building aerodynamics. The next best understood external flows are the flows round cylinders with cross sectional shapes such as circles, rectangles or octagons. This is of some use because these flows are similar in many important respects to those round tall buildings. Such flows are best described by dividing them into two main regions shown diagrammatically in *Figure 2a.*

These regions are distinguished by the pattern of the 'mean stream-lines' of the flow, which at any point are parallel to the average velocity and which approximate to the average path of a particle, for example, the path of a piece of waste paper or airborne pollutant. In the external flow region (E), all these streamlines emanate from the flow upwind, and consequently the flow in this region is sensitive to conditions upwind, for example, to the level of the turbulence or the presence of sources of air pollution.

The flow downwind and close to the sides of the building is usually described as its wake (W). For about 10 to 13 widths downstream, the mean flow recirculates and the average streamlines form loops; this part of the wake is often called the 'bubble'. Down-wind of the 'bubble' the streamlines are all pointing forwards, but the wind speed remains markedly less than upwind. The crosswind variation in the wind speeds at various positions in front of and behind the building are shown in *Figure 2b.*

The most significant feature of the wake is that, whether or not the approaching flow is steady, the

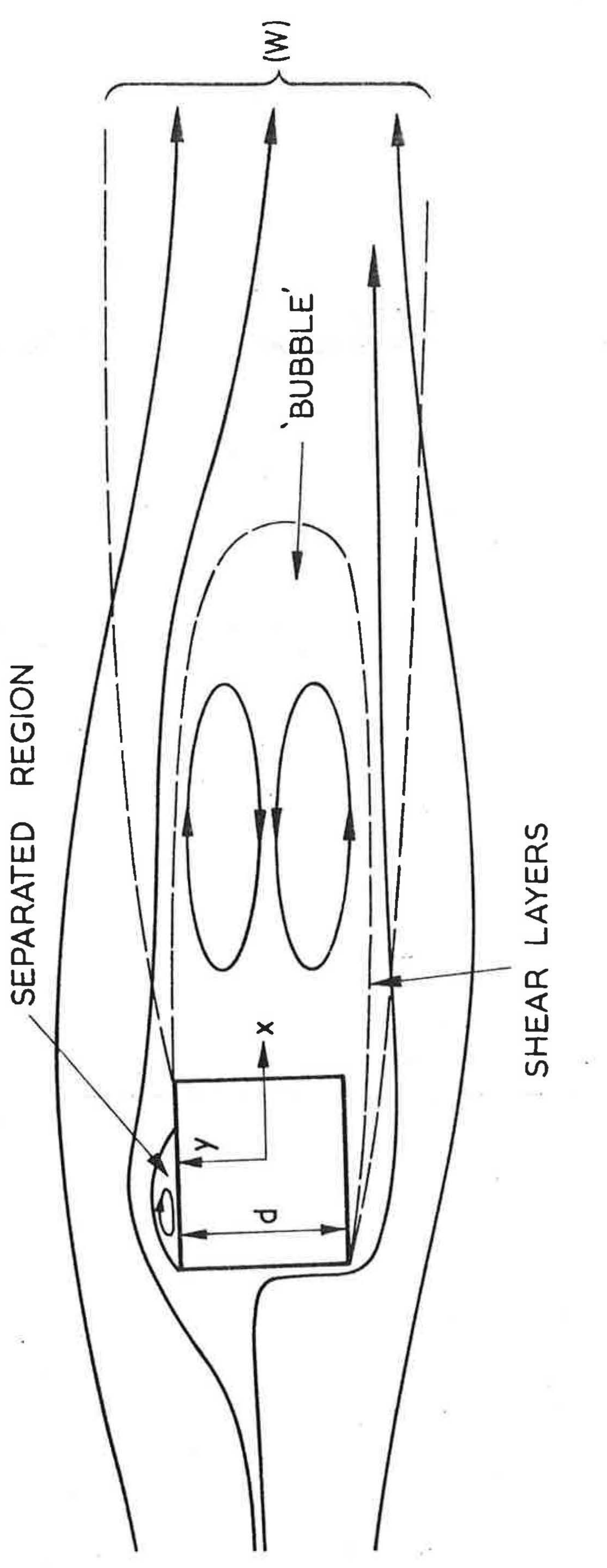


Figure 2(a). Flow round a two-dimensional rectangular cylinder. Pattern of mean streamlines and the postulated flow regions.

Flow in this region is very unsteady, with the unsteady component of the wind being of the same magnitude as the steady component. In the natural wind, even in a city, the unsteady component of the wind is less than 30% of the steady component. Thus the flow in the external region, except very close to the ground, is not as turbulent as in the wake.

In *Figure 3* a typical instantaneous picture of streamlines is sketched. This shows how the edge of the wake region has an irregular shape and that the flows in regions (E) and (W) are more inter-connected than appears from the average picture shown in *Figure 2(a)*.

Having divided the flow into these regions, it becomes possible to devise theories to describe the flow. In the external flow, assuming the upstream flow is uniform, the mean velocities in the x and y directions u, v are given by the solution to Laplace's equation

$$\nabla^2 \ \phi = 0$$

The solution to this equation can often be found analytically, but otherwise it can be computed straightforwardly. The solution is determined by the boundary conditions, which are that the velocity must be parallel to the surface of the body and the wake. Since the wake has such an irregular boundary, this condition is somewhat artificial, and a suitable hypothesis has to be made. Two well-known methods which compare well with experimental results for flow round circular and rectangular cylinders are those of Parkinson and Jandali (1970) and Roshko (1954), the more recent method being simpler to apply. These calçulations enable the distribution of average velocity around the cylinder and the average surface pressure to be predicted; they are not applicable to flow round three-dimensional obstacles in a shearflow.

In the highly unsteady wake region close to the body, any realistic calculation of velocity must begin by predicting the unsteady flow, especially the vortices shed from the sides of the cylinder, which were shown diagrammatically in *Figure 3.* Complete numerical solutions of two-dimensional flow round cylindrical bodies, including all the effects of viscosity close to the surface have been obtained by Harlow & Fromm (1963) and other workers. However, such calculations require enormous computing time because the minute details of the flow close to the surface cannot be

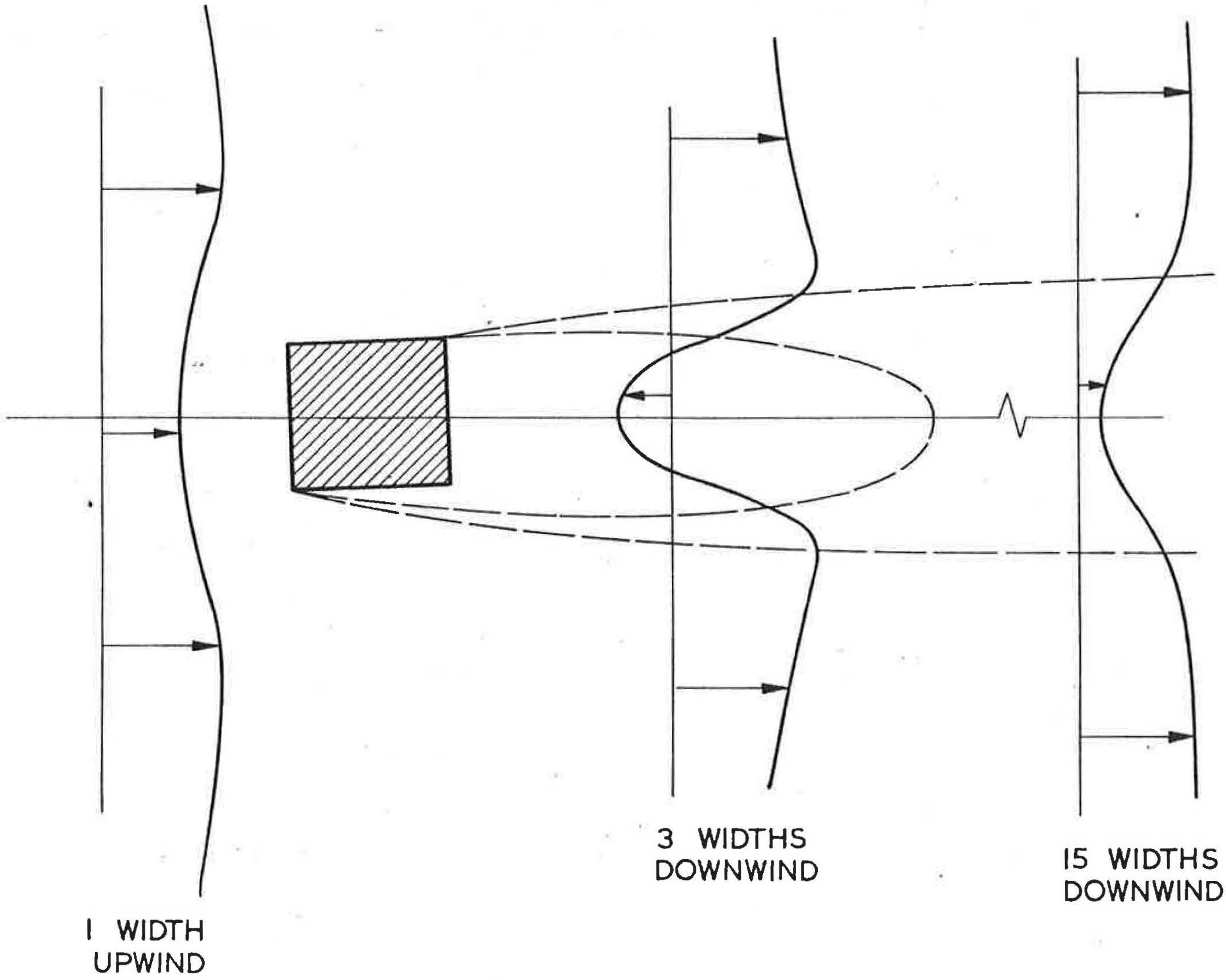


Figure 2(b). Flow round a two-dimensional rectangular cylinder. Variation with y of the x - component of mean velocity at various downstream positions.

neglected. But simpler calculations based on assumptions about the generation of vortices at the surface of the body also seem to predict these wake flows adequately. A recent model is that of Clements (1973), but even this probably needs more computer time than might ever be possible for a design calculation. It also probably produces too much information. Usually all that is needed is to know the frequency of vortices (n) and the average value($\bar{u}$) and fluctuations in velocity u', which can most simply be obtained experimentally. Typically, for a rectangular cylinder with thickness d, in a windspeed $\bar{u}_\infty$, $nd/\bar{u}_\infty \simeq 0.1$ and on the centre line at a point 4 diameters downstream $\bar{u} \simeq 0.5\,\bar{u}_\infty$, $u' \simeq 0.3\,\bar{u}_\infty$ so that fluctuating velocity is of the same order as the mean velocity.

Further downstream, beyond the 'bubble', the average velocity is positive, but the turbulence remains high for over thirty diameters downstream.

Now consider the case of a cylinder placed in a flow which is turbulent but which everywhere upstream has the same *average* velocity. This is a useful idealisation of a tall building in the wind, and it accurately describes the situation of a cylinder placed in a wind tunnel with a grid of bars fixed at the entrance of the tunnel. The changes in the turbulence in the flow round the cylinder can be described theoretically (Hunt, 1973). Two effects occur. Firstly, the obstacle blocks the turbulence, i.e. the eddies must pass round the body. Secondly, the eddies are stretched and distorted by the mean flow, so that their velocities are changed. As an example consider the turbulent velocities on the centre line of a square cylinder. The former effect tends to reduce the turbulent velocities in the flow direction u_x' and amplify those in the perpendicular direction u_y', while the latter effect amplifies u_x' and reduces u_y'. Which effect dominates depends on the relative scale of the building to the

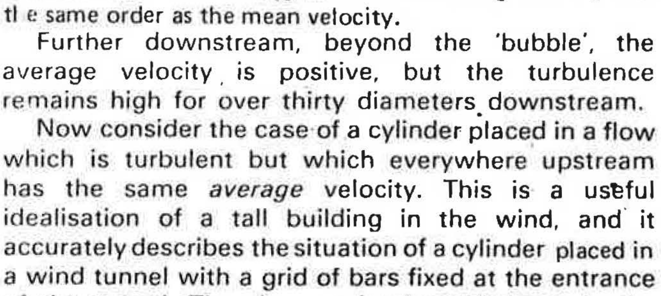


Figure 3. Instantaneous pattern of streamlines showing the formation of vortices.

turbulence—the larger the building the larger the latter effect. Confirmation of these theoretical predictions is provided by the experimental measurements taken on the centre line of a square cylinder in a wind tunnel placed with its front face perpendicular y and at 45 degrees to the wind. See *Figure 4(a), (b).*

In the case of a tall building these results are useful for calculating the dispersion of air pollution, for calculating fluctuating pressures on the building, and indirectly for calculating the turbulence near the ground.

Groups of Two-dimensional Cylinders

Tall slender buildings are sometimes placed close together, for example the World Trade Centre in New York, or power station cooling towers. When the direction of the wind is such that the buildings are not in each other's wake, then similar methods as for a single cylinder, based on potential flow theory, can be used to predict the increase in wind speed between the cylinders. A typical value to be expected between two cylinders is about $2.0\,u_\infty$ as compared with $1.4\,u_\infty$ at the sides of a two-dimensional cylinder. A simple but effective mathematical model of the flow between a bank of cooling towers was developed by Owen, 1967, which showed that the resistance of the whole group of cooling towers slowed down the flow by almost as much as the velocity between them was increased. When cylinders lie in each other's wake, the turbulence behind those up-wind can be amplified and diffused by those downwind. This is a similar situation to that between the tubes of a heat exchanger (Owen, 1965).

Roof Vortices

When the wind flows over pitched or flat roofs, strong vortices often occur. The vortices on the top of a cube-shaped building are shown in *Figure 5 (c)*, which is taken from a review by Ackeret (1965).

Figures 5(a), 5 (b), also from that review, show the pressure distributions over a cube and a delta-shaped aircraft wing, which suggests that flow over a delta wing is a useful model for the more complex flows that occur over flat roofs.

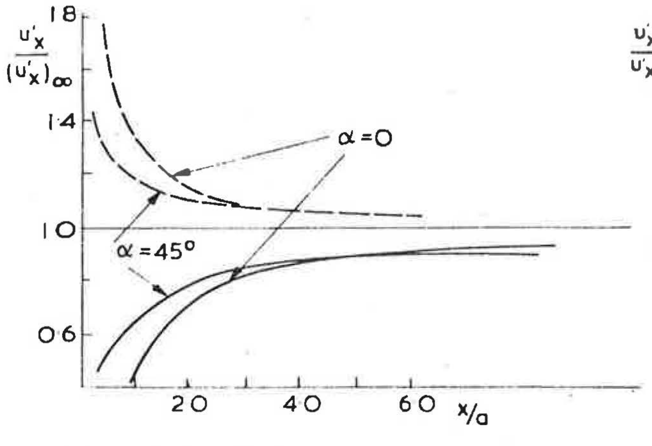
The practical importance of developing a model for such flows is that this may enable us to predict the high suction forces that occur on roofs and also to show how the roof vortices will disperse the exhaust from any proposed chimney on the roof. (See Halitsky, 1968). Lawson (1968) describes the roof vortices which occur on roofs with more irregular shapes than on pitched roofs.

Cylinder in a Shear Flow on a Plane

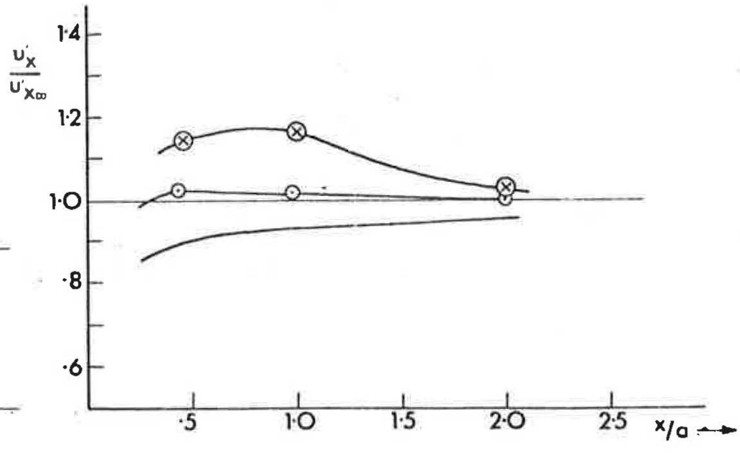
One difference has already been mentioned between a uniform steady flow and the natural wind, namely, the latter's turbulence. The other two main differences are that the velocity of the wind varies with height (the wind shear), and that the atmosphere is bounded by the ground. The effect of these differences is felt by every pedestrian approaching a tall building, namely, a reversal and an increase of the ground level wind speed on the upwind side, violent fluctuations in wind speed on the downstream side, and high winds near the sides, as shown in *Figure 6*.

A measure of this increase in average wind speed at a height a from the ground is the amplification ratio introduced by Wise (1971). $R = \bar{u}(a)/\bar{u}_\infty(a)$, where $\bar{u}_\infty(a)$ is the wind speed upwind at the same height a. A simple but incomplete estimate of these amplification effects can be given in terms of the wind speed $\bar{u}_\infty(h)$ approaching the top of the building, height h. This wind produces a pressure $p_s(h)$ on the upwind face of $p_s(h) \simeq \frac{1}{2}\rho\,\bar{u}_\infty^2(h)$ where ρ is the density of air. For a tall building ($h>3b$), the pressure at the bottom is not zero but may be a half or a quarter of $p_s(h)$. Therefore, there must be a flow down the face of the building, w, which can be no greater than $\sqrt{2p_s/\rho} \simeq \bar{u}_\infty(h)$ This should be an upper limit for the downflow velocity. On low buildings ($h<b$) the pressure over the front face is nearly the same at all heights, and the down flow velocities are small compared with $\bar{u}_\infty(h)$.

Figure 4. The change along the centre line in the root mean square of the x — component of turbulent wind, u_x', upwind of a square cylinder placed in a turbulent wind. Upwind u_x' is equal to $u_{x\infty}'$. Results are given when the upwind face is perpendicular to the flow (α = 0) and is at 45 degrees (α = 45). Also shown are the effects of a change in the ratio, a/L_x, of the size of the body to the scale of the turbulence.



(a) Theoretical predictions when a/L_x is zero and infinitely large.



(b) Experimental results:
— a/L_x = 0.19 Bearman's experiments
⊗ a/L_x = 1.25 Cambridge experiments
} α = 0
⊙ a/L_x = 1.8 Cambridge experiment — α = 45°
(taken from Hunt, 1972).

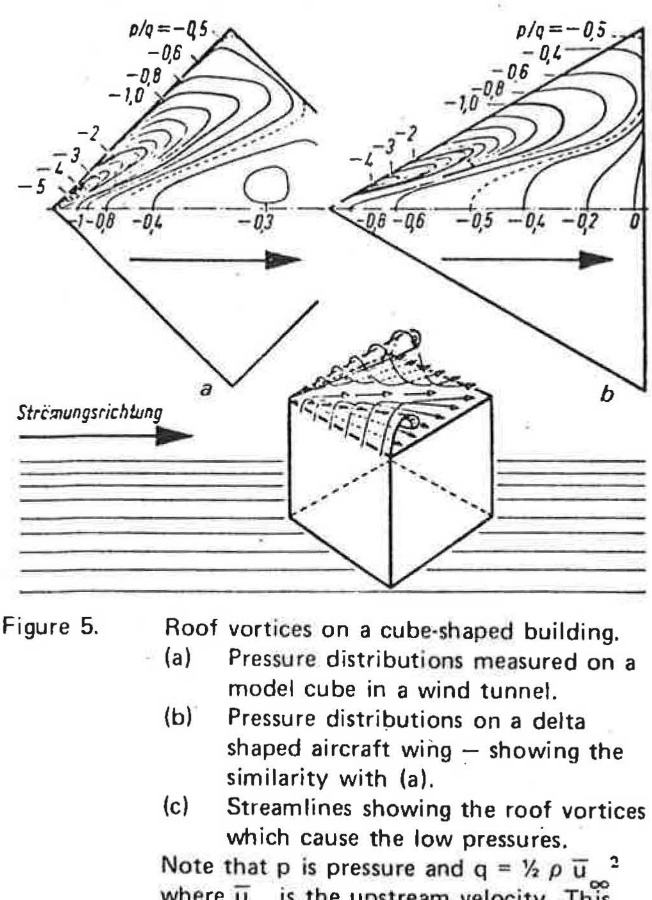


Figure 5. Roof vortices on a cube-shaped building.
(a) Pressure distributions measured on a model cube in a wind tunnel.
(b) Pressure distributions on a delta shaped aircraft wing — showing the similarity with (a).
(c) Streamlines showing the roof vortices which cause the low pressures.

Note that p is pressure and $q = \frac{1}{2}\rho \bar{u}_\infty^2$ where $\bar{u}_\infty$ is the upstream velocity. This diagram is taken from the review by Ackeret (1965).

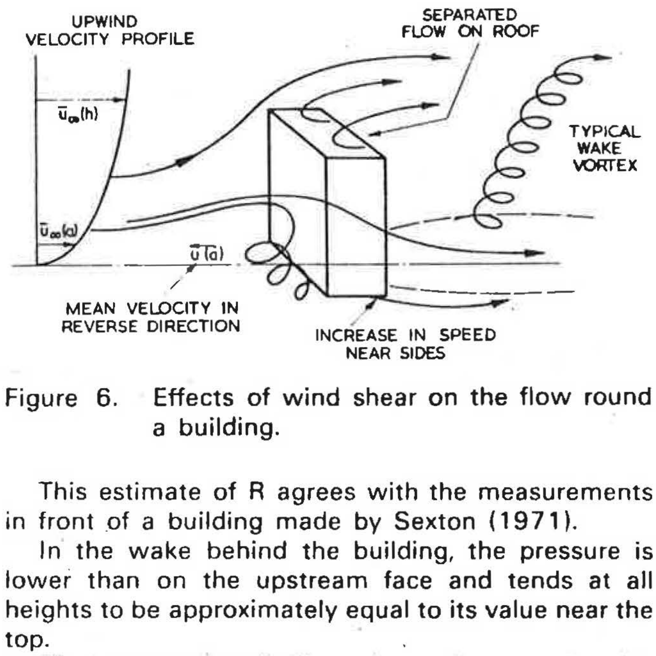


Figure 6. Effects of wind shear on the flow round a building.

See, for example, the experiments of Good & Joubert (1968). When the down flow reaches the ground, then it tends to produce a forward flow which, at a height a, we can estimate from the pressure on the building at the ground $p_s(0)$ to be less than $(\bar{u}_\infty^2(h) - \bar{u}_\infty^2(a))^{1/2}$

Thus, we can crudely estimate the amplification ratio R to be less than $(\bar{u}_\infty^2(h) / \bar{u}_\infty^2(a) - 1)^{1/2}$

This estimate of R agrees with the measurements in front of a building made by Sexton (1971).

In the wake behind the building, the pressure is lower than on the upstream face and tends at all heights to be approximately equal to its value near the top.

Thus, the pressure in the wake on the ground $p_w(0) \simeq \frac{1}{2}C_{pb}u^2(h)$, where C_{pb} is the base pressure coefficient for the relevant cylinder shape. These values of $p_w(0)$ and $p_s(0)$ result in a flow round the base of the cylinder approximately equal to that near the top. This, of course, is *greater* than the velocity near the ground upstream, and at the sides. An upper limit for R is $\bar{u}_\infty(h) / \bar{u}_\infty(a)$.

The effect of wind shear on the unsteady flow in the wake behind cylinders is not understood (Maull & Young, 1972), but experiments do show that vortex shedding is changed, not eliminated. Physical reasoning also shows why vortices in the shear flow

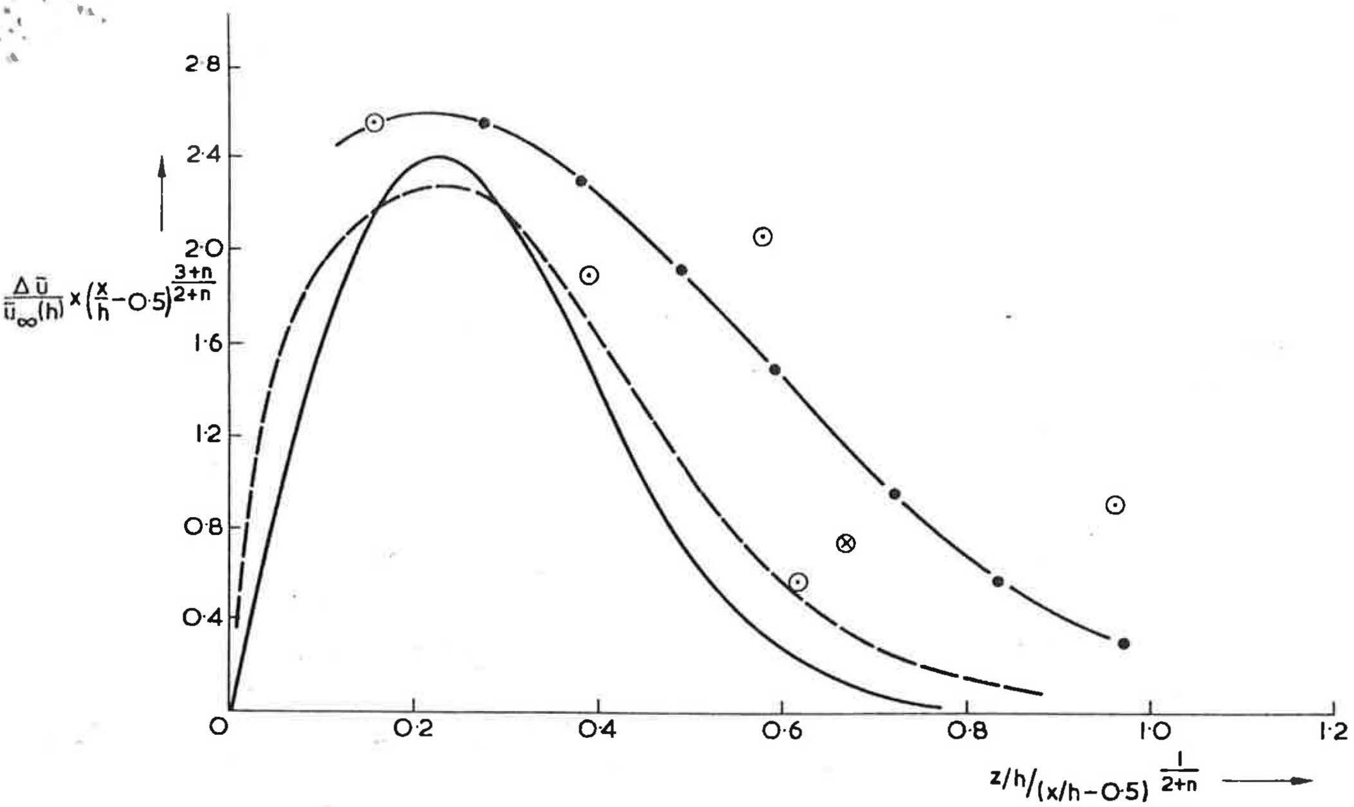


Figure 7. The reduction in velocity $\Delta\bar{u}$ downwind of a cube-shaped building as a function of the distance downwind x, the distance from the ground y, the height of the building h, and n the exponent of the wind's velocity profile ($n \simeq 0.15$ in the country). The theoretical line — is compared with wind tunnel experiments of Counihan — — — and with full scale measurements behind a hangar by Colmer:
x x/h = 2.4 — · — · — best curve through experimental points. (taken from Hunt, 1972).

should produce swirling upward flows, which are often found in the lee of tall buildings.

Flows Round Low Buildings

The wind near low buildings was first studied in Denmark by Jensen with a view to studying how buildings could most effectively provide shelter from the biting winds of Jutland. In general, low buildings do provide shelter from the wind, unlike most tall buildings.

But how low is low? Flow in the lee is always sheltered on average even if more turbulence is created. The flow at the sides always show some increase, i.e. R>1. The big difference between low and high buildings is in the upwind flow. If $R \lesssim [\bar{u}^2_\infty (h) / \bar{u}^2_\infty (a) - 1]^{1/2}$ then taking $a \simeq 2$m and a typical wind profile, we find R<1 if h<8m. Thus, a building below about 8m. should always provide shelter upwind, but above this height some amplification may be expected. A simple theory has been developed to estimate the shelter, or the reduction in velocity Δu (z), at a height z behind buildings with approximately square shape (Hunt, 1971, 1972, Counihan, Hunt and Jackson, 1974). The theory indicates that Δu decreases in proportion to the distance downwind x as $(x/h)^{-3/2}$, as compared with $(x/h)^{-1}$ for a long low building. In practical terms, this means that the shelter lasts for about 10-13 building heights downwind, whereas for a long, low building it can be felt 20 building heights downwind. Results of the theory are compared in *Figure 7* with wind tunnel and full-scale measurements. There are many applications of such simple formulae in the planning of playgrounds, parks and other sheltered areas, and in assessing the effect of one building or row of buildings on another downwind.

Groups of Buildings of Different Sizes

A common situation in shopping centres, groups of office blocks, or city streets is where a building (A) is upwind of another much taller building (B). (See *Figure 8).*

Two main effects occur. Since the wind speed increases with height, for the reasons explained earlier, there is a flow down the upwind face of (B) in the same way as if the upwind building were not present. This downflow again leads to an upwind flow near the ground. If (A) is close enough, it inhibits the back flow. The second effect is caused by the wake flow of (A) impinging on (B), and producing a high stagnation pressure on (B) above the wake boundary and a low pressure below. This difference in pressure produces a strong downflow on (B) and a reverse flow at the ground. This is the familiar vortex photographed in wind tunnel models at the Building Research Station (Wise, 1971). If the buildings are too close, or too far away, this effect is weak.

Two tall buildings placed close together can also induce high wind speeds at ground level. At La Défense outside Paris, where two blocks 80m. tall are only 8m. apart at one corner, wind measurements have given a value of R=3. This

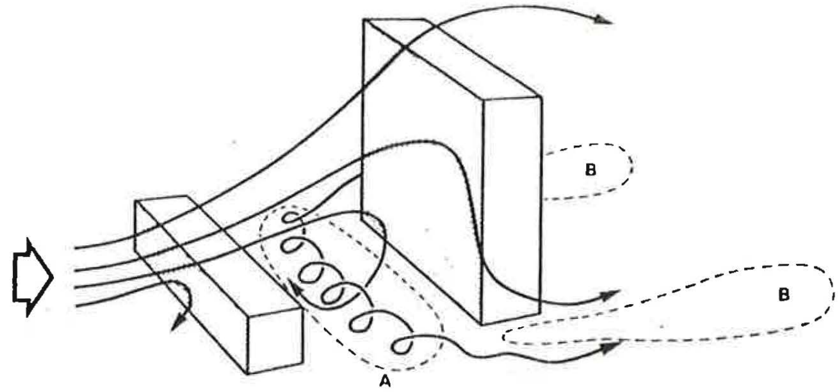


Figure 8. Flow around two buildings of different sizes (taken from B.R.E. Digest 141, 1972)

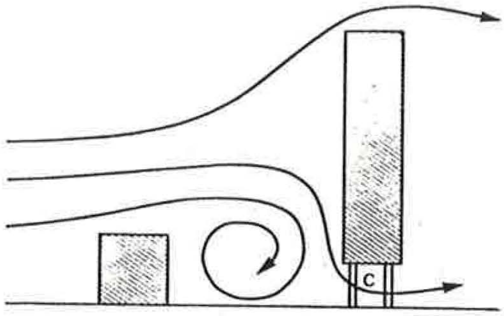


Figure 9. Flow under a tall building on Pilotis (taken from B.R.E. Digest 141, 1972)

is greater than an estimate for R based on the formula $\overline{u}_\infty$ (h) / $\overline{u}_\infty$ (a) which is 2.8. Thus in quite exceptional circumstances our upper limit may be exceeded.

Tall Buildings on Pilotis

This architectural device of placing a tall building on pilotis, shown in *Figure 9*, or of having an open passage way underneath the building often produces an excellent but unwanted wind tunnel at ground level. A simple physical argument suggest that the wind underneath is only a little less than $\overline{u}_\infty$(h), the wind approaching the top of the building. Consequently, as an upper limit, $R \simeq \overline{u}_\infty (h) / \overline{u}_\infty (a) \simeq (h/a)^{0.28}$, if we take the usual formula for the increase with height of wind speed. Thence for a 75m building, taking a = 2.0m, the amplification ratio $R \simeq 2.7$. Halving the height of the building would still produce a value of R = 2.4. Values of R as high as these have been observed by the Building Research Station at a number of sites (B.R.S., 1972), all of which have had to have expensive modifications made to them after the buildings were completed. Ways in which these undesirable winds can be avoided are described in the B.R.S. Digest.

Conclusions

1. The role of computers in predicting the wind round buildings is likely to remain limited to research investigations for several years to come.
2. Fundamental theoretical and experimental studies are beginning to throw up simple descriptive and mathematical models of flows round buildings. These should enable designers to predict the general features of wind round a proposed building or group of buildings at an early stage in the design. Some examples of these models have been given in section three of this paper.
3. To obtain *detailed* information about any new design, wind tunnel studies are necessary. However while criteria for wind conditions which are acceptable to people remain so vague, wind tunnel tests do tend to produce more information than can be used by the architect. □

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