The Effect of Single Buildings and Structures

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The effect of single buildings and structures

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We begin by outlining the various physical effects involved in the flow of the wind round a building, considering first uniform flow round a bluff body and then the added effects of shear and turbulence in the incident flow. Despite the complexity of the flow, some useful theoretical calculations can be made; we mention, as examples, some new results for predicting the turbulence near the upwind face of a building, and others for predicting the velocity in the building's wake. We also point out other problems where a theoretical approach may give some insight into the flow and may, in addition, suggest further experiments. In the second half of the paper various experiments are surveyed, beginning with those on flow round models in wind tunnels. Basic experiments can elucidate the influence of shear and turbulence in the incident flow, and also the effect of shape and size of the building. In other experiments where the natural wind is simulated, the aim is to model the actual wind flows near buildings. Finally full-scale experiments are discussed, in which measurements are made of wind speeds near various buildings, and the experiment at R.A.E. Bedford will be described in detail.

1. Introduction

There are five main reasons why architects need to know about the effect of a building on the local wind.

(1) The first and most important one is that such knowledge enables an estimate to be made of how much people will be buffetted by the wind outside the building, on the ground or on aerial walkways round the building. The problem about investigating this aspect of wind flow is that we do not know what characteristics of the wind contribute most to personal discomfort, a subject touched on by Lawson in another paper of this meeting (p. 493).

(2) Because heating and ventilating systems require a flow of air through the building, the external wind can considerably affect the local velocities near the inlets and outlets of these systems and thus affect their performance.

(3) The wind flow round a building must be known if the dispersal of airborne effluent in its vicinity is to be evaluated, e.g. the dispersal of smoke and fumes from a building's central heating plant, or the concentrations produced by a source of pollution upwind—a problem of some importance in nuclear power stations where stand-by gas turbines are placed near other power station buildings.

(4) A problem not often considered is that of noise created in a building by the wind flowing around it, e.g. the edge-tones produced by the wind blowing round a new library building, in which I have worked, are extremely irritating. Many other examples can probably be found. By knowing more about the local wind, it may be possible to estimate the noise produced and, possibly, devise remedial action.

(5) The last reason is that, because aeroplanes and helicopters are very sensitive to cross winds and vertical gusts when landing, the wakes behind hangars at airports or the wind round tall buildings in cities near heliports or v.t.o.l. sites can present problems to aircraft in landing. It is because of this application that the R.A.E. has set up an experiment to measure wind flow behind a hangar at Bedford.

In this paper we shall not always mention these applications, but they have been borne in mind when describing the various effects of buildings upon the wind.

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2. SALIENT FEATURES OF FLOW ROUND A BUILDING

The reasons why the speed and direction of the wind around buildings is so difficult to measure, to understand or to calculate, are the same reasons why the flow is so different from that around aircraft: first, most buildings are blunt so that they create a turbulent wake as wide as the building, and secondly the wind incident on the building, unlike the flow relative to an aircraft, is sheared and turbulent. To understand these complicating aspects of the flow, we now discuss them separately. Much of this section is lifted from the excellent review by Lawson (1968).

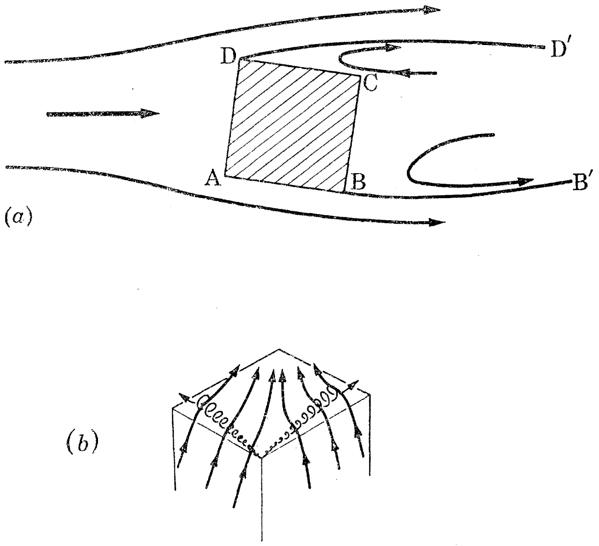

FIGURE 1. (*a*) Flow round a section of a tall rectangular building in a steady, uniform wind. (*b*) Vortices on the roof of a rectangular building.

Assuming the incident flow is uniform and steady, then figure 1*a* shows the stream lines around the section of a tall building. The region of the flow bound by B′BCDD′ is said to be separated and to form the wake. Here the steady component of the wind, or the average over, say, a quarter of an hour, is in some places in the opposite direction to the incident flow, so that if one was travelling with the wind one might be swept round a loop several times before being lost downwind.

Behind the body, even with a steady incident flow, both inside the wake and for a certain distance either side the wind is very turbulent, i.e. as well as a steady component there is a sizable fluctuating component, up to 40 % of the steady component. This fluctuating component is greatest on the boundaries of the wake, BB′ and DD′, which are usually referred to as the shear layers. Over the roof not only does the flow also separate but, as figure 1*b* shows, in separating from the front corner two strong vortices are created. Clearly any ventilation or heating systems placed near these would be seriously affected. These vortices, of course, are responsible for the high peak suctions near the edges of buildings, which are sometimes overlooked, with dismal results.

The effect of shear in the flow is difficult to disentangle from that of the ground, but it is an observed fact that upstream of an obstacle in a shear flow on the ground a vortex is found which creates a downwash on the front face of the obstacle, as shown in figure 2*a*. This can be explained as the ‘piling’ up of vortex lines swept in by the incident flow (see figure 2*b*). The advantage of this explanation is that it also explains the swirling flow to be found downwind on either side of the building. The effects of shear in the incident flow on the separation at the sides or on the top of the building are still not known, and the effect on the roof vortices is equally uncertain, but it is being investigated in some experiments we shall describe later.

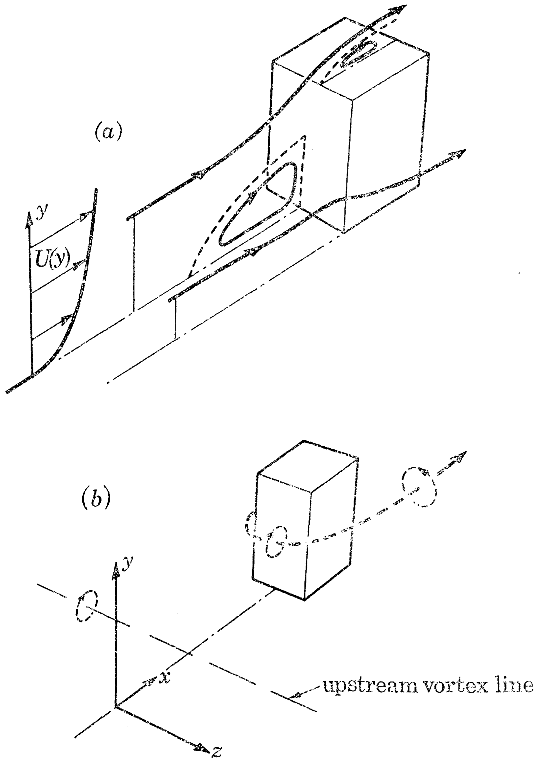

FIGURE 2. The effects of shear in the incident wind on the flow round a building. (*a*) Stream lines. (*b*) Vortex lines.

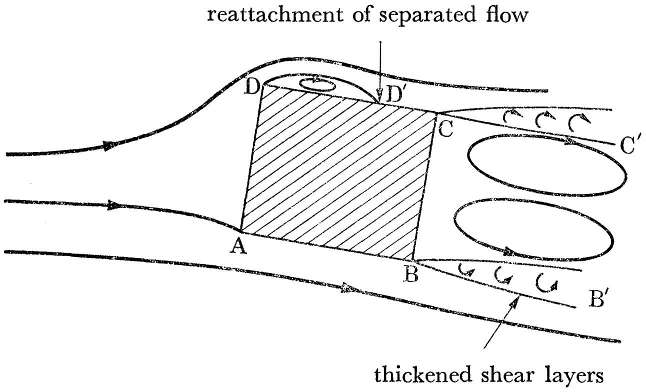

FIGURE 3. Flow round a rectangular building in a turbulent wind.

The addition of turbulence to the incident flow affects both the steady and the fluctuating velocity near the building. There are two basic effects of the turbulence on the steady flow. The first is to force the wake to start nearer the rear of the building. For example, in the case of a rectangular building at an angle to the incident wind, separation occurs at point D whether the flow is smooth or turbulent, but if the flow is turbulent the separated flow can re-attach at D′

(see figure 3); then a second separation occurs at C, so that the boundaries of the wake are B′BCC′ (Vickery 1966). The second effect is to thicken the shear layers which bound the wake region. Since the natural wind is always turbulent, it is probably true to say that, unless the width of the building in the wind direction is small compared with that in the other direction, the flow round a rectangular building is more like that shown in figure 3 than in figure 1*a*. Clearly the fluctuating flow near the building is greatly affected if the incident wind is turbulent, but the way in which the turbulence induced by the building in a smooth flow interacts with that swept on to the building by the wind is not understood yet, though some of the current research to be described is throwing some light on this problem.

3. Application of aerodynamic theory

The first part of this section is primarily addressed to aerodynamicists in the hope of interesting them in developing, or applying, aerodynamic theory so as to understand and then calculate wind flow near buildings. In the second part we describe some recent work which demonstrates the feasibility of theoretically calculating some aspects of such flows, and which produces results of some practical interest.

Starting with uniform flows over simple building shapes, say cubes or rectangular blocks, it is an unfortunate fact that few of the experimental measurements of velocities (or pressure distributions) have been compared with any theoretical calculations, even of the simplest kind. As with the flow round circular cylinders, an improvement on the simple potential flow solution can be obtained by postulating a cavity behind the building in which the pressure is constant at an experimentally determined value (Birkhoff & Zarantello 1957). Then approximate values of velocity and pressure can be (and in some cases have been) calculated in the region upstream of the separation point. Such results may not be accurate enough to calculate the forces on the building, but probably can give sufficiently accurate values of the wind speed and direction around the building. Thus it behoves theoreticians to extend the theory and experimentalists to use what theory there is. Another problem which has been examined extensively, but in a different context, is that of analysing the strong vortices emanating from the corners of building roofs; it appears that the considerable body of knowledge about vortices on delta wings could possibly be applied to this important problem.

The pioneering theoretical work on the effects of shear on the flow round obstacles in a boundary layer was done by Squire & Hawthorne, whose theories can give some estimate of the trailing vortices in a building's wake. However, it is a paper by Lighthill (1956), obscurely entitled 'Drift', that may provide information of more use to architects. From his paper it is possible to estimate the downwash in front of a tall building, caused by the shear in the incident flow, and thence, with further development, it should be possible to work out how the flow on the ground is affected by the downwash.

We shall now describe two theoretical investigations recently carried out at C.E.R.L., in the first of which (Hunt 1971) the problem tackled is that of calculating the turbulence near the upwind face of a building when the incident flow is turbulent, when the effects of shear in the mean flow are ignored. The solution to this problem enables us to estimate the fluctuating wind near the base of tall buildings, data which architects need to know. By developing the theory originally used for calculating the effects of wind-tunnel contractions on the turbulence (Batchelor & Proudman 1954), and then applying it to the ideal situation of flow round a long, circular cylinder (not too bad an approximation to a chimney or a cooling tower), we have found to what extent the turbulence intensity near a tall building is dependent on the size of the building, and how the different components or turbulence are affected by the building. For example, if the *turbulent* components of the wind in the x, y and z directions (as defined in figure 2*b*) are u', v', w', then the theory indicates that the (r.m.s.) values of u', v', w' remain more or less constant near the front face of a tall building about 100 m wide (i.e equal to the average size of eddies in the atmosphere, L_x, technically known as the integral scale of the turbulence). But upwind of a thinner building, say a chimney, 20 m in diameter, u' decreases, w' increases and v' remains approximately the same. Experiments which are described later, performed by Petty at C.E.R.L. and Bearman at N.P.L., have confirmed the theoretical results in some detail. It is not possible to deduce theoretically the turbulent velocities near the sides of the building, where the self-induced turbulence is at its greatest. In this part of the flow the experiments of Cook at Bristol provide some valuable data.

In the second analysis, using various eddy-viscosity assumptions, we have calculated the steady and turbulent components of the velocity in a building's wake well downwind of it, a region of the flow which is practically important in pollution studies and aircraft landing problems. Although the effects of shear and turbulence have been included in the analysis, we have had to restrict the analysis to the wakes of buildings with two basic shapes; if the dimensions in the x, y, z directions (again with reference to figure 2*b*) are d, h, b either

$$h \simeq d \ll b \text{ (a long, low building)},$$

or

$$h \simeq b \simeq d \text{ (a cube)}.$$

The first important result is that the *reduction*, u, in mean velocity in the wake behind a building is related to the *couple*, C, exerted on the building. This result is analogous to the well-known aerodynamic result relating u to the drag on an obstacle in a uniform flow. The reason for difference is that u is reduced by the friction on the ground. If $U(y)$ is the mean velocity of the incident wind, the mathematical form of the relation, which is not exact, is

$$C \simeq \rho \int_{-\infty}^{\infty} \int_{0}^{\infty} y U(y) \, \mathrm{d}u \, y \, \mathrm{d}z, \tag{1}$$

where ρ is the density of air (Hunt & Smith 1969). Stemming from this result and the nature of the governing equations, it follows that behind a long, low building

$$u \propto 1/x, \tag{2}$$

whereas behind a cube-like building,

$$u \propto 1/x^{\frac{3}{2}}. \tag{3}$$

Since the equivalent results for wakes in a uniform flow would have been $x^{-\frac{1}{2}}$ and x^{-1}, these results show how the wake behind a building disappears quite rapidly as a result of the shear and turbulence in the natural wind. The third important result of these calculations is that the velocity deficit in the wake, u, disappears more rapidly than the *additional* turbulence created by the building's wake, so that some distance downwind the only effect of a building on the wind is to increase the fluctuating component of the wind while having no effect on the steady component. The theory gives no information about the wake immediately behind the building, say within three or four building heights. In this region there is little hope of a simple theory working, although the turbulence computing methods developed by Spalding and his colleagues at Imperial College (Gosman *et al.* 1969) might provide approximate values of velocity distributions.

4. MEASUREMENTS OF WIND FLOWS ROUND BUILDINGS: WIND TUNNEL AND FULL SCALE

To be sure about the flow pattern and the wind speed round a building, one has to measure them on the spot. However, this is exceedingly difficult, lengthy and costly, and therefore to examine how different wind conditions or different building shapes affect the local wind by full-scale experiment is simply not practical, and one has to resort to wind-tunnel tests on model buildings. The disadvantage of such tests is that we do not yet know how well they simulate full-scale tests. We begin by describing wind-tunnel experiments, the first set being primarily illustrative in that they show separately how various effects produce different results. The second set are measurements of the wind near model buildings placed in a flow which was modelled as closely as possible to the atmospheric wind. Finally, we describe one full-scale experiment.

As we have already suggested, it is important to know about the flow round an obstacle placed in a uniform flow, before we can understand the flow in a sheared or turbulent flow. Although there are plenty of drag measurements and some pressure distribution measurements, there are practically no measurements† of the velocities near even such simple shapes as finite circular cylinders, rectangular blocks, etc. In this context, the recent experiment of Gaster (1969) on the flow in the wake of a cone is a notable exception. Another criticism, from the architect's point of view, of many experiments on the flow round buildings is that they concentrate too heavily on the wakes of buildings, when it is just as important to know about the wind near the upwind face.

One of the problems of measuring the effects of shear in the incident flow is that such a flow necessarily creates a certain amount of turbulence. If the shear flow is produced by a grid of bars the turbulence intensity is usually about 5 %, whereas, if sloping screens of fine gauze are used, the turbulence is about 0.5 %, which is only 3 % of the atmospheric turbulence intensity. Baines's (1965) paper at the N.P.L. meeting on wind effects described his interesting measurements and flow visualization experiments on the effects of shear on the flow over rectangular buildings, especially near the upwind face. Other flow visualization experiments, in particular those concerned with estimating effluent concentrations near buildings have been described by Halitsky (1968). Recently, in Cambridge, Maull (1969) has examined how shear affects the regular eddies shed downwind of a rigid cylinder, results which may have some application in assessing the fluctuating velocities in the wake of a chimney—a problem of interest to the C.E.G.B. where cooling towers can vibrate at the frequency of eddies shed by upwind chimneys. Other work by McLaren (1970) at Nottingham has been aimed at finding out how the incident shear and the size of the building affects the re-attachment of the separated flow, i.e. to see whether shear can have the effect shown in figure 3. The method has been to inject smoke into the flow on the leeward face of a cube which is face on to the flow. Then, using the notation of figure 3 with CD being the upper face of the cube, if there is re-attachment at D, no smoke from C will get to D. On the other hand, if no re-attachment occurs, smoke fills the entire region B′BCDD′ of figure 1*a*. The main conclusion of these experiments is that if the velocity profile of the wind is given by

$$U/U(h) = (y/h)^n,$$

where h is the height of the building, then for a given value of h as n increases there is a greater tendency for the separated flow to reattach on the top of the cube. With the turbulence level being about 5 % it is not clear in these experiments to what extent the observed effects are

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† As opposed to flow visualization experiments.

mainly caused by shear. Another aspect of these experiments which is very interesting is the behaviour of the vortices emanating from the front top corner when the cube is at an angle to the flow, as in figure 1*b*.

Before describing some experiments on the effect of turbulence in the incident flow, it needs to be emphasized that even in the laboratory it is not really possible to measure the flow everywhere round a model building. For example, except on the 'stagnation' line, i.e. in the middle of the upwind face, the *direction* of the mean flow is different at different points in the flow, which necessitates carefully re-orientating a hot-wire anemometer at each point a measurement is to be made. Thus, the reason why most measurements are made where the mean flow is approximately in the x direction is experimental expediency. A more important snag is that behind a model and close to its sides the (r.m.s.) turbulent velocities are as much as 30 or 40 % of the local mean velocities, so that the output of the hot-wire anemometers is no longer a true measure of the turbulence. Thus readings close to the model can only give a crude indication of the turbulence level. However, new methods are being developed to rectify this, one being the 'pulsed' hot wire of Dr Bradbury at Imperial College. Note that in the field there is much less of a problem in measuring intense turbulence, so that at the moment full scale data can only be compared qualitatively with model scale in the shear layers at the side of the building, and not at all in the recirculating flow at the rear.

There are important effects near the upwind face and near the sides of a building, which are caused by turbulence in the incident wind. Bearman (1970) has measured the r.m.s. intensity of the turbulent component, u', along the 'stagnation' line for a uniform flow approaching the flat of a D shaped cylinder, as shown in figure 4*a*. These experiments were performed in a 0.9 m × 0.9 m N.P.L. tunnel with bi-plane grids creating approximately isotropic turbulence. These results show how the intensity of the turbulence depends on the size of the building relative to the scale of the incident turbulence, and therefore how important it is in model tests to have the correct scale of turbulence. In interpreting these results note that for the atmospheric wind $L_x \simeq 100\,\mathrm{m}$. Figure 4*b* shows similar results for turbulence approaching a cylinder of diameter d obtained by Petty (1971). Hunt's (1971) theoretical curves, drawn with the experimental curves, show reasonable agreement, at least for the practical size of building, i.e. $L_x \gtrsim d$. Comparing the two experimental results, we see that for a given width of building the turbulence intensity is higher in front of a slab shape than a curved shape, a result which might be expected intuitively. The experiments of Cook (1970) at Bristol University are aimed at finding out how the intensity and scale of turbulence affect the flow at the sides and in the wake of a rectangular block with a square cross-section and a height 3 times the side. The results have shown how increasing the turbulence intensity and increasing the scale of the turbulence destroys the vortex shedding in the wake. Petty has found a similar reduction in vortex shedding for a circular cylinder. Cook's results have also shown how the turbulence widens the shear layers on the sides of the blocks. As a result, the region in which the turbulence intensity is greatest (in this case it is 30 % of the upstream velocity), is also widened. It is important to realize that this high level of turbulence cannot be accurately measured, and nor can the mean or turbulent velocities behind the block, so that results such as these should be treated with caution.

Jensen & Franck (1963) were the pioneers in developing a wind-tunnel flow which correctly simulated the atmospheric wind. By allowing a boundary layer to grow naturally along the tunnel, they were able to compare the wind near a model of a group of school buildings to the full scale measurements. The results were remarkably good. Although this method was very successful, it required a longer tunnel than most laboratories can provide; as a result, Armitt & Counihan (1968) at C.E.R.L. have developed a different method of stimulation which requires a much shorter tunnel. In this simulated boundary layer not only does the mean velocity profile compare well with that of the atmosphere, but also the r.m.s. values, correlations and spectra of the turbulence agree with those recently measured by Harris (1968), and others, in measurements of atmospheric turbulence. As one application of this simulated atmospheric boundary layer, Counihan has measured the mean velocity and turbulence in the wakes behind the two rectangular blocks described in § 3, one for which $h = d = \frac{1}{24}b$ and another for which $h = d = b$ (Hunt 1970). For shortage of space we cannot describe these experiments further, except to say that the results agree quite well with the general theoretical predictions already mentioned. In particular, the x^{-1} and $x^{-3/2}$ decay laws, seem to describe the results satisfactorily.

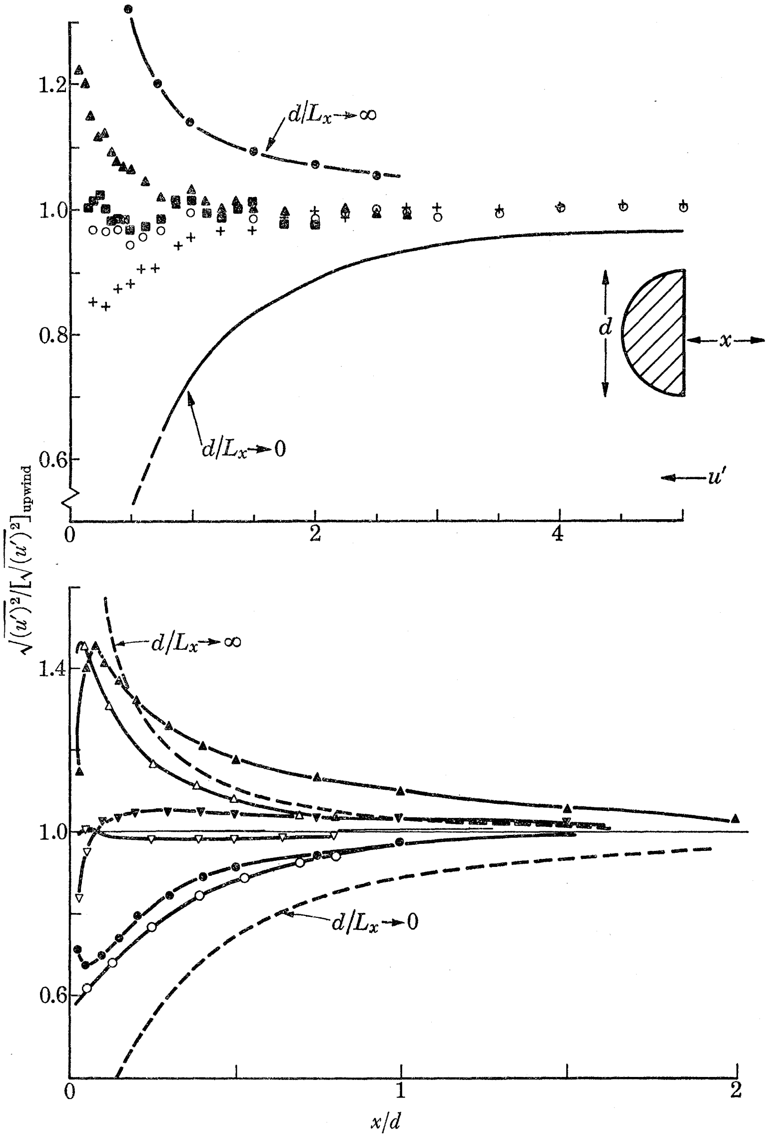

FIGURE 4. The change in turbulent along the stagnation line for flow around two types of cylindrical body. (a) A D-shaped cylinder. Experimental values of d/L_x: +, –0.33; ○, □, –0.67; ▲, –1.33. (b) A circular cylinder values of d/L_x: ○, ●, 0.26; ▽, ▼, 1.06; △, ▲, 3.62. Solid symbols are experimental points, open symbols theoretical.

In view of the importance of knowing about the wind flow round buildings, it is extraordinary that only now is a full experiment under way in which the flow is to be measured in some detail, i.e. the three components of the mean and fluctuating velocity are to be measured at several places and then properly analyzed. Previous experiments, as described by Halitsky (1968), have either been purely qualitative flow visualizations, or else have been restricted to a few mean velocity measurements, e.g. Jensen & Franck's experiment. The R.A.E. experiment (Colmer 1970) is designed to provide information on the wake behind a hangar, no measurements being made around the upwind face or sides of the buildings—a pity from the architect's point of view! Figure 6a shows the layout of the hangar and the towers, on which the wind instruments are placed. Special towers have had to be built, cables led from the towers to an instrument hut, each instrument calibrated and programmes written to analyse the data; these are some of the jobs that have to be done in such an experiment. The instruments being used are cup anemometers to measure the horizontal component and two vanes to give the direction of the wind in the horizontal and vertical planes. Their response time ($\simeq 0.5$ s) is adequate to obtain the information needed for aircraft loads. Measurements are only made when the wind is within 10° of the N–S axis on which the towers are placed, so that the effects of the large buildings to the east are negligible. Only a few results have been obtained so far, but they are quite interesting. First, as shown in figure 6b, it is found that at $x = 5h$ the velocity deficit, u, is appreciable, whereas at $x = 15h$ it is not—a result we found in the C.E.R.L. model tests behind a cube. Secondly, the C.E.R.L. theoretical and model test result was confirmed, that the additional turbulence intensity decays more slowly than u. In fact at $x = 25h$, Colmer finds that the turbulence intensity

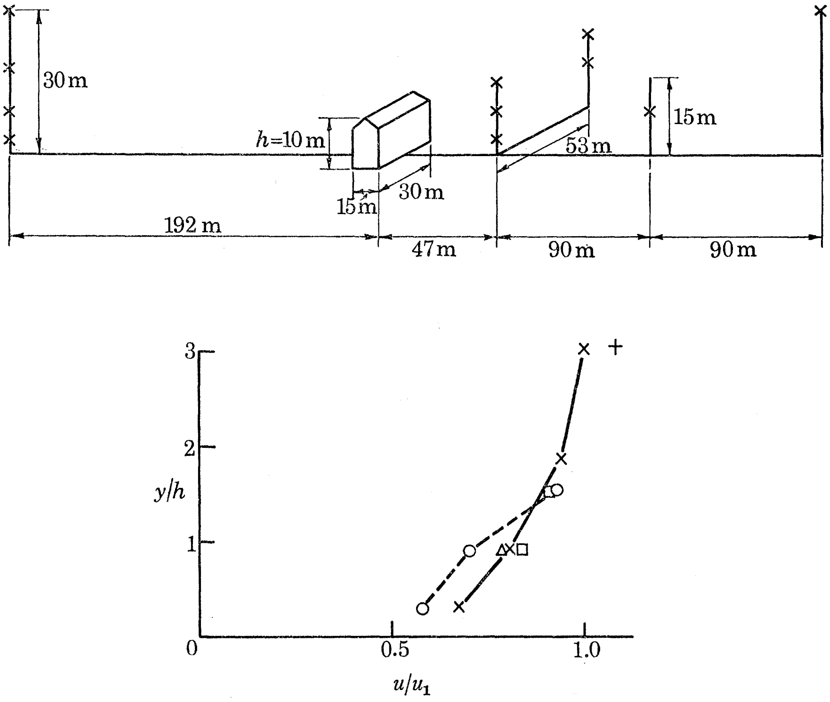

FIGURE 5. Wind measurements near a hangar at R.A.E. Bedford. (Diagram courtesy of M. Colmer). (a) Layout of experimental site. × indicates the position of the instruments. (b) Variation of mean wind speed with height, upwind and downwind. U_1 is the upwind value of U at $y/h = 3$. On centre line: ×, upwind $x/h = 19$; ○, downwind $x/h = 5$; △, downwind $x/h = 14$; +, downwind $x/h = 23$. 1.8 building widths off the centre line: □, downwind $x/h = 5$.

at three times the height of the building is still 10 % greater than the upstream value. In analysing the results of the fluctuating component of the wind, not only are the r.m.s. values and spectra to be computed, but also the probability distributions, in particular the probability of the highest velocity gusts. Finally, it may be of interest to those concerned with model testing that C.E.R.L. are about to perform a thorough model test in their 4.5 m × 1.5 m low-speed wind tunnel, in which the hangar and the surrounding terrain and buildings are modelled. The atmospheric boundary layer would be simulated in the usual way. The results are to be analysed using the same programmes as for the full scale data.

5. Conclusions

We hope the following salient points have emerged from the paper.

(1) There are many aspects of the flow round a building which we do not understand, even qualitatively, e.g. the effects of shear on re-attachment of the separated flows, the nature of the swirling flows downwind of a building. There remain many basic experiments to be done to resolve these and other fundamental aspects of the flow.

(2) There are aspects of the flow which are amenable to theoretical analysis, at least if the approximations are sufficiently bold. For example, a reasonable model, with some detailed results, now exists for the turbulence round the upstream face of a building. It is essential to compare experimental results wherever possible with some theoretical model so that experimental information, as it becomes available, can be reduced to formulae or universal curves which designers can easily use.

(3) Model tests in a simulated atmospheric boundary layer on the flow round particular buildings are a reasonably reliable way to determine the full scale flow, but more detailed comparisons between model and full scale tests are necessary.

(4) There is a substantial amount of experimental and theoretical work under way in the U.K. and elsewhere. It is vital that the results be collated eventually in such a way that they really reach the architects and designers in a form intelligible to them.

I am grateful to many aerodynamicists at C.E.R.L. and elsewhere for telling me about their work and allowing their results to be revealed before they themselves publish them. They are: J. Armitt, P. W. Bearman, M. Colmer, N. Cook, J. Counihan, F. McLaren, D. G. Petty. This paper was written at the Central Electricity Research Laboratories and is published by permission of the Central Electricity Generating Board.

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