PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Problems for the Architect and Town Planner Caused by Air in Motion

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Problems for the architect and town planner caused by air in motion

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This short paper makes no original contribution to knowledge but simply describes and identifies a range of problems encountered in practice by town planners and architects. The term 'architectural' in the subject title of the Discussion Meeting is taken to imply that the results of aerodynamic research are now as applicable to architectural as to engineering problems. Architecture is broadly interpreted as the coordination of many techniques to give significant form to social programmes. As this is a comprehensive activity, it follows that the problems caused by air in motion range from the location and layout of whole cities at one end of the scale, to the design of a window or the control of an ornamental jet of water at the other. In the middle of this range typical problems arise from the siting of buildings singly and in groups, and in the structure and cladding of high-rise and low-rise buildings to resist wind, rain penetration and air-borne pollution.

Preamble

Certain problems caused by orientation and wind have been discussed, in theory as well as practice, since town sites were first selected and buildings planned. Practical methods of ensuring comfort and stability, reducing pollution, and dealing with driving rain and snow, have long been part of local building traditions. Historically, however, there has often been subordination of both experience and logic to outworn doctrine. Vitruvius discussed the effects of prevailing wind on the planning of towns in the first century B.C.; but he appears to have accepted that they blew from fixed directions; and Kenneth Clark noted in his catalogue of Leonardo da Vinci's drawings at Windsor, that these superb delineations of air and water in movement were made by a scientific observer who was none the less so rooted in scholasticism that 'it did not occur to him to disbelieve that the signs of the Zodiac were active forces'.

Systematic analyses of user requirements, predictions of general and microclimatic airflows, and scientific studies of the aerodynamics of buildings, single and grouped, are of this century, mostly of the last 20 years.

The architectural function

The discussion today has the word 'architectural' in its title. This suggests that architects now have much to learn in the application of aerodynamic research to design, and that it is now as applicable to architectural as to engineering problems. It also suggests that the subject can usefully be discussed in a full architectural context, i.e. as a control in the ordering of the built and landscaped environment. It is after all, as the Greek root implies, an *architectural* function, even when exercised by others than architects—to bring together the relevant arts and sciences, the building technologies and the organizations for supply and assembly, so as to give significant form to social programmes, and in doing so to evaluate the costs and risks of building in a particular way.

When the environment under review is on the scale of a region or a new capital city, the initial planning decisions are not taken solely for building reasons. Moreover, the anticipated effects of air movement are not usually the determinants of site selection, which are more often political or demographic, or commercial. The influence of aerodynamic factors on the location, layout and form of buildings within a selected site, also depends on whether the object is to take advantage of the *natural* assets of climate and terrain (and conversely to avoid the hazards), or whether *economic* assets are to be exploited even if this means greater costs of construction or a lower standard of comfort and safety, or both.

Social and economic factors precondition design; and therefore the first problem for the planner at this scale is how to devise and quantify a cost–benefit study, in which aerodynamic factors, among others, can be given their proper weightings. Mathematical models, having proved valuable in transportation studies, are now being experimented with in this and other problems of environmental planning (Wilson 1968).

New capitals

(*a*) *Brasilia*

The location of the Federal District of Brazil, for example, although a more rational choice than that of the District of Columbia in the U.S.A. or the Capital Territory of Australia, was made on political and administrative grounds. Having been made and enacted, a Survey Commission was appointed (Belcher *et al.* 1955) to select, within the Federal District, the ideal combination of factors that would determine the site of the Capital City. One of these was a microclimate free of fog and of strong and disagreeable winds, at an elevation of about 1000 m over sea level; another was the absence of physical barriers such a swamps, gorges and high hills. Five sites in the Federal District had these advantages but what determined the final choice of site for the development of Brasilia, with its planned population of half-a-million, were such assets as:

(i) gently rolling land with grades of not more than (8 %), to assist natural drainage and reduce housing costs;

(ii) bedrock close enough for deep foundations, but not too shallow to require subsurface facilities to be cut in rock;

(iii) an instant site for an airport;

(iv) well-drained soils to support vegetation, and public and private gardens.

In other words, factors likely to lead to economical development costs for a non-industrial, administrative city.

When the actual site was demarcated (before the competition for the Pilot Plan was held in 1957), further meteorological surveys were made and a lake was created round two sides of the City. In the layouts of living quarters, as proposed in the competition designs, aerodynamic considerations were absent for the most part; and in only one case, as I recall, had models been tested in wind tunnels. But structural and wind-load problems were posed in plenty. In particular I recollect a design for a large group of central residential apartment blocks, 500 m in height and of diaper formation on plan. The actual problems caused by air in motion in the residential quarters as carried out, were due mainly to the lack of time given to detailed layout and applied research. For Brasilia was built in three years: with its main public buildings inaugurated, and a population of 100000 in residence in the planned city alone.

The problems were caused by the arrangement of the buildings themselves in the residential quarters, which produced wind funnels, dust traps, and a dearth of small playspaces in the shade.

Brasilia has no frost and no winds of exceptional force or gustiness. Its climate, though not perfect, is suited to its use as an administrative and diplomatic centre. Its aerodynamic problems are small compared with those of accessibility, finance, politics and lack of history.

(*b*) *Canberra and Chandigarh*

Two other capital cities of this century, Canberra and Chandigarh, present a different range of problems. Canberra has a fine landscape and a variety of good liveable situations on the hilly slopes of a flood plain. Before development and tree planting ('a good sheep station spoiled' was the current jibe) it was subject to drought and periodic flood and a diurnal temperature range that is very hard on building surfaces. The careful planting of a million trees, and the damming of the Molonglo River to create 17 km^2 ($6\frac{1}{2}$ mi^2) of lake surface in the middle of the city, have done something to improve the natural microclimate; but there are still frost pockets, and frost-free slopes, sheltered and turbulent areas, and sites where wind is a significant factor in structure and comfort and the cost of both. But there has been time in the 50-year growth of Canberra to assess the comparative advantages, aerodynamically, of different sites and slopes for residential, office, or shopping use; and this has been done more accurately in recent years. Plant nurseries and gardens, some on slopes free of frost, have been protected from nocturnal down-valley winds; a whole shopping centre has been put under one roof and given a controlled climate; tower block designs and layouts have been tested for wind load, cooling, noise, material erosion and other effects of air flow, before being finally located and built. One element which siting and design can do little to improve is the airfield, where hills and prevailing winds and length of runways together impose limitations on use.

At Chandigarh, in the Punjab, the problems, for an administrative capital, of a low-lying site subject to excessive temperatures and humidities had to be met at every scale from the city plan to the ventilation of dwellings. If you cannot afford general air-conditioning you are unlikely to get full productivity out of civil servants over an eight-hour day. The first architects, Mayer and Whittlesey, with Dr Landsberg's advice as climatologist, laid out the streets and quarters to attract as much wind as possible. The later architects, Le Corbusier and Jeanneret and Maxwell Fry, produced building types with the same purpose. Many devices for increasing air movement round buildings were tried out, but whereas the effect of a shaped secondary lid over a flat roof can be tested by a model in a simple wind tunnel, the problems of testing layouts to a larger scale, taking Reynolds number into account, and the effects of macro- and microclimatic and katabatic winds on open and enclosed spaces in towns, are less easy to solve.

Physical models

The question of the scale at which physical models can be ordinarily but accurately used is an interesting one; and architects would like to know more about comparability between air (with smoke as the marker) on the one hand, and water (using dyes or pellets of various kinds) on the other; accepting the point already made in discussion that these are indicators only. This follows the useful work done by the Building Research Station in devising simple wind tunnels for teaching purposes as well as *ad hoc* testing (Sexton 1968*a*).

At Canberra in 1958 a hydraulic model, 27 m long, was formed in concrete, representing the Molonglo River and flood plain as it passed through the future built-up area of the city. With the aid of tanks, floods of 880 m^3 s^{-1} (30000 ft^3 s^{-1}) (such as occurred in 1956) could be simulated.

Confetti and coloured plastic globules of different weights and densities were used to pick out currents and eddies; and these observations were used in the design of margins, inlets, jetties, bridge piers and the lake barrage itself.

More recently, in Natal, we were faced with the problem of designing buildings and parks *behind* the wall of flats and hotels between 70 and 90 m high, which front the famous 5-mile (8 km) beach of Durban; and a hydraulic model was used to test airflow patterns. We wanted to know the effect of wind and orientation on the existing buildings and on various forms of new building proposed inland. In this case Professor Croft of the University of Natal made models of the existing area (to a scale of 1:800) and of the proposed buildings, in woods of contrasting tone and colour. These were alined on the shadowscope and photographed as at 08h00, 12h00 and 17h00 in summer, winter and equinoxes. The models were then transferred to the Hydraulics Flume in the Civil Engineering Laboratories; and using water as a medium, with injected coloured dye representing windflows, observations were made of the effects of the desirable easterly sea-breezes and of the predominant and weather bringing southwesterlies.

On Durban Beach, as at Copacabana in Rio de Janeiro, where humidity is high from December to April, studies of airflow are essential for comfort, as air-conditioning can only be afforded in accommodation of high rental or use value, and even then cannot apply to pavements, bus and railway stations, or stadia.

City centres

The development and redevelopment of city centres present a group of aerodynamic problems of their own. Use, density and land values combine to make them places where multi-level circulation can be both justified and afforded. They are also liable to atmospheric pollution. Suburban smog tends to flow into the centre at night where the rising thermal is strongest; green spaces are usually less in extent; diesel and other exhausts, and sulphur dioxide from heating plants, are more concentrated than elsewhere. If modern redevelopments in cool climates have sometimes produced uncomfortably draughty conditions at ground level, others in more tropical zones have created pockets of stale air with inadequate turbulence to clear them.

Under these conditions, projects for pedestrian decks and underpasses, cut-and-cover sunken roads (such as I have proposed south-west of St Pauls in the City of London), and short lengths of tunnel under conservation areas (as Colin Buchanan has planned for the historic city of Bath)—all these require special studies of ventilation and of the control of microclimates. Mr Penwortham's account of a car blown along an underpass on its handbrake is an illustration.

There are also some associated problems of automation waiting to be solved. Internal bathrooms have switches which turn on the ventilation with the light. As an experiment in sound insulation, P. H. Parkin at B.R.S. is said to have a window which closes automatically on the microphone signal of an approaching plane. In Cape Town there is a fine vertical water jet in the Heerengracht—a pleasure to the eye and ear on a hot still day. But when the sou'-wester blows, the water sprays traffic and pedestrians well beyond the confines of its basin. So a cup-anemometer, on the top of the nearest lighting column, is used to activate a valve which controls the height of the jet in inverse proportion to the force of the wind.

These are *small* devices of environmental control, but open up the prospect of aerodynamic automation on a much larger scale in urban layouts. Subject to running and maintenance costs being reasonable, this would help to solve a number of problems of planning and layout in city centres.

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Airflow round buildings

Even these few references show that the scale of planning problems influenced by climatology and aerodynamics ranges from urban and industrial location to the control of jets in ornamental fountains. The degree of influence extends from amenity and comfort, through productivity, to health, safety and survival. Airflows do more than cool and warm and ventilate; they also help rain and snow to penetrate, and introduce noise and smells and pollutants to areas and regions where they are a nuisance and whence it is costly to exclude them. But the aerodynamic problems that interest the architect most directly and constantly are probably those in the middle scale affecting the stability and maintenance of buildings and the comfort and convenience of those who occupy them.

(*a*) *High-rise buildings*

There are obvious aerodynamic problems connected not only with high-rise but with low-rise buildings, which concern structural engineers, architects, contractors, owners and managers alike. By definition high-rise buildings are those for which wind and earthquake stresses normally exceed the overstress allowances which design codes permit. A low-rise building with load-bearing walls or a beam-column frame can normally maintain the lateral load stresses within this allowance. For taller structures column and beam sizes have to be increased; and Khan (1969), Chief Structural Engineer to Skidmore, Owings and Merrill, in Chicago, calls this increase of material the 'premium for height'. The first requirement for high-rise buildings is to evaluate the design wind loads in a realistic way, so as to reduce the premium for height. Now that high-rise buildings of 60 storeys or more are numerous, interesting developments in economic structural systems are taking place. The 'framed tube', with closely spaced external columns and spandrel girders, has been succeeded for very tall buildings by the 'column diagonal truss tube'. The 100-storey John Hancock Center, recently erected in Chicago, is one of these. It has diagonal members on the faces of the building. Khan notes that analysis vindicated his assumption that the system would act more like a cantilever tube than a frame or truss structure, and that there was insignificant shear lag under wind loads. He adds two relevant comments:

(i) that the relative sizes of the diagonals, spandrels and main ties strongly affect the overall economy and efficiency and, therefore, an optimum proportion for the main members should be worked out;

(ii) 'that a new structural system is only as good as an equivalent architectural solution' (Khan 1969).

Besides the basic problems of economic, efficient and elegant design for wind loads, high-rise buildings pose special problems in exceptional weather and in locations where they are crowded together.

The United Nations Building in New York, for example, was hit by winds of hurricane force when it had just been clad with glass and was nearing completion. I had an opportunity of watching the behaviour of the building under gusts of over 180 km/h, and incidentally of the architect, Wallace Harrison, who feared, not for the stability of the structure, but the damage to its cladding, which could have been enormously costly. However, the ground floor went first, leaving a vent for the wind; and the upper floors were relatively unhurt. Later, however, driving rain—forced *up* the windows, particularly on the lee side—was found capable of penetrating the interior—and detailed revisions to the design of the window wall had to be made. Earlier on the same day I had just escaped being hit more than once by large sections of plate glass from shop windows—

not blown in, but sucked out by the wind in side streets. The discomfort of normal wind tunnel effects—referred to earlier—had reached lethal proportions in weather of exceptional severity.

In any system, whether of electricity generation or building, problems arise in judging the margin of capacity or safety to be designed for the system, and the degree of risk to be taken. Using sophisticated techniques, the risk can be calculated and the safety factors costed (although it seems as if insurances and indemnities are going to be progressively less easy to obtain). Sometimes the risks are not calculated. This appears to have been the conclusion of the Ronan Point inquiry in 1968, where it was shown that a number of recent high-rise buildings were potentially liable to progressive collapse, as a result of explosion, fire damage or wind pressure. Codes of Practice were shown to have taken inadequate account of developments in system-building. The report—in the words of the *R.I.B.A. Journal* (December 1968) 'found the architects wanting for failing to call adequately on the engineers, and the latter for failing to take much interest in system-building in general'. In January of that year, in Glasgow, a wind driving up the Clyde Valley with velocities '...not much greater than those occurring in a normal 20-year cycle'; but with 3 s gusts up to 180 km/h, lifted the roofs of modern flat blocks as well as of old tenements. (Wilson 1968), and the design of roofs, windows and anchorages has been called into question. It was noted that peripheral buildings of lower height were less damaged than those in the middle of this housing estate.

The problem of designing for above-average wind-loads, in single buildings and groups, for high and low blocks and for systems building, are clearly of major concern to architects, because they affect environmental quality, capital and maintenance costs, stability and comfort—all of them factors he is required to coordinate in the total design and layout.

(*b*) *A special case*

When the building is as exceptional in design as the wind forces to be anticipated, a special order of research and experiment must be afforded. The Sydney Opera House is probably at the top of this category. The consulting engineers, Ove Arup and Partners, accepted the plan and the concept of shape with which the architect, Jørn Utzon, had won the competition for this building, even though the surfaces were all free shapes without geometric definition, whose structural viability had to be proved. How the special problems of wind-loading—among many others—were overcome, was told in an interesting paper given to the Institution of Structural Engineers (Arup & Zunz 1969). It is worth noting that there were no comprehensive records of wind speeds, directions or gust durations in Sydney. The wind-pressure distribution over the shells was estimated from a model in wind-tunnel tests at Southampton University and then in the Aerodynamics Division of the National Physical Laboratory, where the open jet tunnel had a much larger working section.

Large engineering structures, such as cooling towers, also create assimilation and amenity problems for planners and landscape architects, particularly in the countryside. In England and Wales the present standard natural draught counterflow hyperbolic tower is 115 m high and 90 m in diameter. A modern 2000 MW power station requires 8 of them, unless the waste heat is disposed of either by direct river- or sea-water cooling. While the Central Electricity Generating Board bases a major research and development effort, particularly since the collapse of a tower at Ferrybridge, on their internal aerodynamic and thermal processes, their external wind loads, and the effects of grouping, those designers concerned with architecture and amenity have to interpret the findings in terms of the visual impact, spacing, and landscape treatment of these colossal pieces of repetitive outdoor sculpture.

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(c) *Low-rise building*

These represent the commonest problems of all. In the U.K., for example, low-rise building includes at least 85 % of all dwellings; and the architects of individual houses and housing estates, and architects responsible for the restoration and maintenance of historic houses, have a clientele increasingly likely to complain, as living standards rise, of a whole gamut of human discomforts and building defects caused by air in motion.

Later contributions to this programme deal with the physical aspects of air-flow problems and describe the research and development that is going on. I want to conclude my short catalogue by referring briefly to their social significance.

Maintenance is usually reckoned in this country to be about 30 % by value of total construction. What proportion of the repair and restoration bill is due to damage, and deterioration by wind, driving rain and airborne pollutants is impossible to say, but it must be substantial. Restoration funds being sought at the moment for major historic structures exceed £50 M. Most old buildings have traditional lore and craftsmanship built into them, which has helped their physical survival, but as they are usually ornamental in their silhouettes and facades, they are particularly vulnerable to erosion. The care of historic buildings almost deserves to be classed as a specialist branch of applied architectural aerodynamics. Low-rise building in general shares, less spectacularly, the same problems. They derive from two constraints in particular: the first is the reconcilation that designers and builders have to make between the dynamic curvilinear patterns of traffic and airflow, and the static rectilinear forms of furniture, rooms, buildings and street blocks. This leads to frequent 'edges' which give maintenance trouble—parapets, eaves, corners, windows, doors and vents of all kinds. The second is the nature of the compromise that is usually arrived at between ventilation and weathertightness complicated by the fact that the narrower the gap the faster the air flows through it. I once had flexible phosphor bronze strips inserted into the sashes of windows fronting the sea at Brighton. These made excellent heat and weather seals under normal conditions; but when the wind reached a force of 9 on the Beaufort Scale (about 70 km/h), they acted as reeds; and each window sounded a loud and a different organ note, which made sleep impossible. Since then I have paid more attention to the collated experience and research circulated by the Building Research Station (see, for example, Sexton 1968*b*; Wise 1969). Mr Wise is contributing to this discussion.

I have said nothing of the specific effects of airborne pollutants on building materials—stone, metal and plastic—nor their general effects, including smell, on human material. But these also should be included in the catalogue that interests the architect.

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