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

The Role of Structural Materials and Forms [and Discussion]

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The role of structural materials and forms

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Aerodynamic and wind effects are governing factors in the strength and stability of many structures and buildings; the important aerodynamic loads arise not only from severe, short-period gusts but also from sustained, less-severe, wind loads. The material properties required to resist these loads are not only static strength, strength under repeated loads, stiffnes sand structural damping, but also long-term integrity of structural form; the need for durability of structural form is one of the limitations in developing the relatively low-grade materials used at present in buildings.

The general conclusion of the paper is that in combating aerodynamic and wind effects, there is probably greater scope at present in devising more suitable structural forms within the limits of existing materials, rather than expecting a radical improvement of materials themselves. Much is now known of the best forms for tall structures, such as chimneys, masts and cooling towers; the multi-storey building has been studied extensively in recent years, and more efficient forms for these could probably now be devised. Knowledge of local wind-loads on structures—as, for example, wind-load concentrations at the corners of rectangular, tall blocks—has advanced considerably in recent years, and these again suggest improvements of structural forms to avoid local structural damage.

1. Introduction

In this short introductory paper, we are concerned with the role of structural materials and structural forms in combating wind-load effects and suppressing or reducing these effects. A number of papers presented to the Symposium and Discussions during the meeting have been concerned with different aspects of wind-loading and the structure of the wind itself; in this particular paper we shall be more concerned with the nature of materials and structures, and the properties of materials and structures required to resist wind loading.

It is relevant to consider first the significance of wind loads for structures and structural materials, and the types of wind effects which are most important; are wind loads and wind effects dominating factors in structural design? Earlier papers have dealt with the wind-loading problems of bridges and large structures, of steadiness and unsteadiness, of the response of structures to atmospheric turbulence, and of wind-induced instabilities; although in many of these areas the resulting behaviour of the structure is dynamic, time-varying, and is frequently described as 'unsteady', they are essentially situations derived from a steady-state of wind flow and turbulence. At the beginning, it should be realized that actual wind loads important to structures and materials (and by this is meant that these loads affect design significantly) vary over a wide range: for example, rare, severe wind-loads are important for overall and local loads on structures; less severe, but more frequent, loads can cause aerodynamic instabilities; once a structure is damaged by rare, severe loads it is prone to further damage by more frequent, less severe loads; again, tall buildings themselves may generate wakes in wind streams which could produce important loading conditions on vertical take-off aircraft operating from nearby city landing sites. It is, therefore, mistaken to assume that significant wind loads are of any single type; indeed, these significant wind loads may have very different origins.

Again, it is worth considering how significant are windloads for engineering structures and materials. As an oversimplified example let us consider the tall, multi-storey building (figure 1), which is under a horizontal wind-loading action. We can simplify the loading on such a building to a vertical dead-load which induces forces at the foundations proportional approximately to the height, h. If the wind load consisted in a uniform distribution of horizontal pressure this would lead to foundation forces proportional, again approximately, to h^2. In fact, the wind is non-uniform, non-steady, and increasing possibly with height, and so there is probably an even stronger dependence on wind effects. In this oversimplified case the wind is all-dominating for an extremely tall building. As another example, let us consider the stresses induced in a thin, flat sheet of material which is used as a roof covering; if t is the thickness of the sheet, then the

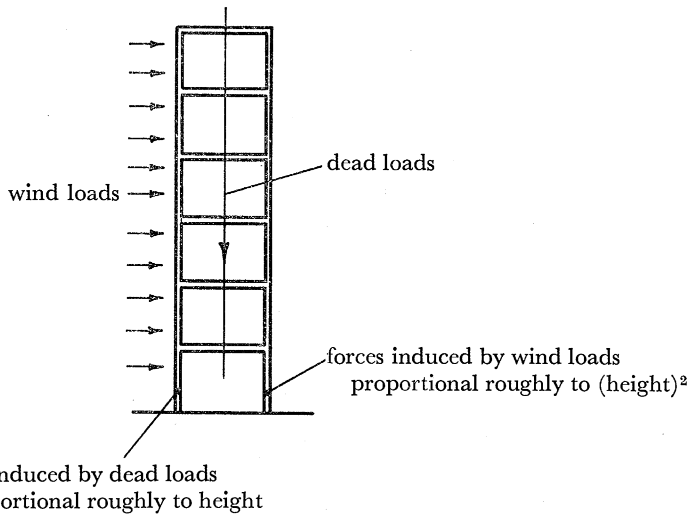

FIGURE 1. Critical dependence of the forces in a structure on wind loading.

bending stresses induced by a lateral wind pressure (assuming this acts in a quasi-static manner) are proportional to t^{-2}, showing again an extreme dependence on thinness. If the sheet has a corrugation spacing, a, and thickness, t, then the bending stress in the sheet is proportional approximately to $(at)^{-1}$, again showing strong dependence on extreme geometrical parameters. As a final example, a tall, slender, cantilever structure, such as a chimney, may be prone to oscillatory behaviour in a wind stream; in this behaviour, the natural frequency of oscillations of the cantilever is important. This natural frequency is proportional inversely to the square of the height, h, of the cantilever, showing an extreme dependence on the tallness of the slender structure.

All these examples, admittedly over-simplified, demonstrate the critical dependence of structural forces and effects due to wind on extremes of tallness, span, thinness, and so on. In other words, wind loading is a primary, and severely limiting, load for structures at the extremes of their linear dimensions, and wind loading is therefore always likely to give considerable problems when we are designing and building at these limits.

2. Main effects of wind loading on structures

In discussing the wind loading of structures we tend to assume that wind-loading conditions can be well defined. In general, however, wind loads are highly non-stationary, random phenomena. This will always make the field of structural design against wind loading a difficult one, and any deterministic methods of design are bound to be only approximate. We have been able in the past to deal with wind loading by introducing excessive factors of safety, and these are built into most deterministic methods of design at the present time.

In some structural problems we may be able to reduce wind loading to an approximate state of quasi-stationary loading. Indeed, our present concepts of wind loading are based largely on the loads generated within a structure in a stationary air-stream, albeit the local conditions around the structure are non-stationary. For example, in tall buildings our present concept of wind loading is a quasi-static one, although many of the empirical factors used in establishing a design load probably cover dynamic and unsteady effects. Again, the dynamic phenomena which we know to occur in certain structures, phenomena such as vortex excitation, galloping, ovalling oscillations of thin shells, are again understood largely in the context of phenomena due to randomly stationary air-streams. These points should be mentioned so that we keep in mind the very rudimentary concepts we have at the present time of wind loading, and the need to study the structure of the wind itself as well as structural effects. The concept of local stationarity of wind loading may be very useful to describe the median response of a structure, but it is questionable whether this simplified description is adequate to give accurately, for example, the probabilities of extreme, rare loads.

3. Materials and structural properties suggested by wind loading considerations

Ideally, what material and structural properties are called for to resist wind loads? Those which are of primary importance appear to be as follows.

(a) *High static strength*

Since many wind effects may be treated as quasi-static, the static strength of a material is important for overall structural strength. Structural form itself plays an important part in the overall strength of a structure, as for example in the plastic behaviour of frames, but high static strength of material will always be an essential feature of structures designed to resist wind loading.

(b) *Static strength under repeated loads*

The ability to resist repeated loads is an important property, and the need for this has tended to be neglected in the past. Many of the materials used in buildings, such as ordinary reinforced concrete, are not necessarily well-suited to repeated loads. In fact, the strengths and stabilities of structures made of such materials may well degenerate with time.

(c) *High stiffness*

Materials and structures require high stiffness to resist wind-loading effects. In many materials, high stiffness may well imply high density; for a wide range of common metals, for example, the ratio of density to the Young modulus is roughly constant. In structures, high stiffness is essential to combat many aerodynamic instability problems, as for example ovalling in thin cylindrical shells; structural stiffness can be improved by change of structural form.

(*d*) *High damping*

Another important feature of materials and structures to resist wind loading is high damping. Some of the materials in common use in buildings possess adequately high damping, but in others, such as metallic shells and frames, the damping may be relatively small. Damping properties should be considered in the early stages of development of a new material. Structural damping on a large scale is also very important and there is probably scope for greater innovation here than in the materials themselves. Large-scale structural damping could be achieved in a number of ways: there is first a need to devise new structural forms which involve mechanical dampers on a large scale, and some of the techniques known to the mechanical and aeronautical engineering fields may well have implications for large civil structures; again, it may be worth exploring whether structural forms can be modified to lead to dynamic responses which involve extensive regions of a structure, thereby leading to energy dissipation within the material of the structure but throughout larger regions.

(*e*) *Integrity of structural form*

A further property to which I should like to draw attention is the need for material and structural integrity during the lifetime of a structure. It is commonly assumed that a structure remains integral during its lifetime and therefore assumes a constant structural form. In fact, many structures undergo fairly radical changes over long periods of time. The example I would like to use as an illustration is a thin, hyperboloidal, reinforced-concrete shell used as a cooling tower.

The shell of such a tower has a thickness which is about $\frac{1}{500}$ of the diameter of the cooling tower. This makes it an extremely thin hyperboloidal shell and one possibly susceptible to buckling by lateral wind forces. From earlier studies of the buckling of model shells in wind tunnels the wind-speeds at which buckling occurs by a general dimpling on the windward face is fairly well understood. At the time of the collapse of the Ferrybridge cooling towers in 1965, when it was realized that some cracking of the shells might be present, horizontal cracking was introduced into some of these wind-tunnel tests and was found to have little effect on buckling loads. Later it was found that many cooling towers in this country were extensively cracked vertically; cracking of the thin, reinforced-concrete shell takes the form usually of a large number of mainly vertical cracks distributed round the circumference of the shell. The origin of these cracks is not well understood: they may be caused by bending stresses, by shrinkage, or by stress concentration effects at the foundation supports or even by combination of these causes. The cracks extend generally from the base of the shell upwards and from the upper rim of the shell downwards, some of the cracks meeting in the central throat region; many of these cracks are therefore quite long, extending effectively over the whole depth of the cooling tower.

Recently, with Mr B. Hayman of University College London, I have been conducting a study of the effects of these vertical cracks on the wind speed at buckling of model cooling towers; these were tested in the N.P.L. compressed air tunnel. In figure 2 are shown the effects on buckling of one vertical crack, two vertical cracks, and so on: the models which are made of thin polyvinyl-chloride sheet are of the order of $\frac{1}{300}$th scale models of hyperboloidal cooling towers. The models are clamped to rigid metallic base plates, and then fitted into the wall of the N.P.L. compressed air tunnel. First, a test on an uncracked shell determines the buckling wind speed of an integral cooling tower; this critical wind speed is well-defined, suggesting that geometrical imperfections are not critical. Next, a simple vertical crack is introduced into the shell, and along the meridian facing the windstream. This was done by making a fine-saw cut through the shell along a vertical meridian, and then sealing this with adhesive tape; the tape was sufficiently flexible to give the crack no bending stiffness, and at the same time prevented the two sides of the crack separating. Thus, the membrane action of the model shell was maintained across the crack; in reality this membrane effect would be provided by steel reinforcement in the shell.

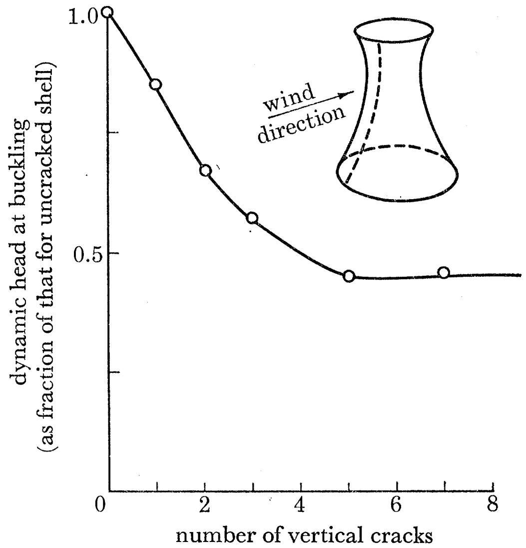

Figure 2. Degeneracy of the stability of a cooling tower due to increasing vertical cracking.

The effect of a single crack on a windward meridian is to reduce the dynamic head at buckling to about 80 % of the head for a completely integral tower. Models with more than one vertical crack were then studied; two vertical cracks, at meridians $\pm 70°$ to the wind stream reduce buckling to less than 70 % of the original dynamic head, while a third crack, now placed between these two, brings the dynamic head down to about 60 % of its original value. Five vertical cracks and more appear to lead to a well-defined degenerate state where the dynamic head is now less than 50 % of its original value. The emergence of a degenerate state for a large number of vertical cracks is compatible with the idea that in such a fully cracked state, there is still some inherent stability in the structure. But in this vertically cracked state, further horizontal cracking could introduce more degeneracies, and the resulting buckling wind speeds are then dangerously near those wind speeds which are commonly experienced in this country.

We can consider the wind-buckling of a cracked cooling tower as a special case of a more general class of problems, in which degeneracies in one form or another lead to a lowering of the stable limit of the structure. The general tendency we find is that the worst arrangement of degeneracies leads to a rapid reduction of buckling load (figure 3). The best arrangement leads to a less rapid degeneration, but complete degeneracy always finally ensues. In general, a small amount of degeneracy in a structure can impair the general stability seriously. Thus, in addition to the general requirements of static strength, strength under repeated loads, high stiffness, low density, and high damping should be added the requirement of material and structural constancy or integrity.

4. Structural foundations

So far we have been concerned with the materials and structural forms used above the foundation level of a structure. How important are wind loads for foundations themselves? In tall, massive structures the foundations carry the overall overturning forces, whether these be dynamic or static, on the structure. In this sense an accurate assessment of the overall overturning forces is important.

In the not-so-slender thin shell structures which are prone to wind loads (and the cooling tower is in this class), the diffusion of wind loads into the foundations is complex and it is impossible to think simply in terms of overall turning forces and the like. Where there is an extensive circumferential foundation, as in the case of the base of a cooling tower, flexibility or inflexibility of foundations may be crucial to stresses in the shell; this is thought to be the case in the cooling tower, where bending stresses may be critically dependent on foundation support conditions. Thus where foundation loads are highly sensitive to structural form, an accurate knowledge of the nature of the wind loading is important.

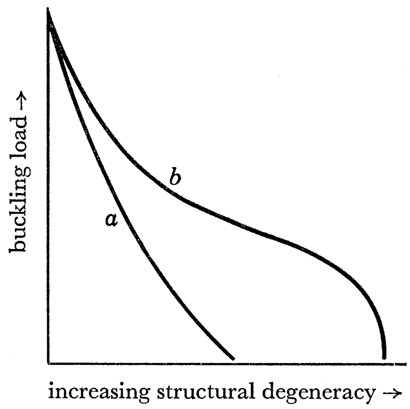

Figure 3. General deterioration of the stability of a structure due to increasing structural degeneracy: (*a*) worst arrangement of degeneracies; (*b*) best arrangement of degeneracies.

5. Materials

When one looks at the materials used in structures against wind loading one is struck first by the comparative lack of progress in the development of the materials themselves over the years. Although there is a continuing refinement in the use of materials, such as brick, concrete and steel, it is not at all clear that these materials are ideal for combating wind loads. More progress has been made in the mixed use of materials in building, as for example developments in the use of reinforced concrete, prestressed concrete, brick in-filled steel frames, and so on.

The cost of materials appears to be a very dominating factor in construction and cost considerations appear to override those of mechanical behaviour. Optimal design (at a number of distinct mechanical design limits) is not therefore practicable in many tall buildings and structures. Because of the cost of material it is very difficult to see for example a widespread use in buildings at this stage of sophisticated fibre-reinforced materials. We shall probably see more innovations in the secondary structures, such as the claddings of buildings, were the general wind pressures are small but locally intense at discontinuities such as the ridges and eaves of roofs.

6. Structural forms

The outlook for general building materials does not suggest many imminent innovations at the present time. The prospects of variants of more appropriate structural forms look more promising. The multi-storey building has been developed on the concept of supporting transverse beams on vertical columns, on a rectangular prism module. In design, these buildings are treated largely as a set of interconnected beams and columns. There is a need here, in dealing with wind-loading effects, for more macro-thinking about the inter-connected system infilled with shear walls and shear floors.

Again, an important wind-loading problem in many buildings is the local loading at the edges and corners of roofs and walls; more thought should be given to the avoidance of these intense local loads as, for example, by providing vents in ridge roofs.

Variants of structural form can also be used in alleviating aerodynamic instabilities. Vortex excitation of chimneys, for example, can be suppressed by providing a cylindrical spoiler around the outside of the chimney to modify the vortex shedding properties of the chimney. A helically straked spoiler round the outside of the chimney can also be effective. The problem of modifying the flow pattern of vortices shed in the wake of a building may also become important near the landing sites of vertical take-off aircraft in urban areas.

One is tempted to conclude from this that because of our limited choice of economic materials, wind-loads are most likely to be combated more effectively by developments of new structural forms. In these developments, we shall be looking for forms which:

(i) minimize aerodynamic drag loads,
(ii) minimize vortex shedding,
(iii) maximize structural stiffness,
(iv) maximize structural damping,
(v) minimize structural degeneracy.

Discussion

P. J. E. Sullivan (*Imperial College London*)

Before contributing to the interesting paper by Dr Chilver, I would like to add my compliments to the organizers for running such a well coordinated two-day meeting at the Royal Society. It is to the credit of the Chairmen that, in spite of the widely different interests of the invited speakers, the discussions were directed to the greatest benefit of the participants and a unity was maintained throughout the meeting.

I was most intrigued by the approach adopted by Dr Chilver on the role of structural materials and forms in aerodynamic stability. In designing structures to resist dynamic loads he considers the effect of the long term integrity of the material on the weakening of the structure. This is a realistic way of tackling these problems particularly if concrete is used.

The physical properties of concrete are continuously changing during its life time. These changes depend on a number of factors such as the properties and proportions of its constituent materials, i.e. cement, sand, aggregate and water, as well as the mixing, placing, compacting and curing of the green concrete. In general a well-designed mix improves with age as it hardens if it is cured in the right environment. If not enough attention is given to curing, the design strength of the concrete may not be reached and deterioration may set in either through adverse environment or overstress.

During the process of hardening exothermal reactions within the cement paste cause an increase in temperature depending on the size of cast and the surrounding formwork. With subsequent cooling, restraints on hardening induce internal stresses, and strains are locked within. These strains are increased by the shrinkage which may occur within the cement paste as the gel water evaporates and also in some type of aggregates. Additional strains arise from the difference in expansions and contractions of the constituent materials. These phenomena initiate cracks and gradual deterioration.

The use of steel rods, to reinforce the tension area of the concrete and thus increase the efficiency of the concrete, can introduce another deterioration factor. The steel reinforcement, in addition, controls the widening of existing cracks in the concrete to acceptable limits. No harmful effects will be experienced by an internal beam if the width of these cracks reach 0.1 to 0.3 mm. On exposed surfaces or in the presence of a corrosive environment such cracks are undesirable because of the risk of steel rusting. This would spall the concrete cover, exposing a larger area of steel to the aggressive environment. At the same time the reduction of the steel cross-sectional area increases the steel strain and further widens the cracks.

Crack initiation may follow certain possible lines of weakness in the concrete due to the mode of construction. Vertical and horizontal joints are necessary to separate one day's casting from another. If these joints are properly located and designed and also well supervised during construction continuity of the concrete is achieved. Poor standard of workmanship of a particular gang of concretors could result in the casting of a mass of concrete surrounded by four weak planes which could open up and sever from the rest of the structure under certain loads. This local failure could be the start of a much more serious overall collapse.

A finished concrete structure be it a multi-storey building framework, cooling tower or chimney, starts life with a number of cracks of all sizes even before any working load is applied. These cracks propogate or stabilize depending on conditions generally within the engineer's control.

The existence of these cracks and potential lines of weakness should be recognized when designing concrete structures, especially those which depend on the material integrity for their stability. Elastic theories applicable to homogeneous and isotropic materials would not give a complete solution to these problems and this was clearly demonstrated by Dr Chilver's model tests on cooling towers.

C. W. Newberry (*Building Research Station*)

Dr Chilver referred to the development of structural form and detail as possibly offering more scope than the development of materials in design against the wind. There is certainly some evidence of the modification of wind effect that can be obtained by the judicious control of internal pressure in a structure. Some 10 years ago it was noticed in the course of the Building Research Station study of wind effects on building that severe damage to low-pitched roofs in hurricane conditions appeared to be related to the presence or absence of roof ventilators; and that roofs which had ridge ventilators more often escaped damage. This led to the realization that a suitably fitted ventilator could lower the air pressure under a roof and so partially balance the external suction which is produced by a wind blowing over a low-pitched roof.

The idea was put into practice when, on a subsequent occasion, a school of light weight construction with a low-pitched roof had the whole roof structure lifted off by the wind and it was desired to reinstate the building in an economical manner. A model tested in the wind tunnel at the National Physical Laboratory indicated that, with a suitable ridge ventilator, the roof uplight force could be reduced to about a half of what it was in the original condition. This reduction in total uplift avoided the need for a stronger roof and for more secure anchorage of the structure to its foundations, and was achieved with a minimal increase in heating load.

Another interesting feature has emerged from an experiment at the Building Research Station. The full-scale measurements of wind pressure on Royex House, London, had indicated a force coefficient of about 0.8; which is, of course, much lower than would have been indicated in the usual wind tunnel test. The difference was attributed in part to the fact that the natural wind is turbulent whereas the wind tunnel flow is relatively smooth. A corroborating experiment on a small structure in natural wind has confirmed the lower force coefficient in the turbulent flow, but, at the same time, adjustment of the permeability of the structure has indicated that the force coefficient is reduced substantially by relatively small permeability, presumably as a result of bleeding air into the wake. Thus, normally permeable buildings may be expected to have a lower force coefficient than would apply to impermeable structures, and it might be justifiable in some cases to duct air into the wake of an air-conditioned (impermeable) building to reduce its total wind load.

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