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Front cover: Windmill in Essex (Photo: Harry Sowden)

Back cover: Model of a building form which absorbs more heat in winter than summer, devised by University of Southern California (Photo: courtesy of Royal Institute of British Architects, London)

The wind environment of buildings

Ken Anthony

Summary

As interest in the climatic aspects of the built environment develops, there follows a need to improve not only the techniques employed in the wind tunnel to predict conditions but also the establishment of tolerance criteria and the manner in which the results of tests are presented.

This article briefly describes the characteristics of wind significant to environmental conditions and reviews the current situation regarding tolerance criteria. It stresses the importance of the averaging interval of wind speed on the 'static' and 'dynamic' effects on people and presents a refinement to the Beaufort Scale to allow for these. Wind criteria ranging from 'comfort' to 'accident' conditions are offered in conjunction with frequencies of occurrence.

The approach and technical procedures adopted by the wind tunnel facility at the University of Bristol are outlined. The novel and flexible manner in which the results are presented, providing the architect or planner with a comprehensive and comprehensible view of the expected conditions, is described.

Introduction

One of the architectural developments of the last decade or so to which we can give our approval is the provision of open public plazas with their gardens and pools within dense building complexes. These are not, of course, a new idea. London is only one city which is famed for its old tree-lined squares but the new factor is the combination of open spaces with taller buildings. Without adequate environmental consideration, this can result in some loss of the very amenity it is intended to provide.

Most of us have heard of, or may ourselves have experienced, wind conditions in the vicinity of buildings which are uncomfortable, disturbing or even, on occasions, verging on the dangerous. Some building developments, mainly in city and urban locations, have earned themselves such notorious reputations that they are avoided by the less hardy members of the public.

Such instances, almost without exception, derive from inadequate attention to the potential problem at the project design stage. Faced with the virtual *fait accompli* of a completed building, it is very difficult to remedy such situations economically and in such a way that the solution is in sympathy with the original design.

In very recent years there has been a growing appreciation of the fact that environmental conditions around buildings are a design parameter and that the wind tunnel is an effective design tool in this relatively new context. In the UK, this realization has developed to the point where some local authorities insist on an environmental wind tunnel study as a precondition to granting initial planning consent. However, such requirements are usually inadequately specified because the present state of the art is not generally understood.

It is not only in the cases cited above that the wind tunnel offers help. It is currently being used from the very inception of large developments to assist in the overall planning; that is, to determine the optimum locations on the site of the various parts of the project both from the viewpoint of their forms and functions and the characteristics of the terrain within which they are to be placed. It is proving valuable also in providing the HVAC design engineer with information on the fluctuating pressures and their distribution over the faces of buildings for use in heating and cooling load assessment and equipment selection.

This article confines itself to the environmental aspects of wind around buildings and does not include structural loadings imparted by the wind nor the dynamic behaviour of structures with its effects on occupants. It outlines the current approach to the subject adopted in our close working relationship and continuing dialogue with Mr T. V. Lawson, Reader in Industrial Aerodynamics, Department of Aeronautical Engineering, Bristol University.

For a clear understanding of the terminology, procedures and techniques employed in this sphere of environmental science it is first necessary to describe briefly some of the characteristics of the wind itself.

The wind

The structure of atmospheric wind is complex. While recent fuller descriptions are to be found elsewhere,[1, 2] for the purposes of this article it is only necessary to look at some of its simpler properties.

Fig. 1 is a typical record of wind velocity at a point plotted against time and illustrates the manner in which the wind speed fluctuates with varying amplitude and time. Because of its intense variability arising from inherent turbulence, the magnitude of wind speed has inevitably to be considered as a random process describable only through its statistical properties.

The simplest of these is the mean value. This will depend upon the time over which the averaging is carried out. It is convenient to consider wind velocity as a long-term mean value upon which the shorter term gusts or fluctuating components are superimposed. From such a trace as Fig. 1, recorded over a period of say one hour, it is relatively easy to determine the mean value over that hour. However, within this period of time, both higher and lower values are evident. If one were to subdivide the hour into say ten-minute intervals and evaluate the mean values of these shorter term increments, one would expect a number of different results distributed about the hourly mean. Similarly, as the increment is progressively reduced to say one minute, three seconds, one second, larger populations of mean values are obtained with more and more dispersion relative to the long-term mean, because the intense peaks and troughs become included as discrete values the narrower the time increment becomes.

These short term values form statistical populations from which it is possible to calculate, through their probability density functions (p.d.f.), the probability of occurrence of any particular magnitude of gust, as shown in Fig. 2. In environmental wind work, as in other fields, one is usually more interested in the peaks of velocity rather than the troughs. Attention is therefore drawn to the upper end of the p.d.f.

It should be mentioned here that the very accurate assessment of maximum peak values and their probabilities demands a record long enough to prove its stationarity, that is, a length beyond which the statistical properties of the variable remain unchanged.

There are, however, economic reasons for accepting records less than their true stationary length. As a consequence, the 99 per cent values of wind speed are often derived and processed rather than the absolute true ones. The 99 per cent value is that which has only a 1 per cent probability of being exceeded, as shown in Fig. 2.

Another, but related, approach[1,2] is to consider the frequency domain of the random wind speed. This involves the spectral density function (s.d.f.) or power spectrum which is a means of describing how the wind energy is distributed across its entire frequency range. Empirical work has resulted in expressions for the spectrum for strong winds over different types of ground surface. That due to Harris[2] is illustrated in graphical form by Fig. 3.

A further property of importance is the gustiness of the wind. This is usually represented by the term intensity of turbulence, expressed as the ratio between the standard deviation (s.d.), or more usually in this context, the root mean square (r.m.s.) of gust speeds and the long-term mean value of the wind speed. There is always some turbulence in natural wind even over the smoothest of terrains. Around buildings it is usually intense, particularly in urban and city situations.

It is generally known that mean wind speeds increase with height above the ground. There are a number of empirical expressions to describe this variation, known as the wind profile, of which the most commonly accepted is the power law. This has the form

$$\overline{V}(Z_1)/\overline{V}(Z_2) = (Z_1/Z_2)^{\alpha}$$

which relates the mean wind velocities, V, at any pair of heights Z_1 and Z_2.

The value of α varies both with the roughness of the terrain and the averaging interval of the wind speed. The greater the surface roughness, the greater will the wind profile be sheared through the boundary layer. It follows also that the terrain-induced turbulence decays with increasing height. In densely built-up areas, the ground plane is effectively displaced approximately to the general roof top level below which winds are extremely turbulent and no discernible profile law exists.[3]

These brief descriptions cover only a few of the characteristics of the wind itself but are, hopefully, sufficient to provide a general understanding of its nature.

Meteorological data

An essential ingredient of any wind study is the local meteorological data. Most, if not all, meteorological agencies throughout the world publish, as a matter of routine, standard wind data which are directly applicable to environmental wind studies. Wind roses, which describe graphically the percentages of time within which winds of various strengths blow from different directions, are useful for general appraisals of average annual conditions, but more relevant are the monthly tables.

These contain for each separate month, the number of hours during which, for each of eight or 12 wind directions, the wind strength is within prescribed ranges of speed. Fig. 4 is an illustration of such a table from data published by the British Meteorological Office.[4] Sometimes such tables are presented on a cumulative basis with wind speeds being defined as being in excess of given values instead of within ranges.

Some of the more 'sophisticated' meteorological agencies also record similar data subdivided into four or more three-hour periods of the 24-hour day (Fig. 5). This information is particularly useful in the study of buildings and their surroundings which have periods of intense use such as in the morning, at midday and again in the evening. Unfortunately, this information is not always published and may have to be specially requested and processed into an applicable form.

Care has to be exercised in applying meteorological data since, although the station from

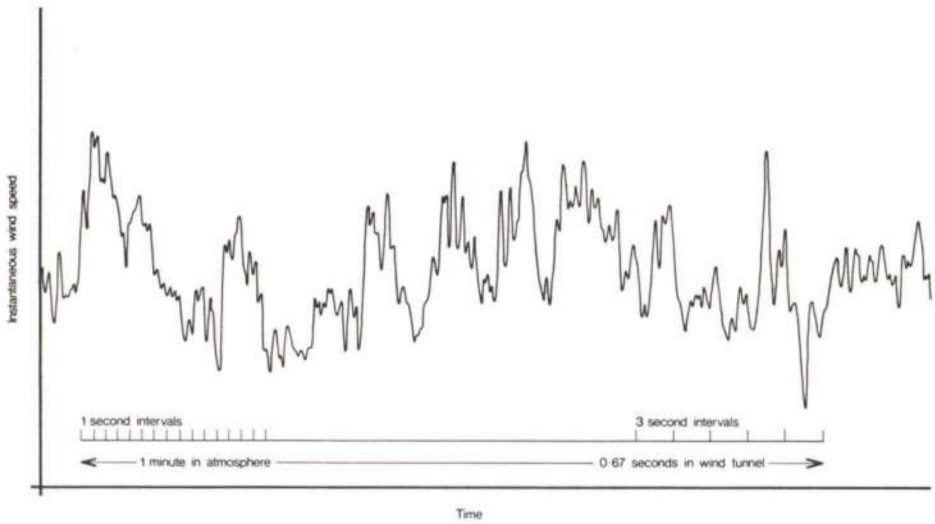

Fig. 1
Typical trace of variation of wind speed with time

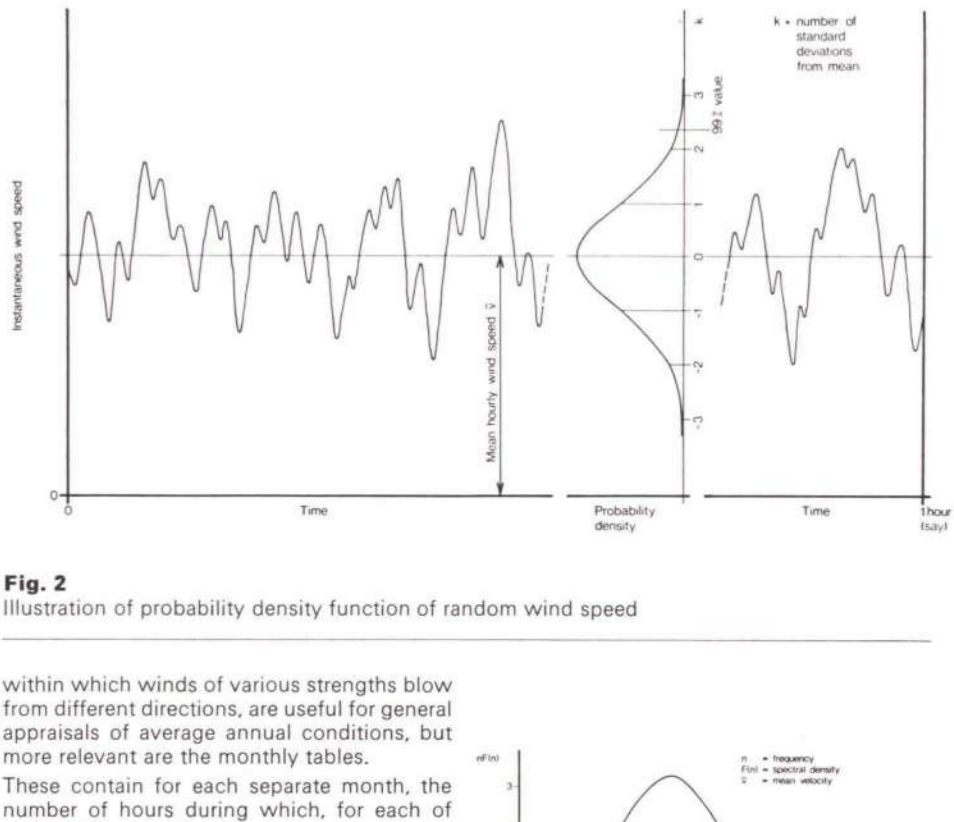

Fig. 2
Illustration of probability density function of random wind speed

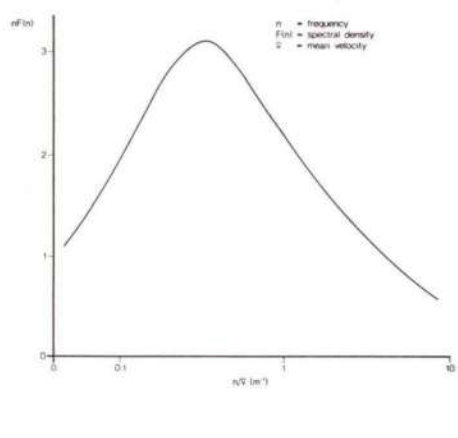

Fig. 3
Graphical representation of Harris' expression for power spectrum of longitudinal turbulence[2]

which the data originate may be close to the project site, differences in topography may well mean differences in wind characteristics. It is, therefore, advisable to obtain a description of the station location, its surrounding terrain, the anemometer situation and height and the sampling time over which the wind speeds have been averaged if these are not provided with the data, so that appropriate adjustments may be made. As far as the British data are concerned, the wind speeds presented in Fig. 4 are hourly means while gusts, because of the response characteristics of the anemometer used, are effectively means over three seconds.

Tolerance criteria

To be able to assess the success of a project in terms of the effects of its environmental climate on people, one needs a set of criteria against which to judge.

The criteria will, by necessity, be concerned with people and it is this which, because it is such a subjective matter, makes their establishment so difficult. Clearly even if it were possible, it would be a psychological mistake to create an environment so 'perfect' that all sense of climatic variation was eliminated.

Within the limits of wind environment, the problem of establishing criteria is compounded by the dependence of what may be considered acceptable on other climatic factors. One, of course, is temperature. Whereas a good breeze in the height of summer may be refreshing, the same wind in the depths of winter may well be decidedly uncomfortable. Similarly, humidity is an associated parameter. Humidity can bring with it conflicting wind requirements. Some air movement can alleviate the discomfort of dampness in the air but extremes of humidity, such as rain or sea-spray carried by high winds, are to be avoided if at all possible. Wind direction can, in itself, bring about changes in temperature and humidity. Winds from the sea, at least in summer, are usually cooler and damper than offshore winds.

It may be possible, given adequate recorded data on temperature, humidity and wind direction, to assess the joint probabilities of these with wind speeds. However, the combined nature of all these variables together

Mean wind speed knots	m.p.h.	Percentage number of hours with winds from 350°-010°	020°-040°	050°-070°	080°-100°	110°-130°	140°-160°	170°-190°	200°-220°	230°-250°	260°-280°	290°-310°	320°-340°	All directions Total
							DECEMBER							
Calm														2.1
1-3	1-3													8.4
4-6	4-7	0.9	1.5	1.4	0.6	0.7	1.5	2.9	1.6	0.7	1.0	0.9	0.8	14.5
7-10	8-12	0.2	1.2	1.3	1.2	1.5	2.9	6.5	3.5	1.8	1.1	1.4	0.8	23.4
11-16	13-18	0+	0.4	0.6	1.6	2.1	3.4	8.7	5.4	2.9	3.3	2.2	0.6	31.2
17-21	19-24		0.1	0.1	0.7	1.2	1.4	2.7	2.2	1.5	2.8	1.0	0.1	13.8
22-27	25-31				0.3	0.9	0.8	1.0	0.7	0.5	0.9	0.3	0.1	5.5
28-33	32-38				0.1	0.1	0+		0.1		0.4	0.2	0+	0.9
34-40	39-46										0+	0.1		0.1
41-47	47-54													
48-55	55-63													
56-63	64-72													
>63	>72													
TOTAL		1.1	3.2	3.4	4.5	6.5	10.0	21.8	13.5	7.4	9.5	6.1	2.4	99.9
								Percentage number of hours missed						0
							YEAR							
Calm														3.3
1-3	1-3													9.3
4-6	4-7	0.8	1.5	2.0	1.4	1.2	1.4	2.2	1.7	1.2	1.3	1.8	1.3	17.8
7-10	8-12	0.7	1.6	2.2	1.9	1.8	2.7	4.9	3.3	2.2	2.1	3.2	1.8	28.4
11-16	13-18	0.5	0.9	1.1	1.7	1.8	3.2	5.8	4.0	2.5	3.2	3.6	1.5	29.8
17-21	19-24	0.1	0.1	0.1	0.6	0.5	0.9	1.8	1.3	0.7	1.2	0.9	0.3	8.5
22-27	25-31	0+		0+	0.1	0.2	0.3	0.5	0.4	0.2	0.5	0.3	0+	2.5
28-33	32-38	0+			0+	0+	0+	0.1	0.1	0+	0.1	0+	0+	0.3
34-40	39-46				0+		0+	0+	0+	0+	0+	0+		0+
41-47	47-54													
48-55	55-63													
56-63	64-72													
>63	>72													
TOTAL		2.1	4.1	5.4	5.7	5.5	8.5	15.3	10.8	6.8	8.4	9.8	4.9	99.9
								Percentage number of hours missed						0.1

Fig. 4
Percentage frequencies of winds at selected stations. Manchester Ringway (British Meteorological Office table, facsimile copy)

Month	GMT	Beaufort force ≥8 (knots ≥34)	6-7 (22-33)	4-5 (11-21)	1-3 (1-10)	Calm (0)	Direction N 340°-020°	NE 030°-060°	E 070°-110°	SE 120°-150°	S 160°-200°	SW 210°-240°	W 250°-290°	NW 300°-330°
JANUARY	03	0.1	1.7	11.0	15.8	2.4	1.4	1.6	2.8	2.2	11.0	2.2	4.3	3.1
	09	0.1	1.6	11.4	14.8	3.2	1.5	1.2	2.5	2.5	10.9	2.7	4.9	1.6
	15	0.2	2.3	12.6	13.8	2.1	1.7	1.4	2.1	2.7	9.2	3.1	5.0	3.7
	21	0.2	1.6	11.3	15.8	2.1	1.6	1.5	2.5	2.5	9.9	3.2	4.5	3.2
FEBRUARY	03	0	0.9	8.2	16.8	2.3	2.5	2.3	2.1	2.3	8.5	3.2	2.2	2.8
	09	0.1	0.5	8.7	15.2	3.7	2.0	1.8	2.3	2.5	8.3	3.0	2.5	2.1
	15	0	1.3	13.4	12.3	1.2	2.5	2.4	2.6	2.0	6.3	3.5	4.2	3.5
	21	0	0.9	8.6	16.6	1.9	2.6	2.1	2.5	3.1	8.7	1.6	3.3	2.4
MARCH	03	0	0.7	8.9	17.4	4.0	1.9	2.9	4.7	4.7	7.4	1.8	1.6	2.0
	09	0	0.6	11.6	14.7	4.1	1.2	2.5	5.2	4.2	7.3	2.0	2.4	2.1
	15	0	2.4	15.9	12.0	0.7	1.8	2.6	4.9	4.7	5.7	2.6	4.1	3.9
	21	0	0.9	11.4	16.4	2.3	1.2	2.8	6.5	4.8	6.4	2.3	2.1	2.6
APRIL	03	0	0.5	7.0	19.6	2.9	2.6	2.9	1.7	2.2	7.9	2.8	4.7	2.3
	09	0	0.6	12.6	14.0	2.8	2.4	2.7	2.3	1.1	6.5	3.4	4.4	4.4
	15	0	1.5	15.2	12.9	0.4	2.2	2.5	3.5	1.2	4.6	3.4	7.0	5.2
	21	0	0.5	5.9	21.6	2.0	2.0	4.4	3.2	2.3	4.1	4.0	3.7	4.3
MAY	03	0	0.2	7.6	20.3	2.9	1.7	4.6	3.8	3.4	6.7	2.6	3.1	2.2
	09	0	0.8	13.8	14.7	1.7	2.1	4.6	3.4	1.9	5.8	3.2	3.7	4.6
	15	0	1.3	15.3	13.8	0.6	1.7	4.4	2.8	2.2	5.3	2.7	5.4	5.9
	21	0	0.4	6.6	22.4	1.6	0.9	4.9	4.5	3.3	3.4	3.5	4.7	4.2
JUNE	03	0	0	5.4	20.4	4.2	0.9	2.7	2.7	2.2	8.6	3.1	3.8	1.8
	09	0	0.2	10.1	17.9	1.8	1.6	1.8	2.6	1.4	6.1	4.0	7.6	3.1
	15	0	0.7	14.8	14.4	0.1	1.1	1.5	3.8	1.7	3.6	4.4	8.3	5.5
	21	0	0.1	6.2	21.8	1.9	1.5	2.4	4.1	1.6	3.2	3.8	6.0	5.5

Fig. 5
Average frequency of wind speed and direction at 0300, 0900, 1500 and 2100 GMT from 1950-59. Ringway (A meteorological agency table, facsimile copy)

with the different attitudes and responses that individuals have towards weather conditions around the world, make it very difficult if not impossible to set global or even national standards of acceptability.

There is a clear need for research on the physical and psychological aspects of this complex problem but at a simpler level, some progress is being made by considering criteria in terms of the wind alone.

In our work, we recognized early that there are two basic sorts of wind which may affect people. The first is what might be termed the 'dynamic' effect – the short gust which removes hats, reverses umbrellas and, more importantly, unbalances people. The other sort could be called the 'static' effect – the average wind condition which would be experienced as one walked across the site or stayed for a while at any particular point.

Furthermore, in the case of design stage investigations into potential conditions, it was felt that a tiered set of criteria, divided into 'acceptable', 'tolerable' and 'unacceptable' categories would enable the architect or planner to assess more readily the courses of design action open to him. 'Acceptable' conditions at any location need no action by the architect. 'Tolerable' conditions give the architect the opportunity to consider or call for remedial suggestions and have these tested in the wind tunnel. The finally decided course of design action will depend upon the intended use of the particular location, its importance to the success of the project, the influence that remedial measures may have on the overall architectural design and planning and, of course, the cost of the solution. If the conditions fall within the 'unacceptable' category, then some remedy is essential.

The relevance of 'frequency of occurrence' was also recognized and it was decided to attach percentages of time to each of the three categories.

Another aspect of criteria concerns 'time of day'. Conditions which may be unacceptable during peak periods of use, for instance at midday, may well be acceptable during night time hours when the development is vacant.

There is, as yet, very little quantitative data upon which to establish wind criteria. While much research has been undertaken by physiologists and bio-climatologists, it tends to be concentrated on the more extreme conditions to be experienced in the arctic, the tropics and space or indoors where air speeds are very low. The interest in conditions within the built environment has been initiated and is being fostered by practising engineers and architects who will, no doubt, themselves admit that they are not the best qualified to judge. Any guidance in this respect from experts in these fields would be gratefully received by those active in the application of criteria to building projects.

However, a start has been made. For the 'dynamic' effect of wind on people, we adopted the standard three-second averaged gust as the parameter in our early work. The initial associated velocities and frequencies of occurrence in each criterion category, admittedly chosen more by intuition than experience, are given in Fig. 6. These were later presented by Lawson[5] at a symposium on external flows, at Bristol in 1972. Melbourne and Joubert[6] have observed in full scale situations that gust speeds of the order of 23 m/sec are sufficient to physically unbalance able-bodied pedestrians and suggest that from an 'accident' or 'danger' viewpoint, one criterion worthy of adoption is that gust speeds in excess of this value occurring once a year should be considered unacceptable. In addition, they have adopted a 'comfort' criterion which defines as unacceptable gust velocities in excess of 15 m/sec for 1 per cent of the total time.

At the Bristol symposium, Hunt and Poulton,[7] who had commenced studies on the interaction of the dynamics of wind and walking, suggested that the much shorter averaging interval of between 0.1 and 0.5 seconds is significant but did not offer any associated wind speeds. They did place emphasis upon the intensity of turbulence as a factor, especially at the lower mean wind speeds because of the consequent eye irritation and disturbance to clothing and hair. At higher mean velocities, it becomes more a matter of drag forces on the whole body and the necessary power to overcome them.

Averaging Interval	Wind speed and frequency	Criteria		
		Acceptable	Tolerable	Unacceptable
3 seconds	Beaufort	< 6	7 - 8	> 9
	Velocity m/s	< 14	14 - 20.5	> 20.5
	Hours/week	all	< 1	$> 7\frac{1}{2}$
	% of time		< 0.6	> 0.3

a

Averaging Interval	Wind speed and frequency	Criteria		
		Acceptable	Tolerable	Unacceptable
5 minutes	Beaufort	< 3	4 - 5	> 6
	Velocity m/s	< 5.5	5.5 - 11	> 11
	Hours/day	all	< 1	$> \frac{1}{2}$
	% of time		< 4	> 2

b

Fig. 6
Early tolerance criteria

Beaufort range	10 minute mean wind speed, m/s	Effects
0	0 - 0.4	Calm. Smoke rises vertically.
1	0.5 - 1.5	Smoke drifts
2	1.6 - 3.3	Wind felt on face. Leaves rustle.
3	3.4 - 5.4	Hair disturbed, clothing flaps. Light flags extended.
4	5.5 - 7.9	Dust and loose paper raised. Hair disarranged.
5	8.0 - 10.7	Wind force felt on body
6	10.8 - 13.8	Difficult to walk steadily. Open umbrellas used with difficulty. Hair blown straight
7	13.9 - 17.1	Inconvenience felt when walking
8	17.2 - 20.7	Walking progress impeded. Gusts disturb balance.
9	20.8 - 24.4	People blown over in gusts

Fig. 7
Land Beaufort scale

It seems, from the albeit limited information available, that the short duration gusts are significant and that wind speeds of about 20–23 m/sec constitute an upper bound to the 'dynamic' criteria. However, it is less clear what constitute acceptable frequencies of occurrence.

For the 'static' effect there is less guidance. The criteria originally set up on one of our early projects were based on five minute mean values and are presented in Fig. 6. Melbourne and Joubert do not appear to have considered the longer term means. Wise and Penwarden[8] and Penwarden[9] have suggested that at a speed of 5 m/sec dust is raised and wind becomes annoying, at 10 m/sec it is definitely disagreeable and that at 20 m/sec it is likely to be dangerous. The averaging interval of these velocities was not specified but there is good reason to believe that they are 10-minute means. Hunt and Poulton,[7] in studying the energy consumption measured through the rate of breathing when walking and running against the wind, suggest an acceptable level of 5 m/sec at which wind speed the increase in energy expenditure over that in still air is only about 12 per cent, but at 14–17 m/sec the energy requirement is doubled.

More recently, Hunt has proposed a criterion based on the intensity of turbulence arising out of experiments on reactions of people subjected to various conditions in a large wind tunnel.

In our work, we have adopted the Beaufort Scale to define ranges of wind speed. This may at first seem archaic but has proved to be most useful in a number of respects. The original scale formulated in 1805 has been adapted to describe the effects of wind to be seen and felt by people ashore rather than at sea. This 'Land Beaufort Scale' is presented in Fig. 7. Its main advantages in use are that it is illustrative of the effects of different wind speeds when introducing and discussing the subject of environmental wind with architects and clients, and it provides a convenient and recognizable shorthand in the processing of data and the presentation of results.

All the criteria so far mentioned and quoted have used the Beaufort Scale as a basis, but none of them accounted for the averaging intervals associated with different effects on

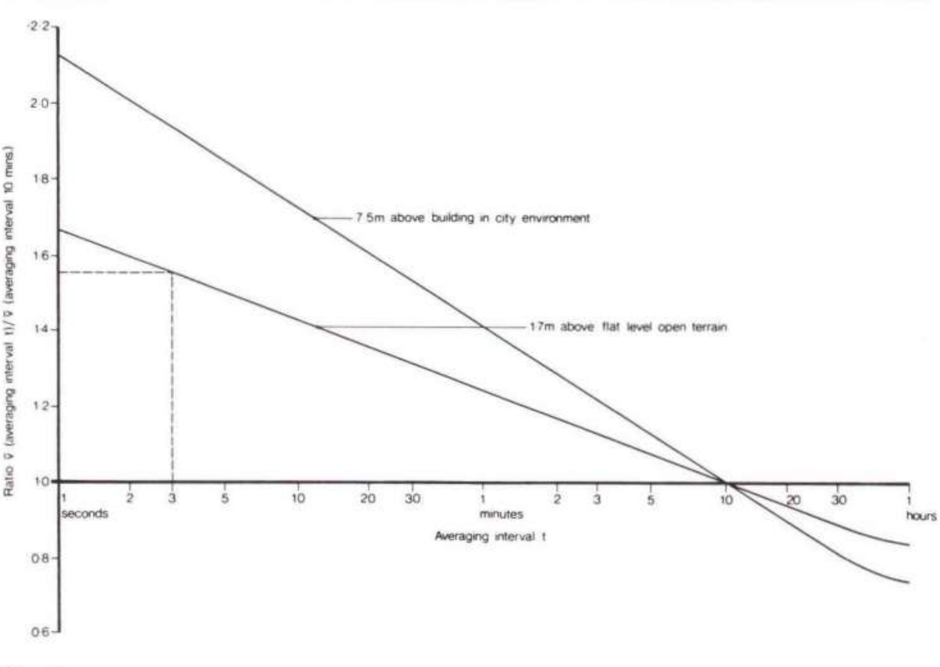

Fig. 8
Relationship between wind speeds of different averaging intervals for two particular situations

people within the Beaufort ranges. We have already seen the significance of the averaging intervals. In establishing his scale, Beaufort used fairly crude measuring instruments with the result that the averaging interval of his quoted wind speeds was about ten minutes. Remembering that wind speed has the appearance of Fig. 1, within the 10-minute period over which each Beaufort wind speed was averaged, there will be shorter period peaks of velocity in excess of the 10-minute mean value. For example, 13 m/sec is considered in the straightforward Beaufort Scale to be at the top of Force 6 but associated with this 10-minute mean velocity, there will be short gusts of say 20 m/sec which without correction appear as near the top of Force 8.

In order to utilize the Beaufort Scale effectively, this point must be recognized and allowed for. To do this, resort has now been made to the data published by ESDU[10] from which the relationships between wind speeds of different averaging intervals may be assessed. Fig. 8 illustrates the relationship for strong winds for two different situations. As turbulence varies with ground roughness and height, there is clearly no unique curve for Fig. 8. From the family of curves that one could draw, we have selected as a basis the one applicable to a height of 1.7 m (head height) over flat level terrain. Fig. 9 represents the influence of averaging interval on the Beaufort Scale for this particular circumstance. The information contained in Figs. 8 and 9 now enables any appropriate duration wind speed to be considered and any meteorological data to be used whatever averaging interval it employs. The original wind speed criteria adopted for our early projects, Figs. 6a and 6b, have now been rationalized and simplified into a standard form:

Unacceptable – for wind speeds greater than Beaufort 6 for
- >2.8 per cent of the time (>20 hours/month) – designated 'U'
- >2 per cent <2.8 per cent of the time (>14.4 <20 hours/month) – designated 'u'

Tolerable – for wind speeds greater than Beaufort 4 for
- >5.6 per cent of the time (>40 hours/month) – designated 'T'
- >4 per cent <5.6 per cent of the time (>28.8 <40 hours/month) – designated 't'

Acceptable – for wind speeds less than Beaufort 4 all the time.

These contain the entire range from mean (comfort) speeds of less than 5 m/sec to gust (accident) speeds in excess of 22 m/sec.

These criteria are, of course, able to be adjusted according to any particular project circumstance. On a number of recent projects, we have established wider ranges of criteria with additional categories in which both the wind speeds and frequencies of occurrence have been modified to suit the project use and the general climatic conditions. It is felt that initially the criteria should be fairly stringent so that critical areas can be identified for further, more detailed, consideration. We have also begun, in a simple way, to take account of the relationships between wind speed, temperature and humidity.

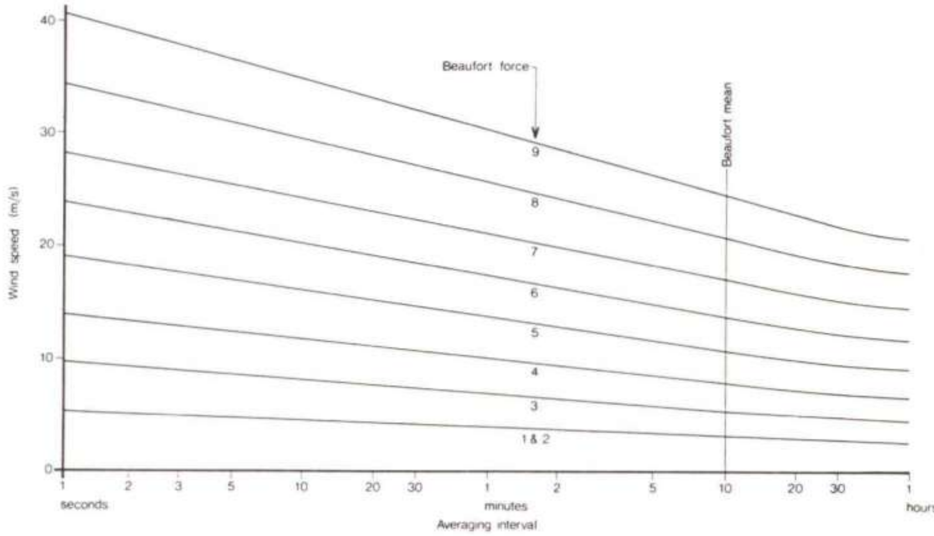

Fig. 9
Relationships between Beaufort ranges and averaging interval of wind speed

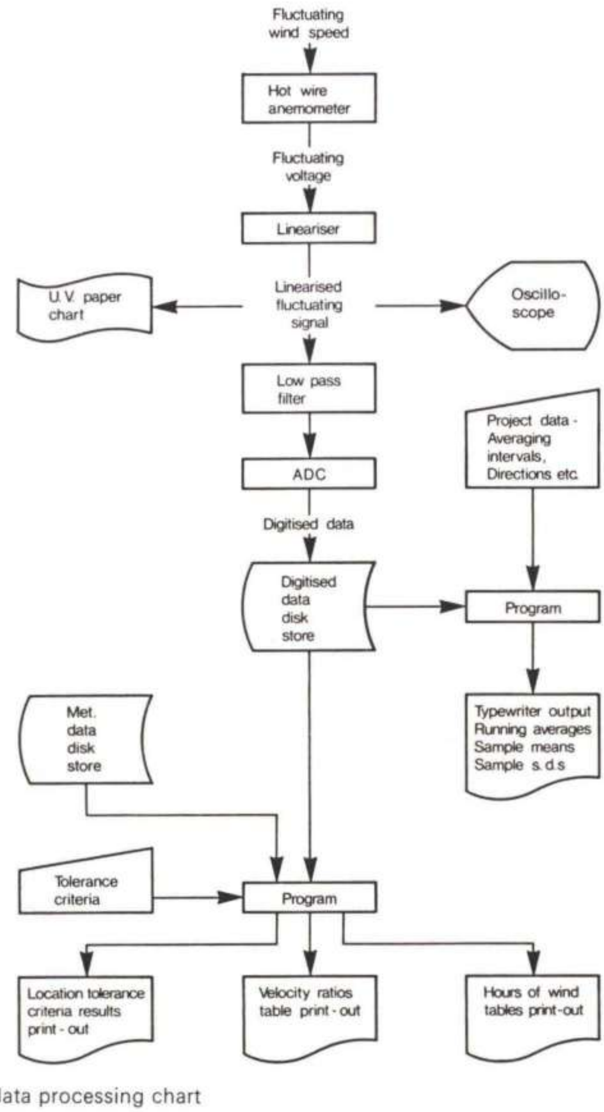

Fig. 10
Diagrammatic data processing chart

The wind tunnel and models

Reliable testing for environmental effects calls for a number of particular requirements within the working section of the wind tunnel.

Perhaps the most fundamental of these is that the natural wind approaching the site be modelled as accurately as possible. The two main features which characterize the natural wind are its profile and its turbulence properties. The two are inseparable because they arise in reality from the same source, namely the shape and size of the 'texture' of the ground.

In the wind tunnel, these are usually initiated by the presence, upstream of the model, of such devices as grids and 'shark's teeth' turbulence generators. Additionally, it is usual to 'roughen' the upstream floor of the tunnel with solid blocks appropriate to the surrounding terrain. These means alone call for considerable upstream lengths and large working sections since the entire boundary layer is simulated. Such large wind tunnels are expensive and space-consuming. At Bristol University, Cook[10] recently devised a technique which combines the grid and roughness elements with a step in the tunnel floor. This simulates the lower third of the atmospheric boundary layer with similar accuracy and allows models of around 1 : 250 linear scale to be accommodated in the 1 m by 2 m working section of the Bristol tunnel without blockage correction problems.

The choice of linear scale of the model is also important. Apart from its appropriate size within the working section, other considerations are the accuracy of the modelling of the surface details of the buildings and the ability to survey the project comprehensively in the wind tunnel. Surface features can influence the environmental wind flows significantly.

Buildings with strong vertical emphasis, achieved through deep vertical grooves or projections, augment the drawing down of wind from above and its deflection, often at increased velocity, on to the low level public spaces. Buildings with deep horizontal texture, such as that provided by balconies, tend to reduce the velocity of the downdraught but make it more turbulent. Such balcony areas would most probably be points of interest in an environmental wind study and must, therefore, be modelled.

The models themselves are normally made of plywood, but virtually any stiff material is suitable. In cases where one needs to study the wind conditions within the structure, for example in arcades or below plazas, transparent acrylic plastics are used to provide the necessary visibility. If it is envisaged that pressure measurements may be called for at some time during the test series, the model maker must be advised so that he can design the model accordingly. It is often difficult to modify an existing model to accept pressure tappings.

Architects' drawings comprise the basic information from which models are made, but in order to simulate the surroundings, detailed street maps with present and future building heights should be supplied. Particularly useful are sets of oblique aerial photographs of the site. It is possible, of course, to obtain all the information needed from stereo pairs of photographs but this calls for special equipment and skills which are relatively expensive and time-consuming. Most universities would have such facilities however.

In most environmental wind tunnels, to simulate different wind directions, the model and its immediate surroundings are mounted on a turntable set into the tunnel floor. At Bristol University, the turntable has a diameter of 1.9 m within which the site surroundings are modelled accurately. Upstream of the turntable, the general outer terrain is represented by a number of blocks of various sizes and shapes. Any feature of significant influence, such as a large building, embankment or hill, is modelled at the appropriate wind direction.

The wind speed at which the tunnel is run is not very critical provided that the model shapes are not Reynold's Number dependent. The main criteria are that the resulting 'signal-to-noise' ratio of the instrumentation should be acceptable and that the ambient wind noise should be tolerable to the technicians. The point at which the tunnel wind speed is established is termed the reference point and its position is selected such that the wind at this location is not influenced by the presence of the project in question. This usually results in the reference point being some way above and to windward of the highest element in the complex.

The relationship between the velocity scale, V_s, (ratio of wind tunnel reference velocity to full scale reference velocity) and the linear scale, L_s, leads to the concept of time scale, T_s, such that $T_s=L_s/V_s$. This time scale parameter is of the utmost importance in the measurement of wind speeds of differing averaging intervals and of power spectra. A linear scale of 1:250 together with a velocity scale of 1:2.8, say, leads to a time scale of 1:90 which means that in effect the fluctuations in tunnel wind speed occur 90 times as fast as in the atmosphere. A full scale three-second mean becomes equivalent to a 1/30 second mean in the wind tunnel. Clearly, to estimate mean values over 1/30 second, one has to measure a number of values of wind speed at a frequency of 90 Hz or more depending on the required accuracy. In some instances, one is interested in one-second full scale averages and so the frequency of tunnel measurements must be higher still. This calls for rather special instrumentation and technique.

AVERAGING INTERVAL MINS	SECS	LOCATION	WIND DIRECTION 0	30	60	90	120	150	180	210	240	270	300	330
	3	28	59	42	27	73	112	111	64	85	107	117	113	86
10		28	13	5	3	10	45	27	10	25	32	48	43	27
	3	29	76	106	179	187	179	144	173	187	185	144	168	170
10		29	20	53	72	84	68	55	57	79	86	58	61	49
	3	30	74	139	144	129	101	59	75	113	78	46	51	69
10		30	23	56	60	67	33	13	19	29	29	18	17	23
	3	31	64	126	129	119	82	87	166	202	145	86	59	56
10		31	15	46	48	44	21	20	45	73	81	42	22	14
	3	32	36	45	69	130	94	63	123	144	58	83	42	59
10		32	5	4	6	29	35	16	43	34	9	31	10	15
	3	33	34	67	76	54	40	32	100	94	63	75	91	75
10		33	4	22	27	19	12	8	11	21	17	34	42	19
	3	34	49	69	70	117	81	58	60	86	103	96	114	60
10		34	7	19	25	56	30	10	12	23	32	48	52	13
	3	35	47	34	58	56	37	28	26	71	69	82	67	37
10		35	10	11	22	14	5	3	4	13	18	35	32	4
	3	36	142	184	169	136	119	187	196	264	209	113	87	105
10		36	56	69	74	66	33	77	94	131	73	37	28	40
	3	37	109	227	169	183	125	60	82	98	88	81	50	72
10		37	47	108	83	81	44	21	33	34	39	29	14	22
	3	38	213	150	127	136	40	125	177	229	105	119	114	169
10		38	128	87	76	61	8	49	93	117	49	48	33	73
	3	39	144	188	175	213	136	225	279	225	149	141	72	112
10		39	72	86	94	117	36	74	159	132	84	75	24	29
	3	40	80	98	103	99	186	165	206	235	140	145	133	94
10		40	36	37	28	33	51	46	57	122	76	72	49	19
	3	41	77	90	113	14[illegible]	98	69	50	127	120	120	91	55
10		41	24	21	30	56	34	18	14	41	61	54	36	24
	3	42	97	83	90	127	113	141	141	205	143	155	184	79
10		42	37	17	19	44	40	40	41	100	75	75	71	36
	3	43	139	137	86	101	81	133	193	196	99	131	102	90
10		43	54	59	26	25	21	40	72	63	32	43	37	24
	3	44	74	105	126	97	90	159	178	178	55	60	87	91
10		44	23	43	38	43	35	52	62	76	17	15	32	30
	3	45	129	125	77	86	38	110	101	86	60	79	45	95
10		45	50	44	27	23	5	26	35	33	28	29	12	20
	3	46	82	76	133	132	140	111	151	233	87	64	73	76
10		46	26	22	35	48	43	26	47	77	32	11	18	25
	3	47	39	25	50	70	61	11	12	42	38	42	29	36
10		47	4	1	9	11	6	0	0	3	4	4	3	4
	3	48	216	221	185	183	120	142	147	146	81	100	80	158
10		48	111	128	101	91	38	56	63	57	37	29	18	56
	3	49	99	132	101	101	150	178	170	114	89	60	76	96
10		49	29	39	26	43	65	77	44	33	25	16	22	37
	3	50	15	15	21	17	25	80	31	48	70	56	35	31
10		50	0	0	1	3	3	37	5	10	14	15	7	4
	3	51	36	38	43	99	150	50	41	100	115	164	121	88
10		51	5	4	7	24	42	9	7	18	29	49	47	25
	3	52	118	153	154	122	127	130	129	128	127	129	177	188
10		52	48	59	68	56	57	51	49	52	58	48	70	76
	3	53	111	144	122	129	109	124	128	149	149	121	103	145
10		53	59	61	55	48	44	44	57	58	59	49	49	61

Fig. 11
Velocities at locations expressed as percentages of the reference velocity. Computer print-out

Instrumentation, technique and results presentation

The procedure adopted at Bristol for a typical environmental wind study and the process originating from the fluctuating wind speed through to the printing of results is expressed diagrammatically in Fig. 10. Prior to any measurements being made at the selected locations, the simulation of the approaching wind characteristics is checked by measuring the power spectrum at the reference height. This is superimposed upon Harris' representation, Fig. 3, for the particular terrain. Only when there is close agreement does the test begin.

The instrument generally used in the measurement of rapidly fluctuating flow is the hot wire anemometer. The one used at Bristol is of the constant temperature type with a response of up to 100 KHz. The fluctuating voltage output from this type of anemometer is not directly proportioned to air velocity across the entire range. The emanating signal has to be passed through a 'linearizer' before being processed further. The sensing head of the anemometer is very small – hardly larger than a match head – and is carried by a slender arm attached to a carriage in the roof of the wind tunnel so that it may be 'navigated' from outside in any of three orthogonal planes simultaneously.

In order to evaluate mean values of wind speed of whatever averaging interval, the fluctuating voltage from the linearizer is then sent through a low pass filter. This effectively filters out all frequencies higher than the one corresponding to the averaging interval of interest. From the filter, the fluctuating signal is passed to an analogue/digital converter, ADC, which transposes the continuous filtered data to digital form suitable for further processing by computer. Although adjustable independently of each other, the filter pulse rate and the ADC readings frequency are selected in conjunction with each other relative to the averaging interval of the wind data being processed and the accuracy of the averaging operation considered necessary.

The digitized data then passes automatically to disk store. To the right of Fig. 10, it passes direct to the computer, having been identified by project data entered on a typewriter console next to the operator. The project data consists of the averaging interval(s) required, location reference, wind direction reference, filter pulse rate and reference point height and is entered for each anemometer position and each wind direction. The computer then prints out, through the typewriter console, a table of mean values and standard deviations for each location and the reference point. This basic information, primarily for use by the laboratory staff, is automatically transposed to form a table of velocity ratios between location velocities and the reference velocity. Fig. 11 illustrates a typical velocity ratio table, a copy of which is always included in the final report. Its basic use is one of comparisons between conditions at each location point, but an interesting variation to this table has sometimes been offered to clients of projects which include such facilities as shops and restaurants. In the modified table, the location velocities are related not to the reference velocity but to the equivalent open country mean hourly wind speed which is the basis of daily synoptic charts published by meteorological agencies. Such a table could be given to particular tenants of the development – for instance the proprietor of a restaurant with open-air lunching and dining facilities who, by referring to the morning newspaper and the velocity ratio table, could assess the expected conditions that day.

At the completion of the anemometer survey, the accumulated data is processed further. At Bristol, a library of disk-stored wind data of the type illustrated in Fig. 4 for many town and city locations has been compiled for ready access. The meteorological data relevant to the site and anemometer output from the wind tunnel are then combined and processed by computer to produce 'hours of wind' tables. These set out, month by month and for the year as a whole, the numbers of hours at each location during the wind of each chosen averaging interval is expected to be within each Beaufort range. An extract from a typical print-out is given in Fig. 12. Months are numbered 1 to 12, while the year is assigned the number 13. Beaufort ranges are indicated as B2, B3, etc. The pairs of location reference numbers differentiate between three-second and ten-minute means in this case.

Although of considerable value for reference, these 'hours of wind' tables are hardly an ideal form in which to present the results to an architect or planner. In any case, it does not relate conveniently to the tolerance criteria previously established. In early projects the several thousand numbers were scanned by eye and placed in each acceptability category. Today, this tedious task is undertaken by the computer which then prints out a simple 'table of acceptability criteria results'. A part of a typical result is shown in Fig. 13. In this table, categories are denoted 'U', 'u' and 'T', 't' for unacceptable and tolerable conditions. Acceptable conditions are left blank in the tables.

This form of table has proved to be a most useful way of presenting the results. Conditions at any location for any month may be identified at a glance as can their variations throughout the year. It allows the architect to reconsider any location depending upon its sensitivity and use from month to month.

In those instances where the intensity of use of public spaces varies considerably with the 'time of day' and for which the appropriate meteorological records are available, it is possible to go even further. Fig. 14 is a copy of an extract of the results in tolerance criteria terms for one particular location of a project under three different plaza roof configurations. For each month there are seven separate 'time of day' classifications which illustrate not only how conditions vary throughout the year but also through the 24-hour day. From such a form of presentation it is possible to make balanced judgements. Conditions designated 'U' or 'u' could, for example, be tolerated if their incidence were mainly concentrated into the night-time hours. Thus, having identified critical areas and their expected troublesome periods of occurrence, this form of presentation does allow the original criteria to be re-graded if required.

MONTH 1

LOC.	B2	B3	B4	B5	B6	B7	B8	B9	B10
33	225.9	230.1	123.2	20.7	2.8	.0	.0	-.0	.0
33	581.8	20.8	.1	.9	.0	.0	.0	.0	.0
34	158.8	192.5	163.2	67.9	18.4	1.9	.0	.0	.0
34	515.3	80.4	7.0	.0	.0	.0	.0	.0	.0
35	269.5	215.6	103.2	13.0	1.3	.0	.0	.0	.0
35	587.1	15.3	.2	.0	.0	.0	.0	.0	.0
36	77.8	90.3	122.4	105.5	79.4	56.1	39.0	22.5	7.0
36	302.3	165.0	94.8	27.5	11.4	1.6	.0	.0	.0
37	147.2	186.1	161.8	68.5	24.5	10.9	3.0	.6	.0
37	470.4	102.1	26.6	3.5	.0	.0	.0	.0	.0
38	91.5	106.1	165.7	127.2	63.6	22.7	19.3	4.7	1.8
38	303.4	190.5	75.7	26.5	5.7	.8	.0	.0	.0
39	81.8	72.3	133.8	120.9	112.1	46.3	26.9	5.1	2.4
39	200.0	178.3	156.3	50.0	14.5	2.8	.8	.0	.0
40	84.3	103.6	151.1	111.2	89.3	35.0	18.5	7.5	1.8
40	300.5	153.1	107.5	33.5	7.1	.9	.0	.0	.0
41	125.9	141.6	172.5	109.8	41.5	10.0	1.5	.0	.0
41	412.0	154.5	34.6	1.5	.0	.0	.0	.0	.0
42	86.6	97.9	147.8	110.9	92.8	42.8	18.8	4.3	.6
42	280.1	176.7	115.6	27.5	2.8	.0	.0	.0	.0
43	95.5	144.5	176.0	101.4	53.6	20.6	8.4	2.6	.0
43	474.0	114.9	13.2	.5	.0	.0	.0	.0	.0
44	137.6	221.1	105.2	47.7	22.6	14.4	2.8	1.1	.0
44	520.5	58.6	21.9	1.6	.0	.0	.0	.0	.0
45	202.7	237.5	132.3	23.9	5.9	.4	.0	.0	.0
45	574.5	27.8	.4	.0	.0	.0	.0	.0	.0
46	141.7	193.5	148.9	55.6	28.5	14.0	13.7	4.9	1.6
46	518.1	61.2	21.6	1.8	.0	.0	.0	.0	.0
47	467.8	128.6	6.1	.2	.0	.0	.0	.0	.0
47	568.8	.0	.0	.0	.0	.0	.0	.0	.0
48	100.9	151.0	167.6	96.3	55.2	22.0	8.6	.7	.3
48	403.2	133.9	48.4	14.9	2.2	.0	.0	.0	.0
49	141.0	209.0	168.5	68.0	12.4	2.6	1.0	.1	.0
49	574.4	25.6	2.7	.0	.0	.0	.0	.0	.0
50	384.6	155.7	55.7	6.5	.2	.0	.0	.0	.0
50	547.9	.7	.0	.0	.0	.0	.0	.0	.0
51	175.5	117.5	140.3	101.0	44.8	16.4	5.7	.9	.5
51	533.1	63.6	5.9	.0	.0	.0	.0	.0	.0
52	80.6	91.3	185.6	133.4	78.4	26.2	5.5	1.7	.0
52	323.0	231.5	45.3	2.8	.0	.0	.0	.0	.0
53	87.7	97.0	184.8	121.3	83.5	19.4	8.0	.9	.0
53	339.3	225.9	36.5	.9	.0	.0	.0	.0	.0
54	.0	.0	.0	.0	.0	.0	.0	.0	.0
54	.0	.0	.0	.0	.0	.0	.0	.0	.0
55	.0	.0	.0	.0	.0	.0	.0	.0	.0
55	.0	.0	.0	.0	.0	.0	.0	.0	.0
56	.0	.0	.0	.0	.0	.0	.0	.0	.0
56	.0	.0	.0	.0	.0	.0	.0	.0	.0

Fig. 12
Extract from typical 'Hours of Wind' table

Two features of the facilities at Bristol University which, although appearing in Fig. 10 have not yet been mentioned, are the oscilloscope display and the ultra-violet sensitive paper chart. These are of value in describing to architects the characteristics of wind at locations on the site. They both offer a visual representation of the nature of the wind, the chart providing a permanent record and the display providing an immediate but transient description.

Throughout the entire investigation of a project, great emphasis is placed on the advantages of continuous liaison with and involvement of the architect, even to the extent of taking part in trying out in the wind tunnel various remedial measures to troublesome locations. The oscilloscope display is a particularly graphic way of illustrating 'before and after' conditions prior to more comprehensive re-study.

Conclusions

The environmental climate in the vicinity of buildings, particularly in the context of urban and city situations, is receiving increasing attention and, in this respect, the wind tunnel is proving itself to be an effective design tool. Its contribution extends from the inception of the project to the detail design of features of the buildings themselves. It can provide valuable information ranging from the wind regime over the topography of the site to the very local effects of wind on people.

It is believed that a very effective and flexible facility for the investigation and reporting of environmental wind conditions has been developed at Bristol. The 'static' and 'dynamic' effects are allowed for in line with current thinking. The Beaufort Scale is used to describe ranges of wind speed but has been reworked to allow for the influence of averaging interval on the values of peak velocities.

It is recognized that the wind aspects are only one of several climatic factors which should be included in any set of tolerance criteria. The criteria offered in this article have been formulated basically for urban and city situations to cover the range of wind speeds relevant to comfort at the lower end to accident at the other. They may be considered to be relevant to temperate climates but are tentative pending further data, particularly their relationships with other parameters such as temperature, humidity, activity and clothing. In dividing the criteria into 'acceptable', 'tolerable' and 'unacceptable' categories and presenting the results month by month, the architect is provided with an overall view of the conditions throughout the year and is afforded the opportunity to regrade the criteria if he so wishes.

The procedures employed and the close involvement of the architect throughout project investigations have proved most valuable in evolving designs which in many cases have eliminated all potentially troublesome conditions originally identified.

LOC	YEAR	MONTHS											
	3s10	JAN 3s10	FEB 3s10	MAR 3s10	APR 3s10	MAY 3s10	JUNE 3s10	JULY 3s10	AUG 3s10	SEPT 3s10	OCT 3s10	NOV 3s10	DEC 3s10
2	T T	T U	T U	T u	T u	T T	T T	T T	T T	T T	T T	T T	T u
3													
4													
5		t t											
6													
7													
8		t	t										
9													
10													
11		t	T										
12													
13													
14		T	T		t							t	t
15		t	t										t
16													
17	T	T	T t	T	T	T				t		T	T
18													
19	T t	T T	T T	T T	T T	T t	T t	T t		t t		T t	T T
20													
21													
22													
23													
24													
25													
26													
27	t	T	T	t	T							t	T
28													
29	T	T T	T T	T t	T t	T	T	t	T	T	T	T t	T t
30													
31		T t	T t		t					t		t	t
32													
33													
34													
35													
36	T t	T T	u T	T t	T T	T	T	t	T T	T T	T t	T T	T T
37						t							
38	t t	T T	T T	t t	t t	t			t t	t t	t	T T	T T
39	T T	T T	T u	T T	T T	T T	T	t	T T	T T	t T	T T	T T
40	t t	T T	T T	t t	T T				t t	T T	t	T T	T T
41													
42	t	T T	T T	t	T t				t	t		T	T t
43		t	T									t	t
44			t										
45													
46		t	T						t	t		t	t
47													
48		t	T T	t t	t	T T							

Fig. 13
Extract from typical table of acceptability criteria results (by month)

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Most credit for the development of the approach described in this article is due to Mr T. V. Lawson of the University of Bristol. Particularly appreciated is his continuous interest and work in helping to solve real design problems.

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Location	Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Averaging interval	Roof scheme
	A	A	T^{TAA}_{tTT}	A	A	A	A	A	A	A	T^{TAA}_{TTT}	T^{TAA}_{tTT}	A	5 min.	1
	t^{TAT}_{tTt}	T^{TAA}_{TTT}	A	A	A	t^{tAt}_{TTt}	t^{tAA}_{uTA}	u^{utU}_{TTT}	t^{TAT}_{tuu}	T^{TAT}_{TTT}	u^{uTT}_{tUU}	u^{TAT}_{uUu}	T^{TAA}_{TTT}	3 sec.	
5	A	A	A	A	A	A	A	t^{TAt}_{ttA}	A	A	t^{TAt}_{Tuu}	A	A	5 min.	2
	A	t^{tAA}_{tTT}	A	A	A	t^{AAt}_{Ttt}	A	t^{tAt}_{tTt}	t^{ttt}_{tTT}	t^{AAt}_{tTt}	t^{ttT}_{ATt}	T^{tAt}_{TTu}	A	3 sec.	
	A	A	A	A	A	A	A	A	A	A	A	A	A	5 min.	3
	A	A	A	A	A	A	A	t^{tAt}_{ttA}	A	A	A	t^{tAA}_{ttt}	A	3 sec.	

Key: $1^{2\,3\,4}_{5\,6\,7}$

1: 24 hour period
2: 12 hour daytime period
3: 12 hour nighttime period
4: 3 hour period centred on 0900 hrs.
5: 3 hour period centred on 1200 hrs.
6: 3 hour period centred on 1500 hrs.
7: 3 hour period centred on 1800 hrs.

Fig. 14
Extract from typical table of acceptability criteria results (including 'Time of Day')

Flatjacks and some of their uses

Poul Beckmann

It is often difficult to understand fully and hence properly ascertain the forces and deformations which arise in structures and, even when we think we have succeeded, it is sometimes inconvenient to have to accept the consequences. In those circumstances the solution to the problem may be to induce predetermined forces and movements into the structure and flatjacks offer a convenient means of doing this in many cases.

The flatjack and its basic hardware kit

The basic flatjack is a mild steel capsule, circular in plan and with a cross-section which is initially dumb-bell shaped. The dished portions are packed out with specially chamfered circular steel thrust plates or filled with resin mortar before the jack is placed between the surfaces to be jacked apart. When the jack is inflated with a liquid the hydro-static pressure is transmitted by the flat portions of the capsule through the thrust plates, or the mortar filling, to the jacked surfaces, whilst the toroidal rim of the jack deforms to allow the flat faces to move apart.

The capsule is usually made of two circular pressings welded together along the circumference. A special soft grade of steel, heat treated' after welding, is used in order to accommodate the substantial plastic strains which are necessary to allow the jack to open and close to the full extent of the depths of the rim. The material is about 2 mm thick.

At least one pipe connection is welded into the rim, and for many applications two are provided, offset at 90° to each other to allow easy venting during filling. One of these is subsequently capped off and the other provides the connection to the pump.

The flatjack was invented in 1934 by Freyssinet. It is marketed in the UK by PSC Equipment Ltd, who also offer an extensive jacking service to sites as well as advice to designers on applications. They supply limited numbers of standard sizes off the shelf and hold fairly substantial stocks of standard pressings which are welded up to order. This allows special arrangements of the connections, which are sometimes necessary, to be provided with minimum delay.

By cutting standard round jacks in half and welding in straight pressings it is possible to make oval jacks and similarly 'rectangular' jacks can be made using quartered standard jacks for the corners. These special shapes are however not manufactured in this country at present and have to be imported from France.

Flatjacks are usually inflated with a liquid similar to that used in the hydraulic brakes of a car. Where only a few jacks are involved this is usually done by a hand pump.

When a substantial number of jacks have to be pressurized simultaneously the volume of liquid to be moved becomes excessive for the hand pump which, being of positive displacement action, can deliver high pressures to small volumes only. In these situations a motor-driven pump is used. This is usually fitted with an adjustable 'blow-off' valve which enables the delivery pressure to be set to a predetermined value. This is often chosen somewhat above the jacking pressure to compensate for dynamic friction losses in the connecting pipework.

For most short-term uses the jacks are connected to the pump by 6 mm copper tubing. This is easy to fit as it is soft enough to be bent by hand and draped round obstacles much like electric cable.

Where the pipework will be exposed for considerable time to the 'slings and Acrows of outrageous fortune' which are inevitable on a building site, 10 mm steel tubing is usually employed. Both types of 'plumbing' are connected with compression fittings, which, particularly for the copper tubing, require some care and skill in installation and subsequent handling, if leakages are to be avoided.

In order to ascertain the jacking force, the fluid pressure in the jack must be known and this is measured by a manometer. To avoid errors from friction losses in the pipes the manometer is usually positioned immediately next to the jack, and a stop-valve is fitted just 'upstream' of the manometer spur so that the jack can be isolated from the pump and still have its pressure checked.

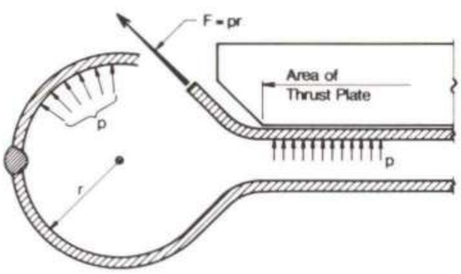


Fig. 1
Diagram showing how the thrust of a flatjack can exceed that corresponding to the contact area of the thrust plate

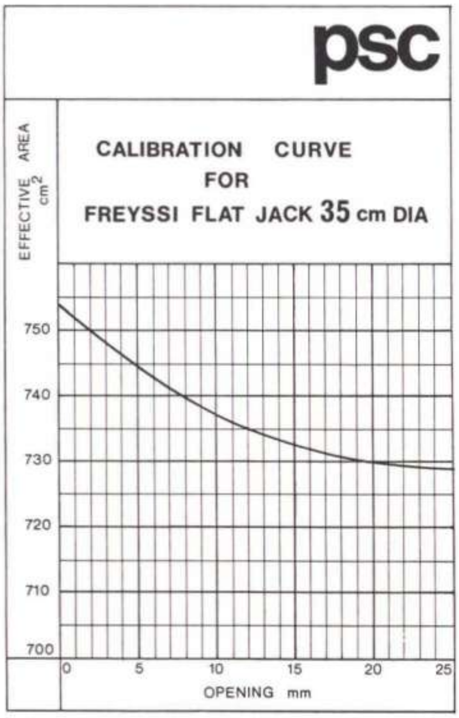


Fig. 2
(Courtesy PSC Equipment Ltd.)

Fig. 3
Hand pump and resin cylinder
(Photo: A' Court Photographs Ltd).

Operating limits

It is fairly obvious from the geometry of the capsule that the circumferential weld, which has to be made from the outside with no backing strip to help root penetration, is situated in a region of high strain during opening of the jack.

The maximum safe operating pressure will therefore to some degree depend on the amount which the jack is required to open. A single 'stroke' will obviously produce less work hardening than a series of 'ups and downs' so if repeated use is envisaged, lower pressures should be employed.

For ordinary uses the makers recommend a maximum pressure of 150 bars = 15 N/mm² and this is perfectly safe for a well-made jack. For applications where pressure has to be maintained for long periods, the pipe joints may however, in the absence of special precautions, prove to be the weak link in the chain and initial choice of a limit around 125 bars may avoid a lot of worry later.

The maximum recommended 'travel' or opening of a flatjack is equal to the depth of the rim, i.e. about 25 mm. If it is intended to re-use such a jack, it should be annealed after being re-compressed.

If a greater total travel is required, two or more jacks may be used in tandem.

There have been several instances in which these limitations either on pressure or travel have been unintentionally exceeded by considerable amounts without ill effects. This indicates a reassuring margin which must, however, not be used to 'advance the frontiers of technology' during the design stage, but should be reserved for possible site emergencies.

Capacity and calibration

The force exerted by a hydraulic jack is equal to its effective piston area multiplied by the pressure of the liquid. Whilst the latter can be measured fairly simply by the manometer, the effective area of a flatjack varies with the opening of the jack and is not a simple function of its manufactured dimensions.

When closed or nearly closed the effective area is somewhat larger than the contact area between the flat face of the jack and the thrust plate/mortar infill. This is due to the vertical component of the meridional hoop tension on the inside of the toroidal rim being transferred by shear and bending to the edge zone of the contact area.

The gain in effective area from this effect is proportionally greater for the smaller jacks, but cannot be ignored even for diameters of 300 mm and more.

For ordinary applications where extreme accuracy is not necessary, the manufacturers provide calibration curves for the standard range of jacks (70 mm–920 mm overall diameter with corresponding maximum thrust from 20 kN to 8680 kN). These curves show the effective area as a function of the travel and illustrate the decreasing effect of the hoop tension with increasing opening.

It is a fairly simple matter to calibrate a flatjack using a hydraulic press which has been checked against a proving ring, and this should be done when accurate knowledge of effective area is essential, and of course for non-standard sizes. The jack is filled and connected to its manometer and pump and, with its thrust plates, placed between the platens of the press, which are adjusted to allow the desired travel of the jack to occur. By inflating the jack and reading corresponding values of pressure on the jack manometer and load on the indicator on the press, the effective area can be deduced.

By increasing the pressure in the jack it is possible also to test it in the press to something like 25 per cent above the rated capacity and, if for reasons of limited space one is forced to use high pressures in the jacks and if the consequences of a failure could be serious, such pre-tested jacks should be specified.

For certain applications, such as resin filling, an initial minimum gap of about 3 mm is desirable. This initial opening can conveniently be done as part of the pressure testing in the same press.

Once a flatjack has been individually calibrated it can of course be used as a load cell itself and, whilst not capable of extreme accuracy, the combination of flatjack and manometer is inexpensive, can generally be inserted in a gap only 40 mm wide, is weatherproof and will function independently of any electronic gadgets.

Temporary and permanent incorporation in the works

Usually flatjacks are a temporary feature of the works. They are installed and inflated, the required force is induced in the structure and/or a specified gap is opened up and, after an interval to ensure that the situation is static, the gap separation is made permanent by steel wedges between the flatjacks, which may subsequently be removed and the gap grouted up. Alternatively the jacks are part of a temporary support system and are removed with it.

It does however happen that there is no room to insert wedges or no way of grouting the gap, and thus fill it permanently. In this situation there is a need to solidify the jack in its inflated state and thus turn it into a permanent packing piece. This can be done in one of two ways depending on whether or not the jack can be temporarily de-pressurized.

If, by temporary wedging or similar means, it is possible to release the pressure in the jack, it will, bar a negligible amount of elastic recovery, remain in its inflated shape. It will now be possible to replace the hydraulic fluid with cement grout, either by draining and re-filling or by displacement injection. The first method is much the simpler as the hydraulic fluid can be flushed out by an injection of solvent prior to grouting. The second method requires the jacks to be vertical or in a sloping position in order that gravity displacement of one liquid by the other can take place under pressure. The connections can be placed wherever convenient, provided they are continued inside the rim as small bore steel tubes to the upper and lowermost points so that the grout filling can proceed from the bottom of the jack and displace the hydraulic fluid without too much intermixing. Even so, considerable 'bleeding off' may be necessary until only neat grout emerges from the top connection.

An alternative is to have pairs of jacks in tandem of which one jack in each pair is left dry and flat during the jacking operation and, once the 'active' jack has been de-pressurized, is inflated with grout, flattening its partner in the process.

The handicap of cement grout as a permanent filling medium is that it is not capable of being pumped at the pressures normally used for activating flatjacks because it tends to dewater and cause blockages and PSC recommend a pressure limit of 75 bars. Epoxy resins, however, do not suffer from this limitation and a number of interesting techniques are possible using these latter-day magic potions.

There is however a basic difficulty to overcome: the normal cold-setting resins will harden just as happily in pipework and pumps as in the flatjacks themselves.

One solution to this problem is the 'resin cylinder'. This is a fairly long cylinder with bolted on, removable, ends which accommodate couplers for the standard 6 and 10 mm tubing. In the cylinder a tight-fitting piston is free to move from one end to the other. A 'dose' of filled resin with a setting time of two to four hours is placed in one end of the cylinder. The end is bolted on and connected with the shortest possible length of tubing to the empty flatjack via its close-coupled stop-valve. The other end of the cylinder is now connected to a standard pump circuit filled with hydraulic fluid. When the fluid is pressurized by the pump, it will force the piston along the cylinder and the piston, in turn, will force the resin into the flatjack. Once the required pressure has been attained, the stop-valve is closed and the resin cylinder and its plumbing can be removed and cleaned with solvent before the resin has set.

If it is feasible to locally heat the flatjacks to 100°–120°C there is a possibility of using a hot-curing resin. This removes the time limit on the operation and this is most valuable if many jacks are involved, needing individual pressure adjustments, but our experience so far has shown that there are many, very difficult, problems associated with this technique, even though they have been overcome in one large-scale application.

Examples of applications

The classical application of the flatjack is the release of large span concrete bridge arches from their centring. This can be a critical operation, for if during the process of dismantling the scaffold a non-symmetrical portion of the arch is left unsupported before the full weight is transferred to the abutments and thus the arch thrust mobilized, the dead load moments in the unsupported portion may become large enough to cause failure.

This problem is overcome by inserting flatjacks vertically in a joint formed in the crown of the arch. When they are inflated to exert a thrust equal to the arch thrust due to self weight, the arch will lift off the formwork which can then be removed in any convenient way. The gaps are wedged solid, the flatjacks may be grouted up or removed and the voids are grouted or concreted up.

This method also eliminates the moments which otherwise are induced into encastre arches due to the shortening of the arch under its axial thrust.

A recent notable example of this application is the Gladesville bridge near Sydney in Australia, which has a clear span of 305 m, and where 224 flatjacks in four layers were inserted at the third points of each arch to give a thrust of 65,000 kN and allowing a movement of 100 mm. The jacks were here used not only to provide the thrust, but also, by differential inflation, to control the position of it.

There are occasions when it is desired to induce a force which remains constant irrespective of deformations of the structure. This can be done by connecting flatjacks to a pressure stabilizer which will maintain practically constant pressure although the flatjack is expanding and contracting.

When the raking shores for the east end of York Minster were designed, there was concern about settlement of their foundations, and the fact that the over 20 m long steel struts could, within a day, vary 5 mm in length due to thermal movement, caused anxiety about local crushing of the stonework where the shores were built in.

To overcome these problems the base plates of the shores were each supported on two 480 mm flatjacks in tandem. The feedpipe between the pump and the jacks was connected via a spur to a nitrogen-filled cylinder, which, having a volume which was large compared with the volume changes of the flatjacks, would absorb these with negligible pressure variations. The nitrogen cylinders were, together with the pumps and manometers, housed under cover and protected from the worst of the diurnal temperature fluctuations. They were frequently inspected so that adjustments could be made for seasonal variations and foundation settlement. On one occasion however it was found, after a lapse of some time, that due to the settlement of a buttress during the underpinning operations, one base plate was resting hard on the steel packs which had been placed as 'emergency buffers' in case of jack failure. The steel packs were however eventually withdrawn with the manometer needle pointing well past the 200 bar mark and the jacks took over their function for the remainder of the work as if nothing had happened!

With the strengthening of the tower foundations of the Minster, the problem was to mobilize the bearing capacity of the new foundation areas without having to wait for further settlement of the existing fabric. This was achieved by placing a 600 mm thick nominally reinforced concrete pad under each of the new foundation blocks which were prestressed to the existing masonry, and by inserting flatjacks in slots created by inverted concrete troughs.

When the prestress had been stabilized and the tendons grouted, the flatjacks were inflated in steps to 35, 70, 88 and 105 bars successively, each pressure increment being applied when the downward movement of the lower pad had ceased. In this way the clay was compressed and the pore water allowed to disperse so that the new foundations would safely carry their share of the total load.

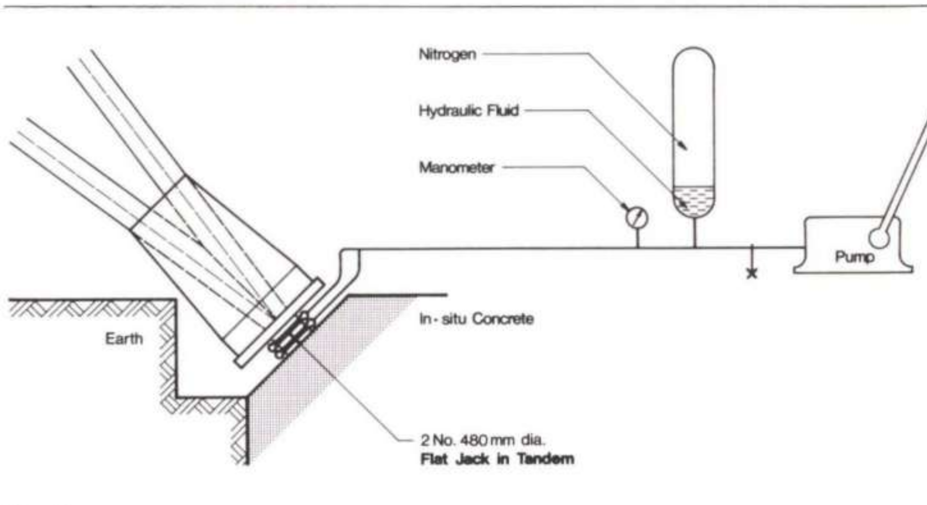


Fig. 4
Arrangement of flatjacks and pressure stabilizer for raking shores at York Minster

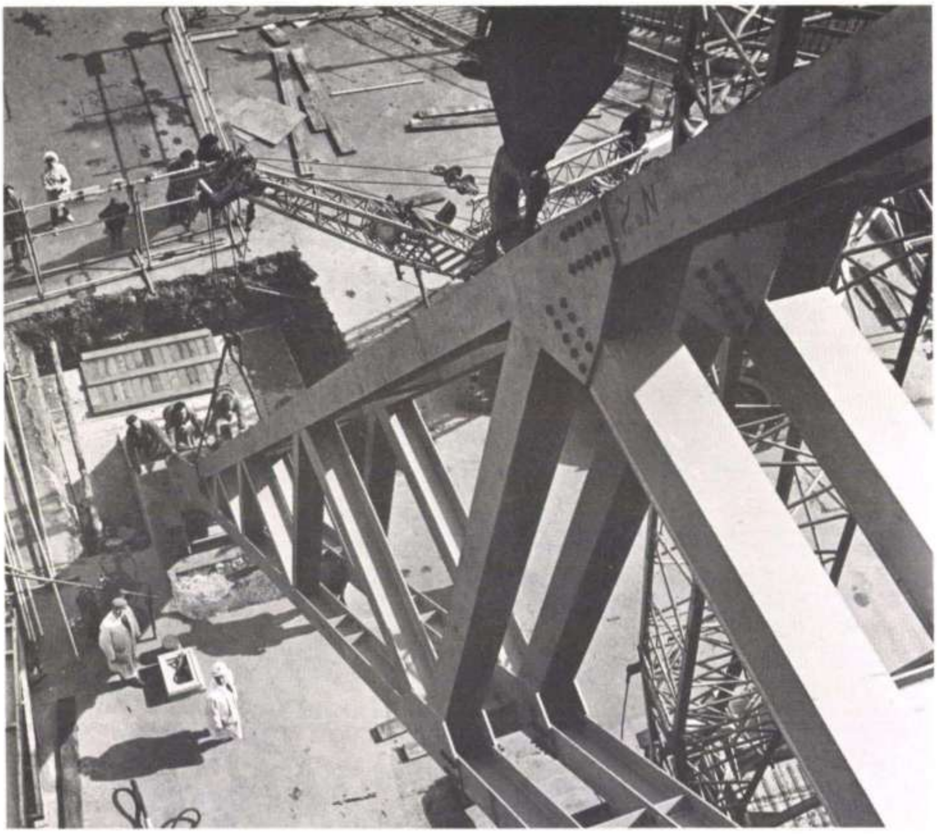


Fig. 5
Raking shore to east end gable of York Minster

Fig. 6
Placing 'sandwich' of tandem flatjacks and thrust plates under base plate of raking shore to east end of York Minster

(Photos: 5, 6 and 8 Shepherd Building Group Ltd.)

Fig. 8
Placing flatjacks and inverted concrete troughs prior to casting foundation extension to central tower of York Minster

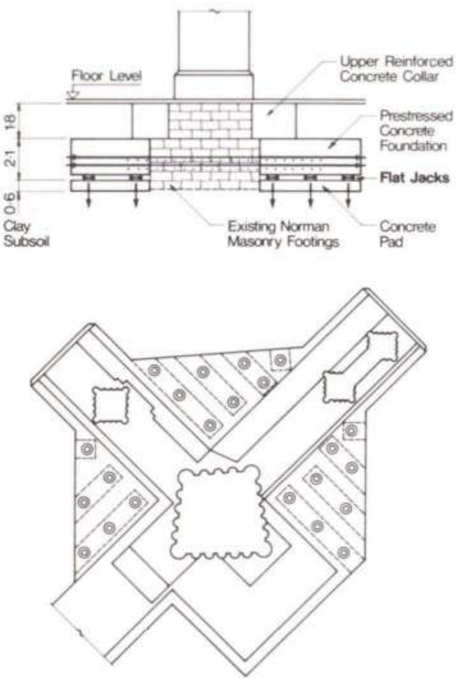
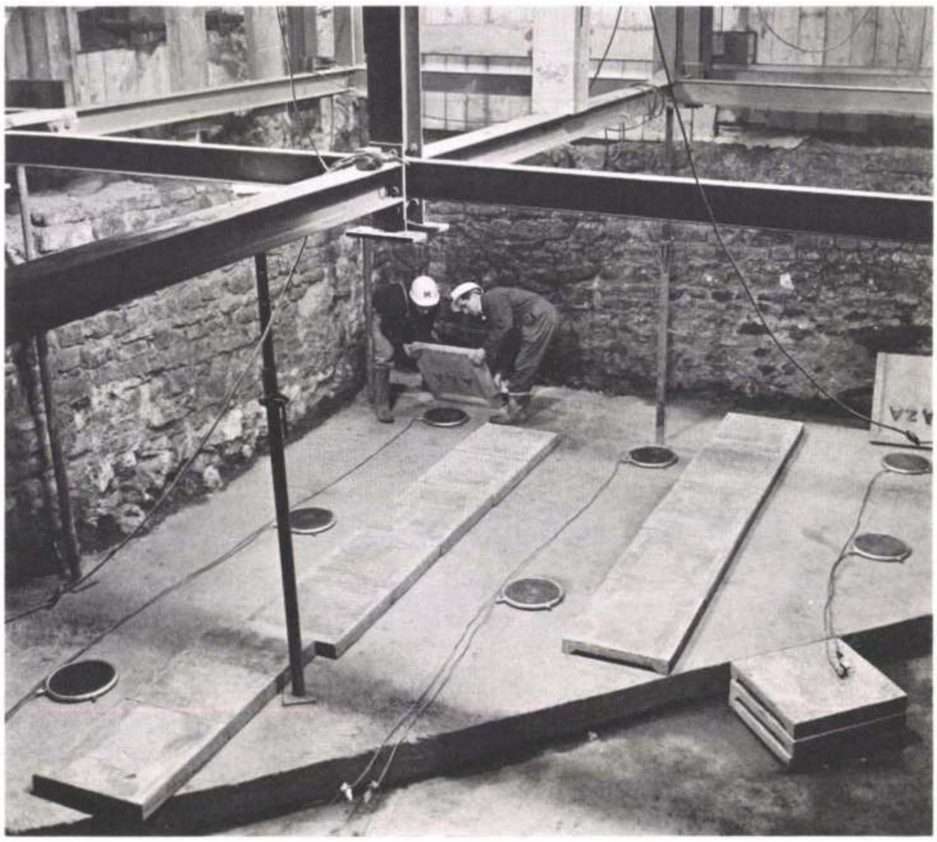


Fig. 7
Section and plan of flatjack arrangement for foundation strengthening to the central tower of York Minster



The gaps which developed between the upper foundation blocks and the lower pads were generally in the order of 20–25 mm but at one corner a movement of over 30 mm was measured. Despite the relatively low pressures a number of leakages occurred in the joints to the copper tubing. The layout of the plumbing however enabled the offending jacks to be isolated and in one or two cases they were withdrawn and replaced. At the end of the operation the gaps were grouted but the jacks were merely de-pressurized and left in, as they were surrounded by grout.

The same principle of introducing pre-determined forces into a statically indeterminate system was applied, albeit on a reduced scale, to one of our early South African jobs: the UK Pavilion on the Rand Centre in Milner Park near Johannesburg.

The guyed pylons which provide the wind stability had their baseplates placed on flatjacks. When the roof structure had been completed, the jacks were inflated so as to lift the pylons and thus pre-tension the guy ropes. When the calculated force had been achieved, the base plates were packed up on steel shims and the flatjacks removed prior to grouting of the gap.

This was an application of flatjacks in a context of lightness and elegance and, as such, in contrast to the more common, heavy duty use of these devices to control the movements of the sides of large basement excavations.

Speed of construction and other considerations often make it desirable and sometimes inevitable to strut the retaining walls nearly horizontally right across the full width of the basement. Such strutting will, however, shorten appreciably under the compression induced by the earth pressures, and in doing so will allow the sides of the excavation to move inwards.

Such movements could lead to extensive damage to adjoining property and to boundary roads and should therefore, as far as possible, be eliminated.

This can be done by inserting a number of flatjacks in tandem in the struts and inflating them to provide the appropriate forces in the struts. In this way the struts can be allowed to shorten while the flatjacks expand and thus keep the distance between the retaining walls constant.

One completed large scale example of this application is the basement to the Carlton Centre in Johannesburg which measures approximately 169 m by 133 m in plan with a depth of about 20 m, and where the bracing structure took the form of an octagonal ring rather than straight struts.

The current heavy-weight example of excavation bracing is at the Barbican Arts Centre where, at the time of writing, blocks of four 1080 mm diameter flatjacks in tandem have been installed at the ends of the tunnels which serve as bracing members for the 22 m deep excavation. Each block is designed to provide a thrust in the order of 13,000 kN and the jacks will at the end of the operation be solidified under pressure, using displacement injection with automatic control of the bleed valve. For reasons of access the inlet and outlet have to be adjacent to each other on the side of the jacks and, to enable proper displacement to take place, the connections continue inside the rim of the jack through nearly 90° to the top and bottom respectively of the jack when placed in the works.

Some years ago we were called in as advisers, when failures of some of the joints between the loadbearing precast concrete mullions in a multi-storey office block had resulted in the concrete façade structure being considered suspect. In order to eliminate all doubts about structural adequacy it was decided to transfer by jacking the load from the concrete mullions to new steel stanchions which were to be inserted immediately inside the mullions.

The problem here was that, in order to avoid punching shear failures in the floor slabs, all the steel stanchions in one vertical line had to take up load simultaneously, and on top of this the stiffness of the floor slabs and the cladding led to lateral load transfer so that, to be successful, jacking would have to be carried out on several consecutive vertical lines of stanchions at the same time.

Each vertical line of jacks was to be connected to a 'rising main' fed from its own pump, but it was considered impractical to have jacks tailor-made to exact size to enable them to exert the exact jacking force required at each floor when connected to their common rising main. The jacks were therefore arranged as pairs or singles of standard size, and this meant that on some floors the specified jacking forces would be achieved at much lower pressures than on others. It would therefore be necessary to gradually increase the pressure in the rising main and to turn off the stop-valves

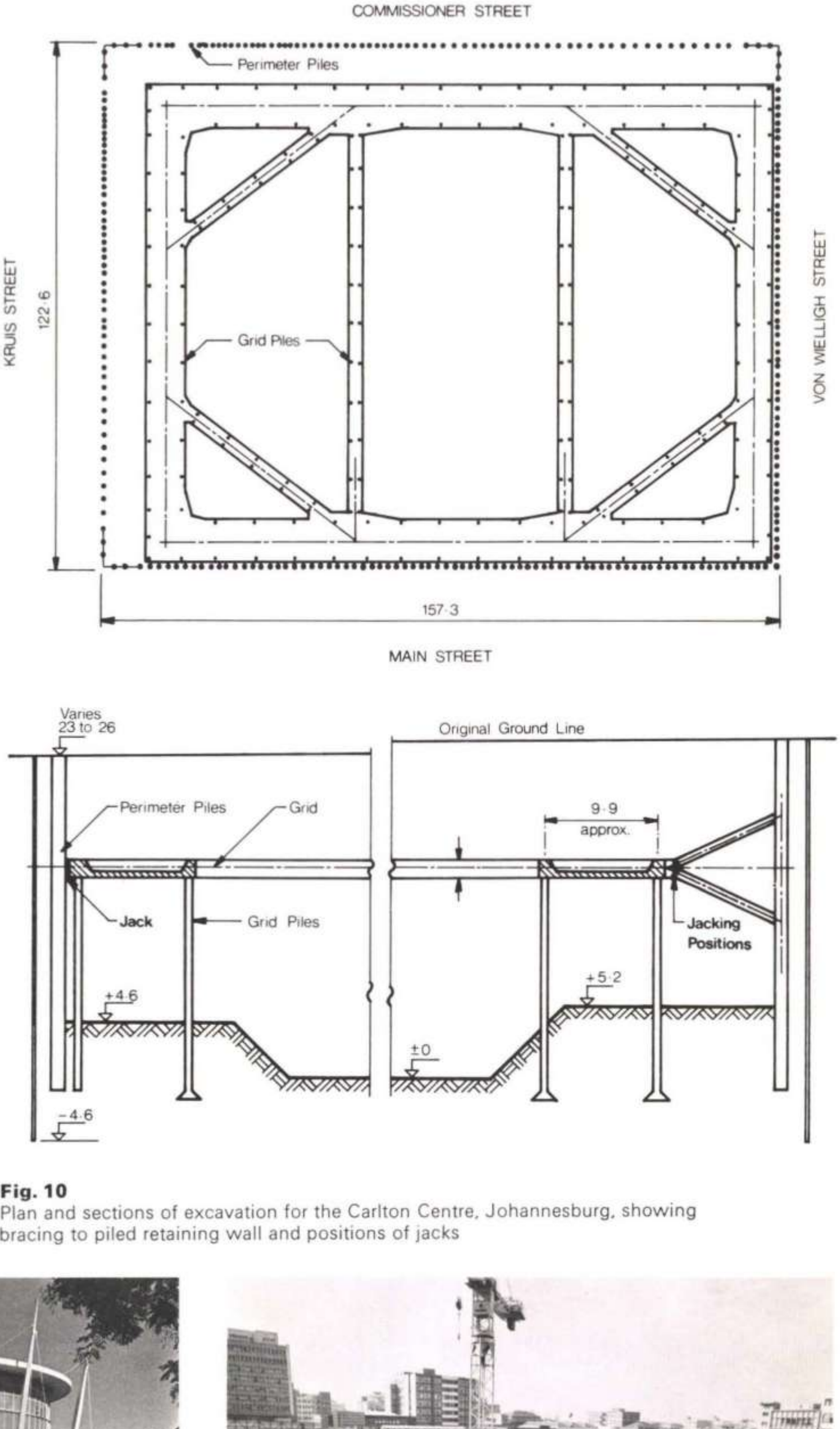


Fig. 10
Plan and sections of excavation for the Carlton Centre, Johannesburg, showing bracing to piled retaining wall and positions of jacks

Fig. 9
UK Pavilion, Rand Centre near Johannesburg. The cables were stressed by raising the pylons on flatjacks. (Photo : Brian Jouxsow)

Fig. 11
View of the Carlton Centre excavation, showing bracing to piled retaining wall. (Photo : A. A. Gordon)

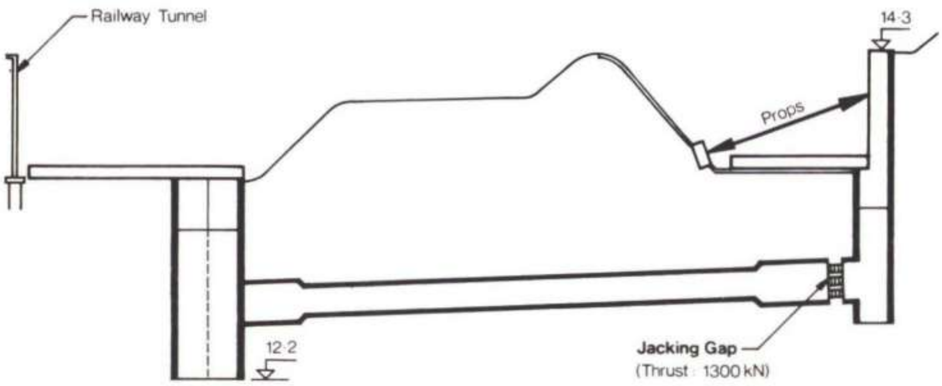


Fig. 12
Section through excavation for Barbican Arts Centre, showing bracing tunnel and jacking position

Fig. 13
Concrete block encapsulating four 1800mm diameter flatjacks in tandem for use in bracing to retaining wall at Barbican Arts Centre
(Photo: A'Court Photographs Ltd.)

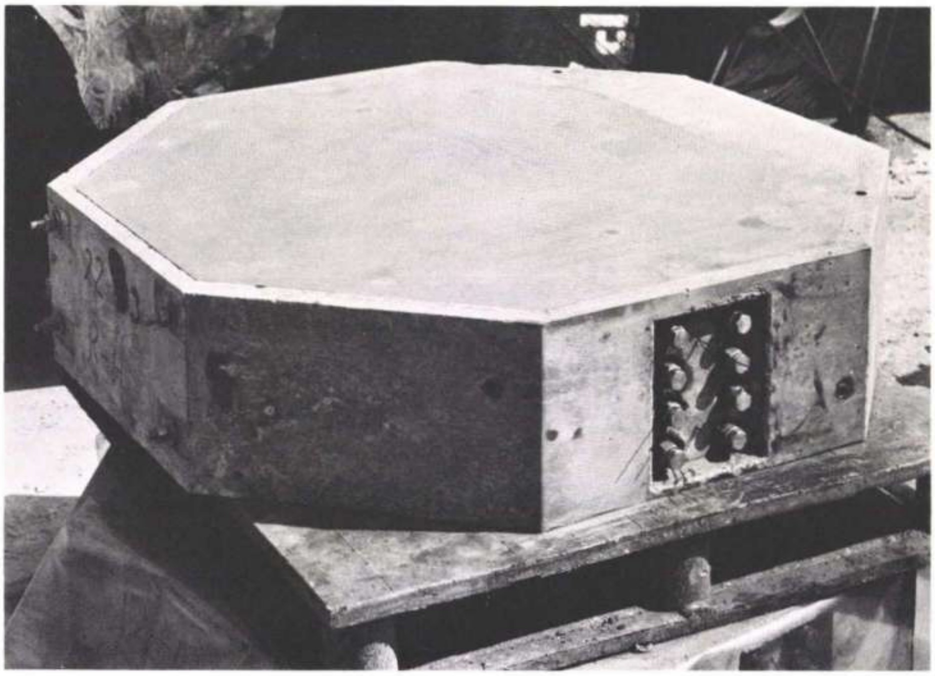
to the jacks when their manometers indicated the pressure corresponding to their specified jacking load.

The sizes of the stanchion cap plates did not allow the use of temporary or permanent steel packs, so the jacks had to be solidified under pressure at the end of the operation. As the jacking also had to proceed along the façade with consecutive vertical lines having to be jacked to gradually increasing pressures (to limit distortion of the concrete structure), direct inflation with a resin having a pot life that might only be stretched to six hours could not be contemplated.

Laboratory trials showed that there were difficulties in completely displacing the hydraulic fluid with resin due to the horizontal position of the jack, and moreover that it was extremely difficult to manually control the bleeding-off process so as to avoid pressure fluctuations which in the real building could result in punching failure of the floor slab.

It was eventually decided to pressurize the whole system with a heat curing resin which at normal ambient temperature had a pot life of months but which could be cured overnight at 100–120°C by surrounding the stanchion tops and the jacks with insulated electrical heater jackets.

Unfortunately the recommended resin tended to shrink on curing; and although it was a very slight shrinkage it meant that some of the jacking force was lost. Mr John Harvey of PSC then hit upon the idea of minimizing this



loss by reducing the volume of resin in the jacks. To this end the jacks prior to filling were pre-packed with single size 3mm shingle from Chesil Bank (the only place where you will find shingle naturally sorted: 2mm at West Bay gradually increasing to 100mm at Portland).

That the curing reaction, once started, was exothermic and therefore required the heating current to be cut off at rather lower temperature than foreseen, was just another snag that became apparent during the course of the work, as did the fact that a resin classified as 'low viscosity' could, when situated in an unheated building in a British winter, become so thick that it took an hour for a pressure increment induced at the pump to register on a jack manometer two floors up!

Safety precautions included a hydraulic circuit employing several pumps, each of which could be connected to any or all of the vertical rising mains and each of which could conversely be isolated and removed in case of failure. Similarly every jack could be isolated from the circuit. All the pumps were set up in a bank on a floor half-way up the building and an intercom system enabled the foreman in charge of the operation to keep in touch with the fitters on every floor and monitor progress as 40-odd jacks were brought up to their various specified pressures and isolated in turn.

A thermo-electric probe, inserted in one of the connection 'spouts', enabled the temperature of the resin to be monitored during the curing operation. This facility was used to ascertain the optimum heating sequence to be established, and subsequently this was implemented by time-governed manual switching, checked by examining the colour of thermo-indicating paint applied to the stanchion tops.

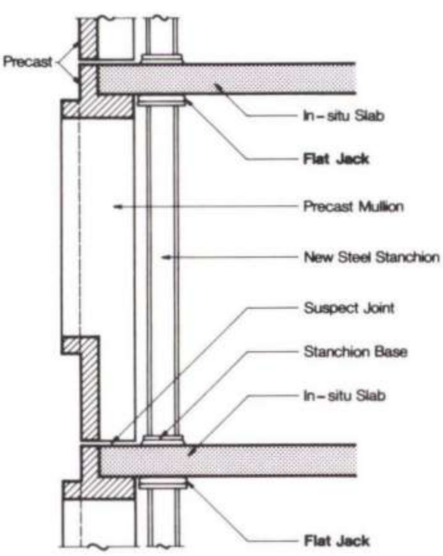


Fig. 14
Arrangement of steel stanchions and flatjacks to relieve precast façade panels of load

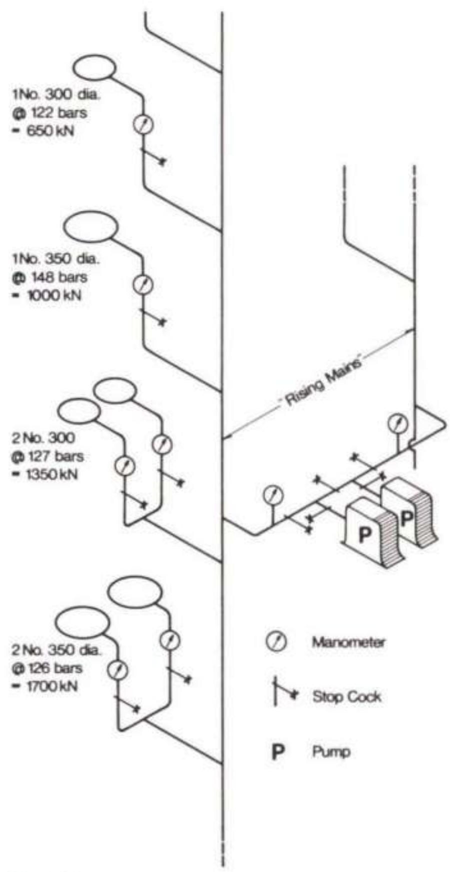


Fig. 15
Diagram of hydraulic circuit for simultaneous load relief of precast façade panels in multi-storey block

Creating building forms responsive to environmental forces

Kenny A. Gerlach

Abstract
The actions of environmental forces have the most significant impact on the rate at which buildings utilize energy. Appropriate methodologies are developing to counter the waste and reconsider building design in terms of discovering how the efficient responsiveness of nature itself deals with the problem. Design implications rest in finding optimal surfaces and forms which minimize these external effects. Although the remaining problems are finding means of handling the complexities of analysis.

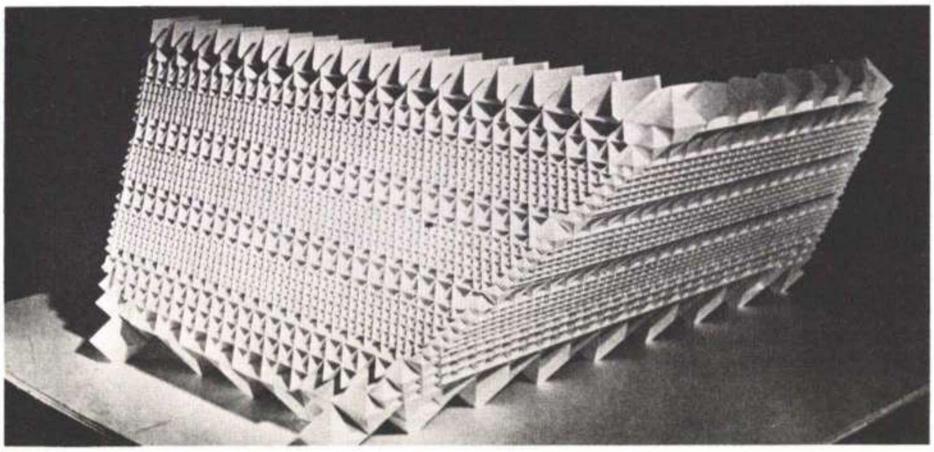


Fig. 1
Model of a high-rise building developed from tetrahedron light-gravity study (Photo: Courtesy of Royal Institute of British Architects, London)

System response to environmental stress

Buildings are subject to the same natural forces that have produced the high degree of differentiation we are used to seeing in nature. We have tended to make buildings which demonstrate, to a very low degree, the differentiation of force effect. It is not unusual to find a building that looks quite the same in New York, London or in Sydney.

There are some very good reasons for this. One of them is the rapid change in cities which we have taken to be normal. This makes it very difficult to predict, from year to year, what is going to be constructed in the near proximity of a single building. Careful design might be to no avail if suddenly the building is placed on another adjacent site, or a larger structure is constructed nearby, influencing wind patterns and sun exposures.

The second major reason, as suggested by many observers, that our buildings do not exhibit the high degree of differentiation of a natural system, is our mechanistic tendency to over-simplify problems with redundancy acceptable to us but not to nature.[4, 9, 13]

In spite of the real conditions presently in contradiction to application, there is some usefulness in considering the building as if it were directly affected by the natural environment. Since the main forces of the natural environment, such as sun, wind, water and gravity, tend to be recurring and therefore predictable, at least some of the reasons for treating the building as a closed system might be overcome. The building might then respond directly and begin to exhibit some of the attributes of flexibility and adaptiveness as found in natural systems.

Change in the natural environment will always initiate a response in the interacting system of a building. This response involves an exchange of energy and results in a cost. Such costs will increase if systems are located in areas where environmental change is great. This notion about system-environment interaction allows a general description for a 'least cost' system response which is quite independent of any commitment to orientations of specific urban functions. The fundamental criteria for developing an optimal building form and surface will be dependent upon the condition whereby the potential for an energy exchange is minimized.

Evolution of building form and surface

Hundreds of years ago Vitruvius succinctly said why there should be different building shapes: '. . . the style of building ought manifestly to be different because in one part the earth is oppressed by the sun in its course; in another part the earth is far removed from it; in another it is affected by it at a moderate distance.'[13]

Ralph Knowles, of the University of Southern California, had engaged upon some pioneering research by asking: . . . can we, if we deal with large enough parts of the environment, make arrangements which are as subtly responsive as those in nature ?'[9] With that lies the possibility of building form and surfaces being truly responsive to environmental forces. So in his laboratory he began to look at form in conditions of simulated environments. What resulted from a series of low velocity wind tunnel, light and water erosion tests were forms that had been shaped in order to optimize a certain condition relative to recurring environmental forces. The optimally derived spatial systems tended to suggest that individual increments be small on the surface and large inside, small at the top and large at the bottom. Fig. 2 illustrates such a possible application of his findings.

What if a form-location mismatch for a building exists? The effects of maintaining an inappropriately formed envelope will manifest itself in higher costs for mechanical compensation. The response to stress is provided by more heating or cooling with appropriate quantities of fuel and exhaust of waste materials.

Just as Knowles tried to demonstrate the relationship of building shapes and sizes to the natural environment, the two Olgyay brothers at Princeton University had earlier made significant contributions in relating environment to building shape. They aptly observed: 'The right shape building is not only an esthetic nicety, but can also save up to 10 per cent in heating–cooling loads'.[13]

It was pointed out by their study how much cheaper the truly optimum shape is to heat and cool as compared to the more commonly accepted square shape held to be the optimum.

In Minneapolis: 1.4 per cent cheaper to heat; 1.6 per cent cheaper to cool.

In New York: 4.6 per cent cheaper to heat; 4.2 per cent cheaper to cool.

In Phoenix: 26.7 per cent cheaper to heat; 2.5 per cent cheaper to cool.

In Miami: 16.3 per cent cheaper to heat; 8.1 per cent cheaper to cool.

To structure response to change in the environment, the Knowles' Owens Valley Study made the mode of response (location, form or metabolism) a function of the interval of environment variation.

The methodology of the study followed a three step procedure:

(1) First, it determined the attributes of the envelope that makes it responsive to the environment. This being concerned with a family of scales and shapes and commonly representing a range of surface/volume ratios.

(2) Second, it established a form vocabulary combining scale and shape to be expressed as a 'form coefficient'.

(3) Finally, it matched the building to a particular set of environmental conditions.

The study demonstrated the importance of the premise that increasing rates of energy consumption are unnecessary if the tools of location and form are first employed to reduce the main body of environmental stress. What remains can more easily be handled with reduced energy inputs. Building metabolism then becomes, as it is in nature, an adjustment or fine tuning device to handle short interval changes rather than a mechanism for handling all environmental change of whatever interval.

In particular the researchers at Princeton studied the thermal forces on buildings and their effects on various shapes for four climatic regions of the United States (cold, temperate, hot-arid and hot-humid). Their findings were[13]:

(1) Adverse air temperature acts to compress buildings into compact form to present the least surface.

(2) Radiation tends to elongate certain sides, usually the north and south, to receive more sunlight.

Upon computing the thermal inputs on the interior of various shaped buildings on a quantitative basis, the following conclusions were drawn:

(1) All the shapes elongated on the north–south axis work both in winter and summer with less efficiency than the square one.

(2) The square building is not the optimum form in any region.

(3) The optimum lies in every case in a more elongated form somewhere along the east–west direction.

The objective of Knowles' research was the organization of information leading to the development of a prototype structure that is systematized through the geometric modelling techniques of analysis; the structure to be vertically orientated, space enclosing, and having properties of environmental control for useful occupation.

Professor Knowles' study was accomplished in four phases.[11] Phase I established the means of analysis in which fundamental geometric ordering of form surfaces were realized by means of intersecting planes.

Forms studied were the cube, tetrahedron, hyperboloid of revolution of one sheet, ellipsoid and prism. These particular forms were selected because they are common to single, isolated buildings.

Phase II defined, measured and recorded the environmental forces as the components of light, gravity, heat and wind along with their effects on the surfaces of the five forms.

In Phase III each surface response under a single force was graphically indicated and measured on the planes with the original form as a reference. Systems of planes acting as graphs are compared on the basis of area required to produce a working response under the conditions set.

The final Phase IV dealt with the study of surface responses manifested by size, shape and attitude of planes which were graphic indicators of the simultaneously acting environmental forces of light and gravity. Systems of planes acting as graphs are compared in terms of the amount of planar surface acting in direct response to both forces. One of the provocative forms that evolved, shown in Fig. 1, resulted from two environmental constraints of light and gravity.

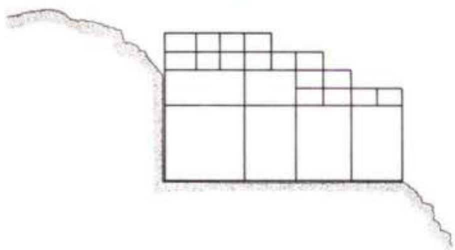


Fig. 2
An environmentally responsive form for a hillside structure of differentiated increments

The problem for generating a surface in response to sunlight, for example, was to maintain a stable condition defined as 'no direct sunlight upon the surfaces of the cube'.[9] Regularly spaced planes were extended just far enough from the surface to maintain the condition of stability previously defined. Such a curious result does not derive from whimsy but from a consistent attitude taken about the way planes will work in relation to a differentiated force (the changing attitude of the sun in this case). The result is that the planes themselves are highly differentiated.

The surface and form results of the study were considered to be graphic indications of real conditions measurable in terms of planes with no thickness, hence no ability to develop structural properties. The models cannot, therefore, be considered real structures. They do, however, suggest an attitude about the multiple use of material disposed to form building surfaces.

By the recognition of the importance for considering environmental constraints Christopher Alexander's words ring of prophecy: '. . . the form that the building will take derives from these sub-systems of physical relationships . . .'.[1]

Maybe because of the rapid advance of technology our modern structures have not displayed the uniqueness of environmental fit which buildings of previous ages displayed. 'So the architect, in reality, had been a climatologist long before he acquired a knowledge of all the other professional activities so closely associated with his work, such as economics, engineering and sanitation'.[15]

Urban form

The complex three-dimensional nature of the shapes being produced, especially of Ralph Knowles, implies that the results could be most applicable to group (urban) form as formerly applied to single building forms. Towns too should be shaped by climate just as the Olgyays believed: '. . . the forms of towns and cities represent composites of influences . . . they are ruled by the same tendencies and characteristics that influence single buildings'.[13]

Knowles preferred to be more explicit in terms of design methodology: '. . . the single increment, i.e. the single building, is not the design tool of the future. It is barely the design tool today. It is the form framework within which increments fit that will be designing'.[9]

Of primary importance is not the relatively small surface increments but the form itself which requires various degrees of differentiation necessary to lend functional stability. As in the epidermal layer of animals, the surface increment must be small relative to the form as a whole and must not cause functional discontinuities. Any surface variations are considered from the point of view of their role in maintaining the stability of the larger form. The buildings of the future will have to conform to the functional perogatives of the urban form. The same criteria to the modification of environmental forces must be extended, not only for buildings, but also for urban districts and entire cities.

Emerging systems of analysis

The engineering design process is broken into two facets,[5] design and analysis, and it is analysis that has been receiving the most attention over the years. Thus, once a design is formulated an engineer can very satisfactorily analyse it but is often not in a position to fully utilize the results of his analysis in a revised design, because until recently, the techniques of design had not been well developed. The normal engineering design is an iterative process (Fig. 3) where design revisions are based entirely on the designer's intuition and experience with no objective guidelines to assist the designer to produce the best design. Often the 'best' or 'optimum' design is not even defined adequately.

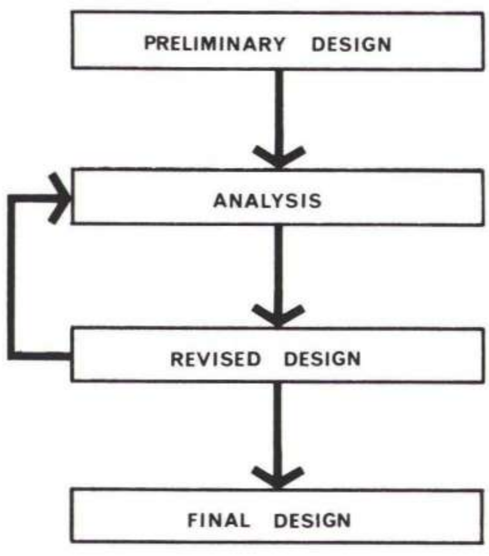


Fig. 3
The engineering design process

Engineering design methodology is in great need of refinement in order to furnish the necessary feedback so that the optimum energy balanced communities we seek may be created. A research group at Strathclyde University in Glasgow offer their observations of the problem: 'One problem which is fundamental to predictive design by cost is to find relationships between measures of hardware systems and their environmental performance and the costs'.[3] In order to cope with the complexities, architects and engineers are turning to computer technology and systems analysis, but it still lacks the capability to organize problems.

In response to such a dilemma a highly flexible computer representation[6] of built forms has been developed for use in evaluating the environmental performance of individual rooms or whole buildings. The resulting outputs of the modelling technique which are produced can be varied quite easily to suit the needs of a particular purpose.

Mathematical techniques such as quadratic programming and modelling with linear constraints[2] in which it may be applied to include determination of overall building proportions have been developed. Another attempt to aid in the representation of complex building forms is the mathematical formulation of point set theory[12] which is both an appropriate and powerful means of representation.

With the assistance of any analysis the designer should keep in mind the objective of D'Arcy Thompson's 'morphology': '. . . of inventing physical things which display order, organization, form, in response to function'.[14]

Conclusion

Why has there existed so long this neglect to ignore the designing process which strives for this optimal fit with its environment? Four main reasons have been offered:[13]

(1) The rush into construction which often precludes thorough design.

(2) The air-conditioning and heating industries, which can correct any architectural mistake in climate, though for a price.

(3) The lack of architectural research telling how a building should be shaped for any given climate. Only designers' instinct and old architects' tales have been available.

(4) The assumptions among architects and owners that there is little to be gained in shaping big buildings to conform with climate (shaping, not just orientating or sun-shading).

The political and social impact of continuing to build structures equipped with costly heating and cooling systems that when most needed might not be operable due to power shortages; systems that could commit a building owner to high initial payments and to increasingly unbearable operating costs, as well as to systems that undergo premature obsolescence, make the development of optimal building forms a high priority.

It has been demonstrated that the potentials for working with the climate and a procedure for inter-disciplinary evaluation of systems designed can make a major impact upon the current environmental crises. The problem is clear and the need is now to direct technology in ways less harmful to our living space. These potentials for a return to the natural, without significant loss of convenience or comfort, could scarcely have been broadly considered had the energy crisis not coincided with those of fossil fuel depletion and pollution.[7]

In order to integrate design and re-establish the response to environmental variables, James Marston Fitch suggests his view: '. . . to master these subtle and intricate interrelations between man, his buildings and the natural environment will require the highest levels of scientific thought. They involve such a bewildering array of variables that they will certainly depend upon the computer for solution. And rather than aiming at the elimination of such basic elements of modern architecture as air-conditioning and artificial illumination, they aim at creating the environmental conditions in which such systems will be able to operate at optimal levels of efficiency, economy and safety'.[4]

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Report on wind and vibration measurements taken at the Emley Moor television tower

Michael Shears

Summary

The paper briefly describes the 330 m high television tower at Emley Moor, with particular reference to the structural steel cantilever mast at the top carrying the aerials.

The instrumentation of the tower with anemometers at the top of the tower and at ground level, and three sets of electrolevel-type accelerometers, is fully described together with the arrangements made for the remote recording of the signals.

The simple recording system adopted is shown to be an effective method of observing the general vibrational behaviour of the tower using records collected over long periods of time.

Some preliminary results of the wind and vibration analysis are presented, including plots of the peak displacement amplitudes of the mast top against windspeed.

Introduction

The 330 m high television tower for the Independent Broadcasting Authority at Emley Moor in Yorkshire, England, came into service in 1971.

The tower structure consists of a 274 m tall, reinforced concrete tubular shell, surmounted by a 56 m high aerial mast of steelwork construction (Fig. 1). The concrete shaft is 24.4 m in diameter at the base and tapers exponentially to a minimum diameter of 6.4 m at the top, where the aerial mast steelwork is held in position at two concrete slabs by horizontal and vertical bearings. The aerial mast steelwork is generally of open, latticed construction in two triangular sections, the geometry of which was dictated by the performance of the aerials. Both sections are enclosed by glass reinforced plastic cladding to give the form of a stepped circular cylinder. The cylinder diameters are 3.66 m over the lower, VHF aerial portion and 1.52 m over the upper, UHF aerial portion of the mast.

Full details of the design and construction of the Emley Moor tower are given elsewhere (see reference).

Following the construction of the tower, a system of instrumentation was installed to facilitate the collection of data for the assessment of the full-scale behaviour of the mast under wind action.

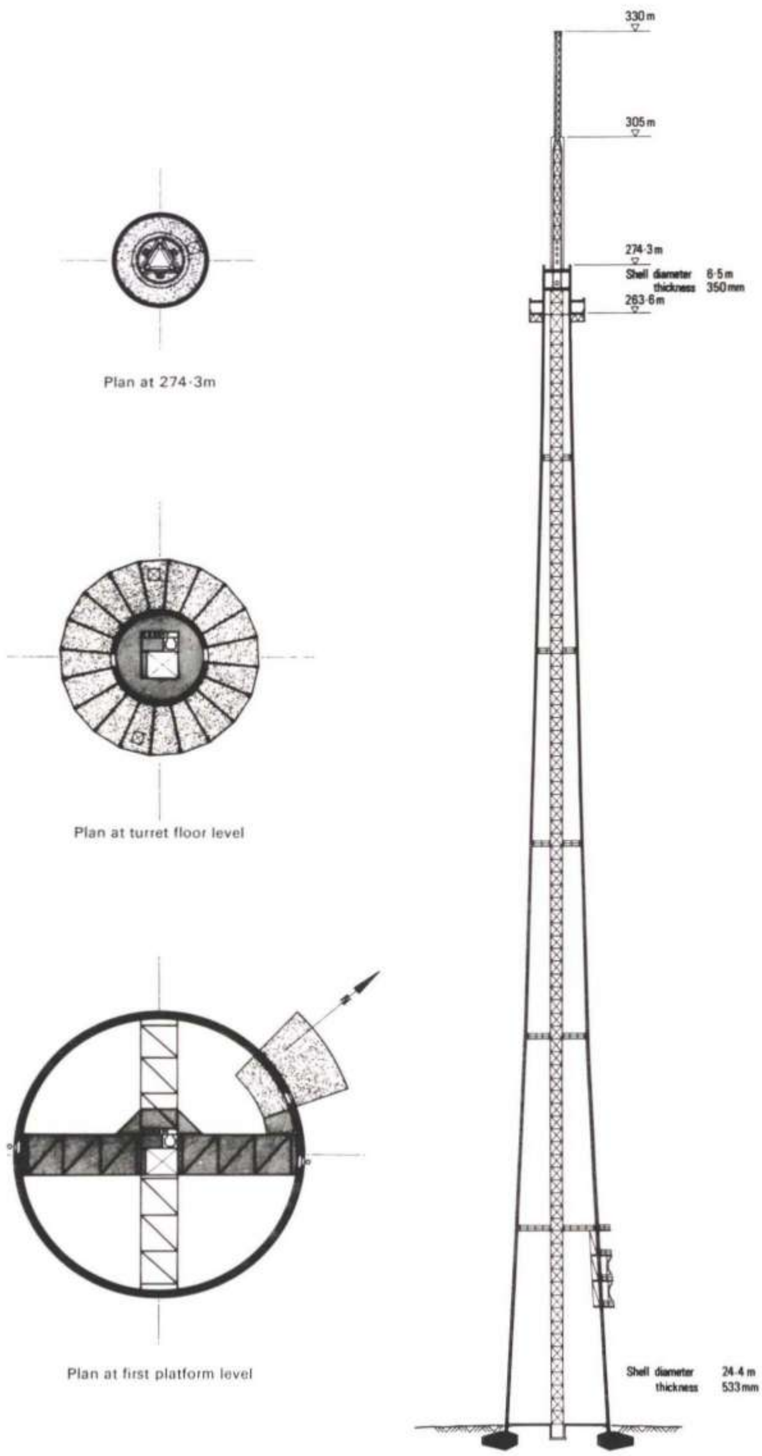

Fig. 1
Tower cross section and plans Emley Moor television tower

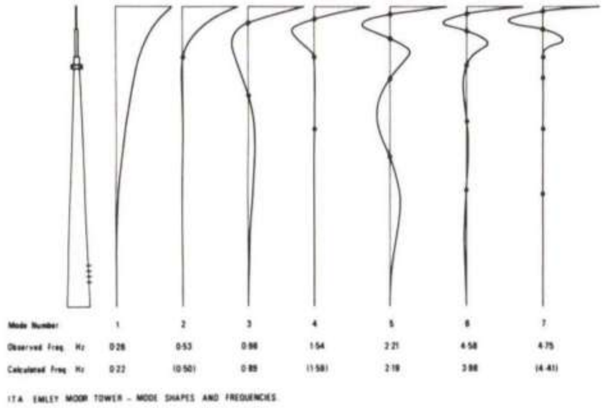

Fig. 2
Mode shapes and frequencies

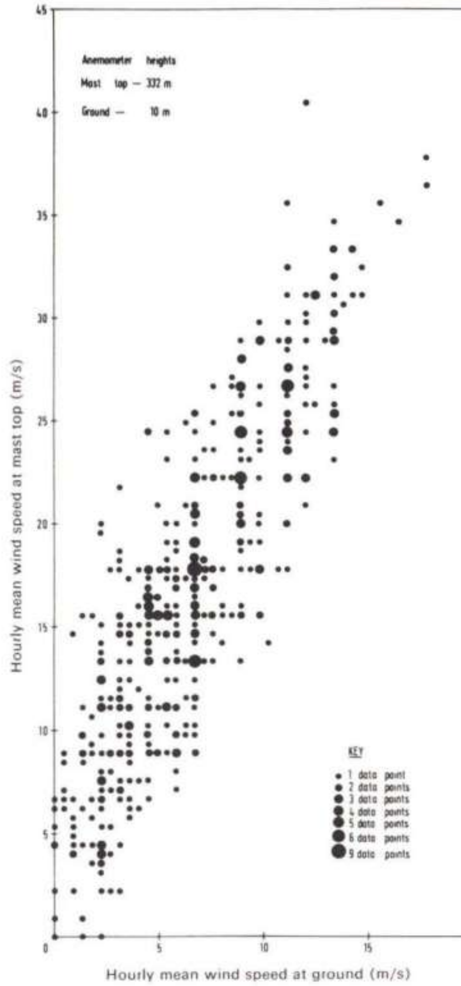

Fig. 3
Plot of hourly mean wind speeds

The main purpose of the instrumentation programme at Emley Moor was to observe the full scale behaviour of the aerial mast for conditions which might lead to sustained, resonant-type vibrations of the kind caused by vortex shedding, particularly at low wind speeds. The instrumentation was also used to measure the behaviour of the tower under other wind conditions in the search for a better understanding of the wind response of tall structures.

Aerial mast frequency behaviour

The frequency analysis of the tower indicated that the aerial mast structure was sufficiently more flexible than the concrete shell, for the mast to behave dynamically as a structural appendage with almost independent frequency-mode characteristics. It can be seen from the overall mode shapes (Fig. 2), that modes 2, 4 and 7 are essentially motions of the aerial mast. Indeed, these vibration characteristics correspond very closely with the first three modes of vibration of the mast structure alone.

Dynamic response studies carried out for the tower design revealed that the aerial mast could be sensitive to gusts and periodic fluctuations of wind forces. In particular, the cylindrical shape and very slender proportions of the mast made vibrations arising from vortex shedding an important consideration.

In view of the operational requirements of the aerials at Emley Moor, it was of prime concern to ensure the absence of regularly occurring, large amplitude vibrations of the resonant-type. To minimize the likelihood of sustained vibrations, particularly at 0.53 Hz, it was decided to attach helical strakes over the upper one-third of the UHF mast cladding.

Instrumentation

Wind speed and direction measurements were taken at the top of the aerial mast, and also at ground level some distance to the west of the tower where the prevailing wind directions were clear of surface obstructions. The instruments installed were Munro type 1M146 cup anemometers and direction vanes fitted with Colvern potentiometers. The upper instruments were mounted about 1.5 diameters above the top of the UHF mast, while the ground level instruments were mounted on an independent 10 m high mast.

Mast vibrations were measured using BAC electrolevel type ELH25 accelerometers mounted in orthogonal pairs, with one axis orientated along the north–south direction and the other along the east–west direction. The electrolevels were calibrated before installation and found to exhibit linear responses up to about 0.18 g.

The accelerometer pairs were located at three levels. Two pairs were attached to the aerial mast steelwork, one at the top of the mast and the other in the transition zone between the UHF and VHF aerials. The third accelerometer pair was positioned at the top of the concrete shell.

It was decided to install a recording system best suited to simple visual analysis techniques. In view of the fact that any significant vibrations were expected to be limited to two or three well separated frequencies, this was believed to be an acceptable method of studying the general patterns of behaviour of the tower, as well as satisfying the primary objective of the instrumentation programme, namely to observe for sustained vibrations at low wind speeds.

The signals from all instruments were received at a common recording panel at ground level with wind speeds and directions recorded continuously on separate two channel paper chart recorders having running speeds of 25 mm per hour.

Signals from the accelerometers were recorded on a six channel, ultra-violet paper chart recorder, the running speed of which was adjustable but was most usefully set to 100 mm/min. The chart speed and sensitivity of the recorder were such that adequate resolution of oscillations was possible with a maximum single amplitude of 0.25 g in the frequency range of 0.5 Hz to 2 Hz.

The ultra-violet recorder was operated automatically under the control of a mast top displacement trip circuit. The signals from the uppermost pair of accelerometers were processed separately and the corresponding mast displacements computed using a double integrator unit. The recorder was tripped when the peak to peak displacement in either direction at the mast top exceeded a preset threshold level, which was adjustable in steps between 25 and 150 mm. The recorder tripping mechanism only operated, however, when the displacement threshold level was exceeded for more than a selected time interval of between a half minute and two minutes. A wind speed inhibit switch prevented the recorder trip being activated unless the wind speed measured at the mast top was above a preset level of between zero and 27 m/s. Once tripped, the recorder operated for a minimum period of 10 minutes, even if the signal dropped below the

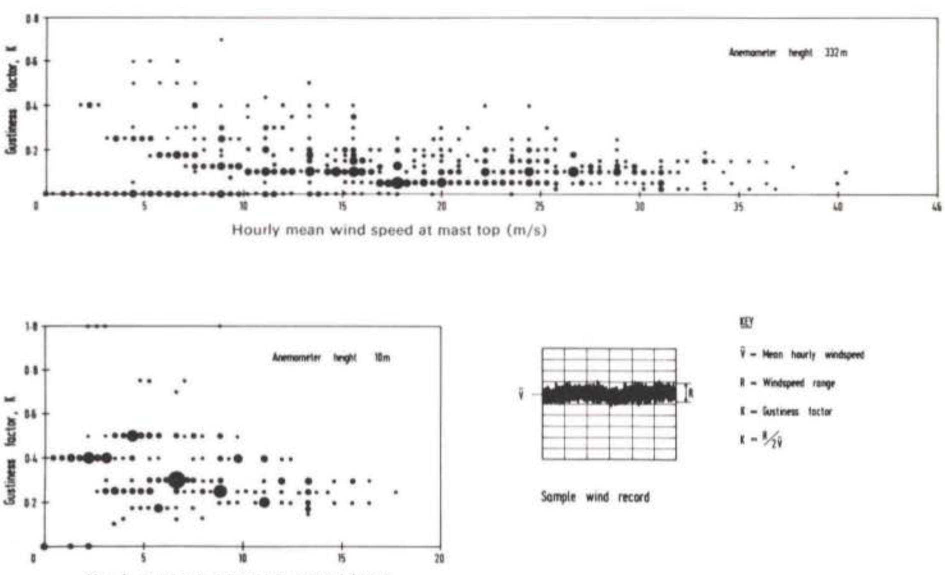

Fig. 4
Plots of gustiness against hourly mean wind speed

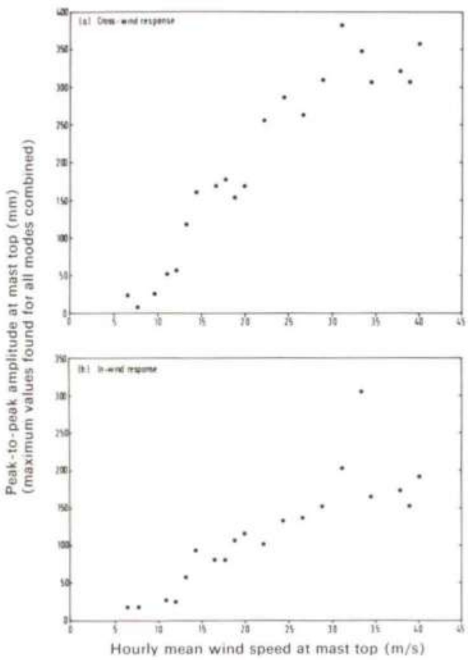

Fig. 5
Plots of mast vibration amplitude against wind speed

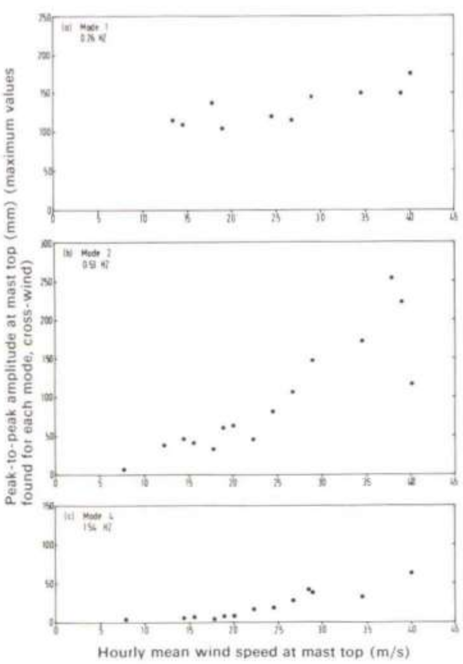

Fig. 6
Plots of modal cross-wind amplitudes against wind speed

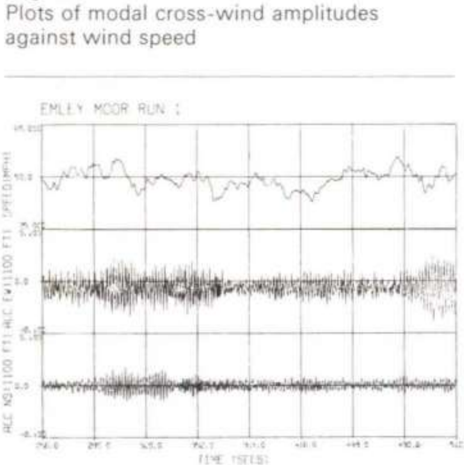

Fig. 7
Computer plot of wind speed and acceleration records

threshold level. At the start and finish of each recorder trip, a marker pulse was applied to the two wind speed charts for later identification of time scales.

A further facility of the recording system allowed records to be made of the mast top displacements obtained through the double integrator circuit, so that the acceleration and displacement time histories for the mast top could be examined together.

Analysis of wind and vibration records

Since visual methods were used in the interpretation and analysis of the records, it was only possible to study the general dynamic behaviour of the tower. However, the great advantages of visual processing of records on paper charts are that general patterns of behaviour and trends can be easily recognized, and analysis is made as simple as possible.

The wind charts for the first few months of records were used basically to determine the wind speeds and directions for conditions of interest in the investiga on of the vibration behaviour of the aerial mast. In particular, the charts were inspected closely to locate all periods of low wind speeds and possible critical wind speeds for vortex shedding.

Subsequently, wind charts covering a period of record of about a year have been examined at three hourly intervals along their length to establish maximum gust speeds, hourly mean speeds, approximate wind directions, and measures of turbulence or gustiness intensity in terms of the range of wind speeds expressed as a fraction of the hourly mean speed (Figs. 3 and 4).

The accelerometer records were scanned for evidence of sustained, resonant-type vibrations. At the same time, note was made of the vibratory behaviour of the mast during all storms, and other conditions producing peak vibration amplitudes, for later detailed analysis. The acceleration traces were also used to measure the full-scale vibration frequencies of the tower.

Three frequencies clearly predominated and were observed throughout all the accelerometer records. These corresponded to the first, second and fourth modes of vibration of the tower. From records taken during periods of high wind speed accompanied by intense gustiness, however, it was possible to observe vibrations at higher frequencies. The acceleration amplitudes at these higher frequencies were generally too small to measure accurately at the recorded scale of 0.16 g per cm. The corresponding mast displacements would, therefore, be quite negligible.

Seven vibration frequencies were observed, and these compared closely with the values predicted for the design of the tower (Fig. 2).

The output from the accelerometers records the dynamic motions of the mast about some relatively slowly varying mean deflected position. The dynamic displacements of the mast corresponding to the recorded accelerations can be evaluated, although this is complicated by the superposition of different frequency components of the motion.

Fortunately, the three predominant natural frequencies are very nearly multiples of each other, in the ratio 1 : 2 : 6, and could usually be found occurring together in simple phase relationships. Simple waveform analysis was then used to separate the various frequency components for independent modal displacement computations. The accuracy of such calculations clearly reduces as the acceleration amplitudes become smaller, particularly for the lower frequencies. The 0.26 Hz frequency component was often the most difficult to estimate, since relatively small acceleration amplitudes at this frequency correspond to large displacement contributions. To try to reduce scale errors of this kind, several wave separation calculations were made for each position studied along the record. Comparisons made with the recorded displacement amplitudes obtained from the double integrator unit, however, indicate that the waveform analysis method is quite accurate.

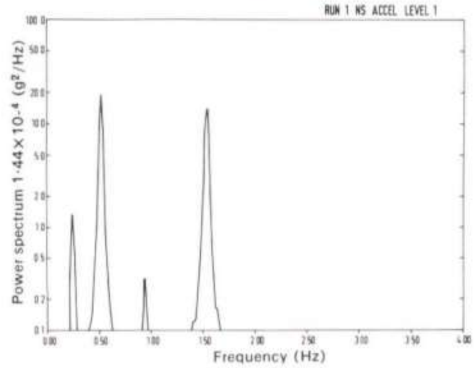

Fig. 8
Computer plot of acceleration response spectrum

The investigation of the behaviour of the mast at low wind speed conditions revealed that records were not tripped by mast top vibrations during any of the critical wind speed ranges. The displacement threshold levels were variously set at 25, 75 and 100 mm peak to peak amplitude. On the occasions when the recorder was manually tripped during periods of low wind speeds, the records indicated peak to peak amplitudes of less than 50 mm at the mast top.

At higher wind speeds, in excess of about 15 m/s, mast vibrations were observed both across the mean wind direction and in-wind. Generally, the cross-wind vibration amplitudes were greater than the fluctuating component in the mean wind direction. Both types of vibration appeared to be fairly random in character, with peak amplitudes increasing with wind speed and with intensity of gustiness. The cross-wind vibrations, however, did exhibit occasional short bursts of response with single frequencies predominating.

The peak to peak displacements of the mast top recorded during each storm analyzed are plotted against hourly mean wind speed in Fig. 5. These displacements are the maximum values obtained for all frequency components combined.

The records indicated that the fundamental mode of vibration of the concrete shaft at 0.26 Hz provides a major contribution to both the cross-wind and in-wind displacement amplitudes, although aerial mast vibrations at this frequency are largely rigid body motions. The separated modal contributions to the cross-wind displacement amplitudes at the mast top are plotted against the hourly mean wind speed in Fig. 6.

Concluding remarks

The system adopted at Emley Moor to obtain wind and vibration records on paper charts, suitable for processing and analysis using visual methods, has proved to be a most effective and simple means of observing the general vibrational behaviour of the tower using records collected over long periods of time.

The instrumentation has also been used, however, to obtain somewhat shorter records on magnetic tape for digitization and computer analysis (Figs. 7 and 8), but further measurement and analysis will be needed before proper comparisons can be made with the predicted behaviour of the tower.

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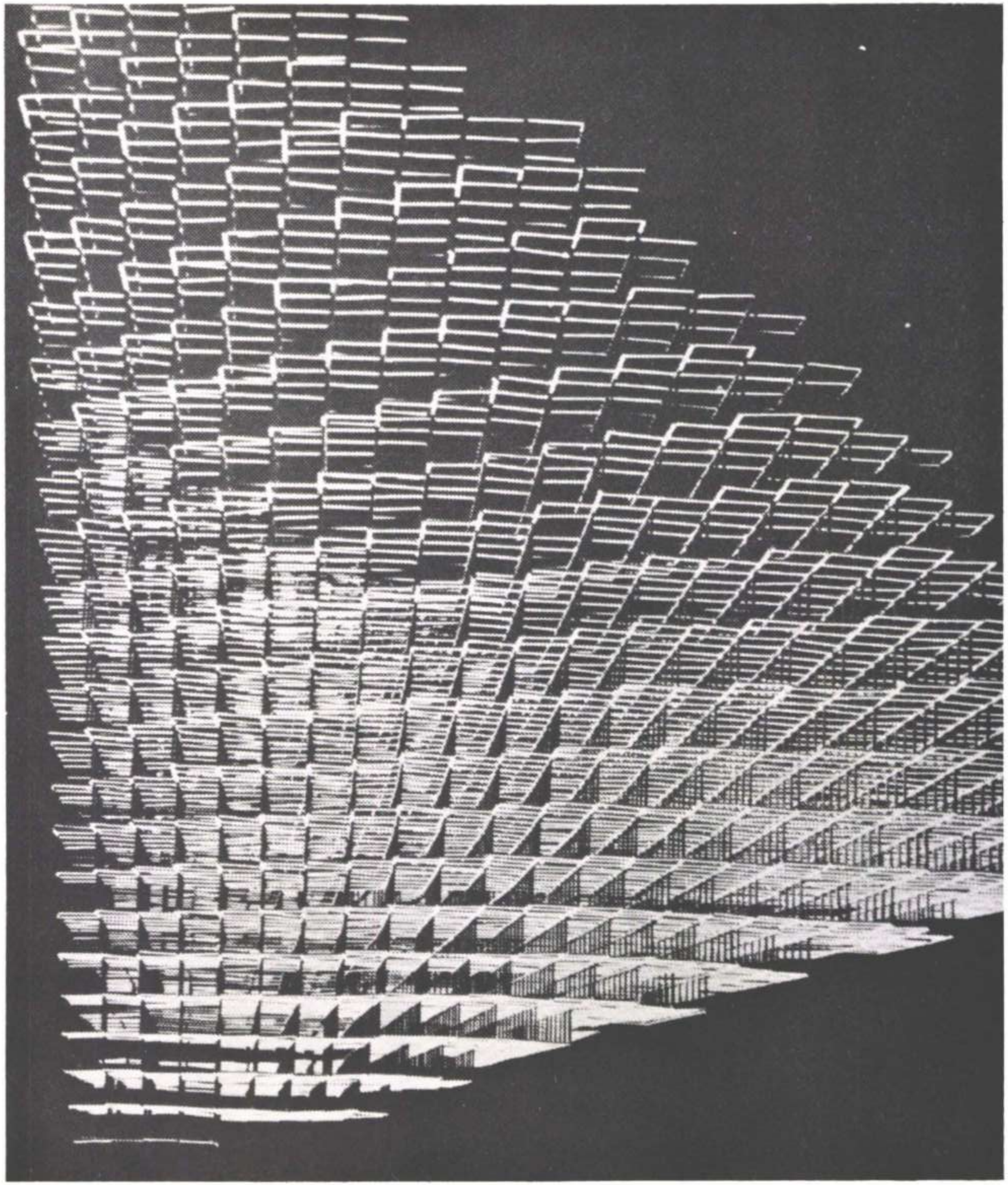

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