

A GENERAL INVESTIGATION OF STRUCTURAL WIND LOADING AND THE EFFECT OF SHIELDING

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ABSTRACT

The effects of shielding on structural wind loading have been examined in a series of wind tunnel tests, using models with simple geometric shapes. Adverse effects were noted in many cases, occasionally on overall loading but more generally on local surface pressures, when compared with the corresponding isolated model. Predictions for a few selected geometries using the PHOENICS computer code indicated significant errors in regions of separated flow.

INTRODUCTION

The bulk of design information on static wind loading, compiled in national building codes for ready reference by structural engineers and architects, is based on model tests of free standing structures. There are compelling reasons for this: the local environment for a particular structure depends critically upon its location, and a representative range of conditions cannot be met by a few standard cases. Also, it has been widely believed that on the whole, wind loading will be at its most severe for a structure which is free standing. It is now accepted however that "shelter" is a mixed blessing, in that it can induce more extreme negative pressures than would be experienced on an isolated building, with obvious implications for roof, cladding and window design.

The majority of model test work understandably relates to specific case studies, but on occasion more general investigations have been made using simple geometrical shapes. Ning Chien (1951) examined vortex formation around models of rectangular section, work which was extended by Hamilton (1962) and Castro (1973) to include the effect of varying the characteristics of the boundary layer. Peterka and Cermak (1975) investigated the extent and condition of the wakes produced by structures of regular shape.

Proximity effects were reported upon by Hamilton (1962) who used two cubical models, and by Leutheusser (1971) with a rather more complex system. The exacerbation of negative pressures was clearly identified, as in the work of Stathopoulos (1984) on the interaction of high-rise and low-rise buildings.

With such a range of possible configurations, it is difficult to rationalise the effects of shielding on wind loads in any useful way. Perhaps an attempt can be made for at least some of the simpler and more commonplace layouts, not with a view to supplanting the wind-tunnel test but rather to extend the general guidelines available in current codes of practice.

EXPERIMENTAL WORK

A study was proposed of the interaction between bluff bodies of rectangular section, mounted upon a ground-plane, when exposed to wind. The initial impetus for the work was from an investigation of wind loads on offshore structures, reported elsewhere (Reeves, 1988), in which the bodies could represent buildings on a platform. Equally, they could represent land-based structures in close proximity. The present study concentrates on the shielding effect of one body upon another, for a few simple geometrical shapes.

The work was carried out in the 5 ft (1.524 m) diameter open jet wind tunnel at the University of Strathclyde. This tunnel has no provision for gradual boundary layer growth; thick boundary layers and high turbulence levels can be generated only abruptly by spoilers and grids, and are thus not stable over the length of the working section. It was decided therefore to conduct tests in a low-turbulence environment with a thin boundary layer, which although inappropriate would allow reference to certain other published results, and should be adequate to establish comparative trends, prior to a more rigorous treatment at a later date. For the same reason, no attempt was made to measure fluctuating components of loads or pressures.

Figure 1 shows the range of model configurations tested (isolated, paired and dissimilar) and indicates the geometric parameters which were varied in each series of tests. The numerical values of these parameters are listed in Table 1, referenced to dimension 'a', the length of the model in the x-direction, which was maintained at 150mm throughout. In specifying forces, coefficients etc. a body-referenced axis system was used throughout, and this is also depicted in Figure 1. For all tests, the wind yaw angle ϕ was varied in 15° increments.

The faces of the models were fitted with sufficient pressure tappings to permit estimation of total loading and the plotting of pressure contours. Given the simple symmetrical shapes, only two or three faces required to be so fitted for each model. The force calculation procedure was validated with one of the larger models attached to a balance; discrepancies were below 8% for all wind directions, and generally well below

TABLE 1 Dimensional parameters of test models, as illustrated in Figure 1.

MODEL	b/a	c/a	s/a
ISOLATED	1, 1.5, 2	1	
	1	1, 1.33, 2.5	
PAIRED	1, 1.5, 2	1	1, 1.5, 2
PARTIAL SHIELDING	1	1, 1.25, 1.75, 2.5	1, 1.5, 2

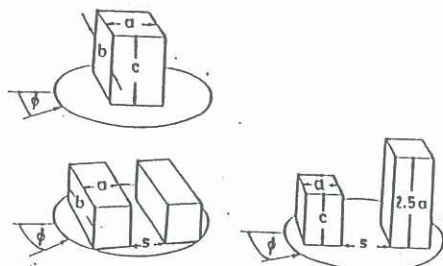


Figure 1 Model layouts and dimensions (see Table 1 for numerical values).

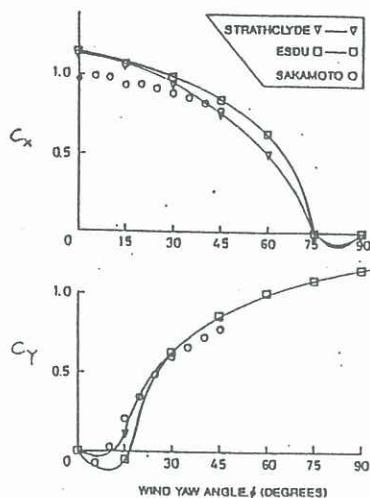


Figure 2 Comparison of overall force coefficients for an isolated cube.

5%. All tests were conducted in a turbulent boundary layer of about 30mm thickness, i.e. 20% of the height of the cubic model. The Reynolds number, based on this height, was about 2×10^5 throughout. Blockage was always below 5% of cross-sectional area, and its effects were therefore ignored.

Data acquisition was by means of a desktop microcomputer, which controlled the sampling of pressures through a solenoid-operated switching unit and stored the signals from the transducer. Numerical processing of the results, carried out at a later stage, produced overall force coefficients and contours of pressure.

DISCUSSION

Isolated Models

The resulting force coefficients for the isolated cube are compared with data from ESDU (1971) in Figure 2. Boundary layer conditions for the two cases were very similar, and acceptably close agreement is observed. By contrast, the results of Sakamoto (1985) which are also depicted in Figure 2 show marked discrepancies, due in part at least to a much thicker boundary layer.

Pressure contours give the expected evidence of flow separation from the roof and sides of the model, with a clear indication of vortex lift on the roof at yaw angles around 45° (see Figure 3). The lowest pressures on the sides occur near the ground, within the boundary layer. The vortex which forms on the lower part of the upwind face is carried around the sides of the body and interacts with the region of separated flow to produce a zone of exceptionally low pressure (see Durgin 1982). This led to a worst case when $\phi = 15^\circ$, at which the side which is exposed to the

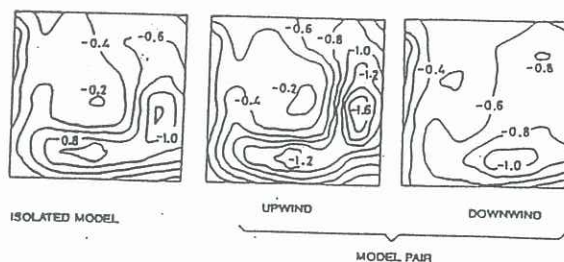


Figure 3 Proximity effects on values of pressure coefficient on the roof of a cube (relative wind direction $\phi = 45^\circ$).

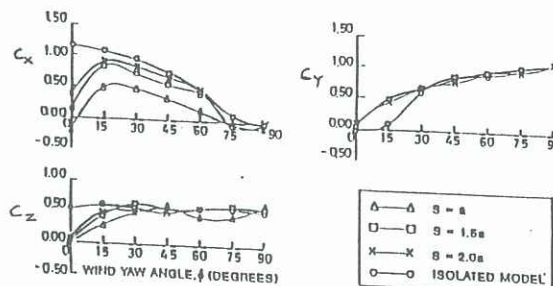


Figure 4 Overall force coefficients for a shielded cube, as affected by spacing and wind direction.

wind retains a small separation bubble; here, mean C_p values of around -1.4 were measured.

Results for the other models were generally as expected. However, the larger models, with a rectangular roof plan, generated substantially lower pressures (C_p down to -2.0) over quite large areas. In contrast, tall models with a square roof plan experienced much less lift than did the cube, perhaps because of the remoteness of the roof from the boundary layer.

Paired Models

The investigation of shielding effects using paired models followed the same procedure. Generally the downwind model of the pair was

instrumented, but in some cases, the upwind model was investigated as well. A full set of results is available in Latiff (1989); what is offered here is a summary of the more significant observations.

The effect of shielding on the overall force coefficients is generally beneficial, as seen from the results for a shielded cube in Figure 4. The effect of variation in spacing between models appears to be progressive. By contrast, measurements on the upstream model of a pair showed some moderate increases in both horizontal and vertical forces.

An examination of pressure contours revealed that the proximity of another model has a strong influence on local pressure coefficients (see the roof contours in Figure 3). The worst case is for the upstream model, where minimum mean C_p moves from -2.0 (isolated) to -2.5 on the roof, and from -1.5 (isolated) to -2.2 on the walls. However a model downwind of another will also experience some increase in the range of surface C_p values, compared to the isolated case.

Dissimilar Models

Here, the downstream model only was instrumented. The effect of partial shielding is to strengthen the eddy on the upstream face of the taller structure (see for example Wise 1971), and thus modify the boundary layer flow near the

ground. The response of wall pressure coefficients in this region was of particular interest.

The results were almost wholly benign: force coefficients are either reduced or unaffected (some slight increase in overturning moment is possible, given the upward movement of the centre of pressure on the upwind face of the taller model), and local C_p values are within the bounds of those observed for isolated models. The effect of varying the separation between models was minimal over the small range of spacings examined.

General

Overall wind loadings as measured by the coefficients C_x , C_y and C_z for models in close proximity deviate from those for an isolated model, as would be expected. The deviation is however very small in many cases, and in most others the forces are reduced. The overall pattern of behaviour is simple enough to suggest that existing codes of practice could be extended to include proximity effects with no great increase in their complexity.

Local surface pressure coefficients are a different matter, being more strongly influenced by boundary layer/wake interaction. Proximity effects increase the observed range of C_p values particularly at the negative end where values of -2 were commonplace and -2.5 was measured in some cases. The most adverse conditions for roof areas arise from vortex lift at wind yaw angles around 45° , as with the isolated models. For walls, extreme effects are produced when the flow passing between adjacent models separates and then re-attaches, with the lowest pressures being produced near ground level, again as in the isolated case. These comments refer of course to time-averaged data; instantaneous peak values show a wide range of variation in turbulent shear flow, with a C_p of -5 being recorded by Stathopoulos (1984) on the roofs of low-rise models, contrasting with a time-averaged minimum of -1 . It is likely that proximity effects can generate instantaneous C_p values which are lower still, perhaps markedly so, and this is clearly an area which merits further investigation. It would subsequently be possible to give some guidelines on the range of C_p values to be expected for buildings in close proximity, but in practice the influence of local site conditions and of the detail shape of the structure will be very strong and will limit the value of the exercise.

COMPUTER MODELLING USING PHOENICS

The PHOENICS code developed by CHAM is well known. As described by Patankar and Spalding (1972) and others, it solves the conservation equations by a finite-domain method. A $K-\epsilon$ turbulence model is employed. The simulation was limited to two simple cases: (1) an isolated cube on a ground plane and (2) dissimilar models - the partial shielding of a tall model by a smaller model upwind. For each case, only one relative wind direction ($\phi = 0$) was examined.

After discussion with CHAM, the numerical parameters quoted by Markatos (1986) for bluff-body work were employed in this simulation. Previous work by Moustafa (1988) on choice of domain size and grid refinement led to the adoption of the domain shown in Figure 5 for the two simulations. A uniform flow at inlet was assigned, resulting in the growth of a thin boundary layer at the plane of the model. Problems with convergence in early trials dictated a staggered grid arrangement with 34, 26 and 45 cells in the x , y and z - directions respectively. Typically around 100 iterations were required to

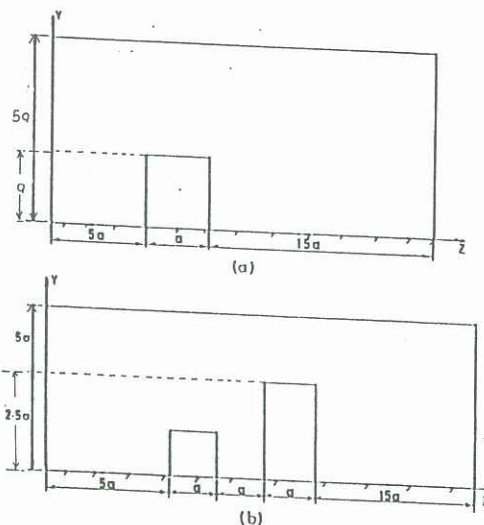


Figure 5 Domain sizes for numerical analysis.

give a converged solution, using around 2 hours CPU time on a VAX-E system.

Output data were available in a number of forms: velocity vector plots and pressure contour maps were produced in each case. For partial shielding, pressure coefficient contour on the upwind face of the larger model are shown in Figure 6. Here, experimentally-derived data are presented for comparison, and it will be seen that agreement is good, both in respect of the shape of the contours and of the numerical values of the coefficients. It should be noted that both sets of contours are limited in their ability to show fine detail with any accuracy, by the restricted number of grid nodes and experimental pressure tappings respectively.

Another pressure contour comparison is given in Figure 7, again for the upwind face. Here, the model is fully immersed in the turbulent wake of an identical model a short distance upstream. Discrepancies between predicted and measured C_p values are now very pronounced, and are on sufficient scale to give substantial errors in the estimation of overall wind loading.

The general trend seems to be a failure to predict the low values of C_p in regions of strongly re-circulating separated flow. Thus the drag coefficient for the isolated cube was under-predicted by 100% almost entirely due to errors in the rear face pressure distribution. For the case illustrated in Figure 6 it is clear that errors will be minimal on the upwind face, but the predicted drag coefficient was 0.5 as against an experimentally-derived 0.8. The suction on the downwind face makes a more substantial contribution to overall drag than in the case of the isolated cube, so errors in rear C_p prediction are more damaging. For the case of Figure 7 however, all faces are in separated flow. The discrepancies on the upwind face are clearly seen, and one would expect further discrepancies at the rear, which in combination might tend to cancel. In fact, PHOENICS predicts a drag coefficient close to zero, contrasting with an experimental value of about -0.4 . Clearly the prediction makes little distinction between the flow conditions upwind and downwind of the model, whereas in reality there is plenty.

Problems with performance in regions of separated flow are well-documented with PHOENICS and other codes which make use of the $K-\epsilon$ turbulence model. For example, discrepancies in the case of a cube on a ground-plane were reported

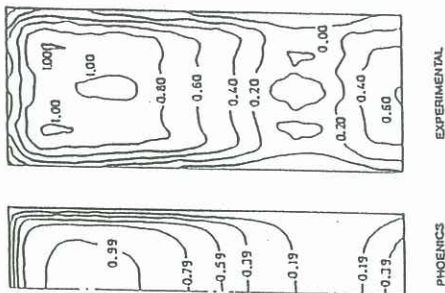


Figure 6
Experimental and predicted pressure coefficients (front face of a partially-shielded model).

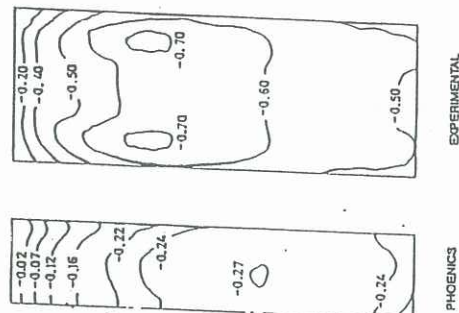


Figure 7
Experimental and predicted pressure coefficients (front face of a fully-shielded model).

by Vasilic - Melling (1977) and by Haggkvist et al. (1986) for simple building models, both singly and in groups. Under-prediction of the negative pressure coefficients on roofs and walls was the major problem, predicted values being numerically too small by factors of up to three. Similar difficulties with PHOENICS applied to cubical models were encountered by Grant et al. (1987), in what was essentially a preliminary to the work described in this paper.

Unfortunately the discrepancies described here are large enough to render the code unsuitable for present application, which is depressing because it can generate information (for example on near-ground velocity distributions) which is difficult or time-consuming to obtain by other means. Reynolds - stress models of turbulence, which appear to perform rather better, are now becoming more widespread, but present some difficulties with convergence and increased CPU time.

CONCLUSIONS AND RECOMMENDATIONS

A series of model tests has been conducted which indicates the effect of shielding upon the wind loading experienced by structures, for a variety of geometrical configurations.

As expected, overall loadings are generally reduced, but a number of cases where forces increase significantly have been pinpointed. The range of observed local surface pressures is extended by shielding, particularly at the negative end. The most adverse effects take place on the upwind model of a pair.

The trends, for overall loading at least, appear to be simple enough to incorporate into general codes of practice.

The computational method employed here was not accurate in a sufficiently wide range of flow conditions to constitute a viable alternative to wind tunnel testing, even for very simple geometrical shapes.

More work is clearly required to quantify the effects of shielding, especially in the matter of instantaneous peak local pressure coefficients. For this a properly-developed boundary layer flow is of course desirable. On the computational side, improved turbulence modelling is the clear priority, both for this and many other applications.

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