PERFORMANCE OF MEMBRANE STRUCTURES UNDER HIGH WIND LOADS

John F. Howell,
Vipac Pty. Ltd.,
Consulting Engineers,
Melbourne, Victoria.

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1.0 INTRODUCTION

Membrane structures built in temperate and tropical areas have wind forces as their main structural design load. This differs from the European and North American experience where snow loading is the important design load and the structure is checked for load capacity under wind forces. The parallels with light weight metal deck roofing are clear and techniques develop which are specific to the design loads. The geometric limitations on metal deck roofing are relatively large and it is unusual to find a metal deck roofing that is other than rectangular and with a constant slope.

This sort of structure is readily amenable to assessment from loading codes such as our AS 1170/2 for wind loads. There may well be disagreement as to the exact magnitude of the design loads as specified in a code and the continuing changes to AS 1170 brought about by committee BD6 are witness to this, nonetheless a designer of a conventional metal deck roof is well served by the prescribed wind loads for almost all of the forms of geometry likely to be used.

In marked contrast to this, the designer of a membrane roof can obtain little guidance from codes of practice as to wind loads. This is particularly the case if the structure has significant biaxial curvature or consists of repetition modules. A recent supplement to the British Code CP3 by Cook goes some way to quantify the effects of multiple in line structures but the effects of complex shape and high curvature are not considered in any code known to the author.

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The purpose of this paper is to evaluate techniques for establishing design wind loads and to relate these to performance. In order to do this it is necessary to briefly discuss some of the principles behind the interaction of flexible structures with the wind.

2.0 RESPONSE OF STRUCTURES TO WIND LOADS

In spite of the simplifying assumption of structural designers that the wind is a load of fixed magnitude and direction, in reality both the magnitude and direction of the wind is varying continuously with time. A further complication is that the variation of magnitude and direction depends on space as well - that is the wind gusts have a size associated with them. It is of course obvious why structural designers prefer to treat the wind as steady and deterministic rather than as a stochastic process varying in both space and time.

Because of the complex and random nature of wind forces the whole process can only be treated using appropriate statistics. Some of these are familiar such as the peak wind speed referred to as the regional design wind velocity in AS 1170. Of course this peak is associated with a probability or recurence of exceedance, often expressed as a return period. Other statistics are the mean wind speed and the variance. We are also aware of the effects of directionality - the idea of a prevailing wind direction - and the next revision of AS 1170/2 will include directional wind speed information from which some reductions in design wind forces will result.

The variation of wind forces with space is considered in an approximate manner in AS 1170 which recognises that although local panels may experience high peak loads, the framing system will not experience the full summation of these peaks due to lack of correlation of the small scale gusts. This idea has significant implication for membrane structures, especially those that are cable reinforced, this is discussed further in Section 3.

With this basic description of the random nature of wind forces, it is appropriate to consider now how these forces interact with structures to produce response - a deflection, a stress, an acceleration etc. This may be most readily discussed using the ideas of spectral analysis to incorporate the dynamic nature of both the wind forces and of structural response. It is well known that membrane structures have a dynamic response - the standard "twang" test which excites local panel resonances is an example of this. The ideas of spectra are well suited to this approach.

Figure 1 shows diagramatically the interaction steps between the wind force spectra - the distribution of wind energy with frequency and the characteristics of the structure defined by it mechanical admittance.

The input or wind force spectra, expressed as power spectral density, f.S(f) shows the variation of the wind forces with frequency. (The apparent drop off at very low frequencies is simply a function of the multiplication by frequency f with f less than 1.0).

The Aerodynamic Admittance curve is a measure of the ability of the structure to organise the wind forces. At low frequencies, the organisation is good with values approaching 1.0. At higher frequenices the organisation decays.

The mechanical admittance defines the response of the structure to a force at frequency f. This shows the well known phenomenon of resonance for a lightly damped structure and a heavily damped structure.

The net result is shown in the lower curves as mean square response. It can be clearly seen that there are two components of response, A_B and A_R. A_B may be viewed as that part of the response which may be considered as quasi static, while A_R is that part of the response which is due to resonance. For heavily damped structures the resonant response is of much less significance than for lightly damped structures where the resonant response may be the most important component of the response. It can thus be seen that a realistic assessment of damping is essential to the computation of the response of flexible or dynamic structures to wind load.

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3. WIND TUNNEL TESTING OF MEMBRANE STRUCTURES

3.1 MODELLING OF THE WIND

It is not appropriate to discuss here the philosophies of wind tunnel test procedures. The early pages of AS 1170 describe well the essential requirements of wind tunnel testing. This simulation requires the dynamic characteristics of the wind (turbulance) to be modelled to an appropriate scale as well as the velocity profile for the appropriate terrain category. This form of simulation is essential and has replaced the early testing in aeronautical wind tunnels using smooth flow.

3.2 MODELLING OF THE STRUCTURE

The most complete type of wind tunnel simulation is where the full dynamic characteristics of the structure are modelled to the same scale (length, time etc) as the wind simulation. This means that the membrane skin is scaled in terms of mass and biaxial tensile stiffness, any cables are similarly scaled and the effects of moving air is also scaled - e.g. trapped air acting as a spring for pneumatic structures or attached air acting as additional mass on a moving membrane. A typical wind tunnel model is shown in Figure 2 after Irwin [2]. As has been developed in 2 above, the evaluation of damping is of great importance if dynamic or resonant response forms a significant part of the system response.

Early estimates of damping were generally performed at low amplitudes and this seriously underestimated the effects of aerodynamic damping. As well, the effects of added mass of the air were not well understood for some time. The tests took a very long time to complete - of the order of nine months for the aeroelastic studies of the Haj campus by Davenport et al.[1] and the Montreal Olympic Stadium by Irwin [2] and their real cost was enormous. Few projects can bear the cost of these full aeroelastic studies but, fortunately, enough have now been performed to allow some general statements. The most reassuring finding is that providing geometric stiffness is provided by biaxial curvature or by reasonable levels of pre stress (or both) then gross dynamic response is not a significant part of the response. This is because the high added mass of the trapped air combined with high aerodynamic damping at peak allowable membrane deflection combine to significantly reduce the dynamic response compared to its importance at low amplitudes. This can be appreciated from Figure 1. These findings are confirmed for the study on the Dalhousie Steel membrane roof reported by Springfield and Sinoski [3] and the Calgary Stadium by Novak and Elashkar [4]. These last studies were based on earlier wind tunnel and theoretical work of Howell [5] and Elashkar[6].

It would thus seem reasonable to consider a full aeroelastic study only for really major projects which can bear the high penalites of cost and time associated with these studies. For projects of somewhat less importance, simpler test procedures are appropriate. For some time now the use of pressure tapped rigid models has been persued as an appropriate method of evaluating the wind loads on medium size membrane structures. This has been undertaken by several workers and a familiar example is the covered stage built by Bilsborough and discussed by Clark [7] in the Membrane Structures Conference of 1983. The assumption of this form of test, shown schematically in Figure 3, is that the motion of the structure is small compared with other characteristic dimensions (such as span) and thus does not significantly effect the flow patterns and hence wind induced forces. The validity of this assumption is somewhat questionable, however, it does provide a reasonable engineering solution to a difficult problem. The errors are likely to be conservative i.e. to over estimate forces, and providing steps are taken to overcome other problems such as Reynolds number effects, the results are generally satisfactory.

Using this technique, information can be readily supplied to the designer in a form that in similar to AS 1170/2. That is, pressures are presented in terms of dimensionless coefficients, C_p, related to a particular design wind pressure. This design wind pressure may be either peak or mean reference wind pressure, nominally measured at the top of the structure. Loads are then evaluated by multiplying C_p by the reference pressure and then by the area over which the pressure acts to yield a patch load. This technique has been used by the author to quantify wind loads on relatively large membrane roof structures at Edinburgh, Gatlinbugh Gap USA, Dolphin Park Toronto, Poole Dorset all for Buro Happold, the Mannheim Gitterschale for Ove Arup reported in the First Australian Membrane Structures Conference [8] and the NSW covered stage reported above.

The main disadvantage with this technique is that it tends to over-estimate the loads transmitted to masts and cable boundaries. The reason for this follows directly from the discussion of Section 2 which addressed the random nature of wind loads in time and space. The result is that where cable boundaries attract load from a significant area of membrane, the cable forces are always less than the sum of the peak pressures over the tributory area. This is because for well separated points, the

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peaks occur at different times. This phenomenon is of course not new and most codes of practice allow a size reduction factor to allow framing members to be designed to lower loads than the vector sum of the peak local panel loads.

This is bourne out by observations of failure of conventional structures under high wind loading. The most common failure mode is associated with local panels and their attachment. It is rare that the framing system fails under wind loading. Of course, a fully scaled aeroelastic model can account for this phenomonon well but the cost and time for this form of study is often prohibitive.

The problem of incorporating spatial correlation of the wind loads has been the subject of much work since about 1977, mainly by Stathopolous [9] who developed the concept of pneumatic averaging. This technique is shown schematically in Figure 4. The author has used it successfully to establish the wind loads on a large (50m square) elevated roof over a coal store at Lamma Island, Hong Kong. A wind tunnel model was constructed, fitted with pressure taps and the net surface pressures i.e. vector sum of top and bottom forces recorded for the surface. The model was also mounted on a force balance to measure the total lift, drag and overturning moment. A simple addition of all the peak forces clearly showed that the total forces of lift and drag were much less than the appropriate vector sum of the local panel loads.

The wind study also included the establishment of pneumatically averaged loads assigned to tributory areas for the roof girders. The vector sum of these loads, while still larger than the measured total forces, was in much better agreement.

The time and the cost of these studies is not insignificant, however, with model making occupying two to four weeks and wind tunnel testing a further week. With tunnel costs typically $1200 per day the cost is substantial.

A further alternative method, and one which is certainly applicable to medium size membrane structures is to directly measure the lift and drag forces and the over turning moment of a model of the structure. For simple and regular structures this is an efficient method of establishing the magnitude of the total forces acting on cables and other boundary elements. It does not yield fabric loads but these may be estimated from past experience and checked to see that their vector sum is greater than the net loads. It is probable that any small error in under-estimating local panel loads will be of no consequence due to the ability of the membrane to undergo high local deflections for the purpose of load shedding.

This approach has been used for the design of one of the schemes for the large tent structures for Expo 88. A light vac formed model of the module was constructed in two days and within about 1 week the study yielded net lift and and drag force and overturning moment. As well the effects of additional structures upstream was quantified.

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3.3 WIND TUNNEL TECHNIQUES

While the above discussion of wind tunnel testing appears to be straight forward, there are several areas where particular attention is required in order to achieve satisfactory results. One of the most important areas is achieving Reynolds Number similarity. Without delving into the mathematics, this simply means ensuring that the flow patterns are reproduced accurately on the model. For conventional bluff bodies, this normally is well satisfied by wind tunnel models. For smooth rounded structures, however, some important flow parameters are highly dependent on both scale and flow velocity. An example of this is separation and reattachment of flow, the phenomona responsible for the high peaks on the structure. For wind tunnel models of smooth shapes, it is thus necessary to use certain tricks to make the model appear to the wind as if it is satisfied Reynolds Number similarity. These tricks include roughening the surface of the model to promote a locally turbulent boundary layer, the use of edge cable trips to model local separation and others. For open membrane structures, the problem is less as separation is nearly always well defined by the relatively sharp edge cable boundary.

The other area of particular importance concerns the design of tubing systems used to measure local pressures and by pneumatic averageing, to establish cable loads. The tubing used to connect the pressure tap to the transducer is itself a mechanical system and like the mechanical system of Figure 1 it has its own resonance. This resonance is governed mainly by tube length. The larger the tube the lower the resonance frequency of the tube. The implications of this are that measurements taken with tubing greater than about 500mm will be over estimating the peak pressures within the frequency range of interest. This is shown in Figure 5. The problem has been recognised for some time and special techniques involving either digital filters or mechanical constructions in the tubing are usually employed to eliminate this problem. Figure 5 also shows the almost flat response of a carefully designed tubing system.

4. CONCLUSIONS

This paper has attemped to discuss the results of over a decade of relatively sparse research into the wind performance of membrane structures. It is still clear that the most accurate form of test is the full aeroelastic wind tunnel study using a fully scaled dynamic model. It is unlikely that these will be used except for major projects due to prohibitive time and cost constraints.

The reassuring results from those tests carried out to date confirm that the response of membrane structures to strong winds is essentially non resonant and static analysis is generally satisfactory providing good geometric stiffness or prestress is maintained. Of course local panel flutter will occur on flat or soft areas but it is not necessary to conduct a wind tunnel test to learn this. One night in a cheap tent in a wind will do.

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The remainder of the paper has discussed alternative wind tunnel techniques for establishing the loads in the fabric and then in the cables and boundary elements.

As a final word of caution, the aerodynamic terminology uses lift to mean a force perpendicular to the wind flow. It should not be assumed to act upward. For some commonly used fabric shapes, the lift force is in fact downward.

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REFERENCES

[1] Davenport & Tryggvason "Aeroelastic Modelling of Pneumatic and Tensioned Fabric Structures" Proc Fifth Int. Conf. on Wind Engineering, Colarado 1979.

[2] Irwin, H.P.A.H., and Wardlaw R.L. "A Wind Tunnel Investigation of a Retractable Fabric Roof for the Montreal Olympic Stadium" Proc. Fifth Intr. Conf. on Wind Engineering, Colorado, 1979.

[3] Springfield, J. and Sinoski, D. "the Air Supported Steel Membrane Roof at Dalhousie University, Halifax, Nova Scotia", Canadian Structural Engineering Conference, 1980.

[4] Elashkar I. and Novak, M. "Wind tunnel Studies of Cable Roofs" Proc. Sixth Intl. Conf. on Wind Engineering, Gold Coast, 1983.

[5] Howell J. "Wind Response of a Model Tension Roof Structure" M. Eng. Thesis, The Univ. of W. Ontario, 1974.

[6] Elashkar I. "Dynamic Response of Tension Roofs to Turbulent Wind" Report BLWT-3-74, The Univ. of W.Ontario, 1974.

[7] Clark G.H. and Sedlak V. "NSW Mobile Stage" Proc. of 3rd Membrane Structures Conference, Melbourne, 1983.

[8] Howell J. "Physical Modelling for Loading and Performance Evaluation of Membrane Structures" Proc. 1st Membrane Structures conference, Sydney 1981.

[9] Stathopoulos, Davenport and Surry "Wind Loads on Low Rise Buildings" BLWT Report SS8-1977 The univ. of W.Ontario, 1977.

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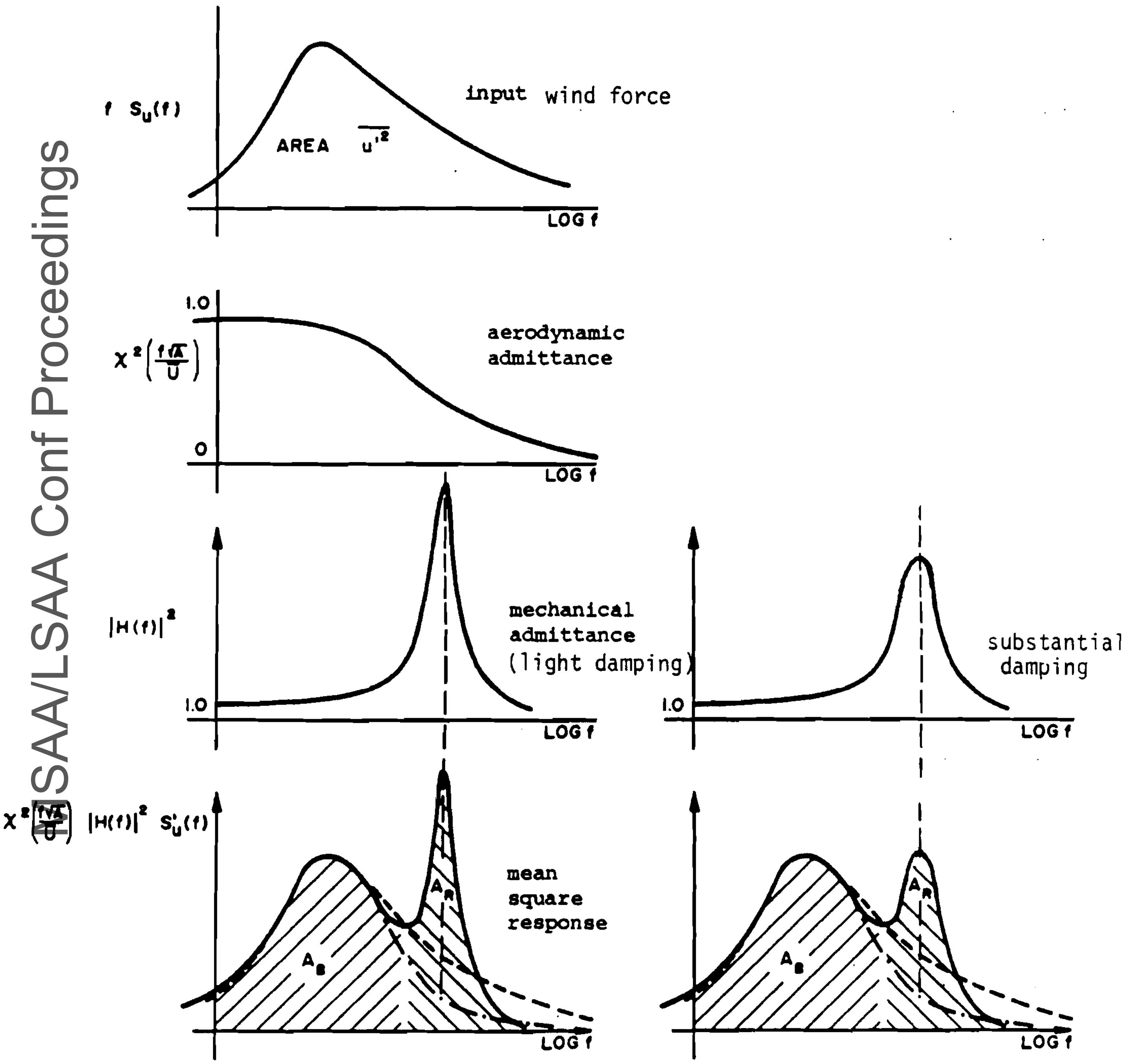

FIGURE 1: REPRESENTATION OF THE EVALUATION OF MEAN SQUARE RESPONSE FOR LIGHTLY AND WELL DAMPED STRUCTURES.

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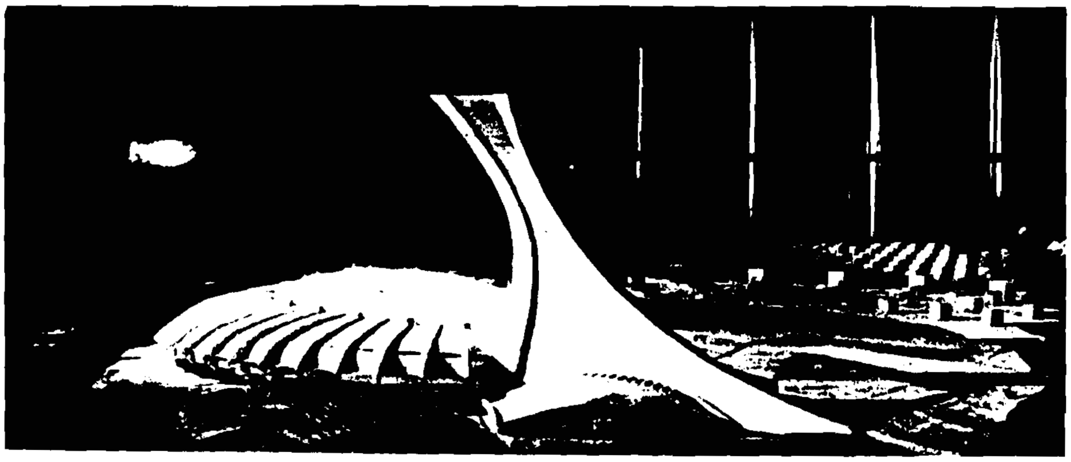
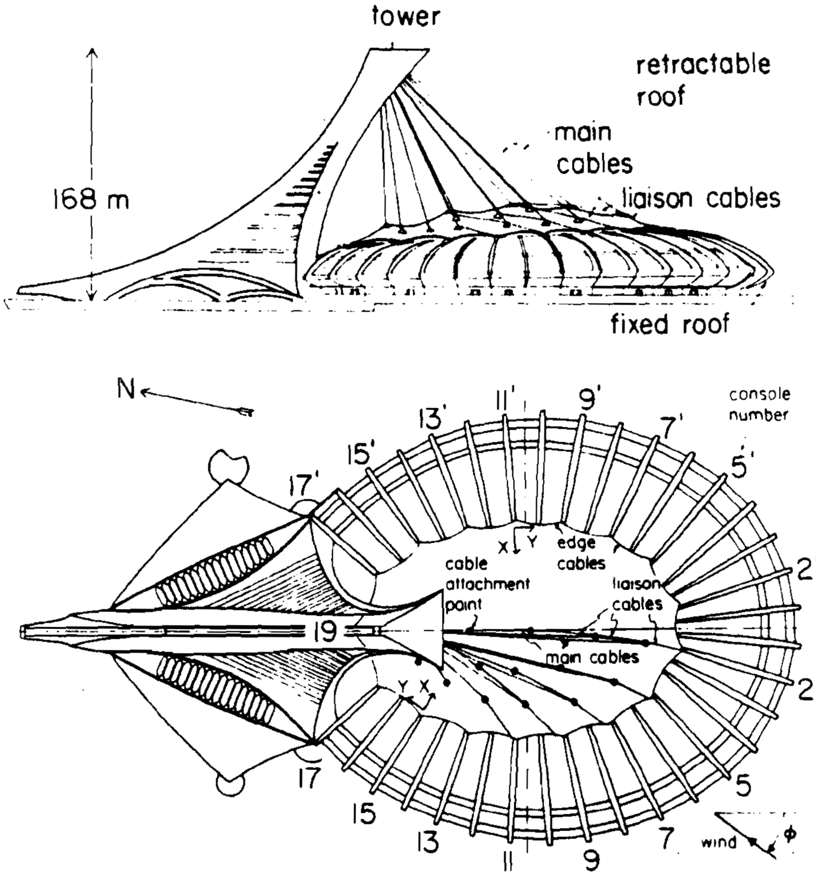


1:100 scale model in 9m × 9m (30ft × 30ft) Low Speed Wind Tunnel



Stadium details

FIGURE 2: MONTREAL OLYMPIC STADIUM WIND TUNNEL MODEL AFTER IRWIN AND WARDLAW 1979

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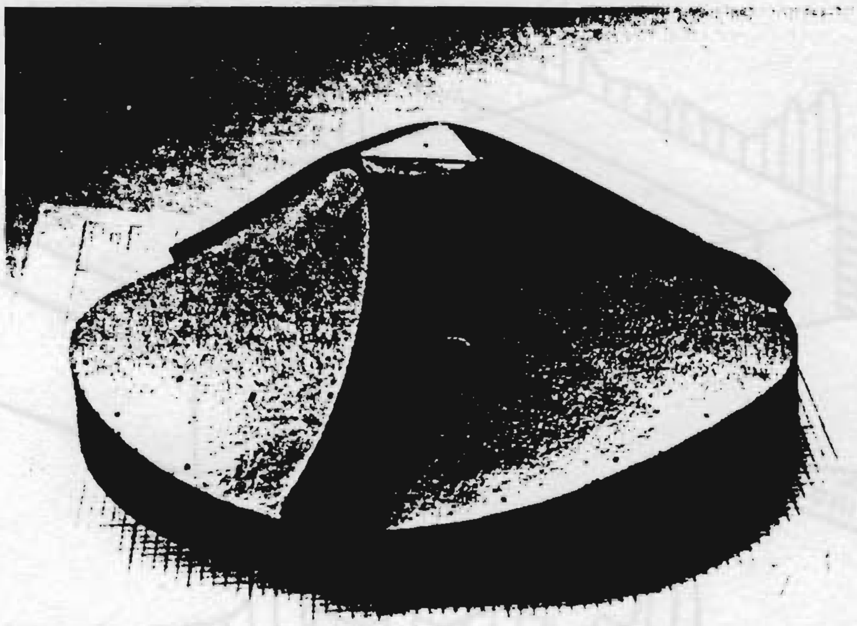
(a) Single unit with the pressure taps visible



(b) Double unit formed by the union of two circular units

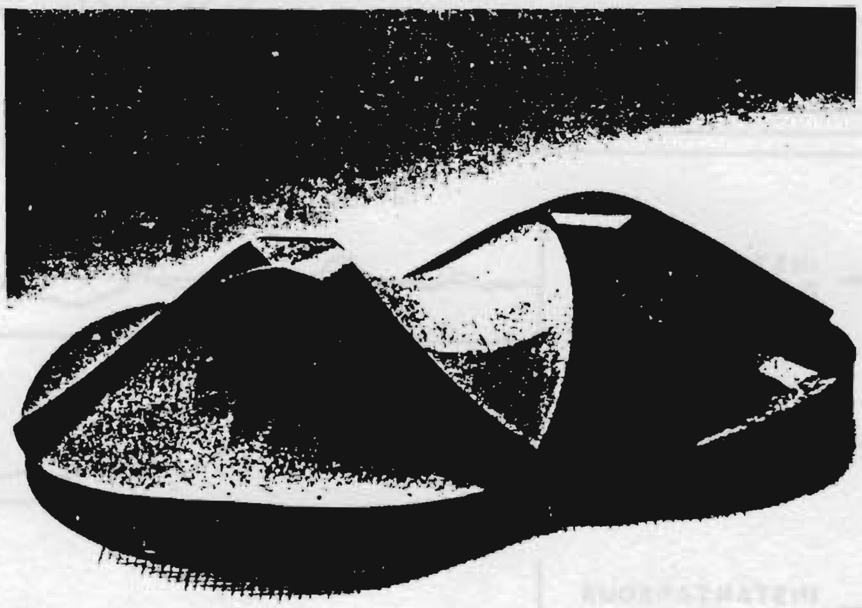


FIGURE 3: VIEWS OF TWO OF THE PRESSURE MODELS

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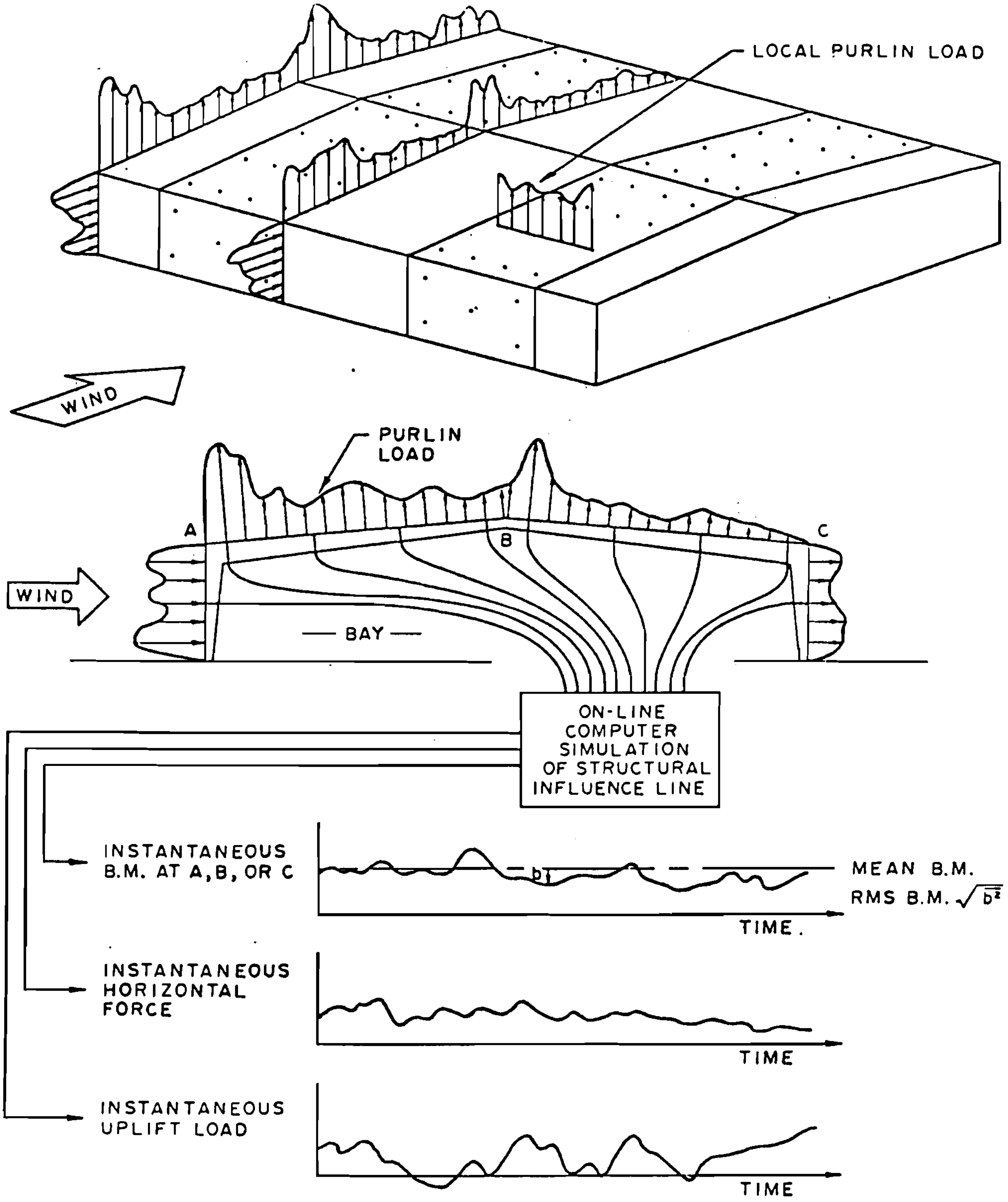

FIGURE 4: **DIAGRAMMATIC VIEW OF UNSTEADY WIND LOADS ON A LOW RISE STRUCTURE**
AFTER STATHOPOULOS 1977

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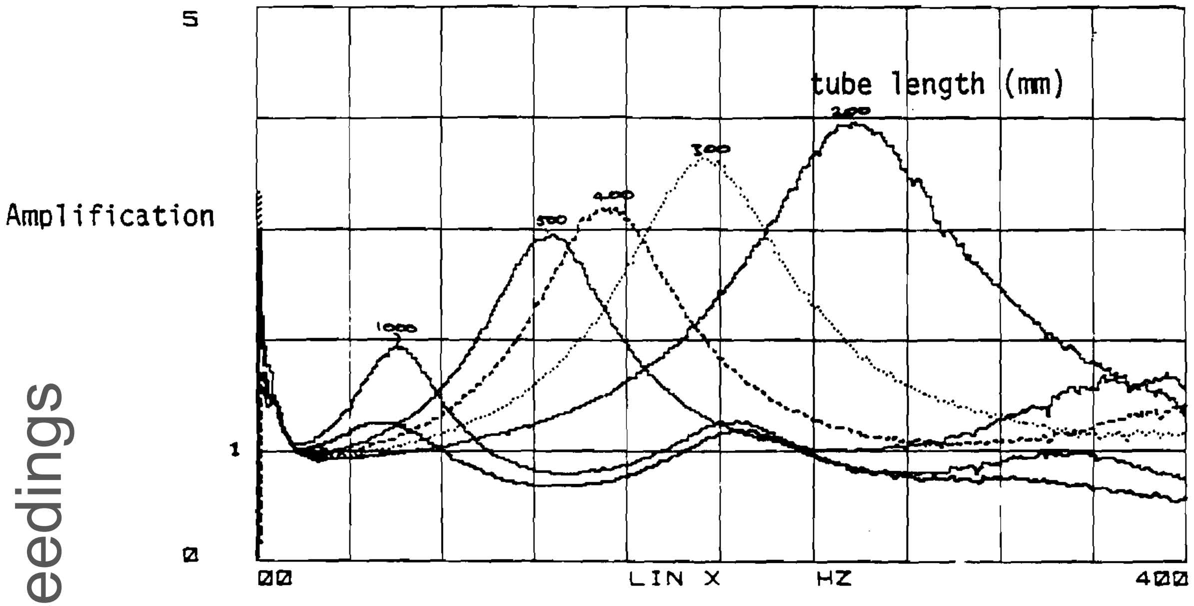

FIGURE 5(a): RESPONSE CURVES FOR UNRESTRICTED TUBES

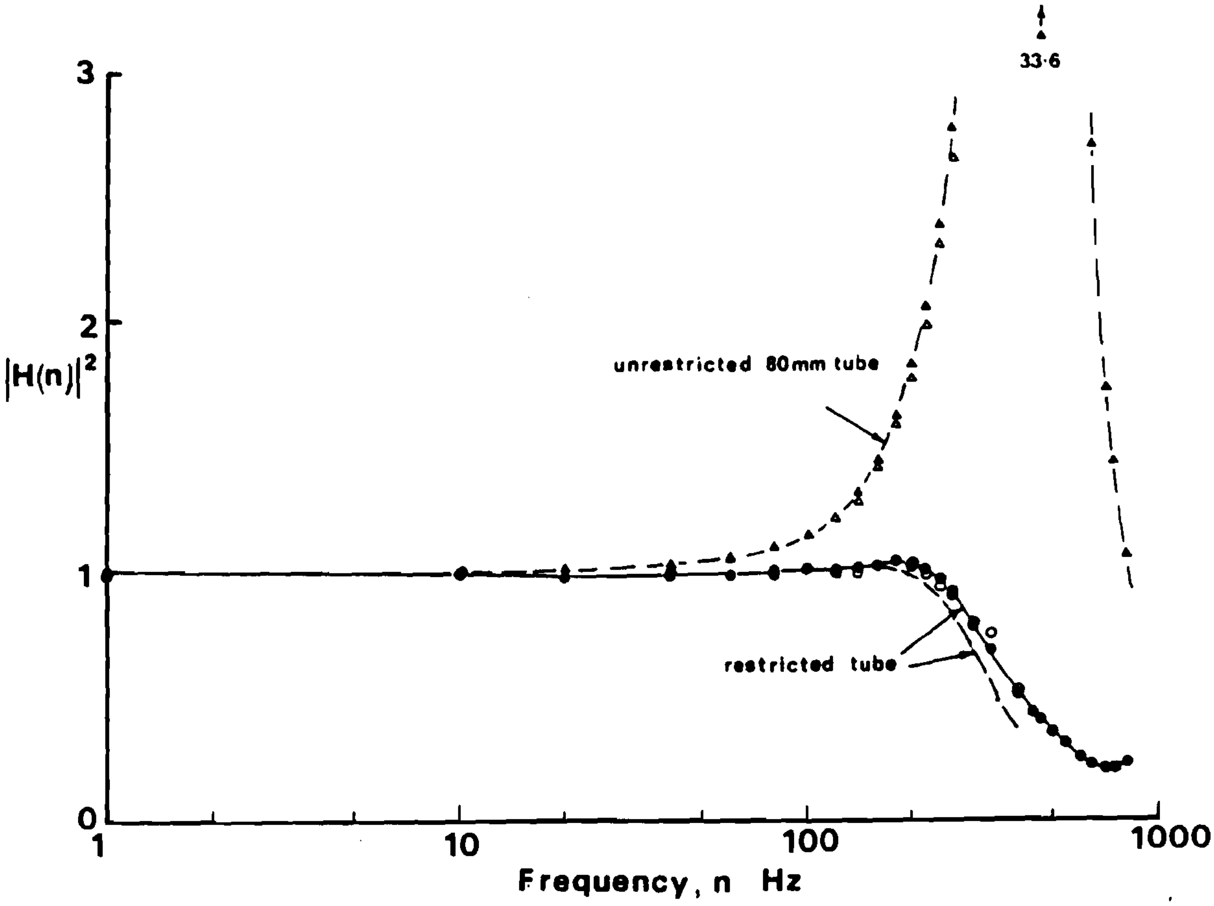

FIGURE 5(b) : Typical amplitude response curves