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Wind loading of large roofs on sports facilities

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Wind is the critical loading in the design of large roofs of partially-enclosed outdoor sports stadiums, and enclosed indoor facilities. However, the response of these structures can be complex, as wind can produce a variety of load distributions and members in the roof structure may respond differently to them; for very large roofs resonant dynamic response may also be significant.
Generally simplified approaches in codes and standards are not appropriate for these large roofs. Code loads may also not be conservative and can result in under design. Over the last twenty years, new approaches have been developed for processing wind-tunnel model measurements to handle the complexities of wind loading and to generate appropriate and realistic load distributions. This paper will discuss the two main approaches to this – one based on recorded time histories of the fluctuating pressures, and one based on their correlations. Several examples will be given of actual roofs that have been designed on these principles including: Sydney Olympic Stadium (an example of an effective static load distribution for the West roof of this stadium is shown below), Wembley Stadium, Ascot Racecourse grandstand, Midfield Terminal, Abu Dhabi, and Wimbledon Centre Court.

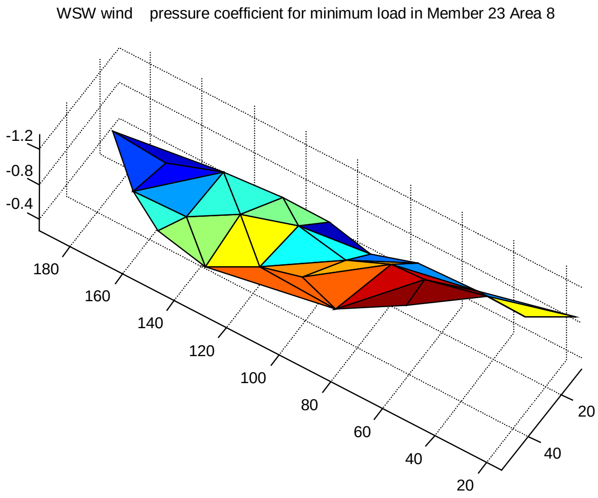


Figure 1. Example of an effective static wind load distribution

Two approaches to post processing wind tunnel model measurements

Because of the large fluctuating component in the wind loading on large roofs, and the nature of the separating-re-attaching flow that produces it, the statistical correlation between pressures at points separated by large distances is small. Designers can make use of this, to the advantage of the cost of the structure, by determining effective static wind load distributions. This approach enables realistic and economical design wind load distributions to be obtained using wind-tunnel tests. Two methods are used:

- In the first approach, correlations between pressure fluctuations at different parts of the roof are measured, and expected pressure distributions corresponding to peak load effects are obtained.
- A direct approach in which simultaneous time histories of fluctuating pressures from the whole roof are recorded and stored. These are subsequently weighted with structural influence coefficients to obtain time histories of load effects. The instantaneous pressure distributions coinciding with peak load effects are then identified and averaged.

The first (correlation) approach is based on the LRC formula, developed by Kasperski and Niemann (1992), which provides the ‘expected’ (in a statistical sense) distribution of instantaneous pressure, that will most likely coincide with a maximum value of a load effect, such as the tension force or bending moment in a structural member of a roof. This equation can be written in its simplest form as:

$\hat{p}_{\mathrm{LRC}}$ at a point on the roof = a peak factor
× correlation coefficient between the pressure and the load effect
× standard deviation of pressure at that point

Of the terms on the right-hand side, the first and third are relatively straightforward to understand and determine. The standard deviation of fluctuating pressure is simply the root-mean-square fluctuating point pressure that is routinely measured in wind-tunnel tests, in the form of a non-dimensional coefficient. The peak factor is typically a number between +/-3 and +/-5 (often +/-4 is used) that depends on the probability distribution of the fluctuating pressure and the sample time used (e.g. 10 minutes to 1 hour in full-scale time).

The second term is the load-response correlation (LRC) coefficient (r_{LRC}), and is less easy to determine. It is the correlation coefficient between the fluctuating pressure at the point of interest, and the load effect (tensile force, bending moment etc.). The latter may depend on pressures from all points on the roof, with the relationship determined by a set of influence coefficients obtained by structural analysis. For this reason, the calculation of r_{LRC} requires knowledge of correlation coefficients for every pair of points, or panels, all over the roof, and are fairly complex calculations for a large roof. However, the matrix functions in EXCEL or MATLAB can be used to advantage for these calculations.

The principles of the correlation approach are explained for a simple two-panel roof in Holmes (2015 – Appendix F).

The direct approach is conceptually simpler, but also requires structural influence coefficients, and a considerable amount of 'number crunching', because averaging over multiple samples is necessary to achieve 'stable' load distributions.

The relative advantages of the two methods are summarized below:

1. Correlation method advantages
   a) less computation time – this is because of the averaging carried out once in the calculation of correlations between the fluctuating pressures,
   b) much less storage of data from the wind-tunnel testing is required.
2. Direct method advantages:
   a) conceptually simpler to understand for the non-wind engineer,
   b) it is somewhat easier to calculate dynamic (resonant) components of loading with this method.

The two methods have been compared by Holmes and Wood (2001) for the same structure, and shown to give very similar equivalent static wind load distributions, within the statistical variability inherent in the two approaches.

The importance of resonant contributions to the wind loading of large roofs (as opposed to long-span bridges, or very tall buildings) is often overstated. The lack of correlation of the applied pressures over a large area means that the generalized forces required to drive the complex resonant mode shapes of a large roof, are usually small in magnitude. There are exceptional cases, such as the roof of the new Wembley Stadium, London, for which the resonant components are significant. The appropriate treatment of these cases is however, beyond the scope of the present paper.

Application of the correlation method to long span structures

The first use of the correlation method of post processing was for the design of the Sydney Olympic Stadium Roof, designed by Modus Consulting Engineers in 1997 as part of the Multiplex Team for the Sydney 2000 Olympic Games. From a designers perspective this was an ideal approach as it identified generally more benign overall wind loads and importantly specific pattern loads that were more critical to the structural design.

Since this first successful application of the correlation method, the first author has stipulated this approach on many long span structures around the world, including Wembley Stadium, London; Ascot Racecourse Redevelopment, Ascot and Wimbledon Centre Court Closing Roof, London. Other structural practices have also adopted this approach on long span structures for example Arup as engineers for the Midfield Terminal at Abu Dhabi Airport.

The correlation method requires a completely different approach by the structural design engineer and generally one in which the engineer has to take a far more active part in the derivation of suitable wind load design cases. In order to 'correlate' the time history of measurements from testing with the behaviour of the structure under wind loads it is necessary to define that behaviour in such a way that it can be used to filter the time history of measurements to find the 'worst case' wind load patterns.

To define the structural behaviour the structural designer needs to carry out the following steps: -

1. Consider the key vulnerabilities of the structure and its general behaviour under load.
2. In conjunction with the wind consultant, determine suitable patches (load areas) on the surfaces of the structure.
3. Determine 10 – 20 key behaviours of the structure under wind loading that would be fully representative of the more onerous deign conditions i.e. the governing wind loads design criteria for the structure. Identify suitable individual design actions that act as markers for each of the key behaviours, e.g. compression in the central top chord element of an arch as a marker of maximum uniform pressure (up and down).
4. Calculate the coefficient sets for each of the design actions, ensuring common understanding of the approach with the wind consultant.
5. Receive wind design load cases, maximum and minimum for each of the design actions, determined by the wind consultant from filtering the time history data set.
6. Apply these load cases as equivalent general load cases to the structure and size elements of the structure based on these load effects from wind.

For example the roof of Stadium Australia in Olympic mode contains three primary elements; the main trussed arch spanning 296m, a perimeter prismatic truss spanning onto the upper tier rakers and an orthogonal space grid between following a hyperbolic geometry.

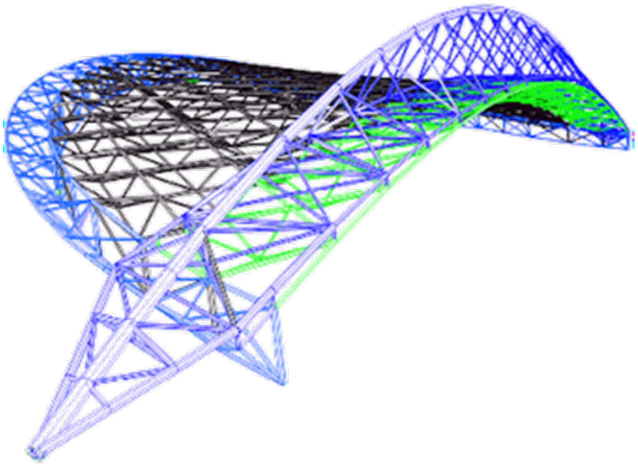


Fig 2 Stadium Australia West roof Structure.

The main trussed arch works by arch action under uniform loads whereas unbalanced loads cause bending in the arch trussing members. Furthermore pattern loading on the main roof surface causes rotation of the arch about its longitudinal axis which is then resisted by bending in the perimeter truss. The key vulnerabilities of this structure were therefore its response to pattern loading rather than uniform pressures and the design actions used as markers of these responses were selected accordingly. For example the axial force in the top chord of the arch at mid span was a marker for uniform pressure and suction whereas the axial force in the lower chords of the arch truss near the quarter span was a marker for bending in the arch truss due to unbalanced wind loads.

Generating the coefficient sets that relate to each design action was somewhat laborious, requiring multiple analysis runs to extract resulting magnitudes of the design action for each loaded patch and then normalising the values. Over time this process has become more automated and the time taken to generate coefficient sets more reasonable.

The roof design for the new Wembley Stadium similarly used a main arch, in this case in conjunction with an upward curving catenary system to resist uplift on the roof. Again this was an ideal use of the correlation method as pattern wind load was typically the critical load case for the roof structure elements. The selection of suitable structural behaviours and design actions as markers of these was further complicated as the roof design incorporated sections which retracted from the East, West and South sides of the roof.

The first author, Stephen Morley, was Director of Design for the structural designers, Mott Stadium Consortium, which comprised Mott MacDonald, Connell Wagner, SKM and Weidlinger.

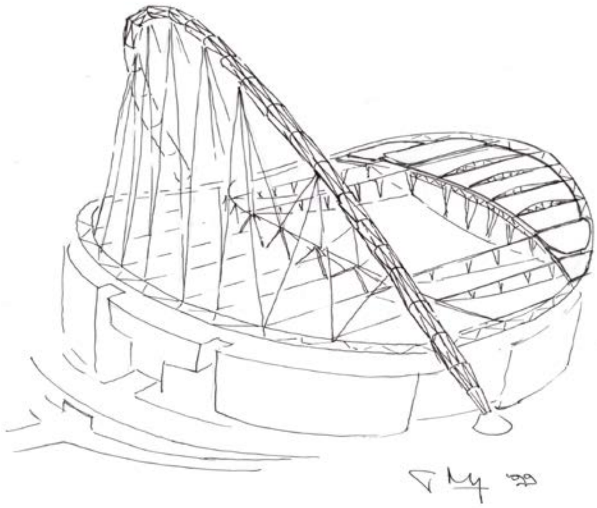


Fig 3 Early structural concept sketch of Wembley Stadium Roof

Wind tunnel testing was carried out by BMT Fluid Mechanics, London and the coefficient data sets were assembled by Connell Wagner, detailed designers of the roof. JDH Consulting contributed through independent development of the final wind load cases for the roof, and by providing wind loads for the main trussed arch, which weren’t measured in the wind-tunnel tests.

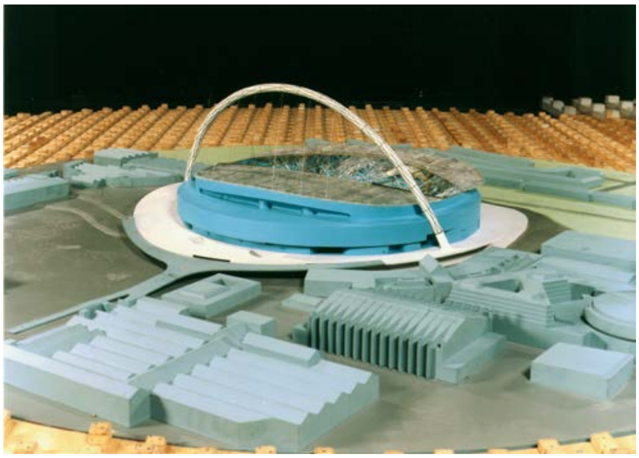


Fig 4 Wembley Stadium London, wind tunnel test model, BMT Fluid Mechanics

BMT produced an animation of the varying wind pressure distributions measured in the testing which strikingly illustrates the turbulent nature of flows over such structures and the reason why the correlation method is such a powerful tool in identifying which of those distributions results in the most critical design conditions for the structure. This approach gave us confidence as structural designers to use very lightweight thrust beam trusses with cable bottom chords for the fixed roof support systems.

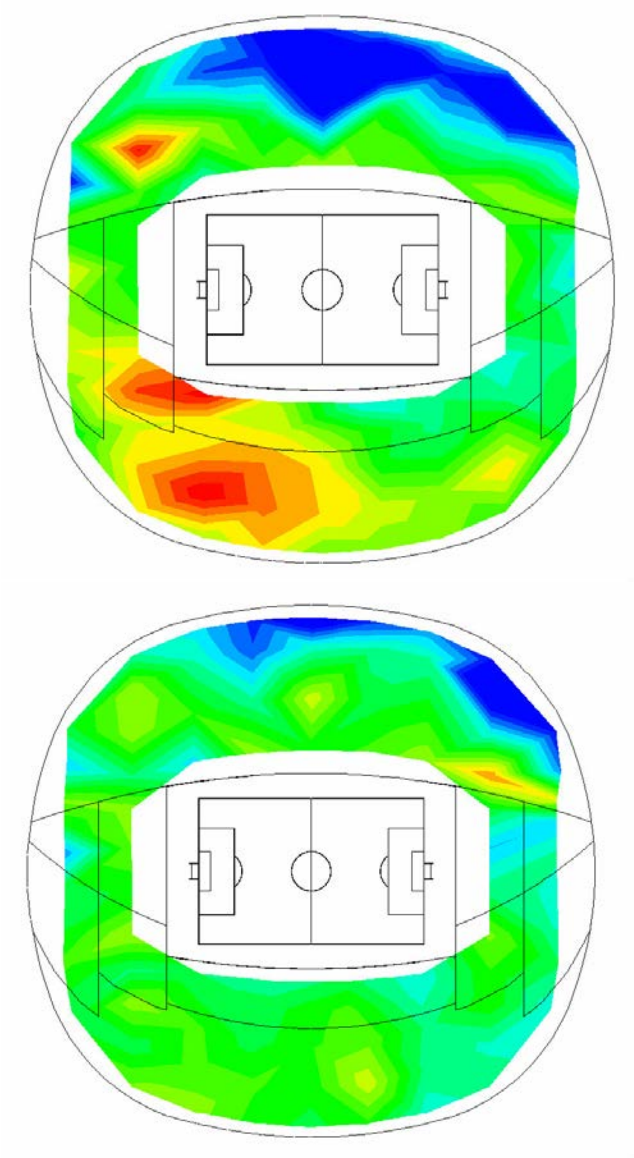


Fig 5 Two depictions of instantaneous pressure distributions from the wind tunnel testing of Wembley Stadium roof, under the same wind direction; courtesy BMT Fluid Mechanics, London

Fig 6 Ascot Racecourse redevelopment, roof trial assembly showing fabric hypar and metal clad sections.

For the Ascot racecourse redevelopment the roof form comprised a series of fabric clad hypar surfaces interspaced by metal clad infills all supported on sculptural tubular steel framing.

Because of the modular form of this roof with its multiple supports the design actions and corresponding coefficient sets were more readily derived and relatively simplistic. The main actions to be considered were differential loading of the fabric and adjoining metal clad surfaces which caused twisting of the cantilevers; this being more critical as the bracing in the prismatic cantilevers was not triangulated. Similarly unbalanced loading front to back of the grandstand roof generated bending in the main rear support columns and was therefore an important design case. In each case a combination of zeros and ones sufficed to describe the structural vulnerabilities sufficient to derive suitable load cases through post processing.

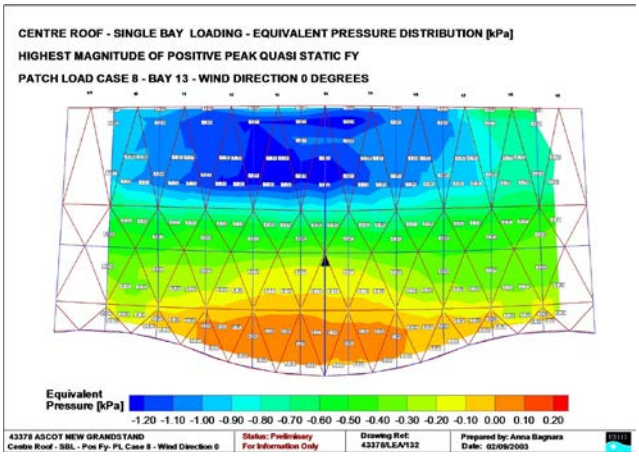


Fig 7 Ascot Racecourse roof, quasi static wind load case example

Similarly for the retractable roof for Wimbledon’s Centre Court, concept designers Bianchi Morley, there was a specific structural vulnerability that made the correlation method a very suitable approach.

Fig 8 Wimbledon Centre Court Closing roof, first use.

The roof design concept required the trusses of the closing roof to stack very tightly to minimise shadowing on the grass. This resulted in very slender trusses, proportionately more slender than an eggshell, having a span to width ration of 100:1.

Consequently the trusses were vulnerable to differential loading between adjoining bays of the folding fabric roof.

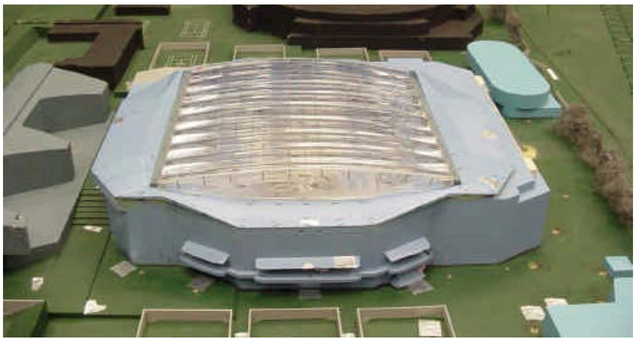
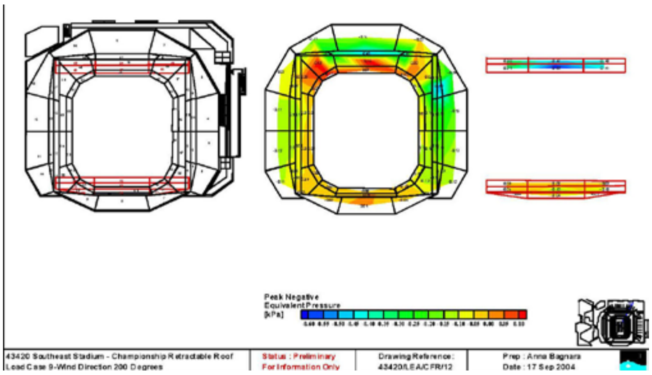


Fig 9, 10 Wimbledon Centre Court Closing Roof – Wind tunnel test model, roof closed, roof open load case below. BMT Fluid Mechanics



Conclusions from experience in use

It must be appreciated that the output is only as good as the initial input considerations leading to identifying suitable design actions; therefore this process is critical to the successful application of the correlation method.

The resulting load cases should not be given a greater level of certainty or accuracy when applied as a general load case than is appropriate. For example automatic optimisation of a structure where wind loads are dominant and have been determined from this method should be used with great caution.

With modern computing power it is conceivable that wind load cases be determined for every single design action in a structure and every element is optimised for this wind loading. However as a structural designer, I consider the discipline necessary in determining a small number of critical structural behaviours and then identifying suitable design actions as markers to0 be a valuable part of the overall design process. The designer needs to fully understand the way the structure works in order to determine these behaviours and markers and that is no bad thing!

References

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