Structure and Wind – A Question of Interaction

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Introduction

The use of wind tunnel testing techniques to determine the design wind actions for structural design of very tall buildings is becoming increasingly necessary, particularly in Australia, which is privileged to have some of the leading wind tunnel testing facilities in the world. In a highly competitive construction and property development environment, owners, developers and constructors of tall buildings are often interested in utilising wind tunnel testing, as the costs associated with such tests are typically off-set by the substantial savings in the structural costs. This is usually due to the reduced derived design wind actions compared with the more conservative code derived wind loads.

Moreover advances in high strength construction materials (e.g. high strength concrete) are producing more taller and flexible buildings of lower natural frequency with the potential to exhibit amplified dynamic response. Often in this situation the structural response of the building is outside the stipulated range of code based techniques, or uncertainty with regard to the potential for motion perception demands that wind tunnel testing be carried out.

This has led to an increasing number of structural engineers being exposed to the challenges of understanding, interpreting and applying the results of wind tunnel test results to the structural design of their building. The adoption of more sophisticated and complex code analyses has however not necessarily been accompanied by a commensurate understanding of theoretical dynamic wind effects, which by nature tend to reflect a statistical envelope of predicted actions rather than model representation of building response to a 'theoretical' wind event. In particular a transition in understanding, from the application of former code-based equivalent static forces, to representing mean and inertial forces in a dynamically responsive structure, needs to occur at the design office level.

Although Australia has made considerable progress towards effectively standardising to some degree, the highly specialised area of wind tunnel testing, it is the opinion of the authors that an improved interaction between the disciplines of structural and wind engineering is required to maximise its benefits. This paper will discuss some of the issues, from a structural engineering point of view, based on the authors' experience in designing tall buildings in the central business districts of Melbourne and Sydney. The objective of the paper is to initiate some dialogue between the two disciplines to gain a better understanding of each other's role in tall building design.

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The structural design of tall buildings

For most structural systems from the basic beam to complex shell structures, one or more of the following structural criteria: stability, strength and serviceability, govern the design. A unique characteristic of tall building design is the significance of all three criteria in deriving a satisfactory structural solution. The principal contributing factor is the presence of lateral loads,

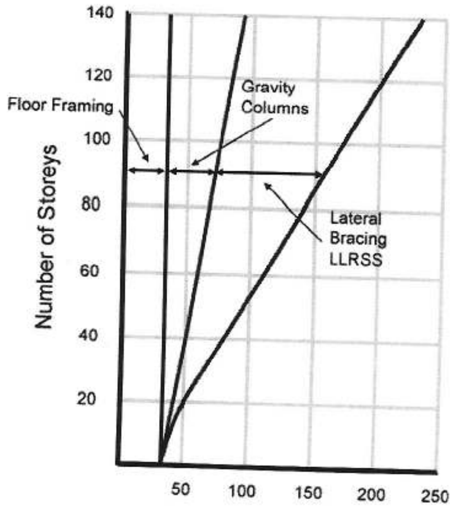

Figure 1 - Weight of steel in tall building

increasing height as illustrated in Figure 1. The structural is typically finalised at an early stage of the design process system due to its potentially considerable impact on the architectural intent. Frequently the physical size of critical elements are also finalised at this early stage. Furthermore, to expedite the construction the detailed design of the foundations is often completed during this early stage, with contingencies applied to the design gravity and wind loads to compensate for the inevitable early inaccuracies in predicting loads.

The design of all structural elements forming the lateral load resisting structural system (LLRSS) of a tall building is dictated by the maximum wind action. Theoretically the design of each element would be governed by a unique wind direction depending on the elements orientation and role in the LLRSS. Due to traditional approach of developing a structural system in two orthogonal directions corresponding to the building grid the number of critical wind cases can be reduced to a few. However it is important to note that for elements that participate in resisting wind loads from both orthogonal directions identifying the critical wind load case requires prudent care.

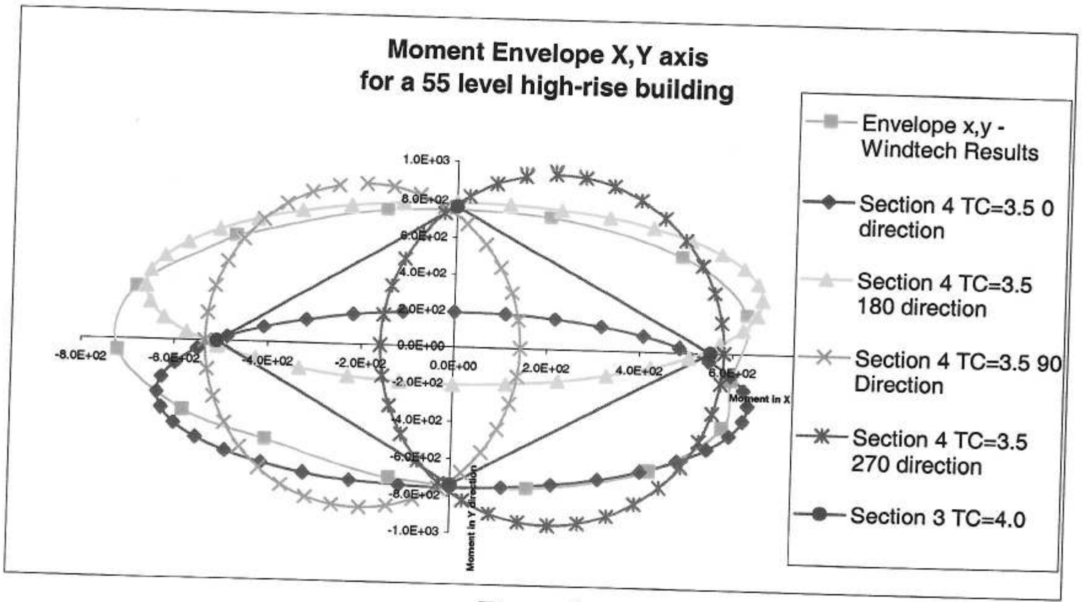

Figure 2

In addition to the strength and stability compliance of all elements, the overall LLRSS must satisfy the serviceability requirements. Excessive deflections can lead to damage of non-structural components and/or unwanted excessive second order structural effects. Satisfactory building performance in terms comfort criteria for its occupant is paramount, emphasising the importance of correct determination of accelerations. With due consideration to the large capital investment of correct determination of accelerations. With due consideration to the large capital investment associated with tall buildings non compliance in comfort criteria could have grave implications in terms of the utilisation of the building for its intended purpose.

Figure 2 illustrates a typical base overturning moment envelope derived from wind tunnel testing for a slender 55 storey building. Code derived wind actions are also included for comparison purposes. In this particular example the wind tunnel derived loads are significantly lower (approximately 15%) for the Y-direction compared with the code derived loads whereas for the X-direction loads both methods give similar results.

Of considerable interest in the design of this building (in Sydney) is the dominance of dynamic inertial forces in governing the structural design of the building. These forces are several times the magnitude of the mean wind action; which is arguably counter-intuitive to the traditional mind-set associated with lateral load design for buildings in Australia. In such circumstances accurate representation of the dynamic response of the building in the wind model is key to obtaining reasonable estimates of the distribution and magnitude of structural actions.

Eccentricities, irregular structural arrangements at podium levels such as basement retaining walls and so forth, may potentially generate torsional first modes and amplified local structural actions in interaction with periodic 'buffeting' effects. The limitations inherent in the structural engineer's theoretical model and the wind engineer's scaled representation in the tunnel, should be point for keen discussion, if not debate during the design process. In the absence of this interaction, the result may be the acceptance of theoretical results as inherently correct, without a detailed understanding of the assumptions and limitations intrinsic to the process.

It is evident that the current design and build process adopted in tall building construction often does not allow sufficient time to develop an accurate set of wind actions, whilst allowing this communication between the structural engineers and the wind tunnel engineers to occur, to fully justify the benefits of utilising wind tunnel as a means of determining the wind loads.

Interaction issues between structural and wind engineers

This section identifies and summarises some of the issues from the perspective of the structural engineer.

- ***Ultimate and Serviceability Models*** – Accurate assessment of the dynamic characteristics of both the wind and the structure is required for the wind tunnel test results to be meaningful for design purposes. In structural terms the ultimate design base overturning moments to satisfy strength and stability limit states should be based on the performance of the LLRSS utilising the appropriate material properties associated for this level of loading. However for deflection and acceleration assessments, at the appropriate serviceability load levels the structural model can be significantly different.

  Generally the material properties are stiffer, in particular for concrete structures and more importantly other secondary structural elements not utilised to resist the lateral wind loads for ultimate limit state will contribute to the overall stiffness of the buildings. The difference in the dynamic characteristics between the two will vary from building to building suggesting a clear need to differentiate the structural models for the two limit states. There is a need for the structural engineers to supply the dynamic characteristics of the building to the wind engineers at both limit states.

- ***Uncertainties and sensitivity analysis*** **–** As emphasised previously the structural form is often finalised at early stage of the design process based on early structural models using the wind tunnel test results. The wind tunnel test results inevitably will change due to further refinements of the structural models. Sensitivity analyses of wind tunnel test results to determine variation with the parameters of the building and the environment is highly desirable.

- ***Critical load cases*** – Identification of critical load cases for structural design purposes is not easily achieved, in particular for structural elements that participate in resisting loads with biaxial effects. The structural engineer who should be fully conversant with the structural model and predicted dynamic behaviour of the building, is best situated to identify the critical load cases.

- ***Interference from future buildings*** **–** Wind tunnel test results are typically based on existing conditions. Wind tunnel tests incorporating proposed future adjacent developments often indicate critical load cases due to periodic wind interference patterns or 'buffeting' effects. Although some genuine effort may be made to investigate interference from future building it is by nature highly speculative.

  The conservatism in the code-derived loads is considered to allow for future buildings. Greater guidance is needed from statutory codes and/or the limitations need to be identified by the wind and structural engineers, before application of the recommended wind tunnel test results for design purposes to avoid hopelessly open-ended design scenarios.

- ***Vertical distribution of lateral loads*** **–** There are some ambiguities in procedures practiced to distribute the lateral loads up the height of a building, in particular for buildings that have a varying plan shape. Clear guidance is required on the procedure for both the static and dynamic components addressing the geometric and dynamic characteristics of the building. This is particularly important for buildings, which utilise transfer structures and/or outriggers at intermittent locations and for buildings, which have significant structural transitions. Accurate assessment of design loads at such locations is just as important as assessment of the base design loads.

- ***Comparisons with code assessment.*** **–** Comparisons of wind tunnel test results with code - derived results should be included in the reporting by the wind engineers. This would enable both parties to appreciate the significance of wind tunnel testing.

- ***Significance of torsion*** **–** For buildings structurally eccentric in plan, greater understanding is required in terms of accelerations, the combined effects of translational and torsional acceleration components and the vertical distribution of the applied torque. With buildings that are large in plan, problematic torsional accelerations may induce high peak accelerations at the periphery of the building.

- The requirements for rotational articulation in an aero-elastic model, to accurately reflect the torsional modes that may be derived from a theoretical modal analysis, should be discussed in detail between the structural and wind engineers.

Conclusion

The use of wind tunnel testing for determination of design wind loads is becoming increasingly common in tall building design as a consequence of:

- Commercial pressures to optimise the structural design
- The adoption of high strength materials and new structural forms in construction producing more flexible structures with low natural frequencies
- The limitations imposed by current codes on the application of code based techniques to long-period structures
- Concerns regarding the serviceability of tall buildings, with regard to dynamic effects and motion perception (especially in an environment of high-rise apartment construction).

There is a need for structural and wind engineers to improve their respective knowledge base in each other's disciplines to maximise the benefits of specialised modelling and testing, and to appreciate the limitations of current structural/wind analysis techniques.