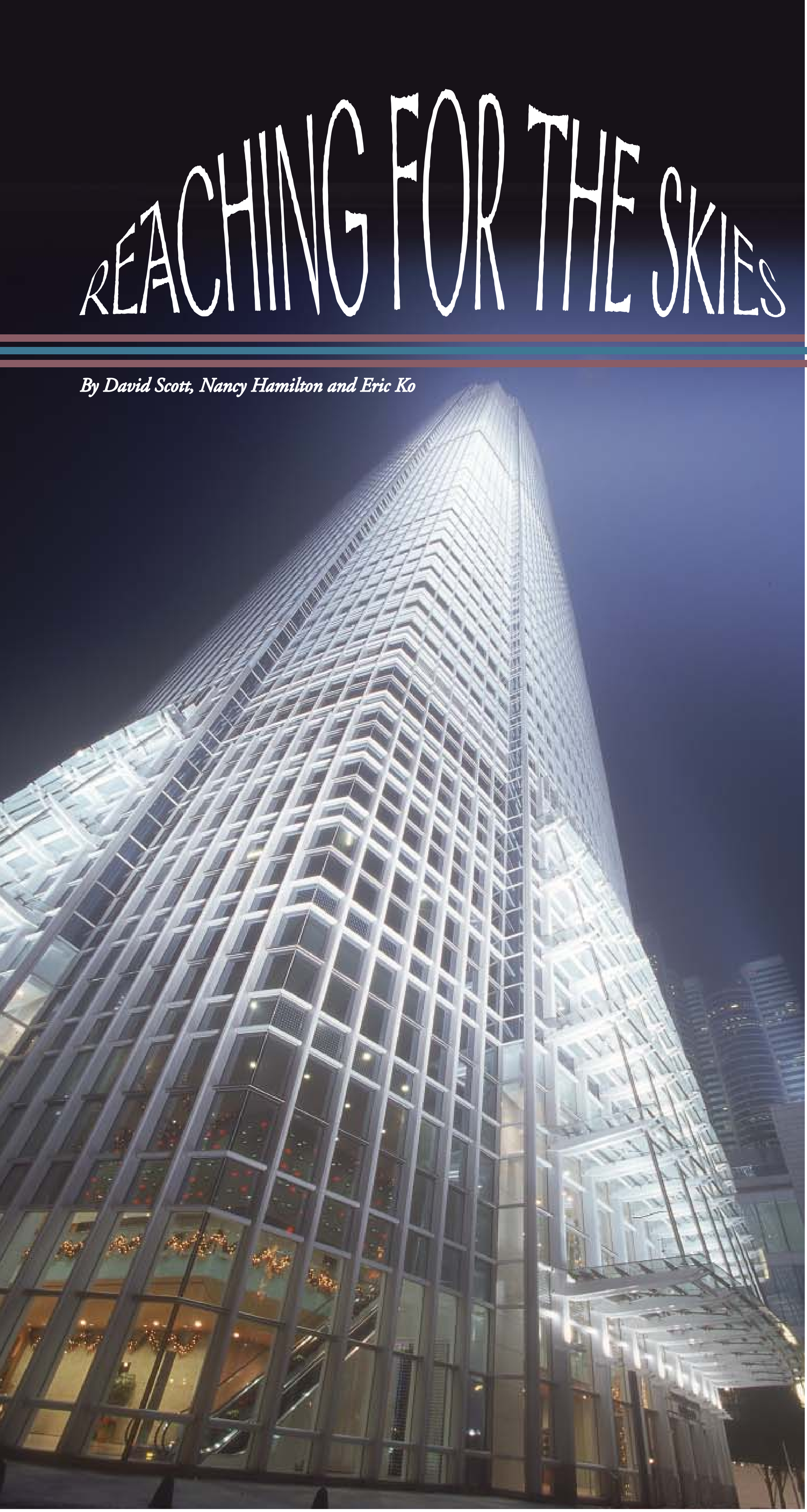
REACHING FOR THE SKIES

Structural Design Challenges for Tall Buildings

By David Scott, Nancy Hamilton and Eric Ko



Tall Buildings by their very nature are big budget projects. Most developers are very focused on minimizing cost. Small savings on a square foot basis can quickly become large amounts of money. It is therefore surprising to some clients that some of the factors which determine efficiency and economy are rather vague and not well defined by codes and standards, and give the engineer substantial latitude to use his experience and engineering judgement. A knowledgeable engineer can use this opportunity to work with his client and make clear choices on design criteria and expected building performance.

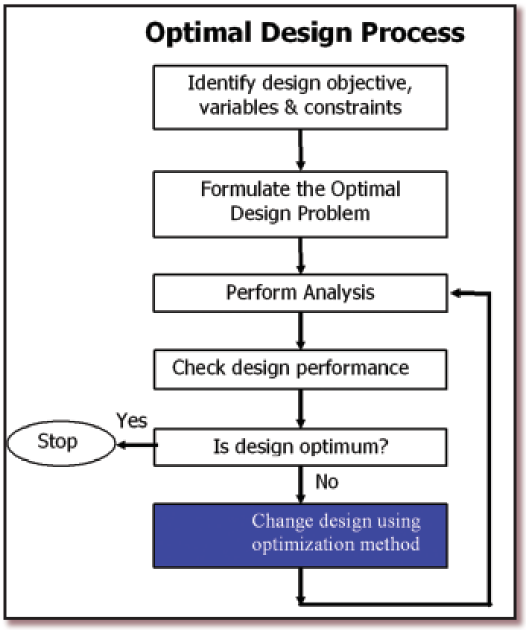
Probably the most significant factor in the cost of a building is the choice of structural systems and materials as described in earlier editions of STRUCTURE. This article focuses on design criteria and key design procedures, and how they too have a substantial impact on total cost. All parties need to have a clear understanding of the design criteria, and what these mean to the performance and cost.

Wind

Tall buildings are flexible structures, and their dynamic response to wind excitation is critical in assessing their loading and performance with respect to deflection and acceleration criteria. Significantly, for many tall buildings, and for most with an aspect ratio of greater than 6:1, the cross-wind response dominates loading and acceleration.

The only accurate way to predict the cross-wind response is through a wind tunnel study. The key to accurate prediction of cross-wind loads and responses is the use of appropriate design wind speeds and turbulence intensities.

Most wind tunnel laboratories will conduct a wind climate analysis that gives realistic estimates of wind speeds for different return periods and a measure of directionality, i.e. from which directions the strongest winds come. This wind climate model is used



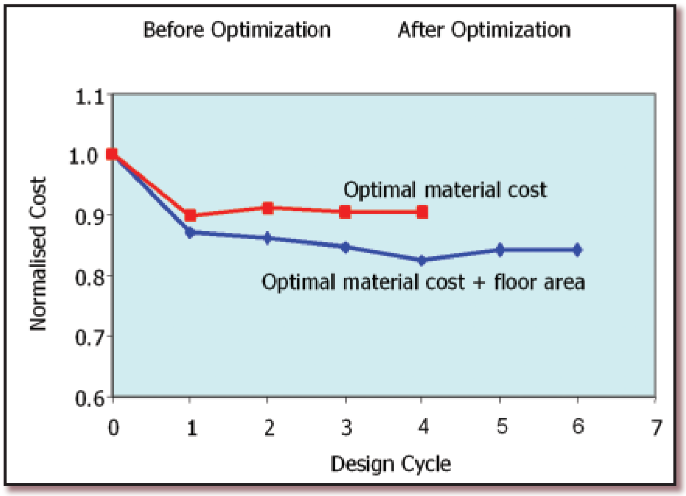


Figure 1: Optimal Design Process

directly in the prediction of accelerations, but for loading it is common to scale up the wind speeds to meet the code-specified design/wind speed at the worst wind direction, while still taking advantage of reductions for other directions.

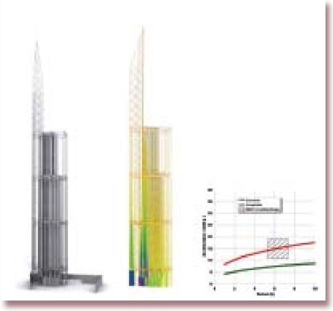


Figure 2: Analysis Model for a Tower with Preliminary Acceleration Limits, Prior to Wind Testing

The turbulence intensity, or gustiness is critical, particularly over the top third of the building. A difference of a few percent in turbulence intensity here can result in very large changes in the response. The assessment of turbulence is particularly important for isolated tall buildings that tower over their surroundings, and requires detail studies of upwind terrain.

As a designer, there are a number of approaches that can be taken to minimize the cross-wind response.

- Rotating the building so that its least favorable aspect does not coincide with the strongest wind direction can be very effective, as cross-wind sensitive buildings can see their peak responses change by 10 to 20% within a 10-degree wind direction change.
- A rounded plan shape. In practice, this means moving away from sharp-edged square plans as much as possible. Even small changes such as chamfered, rebated, or rounded corners can be very effective in reducing the cross-wind response.
- Tapering and stepping back the building shape with height. Making the plan less regular assists in breaking up the correlation of vortex-shedding with height.
- Introducing porosity at the corners, particularly over the top sections of the building. This is commonly done through sky-gardens or refuge floors.

Where these aerodynamic modifications are adopted aggressively, it can be possible to reduce accelerations by 50% or more; however, reductions of 20 to 30% are more common.

The prediction of the dynamic properties of the building: natural frequencies, mode shapes and structural damping have a great effect on the predicted wind loads and accelerations. Most full-scale data shows that dynamic models tend to underestimate the natural frequency, and hence wind loads will be overpredicted. This effect seems to diminish with increasing aspect ratio, perhaps because flexible structures tend to be more determinate and have less secondary structure.

Structural damping is another uncertainty. While there is an increasing amount of data on appropriate values during small vibrations, there is still little reliable data on structural damping at the amplitudes that would be experienced during a design-level storm. The difference in selecting 1% or 1.5% structural damping would result in a difference in acceleration predictions of over 20%. These basic assumptions can be much more significant than structural optimization, which is described later in this article (*Figure 1*).

Accelerations and Occupant Comfort Criteria

The designs of very tall buildings are often driven by occupant comfort criteria, by limits to lateral acceleration. Recent years have seen increasing uses of dampers to mitigate undesirable motions. The subject of occupant tolerance to motion is a highly complex mix of engineering, physiology and psychology and is not well understood, even by many wind engineering specialists. There is substantial ongoing research and development in this area.

Acceleration criteria should cover two conditions; the alarm caused by large motions that may occur in an occasional very strong wind and the annoyance caused by perceptible motions that occur on a more regular basis. Most criteria tend to focus on the latter. For high rise design, accelerations will be considered an issue at the very outset of a project, however they are very difficult to evaluate with any certainty before doing a wind tunnel test. An example of this is shown in *Figure 2*.

The building owner has a major role to play in determining the degree of comfort desirable in the building. Because acceleration limits have been developed from subjective criteria, some clients wish to be involved in the selection of the acceleration design criteria. The motion table at the Hong Kong University of Science and Technology (HKUST) has been designed to reproduce a room undergoing the low amplitude, low frequency motions expected in a very tall building. (*Figure 3*) This motion simulator has also been used by Arup to demonstrate predicted building motions to developers. These demonstrations resulted in one case in which the developer agreed to eliminate a costly damper system from a tall building. In fact, the primary benefit of a damper system in most cases is its ability to reduce the frequency of occurrence of perceptible motion, rather than the magnitude of the most extreme motions.


Figure 3: Simulated Office Environment at HKUST Low Amplitude Shake Table (© Arup)

If acceleration is an issue, stiffening the building is often the least effective response. Although accelerations are reduced, the motions become more perceptible at higher frequencies. The fact that occupants are more sensitive to higher frequency accelerations is not recognised in standard US design practice, but has long been part of international design practice (e.g. ISO6897-1984).

The area of acceptability of wind-induced building motion is by its nature subjective. Current research will lead to more advanced criteria for acceleration limits, in the near future.

Deflection Criteria

Several codes specify a deflection limit of H/500 for tall buildings. Many other codes use the same limit as a guideline. At the same time, an inter-storey drift of H/350 is common. However, there is no compelling reason, other than a historical one, to limit deflections to H/500 if a building can accommodate the P-delta effects and an inter-storey drift of H/350. This is of course based on the assumption that acceleration characteristics are satisfactory, and that appropriate considerations are given to the movement provision within the façade system and the performance of the vertical transportation.

Often lateral deflections are limited to H/400 for buildings subject to hurricane winds and H/500 when subject to normal winds only. This is partly because the 1000 Year Event in hurricane winds is approximately 1.6 times the 50 Year Event, while with normal winds the 1000 Year Event can be higher (1.8 or more).

Blast, Fire and Progressive Collapse Criteria

Recent catastrophic events have precipitated the creation of various standards and guidelines on how buildings (in general) should be designed to resist the effects of explosive attack and mitigate the potential for progressive collapse. GSA's *Progressive Collapse Analysis and Design Guideline* (2003) requires buildings to consider the removal of any column.

There was concern that these guidelines would prohibit designers from developing either economic or interesting buildings. Recent construction of the San Francisco Federal Building demonstrates that these concerns are not warranted. (*Figure 4*)

Tall and iconic buildings are often designed explicitly for extreme events in excess of any code requirements. Sophisticated analysis software is available to explicitly model the non-linear performance of buildings under such events. However, a more common approach is to look at the performance of major buildings with the omission of critical elements in an effort to ascertain how the building will perform if the element is compromised. *Figure 5* shows an analysis of an 82 story tower with two of the eight mega-columns missing. The performance of buildings under extreme conditions depends on their strength and robustness. The fact that this tower was able to withstand removal of two key elements came in part from its ability to resist hurricane wind loads.


Figure 4: Construction of the San Francisco Federal Building, California (© Arup)

There is a fundamental difference between explicitly analyzing the response to a specific event and evaluating the response of a structure following the failure of an element due to an unspecified event. Either approach can be considered to be acceptable. The response of building structures to these severe events has not received the same level of research attributed to natural hazards. These approaches will need to evolve as the industry's understanding of them develops. For today's designer, *both* approaches should be carried out, not only to provide the best level of understanding of the behavior of the structure, but also to provide the highest level of practical resistance against these events.

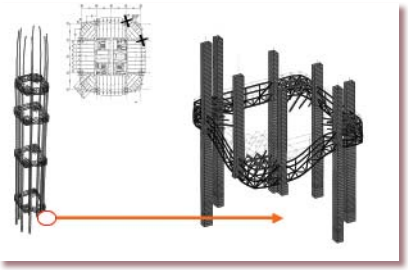


Figure 5: Columns Removed

Non-Linear Staged Analysis

As buildings become taller, the effects of axial shortening become more of a consideration–i.e. the shortening experienced by vertical elements as the gravity loading is added during construction. Of particular consideration is differential axial shortening–where the shortening experienced by different elements is different at the same level in the building. Typically, central cores will shorten differently with respect to the perimeter structure. And clearly, where differential shortening occurs, there are significant implications in achieving the true level of floors within the tower.

In achieving a cost efficient solution for tall buildings, it is often appropriate to use composite forms–a mixture of structural steel and concrete, and super high strength concretes. There are many examples of tall buildings in which the cores are constructed in concrete while the perimeter frame is

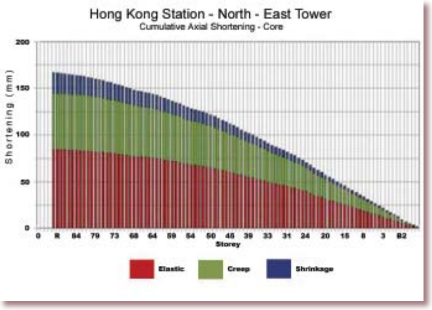


Figure 6: Axial Shortening Predictions

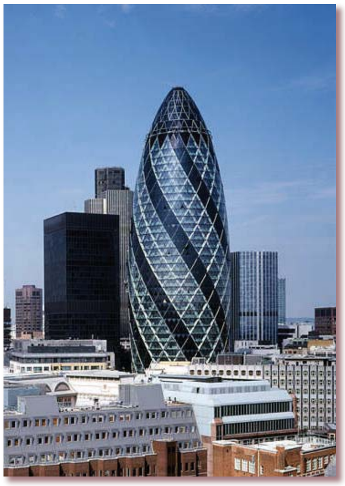


Figure 7: St. Mary Axe, London, UK (© Arup)

constructed in steel/concrete composite. Here differential shortening becomes quite complex. A comprehensive analysis must consider a variety of construction schedules so that the effects of compressive shortening, creep, shrinkage and any locked in stresses from outrigger systems can be appropriately determined. *Figure 6* shows the analysis of the core wall and composite columns for the International Finance Centre. (*See also Figure 8*)

Axial shortening can also be a serious consideration on braced structures, such as 30 St Mary Axe, London. (*Figure 7*) The self weight of the building generates in-plane axial tensions on the floor slab diaphragms that balance the compressive forces in the bracing at the façade of the building.

It is even more complex on non-symmetric structures where the axial shortening causes the floors to twist and tilt under self weight.

Structural Optimization

The efficient design of tall buildings has always been an exercise in balancing the numerous competing design criteria, functional objectives of the building, and the factors that influence the cost of construction. While achieving this balance has traditionally relied on the experience and intuition of the designer, a variety of systematic numerical techniques are becoming popular for finding so-called "optimized" design solutions. These techniques provide the designer with effective tools for quickly exploring, evaluating, and refining design alternatives in a systematic way by allowing the computer to carry out the numerous iterations that would be tedious to carry out by hand.

Figure 8: International Finance Center 2, Hong Kong (© Arup)

These programs can explicitly calculate minimum quantities, or minimum floor area, or minimum cost based on a particular performance goal: for instance minimum steel quantity or to obtain a specific value of acceleration. The process and results are described in *Figure 1*.

Current Trends in Tall Building Design

The conventional rectilinear box form of tall buildings is currently being challenged by a range of creative contemporary architects who are envisioning new possibilities for exciting shapes and forms. Modern architecture today has had great success in building low rise buildings with interesting geometries, and this is beginning to take hold in the tall buildings market.

The advancements in analytical tools and processes has enabled the engineer to better understand the structural behavior of complicated building geometries. Similarly, structural optimization and a better understanding of wind and associated design criteria has given the engineer the tools to create more economic and lighter buildings. These advances, in conjunction with a more sophisticated and confident construction industry, will support the ever-increasing ambition of developers and architects to build higher towers or more iconic buildings at a surprisingly low cost premium compared to conventional construction.

Figure 9: Bejing China Central TV News Headquarters (CCTV), China (© OMA, Rem Koolhaas and Ole Scheeren)

Recent examples of unusual and challenging buildings that are currently on the drawing boards are OMA's CCTV tower in Beijing (*Figure 9*) and the new towers on the Milan Fiera project by Studio Daniel Libeskind, (*Figure 10*) Complications that arise from these geometries would have once made the projects un-buildable. Today these complexities are better understood and can be dealt with efficiently, thanks to numerous advances in tall building design technology and analytical tools.▪

Figure 10: Milan Fiera, Italy (© Studi Daniel Liebskind)

David Scott is a principal with Arup, New York, and can be reached at david.scott@arup.com. Nancy Hamilton, SE is a principal with Arup, Chicago. Eric Ko, SE is a principal with the Arup San Francisco office.

Thanks to Roy Denoon of CPP Wind Engineering for his comments on the wind and acceleration section.

As many designers are not familiar with wind tunnel testing techniques, two manuals have been published to assist in following the process of wind tunnel testing and ensuring the adequacy of the testing product. The ASCE Manual of Practice No. 67 gives an overview of the processes, while the AWES-QAM1-2001, Wind Engineering Studies of Buildings (Australasian Wind Engineering Society, 2001) gives more of a checklist of minimum standards that should be achieved in common tests.