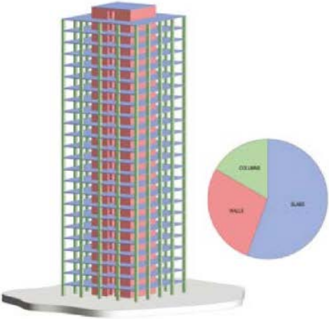


Tall buildings: What's the tall order?

< 111 West 57th Street, the slenderest supertall in NYC and the world with a height-to-width ratio of approximately 24:1. Photo: David Sundberg

^ One half to two thirds of the structural weight of a tall building is in the floor slabs

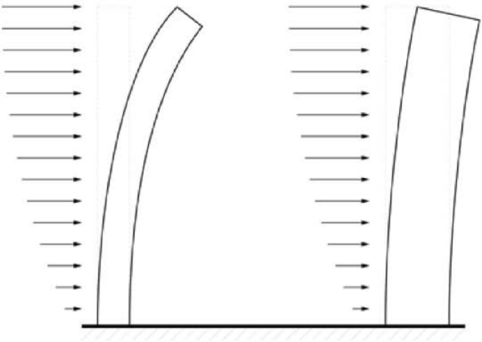
In this article, **Dmitri Jajich CEng FIStructE and Karl Micallef CEng FICE of DeSimone Consulting Engineering's** London office explore what truly defines a tall building – from the subtle efficiencies in floor slab design that can add or remove entire storeys, to the complex structural systems required to resist wind and seismic forces. They reveal how slenderness, stiffness and structural ingenuity determine not only how high we can build, but how gracefully our cities reach for the sky.

Humankind has long reached for the skies; the Biblical account of the Tower of Babel is early evidence of this. For centuries, the Pyramids of Giza have been the world's tallest – and largest – structures, but the advent of the motorised lift (or elevator) brought an unprecedented increase in building height at the start of the 20th century, with the tallest building in the world today (the Burj Khalifa in Dubai) reaching a height of 830m. But what makes tall buildings different from more typical building structures?

Whilst there is no strict definition of what is a tall building and what is the threshold which classifies a building as 'tall', tall buildings are typically characterised by many floors and a slender profile. As such, one of the key differences in a tall building is that any inefficiency in floor slab design can have a significant impact on the overall amount of material in a tall structure. Another key difference is that in a low-rise structure each column or wall needs only to support a few floors above; in a tall building, a single column needs to support the combined weight of dozens of levels above. Equally important as the number of storeys or absolute height of a tall building is the proportions of the structure – the slenderness is defined as the ratio of the height divided by the building width and is, in some ways, the most impactful parameter in differentiating a 'tall' building from a normal structure.

Handling gravity

Consider a floor system which comprises beam and slab construction, with steel beams being 400mm deep and a composite slab 150mm deep. The overall structural depth is thus 550mm. Comparing this with a 225mm reinforced concrete flat slab, the difference is 325mm per floor and if the building has 40 floors, that is an additional 13m in



The deformations and movements of a tall building increase exponentially with increasing slenderness

height. This could lead to either having to lose several floors if there are height limitations imposed by planning bodies or, conversely, the client can fit in three or four extra floors within the same height envelope.

Another implication is floor-to-ceiling heights. Minimising the structural zone leads to potentially having taller floor-to-ceiling heights for the same floor-to-floor height, making it attractive for occupants and having other benefits, such as the ability for natural light to reach deeper into the floor plate.

Minimising floor-to-floor heights also leads to savings in cladding, as there is less facade area if the building height is reduced overall.

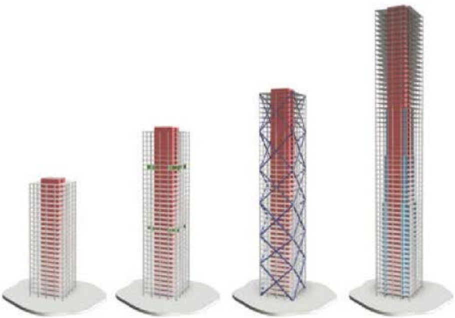
The sheer number of floors also means that an inefficient floor system which is too heavy leads to that penalty occurring many, many times over. Consider a floor system that has a long column spacing which necessitates a 300mm thick flat slab, rather than a tighter grid which only would require a 200mm-thick flat slab. The height saving is not as drastic as previously illustrated, but the 100mm additional concrete thickness per floor results in a much heavier building, with implications on the column, wall and foundation design, as well as additional time to build, cost and material quantities and hence embodied carbon. Thus, the first key item to optimise is the gravity load-resisting system, particularly the floor plate. But there is one other fundamental aspect which makes tall buildings unique.

Resisting wind and earthquakes

A tall building can be thought of as a giant cantilever stuck in the ground (not unlike a flagpole or a fence post); the cantilevering structure is pushed laterally by horizontal loading due to wind or earthquake forces. The lateral rigidity of a tall structure is most affected by the proportions of the building. A theoretical 1km tall pyramid will pose great lateral stability and stiffness, despite being tall because it has a low slenderness, whereas a 10m tall structure that is only 25cm wide (like a flagpole) will be very flexible despite its modest height.

220 Central Park South: This residential tower has a slenderness ratio of approximately 18:1. Photo: Francis Dzikowsky / Otto

Wind speed increases logarithmically with height and so a short building is subjected to low wind loads, making the demand on the structure small. The size of structural members to deal with gravity and/or minimum sizes to enable easy construction and to meet fire resistance leads



❮ As buildings become taller and more slender, the width of the structural lateral system must increase to minimise slenderness and increase lateral stability (left to right: core-only, core and outrigger, braced tube, buttressed core)

to a structure which is inherently stiff enough to limit movement as the wind pushed on the building.

As a building gets taller or more slender, the demand caused by wind increases exponentially and the building would tend to sway significantly more and so requires a structural system which provides not only the strength to ensure it does not topple over but also the stiffness to keep movement low enough such that the building occupants are comfortable and the building itself can perform adequately – for instance, lifts need to be able to go vertically up a lift shaft and if the building moves too much the lift shaft will end up having a banana shape.

This brings about the concept of a 'structural system'. Choosing the right structural system for a tall building is fundamental and it ensures efficient performance without an excessive cost and spatial premium.

One of the most common and simplest structural systems to resist horizontal loading is using shear walls. These would typically be located within the 'core' of the building, enclosing lift shafts, stairwells, service risers and so on, thus serving an architectural and functional purpose but also providing a strong and stiff structural system to resist wind load. The taller the building, the more load it has to resist and thus the walls would need to get thicker and thicker, especially at the bottom of the building where it is rooted to the ground.

If walls get too thick and hence take up too much space (and too expensive and heavy), then an alternative system would be required. In the 1960s and 1970s, the American engineer Fazlur 'Faz' Khan devised charts showing possible structural systems using different materials for different heights and these still form the basis of many engineers' choice of structural systems. Some of these systems are evident in the tall buildings of New York and especially Chicago where Khan worked, such as the 'bundled tube' of the Sears (now Willis) Tower and the 'braced tube' of the John Hancock (now 875 North Michigan Avenue) Tower.

> "Today [1970s], without any real trouble, we could build a 150-storey (sic) building. Whether we will, and how the city will handle it, is not an engineering question; it is a social question."
>
> **Fazlur 'Faz' Khan**

As buildings got taller, further systems were developed, such as the 'buttressed core' for Burj Khalifa and other structural systems which combine cores with gravity systems (the 'core and outrigger') and 'exoskeleton' structures.

The fundamental principle is the same in all cases – what is the most efficient way to resist load and bring it back safely to the ground?

Building higher – and thinking wider

Tall buildings are indeed feats of engineering, but their complexity lies beyond the technical aspects alone; they require large design teams across many disciplines and extensive coordination between them. Tall buildings also require significant financial investment to realise and have many implications, ranging from social to economic to environmental. This quote from Faz Khan sums it up elegantly: "Today [1970s], without any real trouble, we could build a 150-storey (sic) building. Whether we will, and how the city will handle it, is not an engineering question; it is a social question."

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