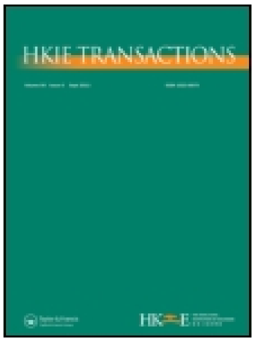

HKIE Transactions

ISSN: 1023-697X (Print) 2326-3733 (Online) Journal homepage: http://www.tandfonline.com/loi/thie20

# The High-rise Building –How High Can We Go?

**Leslie E Robertson PE CE SE DSc(hc) DEng(hc) NAE FASCE AIJ JSCA AGIR & See Saw Teen PE CE HonMASCE Meng**

**To cite this article:** Leslie E Robertson PE CE SE DSc(hc) DEng(hc) NAE FASCE AIJ JSCA AGIR & See Saw Teen PE CE HonMASCE Meng (2005) The High-rise Building –How High Can We Go?, HKIE Transactions, 12:4, 27-35, DOI: 10.1080/1023697X.2005.10668018

**To link to this article:** https://doi.org/10.1080/1023697X.2005.10668018

# The High-rise Building – How High Can We Go?

**Leslie E ROBERTSON** PE CE SE DSc(hc) DEng(hc) NAE FASCE AIJ JSCA AGIR
*Leslie E Robertson Associates, RLLP*
*Email: ler@lera.com*

**SEE Saw Teen** PE CE HonMASCE MEng
*Leslie E Robertson Associates, RLLP*
*Email: sts@lera.com*

*This paper explores the development of the high-rise buildings, from their inception in about 1880 until today. Under the assumption that no great strides will be made in materials technology, the paper goes on to explore structural systems that may be appropriate for buildings as high as 2000 metres, and beyond.*

*Keywords: High-rise Building, Wind Load, Oscillation, Damping Ratio, Frequency, Eccentricity, Space-trusses, Cantilever*

## Introduction

In a paper for the Journal of the American Institute of Architects, it was 1973, we penned the paper Heights We Can Reach. Therein we stated:

> *There is no limitation in the technology of structural systems that would restrict building heights to the present levels of about 1,500 feet (about 500 metres). We could erect a structure more than twice that height in the near future.*

Now, rather later than we had supposed, the high rise building is reaching to and beyond our predictions.

Born in the United States, the high-rise building has travelled to the far corners of the world, with nearly every continent now in the race to construct ever taller. Hong Kong, long the high-rise capital of the world, is finding that other areas of the world are reaching higher, the People's Republic of China, the Middle East, Malaysia, and Taiwan, all have laid claim to the world's tallest; we are working on a 90-storey building in India. Whether or not you are involved in the design of these high-rise buildings, it is good to pause for a moment, to look briefly at the origins of these creatures of our urban life. Then, within the confines of the technology of today, we will go on to explore briefly something of the technological (not societal) heights that we can reach.

## A Bit of History

In 1871 the city of Chicago was nearly destroyed by fire, providing the incentive for the development of high-rise buildings. By about 1880 the first of these Chicago buildings was born. Soon, sixteen story buildings were being constructed. In 1890, a twenty-one storey building had been completed. Before the year 1900, a thirty-storey building had become the tallest building in the world.

Now one hundred years later, these older buildings remain as marvels of the works of these early pioneers in architecture, construction and engineering.

Some of the earliest high-rise buildings were designed for a wind load of 2.4 kPa, but the practice soon reduced the load to 1.4 kPa. Following was a downward revision to 0.96 kPa, but with no wind load for the first 30 m above the ground. Until about 1965, many wonderful buildings were designed under this last criteria, including the Empire State Building (381 m, completed in 1931) [Figure 1].

Carried in the Transactions of the American Society of Civil Engineers (ASCE), prior to World War II there was a lively debate among learned engineers of the need or not for the steel frame to carry any wind load. The reason behind this otherwise irrational concept was the fact that these buildings had, within the boundaries of their columns and spandrels, in-filled panels of heavy masonry walls. The combination of steel and masonry was perhaps five times stiffer than the steel frame alone, and with significant levels of structural damping. For example, the calculated stiffness of the steel frame of the Empire State Building is but one fifth of the as-measured stiffness. This fact was understood intuitively by some engineers of that time, but they lacked the computational tools to include the effects of the masonry in their designs.

*Figure 1 – The Empire State Building*

Prior to World War II, a drift ratio limitation of 1/500 became prevalent. For very tall buildings, under wind-induced excitation, it can be very costly to achieve a stipulated drift ratio. For real buildings, particularly where the flexural component of deflection is included in the determination of drift, in their resistance or their performance under wind loads, these drift ratios have little or no practical or theoretical significance. Unlike Hong Kong, for wind loads, present day Building Codes of the United States do not stipulate drift ratios.

Prior to the design of The World Trade Centre, exterior walls of heavy masonry gave way to the use of metal-and-glass or of resiliently-supported stone-and-glass. While the stiffness and the strength afforded the high-rise buildings of the past could no longer be found in the construction of the perimeter wall, the masonry remained in the centre of the building, surrounding the lift shafts and all else making up the services core. Unfortunately, a number of buildings were constructed making use of the low wind pressure, but, as discussed later, lacking any of the masonry in-filled walls.

## Some of Our Own Buildings

### The World Trade Centre, New York

It was in this historical context that the architect Minoru Yamasaki and The World Trade Centre [Figure 2] provided the impetus for our establishing offices in New York. Standing 415 m and 417 m tall, plus antenna, with clear spans of 10.6 and 18.3 metres, each floor of the World Trade Centre was about 40% of a hectare. Prefabrication in structural steel was used to an extent achieved never before or since. Column/spandrel wall panels were prefabricated three columns wide and three stories high [Figure 3]. Floor panels were as large as 6.1 metres wide with a span of 18.3 metres, complete with profiled metal deck and electrical distribution cells.

*Figure 2 – The World Trade Center: Overview*

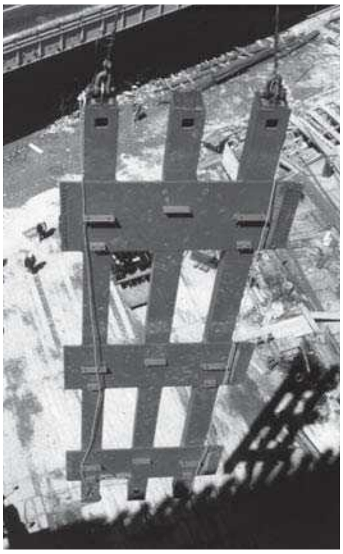

*Figure 3 – WTC Column/Spandrel Assemblies*

The structural concept was that of a 'tube', with all of the lateral forces from wind and earthquake taken in the column/spandrel system of the outside wall. This system required that the area between the services core and the outside wall be free of columns, a circumstance that pleased both the architects and the rental agents.

Lacking experience in high-rise buildings, we set out to determine what was really good and what was less than satisfactory about the work of these other architects and engineers. In that process, we learned so much!

For example, we found that the fire-rated partition systems of that time were of gypsum block or of brick. As the building moved in the wind, the steelwork above moved laterally with respect to the tops of the walls, creating a crack. Accordingly, the walls were excessively permeable; that is, driven by stack pressure, these cracks allowed a vertical flow of air in the building. At that time, energy consumption was not an issue, but of course those buildings consumed excess energy, in no small measure because of that air flow. Of more importance, in the case of a fire, this air flow carried smoke to all of the floors above the fire. In response, conceived originally as a means of reducing the effects of stack-action, we came up with the concept for a new kind of fire-rated partition system now called Shaftwall, made up of metal studs and gypsum wallboard. The system is stronger, lighter and more air-tight than prior construction, and it changed the very nature of structures for high-rise buildings. Let us explain:

Driven by the wind, a tall building drifts more-or-less downwind, oscillating about its principal axes. At and prior to the time of The World Trade Centre, architects and engineers were not concerned with the level of oscillation of their buildings; this follows because the block or the brick walls and partitions of that time added significantly to both the lateral stiffness and to the structural damping. This trace [Figure 4], taken from the Empire State Building, depicts a highly-damped structural system oscillating in the wind. Engineers did not have the tools for determining the effects of that masonry; instead, they had learned from experience that the system performed well. With the introduction of Shaftwall, the structural systems of the past were no longer acceptable. Compare the trace taken from the Empire State Building with the trace taken from the World Trade Centre [Figure 5].

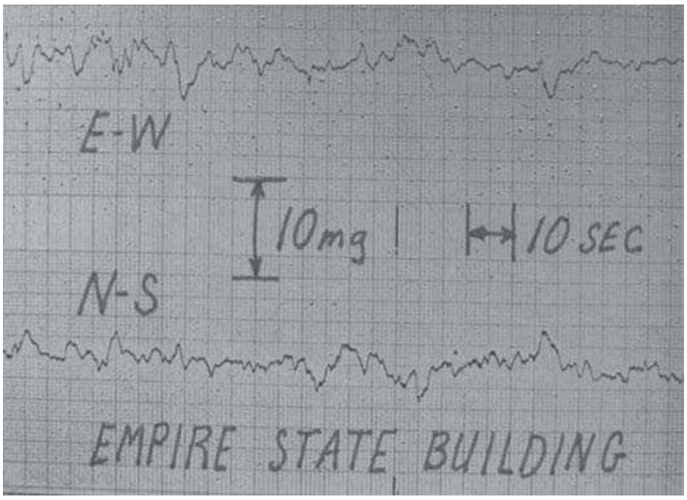

*Figure 4 – Accelerometer Trace from Empire State Building*

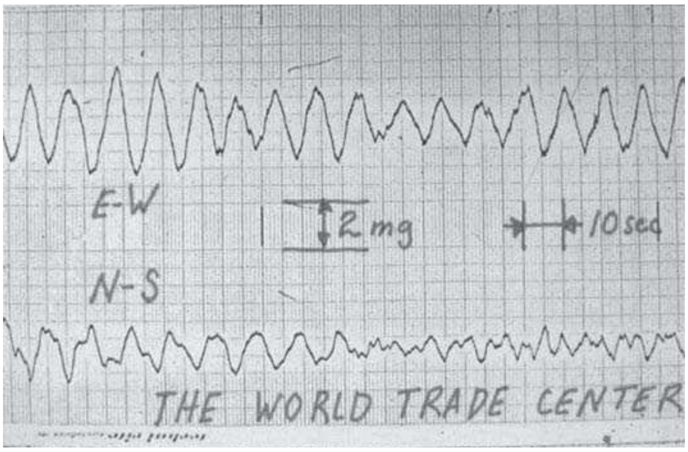

*Figure 5 – Accelerometer Trace from WTC*

How to deal with all of the absence of the masonry? We knew that our building would oscillate in the wind, but we had no idea of the magnitude of that oscillation. Fortuitously, two brilliant Danish engineers, Jensen and Frank, had developed the concept of the boundary-layer wind tunnel. For the first time, in their wind tunnel, it became possible to replicate the real pressures and suctions on small buildings.

Borrowing their concept, and with the vital and creative input from Dr Alan G Davenport, we expanded that technology for use in the design of the World Trade Centre.

The wind tunnel work was coupled with a meteorological study to determine the characteristics of the gradient wind.

For a range of damping rations, from the wind tunnel we knew how much our building would oscillate, but we did not know how much oscillation was acceptable. A variety of motion simulators were available and, while we rode many of them, none was able to replicate the frequency range of our building. In response, we devised two motion simulators [Figure 6], testing the response of people to the wind-induced lateral swaying mode of the towers. From these experiments we established the criteria for the acceptable level of wind-induced lateral swaying motion.

While these various studies provided to us essential information, the need to limit oscillation to acceptable levels now fell into the field of structural engineering. We then developed a viscoelastic damping system

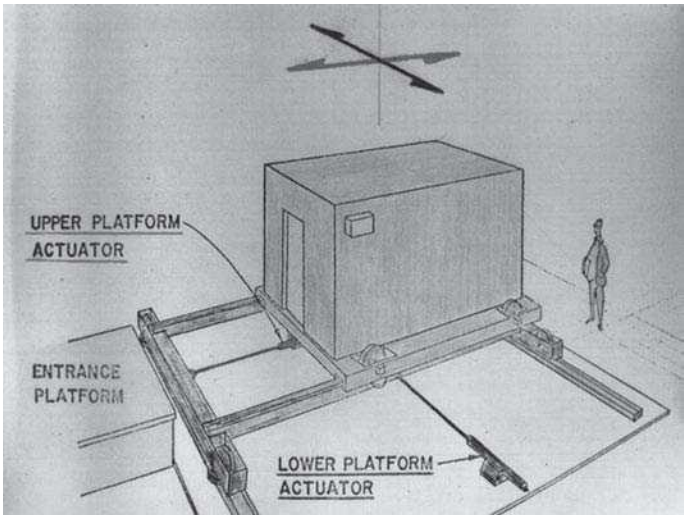

*Figure 6 – Cartoon of a WTC Motion Simulator*

which successfully limited structural oscillation to acceptable values. The damping units consumed a portion of the wind-induced energy of oscillation of the towers.

Of course, all of the studies described herein progressed more-or-less simultaneously.

But, what if all of our structural research had left undiscovered issues of importance? Recognising the lack of historical precedence, we looked for additional redundancy. In response, we developed the concept of outrigger trusses, a system employed commonly in the buildings of today. These outrigger trusses, installed immediately below the roof, provided additional stiffening, strength and robustness.

When finished, being appreciated more by sculptors than by architects, the buildings were opaque from most vistas [Figure 7]. Seen here, the completed building with the sun behind, instead of in front, the airy lightness could be appreciated [Figure 8].

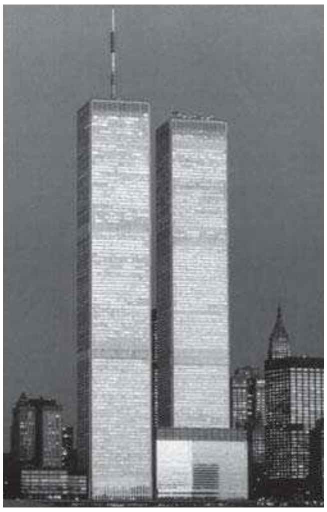

*Figure 7 – WTC with the Sun in Front*

*Figure 8 – WTC with the Sun Behind*

The events of 11 September 2001 are beyond description. Knowing that, in World War II, the Empire State Building had been struck accidentally by a Mitchell bomber, we had designed the towers for the possible impact by a Boeing 707 aircraft; the design was for a low-flying, slow-flying, low-in-fuel, 707, lost in the fog and seeking to land. The Boeing 767's which struck the buildings were a bit heavier, but were flying well above their rated speed, and were fuel-laden, imparting significantly higher levels of energy into the towers than had been anticipated in the design. While the damaged structures withstood the impact, only to succumb to the fires, it should not lead to complacency. This follows because the Mitchell Bomber, the 707's, and the 767's are small when compared to the Boeing 747 and to the new Airbus. Accordingly, we believe strongly that we should not design our buildings to withstand the attack of these aircraft, instead, there are more fruitful ways to save lives.

This is not to say that the structural design of The World Trade Centre has not received adverse comments, sometimes unfairly so. Using the television as his pulpit, one noted structural engineer took it upon himself to criticise the structural design for a perceived lack of adequate anchorage of the floor trusses to the columns and for inadequate robustness of the trusses. Quoting him from the TV program:

> *'They had two 5/8″ bolts at one end of the truss, and two 3/4″ bolts at the other end which is perfectly fine to take vertical load, and perfectly fine to take shear loads, but once the floor elements start to sag during a fire, okay, they start exerting tension forces because it becomes a catenary, like a clothesline, and those two little bolts just couldn't handle it.'*
>
> *'As you start to lose the lateral support due to the floors, the exterior just crumples like a piece of paper or like if you took a sheet of cardboard and you put some weight on it, and you take out the lateral supports it'll just bow right out.'*
>
> *'Had the floor system been a more robust floor system with much stronger connections between the exterior and the inside, I think the buildings probably would have lasted longer. Would they ultimately have collapsed? Maybe not.'*

While that engineer had full access both to the drawings and to the site, it would seem that he neglected to look at either. In fact, the 'two little bolts' were erection bolts, with the final connection by complete penetration welds; the connection was designed to restrain the columns from buckling away from the building. At the level of the aircraft impact, for Tower A, we had designed the trusses and their connections for loads 27 times that of the normal practice, with 'normal practice' being defined as 2% of the axial force in the column, and 13 times for Tower B.

Another fallacy, promoted widely in television programs produced in the United Kingdom and in the United States, is that the fire-induced failure of the trusses, which trusses were thought to lack robustness, caused the ultimate collapse of the two towers.

All of these misrepresentations have been soundly discredited by a $16 million study undertaken by the National Institute of Standards and Technology of the United States.

From this we should learn that it is sometimes best to remain silent, eschewing the TV camera, so as to not unduly cause further grief to the friends and the relatives of those who perish in these complex events.

### United States Steel Building, Pittsburgh

While designing the World Trade Centre, working with the architects Harrison, Abramovitz, and Abbe, we were awarded the commission for the United States Steel Headquarters Building, Pittsburgh [Figure 9]. A bit more than 256 m in height, with each floor being almost 40% of an hectare, until very recently the building was the largest privately-owned building ever constructed.

Triangular in plan, but with serrated corners, the building is supported at its perimeter by columns located outside of the building envelope. The weathering steel columns, being unclad, with the structure steel visually exposed, are subject to changes in temperature from solar radiation, from the atmosphere, and from fire.

From the cross-section of the building [Figure 10] we see that the perimeter columns are attached at every third level to a primary floor and that the two intermediate floors are posted down to the primary floor with 150 mm wide-flange posts.

The concept of the structure is simple [Figure 11]. Imagine a rocking pendulum with a mass at the top; we borrowed the idea of the outrigger trusses used for the World Trade Centre and, by mobilising the perimeter columns to tie the tips of the outrigger trusses to the ground, we achieved

*Figure 9 – United States Steel Building: Overview*

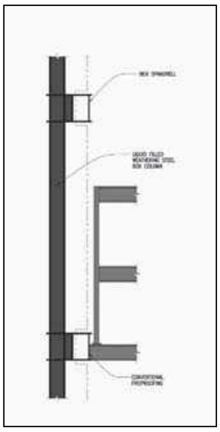

*Figure 10 – USS: Cross-section*

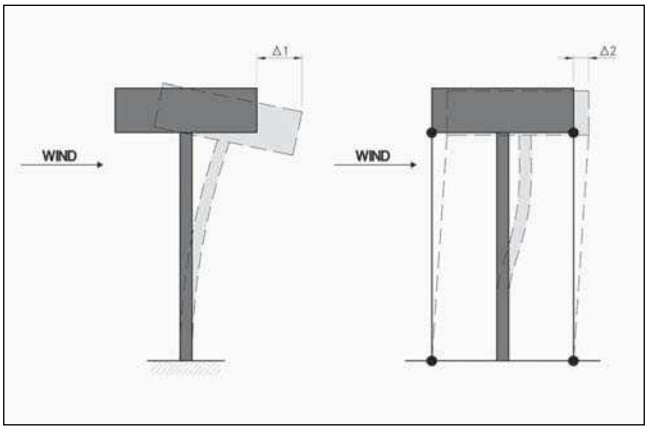

*Figure 11 – USS Pendulum Concept*

a simple but effective structural system, a system not unlike that of an unfurled umbrella, standing on its handle and with the tips of the ribs tied to the ground. As another primary duty, the outrigger trusses inhibit the effects of the thermal expansion and contraction of the perimeter columns. The structural system, then, is that of a braced-core building, capped by an outrigger space-frame, with the exterior columns acting as tension/compression members, a concept that is used to this day in many (most?) super high-rise buildings.

Taken near the base of the building, this is one of a pair of columns located in each of the three corners of the services core [Figure 12]. The centre plates are 200 mm thick of Grade 290 MPa while the perimeter plates are 100 mm thick of Grade 345 MPa. This hybrid design of the column is almost as strong as though all of the steel were of Grade 345 MPa.

Because there was no cladding or conventional fire protection on the perimeter columns, they were liquid-filled to provide fire safety. Making use of corrosion inhibitors and antifreeze, the liquid has a specific gravity of about 1.2. Divided vertically into zones, the columns of any one zone are fully interconnected; within each zone, the liquid circulates freely, up in some columns and down in others, all driven by differences in temperature of the liquid. It being a completely passive system, there are no pumps.

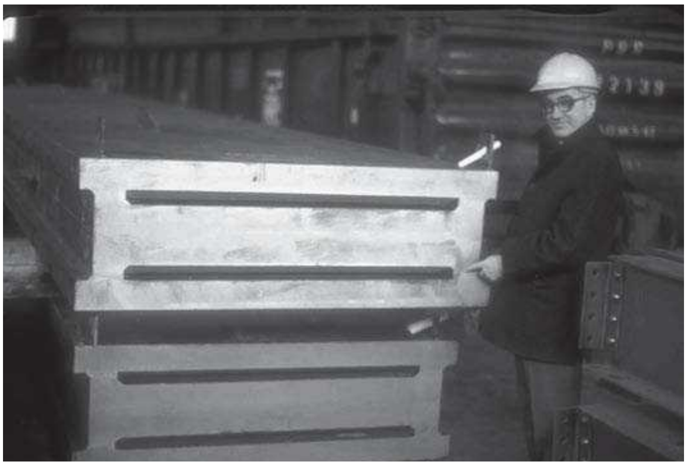

*Figure 12 – USS Core Column*

When finished, the building exemplified one of the dreams of the owners, then the United States Steel Company. That is, this is clearly a steel building, with the perimeter structural system exposed for all to see.

## Bank of China Tower, Hong Kong

Another break-through in our lives and that of our company was the Bank of China Tower, Hong Kong [Figure 13], at the time of construction, outside of New York and Chicago, the tallest building in the world. The architectural design for the project was by that wonderfully talented I M Pei, then of Pei, Cobb, Freed & Partners.

Mr Pei realised fully that the site was next to the Hong Kong and Shanghai Bank; designed by the talented Lord Norman Foster, his is an elegant building, but costing perhaps three times more than was allowed by our budget, and for the same floor area. Certainly, Mr Pei was not prepared to develop a design which was inferior to that of its neighbor. Accordingly, carrying the project in his mind for about a year, he developed this magnificent concept; only then did he accept the design commission. Mr Pei gives us far more credit for the design than we deserve.

The original concept [Figure 14] included an architectural representation of trusses at the refuge floors. As the design evolved, Mr Pei came up with this design [Figure 15] which more appropriately replicates the structural system.

The building is 54 metres square at the base, dropping off a quadrant at a time as it rises to a height of almost 370 metres. Under the action of the turbulent wind, the geometry creates a large torsional eccentricity. By judiciously designing the bracing systems it was possible

*Figure 13 – The Bank of China Tower: Overview*

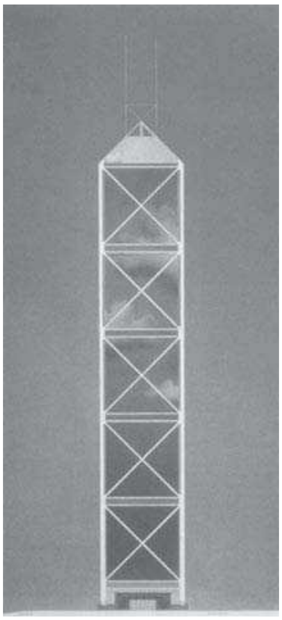

Figure 14 – BOC 'X's'

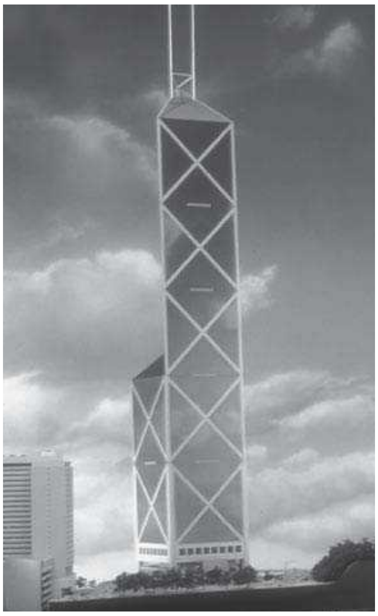

Figure 15 – BOC 'Diamonds'

to minimise both the steady-state and the dynamic consequences of that eccentricity.

Should you be so fortunate as to work with I M Pei, you would learn that every facet of his designs carry an underlying logic. The architectural representation of the diagonals intersect at the very corner of the facade; of course the structural columns must be inside of the building, thus being unable to intersect at the corners. Our approach to this dilemma was to create planar trusses in structural steel with the frames of but two different geometries [Figure 16]. Then, in the corners of the towers, we knitted the columns of the planar frames into space-trusses, all within a reinforced concrete column. The trusses in the refuge floors were used to reconcile the geometry.

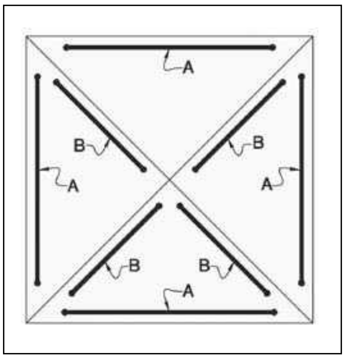

Figure 16 – BOC Plan of Planar Trusses

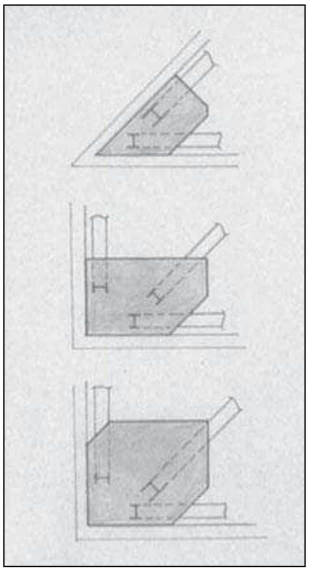

Figure 17 – BOC Plan of a Corner Column

Now, the problem with this approach is the transfer of loads from one plane frame to another and to the enfolding concrete column; clearly, the various vertical elements are eccentric from one another [Figure 17]. Still, we were able to demonstrate that we could accept all of these eccentricities without creating bending moments in either the steelwork or the concrete work. The structure was so designed and stands stalwartly today.

Hong Kong is subjected to typhoons winds; 'typhoon' and 'hurricane' are differing names for the same weather phenomenon. For a hypothetical 300-high building, this graph [Figure 18] depicts the wind and earthquake loads (in this case, base shear) for various places about the world. Perhaps the most interesting lesson to be learned is that, for very tall buildings, the earthquakes of Los Angeles, Tokyo, and other locations on the planet, produce rather lower lateral loads than are produced by the typhoon winds of Hong Kong. For a very tall building, the wind loads exceed the floor loads. In short, for a very tall building, the wind loads tend to drive the conception of the structural system.

In our view, the Bank of China Tower is a most beautiful building [Figure 19], one that has aged extremely well, looking as good or better today than it did when first constructed. It is a tribute to the energy, the talents, and the creative genius of the architect, I M Pei.

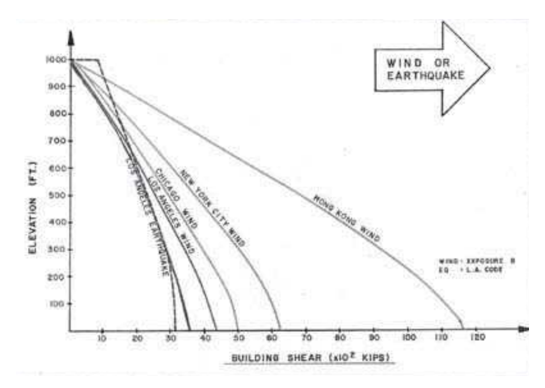

Figure 18 – Lateral Load Comparison

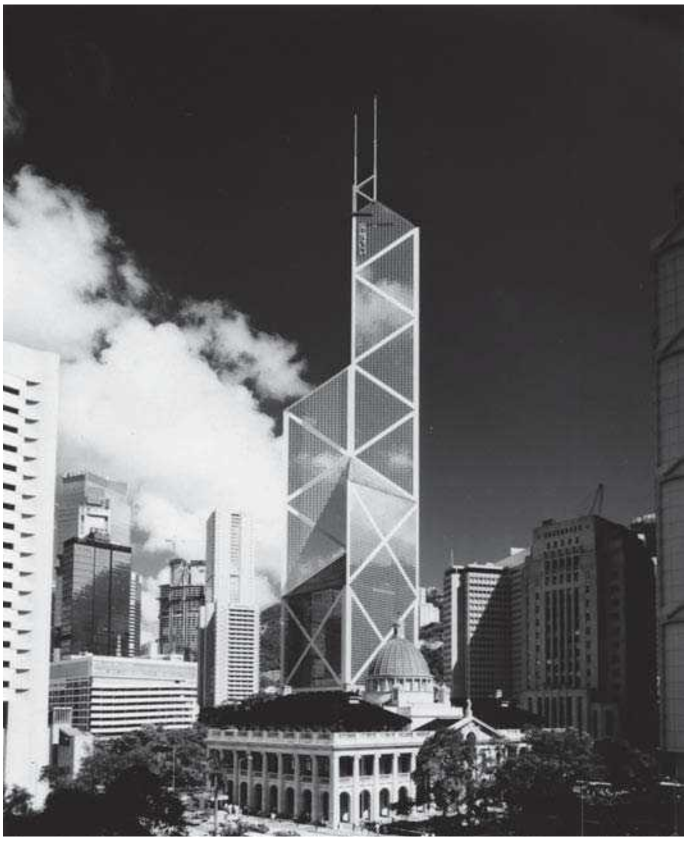

Figure 19 – BOC: Overall

### Shanghai World Financial Centre

This project, with the structural steel now rising above grade, is with William Pedersen of Kohn Pedersen Fox as the design architect. We call it a 1/2 km-high building [Figure 20]. Mori Building Company of Japan is the developer.

The building, having passed through the hands of three other structural

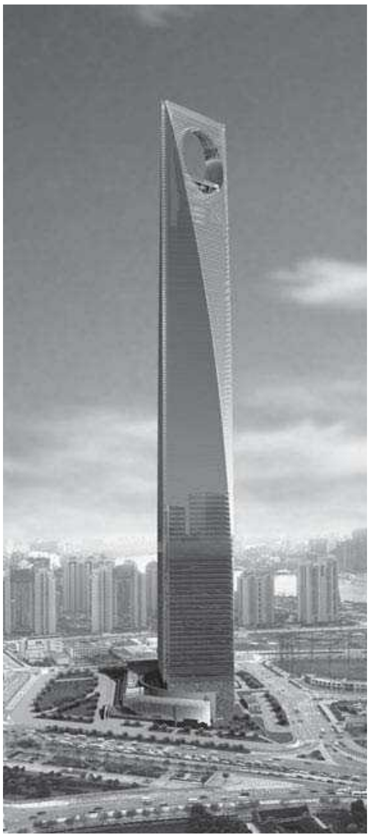

Figure 20 – Shanghai World Financial Centre: Overview

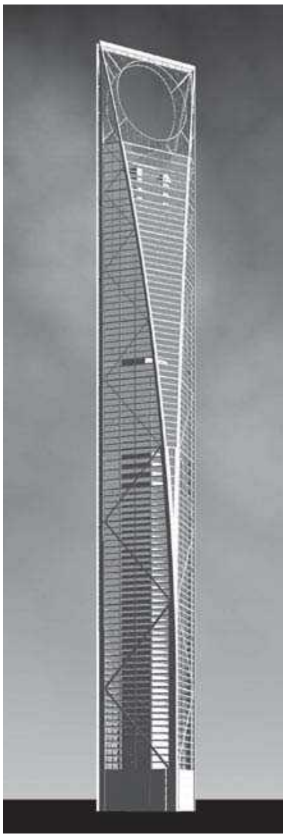

Figure 21 – SWFC Structural System

engineers prior to our involvement, was to be 460 m high. As the design came to us, the foundation piling had been installed. Our charge was to increase the height of the building from 460 to 492 meters and to increase the floor area by 15%, all while making use of the existing piling. This could be done only by making use of a lighter and a more efficient structural system.

Reminiscent of a pair of bent leaves, cantilevering from the ground, we developed this design [Figure 21]. In need of additional stiffness, the leaves are braced across the top. The original design, by other engineers, made use of a moment-resistant space frame at the façade, with closely-spaced columns of considerable size. Seeking to improve the views from inside the building, we chose to use not more than three columns on any one face, keeping the columns small by making them load-bearing for a maximum of 12 floors.

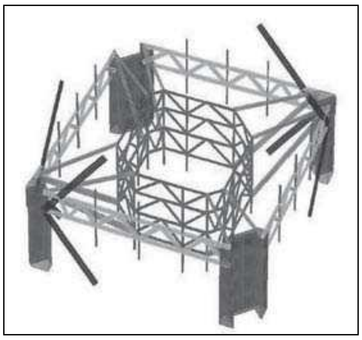

Figure 22 – SWFC Plan Location of Outriggers

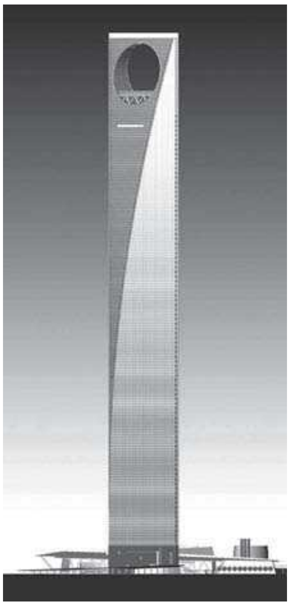

Figure 23 – SWFC Overview

We made use of three-storey high outrigger trusses. Unlike conventional outrigger truss that pass through the services core, we chose to pass the trusses around the core [Figure 22], burying them in the perimeter walls of concrete, in this way improving the space utilisation of the building, simplifying the architectural layout of the services core, and saving in time and in money. Outrigger trusses are complicated, difficult to fabricate and time-consuming to erect; hence outrigger trusses are expensive. Even so, their use contributes significantly to the stiffness and to the strength of the structural system.

We believe that this building reaches the highest level in economy, strength, stiffness and robustness. Perhaps of more importance, we believe the architectural design is most elegant [Figure 23]. For reasons beyond the ken of structural engineers, the ‘hole’ at the top of the building will likely be changed in appearance.

## Moving On Up

While Mount Everest rises to a height of about 8.8 km and the deepest ocean trench is thought to be about 11 km below the ocean’s surface, Man is able to construct even higher, able to exceed the heights of the works of Nature. Even so, associated with the weight of structural materials, there are technological limitations to the height of man-made structures. Take, for example, a rod cantilevered upward from the surface of the earth, carrying only its own weight. As we build taller and even taller, the stress induced by the weight of the rod above begins to approach the yield point or the breaking strength of the material at the base, and it collapses.

Neglecting the effects of wind and earthquake, the expression is simple:

Stress = Density x Volume / Area

Where F is the yield point or the breaking strength of the material and the rod is a cylinder, the expression becomes:

F = (Density) (Area) (Height) / (Area)

F = (Density) (Height) or

Height = F / Density

Resulting in the conclusion that, for very high-strength concrete (140 MPa), the height of the cylinder cannot reach more than about 6 km above the surface of the earth (Figure 24).

For quenched and tempered steels (690 MPa), the maximum height of a cylinder rises to about 9 km. For aluminum (690 MPa), we reach to a height of 11 km and, for carbon/epoxy composites, we attain a height of about 115 km.

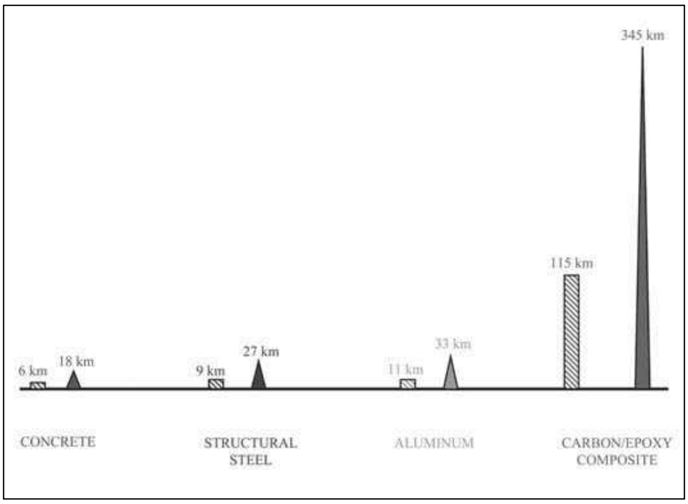

Figure 24 – Maximum Height of Cylinders and Cones Under Their Own Weight

Changing the shape of the section from a cylinder to a cone increases the height to three times that for a cylinder. Should we optimise the shape and take into consideration the reduction in the pull of gravity with height, the stated heights again increase.

### Even Higher?

In the above examples, we have made a variety of simplifications. Where we are to reach even higher, some fundamental changes need take place in our approach.

First, let us shift our structure from Hong Kong to the equator. Here, we are able to make use of the rotational speed of the earth to reduce the forces on our structure.

Second, the pull of gravity decreases as we move away from the surface of the earth. Let us take advantage of this approach.

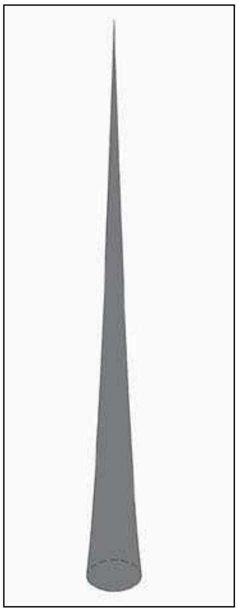

*Figure 25 – Optimum Shape of a Solid Column*

Third, we will optimise the shape so that the stress in our structure is uniform over the height of the structure [Figure 25]. As we do so, we find that there is no limit to the height of a solid column, where that column is required to carry only its own weight.

To make a usable structure, we will construct our tower in the form of a space truss, thus providing both stability against buckling and resistance to the forces of wind and earthquake, the effects of the moving air and the moving earth.

While the computations are too complex for purposes of this paper, we estimate that such a tower of carbon fiber can reach to a height of about 300 km. For a height to width ratio of 20, the tower would have a base dimension of 15 km. Even so, an active stabilising system would be required.

With the structure able to carry only its own weight, it would seem that we have reached the limit of the ability of structures to reach further into the sky. Or have we?

### Higher Yet?

We start out by noting that the height that we can reach is directly proportional to the strength of the material and is inversely proportional to the weight of that material. That is:

H = (Yield or Ultimate Strength)/Density

Where a lighter material can be found, our structure will be able to climb even higher.

What about using an even lighter material than carbon fiber, a gas. For purposes of this discussion we will use the most common of gases, air.

Imagine if you will, a column of air cantilevering into the sky. We cannot use it to support additional weight unless we confine that column of air, holding the air into a fixed geometry. For this purpose, we will use a round shape, with the confining material of carbon/epoxy composite. Next, we will pressurise the confined air such that the air pressure balances the weight of the carbon fiber and of the air above. In order to do so, we will provide bulkheads so as to be able to change the pressure to match the weight of the structure and the air above.

The confining carbon/epoxy composite ring must be circular and must be strong enough to provide the resulting hoop tension. Fortunately, these carbon fiber materials are stronger in tension than in compression.

What have we accomplished? Well, making use of the strongest materials available to this date (2005) it would seem that a usable tower could be constructed to a height of 350 km, perhaps higher.

### What is the Highest?

We have read that the National Aeronautics and Space Administration of the United States has devised a 'space elevator' [Figure 26]. The concept is simple, though the execution carries enormous technological challenges:

- First, we construct that very tall tower, of course, on the equator.
- Second, we find a BIG rock in space, placing it immediately above the tower.
- Finally, the rock is established so that it rotates round the earth at the same radial velocity as that of the earth, one rotation per day, thus, it holds its position directly above our tower.

Now, where the rock is 35,786 km above the surface of the earth, it stays in that orbit. Where closer than 35,786 km, the rock would eventually fall to earth. Where farther than 35,786 km the rock would drift away from the earth. Where stationed well beyond that distance of 35,786 km a radial force is required to keep that rock from drifting away. In short, in order to stabilise the orbit of the rock, we must provide a restraining force on the rock, with that force pointed directly toward the centre of the earth.

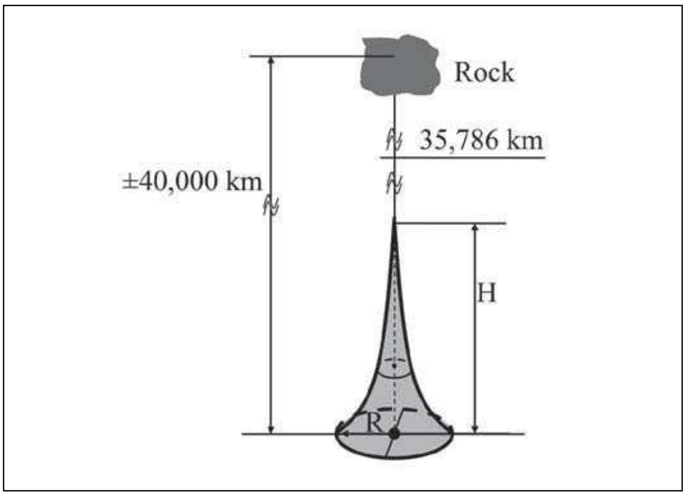

*Figure 26 – NASA's Space Elevator*

As we understand it, under the NASA concept, the rock is tethered back to that very tall tower so as to place the tower in tension. Suddenly, there is constructed a roadway, if you will, from the surface of the earth, up through the tower to the tether, and then out to that magical height of 35,786 km, where a body, rotating about the earth at a rate of one revolution per day, is able to maintain that orbit.

Of course, there are enormous challenges in constructing and maintaining the tower and the tether. Beyond the mundane thoughts, consider that following:

- To compensate for the lateral forces from wind and earthquake, active control devices would be needed throughout the height of the tower.
- This being an undertaking of enormous cost, protection from the accidental or the deliberate impact from aircraft would become a serious concern.
- Under the unlikely circumstance of collision from another object in space, devices may need be installed to warp the tether away from that object.

## A Building 1.5 Miles in Height (2.5 km)

Now, returning from space, we turn our attention to a concept-level project developed with the architectural firm of NBBJ (New York, Seattle and other places) [Figure 27]. The architects Tim Johnson and Peter Pran were just a part of the talented NBBJ team.

*Figure 27 – The 1.5-mile (2.5 km) Building*

The goal of the project was to develop a practical building system that could reach to a height of a mile-and-a-half. The work was carried forward to allow a rough estimate of the probable cost of construction and the like.

In planning such a building, the demands on the infrastructure are enormous. Indeed, the most pressing need in the design is to reduce the floor space and the number of building occupants down to realistic levels. At the same time, the building must have a dimension at the base consistent with the realities of overturning moments, building sway and the like.

The architect Frank Lloyd Wright had proposed (circa 1956) a Mile-High Building [MM]. His concept was for a very slender tower with a kind of tap-root system for the foundations. In his time, such a building would have been impossible either to design or to construct; today, it is possible that his concept could be realised. The architect Norman Foster had proposed (1989) the Millenium Tower to be constructed in Tokyo Bay. Still, as we looked at these unrealised design, we concluded that there might be a better way.

Buildings with a swooping shape as for the Eiffel Tower provides the most logical backdrop for design. Turning to Figure 28, we see that, in a most perfect world, the gravity loads of the building can be used to balance the lateral forces from wind and earthquake, at least partially eliminating the most of the bending and the shear.

On the other side of the coin, the shape produces a building with an enormous floor area. One way to shed much of that floor area is to make the building hollow in the centre, leaving 'rings' of floor space ten to twenty metres in depth. Even so, the floor area would exceed that desired by any developer known to us.

Next, we must use an efficient structural system to resist the forces of wind and earthquake. Of course, we revert to a braced structure [Figure 29].

Now, in a kind of giant leap, we change the ring described above into a series of buildings [Figure 30], and we change the bracing from structural members into this same series of buildings. In essence, we compose a set of individual buildings into the shape of the bracing for a tower.

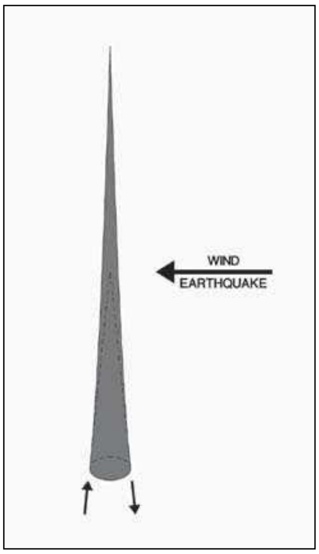

*Figure 28 – Balancing Gravity and Lateral Loads*

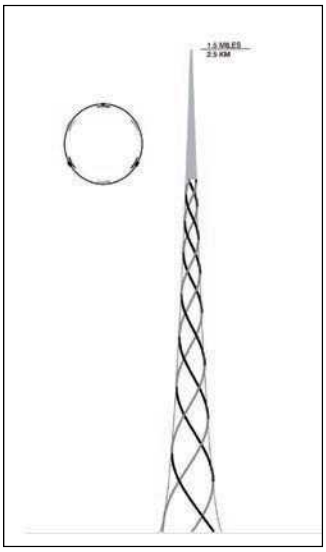

*Figure 29 – The Braced Tower*

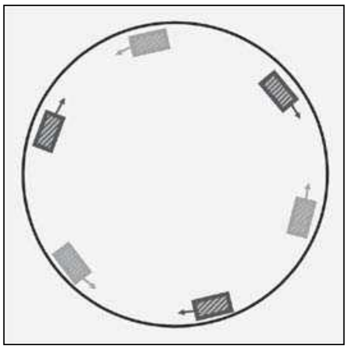

*Figure 30 – Plan View at Base*

What have we achieved? Well,

- The individual buildings are not capable of achieving any great height above ground. However, woven into the form of a braced tower, they become highly efficient bracing members.
- At the intersections of the various buildings, there is a free transfer of people and goods.
- We have reduced the floor area and hence the population of the building down to manageable proportions.
- We have created a building, porous to the oncoming wind, thus creating high levels of aerodynamic damping.
- The design is able to reach to a height of 2.5 km.

### And in Conclusion

The body of work given herein is only a small fraction of the wonderful structural designs developed by the men and the women of Leslie E Robertson Associates. No single person should be singled out as the creator of the structural design of any one of these magnificent buildings.

Indeed, without the strong input, the steady hand and the creative genius of the Architect, the Owner/Developer and the Contractor, these buildings would never have grown to fruition. We remain ever grateful for the opportunities to work with these creative persons and with the talented and high-tech professionals who work with them.

And finally, this lecture would not be possible were it not for the talents of Ir Prof Y K Cheung and for the many men and women, seeking proper recognition of his on-going contributions to the life and to the technology of Hong Kong, men and women who contributed their energies and their financial support to make possible this series of lectures.

## Introduction of the Speaker – Dr Leslie E Robertson

Mr Chairman, Vice-Chancellor, Ir Prof Cheung, Dr Robertson, Ladies & Gentlemen,

It gives me great pleasure to introduce our distinguished speaker and say a few words showing our respect for Ir Prof Y K Cheung. Y K has been a close friend of mine for many years. He is an authority in the development of analytical techniques in engineering and a beacon in engineering education. It is therefore fitting that lectures in Y K's name be inaugurated, and I commend both the Department of Civil Engineering of the University of Hong Kong and the Joint Structural Division for this initiative.

I have been asked to introduce Dr Leslie E Robertson whom I have the privilege to know for over 30 years. He is roughly of my own vintage. Les is an eminent structural engineer with a distinguished and successful career, well-known for his structural design of many notable buildings and structures around the world. These include the World Trade Centre in New York, the United States Steel Headquarters in Pittsburgh, the Bank of China Tower here in Hong Kong, and more recently, the World Financial Centre in Shanghai rising to almost 500 metres.

Originally from California, and a graduate of the University of California - Berkeley in Civil Engineering, he moved to New York City in the 1960s to oversee the design and construction of the World Trade Centre twin towers. He is now firmly rooted in New York.

Les has demonstrated that an understanding of structural behaviour coupled with courage and determination forms the basis of innovation, and can lead to the realisation of dreams in the form of extraordinary buildings. He continues to this day to be very active in his chosen profession and he is an inspiration for us all.

The list of honours and awards bestowed upon Les is immense. The IStructE in 2004 added the prestigious Gold Medal to that list, citing 'for his unique contributions to structural engineering as the leading designer of several of the world's tallest buildings'. I am therefore very happy that in that Gold Medallists' name board at the IStructE headquarters our names are only a few inches apart. Les is a person of energy and enthusiasm, and it is with great pleasure that I now ask Dr Robertson to deliver this Lecture.

*by Ir Dr H K CHENG*

**Leslie E ROBERTSON**

Amongst many other structures, Dr Robertson is responsible for the structural design of the World Trade Centre (New York), the United States Steel Headquarters (Pittsburgh), the Bank of China Tower (Hong Kong), and the Puerta de Europa (Madrid) as well as exceptional museums and the award-winning Miho Museum Bridge (Japan). He received the IStructE Gold Medal, the Gengo Matsui Prize as the outstanding Structural Engineer in the world, the AIA Institute Honour; and was recognised as ENR's Construction 'Man of the Year'. He is a member of the National Academy of Engineering, has been awarded four honorary doctorates, currently is teaching at Princeton University, and is Distinguished Engineering Alumnus of the University of California, Berkeley. He received ASCE's Outstanding Projects and Leaders (OPAL) Award, AISC's J Lloyd Kimbrough Award, Tokyo Society of Architects Honorary Fellowship and Medal, and is the first recipient of the Henry C Turner Award and of the Fazlur Rahman Kahn Medal.

## Vote of Thanks to Ir Prof Y K Cheung

On behalf of the Y K Cheung Lecture Committee, I would like to express my heartfelt appreciation to Ir Prof Cheung for his contributions to engineering sciences as well as his devotion to education.

Ir Prof Cheung already made his name in the engineering sciences with his pioneering works in the Methods of Finite Elements some 40 years ago. His ensuring accomplishments in academic research have earned him the recognition and respect as an internationally renowned scholar.

Ir Prof Cheung has also distinguished himself as a devoted educator. As the then Dean of the Engineering Faculty of the University of Hong Kong, he provided strong leadership to the Faculty with his commitment to academic excellence. With his clear vision for future development, he has helped develop the University of Hong Kong into a top league academic institution in the world during his tenure of its Pro Vice-Chancellor.

In recognising his contributions, Ir Prof Cheung was duly awarded Honorary Fellow of the Hong Kong Institution of Engineers. He was also elected President of Hong Kong Academy of Engineering Sciences which is always the highest honour reserved for the top engineers, like Ir Prof Cheung.

Ir Prof Cheung is an excellent model for our younger generation. Indeed, he has set a good example for them too. Ir Prof Cheung continues to work even after his retirement. His impact is still being felt by all of us.

Once again, I would like to thank Ir Prof Cheung for all his contributions made to us.

*Ir Dr the Hon Raymond HO Chung-tai*

**SEE Saw Teen**

Ms See joined LERA in 1978 and became partner in 1986. Ms See received her Bachelor of Science in 1977 and her Master of Engineering in 1978, both from Cornell University. Ms See has extensive experience working on projects throughout the world. Ms See was Partner-in-Charge of the Rock 'n' Roll Hall of Fame and Museum (Cleveland, Ohio), the Seattle Art Museum, the National Constitution Centre (Philadelphia, Pennsylvania), Baltimore Convention Centre (Baltimore, MD), and the Miho Museum (Kyoto, Japan). She is currently LERA's Partner-in-Charge of the 492-m high Shanghai World Financial Centre and the Structural Audit of the Landmark Tower at Kowloon Station. Her recent experience in Hong Kong includes the AIG Tower and Footbridge and peer review and value engineering of the International Finance Centre Towers 1 & 2, and the hotels of this same development. In 2002, she received a Special Recognition Award from Professional Women in Construction. She is a Fellow and Honorary Member of ASCE as well as a Fellow of the New York Academy of Science.