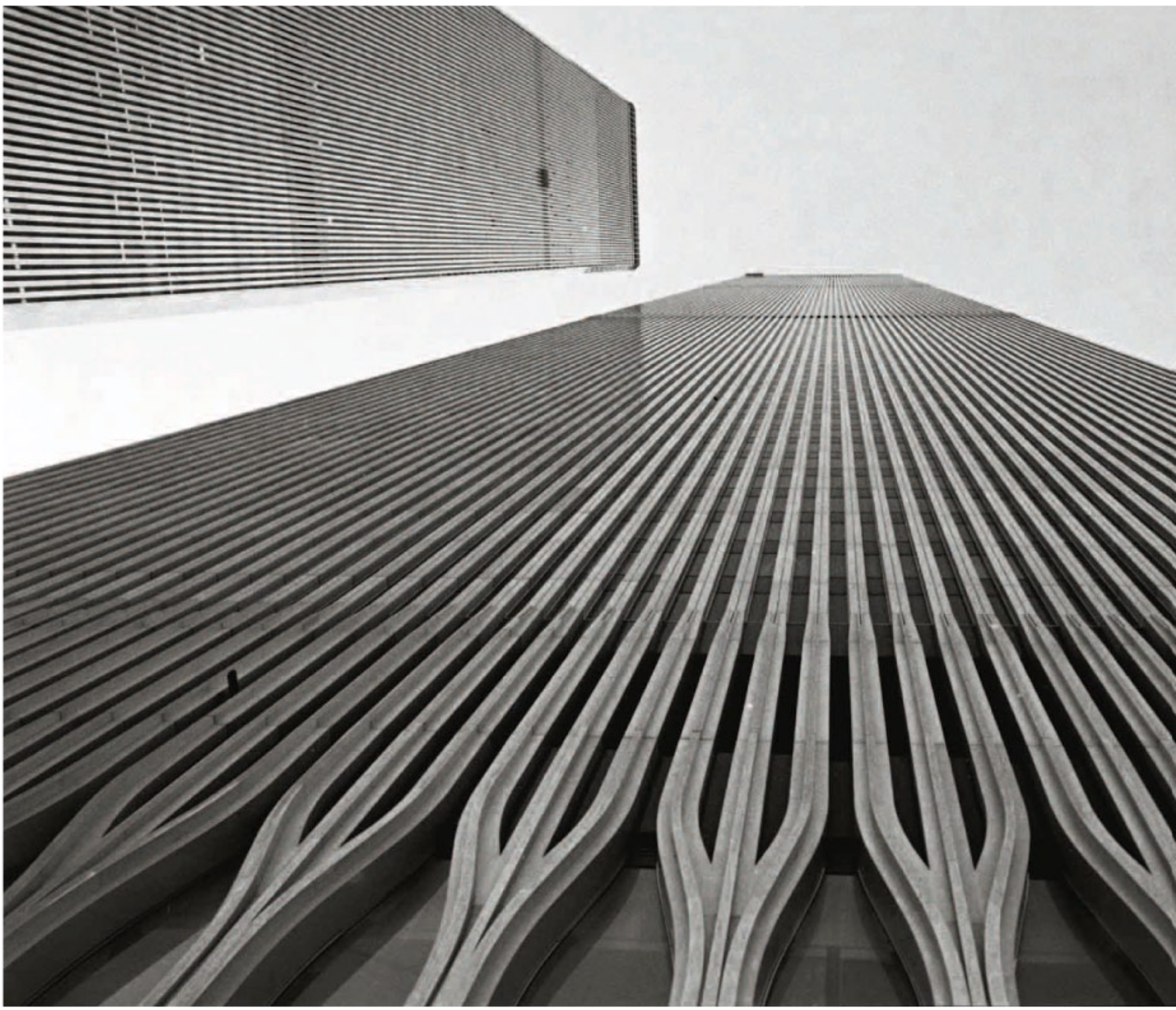
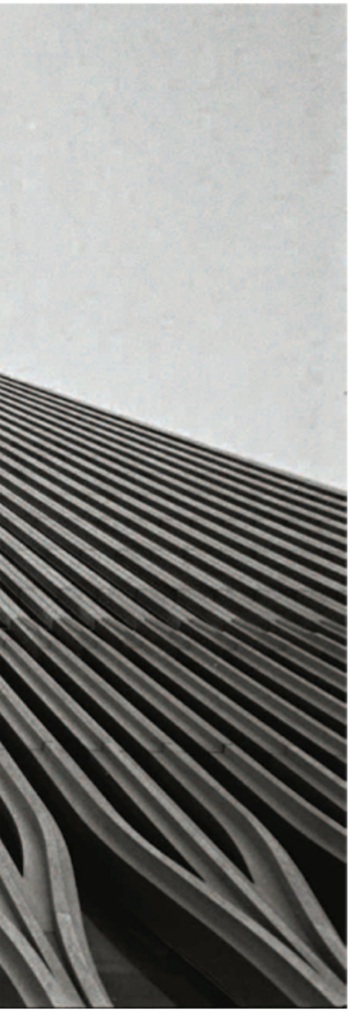
The Tallest Buildings in the World

The lead structural engineer of the World Trade Centre, Leslie Robertson, reflects on the rise and fall of an architectural marvel, write **Eric Uhlfelder** and **William Abrams**.



Originally published as "Towers of Strength" on 9/11/11 in The South China Morning Post

Pictures: The Office of Leslie E. Robertson Associates



Clockwise from left: the twin towers of the World Trade Centre; Leslie Robertson; the Manhattan skyline, dominated by the towers, in 1982.

Ten years ago, he was in Hong Kong, working on the AIG Tower. He was having dinner with colleagues in the Furama Hotel, which would soon make way for the new building, when he heard the news. It wasn't the first time Leslie Robertson's New York masterpiece had been under attack.

Eight years earlier, a huge truck bomb had been detonated under the World Trade Centre (WTC) site in Lower Manhattan. But his recommendation during the design phase to site parking away from directly beneath the towers had proved decisively prescient. When he surveyed the damage the following day, February 27, 1993, Robertson found the towers remained structurally uncompromised.

Given such resilience, those who intended to bring down the towers may have realised then that a more brazen attack from above would be far more public.

When Robertson heard a second plane had hit the WTC, he got up from dinner and found a television, onto which images of Lower Manhattan were being beamed from the other side of the globe.

"I didn't think the towers would fall," he says. "As designed, the weight of the floors above where the planes had hit was being transferred around the holes to the columns below. But as I watched, fearing for all those still inside, a decade of work flashbacked across my mind."

THE WTC WAS BORN out of despair and an extraordinary ambition to revive Lower Manhattan.

In the 1950s and 60s, cities were dying as wealth fled to the suburbs. The big businesses that stayed in New York were moving out of the more constrained spaces of Lower Manhattan's early 20th-century skyscrapers, seeking the more modern, larger office spaces of Midtown.

Chase Manhattan Bank chairman David Rockefeller, founder of the Downtown Lower Manhattan Development Corporation, along with his brother, New York state governor Nelson Rockefeller, and the Port Authority of New York and New Jersey envisioned a massive project to return attention to New York City and Lower Manhattan.

The Port Authority, which was in charge of the project, successfully lobbied for the 10 million sq ft development to be shifted from the East River to the Hudson, providing its Port Authority Trans-Hudson trains running beneath the river direct access. In 1962, the ›› authority selected as its architect Minoru Yamasaki. After considering various models, the authority decided on two 110-storey towers.

The steel structure that made Yamasaki's vision possible was conceived by a relatively unknown Seattle-based engineering firm, Worthington, Skilling, Helle and Jackson. The partner-in-charge was John Skilling and the firm's lead structural engineer was Robertson, then 34 years old.

"What we provided Yama," Robertson recalls, "was something he never dreamed of: closely spaced small columns on the perimeter of the building made into a gravity and lateral-force system that was very redundant and robust. It was exactly what was needed for his architecture."

to lighten the Shanghai World Financial Centre's (completed in 2008) core and then reinforce the external structure with a diagonally braced frame that was further supported by external trusses.

The task facing the WTC team in the 60s was beyond anything builders had ever contemplated. Each storey was to measure nearly an acre. They married 200,000 tonnes of steel, 425,000 cubic yards of concrete, more than 43,000 windows, 320 kilometres of air ducts, 19,000 kilometres of electricity cables and more than 100 lifts. Ten thousand people worked on the towers. It would take 10 years to complete, and, when it opened, in the early 70s, the WTC was so large it was given its own post code.

The WTC under construction in 1969.

"Unless we are prepared to live in an environment that resembles ... caves, we will not design buildings to stop planes"

In many ways, Robertson is an anachronism. He seems to belong to the grand Victorian age of innovation. His deportment is calm and pleasant. He enjoys entertaining friends, listening carefully and speaking softly and precisely. At 83, his eyes still radiate passionate interest in things around him and ambitions to be realised. He fully embraces the advantages that have accompanied him into the 21st century.

Like youthful innovators, he often does things differently, unconstrained by accepted doctrine or norm. He approaches problems with defiant logic, believing man's greatest accomplishments are achieved not simply through close adherence to principles, but in their judicious expansion.

A recent example of his innovation can be seen in Shanghai. Required to build taller and larger than the original foundation was designed to support, Robertson's firm had

"We had already worked well with Yama on half a dozen projects," recalls Robertson, "so he felt very comfortable calling on us to develop ideas for the Trade Centre.

"To me the Trade Centre was a matter of expanding the basic ideas of structure."

It was to become a lot more.

Skyscrapers had topped out in 1931 with the Empire State Building's 102 floors. This limit, which had prevailed for 40 years, was based on accepted engineering practice. Robertson was going to rewrite that limitation, with each tower containing more than twice the floor space contained in the Empire State Building.

Robertson was by no means a leading practitioner of skyscraper engineering. His tallest building to date had been the Yamasaki-designed 20-storey IBM Building in Seattle. But he had already demonstrated an aptitude for overcoming challenges. He had designed the foundations for the eight-kilometre-long Maracaibo Bridge, in Venezuela, turning heads when he opted to use 36-inch deep wide-flange steel beams, instead of steel wire, to fortify the concrete footings. He was one of the first engineers to apply a cross-braced wall – in the 13-storey IBM Building in Pittsburgh – which required less steel than traditional building frames and was an early example of column-free interior space.

For US Steel's headquarters, also in Pittsburgh, he designed liquid-cooled columns to meet the company's demand to leave the building's exterior structural steel exposed

Robertson knew the largest concern in engineering the WTC was the wind, the force of which was even greater than the downward load of the buildings.

"Not only did we have to contend with the turbulence generated by setting two tall buildings next to one another," says Robertson, "we were confronted with various and extreme wind pressures exerted by neighbouring skyscrapers and proximity to the Hudson and East rivers, and the Atlantic Ocean, which was just a few miles to the south."

Wind analyses involved constructing a 1:500 scale model of Lower Manhattan, including the WTC, and inserting it into the most sophisticated wind tunnel of the time, which was housed in Colorado State University.

Unlike traditional skyscrapers based on a grid of columns and beams set apart at 30-foot intervals, Robertson's and Skilling's solution thoroughly reconfigured the columns. He designed a dense row of columns around the perimeter of each tower and another set of columns circumscribing the buildings' core. The two sets of columns were then connected by prefabricated floors.

This created far more open floor space than existed in traditional skyscrapers but, says Robertson, "the exterior walls carried extraordinary weight, requiring them to be even more robust than traditional skeletal walls to counter the lateral force of the wind".

Although they appeared identical from the outside, Robertson found he could further strengthen the towers' wind resistance by rotating one tower 90 degrees. Because each core was rectangular, set inside a square plan, the distance between the core and the exterior walls was longer on two sides. This lent to increased lateral stiffness where it was most effective. To control the sense of movement inside, Robertson's team, along with 3M, invented unique viscoelastic dampers – structural shock absorbers. Nearly 11,000 of them helped regulate motion by absorbing energy generated by the movement of the columns and floor trusses.

During the design phase of the WTC, computer modelling was used for the first time to forecast how a structure would perform under extreme stress, and Robertson used this technology to confirm his structures could withstand a hit by the largest plane of the time: a Boeing 707.

Testing such a horrific hypothesis came down to two basic conditions: removing a series of adjacent columns and floor trusses and seeing how the buildings would absorb the energy of the jet. Robertson found that ›› if a plane was flying at approach speed for landing when it struck one of the towers, it would remain standing.

No one involved with the WTC projected the impact a jet fuel-accelerated fire would have on the integrity of the structures. The National Institute of Standards and Technology's (NIST) investigation of the buildings' collapse – the official government study – agreed: "The computing resources and software necessary to conduct these analyses did not exist in the 1960s." NIST concluded that if the fireproofing of the steel hadn't been blown off by the impact of the jets, the towers would likely have remained standing, just as Robertson said.

There has been extensive study of how the towers performed after they were struck and why they ultimately collapsed. There are those who claim the towers were stalwart for standing as long as they did to give the vast majority of occupants time to exit. Others say the search for efficiency produced structures that may have been susceptible to progressive failure. Ten years after the disaster, the subject remains contentious and difficult to discuss dispassionately.

Professor Robert Bea – one of the United States' leading forensic engineers, who led investigations into the Challenger space shuttle disaster, Hurricane Katrina and the Deepwater Horizon oil-well blowout, and who heads the University of California, Berkeley's Centre for Catastrophic Risk Management – describes Robertson's design as excellent.

"One part of me as an engineer looks at that efficiency achieved and says, 'Well, that's exactly what we should be doing,'" says Bea. "However, it's taken me my entire professional life to learn that anyone's structural system cannot, will not, be perfect. Things will not perform as you expect them to. Things will not be built as you expect them to be. The system has to have a level of protection called robustness that allows it to tolerate damage and defect."

WTC spandrels being transported to the construction site.

"I was ready to pack my bags, not because I felt I let anybody down, but simply due to the suffering associated with my work"

Some studies suggested traditional concrete-reinforced 30-foot structural bays would have better defended the buildings against aircraft hits than did the use of only perimeter and interior core columns. These studies point to the lack of external review of Robertson's design – something that would've been done if the project had been reviewable by the City of New York, because the engineering was breaking new ground and had no reference in the local building code. Being a Port Authority project, however, the city had no authority over it. (This is true for the rebuilding of the World Trade Centre site. However, Robertson's firm performed a peer review of Towers 1, 2, 3 and 7. And his firm is the structural engineer of Tower 4.)

Some questioned the resilience of the unique floor trusses after they lost their fireproofing (from the impact of the jets) and the integrity of their links with the interior and exterior columns. Some argued several specially reinforced mid-building truss systems, called diaphragms, may have reinforced the geometry of the building and could have helped to keep portions of them standing.

However, Robertson says his design met or exceeded all local code requirements. He contends the strength of his buildings lay precisely in his exterior walls, designed to withstand the wind, a key to which was the robustness of the connections between the floor trusses and columns. The NIST investigation found the floor trusses did not fail first. In fact, NIST believed when the trusses lost their lateral strength – due to the loss of fireproofing caused by the impact of the planes and intense heat of the fire – they actually pulled the columns inward. This added further strain to the structure, which was already suffering from misalignment as a result of the impact of the planes.

No structure built for commercial purposes could keep a jumbo jet flying at high speeds from penetrating its facade, says Robertson. Robert Prieto, chairman of engineering firm Parsons Brinckerhoff, agrees: "Unless we are prepared to live in an engineered environment that resembles the complex of caves in Afghanistan, we will not design buildings to stop planes." And Robertson doesn't believe there is any certainty mid-structure reinforcement could have saved the buildings once they were so severely compromised.

Duke University professor Henry Petroski, a long-time student of engineering failure, contends evolution in both nature and things man-made is a push towards greater efficiency and optimisation of materials used. When the process encounters intolerable environmental conditions, it then corrects.

Should the possibility of aircraft being intentionally flown full throttle into buildings become part of environmental conditions for which engineers must plan? It certainly was not in the 60s, when Robertson was designing the tallest buildings in the world. According to NIST, no building code today requires such defence.

The fate of the WTC came down to a simple fact: the level of hate driving a handful of individuals exceeded the imagination, intelligence and commitment that had led tens of thousands of men and women to create two remarkable towers that had the audacity to reach a quarter of a mile into the sky.

This is not much solace for the families of the thousands who perished on September 11 – or for Robertson. Many did come to him in the months that followed, looking for some kind of answer, which he knew he could not provide.

"The first was a young woman, perhaps 13 or 14 years old. Her brother was working on one of the high floors. We met in a park at the foot of Manhattan. The tears came as her body shook. And as we cried together, words were not required."

Perhaps through embraces and tears shed with strangers Robertson, too, partially came to terms with the incomprehensible.

He had thought his career was over. "I was ready to pack my bags, not because I felt I let anybody down, but simply due to the suffering associated with my work. I thought afterwards I had no chance at securing new contracts and felt that even existing jobs were going to get pulled at any moment."

But to his surprise, he received an outpouring of support. Developers were compelled by the strength of his towers that allowed so many to survive such a devastating attack.

So he did what Robertson has always done – he threw himself into his work. His office was awash with projects: the Clinton Presidential Centre in Little Rock, Arkansas; the National Constitution Centre in Philadelphia; the Museum of Islamic Art in Doha, Qatar.

He and his firm have gone on to design some of the world's tallest skyscrapers, among them: the 101-storey Shanghai World Financial Centre, which rises 492 metres; the Lotte Jamsil Tower, in Seoul, South Korea, which is under construction and will be 123 storeys or 555 metres tall; and a 100-storey tower in Kuala Lumpur that will ascend 500 metres.

Time has distanced that terrible day. Still, Robertson quietly carries with him his own unresolved anguish.

"I cannot escape the people who died there ... it's still to me up there in the air burning ... and I cannot make that go away." ■