The Height of Ambition: Part Four

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ince the first steel-reinforced skyscrapers were built in the latter part of the 19th century, these nature-defying structures had always relied for their basic support on a kind of three-dimensional cage, or grid. The grid permeated the entire building -- massive steel columns interrupting the floor space every 20 or 30 feet, no matter which direction you turned. The point was structural integrity: if one of the closely spaced steel bones failed, another would be there to take up the slack, avoiding a total collapse. In case of fire, thick sheaths of masonry -- brick, stone or terra cotta -- around the steel would protect it from the heat, even in out-of-control blazes. The Empire State Building is the apotheosis of this kind of robust, superredundant architectural engineering.

Leslie E. Robertson, the man charged with designing the guts of the twin towers, had a certain disdain for the reliable but uninspiring confines of the traditional high-rise structure. Robertson -- an intense, doe-eyed 35-year-old structural engineer in Seattle -- was a rising star, a hotshot who dismissed the entire East Coast engineering establishment as calcified, unsuited for such a wondrous assignment. Robertson had both conceptual and imaginative muscle and the mathematical prowess to back it up. And he set out to do no less than change the principles of skyscraper design that the Eastern club had written down like laws. ''We were younger -- we were not burdened with all of the baggage of how buildings had been constructed in the past,'' Robertson says. ''In a sense, we were the perfect choice.''

Robertson had a threefold problem to solve. First, he had to hold up the world's tallest buildings and make them resistant to the intense gusts of wind that blew over the harbor, while still remaining true to Yamasaki's architectural vision. Second, he had to meet the Program. Third, he had to economize wherever possible in a project whose rising costs were already being scrutinized.

With a traditional steel-cage design, those requirements were more or less mutually exclusive. For example, the forest of masonry-encased interior columns in traditional high-rises were sturdy, but they were expensive, and they ate up tremendous amounts of rentable floor space. And it would be difficult, if not impossible, to fit Yamasaki's lithe, upsurging conception onto one of those musclebound structures.

So Robertson and the team he led chose the most extreme way out, abandoning the traditional structure altogether. He labeled the era before his team arrived ''the cage of the past'' -- by which he meant not just the structures he wanted to leave behind but also the older engineering minds that, he felt, were trapped by history. In recent years, other high-rise designers began to strip away the masonry that earlier builders had relied upon in favor of lighter components like glass for facades and gypsum -- the chalky wallboard often called Sheetrock -- for interior walls. But none of those designers had ever come close to the leap into lightness that Robertson was about to take.

Yamasaki's design for the facade featured an uninterrupted pattern of alternating steel pinstripe columns and narrow windows that repeated every 40 inches. It was the columns -- so narrowly spaced because Yamasaki, who had a fear of heights, wanted to feel safely confined inside his buildings -- that Robertson and his team decided to put to work in their design. The engineer's key decision was to turn those columns into the main structural elements of the entire building, using them to carry almost half the building's weight, as well as to generate all the lateral rigidity for resisting the wind. This would allow Robertson to erase most of the interior columns, creating a vast amount of wide-open, rentable space.

Asking the perimeter columns to carry the weight was easy: just make the steel strong enough. But stiffening them against the wind was a harder task. Robertson's solution was to connect the exterior columns, 59 of them on each face of the towers, with wide steel plates called spandrels: think of people (the columns) standing in a circle and linking arms (the spandrels). Using exterior columns rather than interior ones for lateral stiffness not only increased the building's floor space; it also let Robertson reduce the total amount of structural steel in the building by at least 30 percent. The steel in the tightly spaced columns became as thin as a quarter-inch toward the top, where it had less load to carry.

Robertson had succeeded in achieving his main goals for these exotic steel trees. But in designing what would become the feathery branches of those trees -- the floors -- he pushed even further toward lightweightness and cost savings. Rather than the massive beams or heavy framings that serve as horizontal floor supports in virtually every large steel office tower, Robertson chose bar-joist trusses -- airy, weblike networks of thin steel bars and angle irons topped with corrugated decking. Those trusses, which spanned as much as 60 feet, had two critical roles: they held up the concrete floors, and they provided lateral support to the exterior columns, keeping them from buckling under the load they carried.

According to Robertson's figures, the trusses worked as well as heavy traditional girders and beams in performing those roles under ordinary circumstances. What he did not take into account was the extraordinary conditions of an intense, violent fire. Girders and beams would be far superior under those circumstances. Thin steel elements heat up and soften faster than thick ones. But in recent conversations, Robertson has said that architects generally handle anything dealing with fire in building projects, not engineers, so he did not think about this reduction in safety.

Robertson and the Port Authority made another choice that proved fateful decades later. They chose not to use thick masonry or cement to encase the three escape stairways in each tower but rather light sheets of gypsum. Although the gypsum was extremely resistant to fire, and less likely than masonry to crack when the building swayed in the wind, it would work only if it remained intact -- and it was much more susceptible to being shaken loose or damaged by an explosion or any other kind of unexpected impact.

There was another factor that Robertson had to take into account: the swaying motion of his buildings. The lightweight steel skeletons would not only put people unnaturally high in the air, as all skyscrapers do. They would let the buildings sway back and forth in the wind, like the biggest, leafiest trees ever planted. Heavy masonry-clad high-rises like the Empire State Building had never had to deal with this problem. For that reason, engineers had never measured how much swaying motion humans could stand before they became dizzy, seasick, frightened or disoriented.

To answer that question, Robertson turned to an expert in human perception in Eugene, Ore. -- a spot as far removed from the New York press as he could find. Paul Hoffman, a psychologist, agreed to perform a secret series of experiments to find out just how much swaying motion was too much. Hoffman purchased a small office building in downtown Eugene and in the summer of 1965 put an ad in the local paper offering free eye checkups at a ''vision research center.'' But it was actually an elaborate ruse: the optometrist who conducted the eye exams was one of Hoffman's employees, Paul R. Eskildsen. And as each patient stared at triangles projected on the wall, a hidden technician would trigger a giant set of hydraulics underneath the room that heaved it back and forth like a big saltshaker.

''This is a strange room,'' one patient said, according to Eskildsen's detailed notes. ''I suppose it's because I don't have my glasses on. Is it rigged or something? It really feels funny.''

Patient after patient reacted the same way -- becoming dizzy and confused soon after the eye exam began. Humans, Hoffman discovered, were much more sensitive to motion than anyone had realized. A few inches of sway over 5 or 10 seconds set off psychophysical alarm bells.

''The people who were most surprised of all were the engineering firm and the Port Authority,'' Hoffman says. First, Port Authority officials trooped out to Eugene. Old photos show them milling around the little optometrist's office, looking flummoxed. Then they insisted on redoing the experiments by swinging a makeshift office on cables inside one of the Lincoln Tunnel's ventilation towers on Manhattan's West Side. ''It was a big packing crate, is what it was, that they had dolled up to look like an office,'' says Eskildsen, who traveled to New York for the new round. ''I had two guys outside who pushed the room. It was hilarious.'' About 40 Port Authority officials rode in the contraption. The results were the same.

Wind-tunnel experiments in Fort Collins, Colo., confirmed that Robertson's initial design would sway far beyond those human tolerances, says Jack Cermak, then a professor of civil engineering and the director of the wind-tunnel laboratory at Colorado State University. Even today, Robertson has no trouble conjuring what two towers full of seasick office workers would have meant: ''A billion dollars right down the tube.''

So he went back to work. He had been kicking around the idea of building shock absorbers into a building, and now he went ahead and developed the idea, eventually patenting it. Called viscoelastic dampers, they were flat metal pieces, two and a half feet long, held together with a tough, rubbery glue developed by 3M. One plate would connect to an exterior column, and two others would be fixed to the underside of a steel truss. When the building swayed in the wind, the plates would slide against one another and damp the motion a little -- a shock absorber. Put 11,000 of them into each tower, as Robertson did, and they became a very good shock absorber.

The second part of Robertson's solution to the motion-sickness problem was a huge support structure called a hat truss, which would sit atop each building and tie its core to its exterior. Robertson realized that the hat truss could add stiffness to the entire building, from top to bottom, by acting as a rigid cap. He also widened the exterior columns slightly, adding further stiffness to the structure.

But Robertson still had one more set of structural calculations to perform. Lawrence Wien, who was continuing his fight against the towers, had begun to remind New Yorkers publicly of a Saturday morning in July 1945, when a B-25 bomber, lost in the fog, barreled into the 79th floor of the Empire State Building. Most of the 14 people who died were incinerated by a fireball created when the plane's fuel ignited, even though the fire was quickly contained. The following year, another plane crashed into the 72-story skyscraper at 40 Wall Street, and yet another one narrowly missed the Empire State Building, terrifying sightseers on the observation deck. Wien and his committee charged that the twin towers, with their broader and higher tops, would represent an even greater risk of midair collision.

They ran a nearly full-page ad in The Times with an artist's rendition of a commercial airliner about to ram one of the towers. ''Unfortunately, we rarely recognize how serious these problems are until it's too late to do anything,'' the caption said.

The Port Authority was already trying to line up the thousands of tenants it would need to fill the acres of office space in the towers. Such a frightful vision could not be left unchallenged. Robertson says that he never saw the ad and was ignorant of the political battle behind it. Still, he recalls that he addressed the question of an airplane collision, if only to satisfy his engineer's curiosity. For whatever reason, Robertson took the time to calculate how well his towers would handle the impact from a Boeing 707, the largest jetliner in service at the time. He says that his calculations assumed a plane lost in a fog while searching for an airport at relatively low speed, like the B-25 bomber. He concluded that the towers would remain standing despite the force of the impact and the hole it would punch out. The new technologies he had installed after the motion experiments and wind-tunnel work had created a structure more than strong enough to withstand such a blow.

Exactly how Robertson performed these calculations is apparently lost -- he says he cannot find a copy of the report. Several engineers who worked with him at the time, including the director of his computer department, say they have no recollection of ever seeing the study. But the Port Authority, eager to mount a counterattack against Wien, seized on the results -- and may in fact have exaggerated them. One architect working for the Port Authority issued a statement to the press, covered in a prominent article in The Times, explaining that Robertson's study proved that the towers could withstand the impact of a jetliner moving at 600 miles an hour. That was perhaps three times the speed that Robertson had considered. If Robertson saw the article in the paper, he never spoke up about the discrepancy. No one else issued a correction, and the question was answered in many people's minds: the towers were as safe as could be expected, even in the most cataclysmic of circumstances.

There were only two problems. The first, of course, was that no study of the impact of a 600-mile-an-hour plane ever existed. ''That's got nothing to do with the reality of what we did,'' Robertson snapped when shown the Port Authority architect's statement more than three decades later.

The second problem was that no one thought to take into account the fires that would inevitably break out when the jetliner's fuel exploded, exactly as the B-25's had. And if Wien was the trade center's Cassandra, fire protection would become its Achilles' heel.

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