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Structural Design of Taipei 101, the World's Tallest Building

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Abstract
At 101 stories and 508 m above grade, the Taipei 101 tower is the newest World's Tallest Building. Collaboration between architects and engineers satisfied demands of esthetics, real estate economics, construction, occupant comfort in mild-to-moderate winds, and structural safety in typhoons and earthquakes. Its architectural design, eight eight-story modules standing atop a tapering base, evokes indigenous jointed bamboo and tiered pagodas. Building shape refinements from wind tunnel studies dramatically reduced accelerations and overturning forces from vortex shedding. The structural framing system of braced core and multiple outriggers accommodates numerous building setbacks. A secondary lateral load system of perimeter moment frames and special core connections adds to seismic safety. Column axial stiffness for drift control was made practical through steel boxes filled with high-strength concrete. Occupant comfort is improved by a massive rooftop pendulum Tuned Mass Damper. Pinnacle framing fatigue life is enhanced by a pair of compact spring-driven TMDs. The soft soil subgrade required mat foundations on bored piles, slurry walls, and a mix of top-down and conventional bottom-up construction with cross-lot bracing. The project illustrates the large and small design decisions in both architecture and engineering necessary to successfully complete a major building in a challenging environment.

Keywords: vortex shedding, high-strength concrete, tuned mass damper, outrigger, fatigue

1. Introduction

Every project has a list of challenges, but for Taipei 101, the new world's tallest building, that list is longer than size alone would imply. Starting with a design height of 508 m [check], it also includes the overall and localized load effects from frequent and extreme typhoons; potentially severe earthquakes; and difficult subsurface conditions, including an inactive fault through the site. Occupants must be both physically and psychologically comfortable with the design, even during high winds and extreme events. Rising from a dramatic, landmark-quality retail mall, the tower has a profile unlike that of any previous skyscraper: a tapering base topped by a series of flared segments. And a couple of temblors rattled the partially-completed structure, reminders of the challenges the design must address. Meeting all these challenges through studies, design and construction was an unforgettable experience for all involved.

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2. Tower Height

The first challenge was the height. Building stories come at an ever-increasing cost, as if the new story is added at the bottom of the building. That reflects the need for supporting all the floors above, for elevator shaft and stairwell space, and for mechanical, electrical, plumbing and fire protection risers. The economic height limit occurs where the added cost of a floor exceeds the added rent the floor will bring. Prior to Taipei 101, the tallest building on the island of Taiwan was the 85-story T&C Tower in Kaohsiung. The major jump in height resulted from the desire of project investors, several financial firms, to occupy space in a landmark building. Projected office space demand of 200,000 m^2 (2.1 million square feet) [check] and individual floor areas based on general office layout standards led to a height of 101 stories. Another 200,000 m^2 occurs in a podium of retail space surrounding the tower base and basement parking.

3. Foundations

The second challenge was the site. Soft rock occurs beneath 40 to 60 m of clay and stiff colluvial soil. The design required a 21 m deep basement, while ground water is usually 2 m below grade and potentially at grade. Based on extensive investigations by Taipei-based Sino Geotechnology Inc. and scheduling requirements, five major components were used to create two different foundation systems. One slurry wall 1.2 m (4 ft) thick surrounds both tower and podium; its 47 m (154 ft) depth cuts off ground water and provides toe embedment well below the 21.8 to 23.5 m (72 to 77 ft) excavation depth. Each podium column bears on a single 2 m (6.5 ft) diameter drilled pier. Sockets 5 to 28 m (16 to 92 ft) into bedrock resist net uplift from a podium pressure slab resisting buoyancy. The single-pier design permitted 'top down' basement construction: a floor was cast to brace perimeter walls, then a story of excavation proceeded below it. Superstructure framing was erected at the same time. As a result, the retail podium opened about a year before the tower topped out.

A second slurry wall, enclosing just the tower footprint, was supported by steel cross-lot bracing as excavation proceeded to full depth. the walls were braced to accommodate construction sequencing. A continuous reinforced concrete mat 3 to 4.7 m (10 to 15 ft) thick transfers load from discrete column and shear wall load points to a distributed pattern of 380 drilled piers, 1.5 m (5 ft) in diameter, spaced 4 m (13.12 ft) on center in staggered rows to resist gravity loads between 10.7 and 14.2 MN (1500 and 2000 kips). Using steel framing minimized building weight, helping to reduce foundation costs.

4. Building Vertical Shaping

The third challenge was the tower shape established by architect C.Y. Lee. Well-regarded in the region and experienced in tall buildings, including the T&C Tower designed with Evergreen, Lee's building shape for Taipei 101 provides an instantly recognizable symbol of Taipei and Taiwan. The repeating modules were inspired by the joints of indigenous bamboo and the tiers of pagodas; each module has a narrower base and a wider top as if a flower opening to the sky. Each module has eight floors, and eight modules form the majority of the tower's height. In the Chinese spoken in Taiwan, 'eight' is a homonym with 'wealth,' making it a very appropriate feature for a financial center. A ninth module that tops the main shaft and supports an architectural spire has a smaller footprint but matching wall slopes. Below the repetitive flared modules, a 25 story base shaped as a truncated pyramid provides improved overturning resistance and lateral stiffness compared to a straight shaft, if the structural system engages the perimeter columns. The transition from lower pyramid to upper modules is highlighted by medallions based on ancient Chinese coins. See Fig.1.

Fig. 1. The Taipei 101 profile shows a truncated pyramidal base topped by eight, 8-story flaring building modules, a narrower equipment/observation deck module and a steel-spined spire

5. Plan Shaping for Wind

The fourth challenge was a high wind environment. Tall, slender chimneys and skyscrapers experience alternating crosswind forces due to vortex shedding: wind passing the object separates from side faces in alternating whirlpools. When vortex formation set by wind speed and building dimensions coincides with building period, large forces can result. Here a typhoon with 100 year return period brings winds of 43.3 m/sec (97 mph) averaged over 10 minutes at a height of 10 m (33 ft). This is similar to a three-second gust of 67 m/sec (150 mph). It can excite a skyscraper with crosswind forces much greater than those normally used for design. During a wind tunnel visit by C.Y. and the authors, RWDI demonstrated that a square tower with sharp corners creates large crosswind excitation. Rounded and chamfered (45^o) corners reduced lateral response, but a 'saw tooth' or 'double notch' corner with 2.5 m (8.2 ft) notches achieved a dramatic reduction. See Fig.2. Architect Lee understood the significance of this shape and incorporated it into the upper module corners from that point on. See Fig.3.

6. Lateral Load Resisting Systems Considered

While low- and mid-rise buildings can rely on an interior core of shear walls or bracing to provide overall tower stability, for the tallest of skyscrapers the full building floor plan width and depth is used to

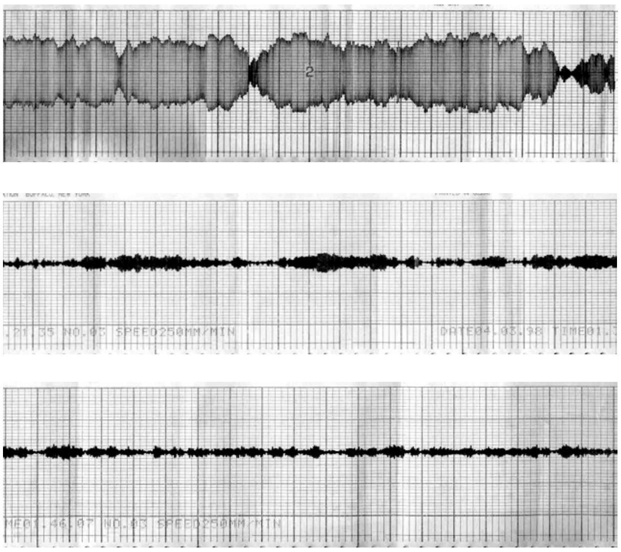

Fig .2. Wind tunnel cross-wind base moments:
Top- square-cornered model with damping at 1% of critical.
Middle- 'sawtooth' plans with two 2.5 m re-entrant corners at each building corner, also at 1% of damping.
Bottom- 'sawtooth' behavior with 2.5% damping.

provide economical overturning resistance and lateral stiffness. A framed tube of closely-spaced perimeter columns joined by deep, stiff perimeter spandrel beams can form a rigid box, but for this project it would block the wide glass expanses desired by the owners, require indirect load transfers at the setback atop each module and involve intrusive internal beams to connect building faces across the 'saw tooth' corners. With a bundled tube of multiple parallel frames criss-crossing the floor, column spacing can be greater for wider windows, but interior frames subdivide floors and adversely affect space planning. A 'tube in tube' of central core and perimeter framed tube permits somewhat wider perimeter column spacing but the other concerns would remain.

Instead we started with a central braced core, but then improves its strength and stiffness by connections to several perimeter columns on each building face

Fig. 3. A close-up of the tower corner clearly shows the 'sawtooth' treatment above Floor 25 for wind vortex reduction.

through 'outrigger trusses' with top and bottom chords incorporated within the framing of two adjacent floors and diagonals through occupied space, preferably mechanical or storage rooms. In this 'megaframe,' outrigger trusses and outrigger columns help stabilize the narrower core. The perimeter framing is more open. Outrigger effectiveness depends on location and on outrigger column stiffness. Belt trusses just above each module setback gather and transfer perimeter weight to two outrigger 'supercolumns' on each face, so the member sizes needed for gravity loads provide axial stiffness as well. See Fig.4. The megaframe approach maximizes views, avoids module setbacks and saw tooth corners, and offers load redistribution if some.

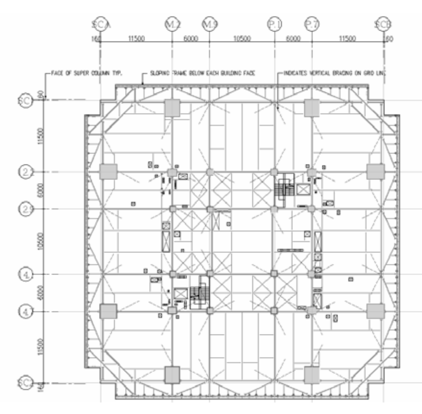

Fig. 4. This typical setback floor plan shows sawtooth corners, a braced core with 16 steel box columns, outriggers to eight perimeter concrete-filled steel box supercolumns, upper (inner) and lower (outer) perimeter wideflange moment frame columns and in-floor bracing to transfer story shear between modules.

members are damaged in unforeseen events. The megaframe approach was then optimized for wind performance and seismic design requirements

7. Design for Lateral System Stiffness

Wind performance was enhanced by building shape as discussed above, but further provisions were still required. To minimize interstory movement that could damage façades and partitions, overall lateral motion and interstory drift were both limited to Height/200 for the ‘50 year storm.’ This may seem flexible, but Taipei winds are extreme: for comparison the tower subjected to a New York City design hurricane would drift only H/400. Because a large portion of tower drift is created by overturning rotation at lower stories, drift control required increased column stiffness. Turner Construction - International LLC, project and construction manager, agreed with us that simply adding steel area was impractical from cost, fabrication and erection perspectives. The solution: hollow columns filled with high-strength concrete, placed by pump to avoid heavy crane lifts. Concrete carries compression economically and, unlike steel, mixtures with higher strength also exhibit a higher elastic modulus.

Taipei 101 core and supercolumns are steel boxes up to level 90, built up from steel plates 50 to 80 mm (2 to 3 1/8 in) thick with full penetration welded splices that took 16 hours with six welders working simultaneously to balance shrinkage effects. Box straps resist bulging, rebar strengthens concrete, and shear studs link concrete and steel. The box core and supercolumns were then filled with 69,000 kPa (10000 psi) concrete where extra stiffness is needed, from the bottom of the basement to level 62. See Figs.5-8.

In addition, the braced core is encased in concrete walls from the foundation to the eighth level.

8. Occupant Comfort

The resulting building frame is stiff compared to equivalent towers. Its anticipated sway period of 7 seconds is significantly shorter than the 9-plus seconds one might normally expect for a 101-story structure. However, building drift control could not independently ensure occupant comfort criteria, considering the great building height, high wind speeds and low inherent structural damping of a steel frame with tight connections that permit little slip or rubbing. Structural damping was a consideration because, while

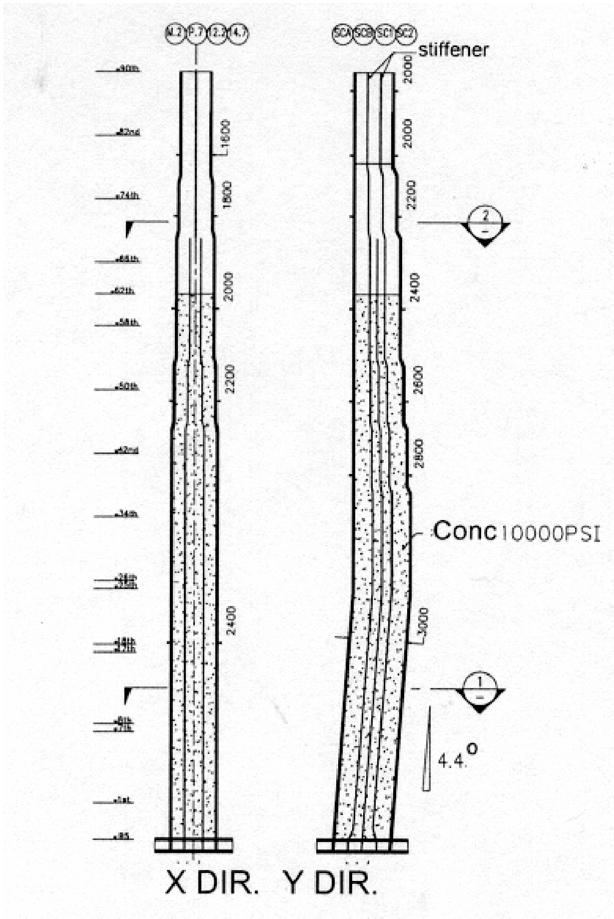

Fig. 5. Supercolumns are filled with high-strength concrete for added stiffeness as shown shaded here.

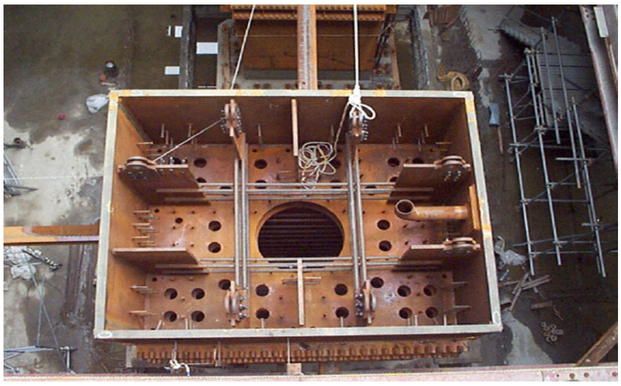

Fig. 6. A supercolumn box just below its field splice location. High strength concrete enters through the pipe at right to fill the box from bottom up in two-story lifts.

each vortex that is shed provides only a small impulse to the building, the effects can accumulate if energy is not removed from the system. In a schoolyard analogy, one pump of a child’s legs doesn’t cause a large swing, but repetition does. Damping in a building removes energy and reduces movement, just as allowing feet to drag on the ground can gradually stop a swinging child.

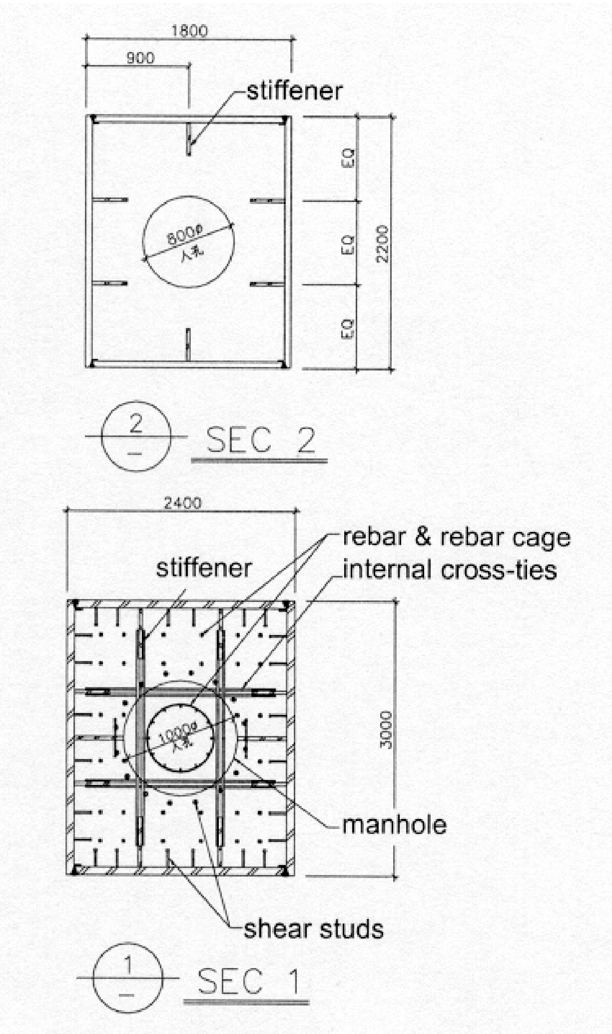

Fig. 7. Supercolumn box plan details show stiffeners, diaphragms, shear studs and cross-box ties.

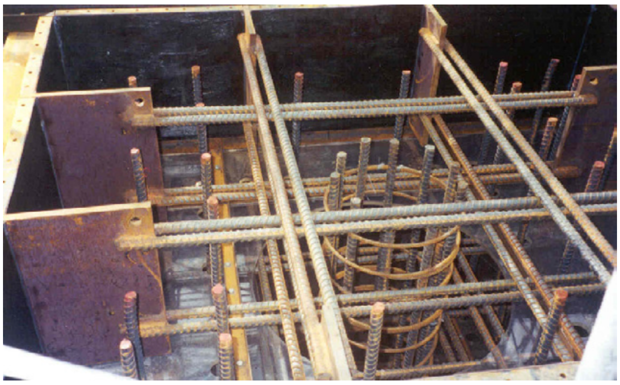

Fig. 8. Concrete fill is reinforced by vertical bars threaded through diaphragm holes and a spiral-wrapped core threaded through the central manhole.

Inherent structural damping is supplemented by a massive Tuned Mass Damper (TMD) that uses building motion to push and pull dashpots, or giant shock absorber, to convert motion to heat by forcing fluid through small internal openings. Dashpots are most efficient working through large motions, but within a building frame relative motions are small. In a TMD, dynamics sidesteps that limitation. A movable block of steel or concrete (the mass) located near roof level is a small fraction of the total building mass. It is arranged (tuned) to sway freely at about the same period or sway rate as the building. When the building sways, the mass will tend to sway in the opposite direction and at a larger amplitude. Any dashpot (damper) bolted between building frame and the TMD mass will experience large motions, as desired.

In the case of Taipei 101, the primary TMD uses a

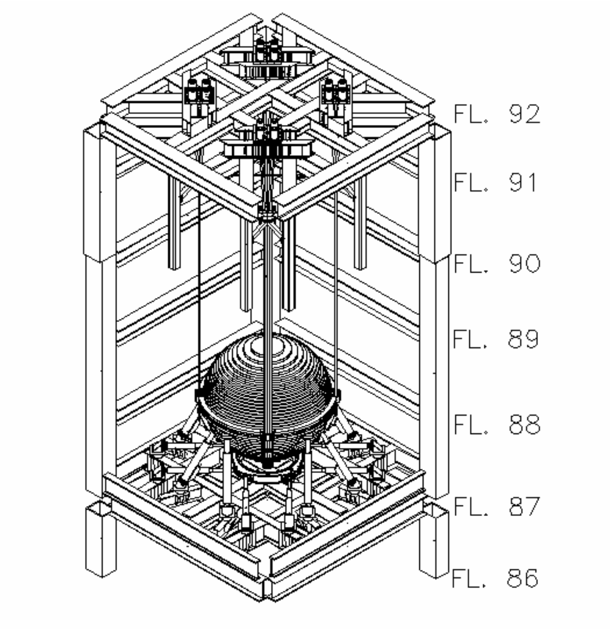

Fig. 9. The pendulum of the main Tuned Mass Damper, a sphere made of stacked steel plates, swings within the top floors of the highest typical building module.

660 Mg (726 tons) mass built up from stacked steel plates to form a sphere visible to building visitors. The mass, equal to 0.24 percent of the total building mass, is located with its equator 1 m (3.3 ft) above level 88. See Fig.9. The swing rate is set by simple pendulum action as it hangs from the 92nd floor. Engineers will fine tune the swing to match the measured behavior of the completed building by adjusting vertical locations of blocks that restrain the suspension cables, much as a guitarist changes string pitch by pressing a string against a particular fret.

The damping effect of the sealed dashpots varies with the square of the velocity of the mass. This means that regular, slow wind-induced sway creates a relatively small resistance force that provides damping while permitting the mass to swing. But in the event of a sudden jolt, as from an earthquake, dashpot resistance will rise dramatically and create a "lock down" effect that limits the motion of the mass. The building is also equipped with other bumper systems for added safety during extreme seismic events.

Occupant comfort was also a key design criterion for the high-speed express elevators serving an observation deck on the 89th level. The elevators rise at 1,000 m per minute (3280 fpm), a new speed record for vertical building transportation. Human ears are capable of adjusting to a decrease in air pressure at this speed, but a descent at this rate could have caused some discomfort, so the rate of the return elevator was decreased to 540 m per minute (1771 fpm).

Office floors are served by double-decked elevators to minimize the space devoted to elevator shafts. The story heights of Taipei 101 are a uniform 4.2 m (13.8 ft) tall to suit the double cabs. The retail floors below, which are served by separate elevators, are 6.3 m (20.7 ft) tall.

9. Seismic Design Issues

While wind is an ever-present environmental condition, Taiwan's geology also mandated that earthquake resistance must be considered. A structural system stiff enough to limit wind drift does not automatically have the overload behavior desired for seismic ductility. But frames specifically designed for seismic ductility can be too flexible for wind conditions. The solution here was to design for stiffness and then check for seismic ductility and seismic strength. For example, where braces are 'opened' (work points do not coincide), in a seismic-controlled design they might be treated as ductile Eccentric Braced Frames with beam sections selected to meet specific proportions that force web shear to control over beam flexure. But such members would introduce undesirable flexibility for wind conditions. Instead, the open 'link' portion of the beam is strengthened by side plates to maintain stiffness and ensure the link is not controlling strength across the eccentric links. At the same time, where flexure was inherent in the design and large rotations were anticipated during seismic events, such as the deep beams crossing core corridors to link braced bays, ductility was provided by a Reduced Beam Section or 'dogbone' detail using proportions developed at the local university. In addition, a dual system was applied: steel moment frames along each sloping face of the building work in parallel with the braced core and outriggers. See Figs. 10, 11. In addition, full moment connections between braced core beams and columns provide an alternative load path in the event of brace member overload.

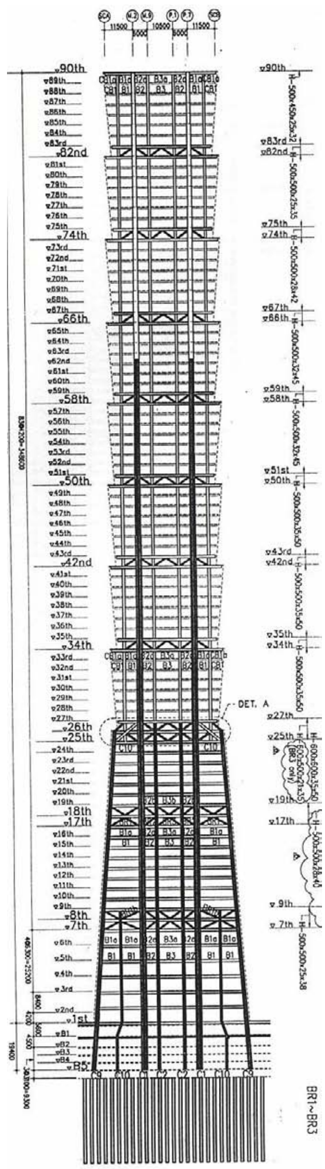

Fig. 10. Elevation of a perimeter moment frame line with belt trusses. Shading indicates extent of concrete fill in supercolumns.

10. Pinnacle Fatigue

The pinnacle posed another set of engineering challenges. Both its uniform cylindrical shape and its building-top location render the pinnacle susceptible to crosswind excitation. Three mode shapes were identified as potentially creating significant stress ranges during storms, with many more cycles at lower

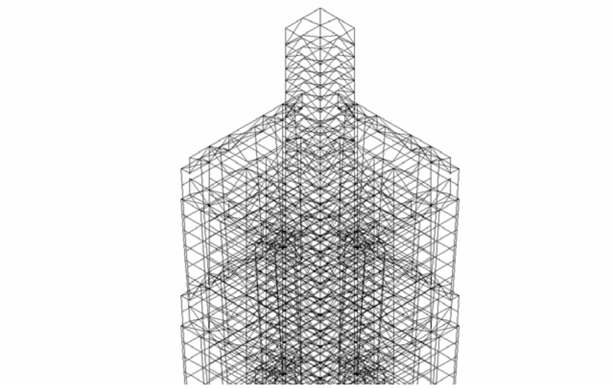

Fig. 11. The 3-D computer model for Taipei 101 shows core bracing, perimeter moment frames and vertical and horizontal trussing at module setbacks every 8th floor.

stresses accumulating at low wind speeds. These conditions made fatigue life an important design consideration for the steel-trussed pinnacle spine.

Fatigue was controlled by two methods. First, dynamic response was reduced by providing local supplementary damping. In addition to the building's primary TMD, Motioneering, of Guelph, Ontario, designed two ingenious compact TMDs to be placed within the uppermost 8 m of the pinnacle. Each has a 4.5 Mg (5 ton) steel mass that can slide on rollers horizontally along two axes, like a bridge crane traversing the width and length of a factory bay. The TMDs are "tuned" with vertical precompressed spring sets tied to the masses through flexible cables and pulleys. Two TMDs are needed due to the multiple oscillation modes that can excite the pinnacle.

The second strategy for fatigue life was determining the most fatigue-sensitive locations and reducing their cyclic stress ranges. Thousands of high-stress cycles and many more lower-stress cycles were processed using Goodman's Simplification to treat variable stress cycles as uniform cycles, and combined using the Modified Miners Rule, a form of weighted average, to establish an equivalent 2 million cycle uniform stress range for further study. Welded splices of the vertical pinnacle trusswork chords were identified as highly stressed by overturning moments, and sensitive to fatigue at one-sided penetration welds. To reduce the stress ranges, steel plate 'ears' on the chords that were originally intended to receive only temporary erection bolts were redesigned to receive permanent connections with plates connected by slip-critical high-strength bolts. By sharing the chord force, these plates reduce stresses in the welded splices and reduce their cyclic stress ranges.

11. Longspan Mall Trusses

Perhaps the most public design feature of Taipei 101 is the unique support system for a longspan skylight in the retail area. It features two parallel trusses with 80 m (262 ft) long top chords made of 600 mm (2 ft) diameter steel pipes curved like a "Yu Ye," a popular local design motif. When linked by vertical T ribs every 4.2 m (13.8 ft) to bottom chords made of 750 mm (2.5 ft) diameter tubes, the result is a cross between a Vierendeel truss and a tied arch. The complex intersections between varying T members as tall as 10 m and curved top chords were detailed using a 3-dimensional modeling program. The trusses were shop-fabricated in thirds and assembled on location. See Fig.12.

Fig. 12. Twin Vierendeel trusses span the shopping mall atrium within the building podium.

12. Conclusion

Taipei 101 provides a distinctive new shape on the city skyline and what is sure to become an internationally-recognized icon for Taiwan. But what the public does not see is equally as dramatic: an unusually stiff and strong frame that required 107,000 Mg (118,000 tons) of steel members and connections, high-strength concrete fill in key columns, and a complex deep foundation system. Tuned mass dampers, one very large and two very small, provide occupant comfort and extend pinnacle fatigue life. Even the building's retail mall has unique structural features. Beyond the height of what will soon be the tallest building in the world, the solutions to structural challenges make Taipei 101 a very special building.

Acknowledgements

We wish to thank Architects Tom Chi and C.P. Wang of C. Y. Lee & Partners for involving us in this unique and challenging project, and Turner Construction - International LLC for working with us to develop practical details and approaches to constructing the unusual building features. We also wish to acknowledge the efforts of Dr. Ling-en Hsiao and Dr. Young Cho on the project in our offices. So many engineers worked on Taipei 101 in Taiwan and in the US it is impractical to list them, but we wish to thank them all. Great projects like Taipei 101 come from great teams, and the engineers at Evergreen and Thornton-Tomasetti were essential to its success.