Ingredients of High-Rise Design

Taipei 101

the World's Tallest Building

By Leonard M. Joseph, Dennis Poon and Shaw-song Shieh

Taipei 101 and the Thornton-Tomasetti Group, Inc. were presented an Outstanding Project Award (New Buildings over $30 Million) in the NCSEA 2005 Excellence in Structural Engineering awards program.

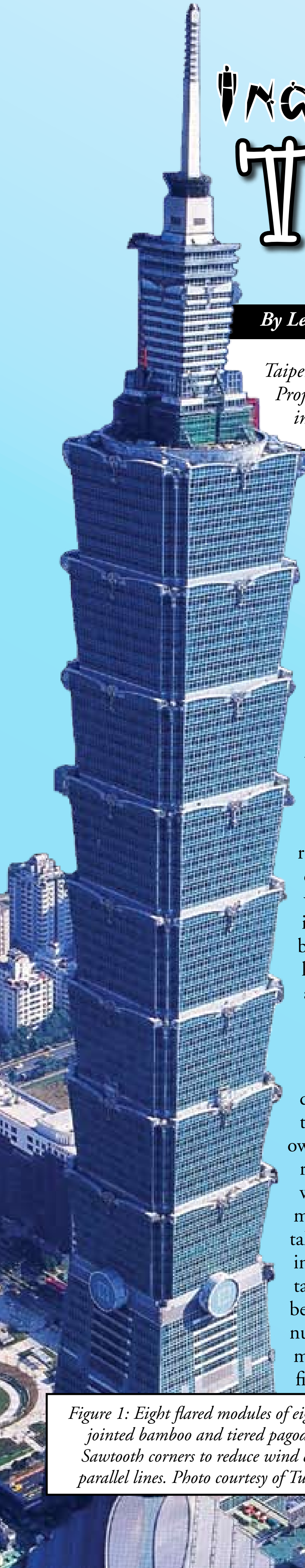

Figure 1: Eight flared modules of eight stories each evoke jointed bamboo and tiered pagodas on Taipei 101. Sawtooth corners to reduce wind effects are visible as parallel lines. Photo courtesy of Turner International.

Recipe for a structural challenge: take one basic office tower, 'super size' to world's-tallest proportions, carve into a unique shape, fan (in typhoons) and shake well (in earthquakes)… Serves thousands (of tenants and visitors)... This is Taipei 101 in Taiwan, Republic of China. With a height of 1667 feet (508 m) in 101 stories, it is currently the world's tallest building. It also features difficult foundation conditions, unusual building shapes, demanding lateral stiffness requirements, mixed structural materials, wind/building interaction, occupant comfort criteria, seismic demands, special ductility details and fatigue life concerns – a veritable smorgasbord of the design issues that apply to many high rise buildings today. A review of the challenges and solutions has relevance to all designers.

Architectural Shaping

The first design issues were the ones driving most commercial construction: money and prestige. Initially, owner Taipei Financial Center Corporation planned that the full-block site would contain several towers of more modest height, providing the same total office space for less cost. But all the investor-occupants wanted space in the tallest one. A single tall tower was the best way to please everyone, and the number of floors resulted from simple math: dividing the area of a typical office floor plate into 2.1 million square feet of projected office space demand. Another 2.1 million square feet accommodates a retail podium and five levels of basement parking.

The unusual tower shape had its own logic. Architect C.Y. Lee of C.Y. Lee & Partners, Taipei, Taiwan drew on local culture, including the regularly-spaced joints in tall, slender indigenous bamboo, the tiers of pagodas and the popularity of 'lucky' number 8, a homonym for 'wealth' in Chinese. Thus the upper portion of Taipei 101 has eight modules, each with eight stories. Each module flares wider at its top, like an opening flower, before the narrow base of the next module starts, forming a setback. The set of modules bears on a truncated pyramidal base, square in plan, creating a narrow 'waist' at Level 26. Above the modules the design is completed by a spire, rising from the Level 91 outdoor observation/roof deck and supported on a base of smaller floors flared to echo the sloped walls below.

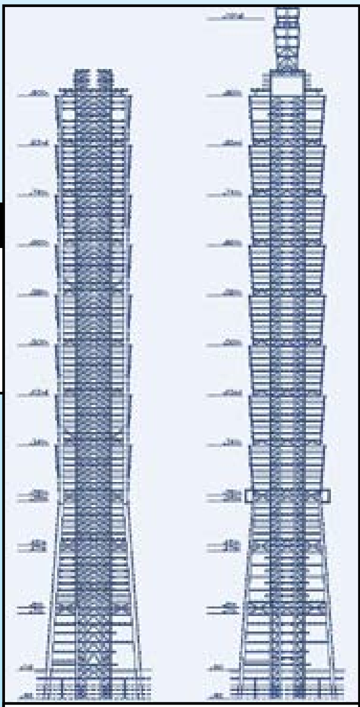

Figure 2: Elevations along interior gridlines show the braced core and eleven sets of outrigger trusses one, two and three stories tall.

The resulting unique profile is instantly recognizable as an icon of modern Taiwan (*Figure 1*). It also has structural implications. For adequate lateral stiffness and strength, a building this tall and narrow cannot rely on a central core alone. This core is relatively compact thanks to extensive use of double-decked elevators. The tallest buildings since the 1960's have gained structural efficiency by placing the lateral load resisting system at the building perimeter – the giant X braces of Chicago's John Hancock Tower and 'diamonds' of Bank of China, the perimeter tubes of the World Trade Center twin towers and bundled tubes of Sears Tower do all the work. Even the 'soft tube' of widely spaced perimeter columns and ring beams resists half the overturning of Petronas Towers. But a perimeter framed tube that followed the sloping façades of Taipei 101 would require transfers at the frequent

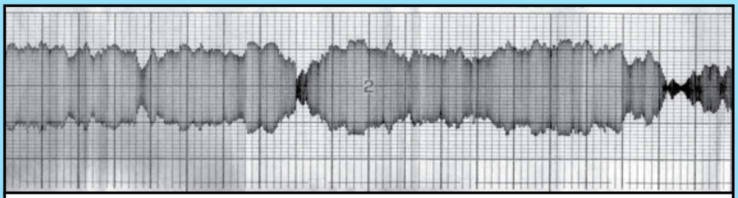

Figure 3a: This tracing from the wind tunnel test with a sharp-cornered tower with 1% damping shows large crosswind overturning moments.

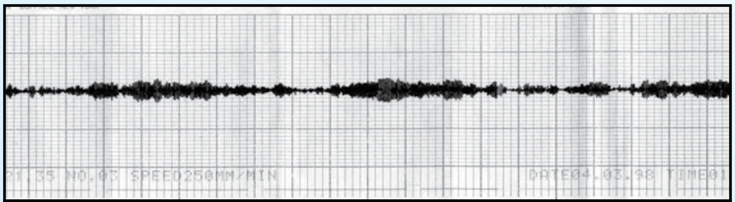

Figure 3b: Replacing right-angle corners with double-stairstep notched corners dramatically reduces wind overturning moments.

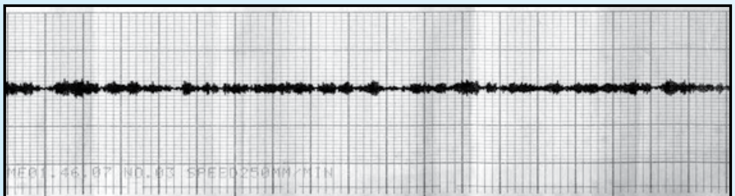

Figure 3c: Increasing building damping from 1 to 2.5% on the notched corner model slightly reduces wind forces.

setbacks. Deflections of those transfers would make the system too flexible to be practical. Transfers could certainly be avoided by carrying the closely spaced columns straight down, but that would mean the columns would either protrude outside the façade planes at narrower floors, or interfere with interior space planning at wider floors. Neither option was acceptable. However, a few columns on each face could be vertical, as long as usage along the rest of the perimeter was not impeded. These were used as outrigger columns in a core-and-outrigger scheme: a square core has four lines of steel diagonal and chevron bracing each way linking 16 core columns. At selected floors the bracing lines are extended out to engage the outrigger columns. Outrigger systems become more efficient and effective with more outrigger levels, and stiffer outrigger trusses. The refuge/mechanical floor on each of the eight modules, and other mechanical rooms, provided ideal opportunities for numerous well-spaced outriggers (*Figure 2*).

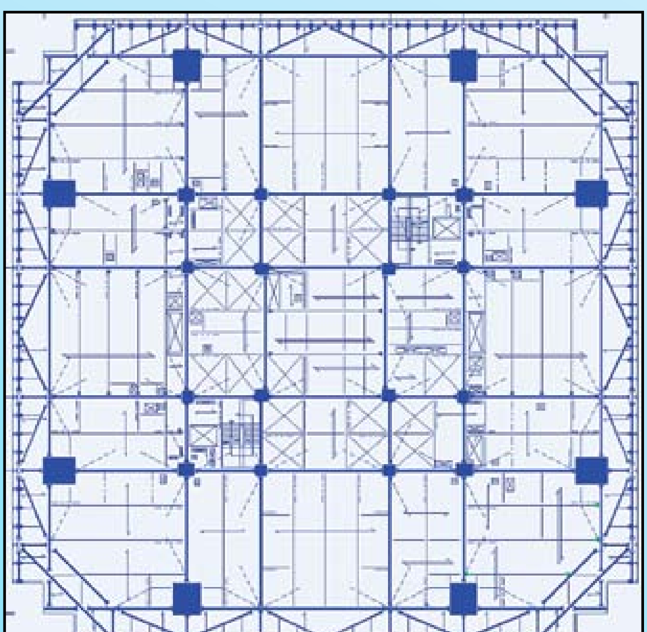

Figure 4: At each setback a criss-cross grid of outrigger trusses links sixteen core box columns to the major outrigger columns on each building face. Underfloor trusses horizontally transfer perimeter moment frame shear.

Of course, design must consider both load application and load resistance. In typhoon regions, minimizing wind force is an economic imperative. Wind tunnel testing at RWDI in Guelph, Ontario, Canada revealed that, based on building plan dimensions and anticipated wind speeds (3 second gusts of 150 miles per hour at an elevation of 10 meters in a 100-year-storm) vortex generation at building corners could occur at a rate matching the tower sway rate or period, causing very large crosswind oscillations. Different corner shapes can disrupt vortex formation, so rounded, chamfered (45°) and stepped or notched corners were tested. Curves and chamfers helped somewhat, but 'saw-tooth' or 'double stairstep' notched corners brought a dramatic reduction in crosswind excitation (*Figures 3a, b, and c*). After witnessing the tests, the architect incorporated double steps 8.1 feet (2.5 m) deep at the corners of all eight typical building modules (*Figure 4*).

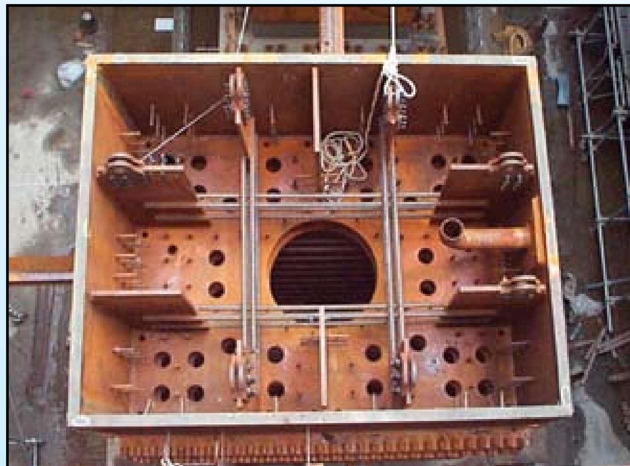

Figure 5: This steel plate box column shows internal shear studs, holes in diaphragm plates for access and vertical rebar, stiffeners, crossties and a 'bottom up' concrete fill pipe at right. Projecting plates at bottom engage a basement concrete slab.

Stiffness and Comfort

Even after reduction, the wind forces are still very large and deflections are a concern. The building frame was to be of structural steel, for three good reasons: to minimize cost of tower foundations by keeping building weight low, to minimize seismic forces by keeping building mass low, and to benefit from a strong, skilled and competitive local steel construction industry. However, a steel structural frame sized just for strength would be too flexible to control interstory drift and overall building sway to avoid damage to nonstructural elements, or to maintain occupant comfort during frequent storms. To limit building sway and interstory drift to height/200 in a 50-year-storm, additional stiffness would be needed. Adding stiffness by adding steel would be expensive. Instead, stiffness is provided by high-strength concrete. Main building columns up to Level 90 – sixteen in the core and two (at upper floors) to four on each face at outrigger lines – are built-up boxes of steel plate 2- to 3⅛-inch thick. The boxes were filled with 10,000 psi concrete up to Level 62 in two-story lifts, using a bottom-up

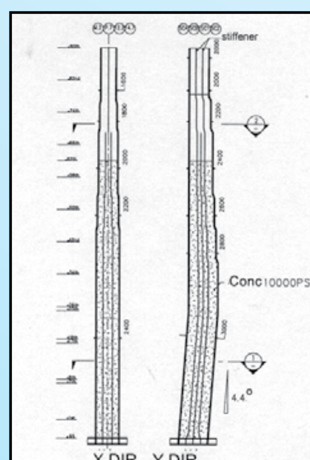

Figure 6: The main outrigger columns slope along the pyramidal base, run vertical and change size at upper floors and are filled with high-strength concrete up to Level 62.

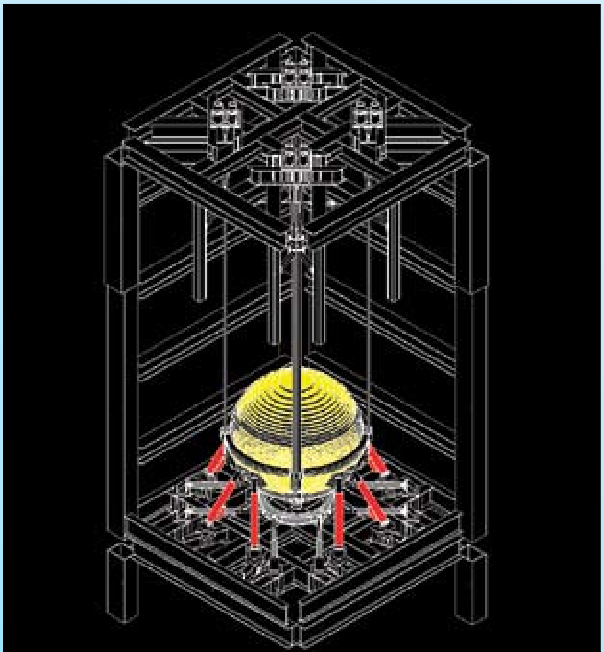

Figure 7: The Tuned Mass Damper is a four-story-tall pendulum with a spherical mass of stacked steel plates surrounded by large dampers or 'shock absorbers'.

technique to minimize trapped air pockets under internal diaphragms (*Figures 5 and 6*). The result was indeed stiff: building period is less than 7 seconds, compared to the 9 seconds one might expect for a tower of this height and slenderness.

While the stiffness target was met, occupant comfort was still an issue. Steel framing has low inherent damping, estimated at 1% of critical damping for moderate windstorms, so cyclic wind excitation can build up over time. This could result in accelerations at upper floors reaching uncomfortable levels. The solution? Add more damping to the building. A Tuned Mass Damper (TMD) occupies Levels 87-91 as the centerpiece of a public lounge. Designed by Motioneering of Guelph, Ontario, Canada, it is a 726 ton sphere of stacked steel plates, suspended from four pairs of steel cables to creates a pendulum equivalent to 0.26 percent of building weight. Adjusting the free cable length tunes the sway rate to match the tower. The mass pushes and pulls large dampers as it swings in opposition to the tower (*Figure 7*). The dampers reduce building sway by converting a portion of the wind motion into heat. This is the largest building TMD installation to date. With the additional damping provided by the TMD, occupant comfort criteria at the upper tower floors are met.

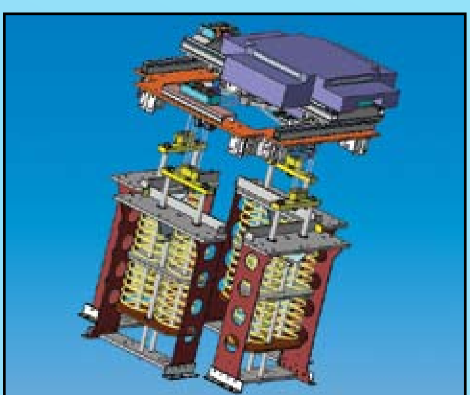

Figure 8: Each of the Tuned Mass Dampers in the spire has a 5 ton steel mass sliding on two-way roller tables and restrained by springs through cables and pulleys.

Fatigue

Other TMD's addressed a smaller structural challenge: metal fatigue. Like the main tower, the slender rooftop spire is a sharp-cornered square in plan, so it is also subject to cross-wind excitation from vortex shedding. However, the small spire width means vortex shedding starts at relatively low, frequently-occurring wind speeds. Millions of cycles of wind sway could occur over the years. In addition, different vibration modes are excited as wind speed varies. The spire has a trussed steel 'spine,' and steel is subject to metal fatigue, gradual crack growth under cyclic axial stresses. Welded connections are particularly susceptible. Vertical chord members of the spine are axially stressed by spire bending. Fatigue life is improved by modifying details to reduce stresses at welded joints in the chord members, and modifying spire behavior to reduce the crosswind forces that generate cyclic stresses. Two compact TMDs were installed to reduce sway, each tuned to one critical vibration mode for the spire. Each TMD has a 5 ton mass sliding horizontally on two sets of orthogonal rollers, like skateboards stacked at right angles. Instead of gravity pulling on a pendulum, the mass returns to its central position by spring sets, cables and pulleys. Dampers link the mass and the building frame (*Figure 8*).

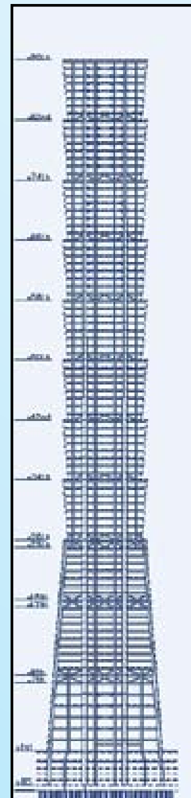

Figure 9: Sloping perimeter moment frames on each face have belt trusses at each setback to deliver gravity load to main outrigger columns.

Seismicity and Soils

Seismic conditions impose a different set of design requirements. By code, a building of this height requires a dual system for lateral loads, so each face includes a perimeter moment frame of comparatively light beams and columns, sloped to follow the glass line. Gravity load in these frames transfers to main outrigger columns by belt trusses at the bottom of each module (*Figure 9*). Outrigger columns sized for stiffness have ample capacity to carry this gravity load, and it helps offset wind uplift forces on the columns. Beams in the braced core and floor are also moment connected to enhance redundancy and provide alternate load paths. Looking at member deformations under seismic load identified 'hot

Figure 10: Yellow dots show locations of Reduced Beam Section 'dogbone' details for enhanced ductility at points of greatest flexural rotation demand.

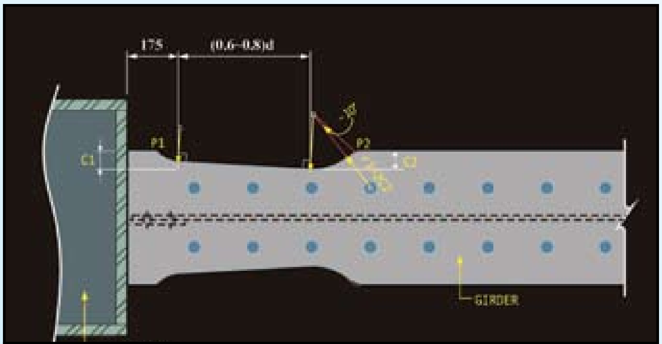

Figure 11: Reduced beam sections were provided by a precise combination of cuts.

spots' where curvature demand was greatest (*Figures 10a and 10b*). In those locations, using reduced beam section or 'dogbone' flange trim details forces yielding to occur within the beam and away from the welded beam-column joint, improving ductility. Reduced section geometry followed the approach of the National Science Council in Taiwan (*Figures 11 and 12*).

Discussion of seismicity brings us back down to the ground, where construction must begin. Geotechnology, Inc. of Taipei determined that drilled, cast-in-place concrete piers were needed to bypass clay and soil 130 to 200 ft deep and deliver load to soft rock by long sockets. Two types of piers are used; 380 piers 5-foot diameter support a tower mat 10 to 15 feet thick. The surrounding podium, in contrast, has one 6.5-foot diameter pier under each column. Socketing the pier 16 to 92 feet into bedrock resists net uplift from a 70-foot deep basement with the water table only 6 feet below grade. Construction manager Turner Construction International and contractor KTRT Joint Venture used the single pier per column to permit 'top down' excavation under the podium: as each pier was installed from grade, the basement portion of the steel column was embedded within. Then steel erection proceeded upward while excavation proceeded downward. Building each basement floor as that depth was reached provided lateral bracing for basement walls and podium columns. This approach permitted the podium retail mall to open well ahead of the office tower. Two rings of basement walls were needed. One surrounded the site, while the other enclosed just the tower footprint to permit tower mat construction by conventional means. Construction schedule benefits were worth the expense of added basement wall costs.

Wind and earthquakes, shaping and shaking, digging and damping: all are 'ingredients' of high rise building design in the 21st Century. The Taipei 101 tower puts them all together in one unique, beautiful, super-sized package.▪

Figure 12: Tapered flange trimming at selected link beams creates a 'dogbone' condition to improve ductility by locating beam yield zones away from welded joints.

Project Team

Owner:
Taipei Financial Center Corporation
Taipei, Taiwan

Architect:
C. Y. Lee & Partners
Taipei, Taiwan

Engineer of Record:
Evergreen Consulting Engineering
Taipei, Taiwan

Engineering Consultant:
Thornton Tomasetti
New York, New York, USA

Wind Consultant:
Rowan Williams Davies and Irwin Guelph
Ontario, Canada

Damping Consultant:
Motioneering
Guelph, Ontario, Canada

Geotechnical Engineer:
Geotechnology, Inc.
Taipei, Taiwan

Construction Manager:
Turner Construction International LLC
Taipei, Taiwan

Contractor:
KTRT Joint Venture

Leonard M. Joseph, P.E., S.E., a Principal in the Irvine, California office of Thornton Tomasetti, has designed high rise, long span and other building types across the U.S. and in Asia and Australia, including Malaysia's Petronas Towers.

Dennis Poon, P.E., a Managing Principal in the New York City office of Thornton Tomasetti, has developed the structural designs for numerous complex large-scale building projects in the U.S. and Asia, including Plaza 66 in Shanghai. He led Thornton Tomasetti's participation in the Taipei 101 design process.

Shaw-song Shieh, P.E., S.E., led the Structural Engineer of Record design team for Taipei 101 as President of Evergreen Consulting Engineering in Taipei, Taiwan, Republic of China.