the Sky's the Limit

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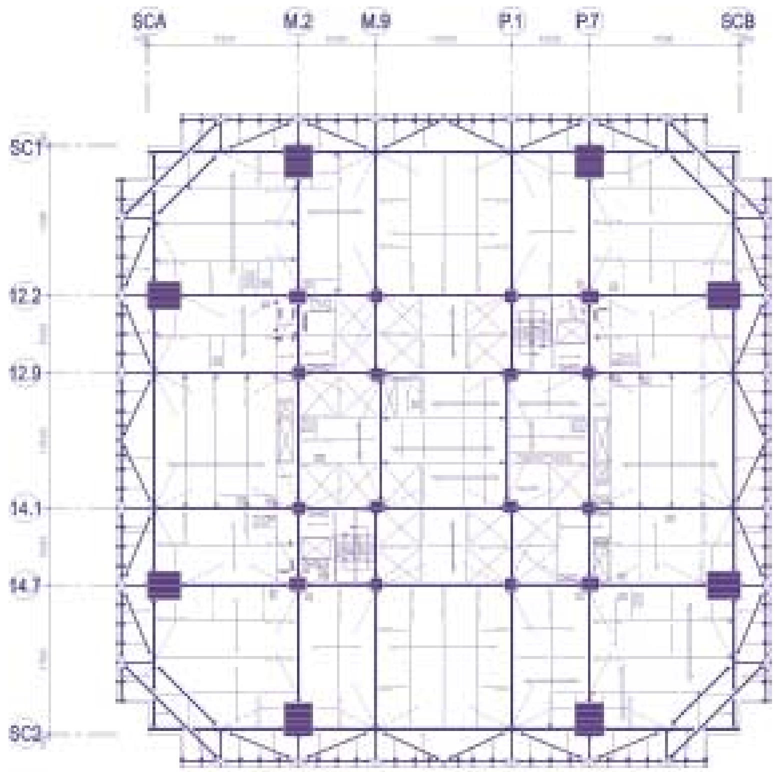
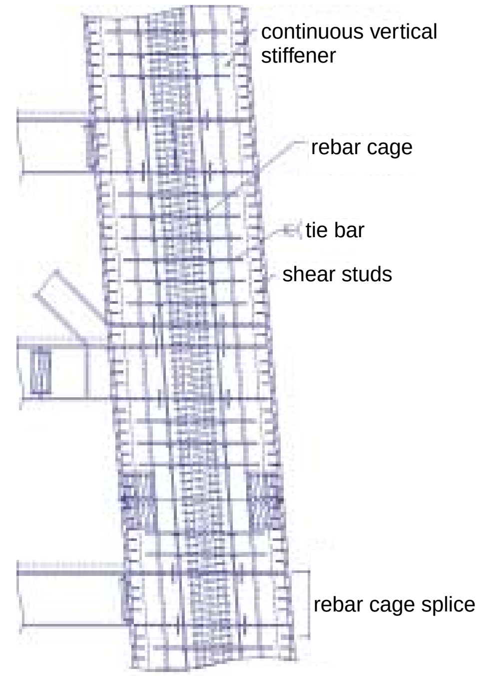
Steel goes sky-high to meet the seismic challenge of Taipei 101, which will top out at 1666' in 2003.



Framing plan for level 50. Shear forces in perimeter frames traverse setbacks with in-floor bracing. Eight super-columns are filled with concrete to the 26th floor to add stiffness.



Section showing concrete-filled portion of a super-column.

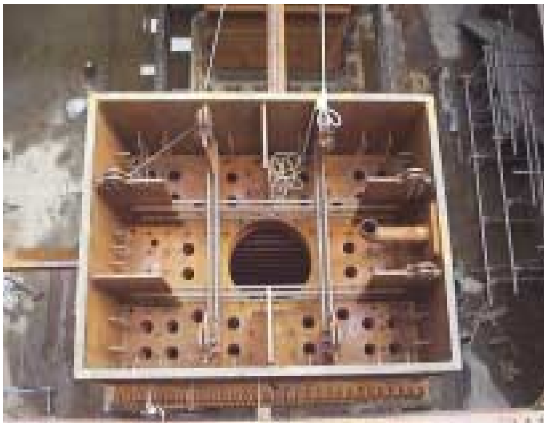
Designing the world's tallest building is a challenge for any location, but some sites are more challenging than others. The 101-story Taipei 101 building is currently under construction in Taipei, Taiwan. In 2003 it will top out at 508 m (1666 ft) above grade, a new world record for buildings. Taipei 101 must address typhoon winds, large potential earthquakes and weak soil conditions. This article will focus on seismic challenges in Taipei 101's design and construction, and the use of structural steel as a solution.

The framing design had to solve five challenges. First was the unusual building shape. The lowest 25 floors taper gradually inward, forming a truncated pyramid. Above is a stack of eight, 8-story high modules with outward-sloping walls, creating a 'waist' at the 26th floor and setbacks at floors 34, 42, etc. The modules also have double-notched corners that minimize wind vortex shedding effects. A narrower tower segment and an architectural pinnacle top the eighth module. The overall effect is of a flower opening to the sky. Façade slopes and setbacks would interrupt columns following the building face, and doubly-notched floor plans would reduce the efficiency of an exterior moment frame trying to 'turn the corner.' Therefore a perimeter tubular-frame system was not suitable for this project.

Second was the need for great lateral stiffness, to limit sway in high winds and earthquakes and reduce the potential for damage to non-structural elements. Third was minimizing overall building mass, to reduce the cost of the deep bored-pile foundation and to keep seismic forces as low as practical. Fourth was net column uplift in this tall, slender and comparatively lightweight structure. The fifth challenge was to provide a high level of safety in the enormous building for the large tenant population and public attention it would attract.

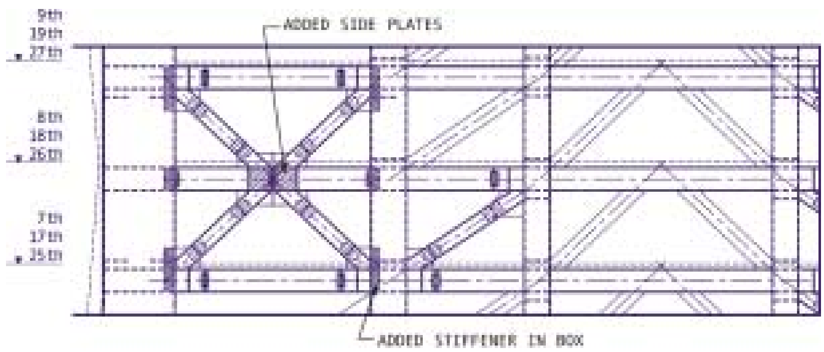
STEEL SOLUTION

The structural solution selected for Taipei 101 meets all of the above challenges. Structural steel framing provides great strength with minimal



View of super-column shell. At the base, the super-columns are 2.4 m by 3.0 m (approximately 8' by 10').

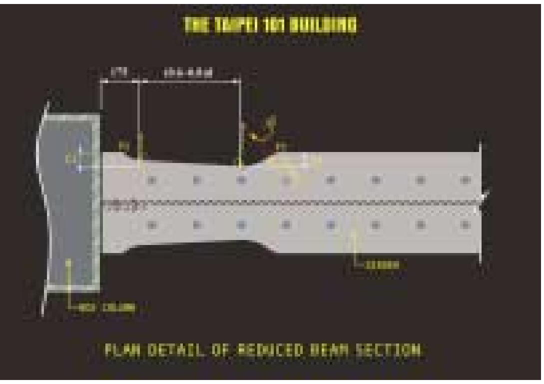
mass. A braced core offers high-shear stiffness with chevron and diagonal braces of I-shaped sections in four planes each way. Overturning stiffness is enhanced by outriggers in two directions. A mix of single-, double- and triple-story outriggers are distributed every eight to ten floors along the building height. On each building face



Elevation of typical braced frame.

they engage two vertical super-columns located to clear façade set-backs. Below the 26th floor, additional outriggers engage two more columns on each face, and belt trusses engage corner columns as well. Steel box-core columns and super-columns are filled with concrete to the 62nd floor, and the other engaged columns are filled to the 26th floor to add stiffness. Wind and seismic-uplift effects are mostly offset by concrete-fill weight and by belt trusses redirecting perimeter dead load to these columns. The small remaining net uplift that can occur in wind and seismic conditions is resisted by full-penetration welded-column splices. For seismic safety, a dual system uses the braced core and outrigger system already mentioned. A perimeter moment frame follows each sloping building face, and core beams are designed and detailed to function as moment frame members.

Highly articulated façade planes, core bracing, outriggers, super columns, and perimeter frames complicated the flow of forces among these disparate elements under gravity and lateral loads. To size members and details for appropriate load distributions and ductilities, Structural Engineer of Record Evergreen performed multiple analyses using SAP90 and DRAIN-2D+. As structural consultant developing framing concepts with Evergreen, Thornton-Tomasetti's parallel analyses used SAP90 and ETABS. Both sets of studies showed local force concentrations related to the large flexural stiffnesses of the super columns. They willingly lean to follow overall building drift, but inter-story drift is less at outrigger floors. This creates local bending and large column shears. It also generates large axial forces in connecting members. The bracing members, column steel and concrete fill were designed to handle these large local forces.



Above and below: At locations where plastic rotation would exceed 0.005 radian in a 950-year return period earthquake, reduced beam sections ("dogbone" cuts) increase moment connection rotational capabilities.

CORE DESIGN AND FRAMING

The core was designed as a concentric braced frame (CBF). To clear architecturally required openings, some work points for adjacent braces were spread apart, creating eccentric links. But the system is not an eccentric braced frame (EBF). A true EBF limits the properties and proportions of link members to ensure link-shear yielding for system ductility. For very tall buildings like Taipei 101, overall building stiffness is crucial to control wind and seismic drifts. Such links could make the framing too "soft." Instead, link regions were strengthened with web doubler plates, and box-out or cover plates across the tips of member flanges, so that CBF braces, not links, control system strength. Brace strength and favorable post-buckling behavior is provided by limiting slenderness per building code and design guidelines.

In a major earthquake with forces large enough to load braces well past elastic limits, the more flexible, but highly ductile, moment frames will act. Moment frames along each face and through the core provide the code-required 25 percent of overall seismic resistance. Shear forces in perimeter frames traverse setbacks with in-floor bracing. Since turning the corner was not necessary, these frames use straightforward "strong way" moment connections. Analysis showed moment frame locations where local conditions concentrated rotational demands. At locations where plastic rotation would exceed 0.005 radian in a 950-year return period earthquake, reduced beam sections ("dogbone" cuts) increase moment connection rotational capabilities. RBS details follow the tapers developed by the National Science Council, Taiwan, Republic of China. For further strength, beam-to-column connections within the braced core system are detailed as moment connections as well. The resulting details are somewhat more elaborate than for axial-only connections, but because the large brace forces require major connections in any case, the additional construction effort was considered reasonable. To minimize the steel member sizes used, high strength steel with 60 ksi yield strength was specified, even for steel plate thicknesses up to 80 mm (3.15 inches). Ductility in the steel plates and framing members was ensured by specifying the yield ratio, through-thickness characteristics and weldability of this material.

The Taipei 101 building is a distinctive addition to the city's skyline and the exclusive group of the world's tallest buildings. As befits those distinctions, its structural design has addressed the demands of architectural form, typhoon winds and seismic safety through creative steel framing.

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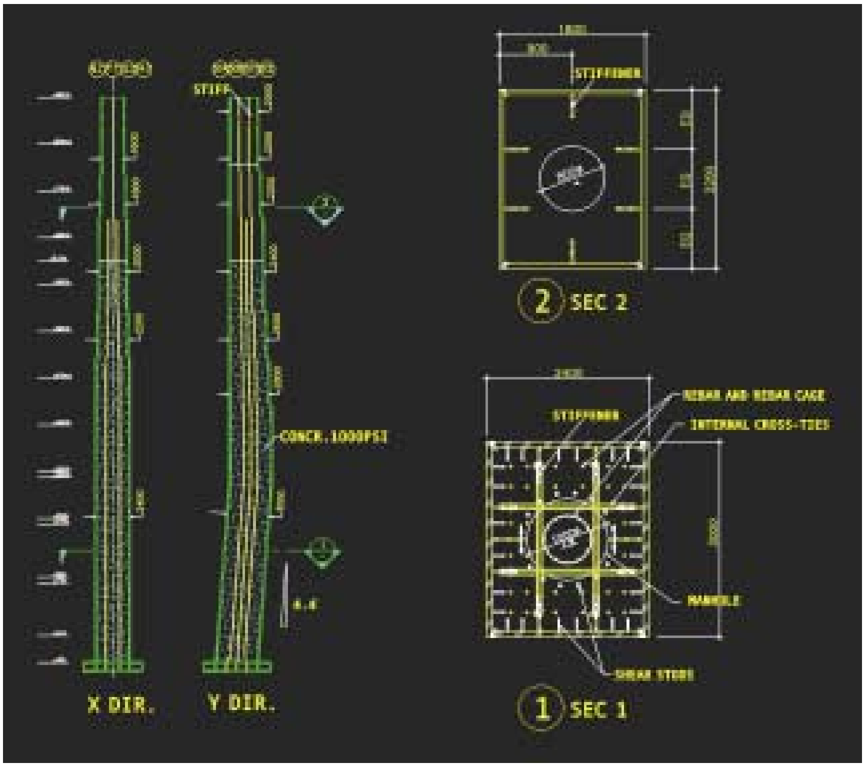

Section through the super-columns. Section 1 shows the detail at the concrete-filled portion of the columns. Section 2 shows the detail at the unfilled portion of the columns.

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