TAIPEI 101 IS AN ICONIC EARTHQUAKE WITHSTANDING HUMAN MARVEL

Formerly known as the Taipei Financial Center, Taipei 101 is an office building in Taipei, Taiwan, standing 508 m tall. When it was completed in 2004, it dethroned the Petronas Twin Towers in Kuala Lumpur Malaysia, 452 m as the tallest building in the world.

Designed by C.Y. Lee & Partners, a local architectural firm and structural consultants from Thornton-Tomasetti Engineers, New York City and Evergreen Consulting Engineers; Taipei 101 is an iconic structure, engineered to withstand strong earthquake tremors as well as powerful typhoons that wreak havoc in Taiwan. It is designed to be resilient against gale winds of 134 mph and the strongest earthquake with an estimated return period of 2,500 years. This performance is mainly attributed to the 660 tonne steel pendulum that serves as a tuned mass damper.

Construction of Taipei 101 began in 1999. The structure was topped out in 2003, and work was completed in 2004. The largest section of the building, between the base and the spire, consists of eight blocks or groupings of eight stories. The building also has a distinctively Chinese character in its resemblance to a stalk of bamboo or an elongated pagoda.

In comparison to a straight shaft, the ninth module, which is the top of the main shaft and supports an architectural spire, has a 25-story base fashioned like a truncated pyramid, which increases lateral stiffness and overturning resistance. Medallions modelled by ancient Chinese coins illustrate the change from the lower pyramid to the upper modules. There are also exterior curtain panels slope 5 & 7 degrees, resembling a shoot of bamboo, and tying back to the mega-columns. The facade is able to withstand an impact of up to 7 tonnes and the Saw-toothed corners greatly reduce crosswind oscillation.

> **"It is designed to be resilient against gale winds of 134 mph and the strongest earthquake with an estimated return period of 2500 years."**

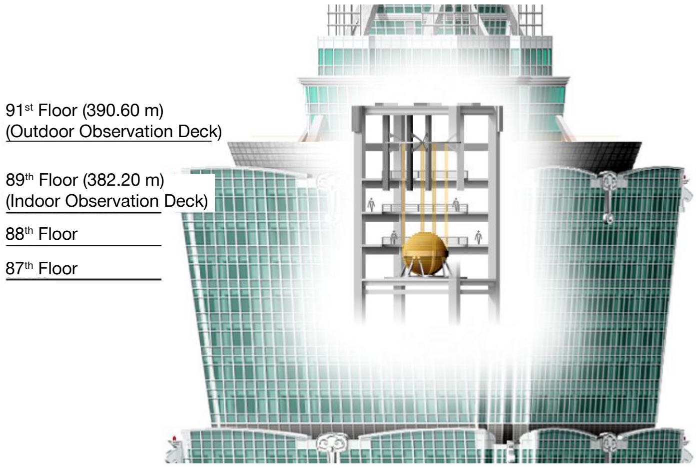
The structural system is core plus outrigger, with 16 steel columns in the core and 8 steel "supercolumns" at the perimeter. All columns are filled with concrete up to floor 62. Massive steel outrigger trusses link the core and perimeter columns every eighth floor. The building's most noteworthy structural element is the tuned mass damper, which can be viewed from the indoor public observatory. Suspended between the 92nd and 87th floors at the building's centre, under conditions of seismic stress, the sway of the damper tends to counteract any sway of the building, thereby rendering stability and eliminating any vibration that can jeopardize the stay. This negates up to 40% oscillation.

Called the "wind damper" or "tuned mass damper", a massive golden ball is suspended beneath the observatory deck of Taipei 101. The wind damper is made up of three major components: an oscillating mass (for inertial force), a spring (for elastic restoring force), and a visco-damper (for energy dissipation). At such a height, the Taipei 101 is a massive skyscraper, and is therefore susceptible to oscillation caused by earthquakes or strong winds. If the shaking is too violent, office workers and tourists inside the building may experience dizziness and discomfort. According to Evergreen Consulting Engineering which supervised the structural design of Taipei 101, when oscillation caused by wind exceeds 5cm/sec^2, people within the skyscraper will experience discomfort.

However, due to its great height, the vibration experienced by the higher office levels is already 6.2 cm/sec^2 in normal weather. The figure shoots up to 7.4cm/sec^2 when there's a typhoon. Both numbers are greater than the recommended 5cm/sec^2. Therefore, Taipei 101 needs a wind damper to reduce the vibration caused by high winds.

While wind is an ever-present environmental condition, Taiwan's geology also directs 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. In addition, full moment connections between braced core beams and columns provide an alternative load path in the event of brace member overload.



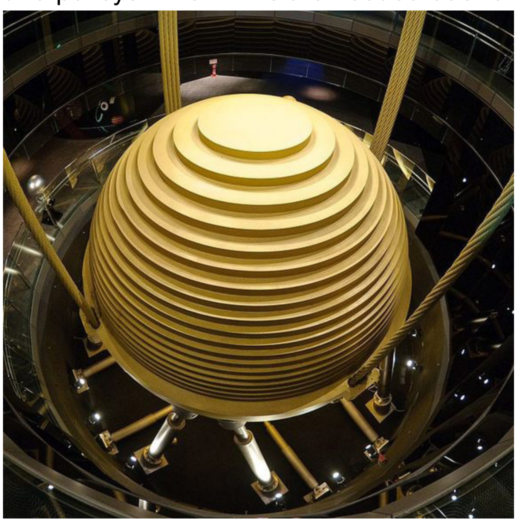
The steel damper weighs 660 metric tons and has a diameter of 5.4 m. It is suspended with numerous tension rods with hydraulic pumps that secure the base. Currently, the wind damper in Taipei 101 is the second largest in the world. It was made by welding together 41 layers of steel boards, each 125 mm thick.

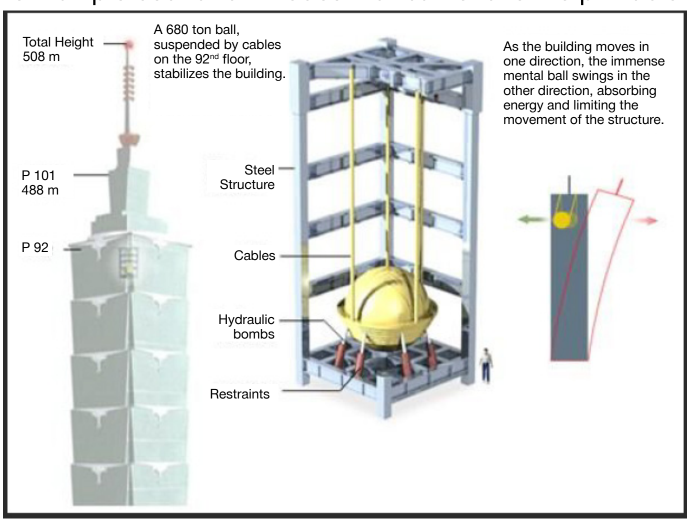
The sheer size and weight of the wind damper made it difficult to move to the construction site, and it was simply impossible for cranes to lift it up to between the 87th and 92nd floors, where it was to be installed. Workers had to send the damper up in smaller pieces, then weld the whole thing together on the spot.

In July of 2013, when Typhoon Soulik made landfall, wind speed in the Taipei area reached Force 14 on the Beaufort scale. At 4:10 in the morning, the wind damper in Taipei 101 experienced an oscillation of 70 centimeters in both directions, the greatest since the building was completed.

On April 18th, 2019, an earthquake measuring 6.1 on the Richter scale struck Xiulin Township in Hualien. At 1:01 in the afternoon, the wind damper in Taipei 101 swung 20 cm in both directions, a record-breaking oscillation that's caused by an earthquake. This ingenious protection mechanism prevented people inside the skyscraper from harm or discomfort.

The pinnacle presented further engineering difficulties. The pinnacle is vulnerable to crosswind excitation due to its uniform cylindrical shape and location on top of a building. With many more cycles at lower stresses accumulating at low wind speeds, three mode forms were found to have the ability to produce substantial stress ranges during storms. Due to these circumstances, fatigue life was a crucial design factor for the steel-trussed pinnacle spine. There were two strategies for reducing fatigue. First, local supplemental dampening was applied to lessen dynamic response. 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 fatigue life technique involved identifying the areas that were most susceptible to fatigue and lowering their cyclic stress ranges. Using Goodman's Simplification to treat variable stress cycles as uniform cycles, thousands of high-stress cycles and many more lower-stress cycles were processed 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.

The Taipei 101 site required a well-planned foundation system in light of the findings of the soil study, which showed that the building site comprises soft soil in the form of clay that is abutted vertically with colluvial soil and has a low load bearing potential. Additionally, at a depth of 40 to 60 m, there is a layer of soft rock called sandstone beneath this layer, necessitating the usage of a solid foundation. The site has a matt foundation with bored piles to distribute the weight of the superstructure. The location's water table is 2 m below the surface and the tower's 21-m-deep basement presses upward on the foundation of the building.

Slurry walls 47 m deep and 1.2 m thick were built to support the foundation and excavation below ground. 380 1.5 m diameter piles and 167 piles placed beneath the platform make up the tower's foundation. To carry the weight of the columns and walls, the piles were covered with 3 to 4.7 m concrete raft slabs.

Notably, during the construction of the Taipei 101, in May 2002, a 6.8-magnitude earthquake rocked Taipei, which brought down two construction cranes, killing five people. The building, however, was not damaged. Taipei 101 is an ingenious marvel, breaking the seismic barriers and showcasing the world the prowess on the engineering capacity.

Structure	Eight eight-story modules standing atop a tapering base, satisfying demands of esthetics, real estate economics, construction, occupant comfort in mild-to-moderate winds, and structural safety in typhoons and earthquakes.
Foundation	The site has a matt foundation with bored piles to distribute the load of the superstructure. The tower has a 21 m deep basement with the water table at the site 2 m below the ground level.
Architect (s)	C.Y. Lee and C.P. Wang
Structural Engineer	Evergreen Consulting Engineering and Thornton Tomasetti
Height	508.2 m
Floors	101 Above Ground, 5 Underground
Construction Period	1999-2004
Cost	$1.9 Bn USD

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