Steel Provides Answer to Building on Top of Existing Parking Garage

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Constructing a new building on top of an existing structure can sometimes feel like trying to fit a square peg into a round hole. Several years after construction had stalled on a prominent development, Thornton Tomasetti was asked to re-engineer the unfinished plans for a mid-rise building near Chicago's Magnificent Mile.

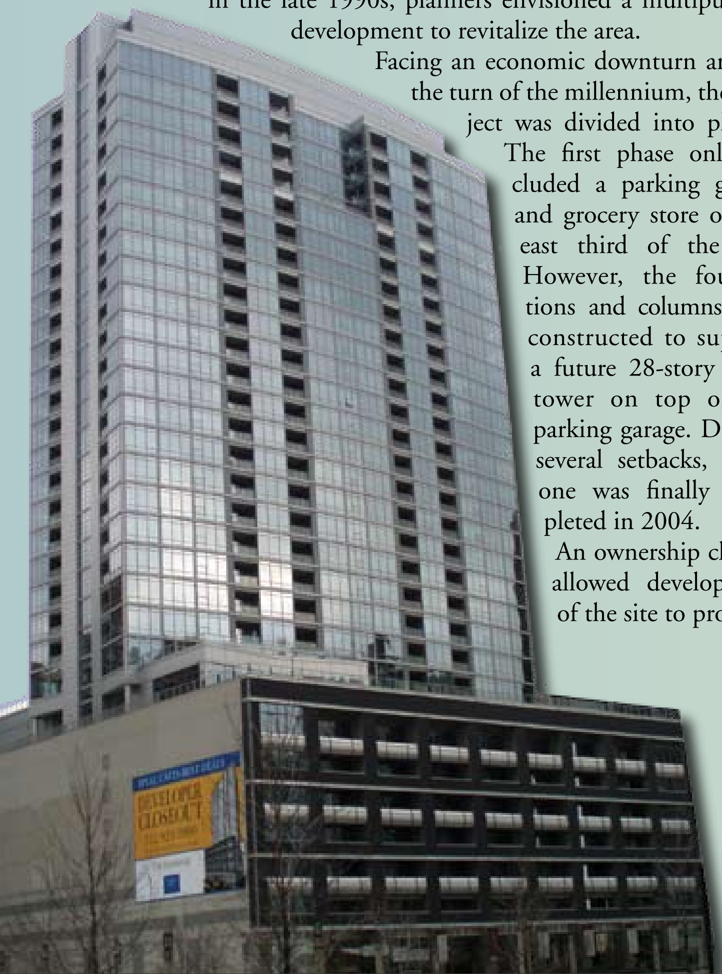
A new development team purchased the property and commissioned an architectural design that varied greatly from the original plans. The key change was from a 13-story square donut shaped tower to a 25-story tower with an elliptical floor plan to be built on top of an existing 8-story concrete garage. The new tower would be centered above a previously designed light core. This loaded the interior columns and foundations beyond their designed capacity. A 6-foot deep transfer mat and a 16-footdeep transfer girder were required to spread the load to columns with adequate capacity. Overcoming these challenges also influenced many other aspects of the building's design.

The construction team likewise faced challenges with the site. A parking garage and grocery store were located in the existing podium. The need to keep these facilities open during construction greatly affected construction sequencing.

The site is located in Chicago, Illinois, just one block away from Michigan Avenue. When development of the site was first proposed in the late 1990s, planners envisioned a multipurpose development to revitalize the area.

Facing an economic downturn around the turn of the millennium, the project was divided into phases. The first phase only included a parking garage and grocery store on the east third of the site. However, the foundations and columns were constructed to support a future 28-story hotel tower on top of the parking garage. Despite several setbacks, phase one was finally completed in 2004.

An ownership change allowed development of the site to proceed.



Thornton Tomasetti was asked to re-engineer the unfinished plans for this mid-rise building near Chicago's Magnificent Mile.

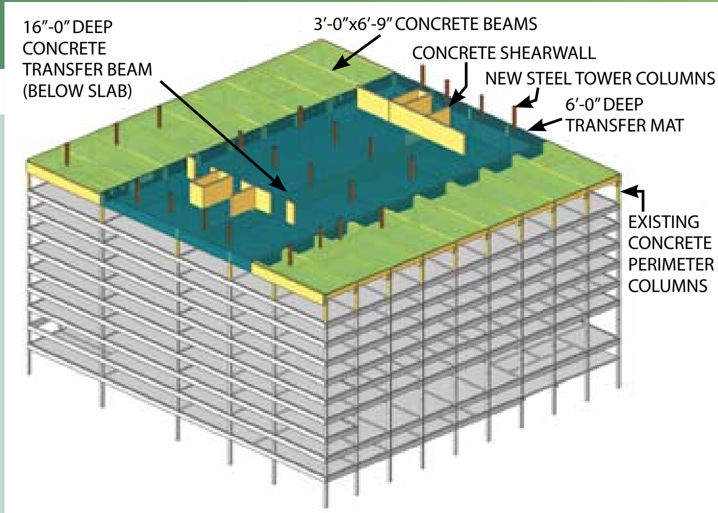


Figure 1: 9th floor structural plan shows column connections to existing structure.

The new developer continued the phased approach. A new team of consultants and contractors also joined the project. In an effort to respond to market changes, the new design team abandoned the hotel concept and began work on a residential tower. The new tower floor layout varied significantly from the proposal that had been used to size the base columns and foundations. Instead of a square hotel tower with a large light core, the new design had a football-like shape and was centered over the base building (*Figure 1*).

Existing Base Plan

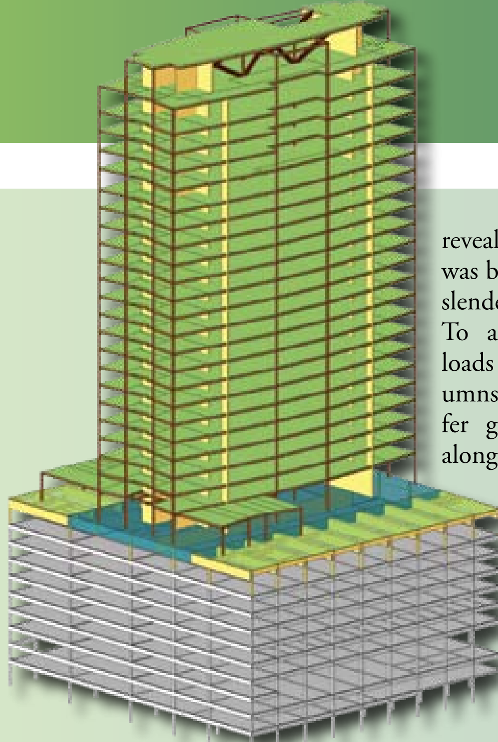
The existing parking garage plan was based on a regular rectangular grid. From east to west, ten column lines were typically spaced at 22 feet 6 inches on center. In the north-south grid, five column lines were typically spaced at 33 feet 9 inches. The perimeter bays of the structure were supported by concrete columns ranging in size up to 3 by 6 feet. However, the four center columns were much smaller, only 3 feet square. The new residential tower would be centered on the podium, about column line-C. Further, the new tower's column layout did not match the existing column grid at all.

The existing structure included eight levels of parking, a supermarket, and many of the MEP systems required for the planned residential tower above. The parking levels were supported on cast-in-place post-tensioned slabs. Lateral forces were resisted with a system of concrete moment frames. Ramps between parking levels served to further stiffen the base against lateral movement.

Structural Design

The most immediate problem faced by the design engineers was how to support the new tower. The tower columns did not align with the existing grid, and the structure itself was centered over columns and foundations that were not designed for such loading. In addition, the podium's lateral system was primarily located outside of the envelope of the planned tower.

To transfer the tower column loads to the existing columns below, the engineer used a 6-footthick concrete mat at the interface between the new and existing structures. The mat also served to transfer the lateral loads from the tower's structural system to the existing parking garage's lateral system. This massive concrete mat would need to be poured 100 feet above grade. Even with a 6-foot thick mat, initial analysis



Complete structural model.

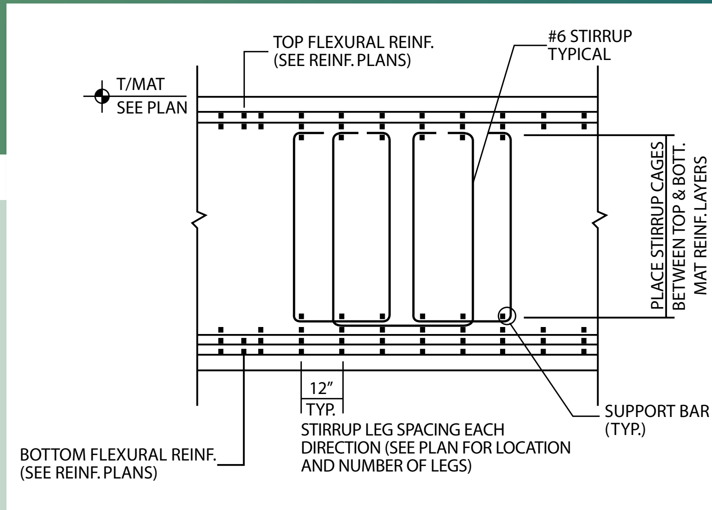
revealed that too much load was being distributed to the slender interior columns. To alleviate some of the loads from the smaller columns, a 16-foot deep transfer girder was introduced along the central column line (grid line–C). The transfer girder spans through the four interior columns to the two large exterior columns on each side. Each column is engaged, and vertical load is transferred according to the relative stifness of each column section and the transfer girder.

Finite element analysis (FEA) software was utilized to determine the vertical load distribution between transfer elements and existing columns. The columns were modeled with spring stiffness equivalent to their elasticity and foundation information. The FEA programs also assisted in selecting the appropriate reinforcing of the mat. All aspects of the concrete design were performed according to the ACI 318. This included capping the highest strength of concrete permissible in strength calculation at 10,000 PSI (ACI), as used in the transfer girder.

About 500 tons of steel reinforcing were required for the transfer mat. The vast majority of this steel was used as longitudinal reinforcing. However, the design for resisting punching shear at both the existing columns and the transferred steel columns required special attention. The resulting detail called for shear stirrups with a varying number of legs to run between the mat's reinforcement layers.

An early analysis of the existing lateral force resisting system indicated that each of the exterior columns would need to be engaged at the tower's base. There was not sufficient diaphragm strength in the PT slab to distribute the entire tower shear from the columns on lines B and D to the full moment frame system. To minimize the amount of concrete necessary, the 6-foot transfer mat spanned only from grids B to D. Beyond that, 6-foot-deep by 3-foot wide beams engaged the mat with the existing exterior moment frame.

In the Chicago area, concrete structures are preferred for residential buildings. However, in order to make the transfer mat and girder system economical, the residential tower needed to be as light as possible. A steel framing system was found to be the best option. W16 beams with 3-inch composite



Shear reinforcement detail.

deck and light-weight concrete typically spanned up to 30 feet. This system provided a sufficient diaphragm so that the floor translated as one plate under lateral loading. To pursue weight savings in the lateral system, steel braced frames were initially considered. However, the oblong tower shape and a floor plan optimized for maximum tenant space left little room for the bracing lines.

The complexity of the structure, plans for adjacent high-rises, and an unpredictable local wind climate convinced the design team to seek wind tunnel testing for the building. Combining mode shape data provided by the engineers with the results of scale model testing in the wind tunnel, specialists concluded that the light-weight steel tower would likely exhibit higher than acceptable lateral accelerations. The local wind environment, funneling winds off of Lake Michigan, had the possibility of exciting the tower in a twisting motion. Although the building was sufficiently strong to resist these winds, the particular motion had the potential to upset the occupants.

The design engineers immediately began discussing options with the architect and developers. With sales beginning on the proposed structure, it was undesirable to restrict the tenant space in any way. The amount of time available to the design team to make a final decision about the new lateral system was also very limited. A building-designspecific finite element analysis package allowed the engineers to consider several possible structural arrangements in the short time frame. The program also quickly computed the building's mass properties and mode shapes. These values were critical to calculations performed by the wind tunnel experts.

Without the freedom to add mass to the building, the structure's stiffness played the biggest role in reducing the uncomfortable wind-induced accelerations. To increase stiffness, the engineers borrowed some structural design elements typically used in commercial high-rises.

First, the engineers proposed changing the lateral system to a stiff cast-in-place concrete shear wall system. Combining concrete core walls with steel framing and columns is common practice in Chicago. Several options for the concrete walls were considered, and, eventually, a plan was approved that included a slender wall extending the full north-south width of the tapered end of the building. Large openings in the wall were required to accommodate the condominium units' floor plans. For even greater stiffness in the east-west direction, a hat truss was added at the 31st floor to link the braced cores located at either end of the tower.

Placement of reinforcement for second lift of transfer mat.

Figure 2 illustrates how the evolution of the building's lateral system improved stiffness and reduced inter-story drift. The switch to concrete walls alone was not enough to fully mitigate the potentially disturbing building motion. Adding the hat truss significantly reduced drift in the east-west direction, especially at the upper levels. In one design, outrigger trusses were planned to link the core with the exterior columns in order to engage these elements in the same way that a stay cable supports a ship's mast. However, the outriggers had little affect on the building behavior. Several iterations of slightly tweaked computer models allowed the engineers to arrive at a structural solution that reduced the building period by over 30% and uncoupled the torsional mode from the primary modes.

To minimize the additional weight applied to the transfer mat by the concrete core walls, the thickness of the shear wall was reduced half-way up the wall, where the stiffness demands were not as great. However, due to the schedule constraints, the steel framing had already been ordered and cut to length. Rather than scrapping the already purchased steel, the design engineers investigated and approved the use of lightweight concrete in the upper floors while maintaining a constant wall thickness. This approach had the added benefit of allowing the climbing form system to move seamlessly through the

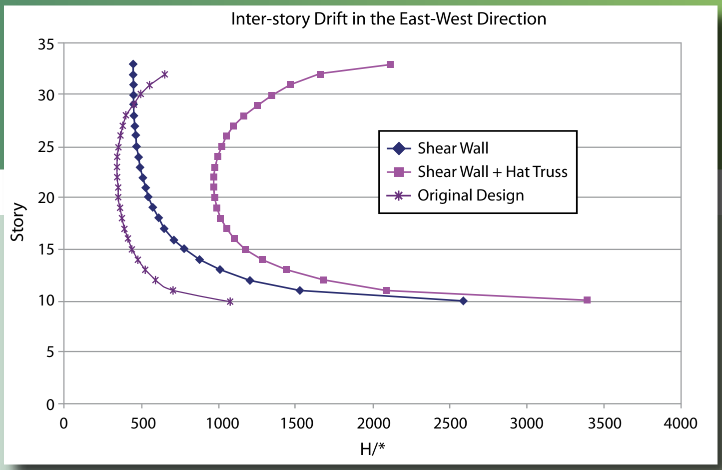


Figure 2: Inter-story drift in the east-west direction.

transition with no adjustment. As a further weight savings, planned cast-in-place concrete stairs were replaced with lighter metal stairs.

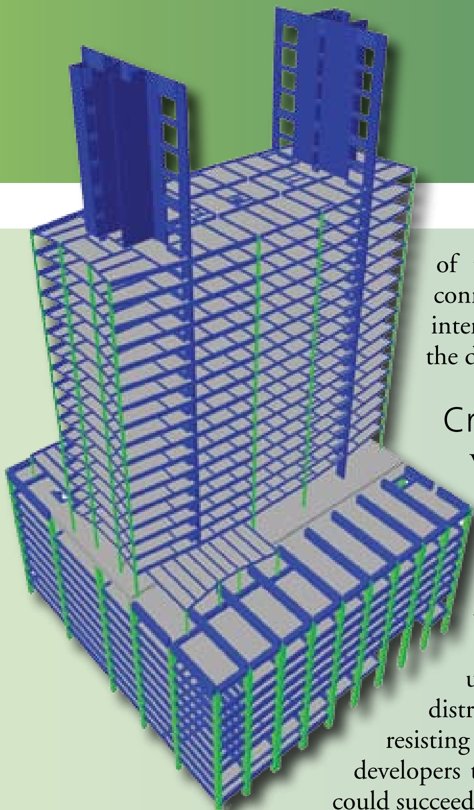
Construction

Adaptation of the parking garage base to support the 25-story residential tower proved to be a big construction undertaking. Simply supplying all of the construction materials was a logistical challenge. Placing these materials required a significant amount of man power, but ensuring that the elements were properly and safely installed required further engineering.

The first major construction challenge was figuring out how to support six feet of wet concrete (the mat) from a series of lightweight post-tensioned parking decks. The supermarket on the 1st floor had to remain open throughout construction, so it was not possible to shore down to grade. Moreover, the existing PT-slabs could not support all six feet of wet concrete, even if the load was shared among 6 of the existing parking decks. To resolve this problem, the engineers re-designed the mat to be constructed in two lifts. The first lift had a thickness of 3 feet 6 inches. The wet weight of concrete could be supported by shoring that extended 6-levels below the mat. This lift included additional shear transfer reinforcement for the second lift. After seven days, the first lift was able to support its own weight and the second lift was poured with the same shoring in place. In this way, the parking decks were actually re-opened ahead of schedule.

After the mat had been poured, work immediately began on the shear walls. A climbing slip form quickly allowed work to proceed upward on the wall ahead of the steel floor framing and columns. The shear walls would always precede the floor framing; but, if they extended too high, the walls would potentially be exposed to wind forces that they had not been designed for. The main wall running in the north-south direction ran almost the full width of the narrow profile of the building, exposing the connected east-west walls to forces that would have been shared with the twin core in the final building condition. Again, finite element analysis was performed to determine that the core could advance 6 stories above the completed floor diaphragm.

The advancing shear walls created another obstacle with the tower crane connections. Since the tower crane would be required to service the entire site, it would need to lead the shear walls as well, forcing a portion of the tie-in steel to be integrated into the floor framing and the uppermost tie-in location to be made to a floor with no diaphragm. Further complicating the situation was the tower crane location. Due to site logistics, the crane was located outside the footprint of the lower podium creating a cantilever of over 50 feet from the tower crane to the connection to the shear wall. To prevent axial loads from being transferred through embed plates designed for gravity only, some



Model to compute stresses on exposed shear walls.

of the steel floor framing connections to the core were intentionally left loose until the deck was poured.

Creative Solutions

With some engineering, a square peg can be fit into a round hole. In this case, a 25-story elliptical residential tower was engineered to fit on an existing square podium. Creative solutions for distributing gravity load and resisting lateral forces enabled the developers to create a building that could succeed in the current economic environment – even if that meant a drastic departure from the originally designed program.

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The new residential tower is supported above an existing 8-story podium by a 6-foot thick concrete mat. To further distribute the load to columns with adequate bearing capacity, a 16-foot deep transfer girder was also necessary. This system required special rebar detailing and a unique construction sequence. Even so, it was critical for the tower to be as light as possible. Engineers creatively used concrete core walls and a steel hat truss to stiffen the building and provide a comfortable living environment for the future occupants. Finally, the construction of the tower presented additional challenges that were likewise overcome by the design engineers.

In the end, creative solutions to design and construction problems facilitated the construction of a new landmark in the Chicago Skyline.▪

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