# Novel Application of Post-Tensioning Solves High-Rise Design Challenges

## Solution provides long spans and efficient transfer of horizontal and vertical forces

*by Bijan O. Aalami, Florian B. Aalami, Jeffrey Smilow, and Ahmad Rahimian*

Post-tensioning is used to reduce deflection, control cracking, and add strength in a wide range of concrete construction projects, including both new construction and retrofit of existing structures. The two principal characteristics of post-tensioning are the precompression that is applied to the concrete and the uplift that is generated to offset gravity loads. A third characteristic of post-tensioning is the generation of hyperstatic (secondary) forces in statically indeterminate structures.

Hyperstatic forces were recently used to resolve a major challenge facing the structural design of 55 Hudson Yards, a high-rise in New York City, NY, that will be partially constructed over and supported by an existing structure. The design scheme required the columns of the existing structure to provide partial support for the new construction. The challenge was to match the anticipated reactions of the new construction, which are governed by the building's architectural design and construction scheme, to the location and capacity of the columns of the existing structure.

While the combined capacity of the columns of the existing structure could support the weight of the new construction, the distribution of the reactions from the new construction was considerably different from the capacities of the existing supports. Among the several options explored, the use of post-tensioning, configured to generate a set of hyperstatic reactions so that the reactions from the new structure matched the capacity of the existing supports, proved to be the most practical and effective scheme. This article presents the highlights of the design challenge and details how the hyperstatic actions associated with post-tensioning were used to achieve the design objective.

### Hudson Yards

According to its developers, Related Companies and Oxford Properties, Hudson Yards is the largest private real estate development in the history of the United States and the largest development in New York City since Rockefeller Center. The project covers 28 acres (11.3 ha) on the west side of Manhattan, and when it is completed in 2024, 125,000 people per day will work at, visit, or call Hudson Yards their home. The site will include more than 17 million ft$^2$ (1.6 million m$^2$) of commercial and residential space, state-of-the-art office towers, more than 100 shops, a collection of restaurants, approximately 4000 residences, 14 acres (5.7 ha) of public open space, and a 750-seat public school. Half of the project extends over an existing rail yard; the 30 active train tracks are slowly being covered by a massive platform that will hold three towers, a retail complex, a 6 acre (2.4 ha) public square, and a new cultural space. The construction is expected to be completed in 2019 and is taking place while the trains remain in operation.

### 55 Hudson Yards

A prominent part of the project is a 51-story commercial office building, 55 Hudson Yards (Fig. 1). One of the first fully concrete-framed high-rises of its class in New York City, the tower will include over 1.3 million ft$^2$ (120,773 m$^2$) of office space. The developers wanted the building to provide modern, efficient floor spaces uninterrupted by columns, and with floor-to-ceiling windows. The solution comprises long-span post-tensioned flat slabs supported by a central core and perimeter columns (Fig. 2). The architects are Kohn Pedersen Fox Associates and Kevin Roche John Dinkello and Associates, and the structural engineer is WSP | Parsons Brinkerhoff. ADAPT Corporation was consulted on the post-tensioned aspects of the design.

Using post-tensioned flat slab construction with lightweight concrete allowed floor spans of up to 45 ft (13.72 m). It also eliminated the need for interior beams. This reduced the floor-to-floor height, allowing the required office space to be

Fig. 1: Rendering of 55 Hudson Yards

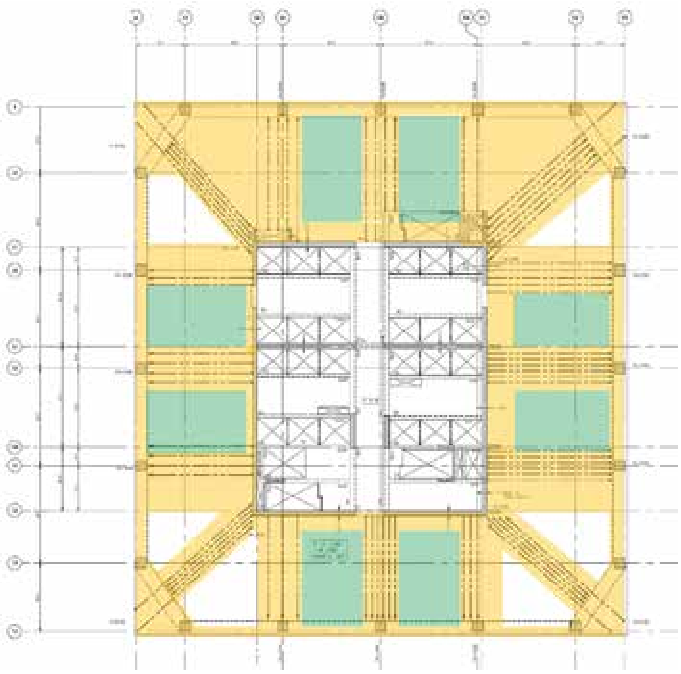

Fig. 2: Plan of typical high-rise (tower) level (Note: Green designates area of future stair opening, additional slab reinforcing is required; yellow designates no future slab penetration is these areas, limited small sleeves may be allowed; and white designates area for small penetration, sleeves, and poke-throughs)

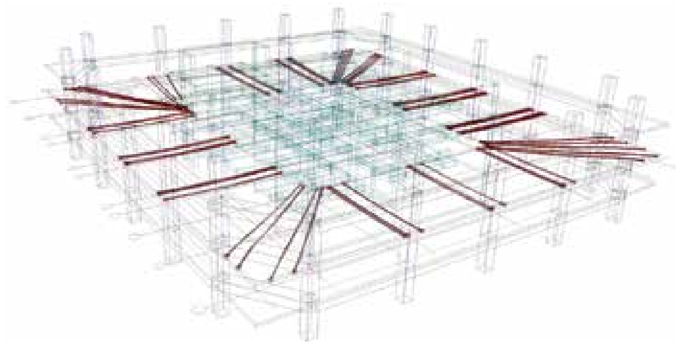

Fig. 3: Overview of tendon layout of a typical floor

accommodated within a total building height of 780 ft (237.74 m). The building features 10 floors of larger base construction topped with 41 typical levels for a total of 51 floors. A multi-level transfer structure has been designed to direct loads from the exterior tower columns to the offset lower column grid. The composite transfer structure is composed of three floor slabs and a series of transfer walls and "walking" columns. Post-tensioning in two of these slabs is used to resist the horizontal tensile forces developed in the composite transfer levels. Profiling of the tendon ties through the transfer plate provide added uplift to support the load from above. This unique transfer system is described in more detail later in this article.

The floors in the tower feature a central core and open, beamless unobstructed space that extends 38.5 ft (11.74 m) from the core wall to the perimeter (Fig. 2). In the base structure, the floors span as far as 44 ft (13.4 m). The typical floors are 9 in. (229 mm) thick flat slab construction with a perimeter beam that is 30 in. (762 mm) deep and 48 in. (1219 mm) wide. The specified superimposed dead load was 35 lb/ft$^2$ (1.68 kN/m$^2$), and the design live load was 50 lb/ft$^2$ (2.39 kN/m$^2$), not reduced. The specified 28-day strength was 7000 psi (48 MPa) for the lightweight concrete (120 lb/ft$^3$ [1922 kg/m$^3$]) in the floors and 12,000 psi (83 MPa) for the normalweight concrete in the columns and core walls. The design of each slab considered three zones specified by the owner: areas for future large openings, areas for small penetrations, and areas with post-tensioning that should not be penetrated in the future.

The floor system reinforcement consists of unbonded post-tensioning tendons and conventional reinforcement. The tendons were grouped and configured to meet the developer's requirement of large tendon-free regions at the center of the floor panels (Fig. 2 and 3), allowing tenants greater flexibility

Fig. 4: Layout of post-tensioning and nonprestressed reinforcement

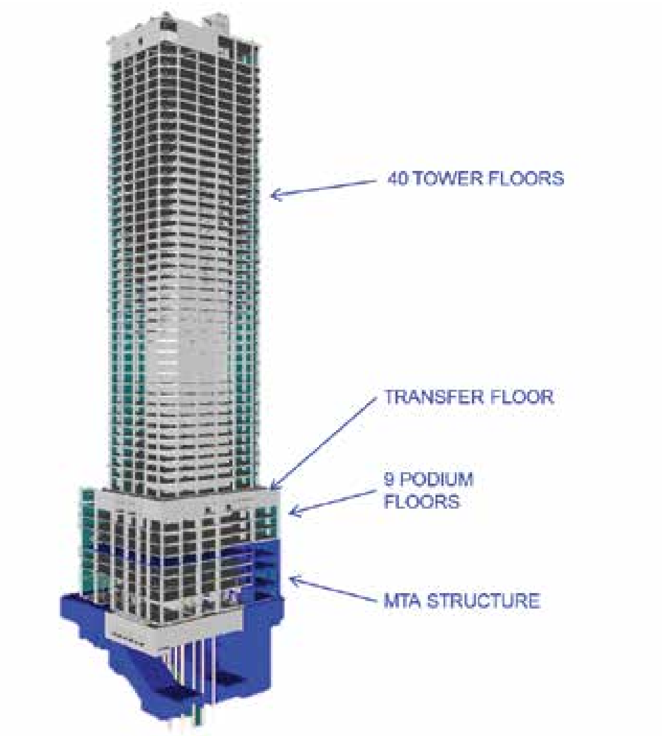


Fig. 5: Structural model of 55 Hudson Yards

for creating internal access between the floors or other structural modifications. The 0.5 in. (13 mm), 270 ksi (1860 MPa), seven-wire strand tendons (Fig. 4) were supplied by Amsysco, Inc., and installed by the primary concrete contractor Cross Country Construction, LLC.

The projection of the building beyond the central core, shown on the right of the structural model of the building (Fig. 5), is supported on the column ends of the existing Metropolitan Transit Area (MTA) ventilation building. A post-tensioned wall system was developed in the new construction over the existing building to bring the reactions from the new construction to within the allowable values of the existing supports.

## Post-Tensioned Wall

The existing ventilation tower had been designed with designated support locations to accommodate future development at the Hudson Yards project. The architectural requirements and the massing of the proposed new construction, however, led to a potential overloading of two of the interior existing support locations, while the exterior support locations were underused. WSP | Parsons Brinkerhoff evaluated several design and construction approaches to redistribute the loads, including the use of a large steel truss in combination with the delayed casting of the central columns. Load redistribution would have been achieved by initially spanning the exterior columns with the steel truss. The central columns would be cast only after sufficient load had been transferred to the outer supports. After installation of the central columns, the remaining construction load would have been distributed among all supports.

Another option, developed in collaboration with ADAPT, was to redistribute the loads using post-tensioning tendons draped from the 10th floor at locations near the exterior columns down to the 8th level at the two interior columns. This alternative allowed ducts to be placed during the level-by-level construction of a concrete wall. Multistrand tendons, supplied by Freyssinet, Inc., would be fed through the ducts and could be stressed from the 10th level, where segments of the wall would terminate. Calculations showed that the proper load rebalancing would occur if the tendons were stressed after completing construction of the 20th floor.

Using post-tensioning in a cast-in-place wall provided a simple solution for rebalancing the reactions on the existing structure, with minimal requirements to manipulate the construction sequence. It also avoided the need for mixing structural steel construction with concrete construction and was shown to be less expensive to implement than the steel truss option.

The design concept of the post-tensioning alternative is based on the hyperstatic forces from post-tensioning. In a statically indeterminate structure, the restraint of the supports to the movement caused by post-tensioning results in a set of forces in the structure; these forces are referred to as hyperstatic actions. In the structural design of post-tensioned

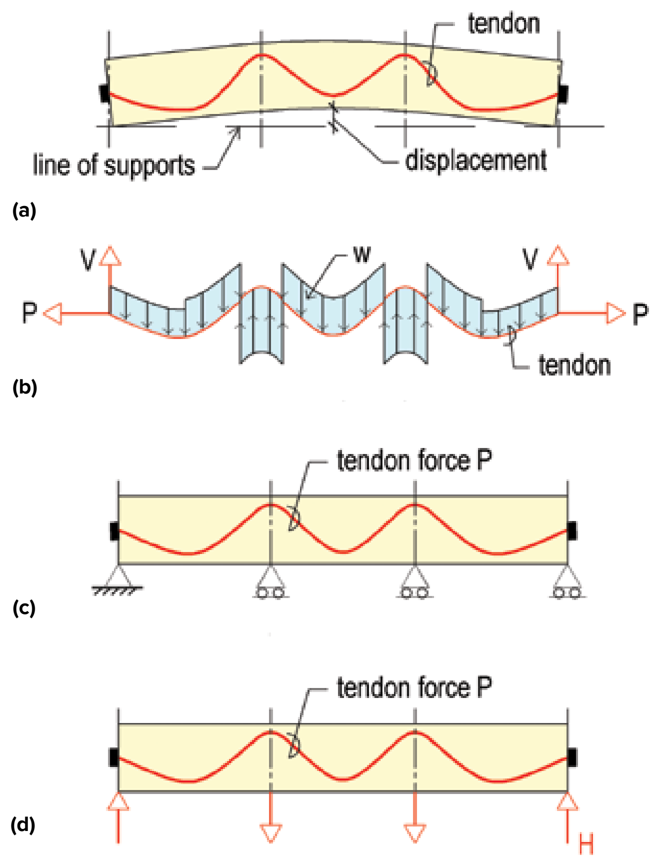


**Fig. 6: Hyperstatic reactions from prestressed members: (a) free member; (b) tendon forces; (c) restrained member; and (d) hyperstatic forces**

members, the hyperstatic effects must be calculated and accounted for along with the other loads on the structure.[1]

Figure 6 explains the concept of support reactions in post-tensioned members. The internal forces generated by post-tensioning tendons deform the member that contains them (Fig. 6(a)). Depending on the loads on the member and the amount of post-tensioning, the post-tensioning forces can actually lift the member off its supports. The forces generated by the post-tensioned tendons and applied to the member that contains them are always in static self-equilibrium (Fig. 6(b)). That means they sum up to be zero. They will deform the member if the member is free to deform, as shown in Fig. 6(a). If the supports of the post-tensioned member are fixed, they will prevent the member from deforming at the connections to the supports (Fig. 6(c)). The resistance to the movement of the member caused by the post-tensioning forces results in a set of reactions at the supports (Fig. 6(d)). These reactions are referred to as the hyperstatic forces from post-tensioning.

Because the forces that generated the reactions shown in Fig. 6(b) are in self-equilibrium, the sum of the resulting hyperstatic forces must also add up to be zero, but the direction and the value of each reaction can be configured through the post-tensioning design. Through judicious selection of tendon profile and tendon forces, it is possible to configure the reactions to act in the direction and amounts required by design. This feature of post-tensioning was used to alter the reactions from the building loads so that they were within the allowable range of the existing supports.

Figure 7 illustrates the application of the concept to the 55 Hudson Yards concrete frame. The hyperstatic reactions from the post-tensioning in the wall were designed so that the column reactions framing into the wall were within the support capacity.

$W_1$ through $W_4$ are the reactions from the superstructure at the base of the columns. Based on the elastic distribution of loads in the proposed structure, the $W_2$ and $W_3$ reactions exceeded the capacity of the existing supports, while the reactions at $W_1$ and $W_4$ were less than the capacity of their supports, but by different amounts. A total of three hundred and sixty-seven, 0.6 in. (15 mm) strands, providing a total of approximately 14,000 kip (62,275 kN), grouped in mostly 31 strands per tendon and arranged as shown, were used to create the hyperstatic forces $H_1$ through $H_4$ at the base of the columns, where $H_2$ and $H_3$ are upward forces, and $H_1$ and $H_4$ are downward forces. The sum of the forces $H_1$ through $H_4$ is zero, but they transfer a load totaling over 5000 kip (22,240 kN) from central supports to the end supports. This

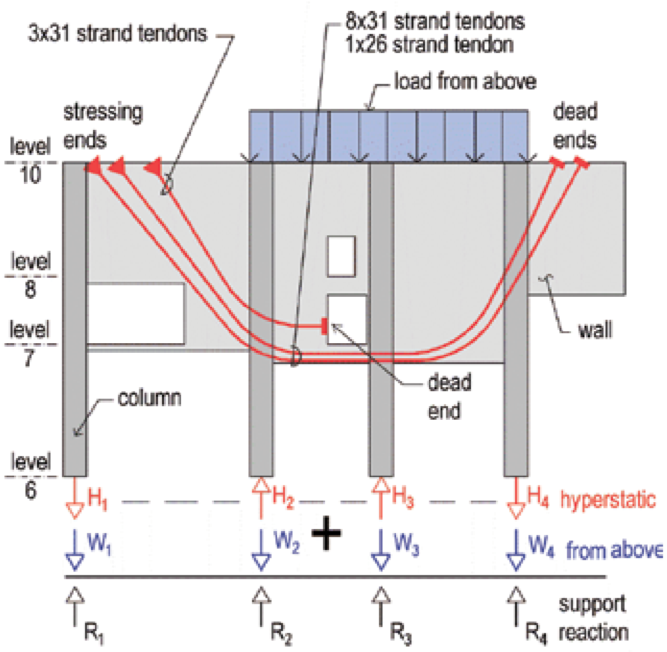


**Fig. 7: Schematic elevation of the lower wall section and its supports**

**Fig. 8: Partial view of construction at Level 8**

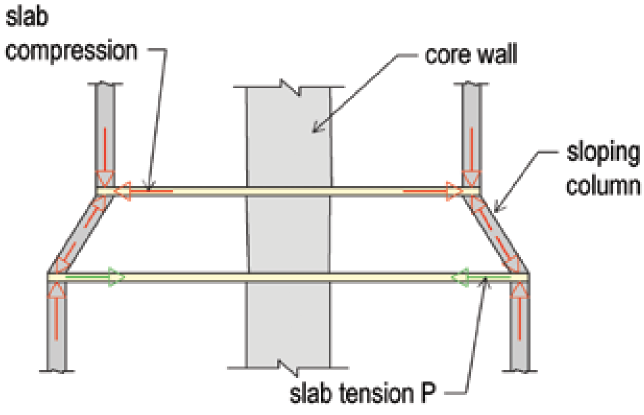


**Fig. 9: Mechanics of generation of tensile forces in the lower slab in spreading the load from smaller to larger slab footprint**

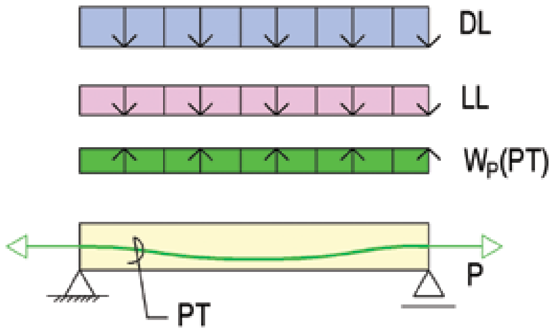


**Fig. 10: Forces on typical span of enlarged floor (Note: *DL* is dead load; *LL* is live load; $W_p$ is uplift from post-tensioning (PT))**

results in the net building reactions $R_1$ through $R_4$, which do not exceed the support capacity.

Figure 8 provides a partial view of the construction of the post-tensioned wall at Level 8 in the building. Ducts (white) for multistrand bonded tendons are being positioned along the path specified in the design. The vertical reinforcing bars on each side of the wall extend up from the level below. The remainder of the wall reinforcement will be placed after the installation of the ducts has been completed. Slab reinforcement, including unbonded reinforcement (green), is also being placed.

A nontraditional but beneficial aspect of post-tensioning in the design is the extended role of the tendon ties in the transition slab between the smaller footprint of the tower, and the larger podium floor below. Figure 9 displays the mechanism of generation of tensile forces in the lower slab. Figure 10 illustrates the forces on a typical span of the lower floor, followed by the required adjustment in the strength design of the floor.

In-plane tension generated in the lower floor can be resisted by adding nonprestressed reinforcement, post-tensioning tendons, or combination of the two.

Post-tensioning to resist tension from the floor transition can be profiled to provide uplift ($W_p$) in addition to tension. The uplift counteracts the effects of dead (*DL*) and live (*LL*) loads, but requires an adjustment in the safety design of the slab from the common case.

While tendons have been used as tie members before, profiling of tendon ties and recognizing their participation in providing the flexural strength of the member they pass through is novel. Equation (1) is the load combination commonly used for strength demand of post-tensioned members (Sections 5.3.1 and 5.3.11 of ACI 318-14[2]), where *HYP* is the hyperstatic effects from flexure of member caused by post-tensioning. It is applicable to the common case when the tendons are anchored at the slab edge, leading to compression in the slab. The moments from this expression are to be resisted by the **combined contributions** of prestressing and nonprestressed reinforcing bars.

Equation (2) is the load combination when the tendon is a tie and is profiled. The uplift resulting from profiling of the tendons, and the effects of uplift on the flexure of the slab—hence the hyperstatic actions—remain unchanged. However, the tendons will not be available to resist the demand moment, as their force $P$ is usurped by the sloping columns. In this case, the applicable demand moment derived from Eq. (2) has to be resisted by **nonprestressed reinforcement and added post-tensioning**.

$$U = 1.2DL + 1.6LL + 1.0HYP \quad (1)$$

$$U = 1.2DL + 1.6LL + 1.0W_p \quad (2)$$

## Project credits

Developer: The Related Companies and Oxford Properties
Architect: Kohn Pedersen Fox Associates and Kevin Roche John Dinkello and Associates
Main Contractor: Gilbane Building Company
Concrete Contractor: Cross Country Construction, LLC
Structural Engineer: WSP | Parsons Brinkerhoff
Post-Tensioning Consultant: ADAPT Corporation
Post-Tensioning Suppliers: Amsysco, Inc., and Freyssinet, Inc.

## References


1. Aalami, B.O., *Post-Tensioned Buildings: Design and Construction*, first edition, PT-Structures, 2014, 396 pp.

2. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)," American Concrete Institute, Farmington Hills, MI, 2014, 519 pp.


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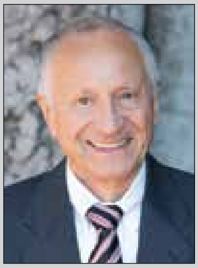

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ACI member **Jeffrey Smilow** is Executive Vice President, USA Director of Building Structures at WSP | Parsons Brinkerhoff and is responsible for all building structures operations throughout the United States. As an integral member of the firm's leadership team, he also oversees all building related engineering disciplines. He has over 38 years of design experience in steel and concrete and has developed a portfolio of high-profile projects including the World Trade Center Tower Three, Columbia University Manhattanville, and the Citi Field New York Mets Stadium, among many others. His work was instrumental in renovating landmarks such as the Plaza Hotel and Grand Central Terminal. A Fellow of the American Society of Civil Engineers (ASCE), he is a licensed engineer in multiple states.

ACI member **Ahmad Rahimian** is USA Director of Building Structures at WSP | Parsons Brinkerhoff. He is the recipient of numerous awards from engineering societies for various projects, including the 2007 AISC Special Achievement Award, 2005 ASCE-CERF Charles Pankow Award for innovation, and the *ENR* Excellence Award as one of the Top 25 Newsmakers of 2003. In his 30 years at WSP, he has engineered numerous projects worldwide ranging from high-rise commercial and residential towers to stadiums and transportation facilities. His projects are counted among the world's most iconic and award-winning structures, such as One World Trade Center and The Shard in London, UK. He received his PhD from the Polytechnic Institute of New York University, Brooklyn, NY. A Fellow of ASCE, he is a licensed engineer and licensed structural engineer in multiple states.