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History of Unbonded Post-Tensioned Concrete in Skyscrapers

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Abstract

Unbonded post-tensioned (PT) concrete has become a widely-accepted construction technique in the United States. The introduction of PT in tall buildings has been relatively recent, but it has become the current standard for concrete deck reinforcement within the past 20 years. This significant advancement has allowed for greater flexibility in architectural interiors, reduced building construction and operation costs, and efficient, yet durable structural designs. The history of post-tensioned skyscrapers in Chicago, and its expansion into other US metropolitan area,with structural design and the manufacturing process involved have produced an unbonded post-tensioning tendon. Furthermore, there are constructability benefits and concerns with unbonded post-tensioning in relation to current building codes and industry specifications. Several high-profile residential buildings and hotels in several US cities provide a connection to real-world examples.

Keywords: Commercial, Concrete, Hotel, Residential, Structural Engineering, Structure

Historical Context

Unbonded post-tensioned concrete has transformed itself from a niche form of structural support system into the standard for high-rise residential and hotel construction in the United States. Unbonded post-tensioning (PT) mono-strand tendons have been used in the United States as a form of concrete reinforcement for buildings since the late 1950s (PTI 2006). The first *Post-Tensioning Manual* was published in 1972, and provided the fundamentals for PT design and construction. Over the course of the next five decades, the literature regarding unbonded post-tensioning developed due to a multitude of product developments and design optimizations. During the 1980s, unbonded PT started to be used on the lower parking levels of high-rise buildings. In the 1990s, the usage of all forms of post-tensioned in United States experienced an eight percent average annual growth rate. However, it wasn't until the 2000s that unbonded PT was regularly used in the residential/hotel/office floors within skyscrapers. Currently, unbonded PT is the main structural floor system in residential towers in the United States, due to several structural and financial benefits.

Material Properties

For high-rise construction in the United States, unbonded post-tensioned concrete is governed by the Post-Tensioning Institute (PTI), American Concrete Institute (ACI) and International Building Code (IBC). An unbonded PT tendon consists of a 0.5-inch- (12.7-millimeter)-diameter, seven-wire strand that is surrounded by PT coating within a 50-mil- (1.27-millimeter)-thick extruded plastic sheathing (see Figure 1). Compared to rebar, which has an ultimate breaking strength of 60 ksi (413 MPa), the pre-stressed concrete (PC) steel strand within an unbonded PT tendon has an ultimate breaking strength of 270 ksi (1,861 MPa) per ASTM-A416. A 0.5-inch PT tendon has a similar weight per linear foot as #4 (#13 metric) rebar.

The purpose of the PT coating is two-fold: to protect the strand from corrosive elements, and to reduce the friction lost during the stressing operation. The lower the friction loss, the higher final effective force per tendon. The tendon has

Figure 1. Plastic extrusion process. © Neel Khosa

Figure 2. Unbonded PT bundle of tendons. © Neel Khosa

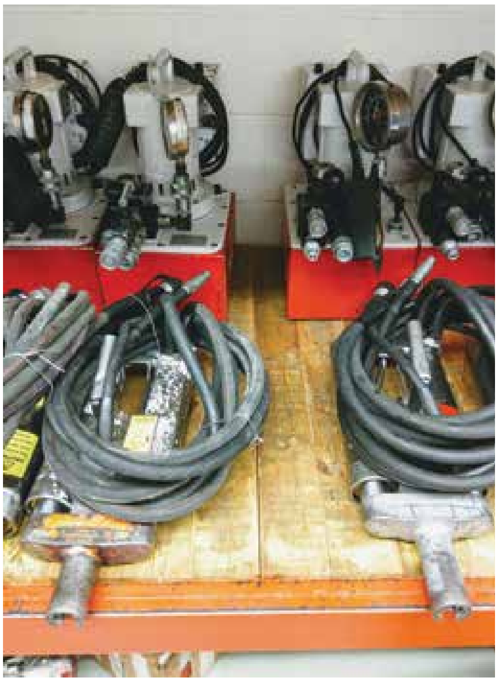

Figure 3. Unbonded PT stressing equipment. © Neel Khosa

Figure 4. Unbonded PT manufacturing plant. © Neel Khosa

encapsulated (or watertight) anchorages (see Figure 2), at each end and at construction joints, which help to transfer the force to the concrete.

Unbonded PT tendons are installed in a parabolic profile prior to the concrete pour. A hydraulic jack and electric pump (see Figure 3) are used to individually stress the PT tendons after the concrete reaches at least 3000 psi (21 MPa). Generally, an unbonded PT tendon will elongate eight inches (203 millimeters) for every 100 feet (30.5 meters) of tendon length, and will provide a final effective force of around 27 kips (120 kN).

Construction Team

Typically, the unbonded PT design is completed by the Structural Engineer of Record, with oversight from the Architect of Record. The PT shop drawings and calculations are done by a PT supplier, while the PT tendon fabrication is supplied by the same PT supplier with a PTI-certified plant (see Figure 4). The PTI certification program is accredited by American National Standards Institute (ANSI). The PT installation is traditionally done by a PT installation company that has PTI-certified personnel (see Figure 5). The construction is overseen by the project management company, general contractor and/or concrete contractor.

Basic Design of Unbonded Post-Tension Flat-Plate Slab

Most unbonded PT slabs in skyscrapers are designed as two-way slabs with a uniform thickness to resist bending in two orthogonal directions (PTI 2011). After the building outline and column layout are determined, the slab thickness is determined by live load, superimposed dead loads, and the span-depth ratio. The concrete cover for fire resistance is determined by ACI and IBC Codes.

There are three types of design methods for a post-tensioned concrete member: load balancing, rigorous, and straight (Aalami 2019). The load-balancing method, which is the most commonly used of the three options, considers the PT tendons removed for service design and added back for safety design. The rigorous method considers the PT tendons retained for service and safety design. The straight method considers the PT tendons removed for service and safety design. Post-tensioning can be modeled with software to balance loads, and to maintain the minimum level of precompression for crack control. Further design analysis should factor in the member moments due to gravity loads, secondary moments, service stresses, punching shear, deflection, and other considerations. The structural engineer will then detail the minimum effective prestressing force on the structural design drawings. The PT Supplier would then convert the specified force into the number of unbonded PT tendons. An efficiently designed and constructed unbonded PT floor system is highly competitive, since it pairs structural durability with economic cost savings that transfer to other building elements.

Figure 5. PT concrete pour. © Neel Khosa

Benefit: Efficient Building Height

Whereas certain marque skyscrapers pride themselves on attaining the tallest building height within their communities, there are extraneous costs to achieving lofty heights. The average skyscraper height grew 1.8 percent annually from 2000 to 2018 (Barr 2019). For real estate developers and lenders, a skyscraper with a lower construction cost per floor area will have a better chance of getting financed.

A key benefit of post-tensioned concrete is the ability to have thinner slabs, without increased deflection, and reduced floor-to-floor height compared to structural steel or concrete solely reinforced with rebar. According to a technical bulletin issued by the PTI, 10 floors of structural steel have an overall height of 125 feet (38 meters) versus only 108 feet (33 meters) for 10 floors with unbonded PT. The impact of the 13.6 percent reduction in vertical height is that the quantities of all vertical elements will be reduced.

Within buildings, unbonded PT is primarily used to reinforce horizontal or sloped concrete slabs, but it has been utilized in vertical wall applications. A typical PT flat-plate slab for residential applications is between seven and eight inches (177 and 203 millimeters) thick. Compared to a building with conventional rebar slabs, a building with unbonded PT slabs can function with thinner slabs and smaller columns. The PTI technical bulletin showed a 16 percent reduction in concrete with a post-tensioned residential building (excluding the foundation). Also, the weight of the steel (post-tensioning tendon and rebar) inside the slabs/beams was 20 percent less in the post-tensioned structure versus a conventional rebar structure. Finally, the vertical height was reduced by two percent in the post-tensioned building.

With a reduced building height due to unbonded PT, there are potential construction savings for all vertical elements such as, but not limited to:

- Piping for mechanical, electrical, telecom, security, plumbing and fire protection
- Façades with curtain wall, precast and masonry
- Concrete columns and shear walls
- Elevators, metal stairs, construction hoists and cranes
- Reduced floor-to-floor height can reduce material for interior finishes (drywall, etc.)
- Reduced need for wind-dampening devices

Additionally, there are potential operational life cycle savings and environmental benefits when the building height is reduced. For example, the building will cast less of a shadow on the ground. This can allow grade-level vegetation to receive more sunlight. Therefore, landscaping costs and water usage for irrigation can be reduced. Secondly, there will be a reduction in the energy required to vertically transport liquids (water), gases, cooled air, people, etc. Ultimately, this should reduce the energy costs for the owners. Additionally, evacuation times are extended to an order of magnitude comparable to that of the potential failure of the skyscraper (Li 2018). A reduced building height would decrease evacuation times for tenants on the upper levels. Finally, the reduced floor-to-floor height

Figure 6. 340 on the Park, Chicago. © Neel Khosa

and volume can reduce HVAC costs within units. Operationally, there would be a reduction in the energy required to vertically transport liquids/gases or people.

The reduction in above-grade building materials transfers down to the below-grade building materials. A lighter building could facilitate a reduction in foundations and retaining walls. Accordingly, the diminished excavation would lower the building's impact on erosion of the surrounding land. Additionally, this could improve the seismic behavior of the building. Taken as a whole, taller buildings lead to higher costs, which leads to higher rents and operational costs.

Benefit: Reduced Building Weight

Since unbonded post-tensioned concrete can reduce the depth of vertical construction elements, a building constructed of these elements could theoretically weigh less than one designed with other structural systems. Accordingly, a lower dead load could be used for structural design. PT buildings use about 20 percent less concrete and 25 to 40 percent less steel than similar reinforced-concrete buildings (Gupta 2012). The reduced weight can allow for smaller foundations and shear walls. This can minimize excavation requirements, the need for caissons and likelihood of affecting the water table.

There are potential savings for the following construction elements:

- Concrete footings, foundations and caissons
- Concrete shear walls
- Soil excavation
- Retaining walls and rock anchors
- Pumping of water for underground work

In terms of operational life-cycle savings and environmental benefits, the impact of building weight on the on surrounding land's erosion will be lessened. Secondly, the potential cost of pumping water to control subterranean flooding can be reduced. Finally, the building should have reduced wind swaying, reduced deflection and vibration, which would be appreciated by tenants. Theoretically, these savings would translate into a building with a lower carbon footprint. Additionally, the holistic approach of a soil-foundation-structure system (Rahimian 2017) should include the benefits of unbonded PT.

Benefit: Quick Construction Schedule

Another important element that has an environmental impact is the speed of the construction schedule. Ideally, structures can be built faster with unbonded PT at no additional cost. Accordingly, the impact of construction on the surrounding environment would be less. It is not uncommon to have a three-to-five-day pour cycle for a high-rise PT building, even in a city with a high urban density. A quick construction schedule reduces the strain on the surrounding ecosystem and infrastructure.

In urban centers, construction projects contribute to vehicular congestion. The daily gridlock of automobiles and trucks creates pollution and smog in the local vicinity. At 340 on the Park, a 62-story unbonded post-tensioned building in Chicago that reaches an architectural height of 672 feet (205 meters) (see Figure 6), construction moved at a rate of one floor every three days (Khosa 2008). The construction team shaved more than two months off their schedule using a combination of post-tensioning, specialized forming and stronger concrete. Ultimately, it reduced vehicular carbon emissions and the strain on local infrastructure. It became the first residential tower in the American Midwest to achieve LEED Silver certification for its design. Ironically, unbonded PT had a minimal direct impact, but a major indirect impact on the LEED point system.

Other unbonded PT skyscrapers, such as Escala in Seattle, completed each concrete floor in one pour (Bacon 2007). Traditionally, the normal unbonded PT concrete pour is around

Figure 7. 55 Hudson Yards, New York. © Lester Ali

Figure 8. NEMA Chicago. © Marshall Gerometta

10,000 square feet (929 square meters) in area. Escala had a floor plate of around 15,000 square feet (1,393 square meters) and utilized a low-shrink concrete mix to eliminate the need for a pour strip to control shrinkage cracks. The reduction in the number of pours helped the contractor stay on schedule.

Additionally, a quicker construction schedule will reduce the number of days with noisy construction (noise emission). Residents in the surrounding ecosystem would not have as much disturbance due to the reduced construction activity. While there are the obvious political, social and economic pressures on constructing structures, we can attempt to protect the ecosystem and reduce the impact of the construction industry.

Office Applications

Until recently, the use of unbonded PT has been almost non-existent in New York City, the largest construction market in the United States. Hudson Yards is a massive mixed-use development in Manhattan built over old rail yards. The 778-foot (237-meter) 55 Hudson Yards (55HY) is a 51-story commercial office building (see Figure 7). The skyscraper is the first major unbonded-PT building and one of the first fully concrete-framed high-rises of its class in New York City (Dispenza 2019).

Originally, the office tower was designed using structural steel, but the project was converted to an unbonded PT structural system. The use of unbonded PT concrete is somewhat unusual in New York City, but was more attractive financially than the original steel-frame system (Smilow 2017).

Figure 8. NEMA Chicago. © Marshall Gerometta

The structural engineer utilized outrigger links, 12,000-psi (83-MPa) lightweight concrete and unbonded PT to thin the slabs in order to reduce the dead load of the building. In total, 55HY had around 250 miles (402 kilometers) of unbonded PT tendons within the floors. The unbonded PT tendons were designed to leave "free areas" so that future stair openings could be added per tenant requirements. Accordingly, 55 Hudson Yards paved the way for other New York City skyscrapers that utilized unbonded PT, such as 1185 Broadway and the supertall 50 Hudson Yards.

Residential Applications

NEMA Chicago, a 76-story skyscraper, has over 1,100,000 square feet of developed area. The 896-foot (273.1-meter) building includes 792 apartment units (see Figure 8). At time of its completion, NEMA Chicago will be the second-tallest post-tensioned building, as well as the eighth-tallest building in Chicago. It is projected to hold the status of the 18th-tallest concrete building and the 20th-tallest residential building in the United States (CTBUH Skyscraper Center 2018).

The bottom 15 stories will be a mixture of parking, office, and residential areas. The amenity level on the 16th floor will have a fitness center, urban lodge, an indoor lap pool, hydrotherapy pools, and an outdoor pool deck for residents. The upper levels will consist of luxury residences. Above the 76th floor, are three floors of mechanical levels, which house a water storage tank that acts as a tuned sloshing damper, according to the building's wind tunnel study. NEMA Chicago is designed to achieve LEED Silver certification.

The structural design (for all levels) deviated from the normal flat-plate slab in high-rise buildings. Instead, an 8.5-inch-(216-millimeter)-thick post-tensioned slab sits on top of an array of post-tensioned interior and exterior beams. The beams range from 25.5 to 45.5 inches (647 to 1155 millimeters) wide by 12 to 15 inches (305 to 381 millimeters) deep. In the residential areas, a 40 lb/ft^2 (195 kg/m^2) reducible live loading and a 30 lb/ft^2 (146 kg/m^2) superimposed dead loading were used. The specified concrete strength is 6,000 psi (41,369 kPa) at 28 days and 3,000 psi (20,684 kPa) at stressing. The structure has roughly 2,250,000 ft (685,000 meters) of unbonded PT tendons, which is equivalent to roughly 585 tons (531 metric tons). Installation of the first post-tensioned deck on Level 2 started late May 2017, and the skyscraper was topped out in April 2018.

The Chicago PT Example

Chicago has long been at the forefront of skyscraper design. Prior to 1960, 90 percent of its 100 meter-plus buildings were built solely with structural steel, while only six percent were with any form of concrete. After 1960, almost 80 percent of its 100-meter buildings were built solely with concrete, according to the CTBUH Skyscraper Center. Furthermore, a growing percentage of those concrete skyscrapers are constructed using unbonded post-tensioning as elevated concrete slab reinforcement (see Figure 9).

Between 1980 and 2006, less than five percent of Chicago's 100-meter-plus buildings had post-tensioned slabs. Whereas over 55 percent of its 100-meter-plus buildings, either completed or under construction between 2007 and 2018, had PT slabs. In the residential/hotel segment, the average height in footage divided by the number of floors was 11.07 feet (3.37 meters) per PT floor compared to 11.31 feet (3.45 meters) per non-PT floor (see Table 1). For an average building of 45 floors, using unbonded PT would save 10.8 feet (3.29 meters) in building height, as compared to the same building without unbonded PT.

Chicago's increased use of unbonded post-tensioned concrete in skyscrapers has started to propagate to other major US metros such as Honolulu, Houston, Miami, and Seattle. For example, in Seattle, 25 out of 35 100-meter-plus buildings, built between 2007 and 2018 utilize unbonded post-tensioned concrete in the structural slabs. The re-emergence of Los Angeles skyscraper construction during the 2010s included PT skyscrapers such as Circa, a pair of 36-story residential towers. Fifty years from now, US urban centers will have a scarcity of open land analogous to that of developed European and

#	Building Name	Height (m)	Floors	Function	Post-Tensioned (R) Height (m)/floor	Non-Post-Tensioned (R) Height (m)/floor
1	Trump International Hotel & Tower	423	98	residential / hotel		4.32
2	Vista Tower	363	101	residential / hotel	3.59	
3	One Chicago Square East Tower	295	76	residential	3.89	
4	NEMA Chicago	273	76	residential	3.59	
5	Aqua at Lakeshore East	262	86	residential / hotel	3.04	
6	One Bennett Park	255	67	residential	3.81	
7	The Legacy at Millennium Park	249	73	residential		3.42
12	One Museum Park	221	62	residential		3.57
14	Waldorf Astoria Chicago	209	60	residential / hotel		3.48
15	340 on the Park	205	64	residential	3.20	
16	Wolf Point East Tower	204	60	residential	3.39	
19	Essex on the Park	189	57	residential	3.32	
20	OneEleven	187	58	residential	3.22	
21	The Grant	181	54	residential	3.36	
22	The Clare	180	53	residential		3.39
23	Optima Signature	179	57	residential	3.14	
24	55 East Monroe	178	49	residential / office		3.63
25	One Chicago Square West Tower	175	49	residential	3.57	
26	Loews Chicago Hotel	173	54	residential / hotel	3.21	
27	Streeter Place	169	55	residential	3.07	
28	AMLI River North	166	49	residential		3.38
29	465 North Park	160	48	residential	3.33	
30	The Paragon Chicago	159	48	residential	3.32	
32	The Columbian	158	47	residential		3.35
33	The Streeter	157	50	residential	3.13	
34	600 North Lake Shore Dr. - S.Tower	156	47	residential		3.33
35	215 West	155	50	residential		3.10
36	The Tides at Lakeshore East	152	51	residential		2.99
37	Parkview West	152	49	residential	3.10	
38	500 North Lake Shore Drive	151	47	residential	3.22	
39	727 West Madison	151	44	residential	3.43	
40	The Ritz-Carlton Residences	151	40	residential	3.77	
41	50 East Chestnut Street	151	40	residential		3.77
42	No. 9 Walton	150	38	residential	3.94	
43	235 West Van Buren	149	46	residential	3.25	
44	Wolf Point West	148	48	residential	3.08	
45	The Regatta	146	45	residential		3.25
46	73 East Lake	145	42	residential	3.46	
47	Lincoln Park 2550	145	39	residential		3.73
48	Moment	145	45	residential		3.23
49	Roosevelt University Academic, SLR	143	32	residential / education / office		4.47
50	Coast at Lakeshore East	142	47	residential	3.03	
51	600 North Fairbanks	140	41	residential	3.40	
52	Kingsbury Plaza	139	47	residential	2.96	
53	600 North Lake Shore Dr. - N.Tower	138	41	residential		3.37
54	Hubbard Place	137	44	residential	3.11	
55	369 West Grand Avenue	137	41	residential	3.34	
56	200 Squared	137	42	residential		3.26
58	MILA	135	40	residential	3.38	
59	Marriott Marquis Chicago	135	40	hotel	3.38	
60	Optima Chicago Center	135	42	residential	3.21	
61	1001 South State Street	134	40	residential	3.35	
62	Marquee	133	38	residential / retail	3.50	
63	Silver Tower	132	39	residential		3.38
65	The Gallery On Wells	131	39	residential	3.36	
66	202 West Hill Street	130	40	residential	3.25	
67	The Sinclair	128	35	residential	3.66	
68	Alta at K Station - East Tower	127	41	residential		3.10
69	10 East Delaware	126	35	residential		3.61
70	MoMo	125	32	residential		3.91
71	State and Chestnut	125	35	residential	3.57	
72	The Chandler	119	36	residential		3.29
73	The Lex	118	35	residential	3.38	
74	The Fairbanks at Cityfront Plaza	118	31	residential	3.81	
76	Hotel Palomar	116	36	hotel / residential		3.22
77	The Aurelien	116	33	residential	3.51	
78	Alta at K Station - West Tower	115	37	residential		3.11
79	1400 Museum Park	114	34	residential		3.36
80	Astoria Tower	114	30	residential		3.80
81	Arkadia Tower	112	33	residential	3.41	
82	1720 South Michigan	112	32	residential	3.51	
83	The Admiral at the Lake	112	32	residential	3.51	
84	K2 at K Station	112	33	residential	3.38	
85	Echelon at K Station	111	36	residential		3.07
86	Walton on the Park	110	31	residential	3.54	
87	1600 Museum Park	109	32	residential	3.40	
88	Exhibit on Superior	109	34	residential	3.20	
89	Alta Roosevelt	108	33	residential	3.27	
90	LINEA	106	33	residential	3.21	
91	Eight O Five	106	33	residential		3.21
92	Eleven40	105	31	residential	3.38	
93	Museum Park Place 2	100	30	residential		3.34
	AVERAGE	**155.7**	**45.7**		**2.17**	**1.44**

Table 1. Relative height, number of floors, and floor thicknesses for tall buildings in Chicago, comparing those constructed with post-tensioned concrete and those without. © Neil Khosa

Pacific Rim megacities. With restrictions in horizontal urban expansion, vertical expansion via skyscrapers will be the main solution to house residents.

The Future of Post-Tensioning Outside the United States

While other forms of post-tensioning have made inroads in Australia, Canada, the Middle East, and the United Kingdom, unbonded PT is rarely used outside the United States. Unbonded post-tensioning is a high-rise construction technique that has been accepted by architects, design engineers, contractors and owners in the United States. The United States has exported its structural engineering services to foreign lands. Likewise, the matured knowledge of unbonded PT developed in the United States can be easily exported to other geographies.

The short-term hurdle of educating designers, owners and politicians abroad and investing in a local manufacturing supply chain can be offset by the long-term economics of lower construction and building operational costs. The raw materials for unbonded PT are already sourced globally. The equipment used to manufacture unbonded PT can be converted to alternate electric sources. The certification programs for personnel can be translated to other languages. In the future, unbonded post-tensioned concrete has a place globally as a form of structural material in skyscrapers.

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