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THAT GREEN THING:
THIN POST-TENSIONED CONCRETE SLABS

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There is a story of an older woman in line at a store who is told by the cashier that plastic bags aren't good for the environment. The older woman apologizes and explains she didn't have the "green thing" back in her day. The story then highlights everything our grandparents—or great-grandparents of millennials—did that were in fact "green": everything from returning milk bottles and walking up stairs (because there were no escalators) to cutting the grass with a push mower, and so on.

This story got me thinking about both the past and the current state of post-tensioned (PT) slab design. Working on projects in Honolulu where there are stringent height limits, a design team is constantly challenged to consider structural systems that are relatively thin. Looking at what was done "back in the day" reveals that those older engineers were pretty "green" as well, designing some very efficient thin PT slabs long before LEED or goals to reduce a project's carbon footprint.

Reviewing old construction documents and skyscraper data for numerous buildings built in the 1970s and 1980s in Honolulu reveals that many towers were built with floor-to-floor heights of less than 8 ft-6 in. (2.6 m), many using PT slabs that are only 5 in. (130 mm) thick. Honolulu-based architect Jo Paul Rognstad developed a design for an extremely efficient high-rise tower that became a prototype of sorts for several towers during that period.

His tower configurations were typically square to slightly rectangular in plan with a relatively small floor plate, less than 4000 ft^2 (370 m^2) per floor. The core of the building included two elevators and a single intertwining exit stair that provided means of egress from each floor. While typically used as residential or hotel structures, many of these buildings were also mixed-use that provide small office condominium space. His work includes approximately 80 condominium projects totaling 11,000 residential, hotel, or office units. Some of his projects in Honolulu are listed in Table 1.

Today, if you were to suggest a PT slab thickness of only 5 in. (130 mm), you would surely be questioned. These buildings are examples of what can be achieved and have been in use for 35 to 45 years, which is a very good track record for thin PT slabs. Jo Paul Rognstad, his engineers, and the contractors who built these buildings did that "green thing" before it was even a thing.

SO, WHAT IS THE DIFFERENCE BETWEEN BACK IN THE DAY AND NOW?

PT slab design circa 1980:

- Analysis was performed in two-dimensional (2-D) equivalent frame design programs using simple computer programs, programable calculators, and hand calculations.
- Slab concrete strength was typically only 4000 psi (28 MPa).
- Shear studs didn't exist.
- Construction documents were hand-drawn.
- Dimensional control during construction was performed with visual surveying equipment.
- Construction quality control was limited to the construction team.

PT slab design circa 2020:

- Analysis is being performed in three-dimensional (3-D) finite element design programs with the ability to print out detailed deflection maps to verify design.
- Slab concrete strength of 5000 and 6000 psi (34 and 41 MPa) are common.
- Shear studs are a readily used option.
- Construction drawings are done in 3-D building information modeling (BIM) formats with the potential for clash detection.
- Dimensional control during construction is performed with electronic surveying equipment and sometimes 3-D laser scanning.
- Construction quality control in many jurisdictions includes third-party special inspection along with the

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Table 1—Limited listing of Jo Paul Rognstad's projects in Honolulu

Project	Height, ft (m)	Stories	Average floor-to-floor height, ft (m)	Year completed
Century Park Plaza Tower A (Fig. 1)	362 (110)	43	8 ft-5 in. (2.6)	1975
Century Park Plaza Tower B	362 (110)	43	8 ft-5 in. (2.6)	1975
Century Center	350 (107)	41	8 ft-6 in. (2.6)	1978
Ohana Maile Sky Court	350 (107)	43	8 ft-1 in. (2.5)	1979
Hawaiian Monarch Hotel	350 (107)	43	8 ft-1 in. (2.5)	1979
Century Square	344 (105)	37	9 ft-3 in. (2.8)	1982
The Aqua Marina Towers	350 (107)	39	9 ft-0 in. (2.7)	1984
Executive Center	386 (118)	41	9 ft-5 in. (2.9)	1984

Fig. 1—Century Park Plaza Towers.

contractor's quality control programs.

So why is it that some 40 years ago, with what might be considered archaic design tools, lower concrete strengths, and possibly lower standards of construction quality control, was it possible to build thin 5 and 6 in. (130 and 152 mm) PT slab systems? Compared to today, with better analysis tools, stronger concrete, and better quality control, the most common slab thicknesses are in the 7 to 9 in. (180 to 230 mm) thick range.

The trend toward thicker slabs may be due in part to some of the following:

- While there has always been some conduit embedded in slabs, the size and number of conduits have seemed to increase in recent years. There has also been a trend toward embedding PEX flexible plastic plumbing in the slabs, further complicating construction.
- Tighter tolerances for slab deflections.
- Fear of litigation.
- Lower design fees and thus less budget available for optimizing the design.

Even with these additional challenges, questions to reflect on are: Is the trend toward thicker slabs due to engineers not taking the extra time to investigate a thinner slab? Are design and construction teams not taking the time to coordinate the systems? While the design community will talk the talk about designing green, they might not actually walk the walk in taking the extra effort to design green.

THAT GREEN THING—EFFICIENT STRUCTURAL DESIGN

While architects and mechanical and electrical engineers have many tools to work with, structural engineers have often limited themselves to only maximizing recycled content of steel or using fly ash or slag to reduce the cement content of concrete in designing green. Sustainable design, however, is also about the efficient use of materials, as noted in the following excerpt from the Minnesota Sustainable Design Guide (1999 to 2001):

Building design and construction use significant quantities of natural resources and materials. The building industry consumes 3 billion tons of raw materials annually – 40 percent of the total material flow in the global economy. The manufacturing process of new materials is water and energy intensive, which contributes to environmental degradation and pollution. Harvesting, extraction, mining, and processing new materials pollute the air and rivers, threatening ecosystems and wildlife habitat.

MATERIALS GOALS

In view of these environmental concerns, sustainable design embodies the following goals:

- Minimize consumption and depletion of material resources; and
- Minimize the life-cycle impact of materials on the environment.

From a structural engineering standpoint, the most significant contribution to practicing sustainable design principles is optimizing the structural systems to reduce material requirements on a project. For concrete structures, one of the best tools is the use of PT. PT concrete slabs typically require 25% less thickness than a conventionally reinforced slab to carry the same loads.

The use of PT in a slab system represents not only a reduction in material requirements but also a reduction in the overall weight of the building. The reduced weight of the floor system has a ripple effect throughout the structure. For the supporting columns and foundations, reduced weight decreases the material requirements in these elements. Because seismic design requirements are based on the overall weight or mass of the structure, reducing its weight through the use of PT can result in lower material requirements for the lateral load-resisting systems and its foundations. In addition, PT slabs can be built quickly—a floor every 3 days in some markets—thereby reducing the environmental impacts of construction duration.

In a 2006 presentation to the Post-Tensioning Institute, C. Nicholas Watry compared a 10-story PT building design to a comparable reinforced concrete alternate in terms of LEED and sustainability. He concluded that seven additional LEED points were available for "Innovations in Design":

- Reduction of concrete material (16% less concrete)
- Reduction of reinforcing materials (20% less steel)
- A less costly structural frame (13% less expensive)
- Reduced building weight
- Lower building height, less shadow
- Faster construction
- Building footprint could be smaller

Well-designed and constructed thin PT concrete slabs help to achieve "that green thing".

PACIFICA HONOLULU

The design of the Pacifica Honolulu (Fig. 2) project, 2012, included 46 stories within a 400 ft (122 m) height limit. This required floor-to-floor heights of no greater than 8 ft-6 in. (2.6 m) at the residential floors and only 8 ft-1 in. (2.5 m) at the parking levels. With clear height requirements of 8 ft-0 in. (2.4 m) in living and bedrooms of the residential floors and 7 ft-0 in. (2.1 m) at the parking levels, the majority of the floor slab area would only allow a structural system that was 6 in. (150 mm) thick.

The program left no room for transfer girders, so the tower column locations had to satisfy residential unit layout requirements while still being able to maximize parking count. This combination of requirements resulted in two primary column grids on the south and north faces of the building: 22 ft-6 in. (6.9 m) at each of the two exterior bays and 33 ft-0 in. (10 m) at the four interior bays. On the east and west faces of the building, however, the tower corner columns create a span of approximately 54 ft (16 m).

The challenge was getting a 6 in. (150 mm) slab to work with spans up to 33 ft (10 m) on the north and south faces and up to 54 ft (16 m) on the east and west. Good collaborative brainstorming sessions were held with the project's architect, AHL, and general contractor, Hawaiian Dredging Construction Company, throughout the design phase of this project. On the tower's exterior, the 33 ft (10 m) upturned beam was discussed as an option to span this longer distance. This beam would provide other benefits because glazing is more expensive than concrete; the overall cladding cost could be reduced. Using concrete on the exterior would also reduce the amount of heat gain that would occur through the perimeter glazing, thereby reducing cooling loads for the residences. Selecting the beam height was based on approaching the visual effect of full floor-to-ceiling glass, reducing safety glass requirements, and having enough depth to stiffen the slab. The final height selected was 18 in. (460 mm) above the finished floor. This dimension worked well at the 33 ft (10 m) span but would still prove to be a challenge on the east and west spaces, where the span approached 54 ft (16 m).

At this longer 54 ft (16 m) span, an expressed concrete X-brace was introduced to the project that ended up doing double duty, not only contributing to the tower's lateral system but also reducing the slab span at most floors. At the widest point of the X, the node of the intersecting concrete diagonals helped to reduce the exterior span as well. At about midspan of this longest span, an interior column happened to be located approximately 11 ft (3.4 m) back from the exterior. Using PT draped in a cantilevered slab configuration off this column was used to limit deflections along the exterior face.

Beams were not an option on the tower's interior grid of columns. Because slightly lower ceilings in this area

Fig. 2—Pacifica Honolulu under construction.

were possible, a thickened band slab was used to span the long 33 ft (10 m) dimension. A wide, shallow 8-1/4 in. (210 mm) deep band was selected to achieve this span. The 2-1/4 in. (57 mm) additional depth was easy to form using a standard 2x4 on its side and 3/4 in. (19 mm) plywood deck, and would create a desired span-depth ratio of at least $L/48$ and have minimal impact on ceiling height. The overall floor system, including the upturned beams and shallow band slabs, were modeled in 3-D to verify both serviceability and strength.

Through the use of PT and creative thinking, tight floor-to-floor requirements, minimized floor thickness, and a very efficient structure was achieved (Fig. 3). "That green thing" was accomplished and resulted in a very efficient 863,000 ft^2 (80,200 m^2) tower with average reinforcing bar consumption of 6.3 lb/ft^2 (300 Pa) and average PT consumption of only 0.60 lb/ft^2 (29 Pa), which are both approximately 15% less than average compared to other towers in Honolulu.

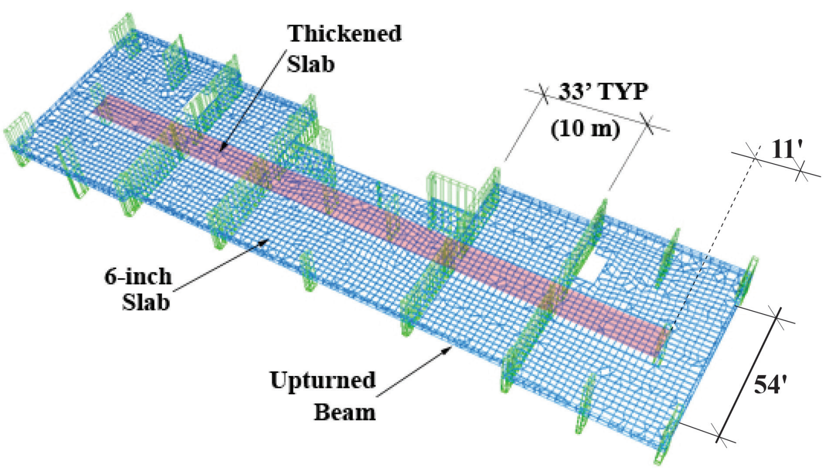

Fig. 3—Pacifica Honolulu typical floor 3-D analysis image.

SUNSET TOWER (KO'OLANI)

The original design for the Sunset Tower project, 1969, included 47 stories within a 400 ft (120 m) height limit. This required floor-to-floor heights of no greater than 8 ft-6 in. (2.6 m) at the residential floors to leave extra height at the lobby and amenity floors. The typical tower floor included a single loaded corridor so all the units would face the ocean.

In the original design, the architects pushed the columns out to the exterior, as is commonly done. In this configuration, the column-to-column span became quite long, requiring a slab thickness of 8 in. (200 mm). Fortunately, on this project, the construction manager, Brett Hill Incorporated, and architect, Benjamin Woo Architects, were collaborative as well and column locations could be adjusted to reduce the slab spans.

The final layout included moving the columns in from the slab edge to create a shorter span with cantilevers at each end (Fig. 4). The dimension of the cantilever was set on one side by the width of the corridor and then was matched on the other side of the building to create a symmetrical layout. This cantilevered layout reduced slab moments and deflections. It also increased the amount of PT drape that could be achieved, as the overall drape was limited to half the slab thickness in the initial single span condition. By simply moving the columns inward, the slab thickness could be reduced from 8 in. (200 mm) down to 5-1/2 in. (140 mm), while the overall PT drape would increase from 3 in. (76 mm) in the simple span 8 in. (200 mm) slab down to 3-1/2 in. (89 mm) in the 5-1/2 in. (140 mm) cantilevered slab configuration. The thinner slab would have better

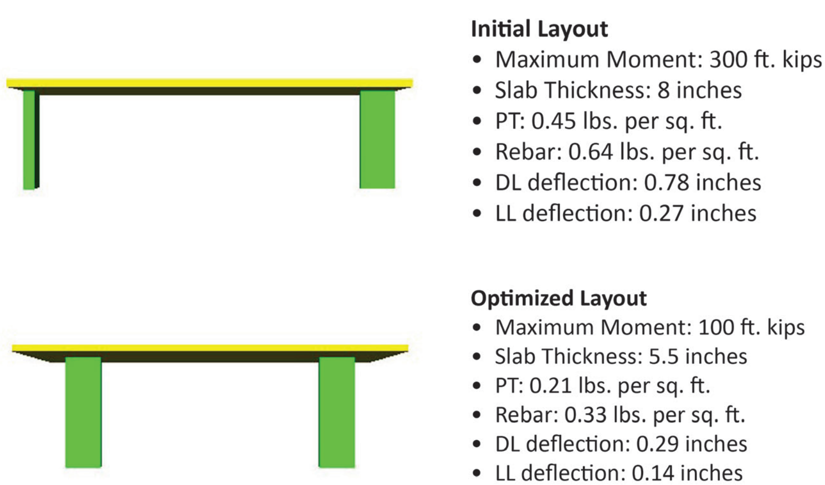

Fig. 4— Sunset Tower column location comparison (quantities for one span direction). (Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN.)

performance characteristics along with lower concrete and PT requirements, resulting in a very efficient structure (Fig. 4). The material use requirements for the floors alone was a 30% reduction, doing the "green thing" before LEED was even a thing.

803 WAIMANU

While not a tower, the eight-story 803 Waimanu urban infill project, currently under development, was severely limited by site restrictions, including an overall height of 65 ft (20 m), limiting floor-to-floor heights to only 8 ft-1 in. (2.5 m). Designed as a loft-type affordable project, ceiling heights could only be 7 ft-6 in. (2.3 m) clear with an overall floor system that could only be, at most, a maximum of 6-1/2 in. (165 mm) thick. This project was originally designed as a stick-framed building using load-bearing light gauge walls supporting a shallow composite concrete topped metal deck floor system spanning approximately 12 ft-6 in. (3.8 m).

A new general contractor became involved as the project progressed and recommended looking at the project as a more conventional PT concrete-framed structure with vertical supports at every other unit wall, resulting in spans of approximately 25 ft (7.6 m) (Fig. 6). The width of each wing of the building was approximately 58 ft (18 m). To reduce the number of columns while still being able to work with a relatively thin slab, columns were set in from the face of the building approximately 5 ft (1.5 m) creating a cantilever; the middle row of columns would be placed such that the interior spans were limited to 25 ft (7.6 m). With a maximum interior bay size of 25 x 25 ft (7.6 x 7.6 m) and some assistance from the cantilevers, it was determined that a 6-1/2 in. (165 mm) thick slab could meet both strength and serviceability requirements. The resulting PT slab was efficient at an average prestress P/A level of 180 psi (1240 kPa). An additional benefit of the PT concrete structure over the load-bearing light gauge wall system was a reduction in the extent of load-bearing elements at the foundation level. Having fewer discreet columns at the foundation reduced the overall number of piles required for the building. The required depth, size, and reinforcement of grade beams were also significantly reduced, as these would no longer be needed to transfer load-bearing light gauge walls to supporting piles.

TIPS FOR DESIGNING THIN PT SLABS

There are several factors to consider in the design of PT slabs. The three primary considerations are strength, serviceability, and constructability. These are the same when designing thin PT concrete slabs; however, more attention may need to be paid to constructability.

The following are some tips to consider:

- The thickness should be appropriate for the span. Following this simple rule will typically yield satisfactory strength and serviceability performance—keeping in mind that also means thinner slabs can be appropriate for shorter spans or lower load requirements. An old rule of thumb was to use a slab thickness with a span-depth ratio of approximately $L/48$. This span-to-thickness ratio will typically work for slabs with lower live loads, such as parking decks and residential floors and a slightly rectangular bay. For example, for parking decks with bay sizes of 30 x 27 ft (9.1 x 8.2 m), a 7-1/2 in. (190 mm) thick slab should work comfortably. For heavier live loads, square bays, and long end bays, slightly thicker slabs may be required, starting at approximately $L/45$. If the slab design is working with an average amount of prestress of approximately 150 to 250 psi (1030 to 1720 kPa), that will be a good indicator of an appropriate slab thickness.
- Don't be afraid to discuss with the architect and owner some minor adjustments in column locations. Moving columns in from the exterior of the slab, for example, can result in a shorter end span along with a cantilever that can help reduce moments and deflections in the end span. In addition, the PT tendon drape can be maximized in spans adjacent to a cantilever.
- Using repetitive banded slabs in rectangular bays, or when necessary for some longer spans, can yield very efficient floor systems. Depending on the contractor's preferred forming system, band slabs, when properly proportioned, can be relatively simple to form. The band slab dimensions should consider typical

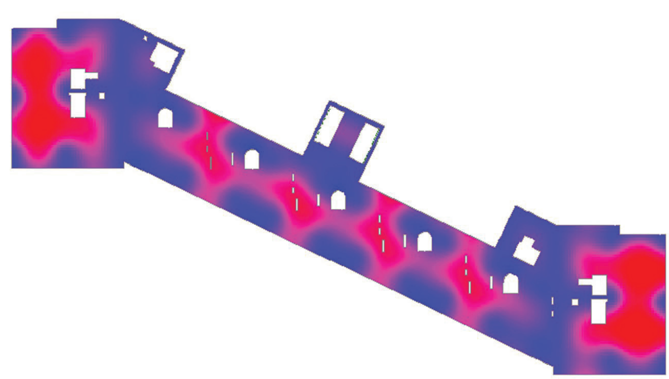

Fig. 5—Sunset Tower slab deflections.

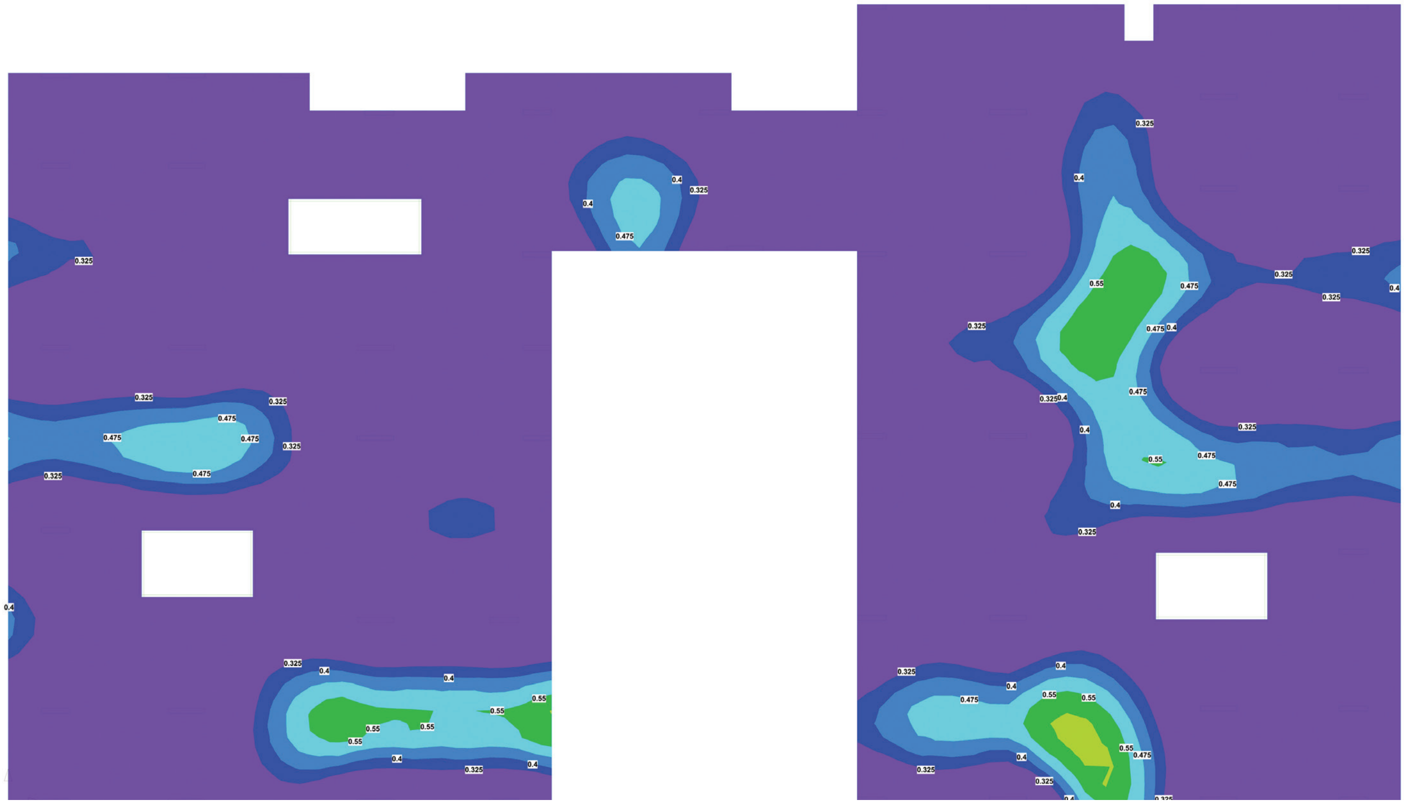

Fig. 6—803 Waimanu slab deflection plan.

plywood forming widths and thicknesses along with the grid spacing.

- Consider making some slab thickness transitions in the structure with the project team. While it is typically easier to form a true flat-plate slab with no transitions, the benefits of making a thickness transition for an occasional longer span or heavily loaded area may outweigh the additional labor. BASE conducted a peer review of a parking deck with 30 ft (9.1 m) spans where the PT slabs were designed throughout at a relatively thick 9 in. (230 mm). During that review, it was noticed that there happened to be one small area in the floor plan where the end span was 33 ft (10 m) long, which was the driver for the thicker 9 in. (230 mm) slabs throughout. This one bay represented less than 10% of the overall floor area. By transitioning to a thinner slab outside of this bay, savings could be found for the remaining 90%.
- As with any slab system, serviceability, particularly deflections, must be verified. This may not be as critical for parking decks, but it can be the controlling design criteria for exterior bays in residential and office uses where glazing tolerances demand tighter deflection criteria or interior bays where floor finishes require smaller deflections. In some cases, deflections may need to be limited to half of what the code allows.
- Regarding constructability, more attention should be paid to what is happening in and around the tendon anchors when designing thinner slabs. Anchors may need to be placed horizontally rather than vertically, thus taking up more space in the anchorage zones. Standard hooks, per ACI 318, of the additional bonded top reinforcement required by code will also likely need to be turned on an angle at the slab edge to fit within the thinner slab, which will take up additional space as well. Additional coordination may be required for other embedded items such as glazing anchors, which might be needed in these areas.

Steven Baldridge, *P.E., S.E., LEED AP, is the Principal and Founder of BASE with offices in Honolulu, Chicago, Florida, and Guam. He has 37 years of experience as a structural engineer and is a former Director of the Applied Technology Council and charter member of the Structural Engineering Institute. He studied PT under Antoine Naaman and Ned Burns and started his career in Chicago designing PT apartment towers, office buildings, and parking structures. That background was the "base" of a career that includes 50 high-rises, most using PT concrete, in a diverse range of uses from affordable workforce housing and luxury apartments to transit-oriented mixed-use projects.*