POST-TENSIONED CONCRETE

PRINCIPLES AND PRACTICE

THIRD EDITION

K. DIRK BONDY & BRYAN ALLRED

Post-Tensioned Concrete
Principles and Practice

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Preface

Writing this book has been a labor of love and it actually began back in the mid-1990s, though I didn't realize it at the time. Much of the early chapters were written when I was teaching *Prestressed Concrete Design* at California Polytechnic State University at Pomona. I was a young man at the time, but I was lucky enough to have access to some of the greatest post-tensioned concrete engineers in the world. Over the years Bryan and I have learned the *art* of designing and detailing post-tensioned concrete from men such as my father, Ross Ellena, Ed Workman, Merrill Walstad, Florian Barth and Chris Deetz. We both owe a tremendous debt of gratitude to all these men for sharing their wisdom. I also want to acknowledge Trailer Martin, C.K. Allen, Bob Englekirk and Jim Cagley who were friends of my father before I even knew I wanted to be a structural engineer and offered opportunities and served as role models for me throughout my developing career.

Like most structural engineers in the post-tensioned concrete industry, Bryan and I were waiting for my father to write this book. But when it became clear that he wasn't going to, we decided to step up and take on the challenge. The book is a combination of history, academic notes intended for use at the university level, design examples straight from actual jobs that Bryan and I have designed and practical applications and detailing intended for the practicing engineer. Chapter 1 describes the history of post-tensioned concrete in the United States as only my father can tell it. Chapters 2 through 8 are currently the notes that I use to teach *Design of Prestressed Concrete Structures* at UCLA. Chapters 9 through 13 are practical design examples in which we attempt to address many of the decisions faced by practicing engineers on typical projects including proper computer analysis and modeling techniques. Chapters 13 and 14 contain the true art of detailing and observing the construction of post-tensioned concrete. This knowledge was obtained over many years of working on our own projects and from listening and learning from the men who were the pioneers of post-tensioned concrete. Chapter 15 is a thorough discussion of the slab on grade industry, which represents more sales of post-tensioning tendons than all other post-tensioning applications combined. And finally, Chapter 16 discusses arguably the most fun and challenging application of post-tensioning – external post-tensioning.

I want to acknowledge and thank my 2012 UCLA CEE 143 students for helping me iron out the class notes, and in particular Mr. Ryan Nakamoto and Mr. Christopher Smith for their reviews of the design example chapters.

K. Dirk Bondy

This book reflects what Dirk and I do on a daily basis as structural engineers who specialize in post-tensioned buildings. When my children ask me what I do for a living, I will give them this book and say "This should explain it." We tried to cover every detail from the beginning theory of balanced loads to what to look for during the final structural observation. Over the years, we have engineered small residential foundations to large hotels and everything in between. If it's in a building and post-tensioned, we have designed it, seen it constructed and tried to describe how to do it in the following chapters. As Dirk wrote, we have both been extremely fortunate to be mentored by literally some of the best post-tensioning engineers in the world. This book was written by them as much as us and will hopefully help other engineers learn the *art* of post-tensioning.

Bryan Allred

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History of Post-Tensioned Concrete in United States Building Construction

by Ken Bondy

Post-Tensioning – What's That?

It was the fall of 1963. I was 23 years old. I had completed the course work for my Master of Science degree in Civil Engineering at UCLA, and I was almost finished with my thesis. I was barely surviving on my meager teaching assistant salary. All things considered, it was time to…***get a job***.

I was living at the time in the San Fernando Valley, north of the UCLA campus, where I grew up. I hoped that my first professional job could be in that area. So out came the *Yellow Pages*. I sent a brief résumé to all of the structural engineering firms in the Valley, and I got about ten responses. I had interviews at all of those ten firms, and soon had offers from five of them. All of the firms were offering about the same salaries and benefits, so I had little objectively with which to make a decision. But there was something unique and unusually appealing about one of the firms. I felt a good connection with the engineering supervisor who interviewed me. His name was Ray Itaya, and the firm's name was T.Y. Lin & Associates. Ray offered me a job and I accepted.

My very first introduction to prestressed concrete came in one of my graduate structural analysis courses at UCLA. The introduction lasted about fifteen minutes, and consisted of calculating some flexural stresses at midspan in a simple-span beam. I had no idea prestressed concrete was about to become my life's work. It's funny; many of the crossroads in our lives are passed without realizing their importance, without sensing that the path we choose will change everything to follow. Seemingly inconsequential decisions and events make profound changes, and yet often we do not realize their significance at the time. When I accepted the job at T.Y. Lin & Associates in 1963 I did not know that I would be introduced to post-tensioned concrete by ***the*** pioneering U.S. firm in that new field. I did not know I would learn the fundamentals of prestressed concrete design from T.Y. Lin himself, who was becoming the most respected individual in the history of prestressed concrete in this country. I did not know that the decision to go to work for this firm would change my life forever.

My career as a specialist in the design and construction of post-tensioned concrete buildings spanned almost the entire history of their use in the United States. I missed a few years when tendons were predominantly used in lift-slab construction, but I did get involved in several lift-slab projects and I got to know many of the people in the lift-slab industry.

I was moved and flattered when my son Dirk, who is also a specialist in post-tensioned concrete (bad genes?) and an outstanding structural engineer, asked that I write the first chapter of this book. In the following pages I will address the major landmarks which molded the present U.S. post-tensioned concrete building industry.

Thanks to Lift Slabs!

The U.S. building post-tensioning industry owes its existence to lift-slab construction. The first lift-slab buildings were built in this country in the mid-1950s using non-prestressed slabs. Problems were encountered during lifting in these early slabs because of their weight, and large deflections developed after construction due to flexural creep. Post-tensioning was being widely used in European bridges at that time, and the first post-tensioned bridges had been built in the United States and were functioning well. Post-tensioning offered a potential solution to the problem of weight and deflection in lifted slabs in buildings. The problem was that all of the existing post-tensioning systems available were in Europe, and most of those systems were heavy bonded multi-strand systems not suitable for slab construction. One of the European systems, however, held some promise for use unbonded in thin slabs. That was the BBRV or "button-headed" tendon system. This system consisted of parallel-lay ¼" diameter high-strength (240 ksi) wires which passed through a steel bearing plate and an externally threaded stressing washer, with "buttons" cold-formed by impact on the ends of the wires. The buttons were anchored against the outside face of the stressing washer, which attached to a hydraulic ram that elongated the wires and applied the stress. The prestress force was held by steel shims inserted between the stressing washer and the bearing plate.

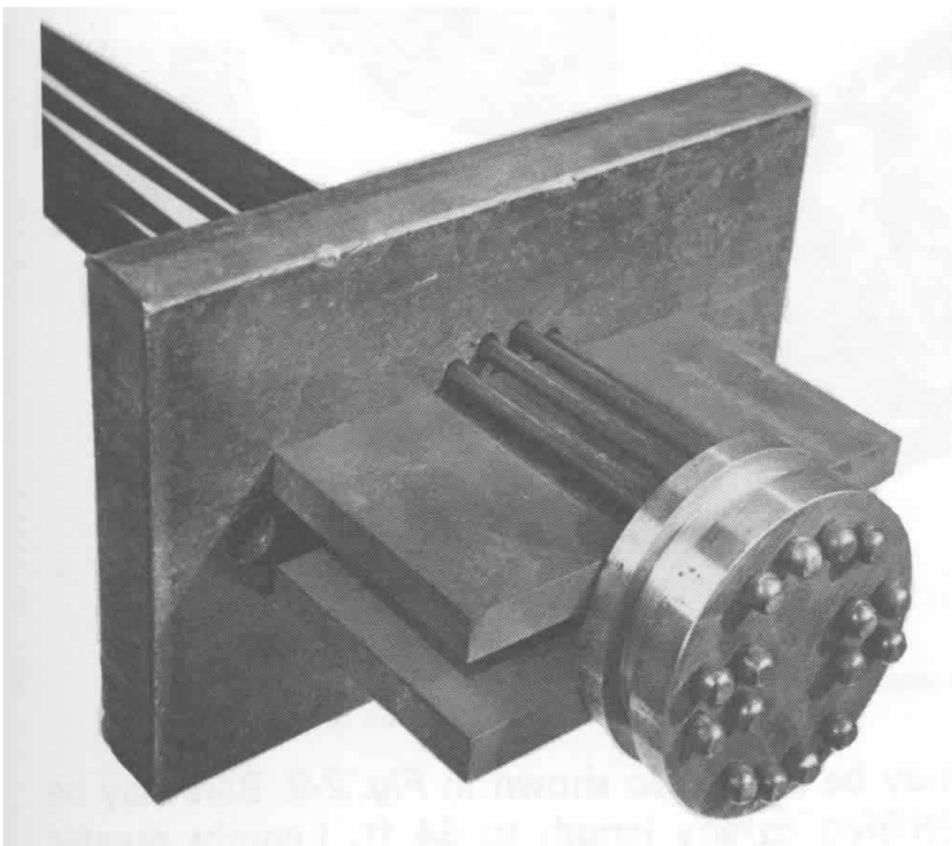


Fig. 2-3 – Button-head anchorage, stressing end, non-grouted

Button-Headed (BBRV) Anchorage

To address the problems of weight and deflection, each of the early lift-slab companies went to Europe and returned with a license to fabricate and use an unbonded BBRV tendon system. Some "independent" companies (not involved in lift-slab construction) also obtained BBRV licenses and began to engage in the general marketing of post-tensioned buildings; those included Prescon, Ryerson, American Stress-Wire, and a few others.

Post-tensioning slabs in lift-slab buildings reduced their weight by about 30 percent, making lifting easier, and solved the deflection problems. For a short time the lift-slab industry thrived and many quality lift-slab buildings were built. However, while solving some problems, the button-headed tendon system created others. First, since both dead-end and stressing-end anchorages were attached in the factory, button-headed tendons had to be fabricated to a precise length between slab edge forms, with very little tolerance. If the as-delivered tendon length was shorter or longer than the length between edge forms, either the tendon had to be replaced with another one of the correct "exact" length, or the edge forms had to be moved.

Next, button-headed tendons required some type of stressing pocket at their stressing-end to cover the shims and stressing washer which protruded out from the bearing plate. Some contractors used a continuous edge strip to cover the anchorages; others preferred a "saw-tooth" arrangement with a pocket at each anchorage. But in both cases a second concrete pour was required to fill the pockets or the continuous edge strip.

Finally, button-headed tendons required bulky and expensive couplers when intermediate stressing was required. The coupler was usually provided in the form of a large high-strength steel stud, externally threaded, that screwed into an internally threaded hole in the stressing washer. Tendon friction in wire tendons at that time limited stressing lengths to about 80 feet from one end, and twice that, or about 160 feet, from two ends. Any building longer than 160 feet in either direction therefore required an intermediate construction joint, intermediate tendon stressing, and expensive couplers. Most buildings required such a joint.

The First Strand Post-Tensioning System

The first strand post-tensioning system used in the U.S. was developed in the early 1960s by Edward K. Rice, the president of T. Y. Lin & Associates. The T. Y. Lin firm did consulting work for many precast concrete plants, and of course they all used seven-wire strand for prestressing steel, anchored at the bulkheads with various types of wedge anchors. T. Y. Lin & Associates had begun designing buildings with some post-tensioned members, and Ed was keenly aware of the construction problems with the button-headed tendons on those projects. Through his familiarity with the use of strand in precast/prestressed concrete members, he also recognized that the use of a strand system with wedge anchorages would solve all of the problems inherent in the button-headed system. Responsive to all of this, Ed designed and patented the first wedge anchorage for use with seven-wire strand in post-tensioned applications. He formed a separate company to market the strand system. That company was called Atlas Prestressing Corp. Ed sold Atlas to Harold D. Long, a young engineer working for T. Y. Lin & Associates at the time, and Hal became its first chief executive. Atlas was based in Van Nuys, California. Through my design work at T. Y. Lin & Associates I became enthralled with post-tensioned concrete as a structural system, and familiar with Atlas as a company. I joined Atlas in 1965, after about three years with T. Y. Lin & Associates.

Atlas, under Hal Long's leadership, introduced the strand post-tensioning system to the U.S. construction market in 1962. Although competition with the button-headed tendon firms was fierce, Atlas met with much success because the strand system eliminated all of the construction problems inherent in the BBRV tendons. The strand system did not require exact length; the strand could be cut a few feet longer than the finished slab length, and the excess strand was simply trimmed off after stressing. The strand anchorages did not require formed stressing pockets or edge strips. A small two-piece round rubber “grommet,” positioned between the anchorage and the finished edge form, recessed the anchorage a few inches back inside the slab from the edge. When the grommet was removed after concrete placement, it formed a round hole into which the jack nosepiece was placed when the strand was stressed. A portion of the grommet also filled up the space inside the anchorage, preventing ingress of cement paste from the back of the anchorage during concrete placement. After stressing and cutting off the excess strand just inside the finished face of the concrete, the small hole was simply filled with grout and finished flush with the slab edge. Stressing at intermediate construction joints was easy; the strand was cut to the full length of the slab and an intermediate anchorage was simply slid onto the strand and stressed at the intermediate construction joint using open-throated stressing jacks. The remaining length of tendon was then rolled out into the next pour.

That is not to say that the first strand system was completely problem-free. The first strand-wedge anchorage consisted of a coil of high-strength wire with a tapered shape to receive the wedges. There was no bearing plate used with this anchorage; the small steel plate shown was used only to attach the anchorage to the forms with nails passing through the nail-holes. The prestressing force was transferred to the concrete not by bearing but by the direct tensile resistance of the concrete to the lateral forces generated by the wedges on the inside surface of the coil. This required significant concrete tensile strength in the anchorage zone.

Coil Anchorage

Many concrete breakouts occurred when coil anchorages were stressed. These breakouts were particularly prevalent in lightweight concrete, which was widely used in California in the 1960s. Often, in the early Atlas years, a few of us would gather together in the office after work and discuss the events of the day. Occasionally our field superintendent, Tom Anderson, would stop by, and he would invariably be bruised and bloodied from repairing the current day’s coil anchorage breakouts. Referring to the coil anchorages, Tom started saying that the *“…damn things should be chained together…”* That caught on, and eventually became the theme for an award that was given to the Atlas Employee of the Year at our annual Christmas party. Here is the Thomas E. Anderson Award in all its glory:

The Thomas E. Anderson Award

It became obvious to Hal Long that the coil anchorage had to be replaced with a bearing-type anchorage. Dick Martter, an extremely talented mechanical engineer and one of the first Atlas employees, stepped up to the plate and, with help from Hal, developed the first ductile iron casting. It went into service for the first time in 1965, the year I joined Atlas. The use of ductile iron, a casting material with ductile properties, permitted a bearing plate surface to be combined with the "barrel" ring containing the tapered hole housing the wedges in a single casting piece. The development of the ductile iron casting was a huge event in the history of post-tensioned building construction, and ductile iron castings similar to the original design by Martter continue to be used as the industry standard today.

The Battle Between Strand Systems and Button-Headed Wire Systems

Contractors quickly recognized the advantages of the strand system, and with a philosophy of good service and dissemination of structural design information to practicing structural engineers, Atlas grew rapidly. However, competition from the established button-headed tendon firms was vicious. It was Atlas versus everybody else, and after a fierce five- to six-year struggle, Atlas eventually won the battle of the marketplace by the late 1960s, and all of the surviving button-headed tendon firms switched to strand systems. Button-headed tendons became extinct in the U.S. construction industry, and virtually all post-tensioning in building construction has been with strand tendons with wedge anchorages since 1970. In a ten-year period from the mid-1960s to the mid-1970s Atlas grew from the smallest to the largest of the U.S. post-tensioning firms with division offices throughout the country and an operation in Western Europe based in Amsterdam.

What Happened to Lift Slabs?

The concept of lift-slab buildings was a good one. It eliminated concrete forming, a major component of concrete building cost, and had many other inherent advantages. The cost of the specialized equipment could be amortized over many buildings. However, the lift-slab companies, in my opinion, made a fatal marketing mistake which forever affected their penetration into the construction market. They combined the cost of the lifting with the cost of the tendons into one bid price which was provided to the general contractors on each new building project. This meant that independent post-tensioning companies could not bid on lifted projects. The lifting companies would not expose the tendon price, and therefore a tendon bid submitted by an independent post-tensioning company was meaningless because there was nothing with which to compare it. This had short-term advantages for the lifting companies; it allowed them to shield their tendon prices from competition from other tendon firms. But the practice had serious long-term consequences for the lifting industry, and eventually resulted in the downfall of what could have been a major construction industry.

Since independent tendon companies were excluded from bidding on lift-slab projects, our company, Atlas Prestressing Corp., decided to form alliances with the emerging flying form industry and provide a bid to the generals for a completely cast-in-place building. Joint promotion between Atlas, flying form companies, and progressive concrete contractors allowed direct competition with lifted buildings. The use of cast-in-place post-tensioned buildings using large-panel flying form systems was highly competitive with lifted buildings (particularly with their inflated tendon prices), and by the late 1960s cast-in-place buildings became preferred to lifted buildings, and lift-slab construction largely faded into obscurity.

I believe that if the lift-slab companies had encouraged competition from independent tendon companies, instead of trying to exclude them, lift-slab construction, with all its inherent advantages, would be a significant factor in today's medium-rise building market.

Landmarks in Post-Tensioned Buildings

Looking back over my long career as a specialist in post-tensioned concrete, I would cite the following as the most significant developments affecting the growth and use of post-tensioned concrete in U.S. building construction:

The introduction of the strand/wedge system to replace the button-headed tendon system

The development of the ductile iron casting for single-strand unbonded tendons

The introduction of the "load-balancing" method for the design and analysis of post-tensioned concrete members

The introduction of the "banded" tendon system for two-way post-tensioned slab systems

The formation of the Post-Tensioning Institute

The use of computers in the design of post-tensioned buildings

The first two landmark events, the introduction of the strand system and the development of the ductile iron casting, have been discussed above. Following is a brief discussion of the others.

Load Balancing and Teaching Engineers How to Design

Perhaps the most important single event in the history of post-tensioned concrete building construction was the introduction of a simplified method for the design and analysis of complex, indeterminate post-tensioned concrete members called "load balancing." This was done in a paper written by T. Y. Lin himself, published in 1963 in an ACI Journal paper. It involved mentally removing the tendon from the concrete member, and replacing it with all of the forces that tendon exerts on the concrete. T. Y. didn't invent the load balancing method, but he did more than any other individual to explain it and disseminate information about its use. The concept was brilliant, easy to understand, and greatly reduced the mathematical drudgery involved in other design and analysis methods. It made the design of post-tensioned concrete members as easy for the practicing engineer as the design of non-prestressed concrete members. This design simplicity encouraged structural engineers to select post-tensioned concrete as the preferred framing method.

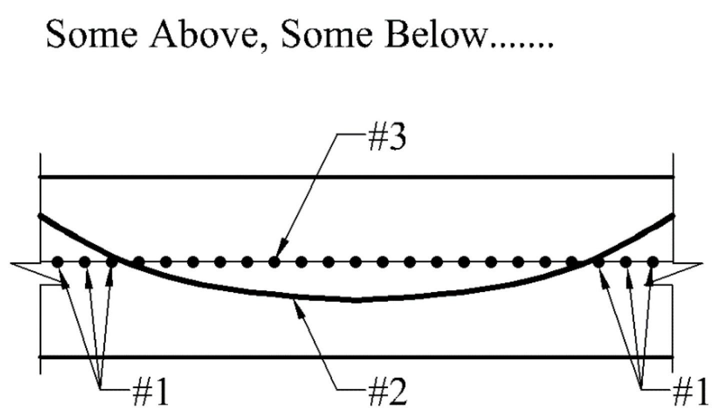
Even though information was available about load balancing and simplified design methods for post-tensioned structures, engineers were not quick to pick it up, and the growth of post-tensioning lagged in the early to middle 1960s. Almost all the design work was being done by T.Y. Lin & Associates and a handful of other firms. Atlas Prestressing Corp. was the first firm to recognize that the growth of the post-tensioning industry was dependent on disseminating effective design techniques to practicing structural engineers. The structural engineer was the primary decision-maker on the use of post-tensioning, and if he or she was not familiar with P/T design, the building was unlikely to be post-tensioned. Atlas, primarily through its president Hal Long, knew that the best way to increase sales of post-tensioning was to teach engineers how to design it.

Thus, for a ten-year period starting in the mid-1960s, on behalf of Atlas I presented more than one hundred one-day design seminars to invited groups of practicing structural engineers. They were held in most major U.S. cities and in Western Europe and Japan. They were free of charge to the attendees and we provided them lunch and cocktails at the end of the day. We would walk the audience through a detailed, state-of-the-art design of several typical post-tensioned concrete framing schemes, one a two-way slab in a residential building, and one a post-tensioned parking structure. At the seminars I would make it known that Atlas was willing to provide free in-house design assistance for these engineers to help them with their designs.

We would start getting calls from attendees within weeks of the seminars (*"I've got a job here where post-tensioning might work, can you come in and take a look at it??"*) In their seven U.S. division offices, Atlas developed a staff of more than 100 licensed engineers to handle this design assistance work, and the other design services we were providing (mostly on design/build projects). It was not unusual for Atlas to register a sale of post-tensioning tendons within one year of, and directly as a result of, the design seminars. Occasionally that happened in as little as six months. The seminars were wildly successful and were the primary reason that Atlas grew, in less than ten years, from the smallest to the largest post-tensioning firm in North America.

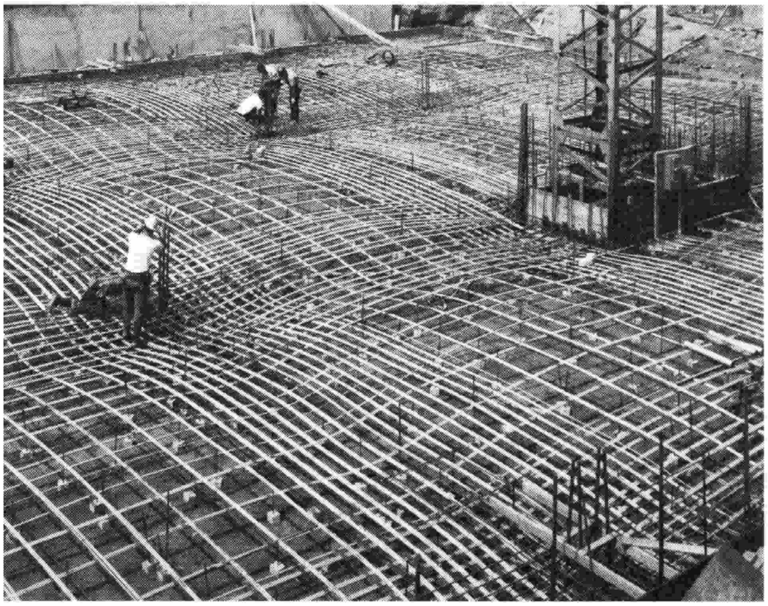
Banded Tendons

Two-way post-tensioned slabs have been a popular type of framing in concrete building construction. When this type of framing started to be commonly used, tendons in two-way slabs were installed in each of two orthogonal directions with some located in the "column strip," an imaginary area centered on the column lines and extending one-quarter of the bay width on either side of the column. The remaining tendons were installed in the "middle strip," the area located between the column strips. Since the tendons were "draped" in a curved vertical profile (generally parabolic), high at the column lines and low at midspans, each individual tendon would typically have some perpendicular tendons above it, and some below it, as shown in the figure below. This tendon arrangement was generically known as a "basket-weave" system.



Basket-Weave Tendon Profiles

In order to install such a system of woven tendons, the tendon detailer had to locate and identify the single tendon which was below all other perpendicular tendons. That tendon, or group of tendons, was identified on the placing drawings as tendon sequence #1. Next the detailer found the tendon in the other direction which was below all other perpendicular tendons, with the exception, of course, of tendon sequence #1. That tendon, or group of tendons, was identified as tendon sequence #2. All tendons in the slab were identified in this manner with a sequence number. Each tendon had to be installed with the precise sequence number, or a bird's nest of tendons would result and the tendons could not be chaired at the proper heights. Often slabs would have 30 to 40 sequence numbers. An example of a sequenced "basket-weave" two-way slab (in this case a foundation mat) is shown below:



Two-Way Foundation Mat with Basket-Weave System

In 1968, the most famous post-tensioned building in history was built. Its primary fame was not because it was post-tensioned, but because of what eventually happened in it. It was the Watergate Apartments in Washington, D. C. Yes, the very same one you are thinking of. Watergate is also famous for another reason; it was the first building ever built using a two-way post-tensioned slab with a new and innovative tendon distribution, which came to be known as the "banded" tendon distribution.

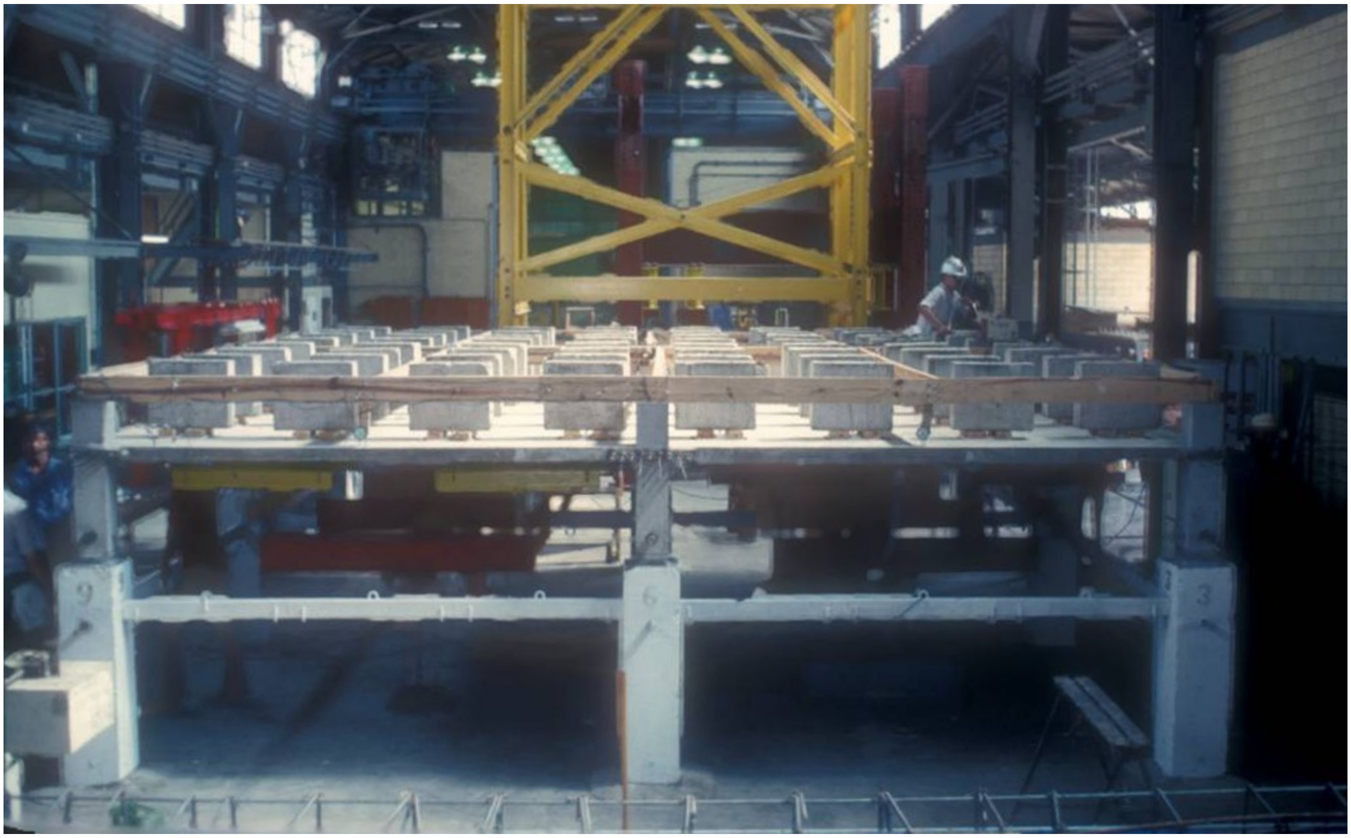
The Watergate

In the architectural design of the Watergate building, the floor plan was curved and columns were located randomly in areas which substantially hid them, including walls, duct spaces, closets, etc. The resulting column layout did not line up in either direction. No column was spaced any farther than about 22 feet from any other column; however, the concepts of gridlines, column strips, and middle strips were meaningless. The structural designers of the slabs (a joint effort of T. Y. Lin & Associates and Atlas Prestressing Corp.) were perplexed because, using conventional two-way slab techniques, there was no obvious path for slab loads to columns. Someone in the team suggested connecting columns in one axis of the building with imaginary straight lines between individual columns, and thinking of those lines as a series of beams, or hard points. A "band" of tendons could be run along that line connecting columns in one direction, then in the other direction tendons could be spaced uniformly over bands. With this concept, the load path became obvious, and the forces and profiles for both the band tendons and the uniform tendons could be easily calculated.

This tendon layout, with all of the post-tensioning tendons in one direction located in a narrow band over columns, and tendons distributed uniformly with no regard for imaginary column strips and middle strips, had never been done before. However, the Watergate design team saw no alternative and the design and construction proceeded with the unique tendon layout. The performance of the slabs appeared to be good, and the tendon installer reported a significant savings in tendon placing costs when compared to the conventional "basket-weave" system. The primary labor savings resulted from the elimination of tendon sequencing. In this new banded layout, ***all*** of the band tendons were placed first, and then ***all*** of the uniform tendons. Ironworkers did not have to place individual series of tendons, alternating in each direction, according to a complex sequence.

Typical Banded Tendon Layout

Since the Watergate Apartment building, built almost forty years ago, the banded tendon layout has become the standard method for placing tendons in two-way post-tensioned slabs. The adequacy of the banded tendon layout has been confirmed by the functional performance of hundreds of millions of square feet in service, and numerous laboratory tests, starting with a landmark testing program at the University of Texas at Austin in the early 1970s, supervised by the legendary professor and researcher Dr. Ned H. Burns.



Four-Panel Test at University of Texas

Formation of the Post-Tensioning Institute

Engineers, contractors, and material fabricators in the post-tensioning industry recognized early that they needed an industry organization to represent their interests and to disseminate design and construction information relative to this specialized field. From the late 1960s through the mid 1970s the post-tensioning industry was represented as a group within the Prestressed Concrete Institute (PCI), now the Precast/Prestressed Concrete Institute. However, as the industry grew, it became apparent that a separate organization, dedicated solely to post-tensioned concrete design and construction, was needed.

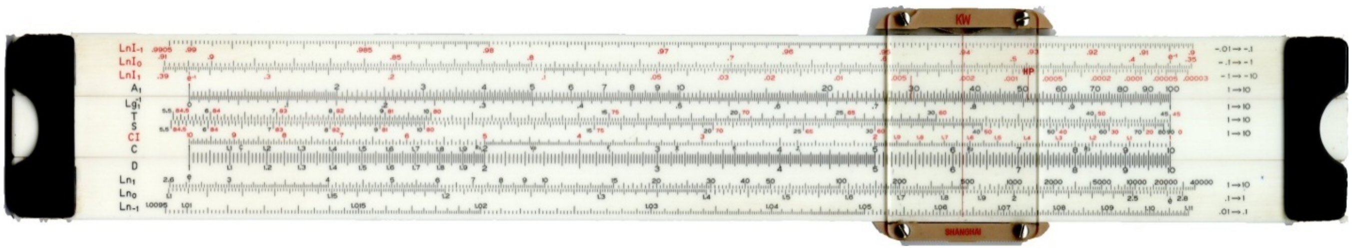
Pursuant to this, the Post-Tensioning Institute (PTI) was formed as an independent organization in 1976. Now thirty years old, PTI provides all those with an interest in post-tensioned concrete a single unified voice and source of design and construction information. Since its founding, PTI has been guided by three extremely talented Executive Directors: Cliff Freyermuth, Gerry McGuire, and its current Executive Director, Ted Neff.

PTI has matured and grown as the industry has grown. PTI now publishes a Journal with informative articles about post-tensioning design and construction issues, and holds well-attended annual engineering conferences. In many cases, PTI documents and committee reports establish the standard of care for design and construction of post-tensioned concrete structures. PTI is now recognized internationally as the premiere source of information about post-tensioned structures worldwide.

Computers

No discussion of the history of post-tensioning in U.S. buildings would be complete without addressing how it was influenced by computers.

When I graduated from UCLA in 1963, and started my first engineering job with T. Y. Lin and Associates, my primary mathematical tool was a slide rule.



Slide Rule

My slide rule could multiply and divide, but it didn't know where the decimal point was. I had to figure that out myself. Now, 50 years later, I can do a dynamic analysis of a 40-story building, with all the decimal points in the right place, on a flight between San Francisco and Los Angeles, on a laptop computer about the size of a book…..while sipping a glass of Shiraz. Just kidding about the Shiraz; I would never do that.

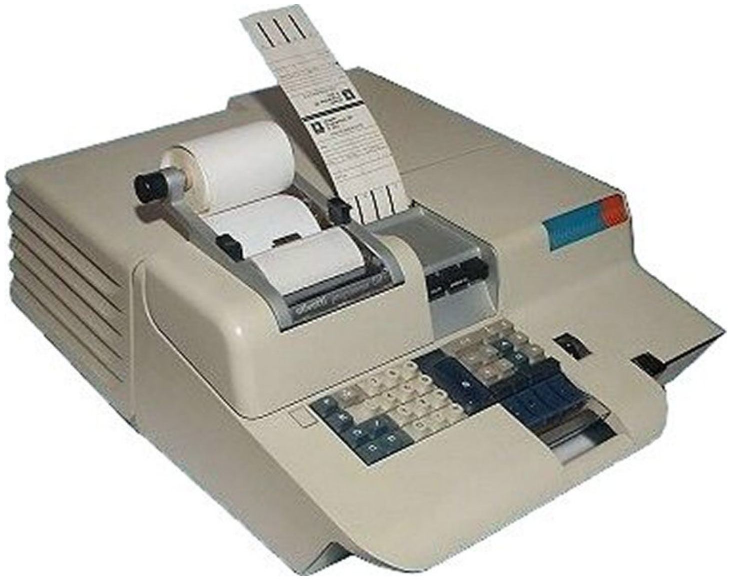
Just in one lifetime the changes in computing power have been astonishing. From slide rules to personal computers the size of a notebook (with more power than the original mainframe computers that took up an entire air-conditioned large room), the improvements in computing power are breathtaking!

Let's take a look at my personal journey through this whirlwind of technology.

The Dawn of the Computer Age

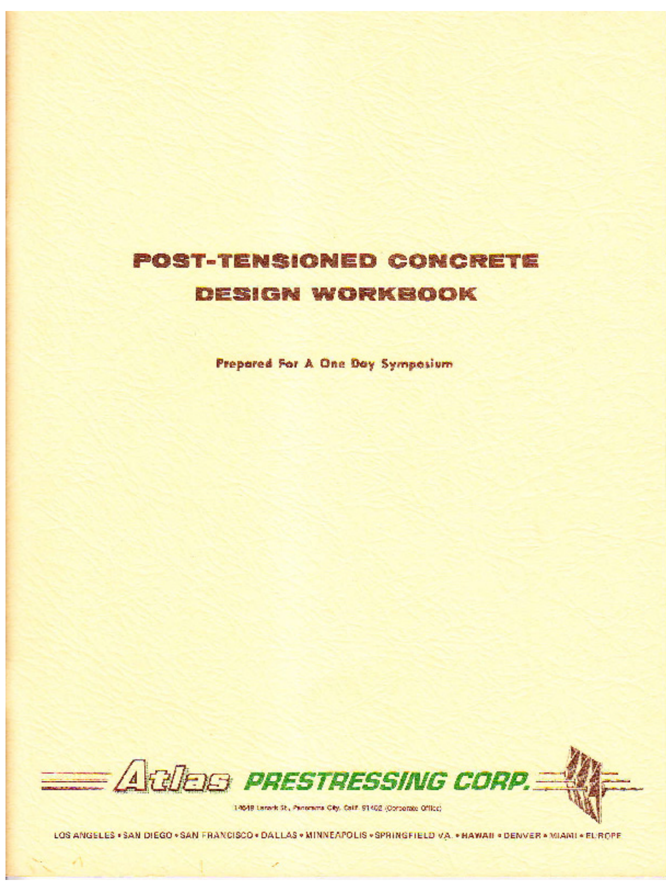
My first contact with machine-assisted design came in 1966, when I was employed by Atlas Prestressing Corp., and I was introduced to the Olivetti Programma 101.

The Olivetti was like a giant hand calculator. It was 19" wide, 24" deep, 7.5" tall, weighed 78 pounds, and, for the first time, showed the potential for machine-assisted calculations. It sold in 1966 for about \$3,500. It could add, subtract, divide, multiply, and calculate a square root. It could record and execute a limited number of program steps on plastic magnetic cards, and the output data was printed on a roll of calculator paper, like an old "adding machine." There was no programming language; communication with the Olivetti was in machine language (enter a number into the X-register, arrow up into the Y-register, divide Y by X, store the answer in register ZZ).



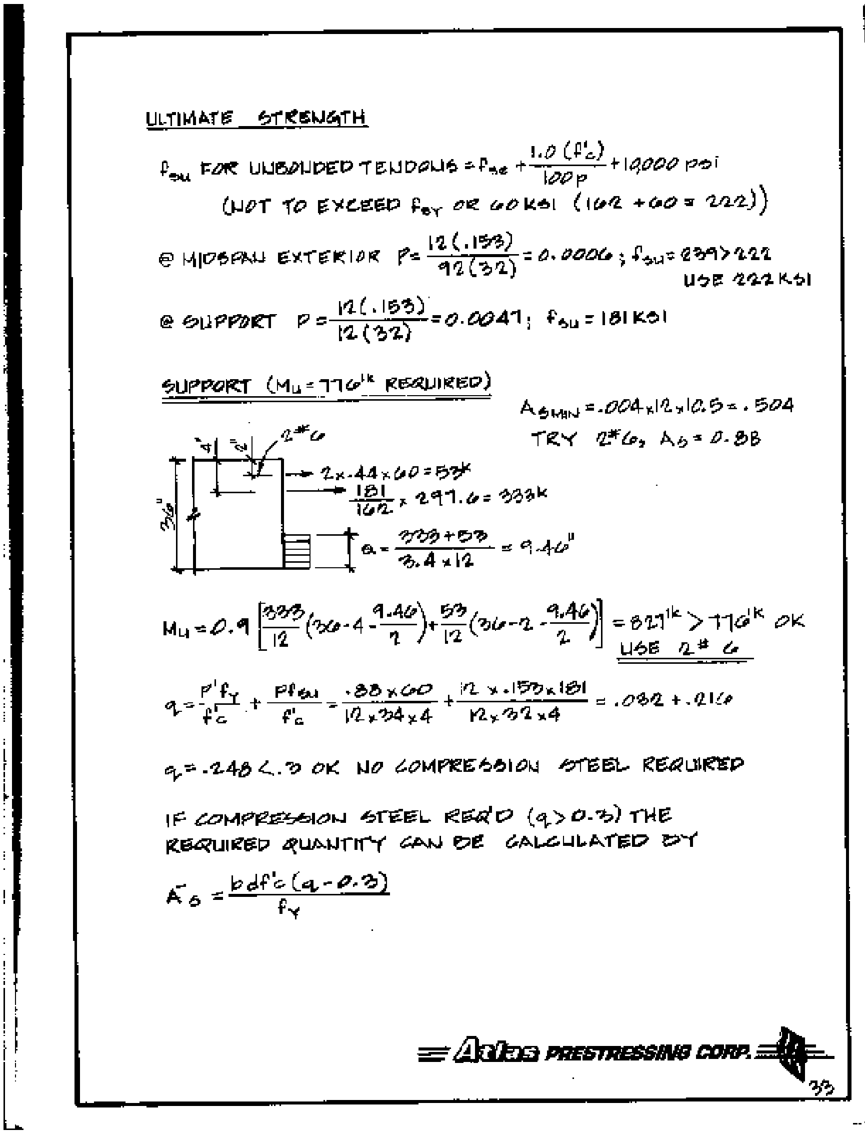
<u>Olivetti Programma 101 (1966)</u>

We would trim and tape the output to preprinted 8.5x11 calculation sheets with predetermined locations for the input and output data. For a short time in the late 1960s scissors became a primary structural design tool. When I was with Atlas I presented a series of one-day seminars on the design of post-tensioned concrete to groups of practicing structural engineers throughout the country and in a few foreign countries. At these seminars we provided the attendees with a design workbook whose cover is shown below:



<u>Seminar Workbook Cover</u>

One of the design examples I presented was for a post-tensioned beam, such as might be used in a cast-in-place parking structure. First, I went through the hand calculations for the beam, part of which shows the design for nominal strength:



ULTIMATE STRENGTH

f_{su} FOR UNBONDED TENDONS $= f_{se} + \frac{1.0\,(f'_c)}{100\rho} + 10{,}000$ psi

(NOT TO EXCEED f_{sy} OR 60 KSI (162 + 60 = 222))

@ MIDSPAN EXTERIOR $\rho = \frac{12(.153)}{92(32)} = 0.0006$; $f_{su} = 239 > 222$

USE 222 KSI

@ SUPPORT $\rho = \frac{12(.153)}{12(32)} = 0.0047$; $f_{su} = 181$ KSI

SUPPORT ($M_u = 776^{\prime k}$ REQUIRED)

$A_{s\,MIN} = .004 \times 12 \times 10.5 = .504$

TRY 2#6, $A_s = 0.88$

$2 \times .44 \times 60 = 53^k$

$\frac{181}{162} \times 297.6 = 333^k$

$a = \frac{333 + 53}{3.4 \times 12} = 9.46''$

$M_u = 0.9 \left[\frac{333}{12}\left(36 - 4 - \frac{9.46}{2}\right) + \frac{53}{12}\left(36 - 2 - \frac{9.46}{2}\right)\right] = 827^{\prime k} > 776^{\prime k}$ OK

USE 2#6

$q = \frac{\rho' f_y}{f'_c} + \frac{\rho f_{su}}{f'_c} = \frac{.88 \times 60}{12 \times 34 \times 4} + \frac{12 \times .153 \times 181}{12 \times 32 \times 4} = .032 + .216$

$q = .248 < .3$ OK NO COMPRESSION STEEL REQUIRED

IF COMPRESSION STEEL REQ'D ($q > 0.3$) THE REQUIRED QUANTITY CAN BE CALCULATED BY

$A'_s = \frac{bdf'_c\,(q - 0.3)}{f_y}$

ATLAS PRESTRESSING CORP.

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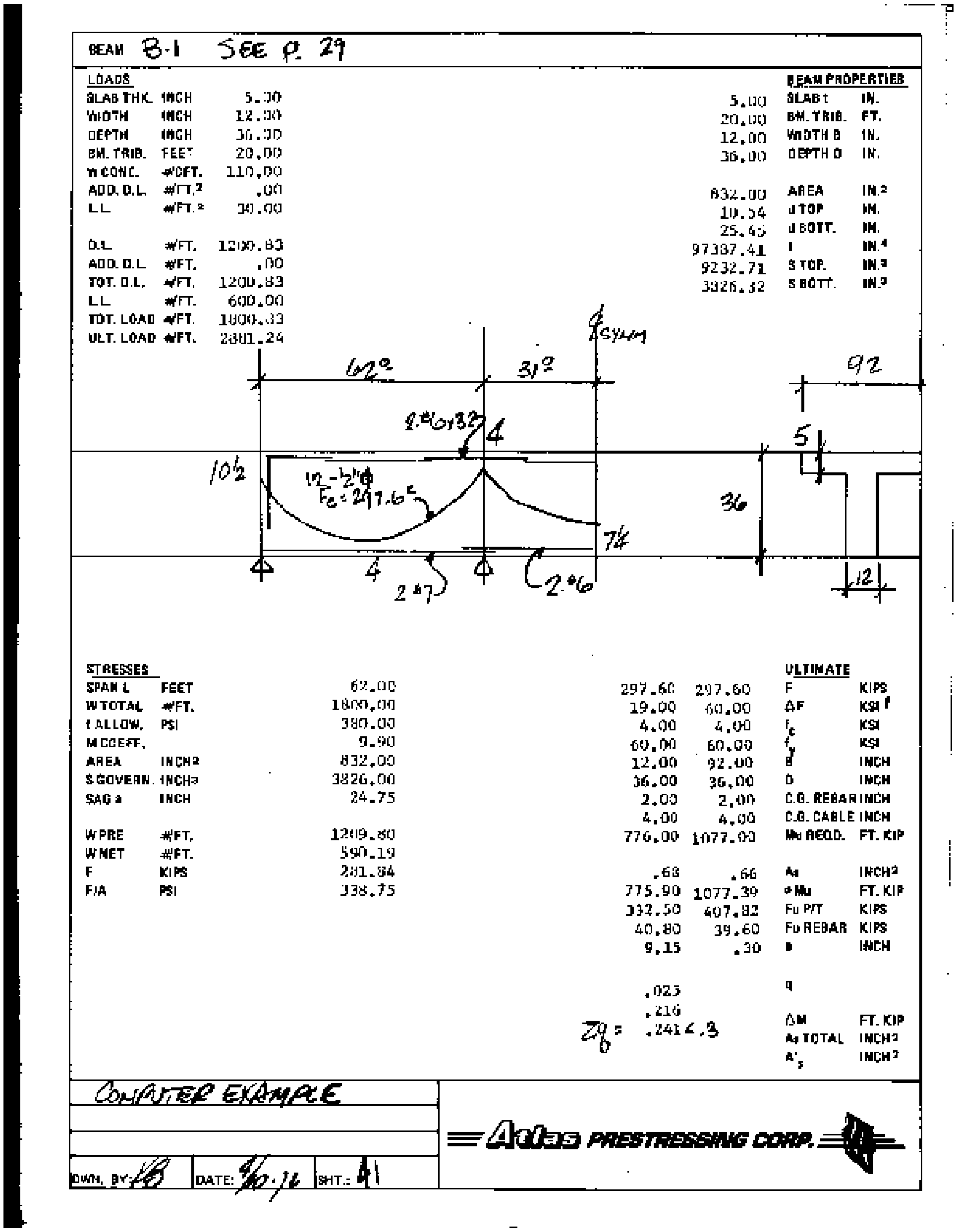
Hand Calculations for Beam Strength Design

Next, I presented a sheet which showed the way we were actually doing this type of design at Atlas, a preprinted sheet with input and output labels in prearranged locations. We had a series of recorded "programs" on magnetic cards. For beam design we had four small programs: one which calculated beam loads from input geometry and data, one which calculated section properties, one which determined the prestressing force and flexural concrete stresses, and finally, one which calculated the required amount of non-prestressed reinforcement.

We would take the output strips of calculator paper for each of the four parts of the design, trim them with ***structural*** scissors, and tape them onto the preprinted calculation sheets in the proper locations. I had the audacity to call this sheet a ***"Computer Example!"*** And I guess, in kind of a primitive way, it was.



“Computer Example”

The Wang Era

The next landmark in the evolution of computer-aided design came with the introduction of the Wang 700 series of “super calculators.” The Wangs still used machine language, but they had much more capacity than the Olivetti with many more registers and much more storage. Program steps were recorded on audio cassette tapes, and output could be printed on large sheets with an IBM Selectric typewriter. The Wang 700 machine is shown in the two figures below, the second showing it with peripheral equipment (typewriter, auxiliary tape reader) attached:

Wang 700 "Super Calculator"

Wang 700 With Peripheral Equipment Attached

With the Wang 700 series machines we could write a crude analysis program in a series of independent routines, each small enough to fit into the machine's storage capacity. When one routine was completed, we would print the input and output, then delete as much of the data as we could to make room in storage for the next routine. The answers, and some of the input from one routine, were used in the next. It was tedious, but it was better than anything else that existed at the time, and it was certainly better than doing the calculations by hand.

The Wang programs were based on analysis, not design. It simply did not have enough capacity to perform a true design involving loops, decisions, and iteration to a final design. We would input a first guess at geometry, force and profile, perform an analysis on the given configuration (calculate stresses and reinforcement), and if we were not happy with the results we would change something and start over, iterating manually to a final acceptable design. Moments and shears were calculated with 2-cycle moment distribution, done either by hand or with a programmed routine on the Wang. The capacity of the Wang did not permit the use of matrix techniques.

The First Personal Computer

Wang revolutionized the engineering world by introducing, in 1973, the first real personal computer, the Wang 2200. It had its own programming language, a BASIC interpreter, and could perform loops and mathematical decisions. It had a mighty 4 KB of random access memory (RAM); thus, it required some tedious programming. As with its predecessor the 700, with the 2200 we would input some data, do some calculations, print the answers with a Selectric typewriter, delete unnecessary data, input some more data, do some more calcs…..and so on until we got an acceptable design.

Wang 2200

Program code on the 2200 was recorded (read only) on standard audio cassette tapes, and the output printed on 8.5x11 sheets with the Selectric typewriter. For the first time, output could be printed in a tabular format with rows and columns. The Wang 2200 created some great programmers – if you could program this thing in BASIC with 4 KB of RAM you could program ***anything***!

The IBM Personal Computer

The world changed forever in 1981 when IBM introduced the first IBM Personal Computer (the "PC"). It had two floppy disk drives, each permitting both reading from and writing to the disk. Flexible printing with virtually unlimited formatting could be done on a dot matrix printer. A large monitor made input/output operation much easier. The first PC had 64 KB of RAM (luxurious, who could want more than that?) and a dazzling processor speed of 4.77 MHz. There was no hard drive. It came with a sophisticated "GW-BASIC" (nicknamed "gee-whiz") language developed by Microsoft, which also developed the disk operating system (DOS) which controlled access, storage, and all internal operations.

The First IBM Personal Computer (1981)

In 1983, two years after the introduction of the first personal computer, IBM introduced the greatly improved IBM XT. It was the first computer to have a built-in hard drive (a huge 10 MB). Along with the hard drive, the XT had two floppy disk drives. RAM was doubled to 128 KB, and the processor speed remained at 4.77 MHz.

IBM XT (1983)

The XT allowed vast improvements in programming. For the first time matrix methods became feasible, and with the increased RAM we could do true design programming with decisions and iterations to a final design. Much more sophisticated routines were possible, such as the one we developed for punching shear in two-way slabs. Finally we didn't have to spend most of our programming time juggling and printing data.

The first version of our widely used post-tensioning design program ***PTData*** was developed on the IBM PC and finalized for use on the XT. ***PTData*** was first made available to the engineering community in 1983 and eventually sold over 500 licenses. It was recently converted to Windows 64-bit and VisualBasic.net by my son's firm Seneca Software Solutions, Inc., which maintains and markets the program now.

Windows

Perhaps the most significant landmark in computer history came in 1985 with the introduction of Windows by Microsoft. Windows quickly replaced DOS as the prevalent PC operating system. Microsoft also developed an improved BASIC programming language which it called Visual Basic. third party programmers now had access to all the beautiful Windows interfaces and I/O routines. Windows was originally a 16-bit system, but changed to 32-bit in 1994 requiring a major conversion for 16-bit programs. In 2009, Windows changed again to a 64-bit system and introduced VisualBasic.net, an advanced BASIC programming language.

With the advent of Windows came huge improvements in memory, processor speed, and disk storage. RAM has increased from 64 KB on the first PC to a typical 4 GB now, an increase of more than 60,000 times. Processor speed has increased from 4.77 MHz to 1.4 GHz, an increase of about 3,000, and now with 1+ terabyte hard drives easily available and inexpensive, disk storage has increased about 100,000 times since the first 10 MB hard drive on the XT.

Post-Tensioning Design Programs

In the early 1970s the market for post-tensioning in buildings was rapidly growing. One major reason for this growth was the dissemination by Atlas of design information to practicing structural engineering firms through seminars and design assistance to those firms. More engineers were learning how to design post-tensioned buildings and, as a result, more post-tensioned buildings were being built. To handle this volume of engineering work, Atlas grew and maintained a large staff of licensed engineers (more than 100) in their various offices throughout the country.

With the availability of a true personal computer (the Wang 2200), and having for the first time the capacity to run a real post-tensioned design program, Atlas decided that it was time to develop one. The conversion of our Wang-based machine language routines to a comprehensive design program written in BASIC looked like a major undertaking. Through PTI committee work I had become friends with Merrill Walstad, the chief structural engineer for the VSL Corporation, a competitor active in post-tensioned concrete building work. Atlas and VSL made the decision to develop the program jointly, with Atlas providing most of the programming work (we had full-time programmers on staff) and VSL providing funding and support. Surprisingly, this unlikely relationship worked, and in a period of about six months the program was functional and both Atlas and VSL began to use it in-house for their design services.

Both Atlas and VSL made the decision NOT to market the program commercially, but rather to limit its use to in-house proprietary design services. However, Merrill left VSL and I left Atlas at about the same time in 1976 to start our own firms, Merrill a structural design firm (Walstad Engineering, Inc.) and me, with my partner Chris Deetz, a construction firm and a structural design firm, both specializing in post-tensioned concrete buildings (Seneca Construction Systems, Inc. and Seneca Structural Design, Inc.) Merrill and I continued the relationship we had developed at Atlas and VSL and worked together on several projects. We of course had the source code for the Wang 2200 program we developed at Atlas/VSL, and we recreated the program and used it for our own design work for about five years. In the early 1980s, when the first IBM PC was introduced, Merrill and I decided it was time to develop a state-of-the-art post-tensioning design program which would run on the PC and which we would make available to the general engineering public. To accomplish this, we formed a corporation called Structural Data, Inc. (SDI) and made the decision to call the new program "***PTData***."

Along with Merrill and me, an original SDI partner was Nick Watry, a close friend of both of ours, who was running a growing structural design firm in the San Francisco Bay Area (Watry Design Group) and who had an interest in the development of the program. As work on the program progressed, Nick's interest in SDI faded and we bought him out. I think Nick decided it was in his best interest to keep his post-tensioning expertise in-house and not make it available, through the program, to potential competitors. The buyout was amicable and Nick has remained a great friend and colleague throughout the years.

PTData was completed and first offered for sale in 1983. The original version was written in GW-Basic based on the DOS operating system. Merrill developed the original I/O routines and I did all the other technical programming. The program was converted to 16-bit Windows in 1985 and then to the 32-bit version in 1994. Merrill ran all other aspects of SDI business, sales, accounting, etc., and we jointly handled the technical support. It was an extremely successful venture and we eventually sold about 500 licenses.

PTData was the first commercially available computer program sold for use in the licensee's office. However a program called **POSTEN** was previously available (since 1971) but it was "rented," i.e. the customer filled out data forms, submitted them to the **POSTEN** office, which ran the program on a mainframe and returned the output to the customer. As powerful personal computers became available, the concept of a "rented" program became less appealing to structural firms, and the use of **POSTEN** decreased dramatically. In 1991 a licensed version of **POSTEN** was made available, but by that time it was too late to compete with the other established programs which could be run in-house on the licensee's computers.

A few years after ***PTData*** began to be sold, another competitive program called "**ADAPT**" was developed and marketed. From that time to the present day, a period of almost 30 years now, ***PTData*** and **ADAPT** have dominated the market for post-tensioned concrete design software. The last several years have also seen new software developers entering the market, mostly with very complex, three-dimensional finite element analysis programs.

In his design classes at UCLA my son Dirk effectively integrates ***PTData*** computer calculations with hand calculations, and the combination results in a very powerful learning tool for students, who today are highly computer literate. Examples of the use of the computer as a learning tool can be found in the design examples in this book, starting with Chapter 7.

In the late 2000s Windows converted to a 64-bit system and Microsoft introduced a new version of its BASIC programming language, VisualBasic.net. Our 32-bit Windows version of ***PTData*** would not run in the 64-bit environment, and faced with another major conversion and lured by retirement, Merrill and I decided to end our long run and hand our interests in the program over to Dirk's structural engineering