Post-Tensioned Concrete in U.S. Buildings

A Half-Century Overview

….in PTI's 40th year!!

By

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POST-TENSIONING INSTITUTE
Stressing the Stronger Concrete Solution™

2016!!!

- The 40th anniversary of the founding of…

The Post-Tensioning Institute

Seems appropriate now in PTI's 40th Anniversary Year…

- To reminisce about this great industry
- My experience is all in building design and construction
- Let's journey back through the history of post-tensioning in U.S. buildings…
- As seen through my eyes….

53 Years Ago…

- It was the fall of 1963
- I was 23 years old
- I had completed my MSCE course work here at UCLA
- I was almost finished with my thesis
- I was living on my meager Teaching Assistant salary
- All things considered, it was time to…..

Get a Job!!!

Out Came the Yellow Pages

- Any structural firms hiring in the San Fernando Valley (about 50 miles north of here)?
- A few were, and I was hired by one!!!
- Their name was…..

T. Y. Lin and Associates

Crossroads

- Decision to go to work for T. Y. Lin and Associates would change my entire life
- Pioneering firm in prestressed concrete
- Started a long career as a specialist in post-tensioned concrete design and construction

Exciting Time for P/T Concrete

- Had been used in buildings for only a few years
  - Mostly in lift-slab construction
- Prestressed concrete had just been introduced into ACI Building Code (1963) for first time
- In the next 50 years my career spanned every major landmark in the development of p/t concrete in buildings

Thanks to Lift-Slabs!!

- US post-tensioning industry owes its existence to lift-slab construction
- First lift-slab buildings in the US were built in the mid 1950s using non-prestressed slabs

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Problems With Early Lift-Slabs

- Problems with deflections and slab weight in long 2-way spans
- To solve deflection and weight problems, lift-slab companies changed to post-tensioned slabs
  - Reduce slab weight by +/- 30%
  - Eliminate dead load deflection

No Existing U.S. P/T Systems

- Lift-slab companies went to Europe for help
- Most existing hardware was for large grouted multistrand tendons in bridges (Freysinnet, Magnel)
- Only European system feasible for building construction with light unbonded tendons was the BBRV "button-headed" tendon system

Button-Headed Tendon Era

- Each lift-slab company returned with a license to market the button-headed tendon system
- Some “independent” companies (Prescon, Ryerson, others) also obtained BBRV licenses.

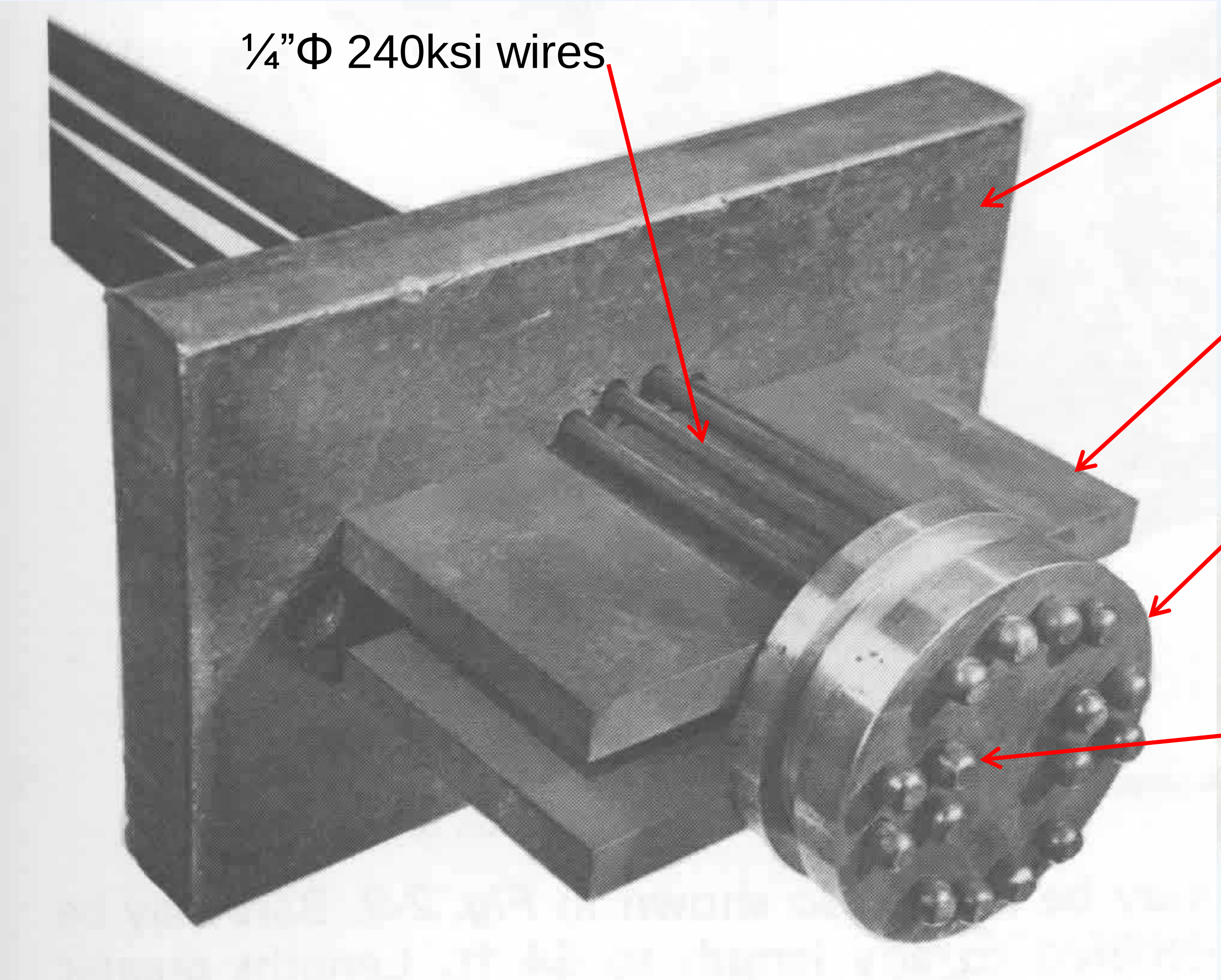


Fig. 2-3 — Button-head anchorage, stressing end, non-grouted

Button-Headed (BBRV) Anchorage

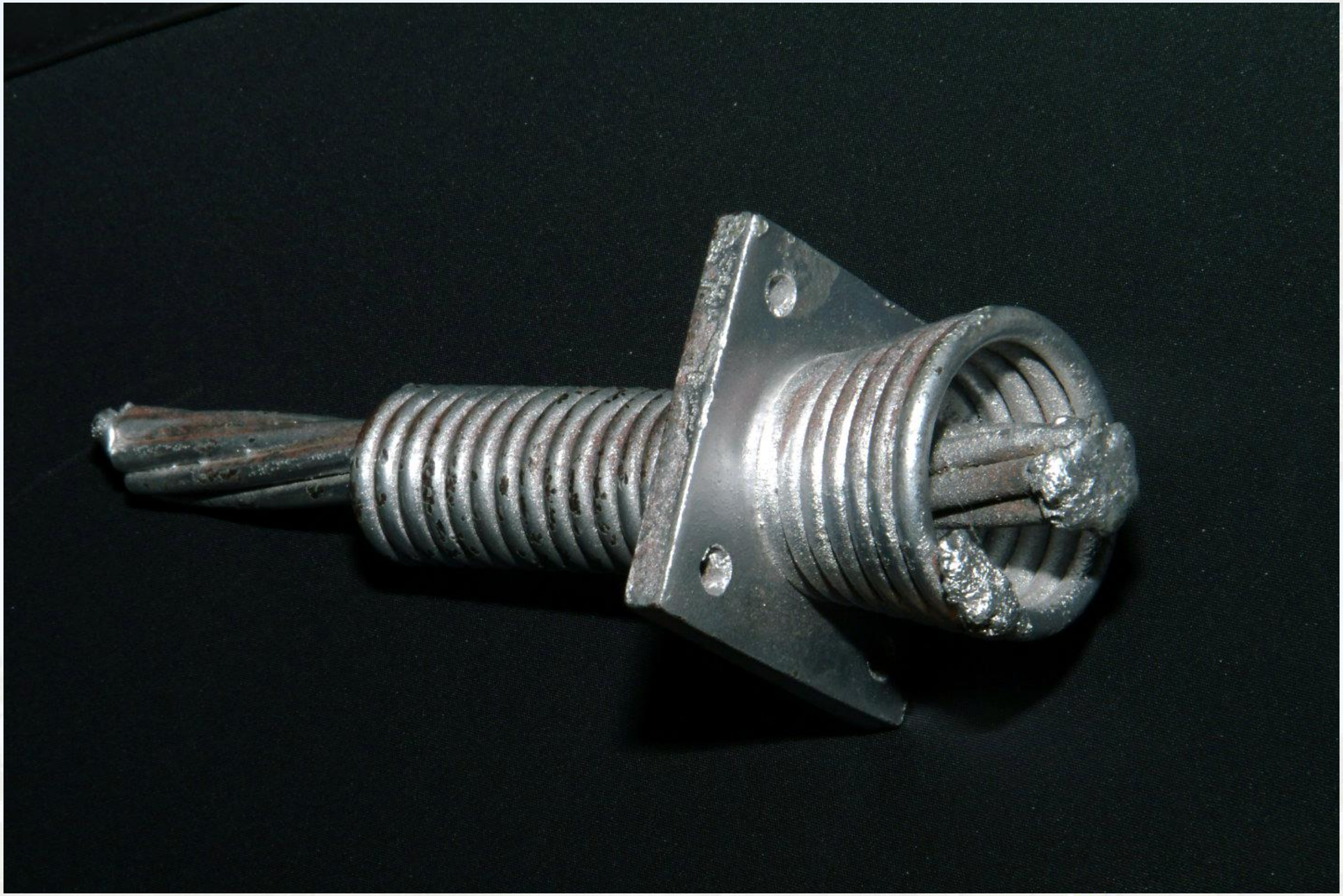
P/T Solved Deflection Problems But BBRV Tendons Created Others

- Both stressing and dead-end anchors attached in the factory
- Required exact length
- Required stressing pockets to cover shims
- Bulky and expensive couplers when intermediate stressing required

Strand P/T System Introduced in 1962

- Developed by ***Ed Rice*** (PTI Legend, president of T.Y. Lin & Associates – consulted for precast companies all using 7-wire strand)
- Introduced by Atlas Prestressing Corp.
  - Company I went to work for in 1965
- Did not require precise length
  - Tendons could be cut several feet longer than concrete length
- Did not require stressing pockets
- Did not require couplers (intermediate “slide-on” anchors)

The First Strand/Wedge Anchorage Used in the U.S.!



Relied on Concrete Tensile Strength

- Many breakouts occurred during stressing, particularly in lightweight concrete
- Atlas employees would gather in the office after work, occasionally joined by field superintendent Thomas Anderson
- Tom would be bruised and bloodied from repairing the day's coil anchor breakouts
- Started saying that the ***"…damn things should be chained together…"***

Caught on - Became the Theme for an Award…

- Given to the Atlas ***“Employee of the Year”*** at our annual Christmas party
- Named in honor of field superintendent Tom Anderson

The Thomas E. Anderson Memorial Award

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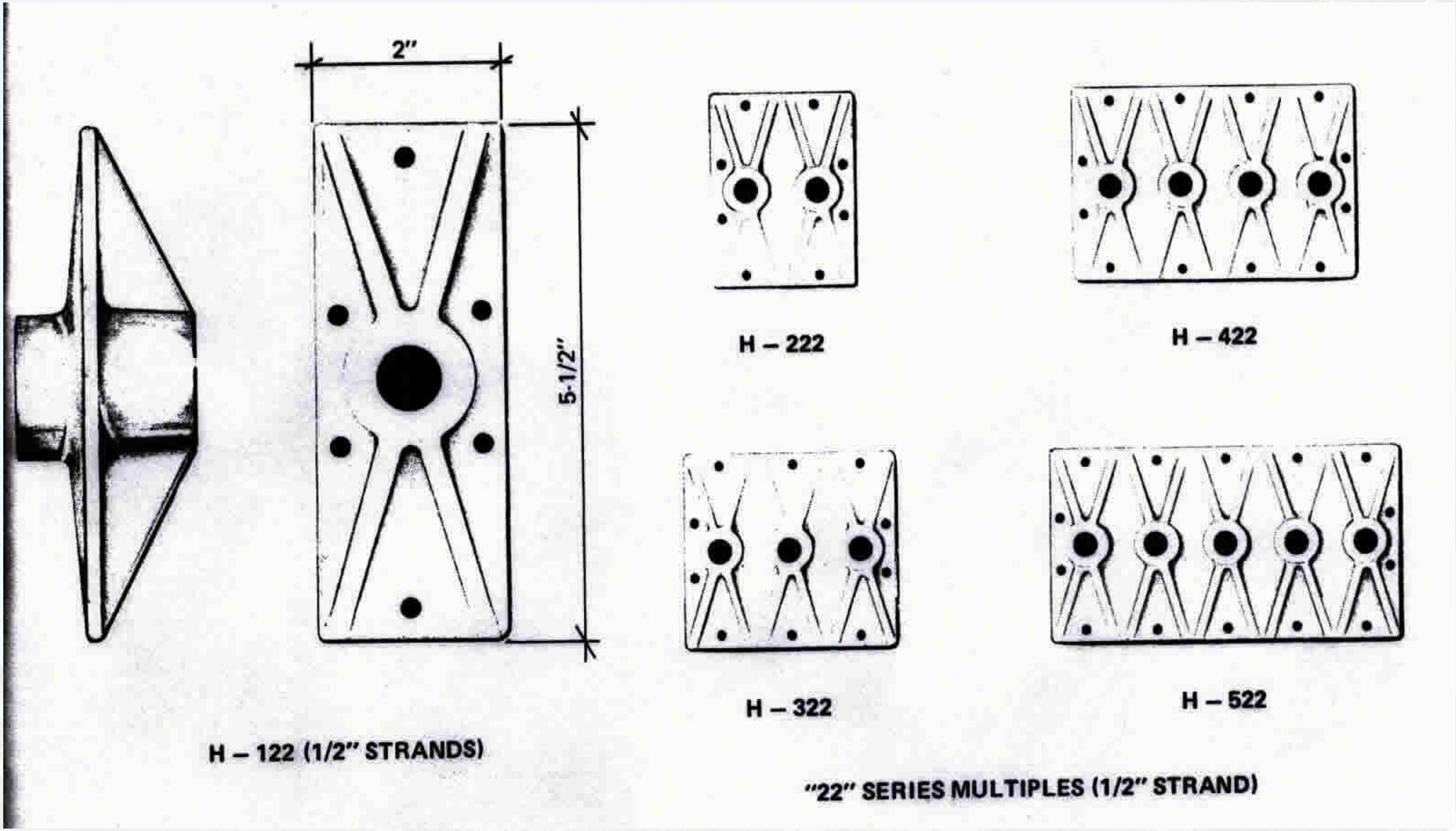
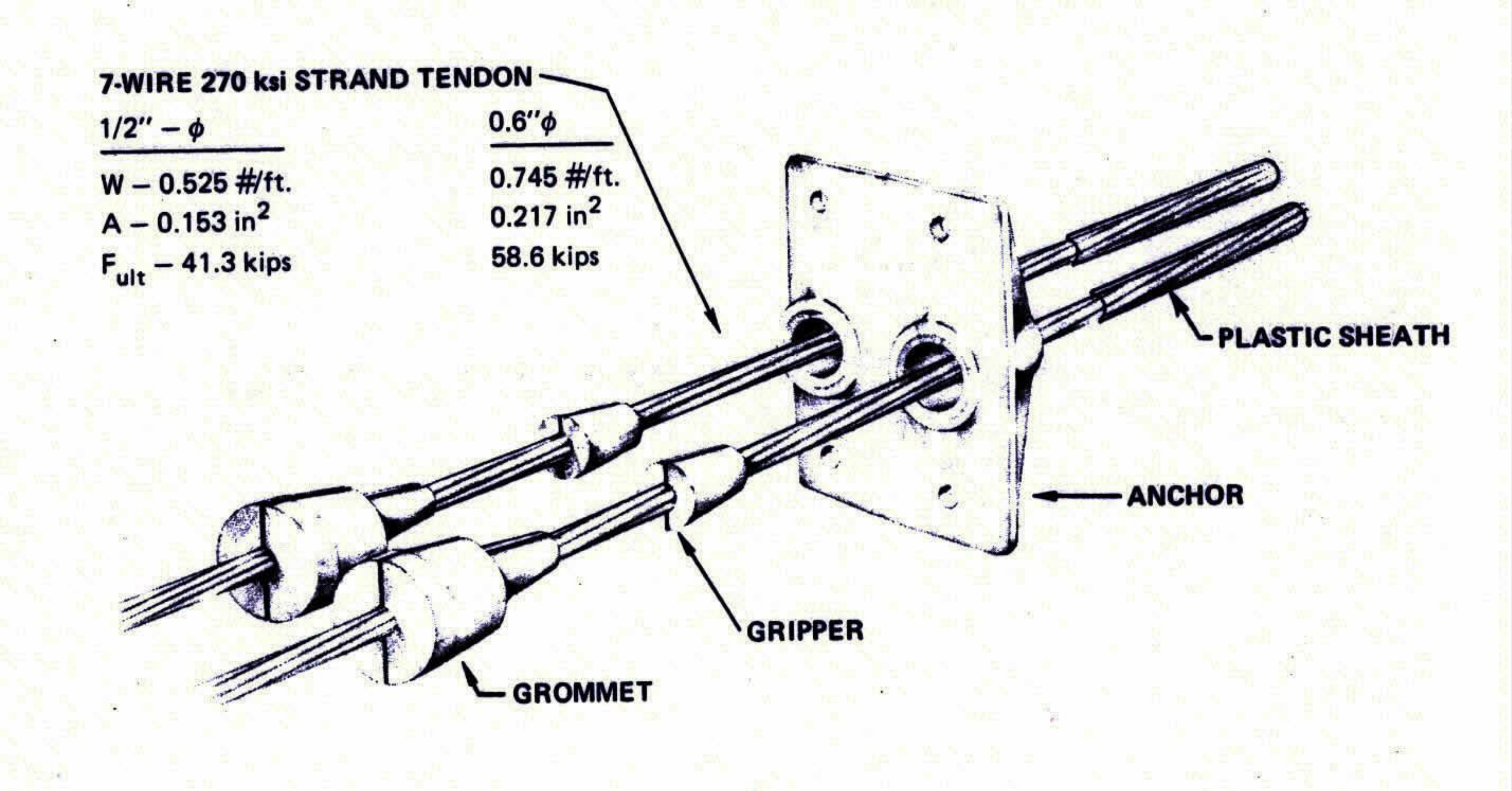
Time For a New Anchorage

- Atlas developed a bearing anchorage made of ductile iron, combined the bearing surface with the wedge cavity
- Designed by PTI Legend Richard Martter
- Introduced in 1963

Ductile Iron Castings



The Original Atlas Strand PT System



Strand System vs. Button-Head System

- Atlas vs everybody else
  - Prescon
  - Ryerson
  - Western Concrete Structures
- After fierce 7-8 year struggle, by the late 1960s Atlas had won the battle of the marketplace
- Button-headed tendons became extinct
- Virtually all building p/t has been with strand tendons ever since.

How Much Post-Tensioning?

- Based on PTI tonnage statistics from 1972 and reasonable estimates before that…
  – About 5 billion square feet of building construction with unbonded post-tensioning
  – About 50,000 post-tensioned buildings in the US
- Does not include bridges, earth applications, residential foundations

Landmarks in P/T Buildings

- Introduction of strand systems
  - Replaced "button-head" tendon system
- Development of ductile iron castings for single-strand unbonded tendons
- Introduction of "load-balancing" design method
- Introduction of "banded" tendon layout for 2-way slab systems
- Formation of Post-Tensioning Institute
- Improvements in corrosion resistance

Most Important Single Development

- The introduction of the “load-balancing” or “equivalent load” design method by T.Y. Lin in 1963
- T.Y. wasn’t the first to use it but did more than any other individual to explain it and disseminate information about it.
- Made the design of prestressed concrete as easy as the design of non-prestressed concrete – just another load
- Encouraged the selection of p/t as the preferred structural system

Building Codes

- Post-tensioning virtually absent from ACI 318-71 *(“ignore secondary moments”)*
- I joined ACI 318 in 1973
- ACI 318-77 and 83 were greatly improved
  - Reflected testing at Texas and Washington
  - Banded tendon distribution
  - Minimum bonded reinforcement requirements
  - More attention to indeterminate structures
- Codes have continued to improve with increased p/t expertise on ACI committees

Construction Advances

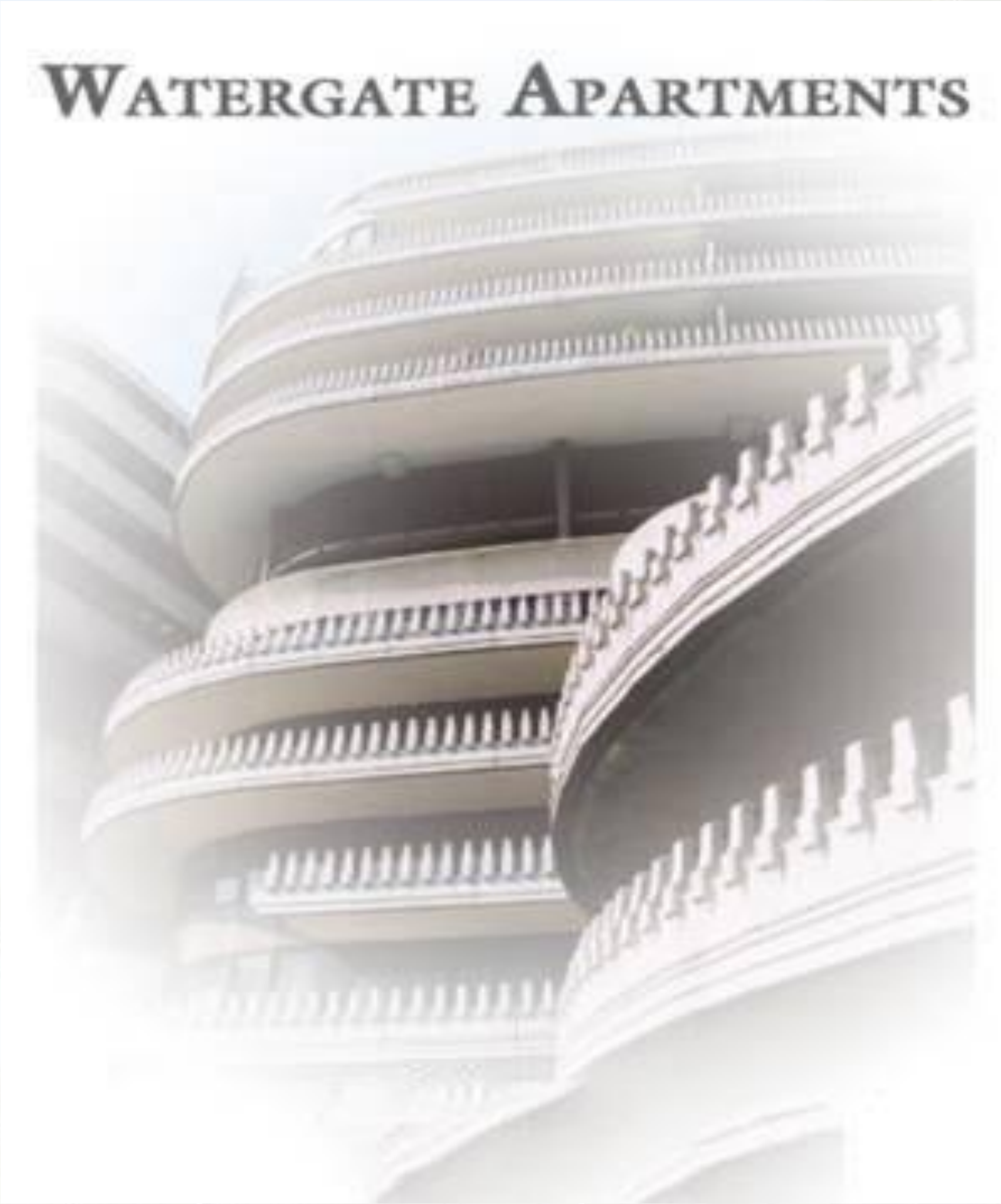
- Banded tendons in 2-way p/t slabs

Banded Tendons in 2-Way Slabs

- First used in the most famous post-tensioned concrete building ever built…

The Watergate Apartments in Washington, D.C.

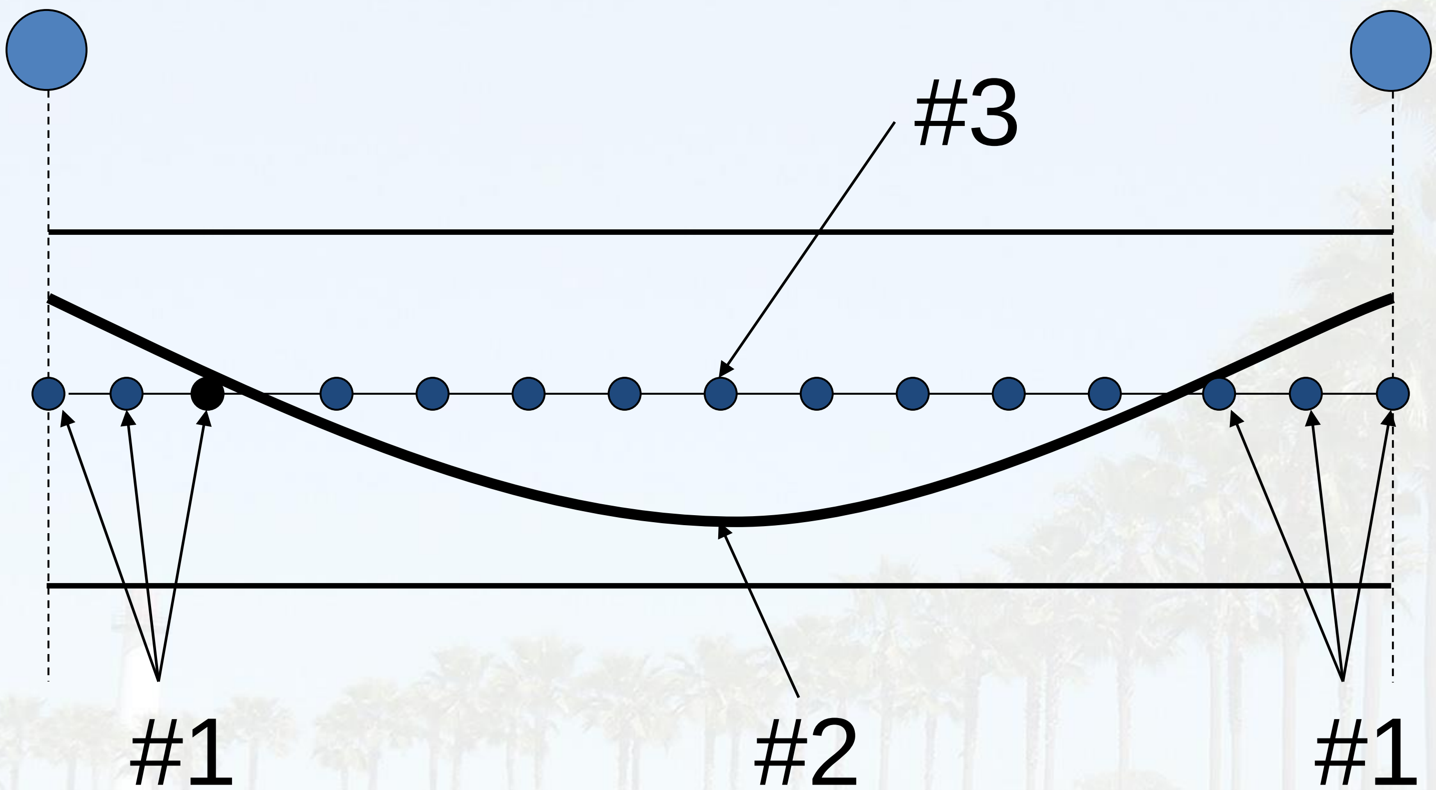
(1968)



Basket-Weave Tendon Layout for 2-Way Slabs

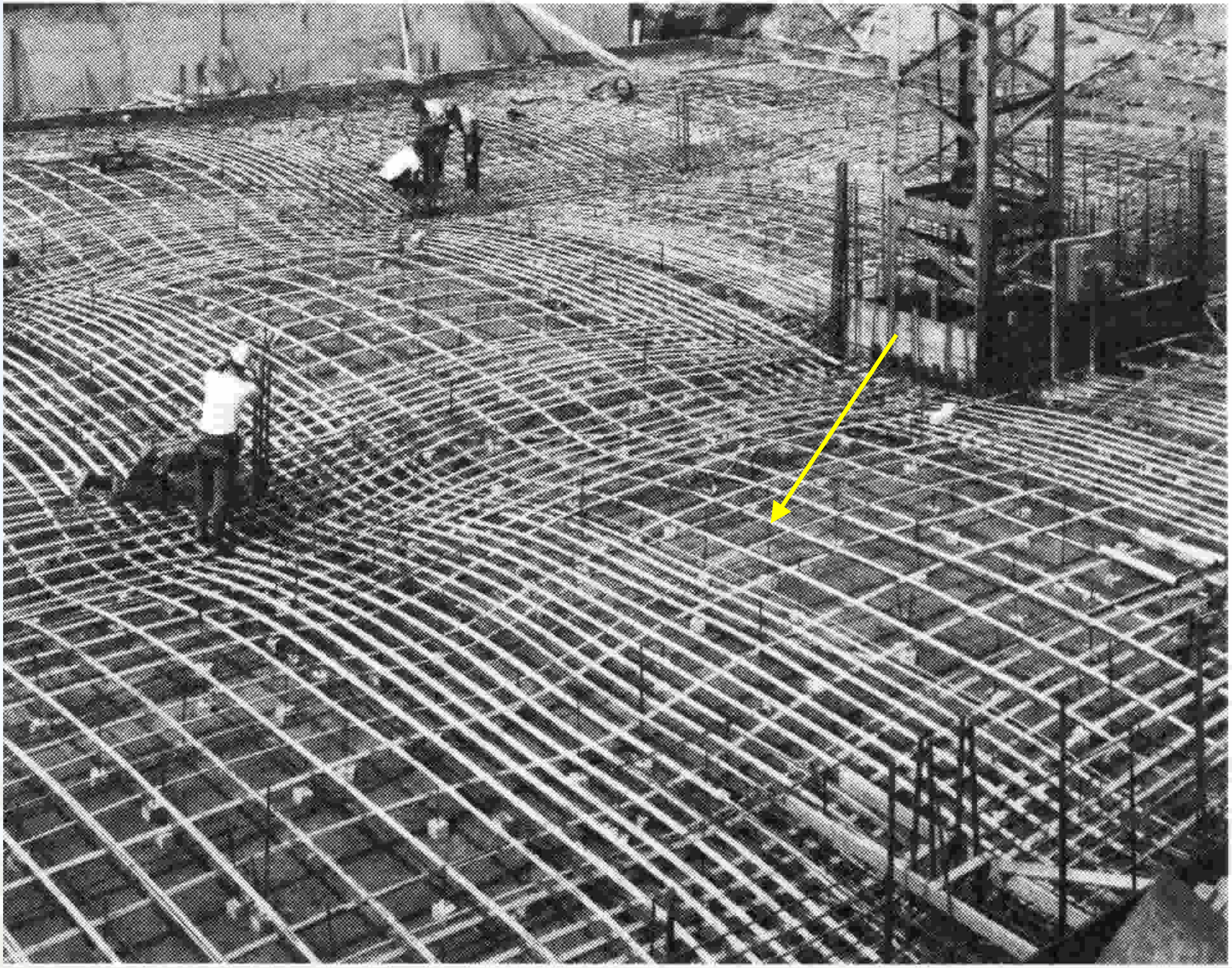
- Some in "column-strips"
- Some in "middle strips"
- Tendons were "draped" in curved vertical profile
  - High at column lines
  - Low at midspans
- A single tendon profile had some orthogonal tendons above it and some below it

Some Above, Some Below…



Sequencing

- Detailer had to find the single tendon which was below all other tendons
  - Sequence #1
- Then had to find tendon in perpendicular direction which was below all remaining tendons
  - Sequence #2
- Typical slab would have 30-40 sequence numbers



Tendons Had to be Installed in Sequence

- Any errors in placing sequence resulted in "birds-nest" when chaired

Back to Watergate…

- In the Watergate building, columns didn’t line up in either direction
- Spans were short (22’ max) but colums were located where they could be hidden with no regard to a grid system
- Building was curved, no grid-lines, column locations identified by coordinates
- Column/middle strip concept meaningless
- Load path virtually impossible to follow

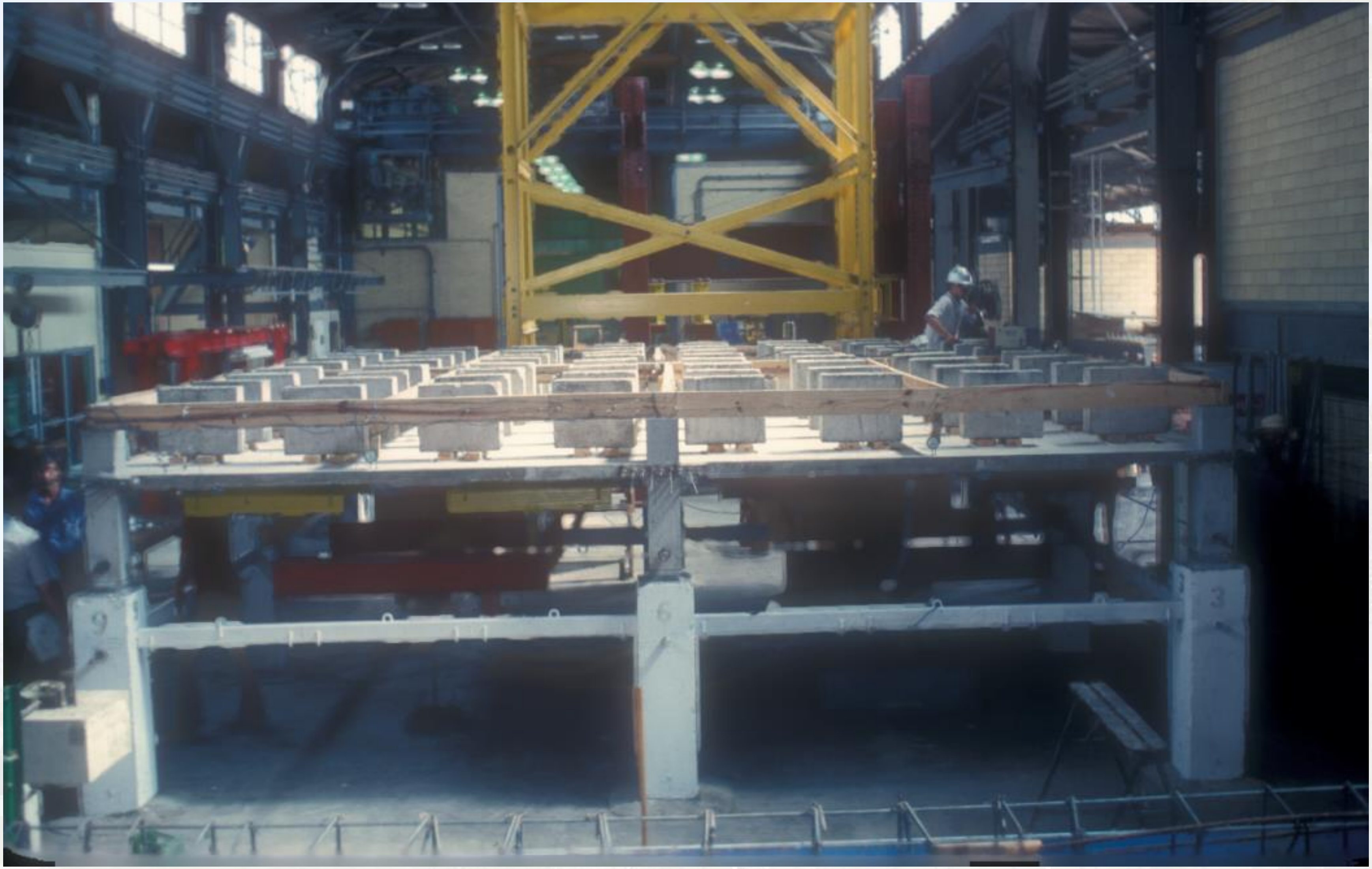
Slab Design Engineers (T.Y. Lin and Atlas Prestressing Corp.)

- Conceived the load path as a one-way slab
- Developed a tendon layout where all of the tendons in one direction were placed in a narrow “bent” band connecting columns
- All of the tendons in the orthogonal direction were uniformly distributed.
- Load path was easy to follow, like in a one-way beam and slab system

It Worked!

- And it resulted in a significant savings in labor costs
  - Eliminated tendon sequencing
  - All band tendons installed first
  - All uniform tendons installed next
- Has become standard method for tendon layout in 2-way slabs for more than 40 yrs
  - Hundreds of millions of square feet in service
  - Behavior studied and verified in numerous laboratory tests

4-Panel Test at University of Texas



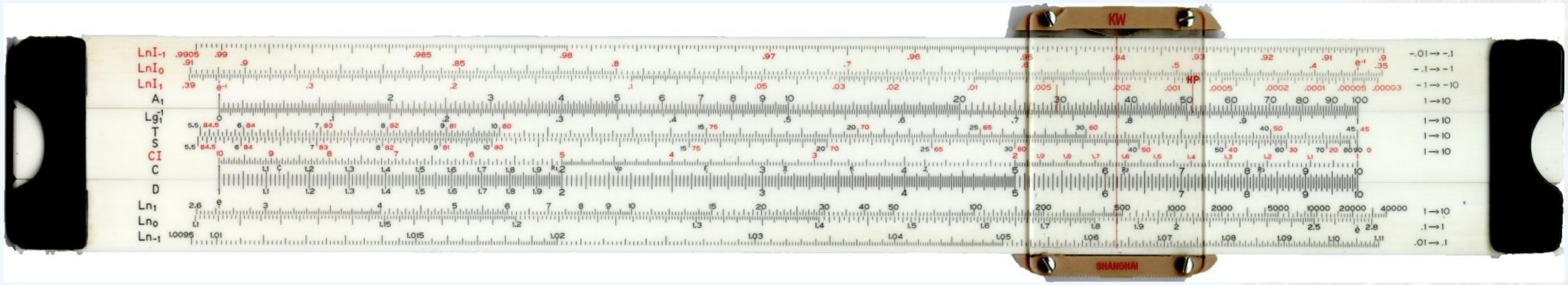
No Discussion of P/T History Would Be Complete Without…..

- A discussion of the use of computers in P/T concrete design…..

When I Graduated From UCLA in 1963

- And started my first job with T. Y. Lin and Associates…..

My Primary Mathematical Tool…



- Could multiply and divide.
- Didn't know where the decimal point was.

Now.....

- I can do a dynamic analysis of a 40-story building on a flight between San Francisco and Los Angeles…
- On a laptop computer about the size of a book….
- While sipping a glass of cabernet (kidding)
- With all the decimal points in the right place

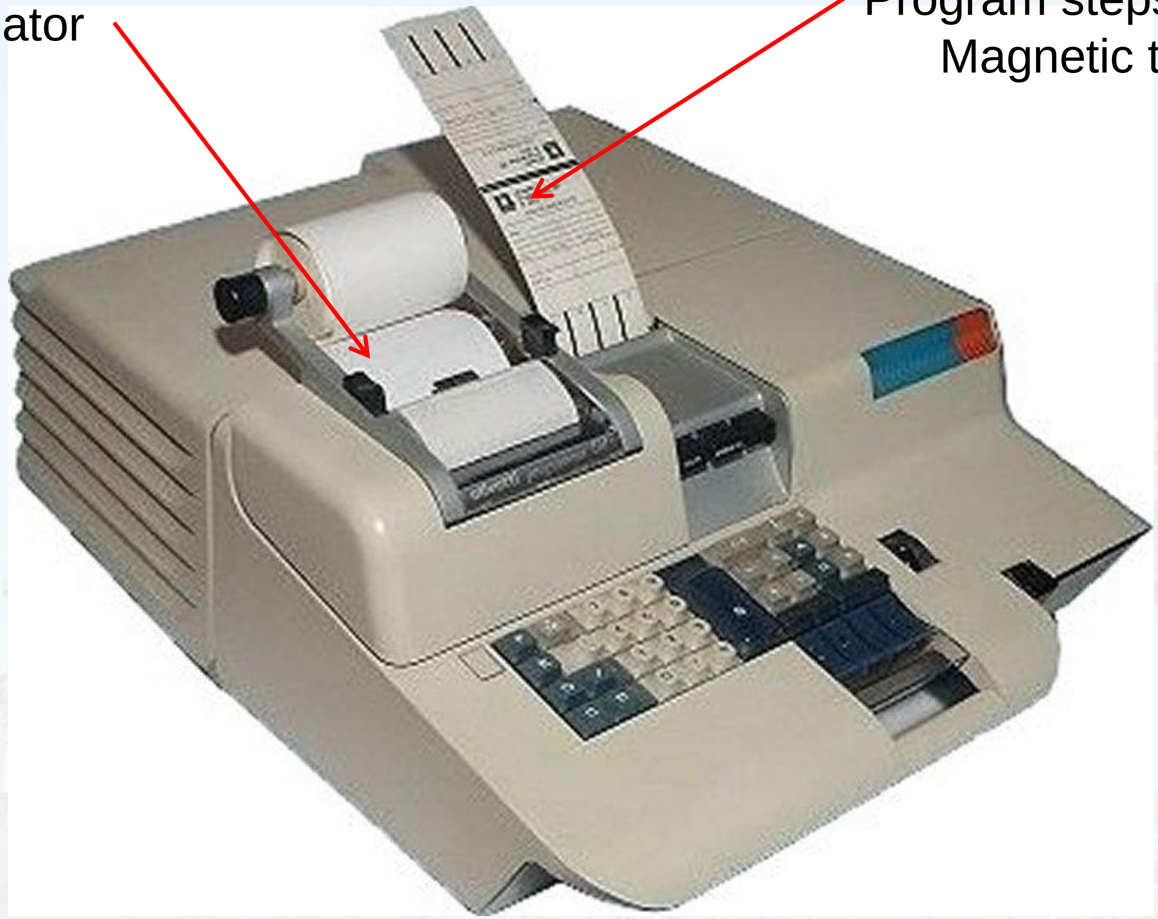
Just In One Lifetime…

- The changes in computing power have been astonishing
- From sliderules to personal computers the size of a notebook….
- With more power than mainframes that took up an entire (air conditioned) large room
- Let's look a quick look at my personal journey through this whirlwind of technology

Olivetti Programma 101 (1966)

Output printed on roll of calculator paper

Program steps recorded on Magnetic tape strips

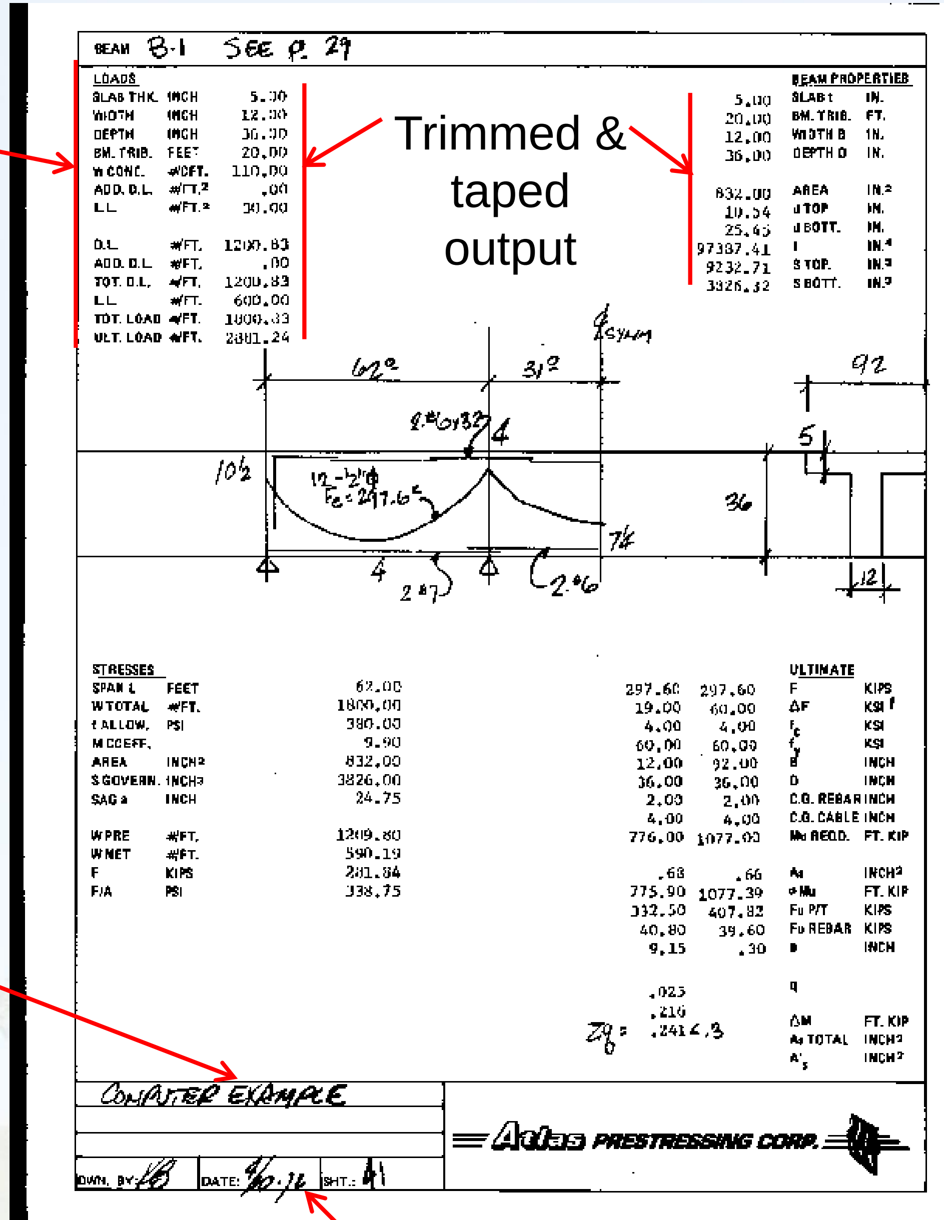


Olivetti Programma 101

- Very large hand calculator – showed power of machine-assisted calculations
- Machine language (enter, arrow up, divide, store)
- Records program steps on magnetic strips (like a "macro")
- Input and output printed on roll of calculator paper (single column strips)
- Output strips trimmed and taped to preprinted calculation sheets
  - Scissors became primary structural design tool

Preprinted variable titles on calc sheet (beam, slabs)

Trimmed & taped output



BEAM B-1 SEE p. 29

LOADS		
SLAB THK.	INCH	5.00
WIDTH	INCH	12.00
DEPTH	INCH	36.00
BM. TRIB.	FEET	20.00
W CONC.	#CFT.	110.00
ADD. D.L.	#FT.²	.00
L.L.	#FT.²	30.00
D.L.	#FT.	1200.83
ADD. D.L.	#FT.	.00
TOT. D.L.	#FT.	1200.83
L.L.	#FT.	600.00
TOT. LOAD	#FT.	1800.83
ULT. LOAD	#FT.	2881.24

	BEAM PROPERTIES	
5.00	SLAB t	IN.
20.00	BM. TRIB.	FT.
12.00	WIDTH B	IN.
36.00	DEPTH D	IN.
832.00	AREA	IN.²
10.54	d TOP	IN.
25.45	d BOTT.	IN.
97387.41	I	IN.⁴
9232.71	S TOP.	IN.³
3826.32	S BOTT.	IN.³

STRESSES		
SPAN L	FEET	62.00
W TOTAL	#FT.	1800.00
f ALLOW.	PSI	380.00
M COEFF.		9.90
AREA	INCH²	832.00
S GOVERN.	INCH³	3826.00
SAG a	INCH	24.75
W PRE	#FT.	1209.80
W NET	#FT.	590.19
F	KIPS	281.84
F/A	PSI	338.75

		ULTIMATE	
297.60	297.60	F	KIPS
19.00	60.00	ΔF	KSI
4.00	4.00	f'_c	KSI
60.00	60.00	f_y	KSI
12.00	92.00	B	INCH
36.00	36.00	D	INCH
2.00	2.00	C.G. REBAR	INCH
4.00	4.00	C.G. CABLE	INCH
776.00	1077.00	Mu REQD.	FT. KIP
.68	.66	As	INCH²
775.90	1077.39	ϕ Mu	FT. KIP
332.50	407.82	Fu P/T	KIPS
40.80	39.60	Fu REBAR	KIPS
9.15	.30	a	INCH
		q	
.023			
.216		ΔM	FT. KIP
Zq = .241 < .3		As TOTAL	INCH²
		A's	INCH²

COMPUTER EXAMPLE

ATLAS PRESTRESSING CORP.

DWN. BY: LB DATE: 9/10/72 SHT.: 41

Hah!

1972

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Wang 700 Series (1970)

Y register

X register

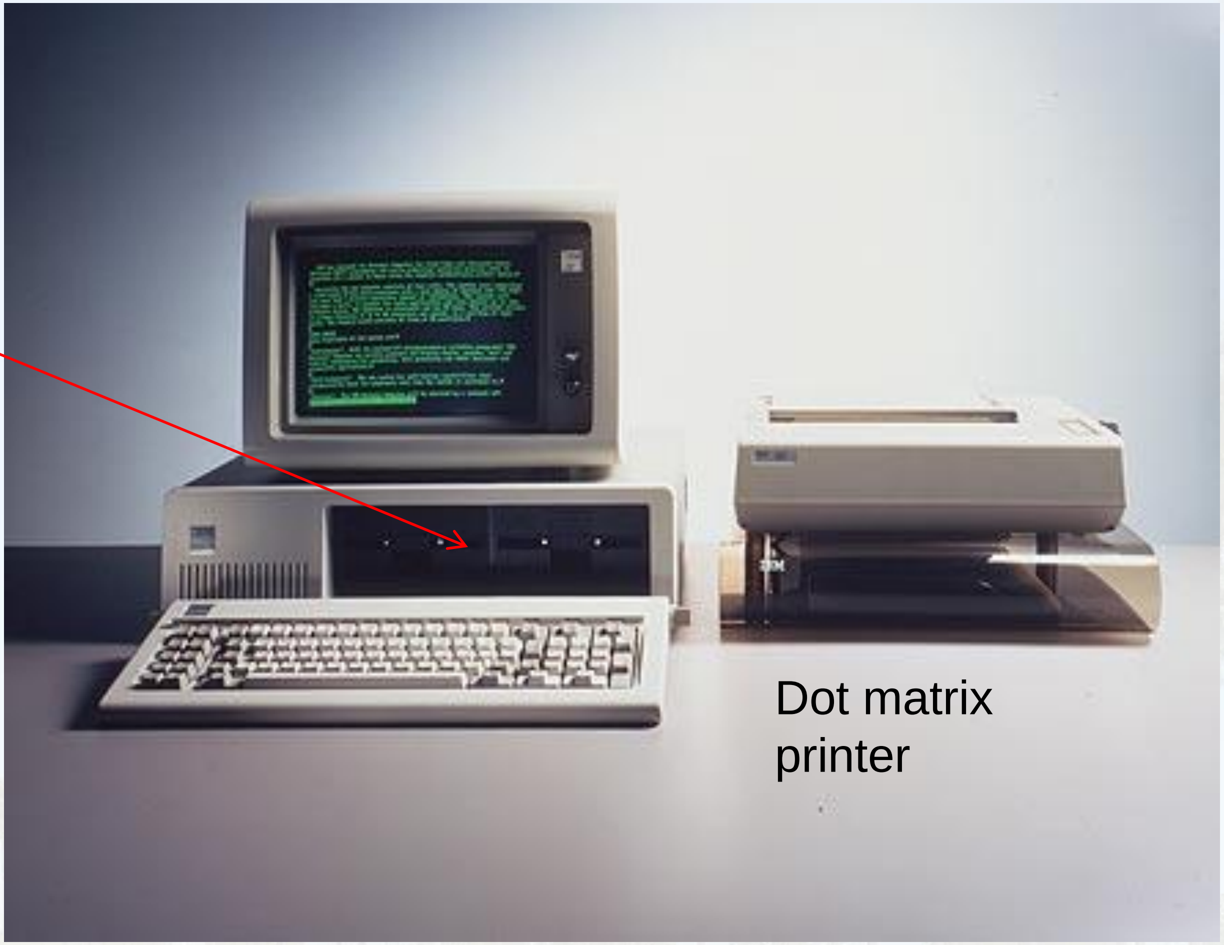
Wang 2200 (1973)

First REAL personal computer

(BASIC interpreter – 4 KB RAM!)

IBM Personal Computer (1981)

2 Floppy
drives



IBM XT (1983)

In One Lifetime….

- Since the first personal computers…
  - Greatly increased RAM
    - 64KB to 4GB (≈60,000x)
  - Greatly increased processor speed
    - 4.77MHz to 1.4GHz (≈300x)
  - Greatly increased disk storage
    - 10MB to 1 Terabyte (≈ 100,000x)

Problems With Post-Tensioning

- Restraint-to-shortening
  - Mechanics of RTS different in prestressed and non-prestressed members
  - Engineers had to learn how to design p/t floor systems with levels of cracking normally accepted in non-prestressed floor systems
  - Methods
    - Joinery details
    - Non-prestressed reinforcement

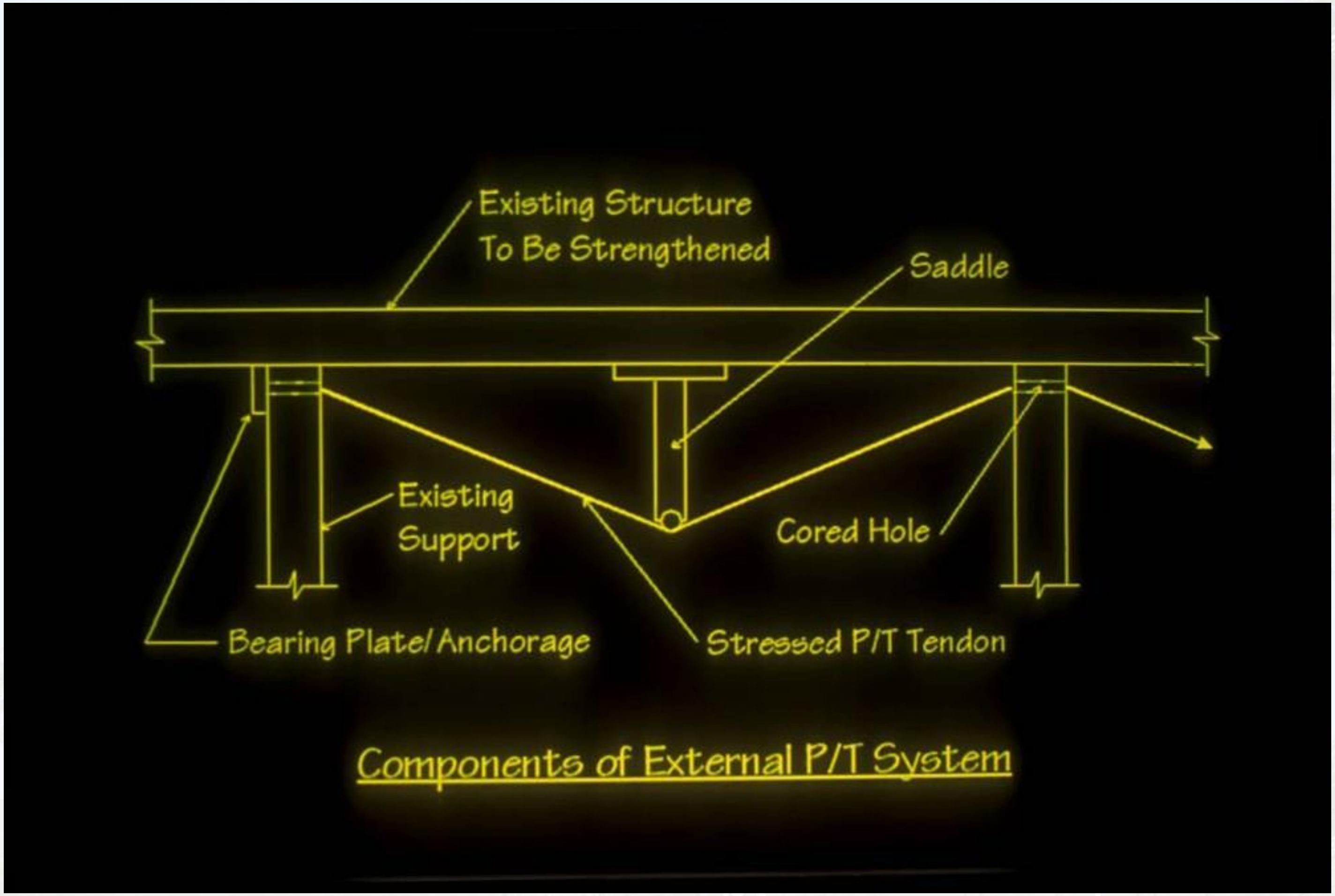
Biggest Problem

- Tendon Corrosion
  - Early sheathing and grease were inadequate for aggressive corrosion environments
- Material specifications developed by PTI have largely solved early corrosion problems
  - Improvements in sheathing material, coatings, complete encapsulation

The Future

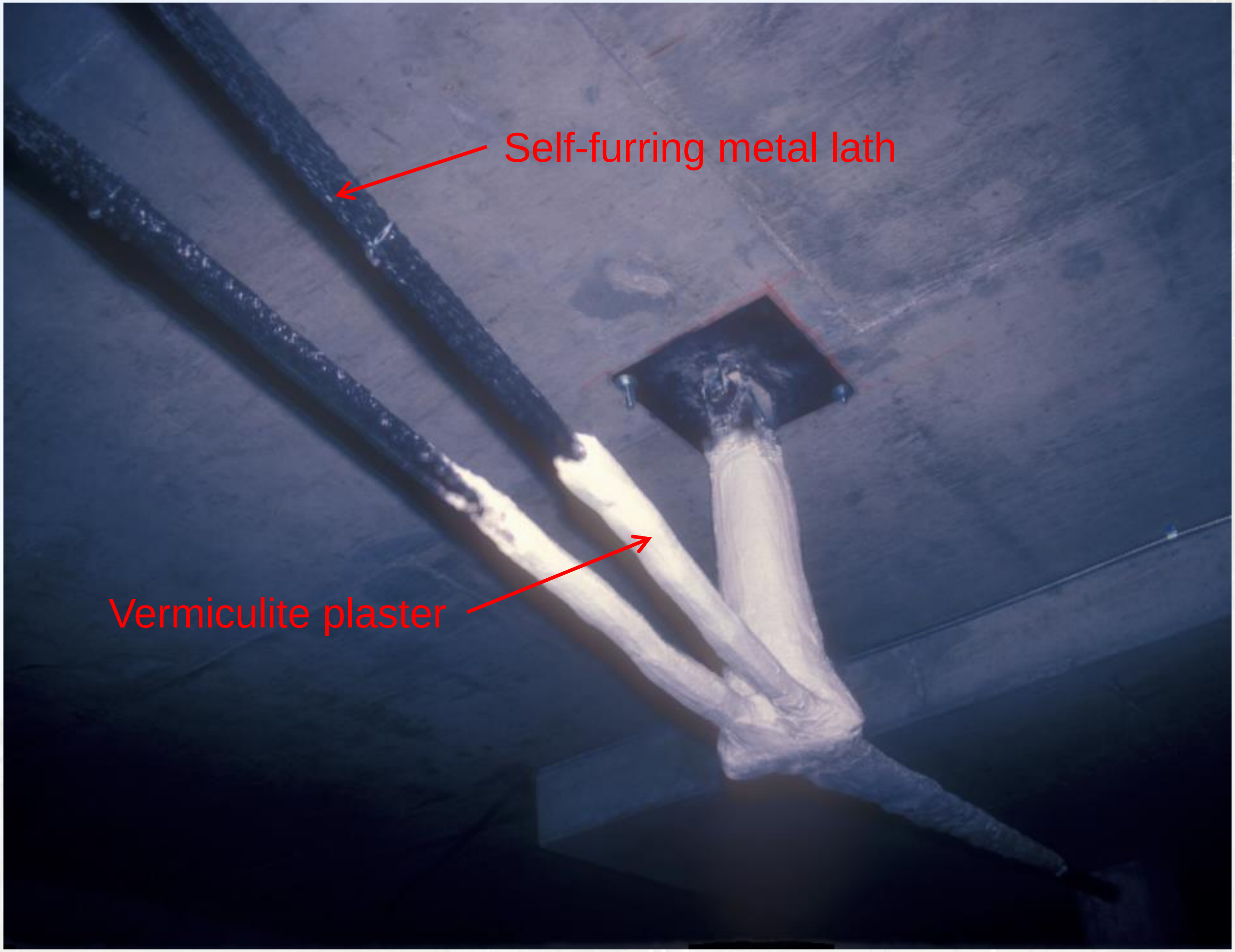
- Strengthening existing buildings with externally applied p/t tendons
  - Very **green**
    - Retrofit versus replacement
  - Extend useful life - ***sustainability***
- Tall concrete buildings

Strengthening With External Post-Tensioning



Two-Way Slab with Load at Mid-Panel

Fireproofing



Tall Buildings

- Historic perception that tall buildings must be built with structural steel
- High-strength concrete makes column sizes reasonable
- P/T reduces weight of floor systems (±30%)
  - Results in savings in all load-carrying members
    - Columns
    - Foundations
    - Seismic system (frame or walls)

Advantages

- Cost
  - Reduced height and volume
  - Exposed exterior frame beams and columns
- Fire and blast (catastrophic load) resistance
  - Concrete is inherently fire-resistant
  - Expose exterior beams and columns
    - No vertical path for fire from floor to floor
    - Substantial savings in curtain wall (25%)
- Sound and vibration

3900 Alameda

Burbank, CA

Tallest Concrete Building Ever Built in Seismic Zone 4 (at time of construction – late 1980s)

See “PT Treasures”

3900 Alameda, Burbank

- 32 stories
- Completely cast-in-place
- 7" thick post-tensioned flat plate floor system
- Monolithic, c.i.p. downturned perimeter ductile moment frames
- Most frame beams and columns exposed at perimeter
  - Replaced 25% of exterior curtain wall system
  - Improved fire resistance between floors

Paramount Apartments at 3rd & Mission San Francisco, CA

Completed 2002

FEATURES

- 43 stories - tallest concrete building in SDC - D, E, F.
- First post-tensioned precast concrete moment frame building in Seismic Zone 4 (SDC – F).
- First use of post-tensioning (unbonded) as primary reinforcement in SMRF beams.
- 2-way post-tensioned flat plate floor system
  - Minimizes dead load and reduces vertical and lateral loads
- Post-tensioned Mat Foundation.

It's Been a ***GREAT*** ride!!!

Thank You!!