Post-Tensioned Concrete in Buildings

A 40+ Year Overview

By

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ACI Fall Convention

San Francisco, October 2004

41 Years Ago…

- It was the fall of 1963
- I was 23 years old
- I had completed my MSCE course work at UCLA
- I was almost finished with my thesis
- I was being supported by my wife and 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?
- One was, and they hired me!!!
- Their name was…..

T. Y. Lin and Associates

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 41 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
- 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

No Existing U.S. P/T Systems

- Lift-slab companies went to Europe for help
- Most existing hardware was for multistrand tendons in bridges
- Only European system feasible for building construction was the BBRV “button-headed” tendon system
- 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.

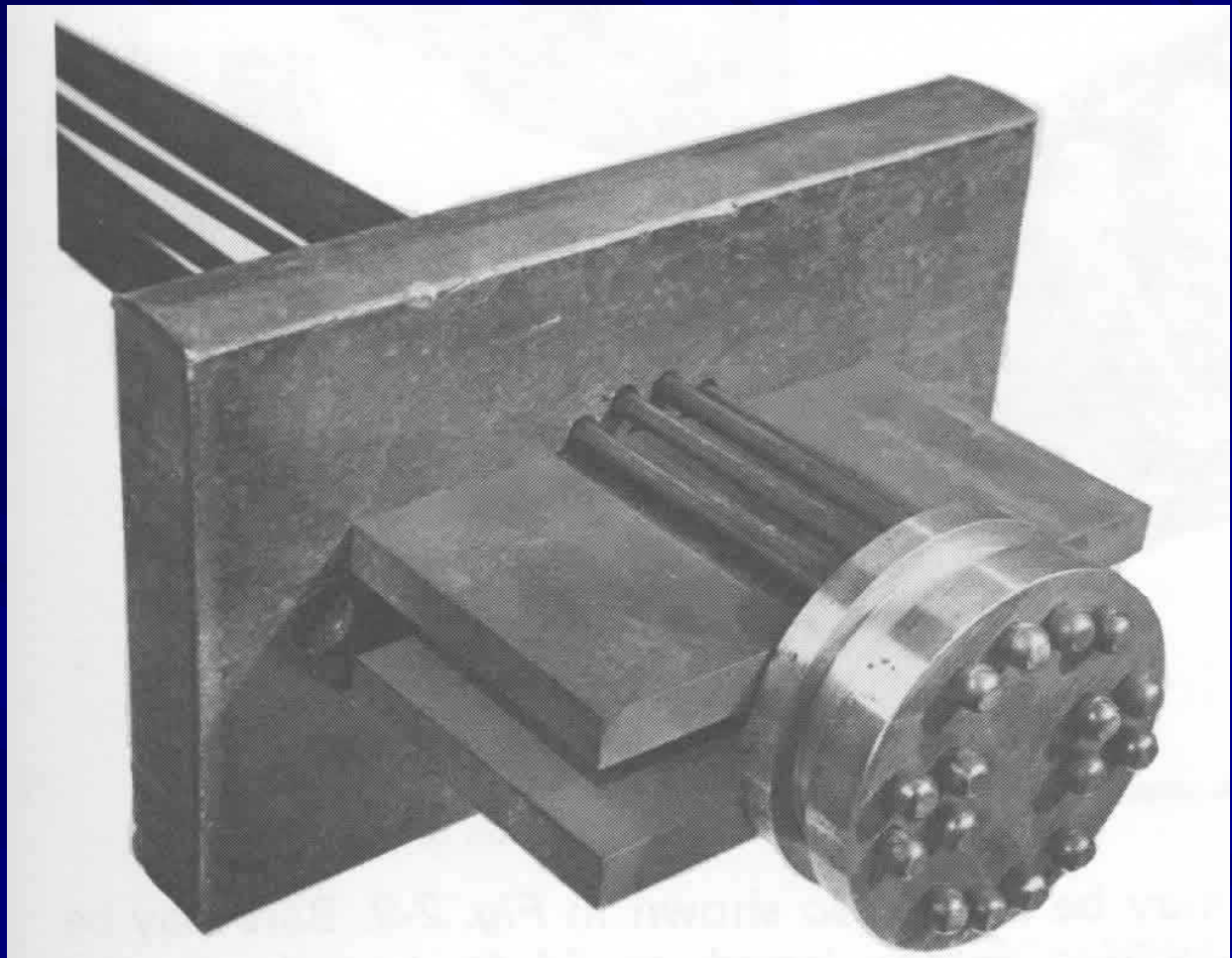


Fig. 2-3 — Button-head anchorage, stressing end, non-grouted

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 (president of T.Y. Lin & Associates)
- Introduced by Atlas Prestressing Corp.
- 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)

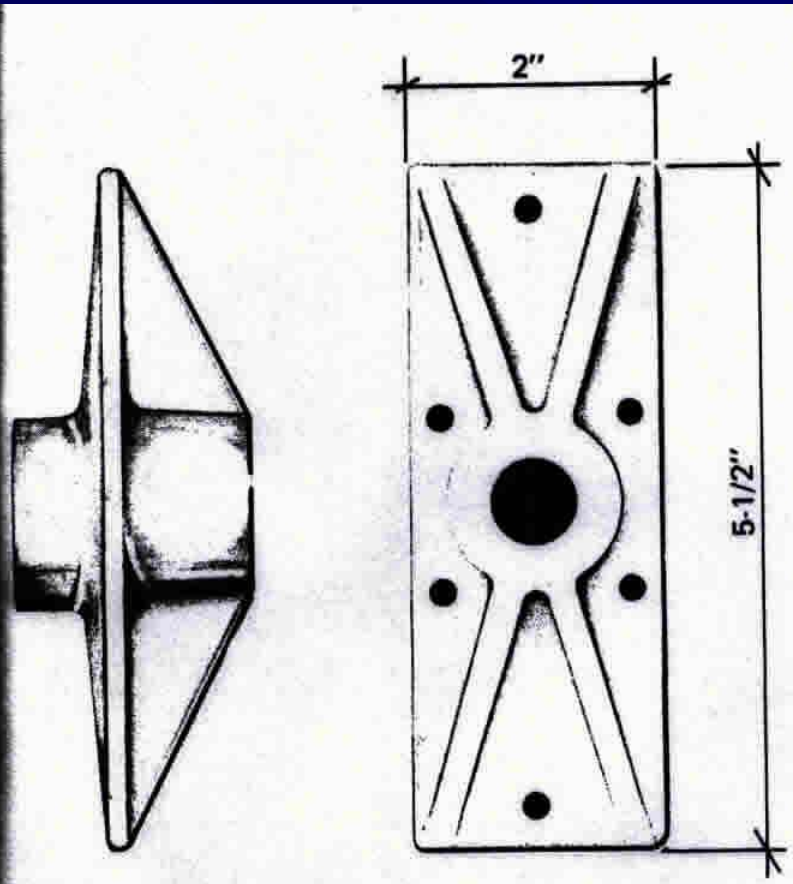
The First Strand/Wedge Anchorage Used in the US!

Relied on Tensile Strength of Concrete

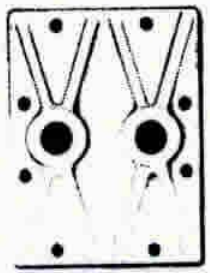
- Many breakouts occurred, particularly in lightweight concrete
- Atlas field superintendent (Tom Anderson) suggested chaining anchors together
- Led to award
  - Recognized Tom's contributions
  - Recognized subsequent contributions of other Atlas employees

The Thomas E. Anderson Memorial Award

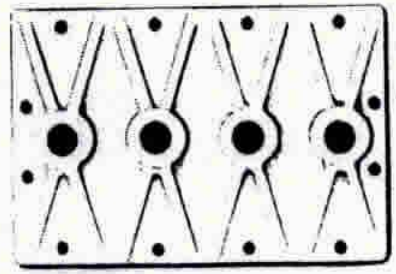
Replaced by Ductile Iron Castings in 1963



H – 122 (1/2" STRANDS)



H – 222



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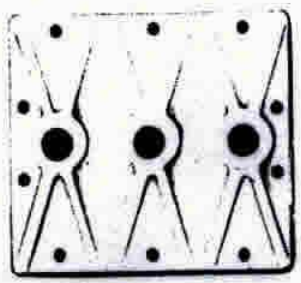

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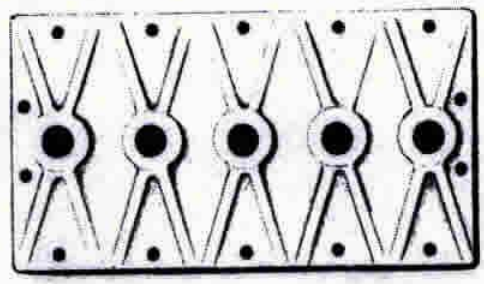
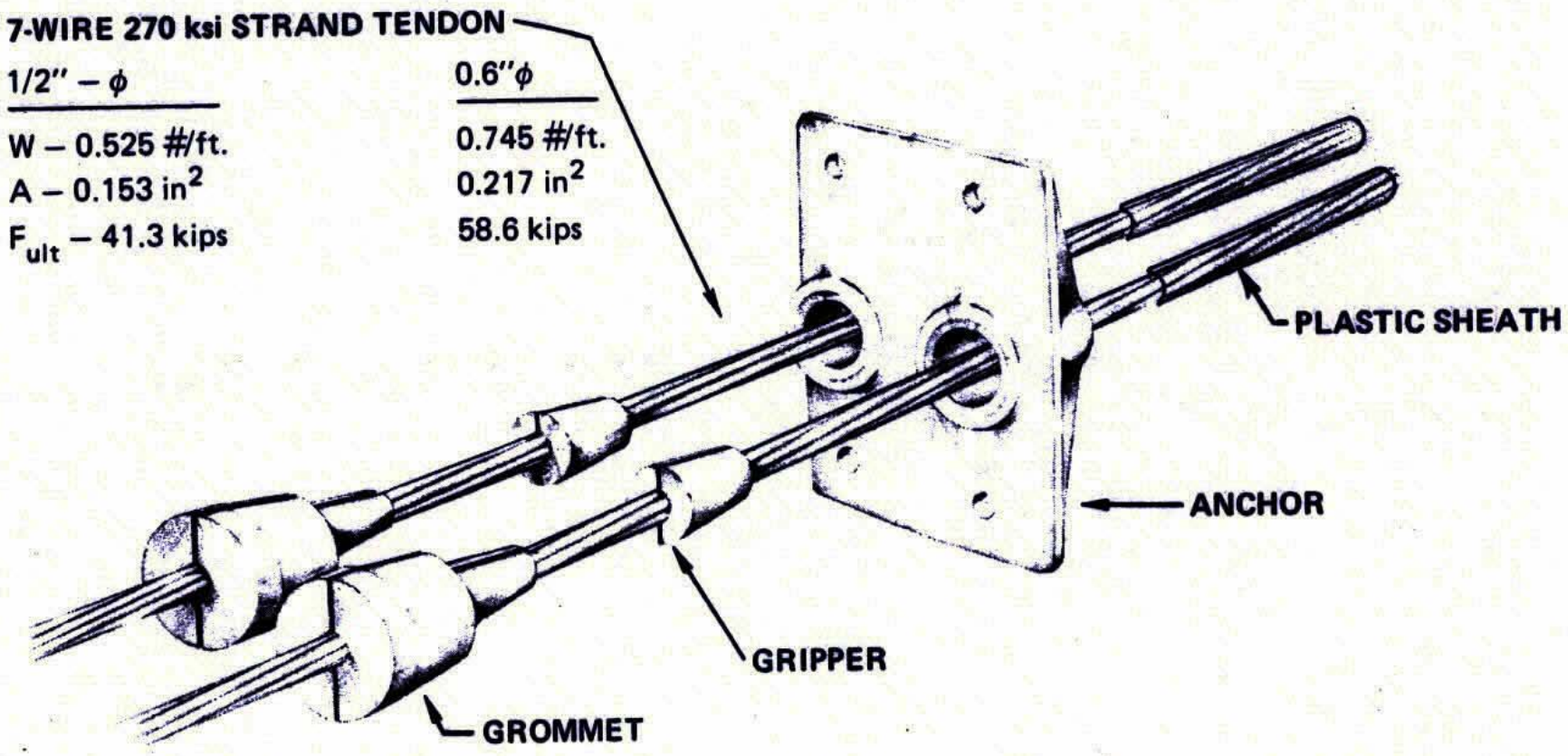


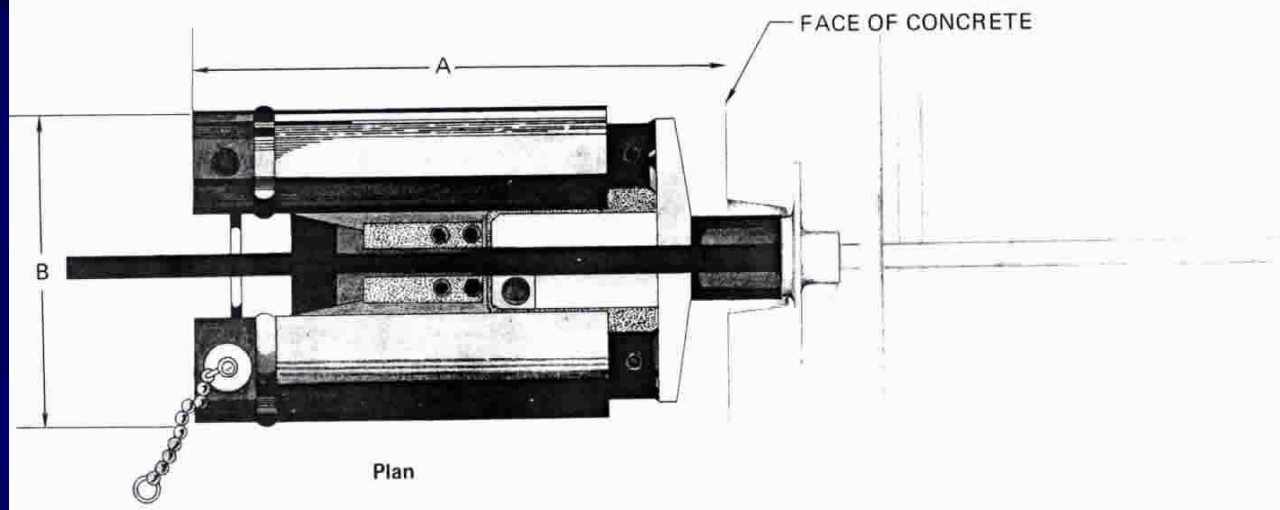
H – 522

"22" SERIES MULTIPLES (1/2" STRAND)

Integrated Bearing Area with Anchorage

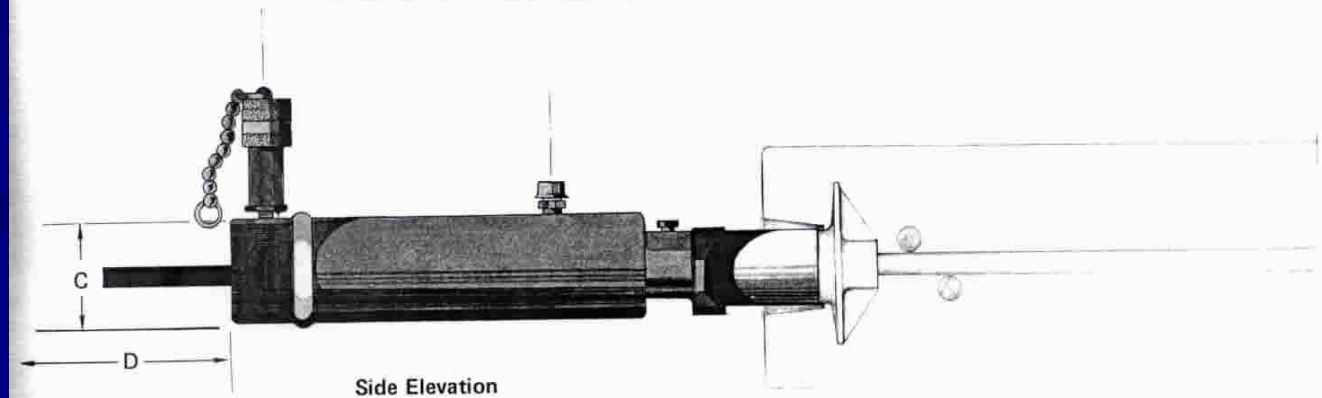


Small, lightweight stressing equipment



Plan

STRAND DIAM	STROKE D	A	B	C	WEIGHT
1/2"	3"	7 3/8"	7 1/2"	2 3/4"	24#
1/2"	6"	10 1/2"	7 1/2"	2 3/4"	29#
1/2"	8 1/2"	13 1/4"	7 1/2"	3 7/8"	39#
1/2"	10"	14 3/8"	7 1/2"	2 3/4"	36#
0.6"	9"	24"	9 1/4"	5 1/2"	55#



Side Elevation

Bearing Anchor in Use

- SOG application (largest US use of p/t)
- Tendon shown is encapsulated

Strand System vs. Button-Head System

- Atlas vs everybody else
  - Prescon
  - Ryerson
  - Western Concrete Structures
- After fierce 5-6 year struggle, Atlas wins battle of marketplace by late 1960s
- Button-headed tendons became extinct
- Virtually all building p/t has been with strand tendons ever since.

What Happened to Lift-Slabs?

- Lifting companies ***combined*** lifting and tendons in their bids
  - Excluded independent p/t companies (like Atlas Prestressing Corp.)
- Independent p/t companies couldn't bid on lift-slab jobs
- What did we do…..???

Formed Alliances With Emerging Flying Form Industry

Direct Competition

- Joint promotion between p/t companies and flying form companies allowed direct competition with lifted buildings
- Cast-in-place p/t buildings using large-panel flying form systems were highly competitive with lifted buildings
- By late 1960s c.i.p. buildings became preferred and lift-slab buildings became rarely used.

Short-Sighted?

- If lift-slab companies had not originally tried to exclude independent p/t companies
- Lift-slab construction would be a significant factor in today's medium-rise building market.

Landmarks in P/T Buildings

- Introduction of strand systems
  - Replaced “button-head” tendon system
- Development of ductile iron castings for single-strand 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” 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

Promotion of P/T in Buildings

- Atlas Prestressing Corp. recognized in mid 1960s that the most effective way to increase the market for p/t was…
- …to teach engineers how to design it
- …and to assist them in their designs
- With this marketing philosophy, Atlas grew from smallest to largest p/t firm in less than ten years.

Seminars

- Atlas sponsored over 100 one-day design seminars between 1965 and 1976
- Held in most major US cities and in western Europe
- Attended by more than 2000 practicing engineers
- Often resulted in p/t building within 6 months of seminar

Building Codes

- Post-tensioning virtually absent from ACI 318-71 (“ignore secondary moments”)
- 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 more p/t expertise on ACI committees

Formation of PTI

- Post-tensioning was represented as a division within PCI in late 1960s through mid 1970s
- PTI formed as an independent institute in 1976
- PTI gives contractors and engineers a single unified source and voice for p/t design and construction information
- Establishes a standard of care in many areas of design and construction

Construction Advances

- High-rise construction in Hawaii
- Banded tendons in 2-way p/t slabs

Honolulu Skyline circa 1977

Wall Jump-Forms and Flying Deck Forms

Slabs Hung From Walls

3 Days per Floor

- Place slab concrete on Monday morning
  - Walls and columns are two lifts above
- Stress tendons on Tuesday morning
  - Oversize anchors (4x6) to permit stressing at 1,500 psi – achieved in 24 hours
- Fly forms on Tuesday afternoon
- Install tendons and rebar on Wednesday
  - Placed through sleeves in walls and columns
- Place slab concrete on Thursday morning

Banded Tendons in 2-Way Slabs

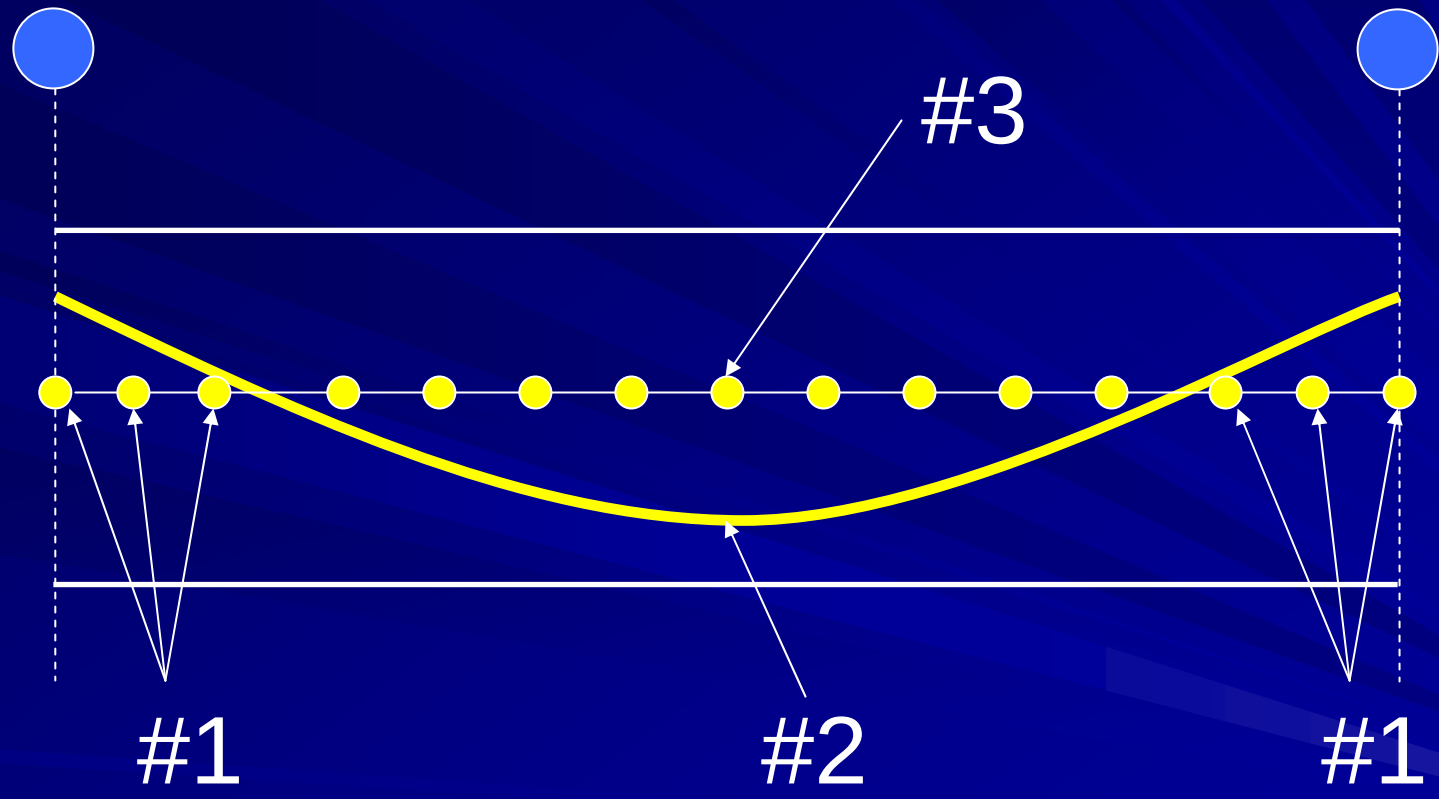
- First used in the most famous post-tensioned concrete building ever built…

The Watergate Apartments in Washington, D.C.

Basket-Weave Tendon Layout for 2-Way Slabs

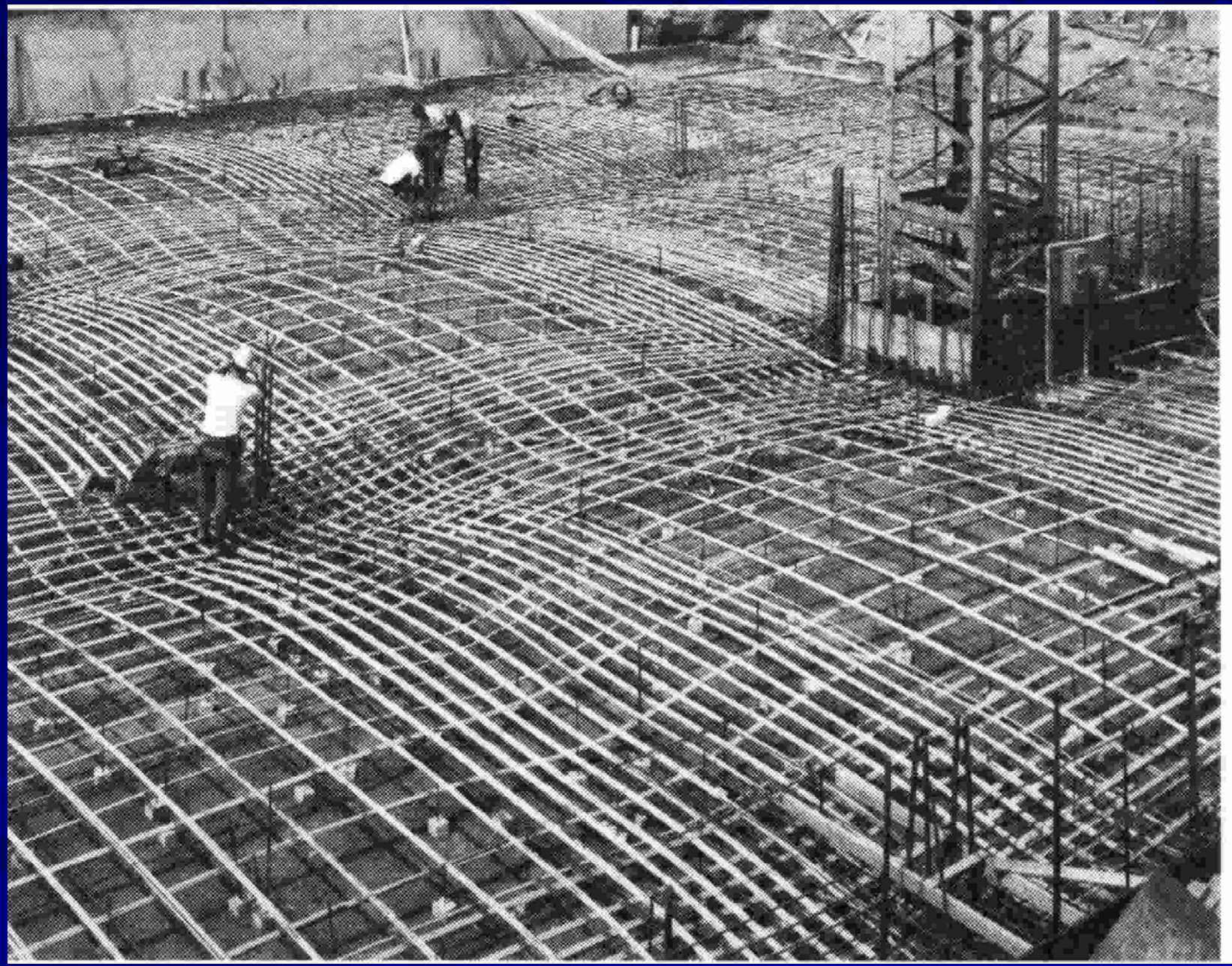
- Some in “column-strips”
- Some in “middle strips”
- Tendons were “draped” in curved vertical profile
  - High at column lines
  - Low at midspans
- A single tendon profile had some orthogonal tendons above it and some below it

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
- Column/middle strip concept meaningless
- Load path virtually impossible to follow

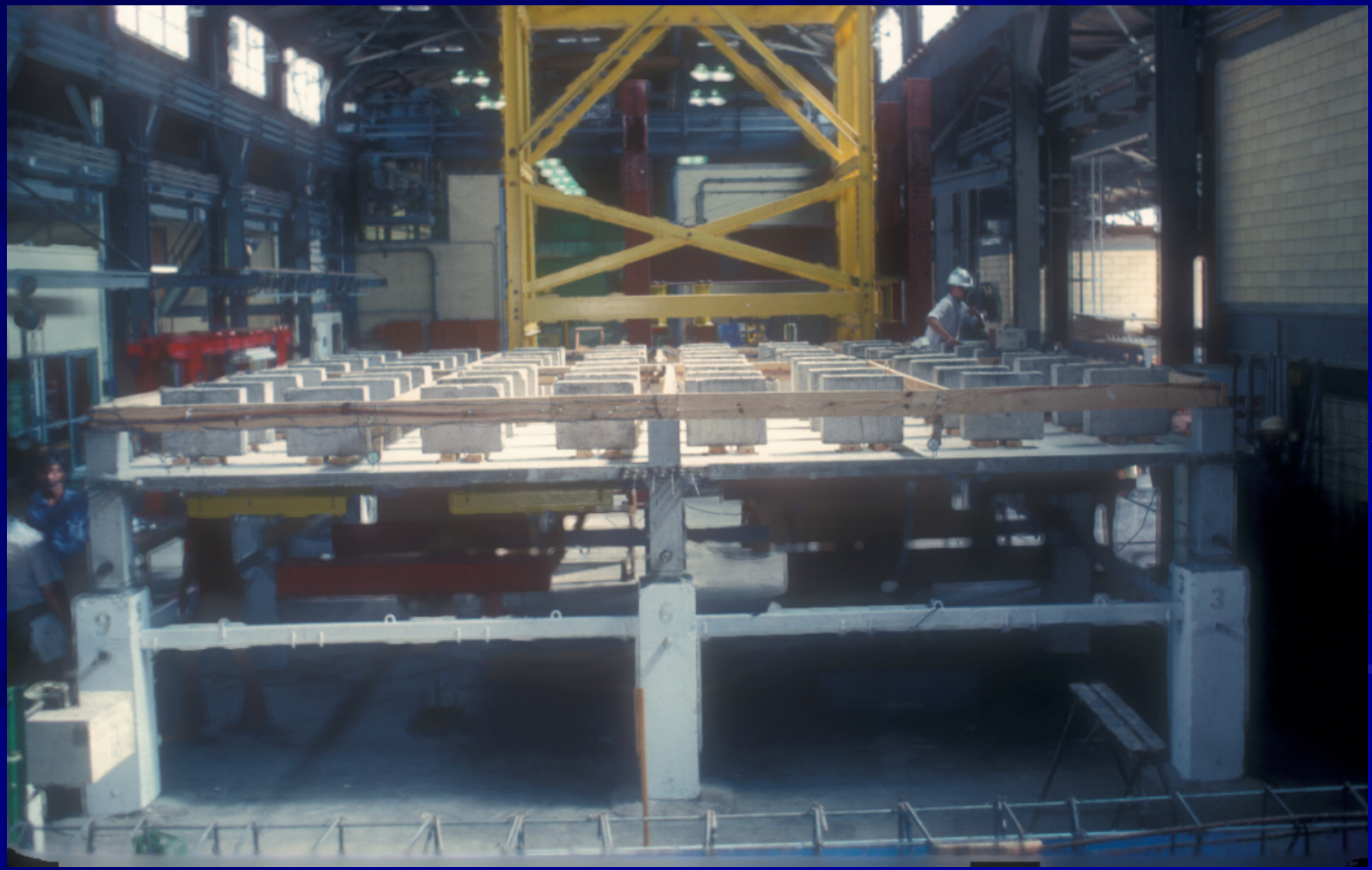
Slab Design Engineers (T.Y. Lin and Atlas Prestressing Corp.)

- 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
  - Hundreds of millions of square feet in service
  - Behavior studied and verified in numerous laboratory tests

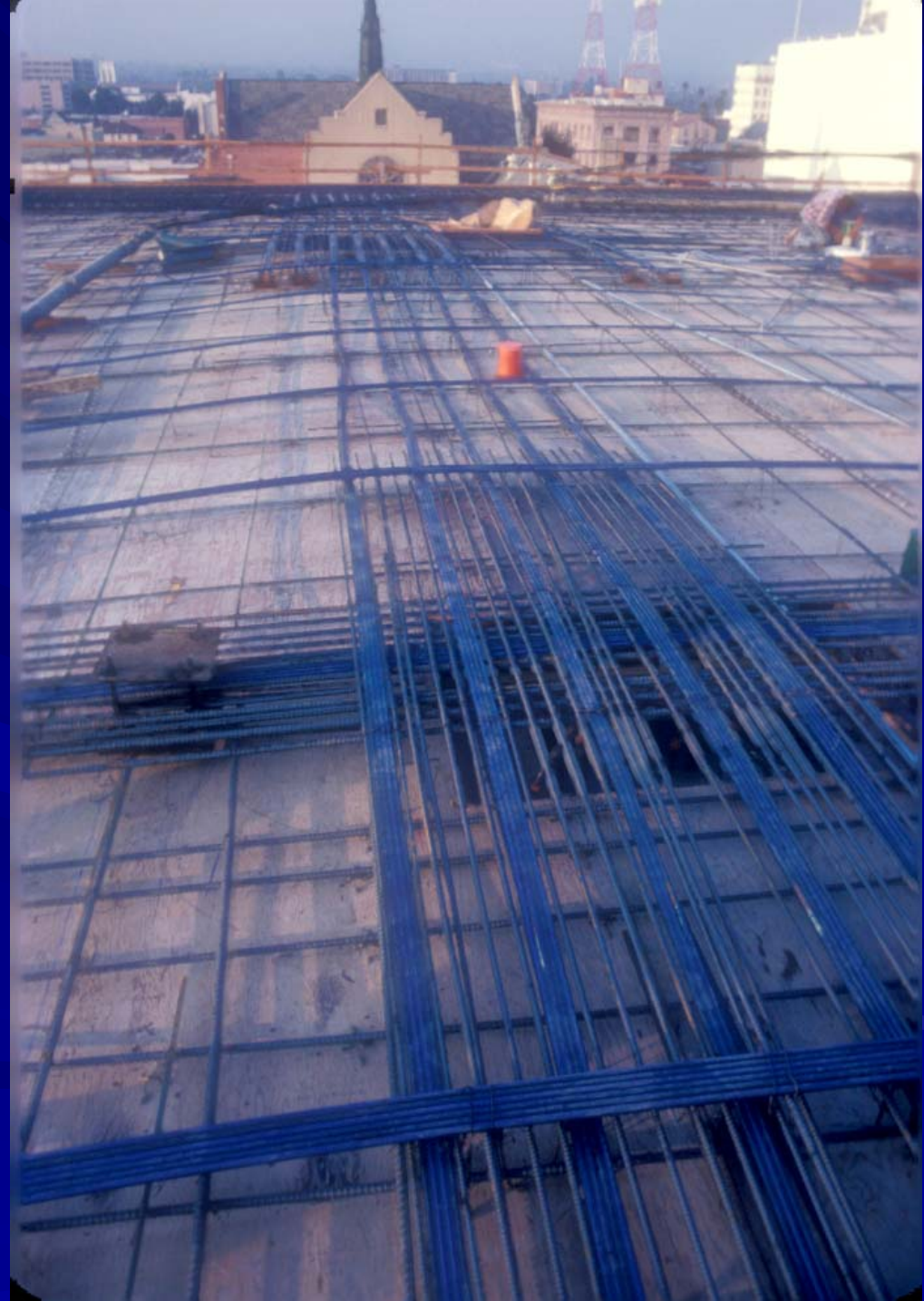
4-Panel Test at University of Texas



Simple Light Tendon Layout

Notice Anything Unusual?

Simple
But
Heavy
Tendon
Layout



Complicated Tendon Layout

Problems

- 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

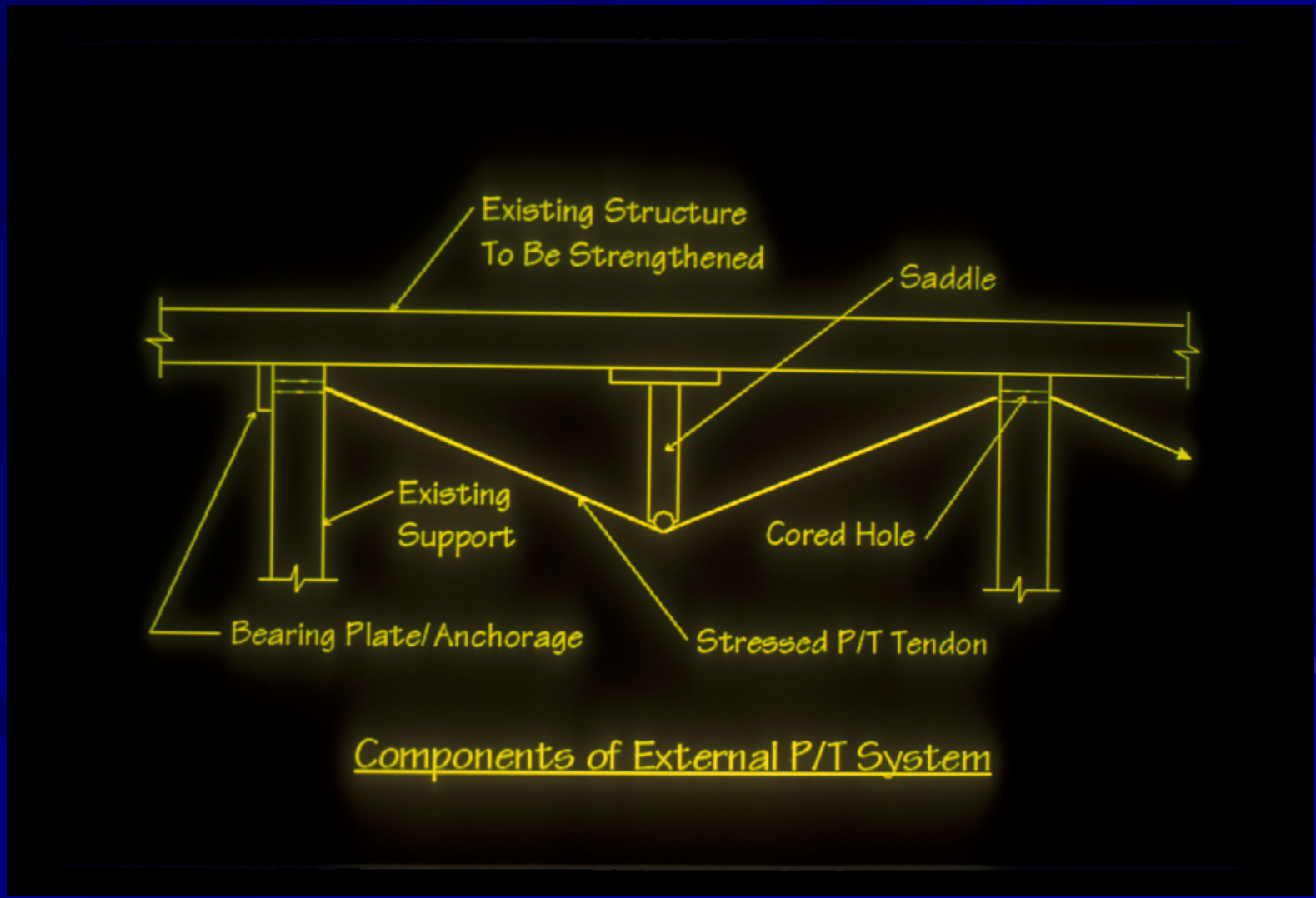
Biggest Problem

- 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

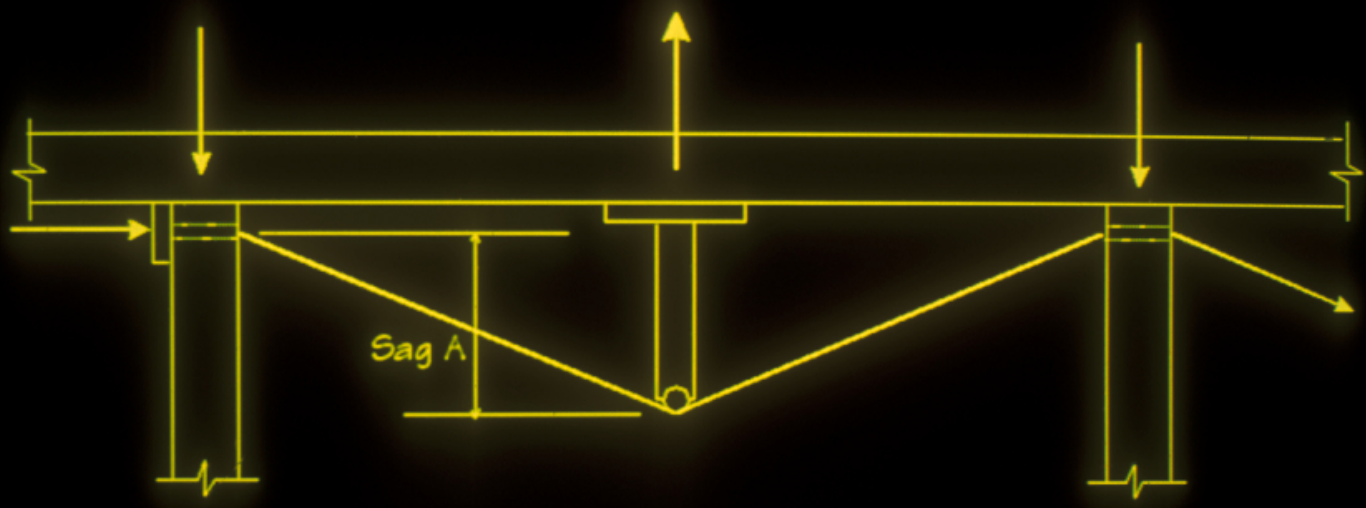
The Future

- Strengthening existing buildings with externally applied p/t tendons
- Tall concrete buildings

Strengthening With External Post-Tensioning

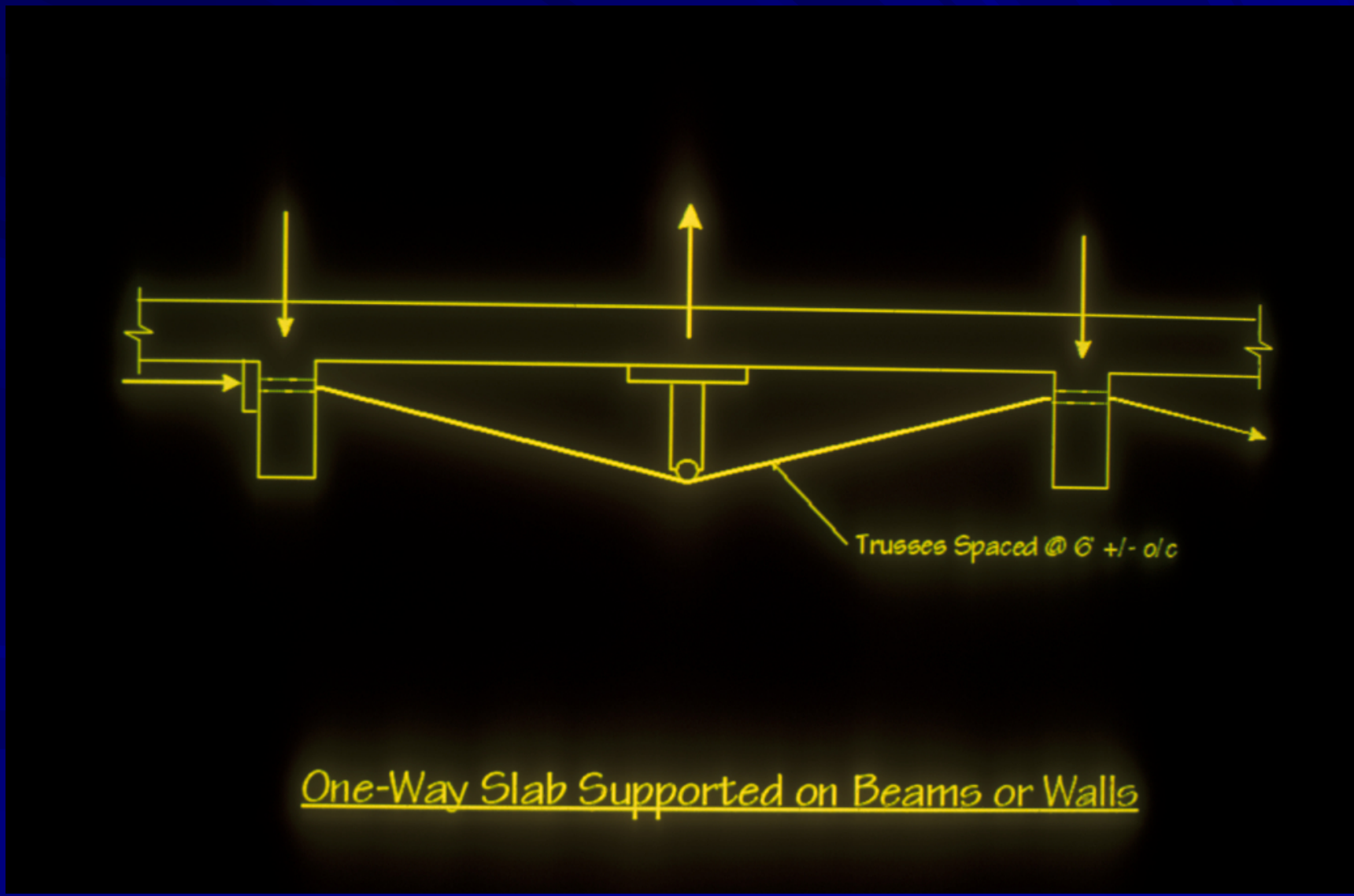


Loads

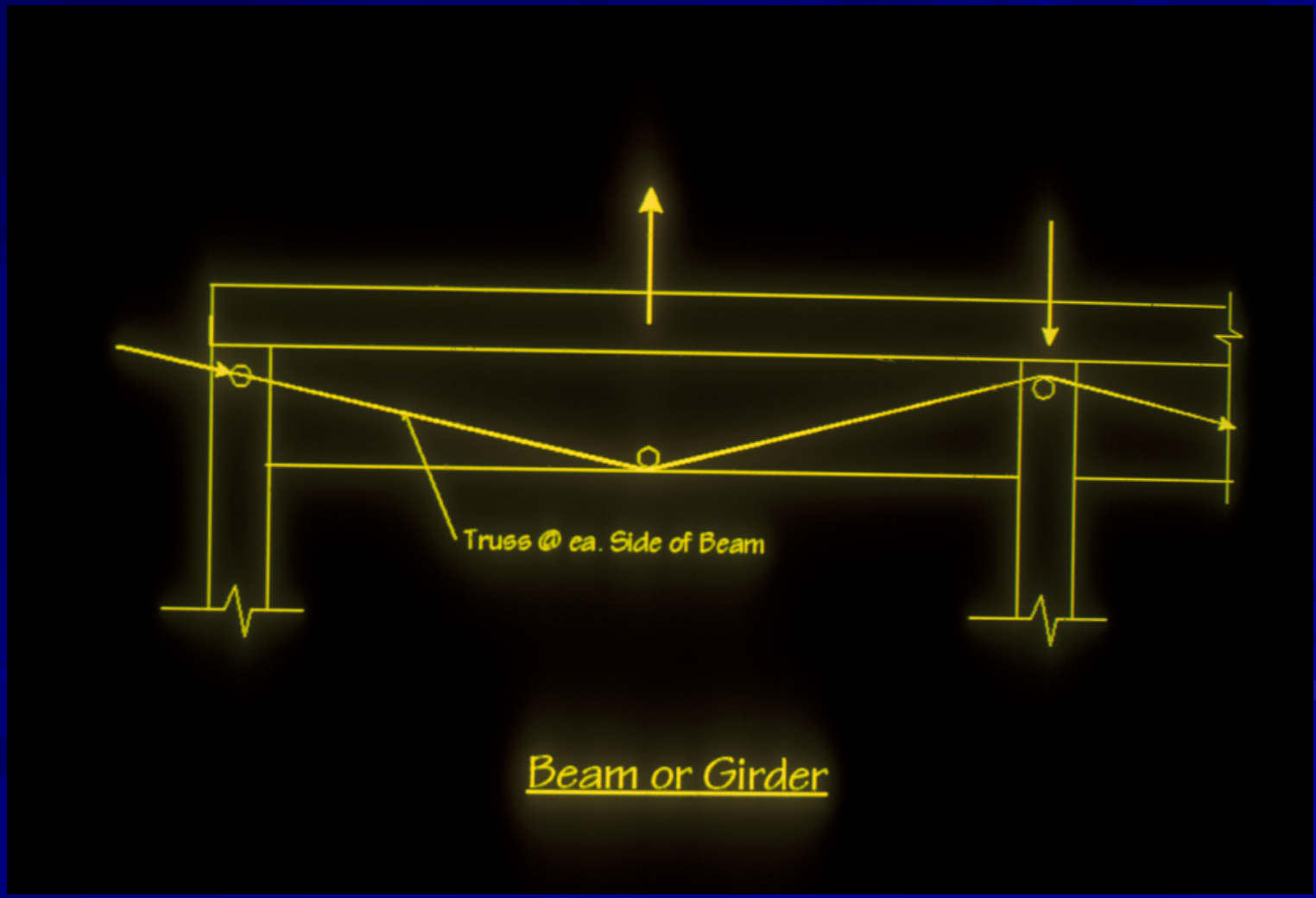


Loads Applied by External P/T System

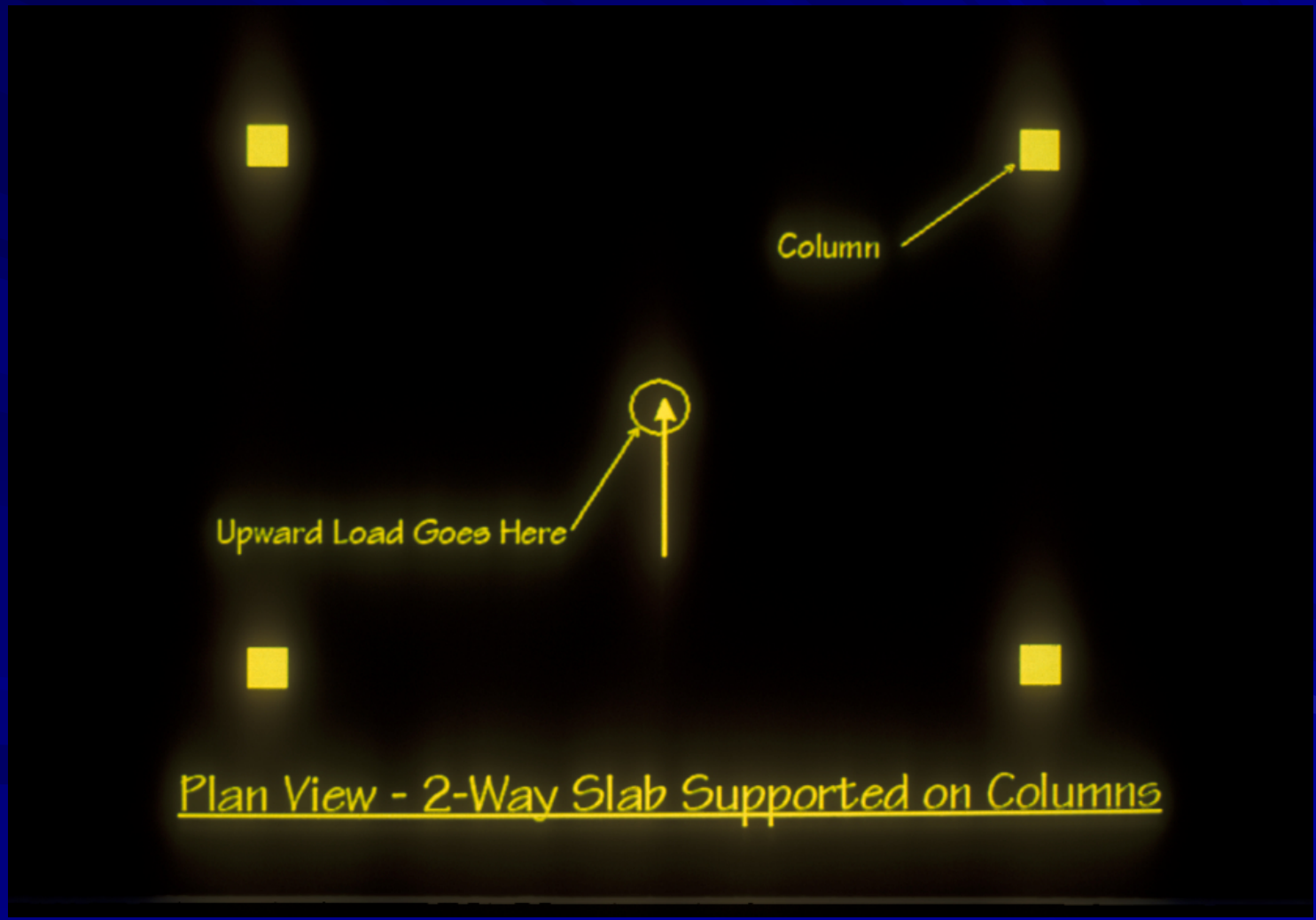
One-Way Slabs



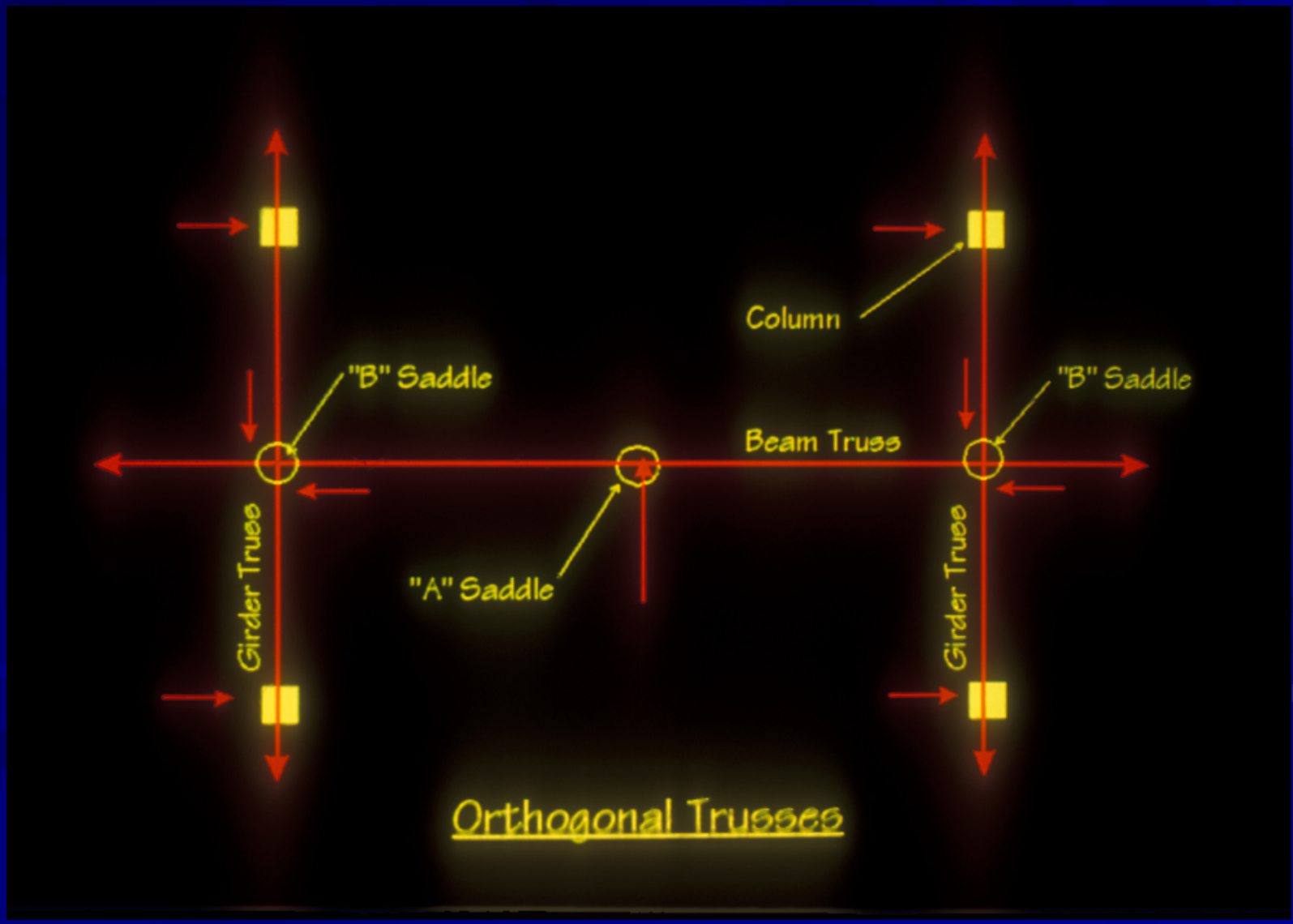
Beams and Girders



2-Way Slabs

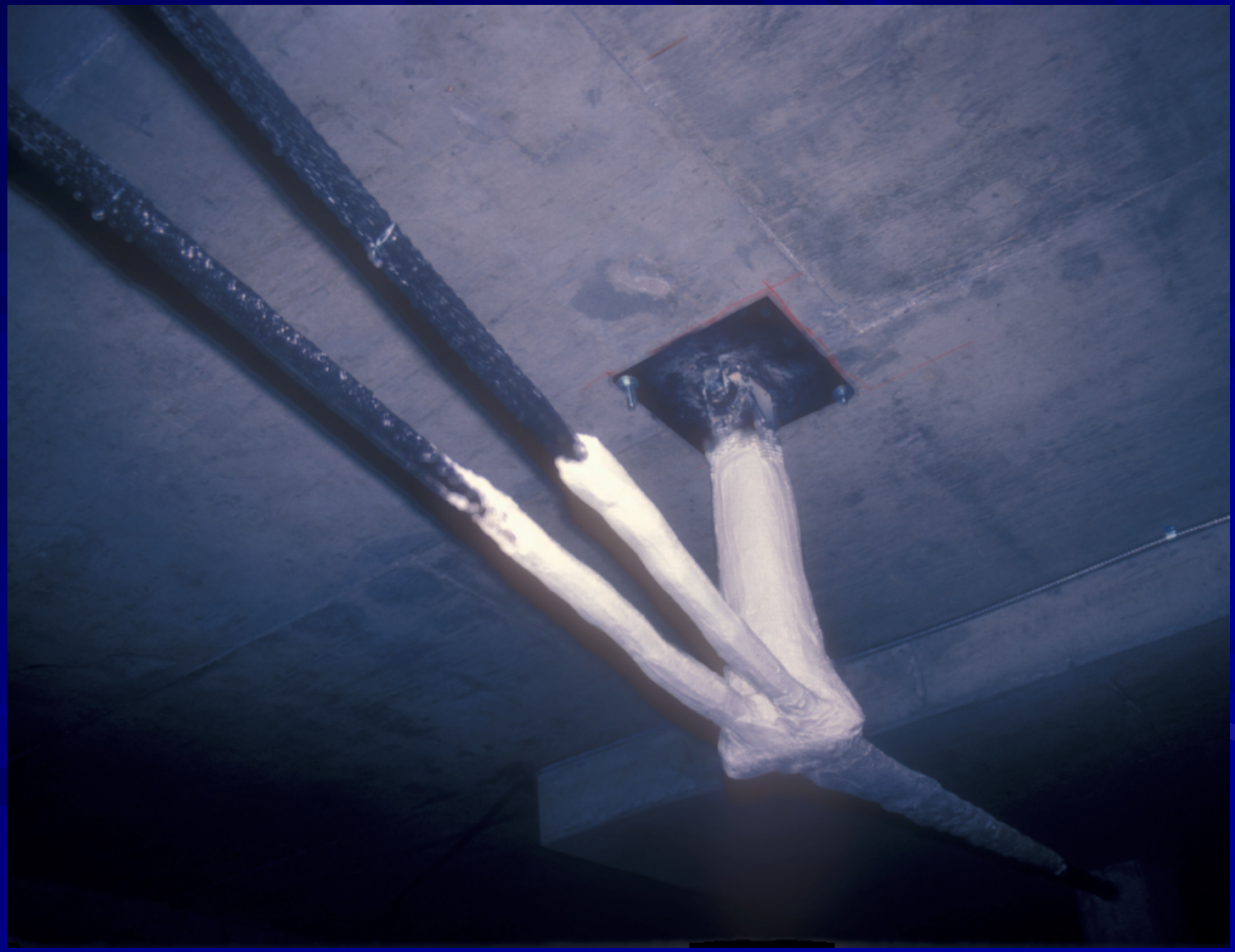

Column
Upward Load Goes Here
Plan View - 2-Way Slab Supported on Columns

Orthogonal Trusses

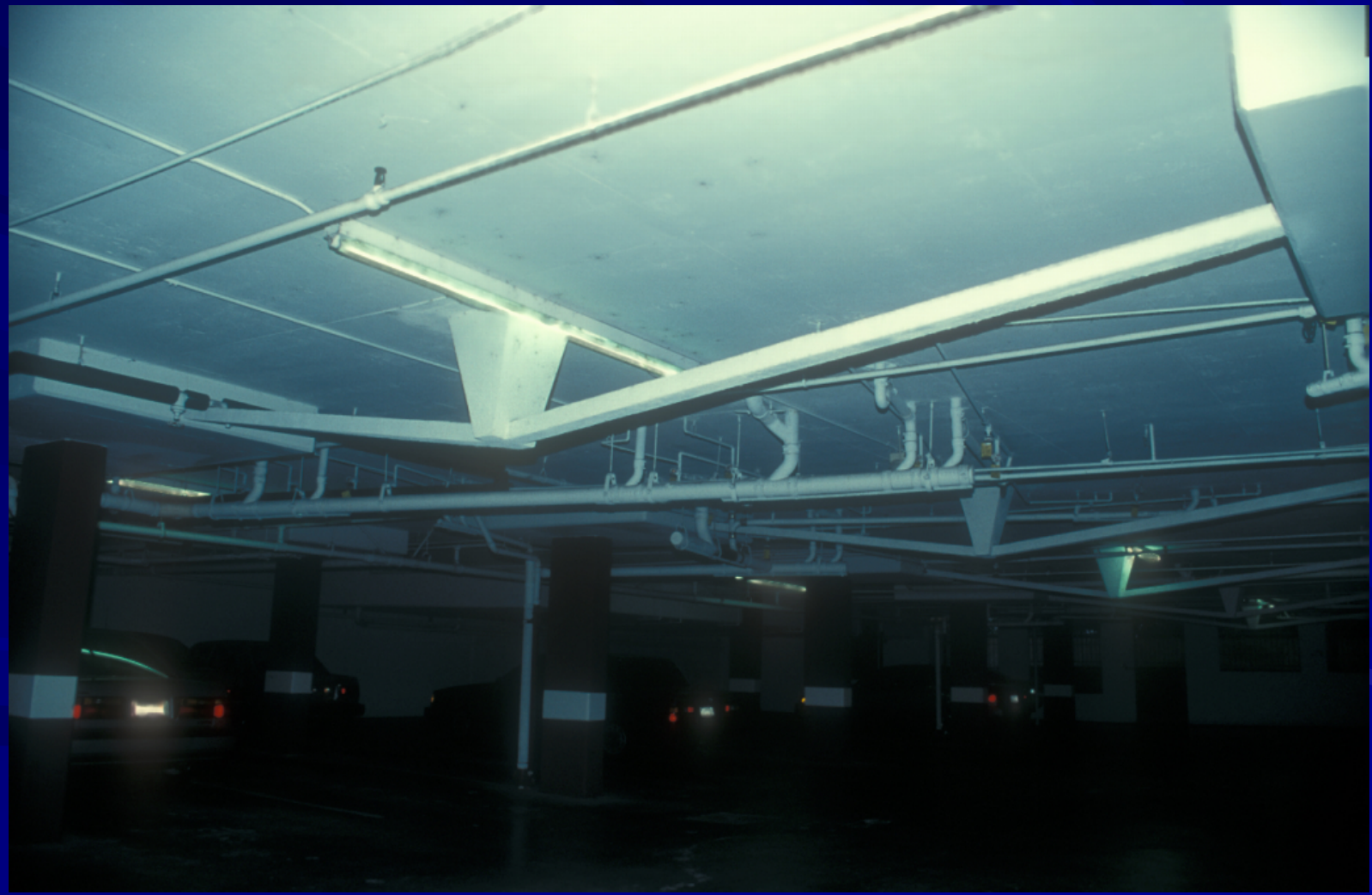


Two-Way Slab with Load at Mid-Panel

Fireproofing



Fireproofing Options



10-Story Building Strengthened From Below First Floor

Tall Buildings

- P/T reduces weight of floor systems
- High-strength concrete makes column sizes reasonable
- Advantages
  - Cost
    - Exposed exterior frame beams and columns
  - Fire and blast resistance
  - Sound and vibration

3900 Alameda

Burbank, CA

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

Thank You!!