University of Minnesota
Driven to Discover®

Structural Engineering
Webinar Series
September 27, 2024

Lessons from Failures for Structural Engineers

David B. Peraza, PE
dperaza@exponent.com

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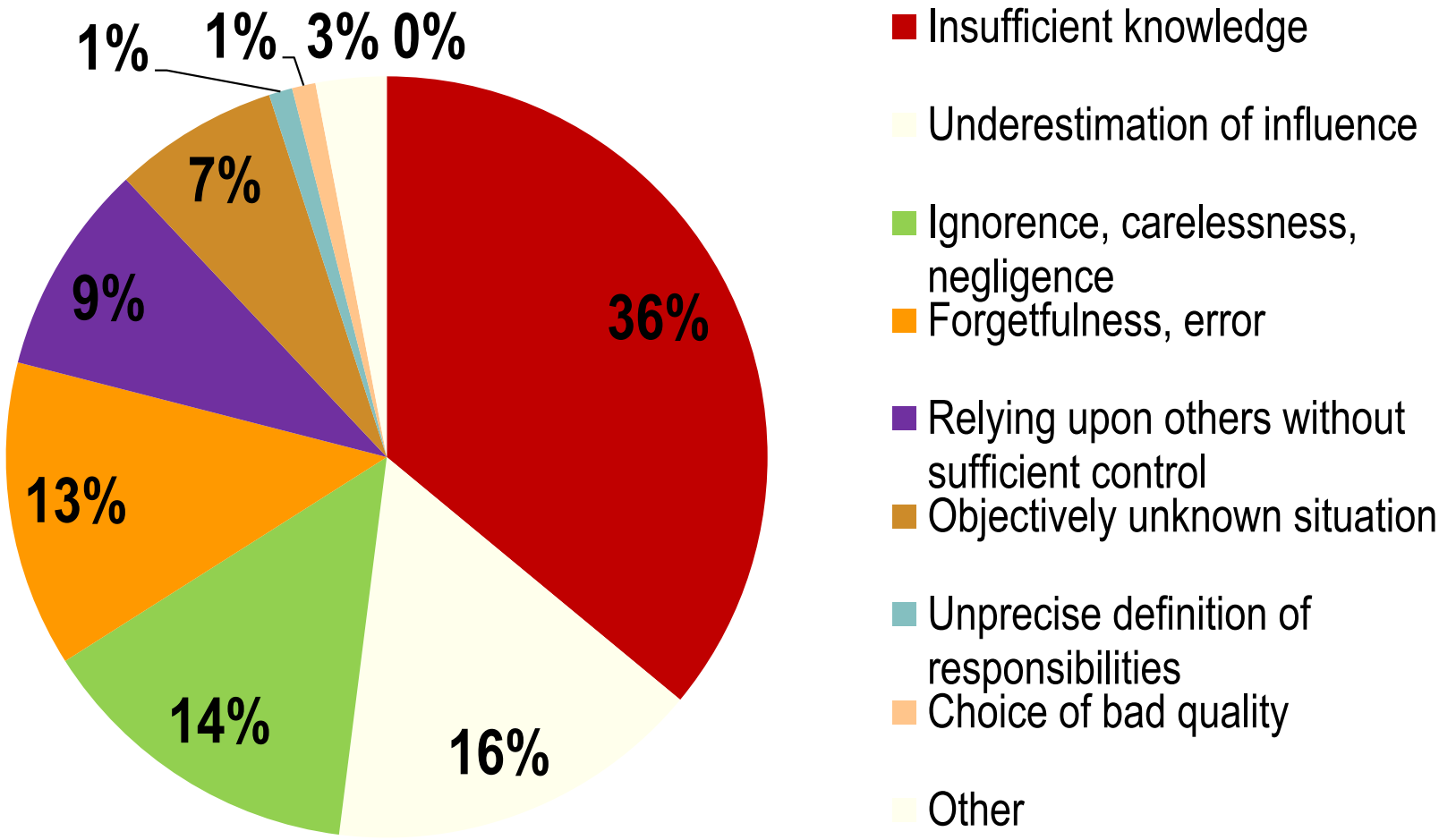
Causes of Failures

When Engineers are at Fault



Matousek and Schneider, (1976) . Based on 295 cases.

Those who cannot remember the past are condemned to repeat it

George Santayana, 1905

Cases

- Hyatt Regency Walkways Collapse
- Hartford Coliseum Roof Collapse
- Metal Deck Collapse
- Tropicana Parking Deck Collapse
- Renovation of Vintage Building

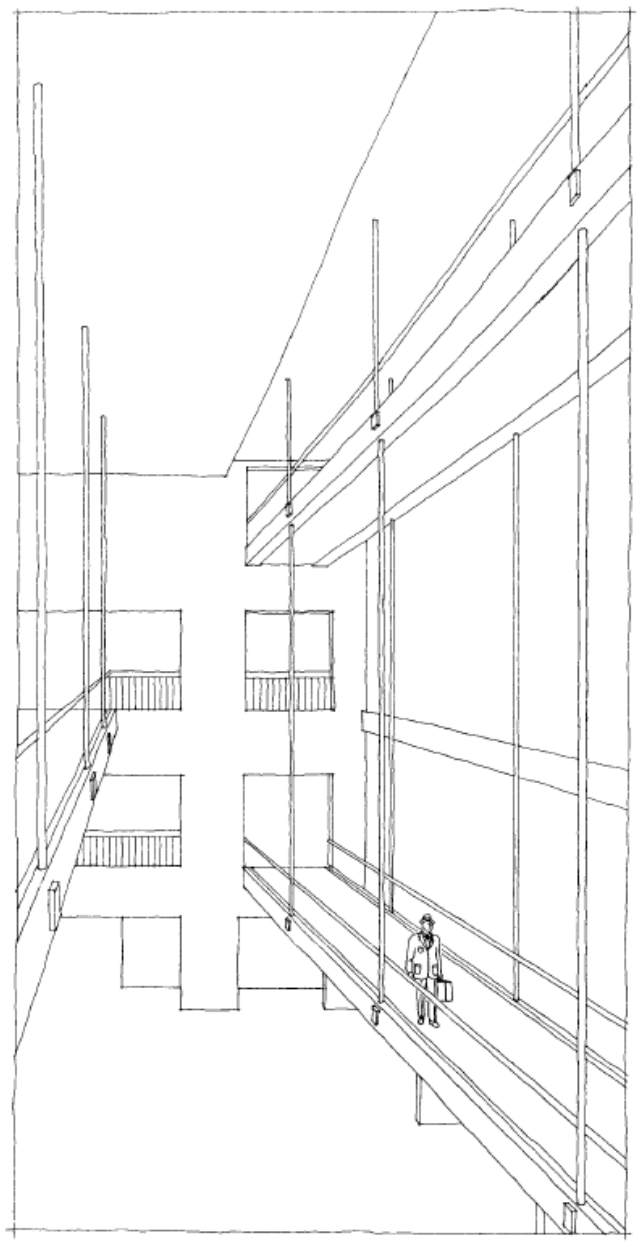

What we've got here is a
FAILURE TO COMMUNICATE

Hyatt Regency Walkways Collapse
Kansas City, Missouri

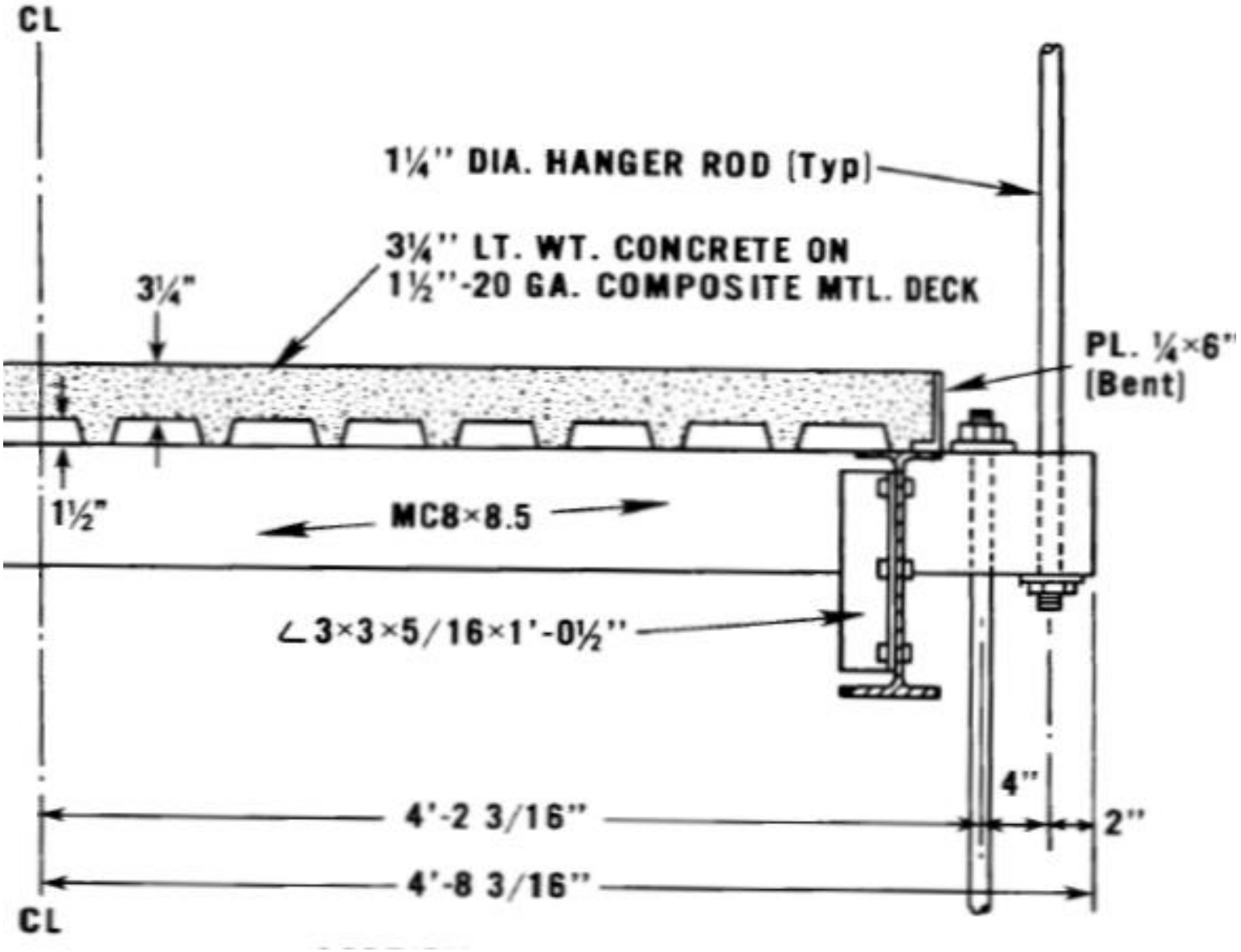
- July 17, 1981
- 114 dead
- 200 injured
- After 2 years of litigation, Owner settled lawsuits for about $100,000,000
- Engineers lost licenses

The Building

- 750 room hotel
- Built 1980
- 3 walkways through atrium
- Walkways suspended from roof



As-Built Cross-Section of Walkway



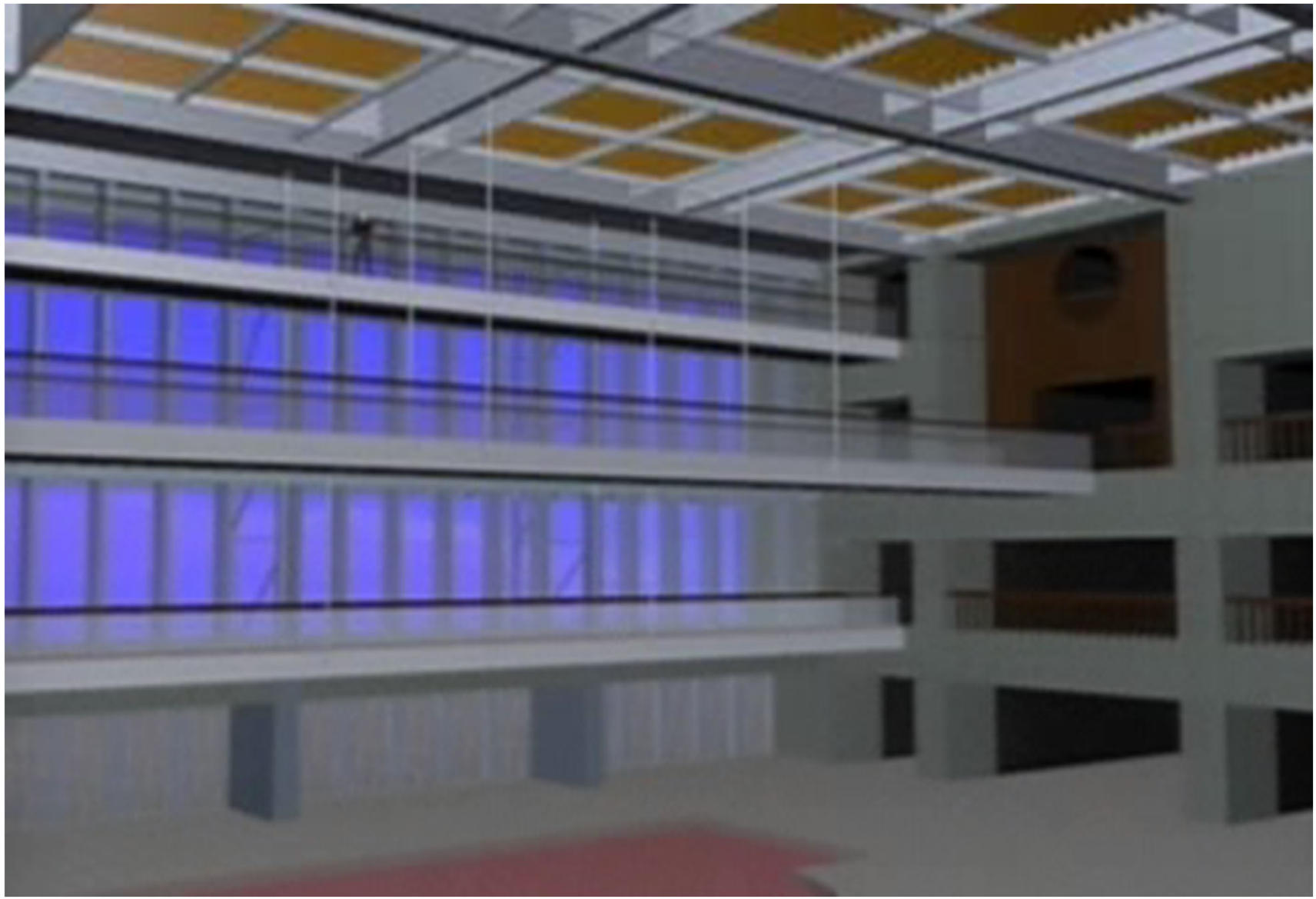
The Collapse

It was a Friday evening at about 7:45 p.m. when my wife and I returned home to a ringing telephone. The call was from Herb Duncan, one of the principal architects.

His first words to me—"There has been a collapse at the Hyatt"—shattered me to the core. Herb told me that one of the walkways had collapsed, "Several may have been killed and many injured."

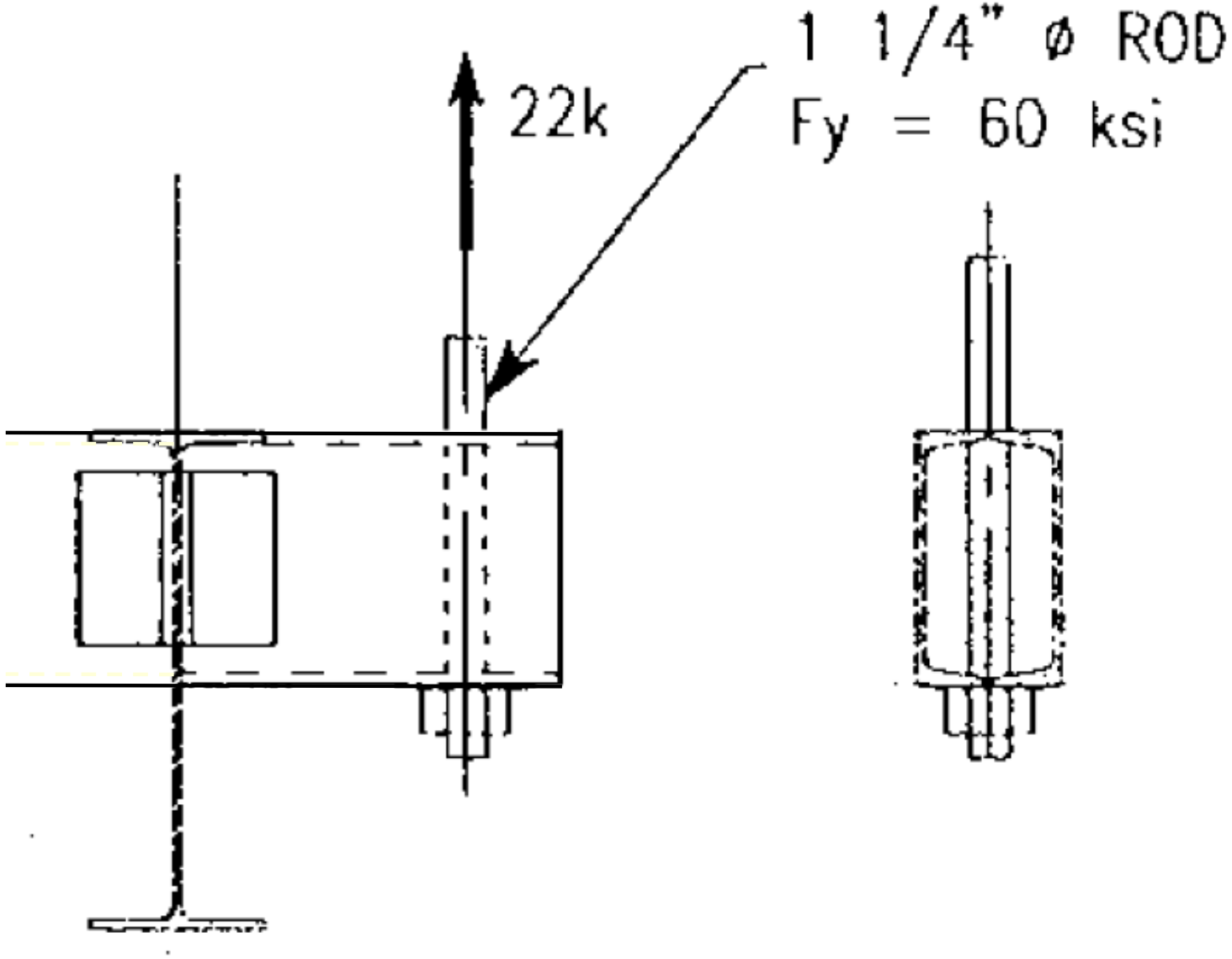
Jack Gillum
Engineer of Record

Animation

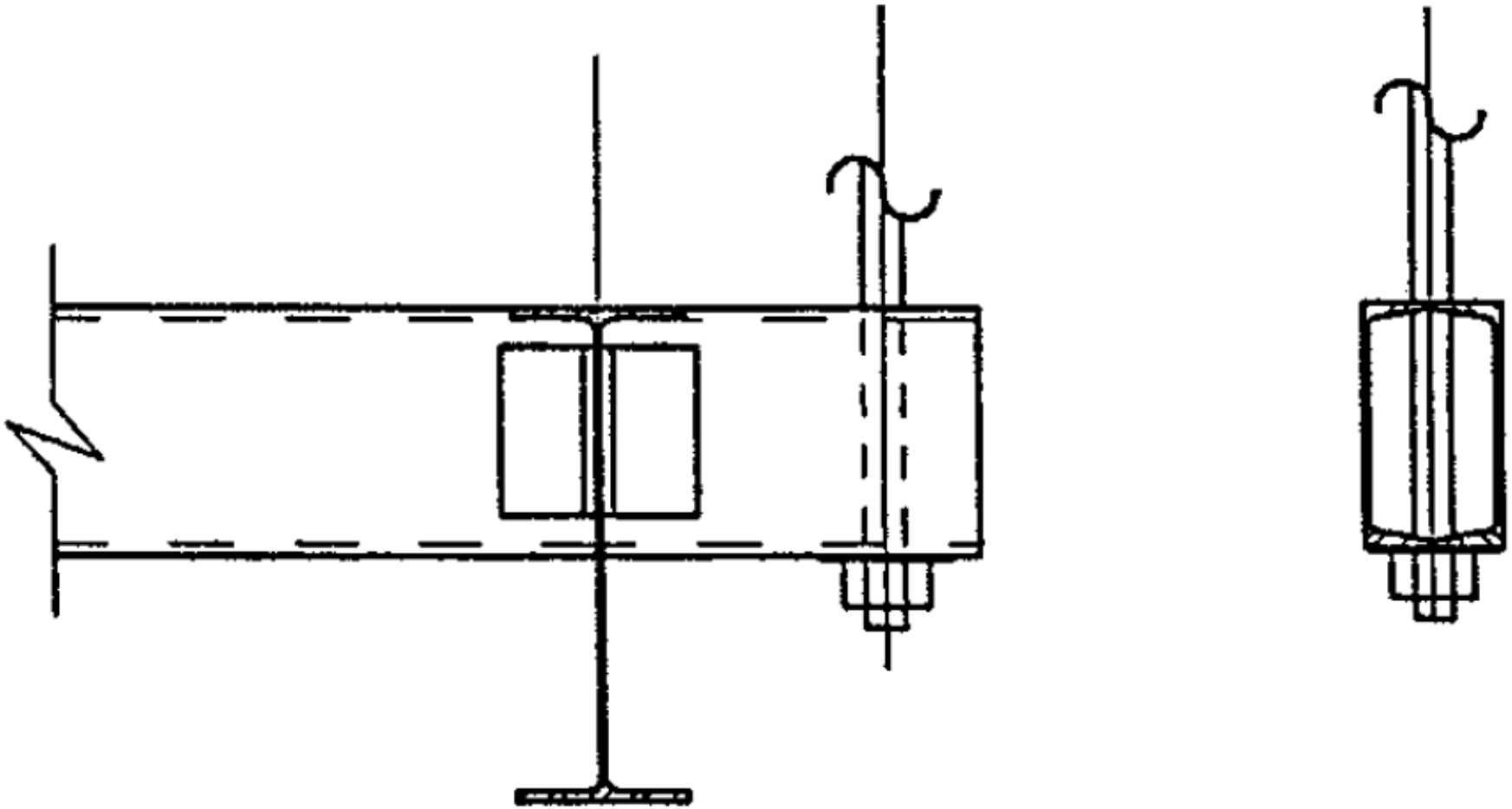


Typical 4th Floor Connection

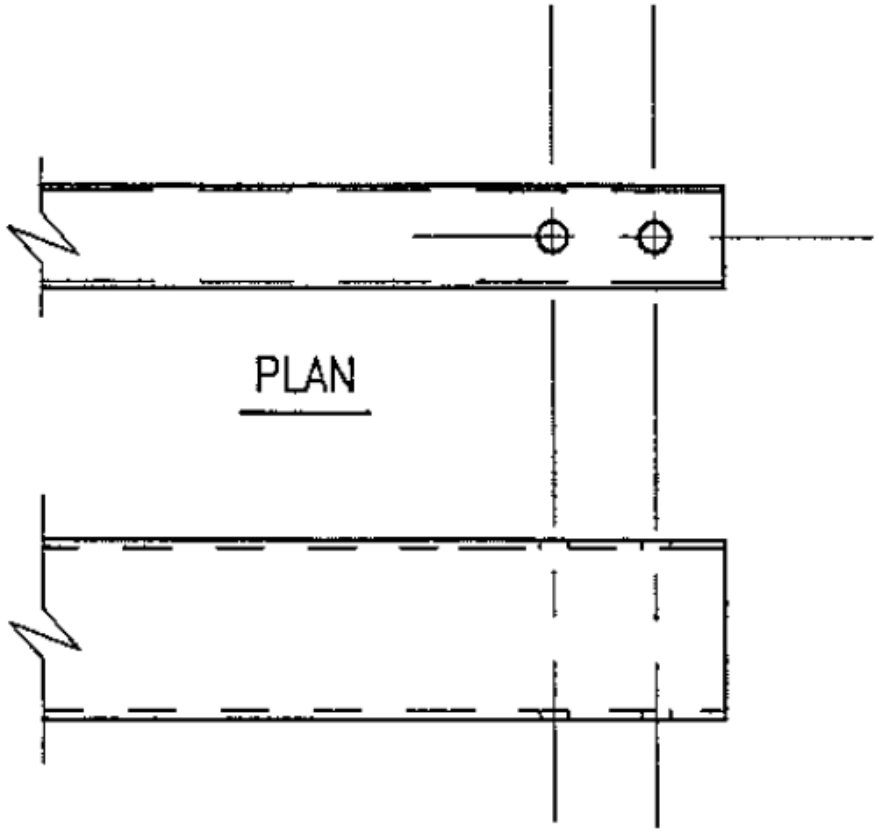
Engineer's Sketch

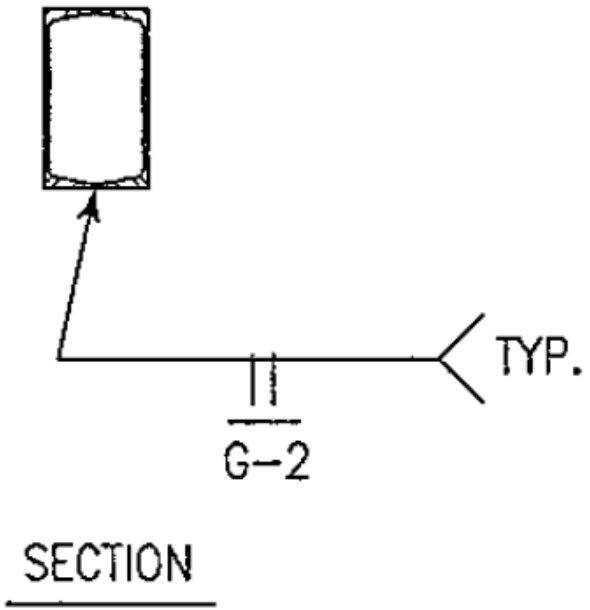


Engineer's Issued Drawing

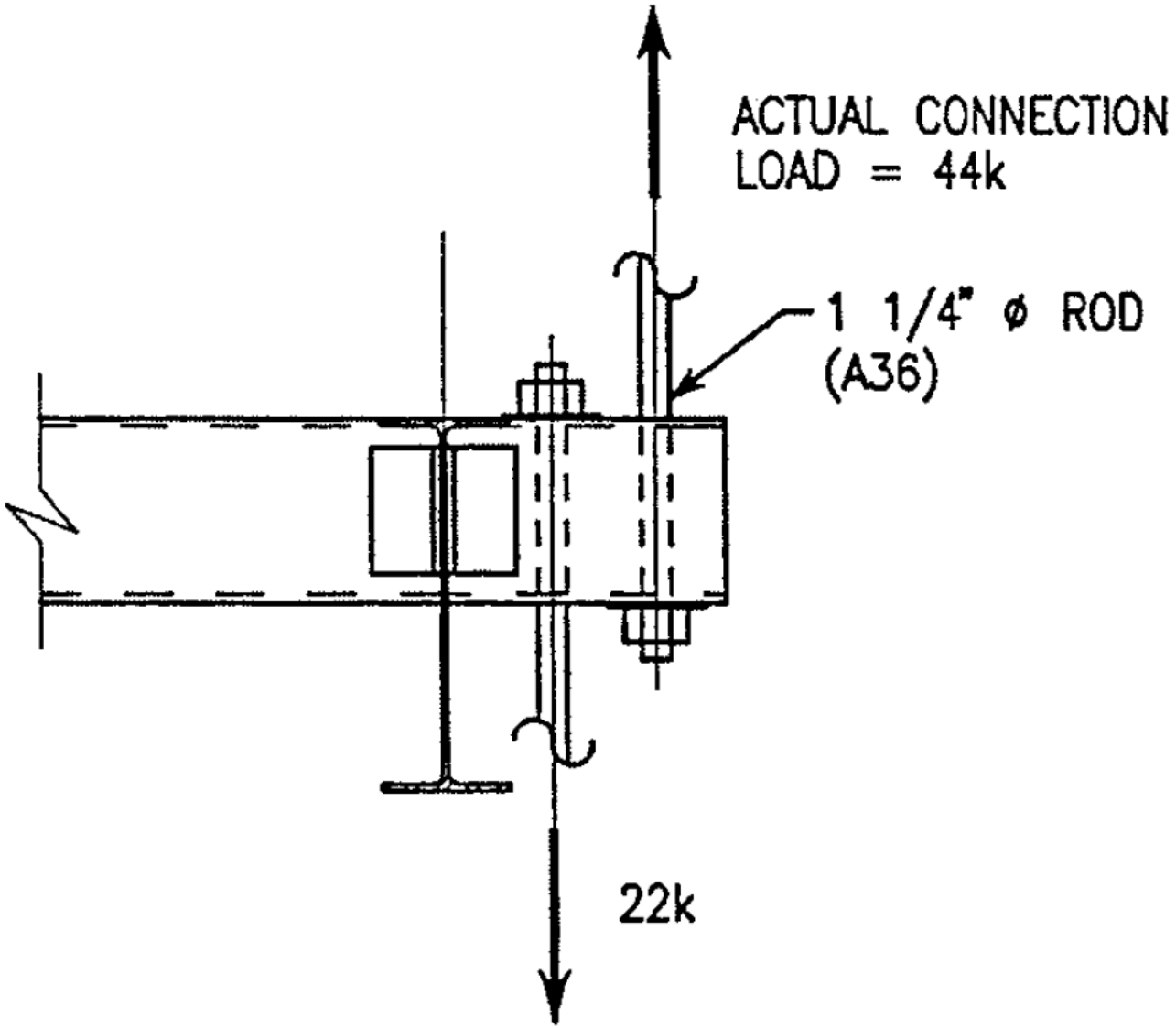


As-Detailed

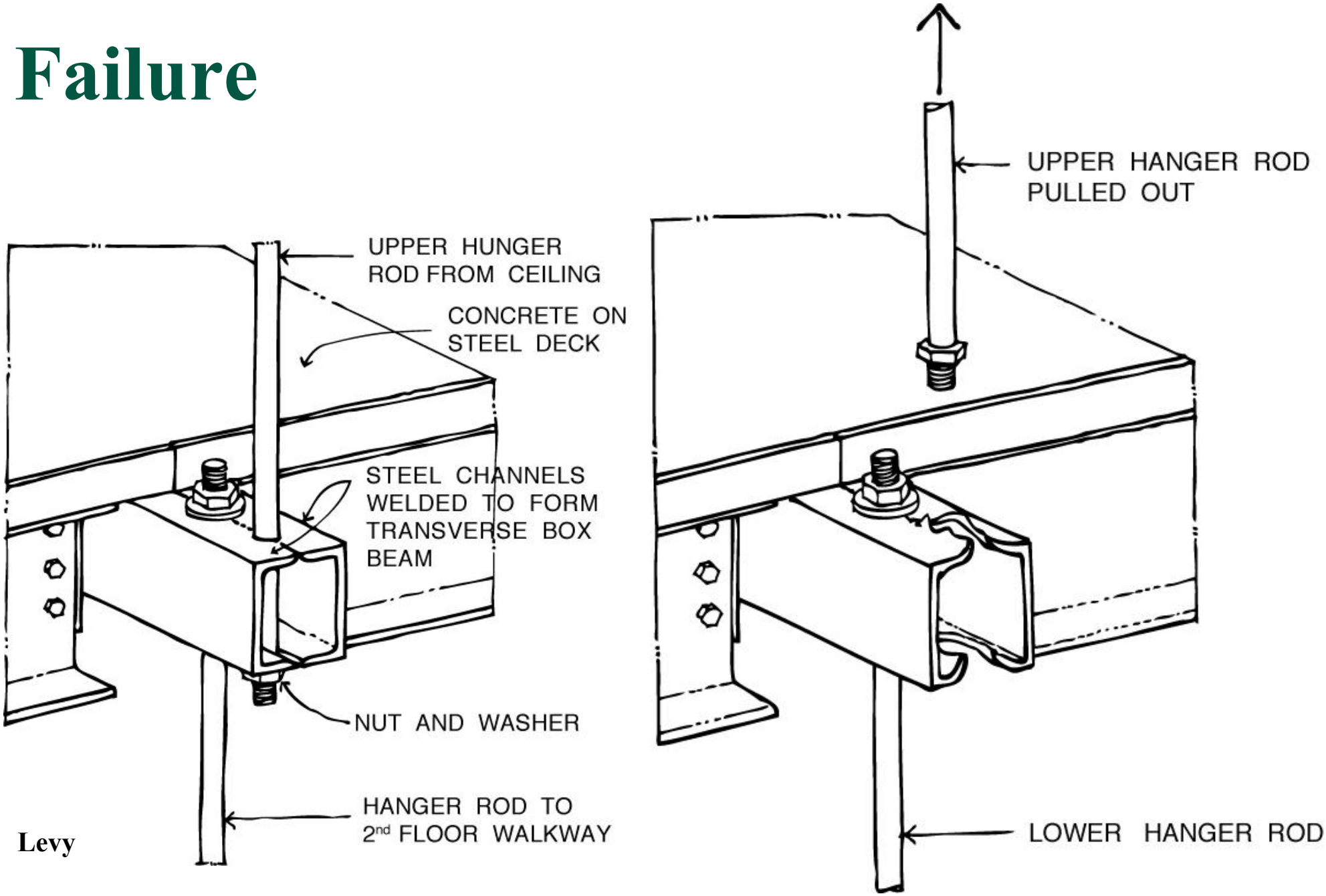




As-Built



Failure



Levy

Engineering Investigation
National Bureau of Standards

- Testing of full size mockups
- Analysis

Findings

- Using original detail, connection strength was 60% of that required by code
- The as-built detail doubled the load on the nut
- Quality and workmanship not an issue

http://www.fire.nist.gov/bfrlpubs/build82/art002.html

Judge's Findings

- 26 week administrative trial (Missouri Licensing Board)
- "Failed to conform to acceptable engineering practice"
- Engineer was responsible for the change from one rod to two rods
- Engineer relied too much on steel contractor
- Engineers found guilty of gross negligence
- Licenses revoked for Gillum and Duncan

ASCE

- **Revoked Gillum's membership for three years, for violation of Code of Ethics**

"Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties."

"Engineers shall approve or seal only those design documents, reviewed or prepared by them, which are determined to be safe for public health and welfare in conformity with accepted engineering standards."

Engineer's Statement

- Design of steel connections was delegated to steel fabricator's engineer
- The failed connection was not designed by anyone
- The detail on the structural drawings was conceptual
- Should have been retained to provide inspection

ASCE's

Journal of Performance of Constructed Facilities

May 2000 issue

Context, per Engineer

- Two key project engineers left firm (prior to design of connection)
- Drafter omitted information
- Fabricator verbally requests change to two rods.
- Due to workload, fabricator used another detailer
- Due to workload, shop drawings were reviewed by senior technician
- Walkways were small part of entire project
- Project was “fast tracked”

Warnings

- Seven weeks before opening, workman reported deflections of ¾” to architect. No follow up
- While installing finishes on box beam, workman noticed deformation at connection. Did not think it was important.
- Handrail deformations reported in memo during first year. No follow up

Lessons Learned

- **The connection was never designed**
- **Need quality control for design that can handle:**
  - Schedule and workload pressures
  - Changes in staff
  - Omissions
- **Non-typical details need special attention**
- **Peer review for important structures**
- **Memorialize verbal understandings**
- **Warnings need to be reported and addressed**
- **Inspection quality?**

More Information
Hyatt

May 2000 issue

Journal of Performance of Constructed Facilities

http://scitation.aip.org/cfo/

Published by

ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS


“That does not compute”

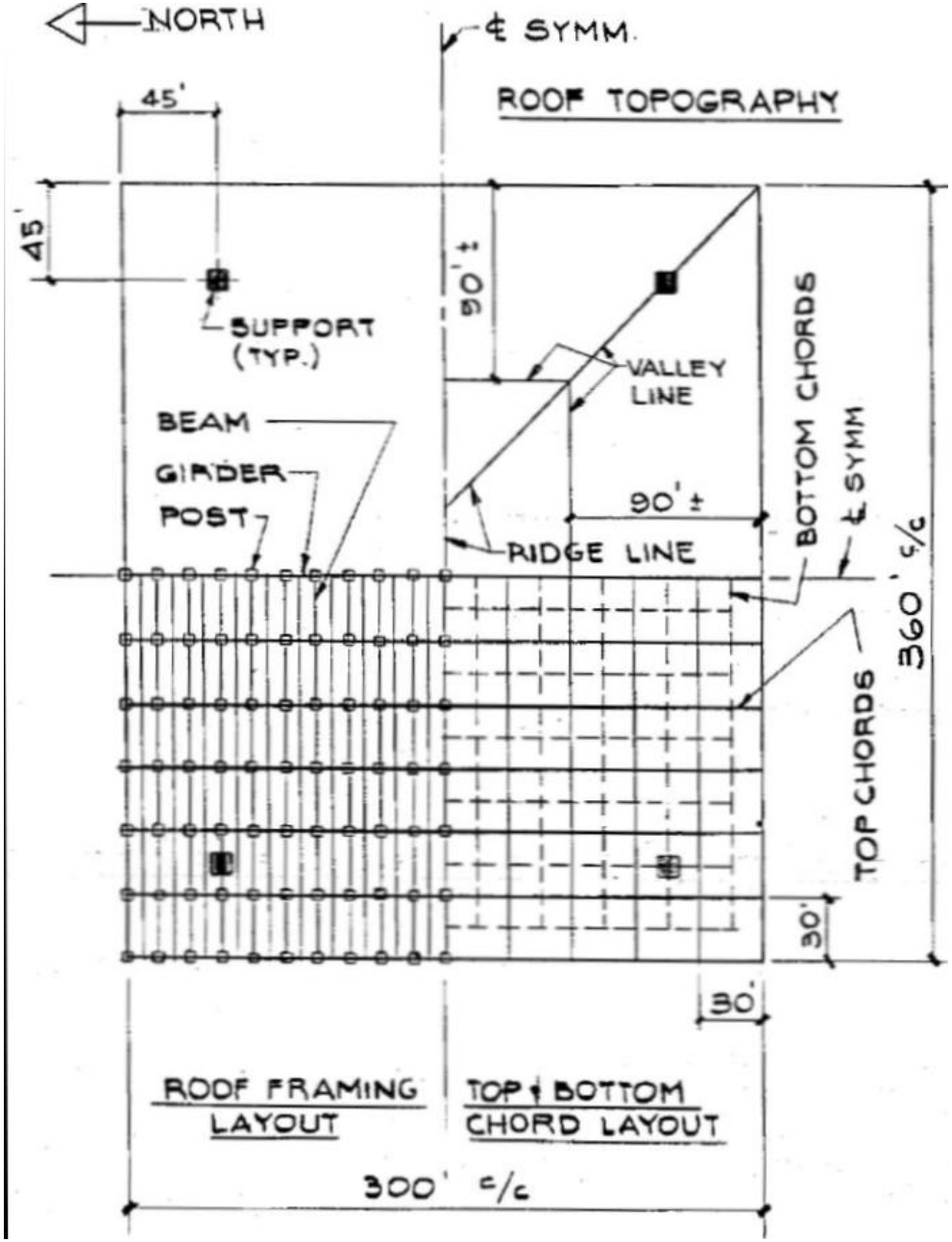
Hartford Coliseum Roof Collapse

Hartford, CT

- Constructed 1973
- Collapsed 1978
- Light snowfall
- No injuries or fatalities

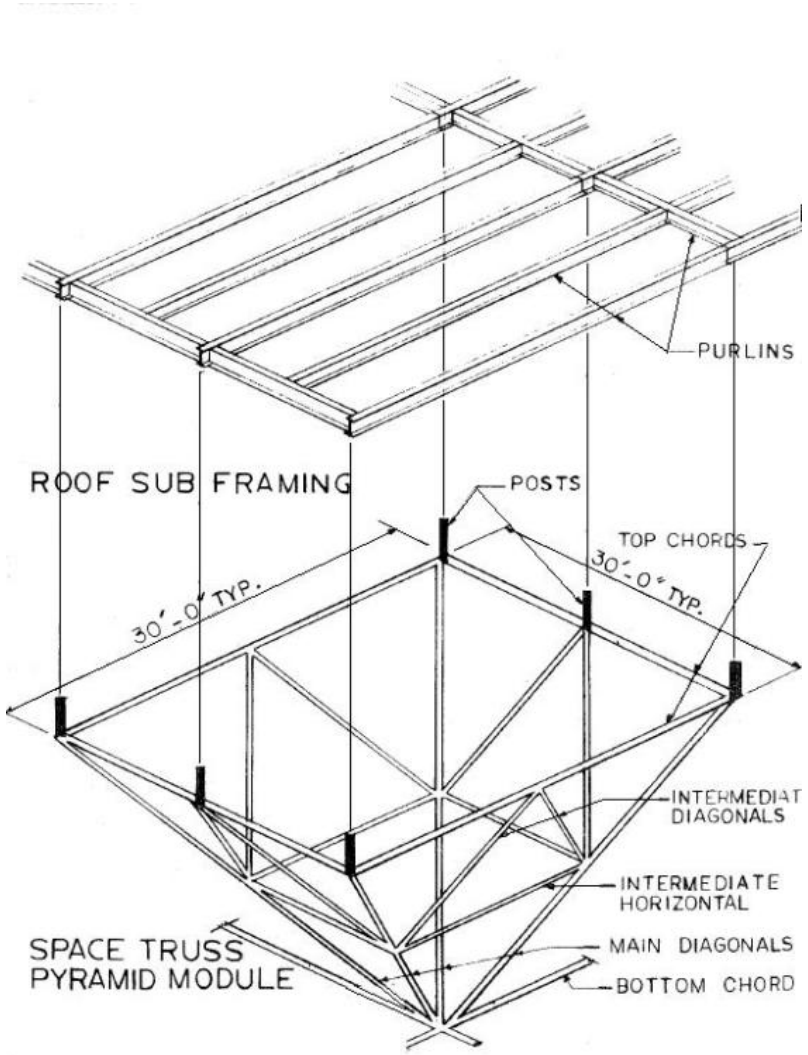
The Roof

- 360’ x 360’ x 22’
- Space-frame
- Offset top/bottom grids
- 4 pylons
- Cantilevered perimeter
- Drainage toward center
- Elevated roof framing

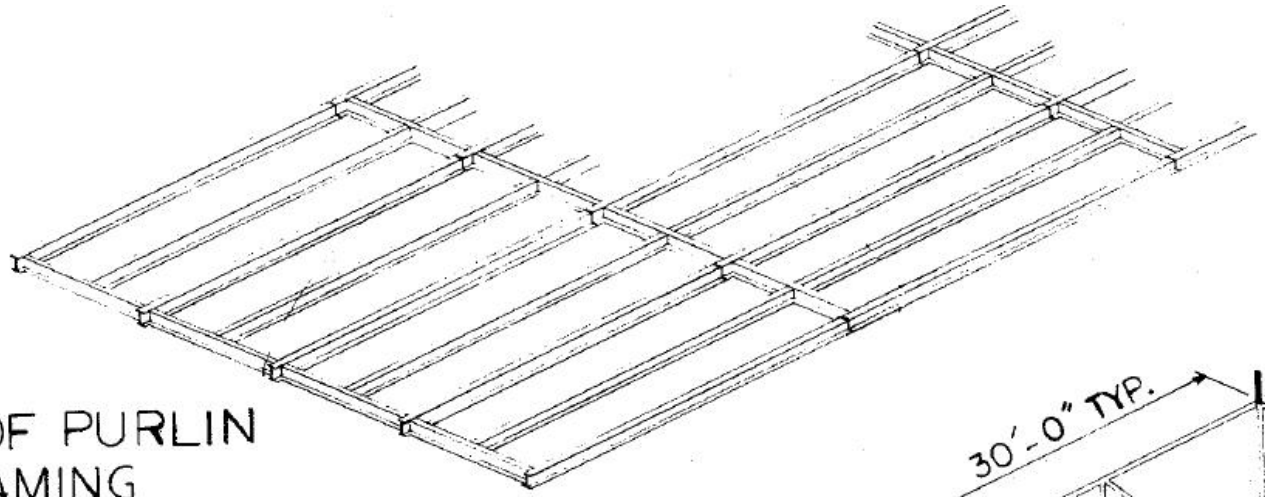


Structural System

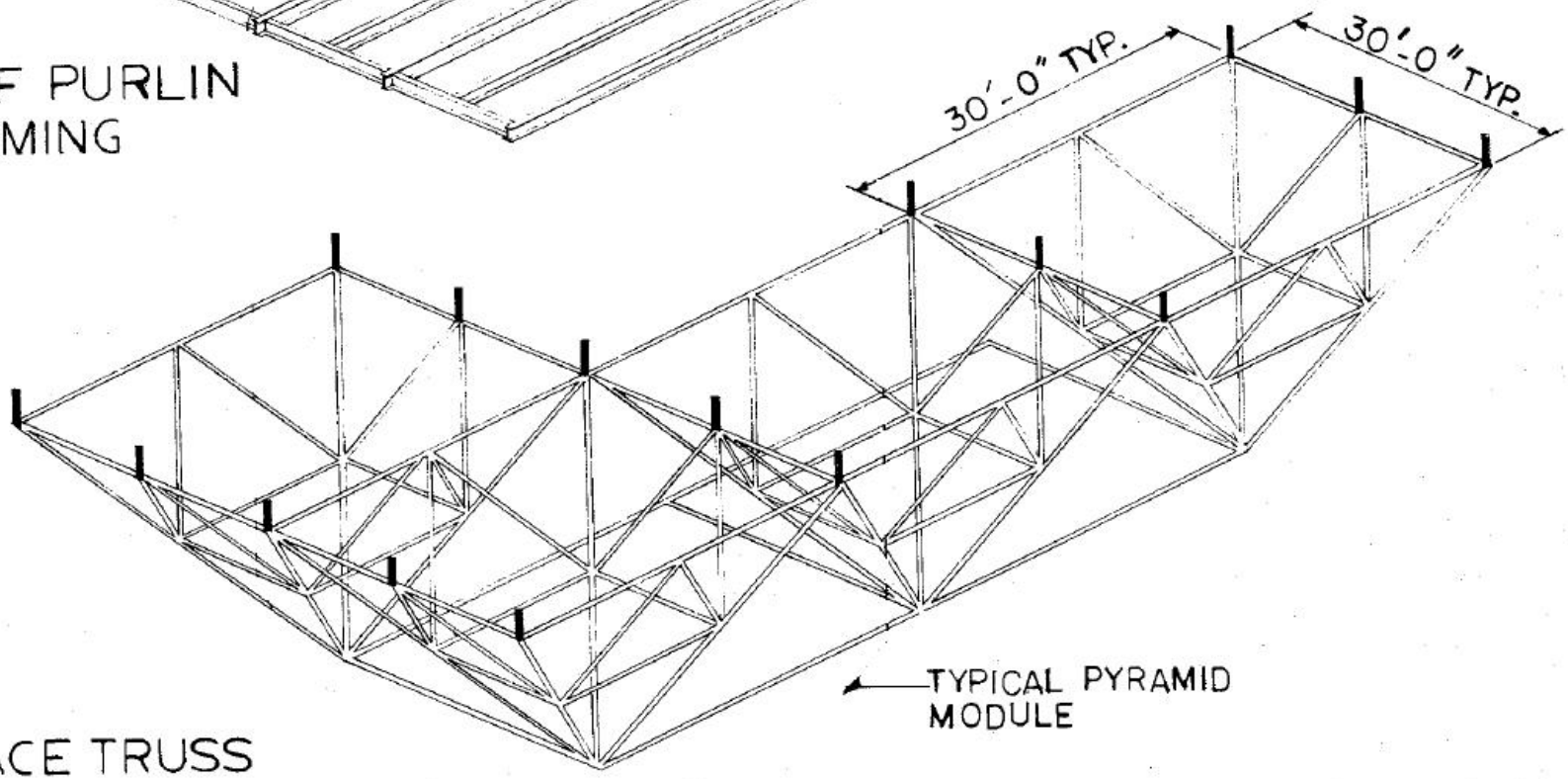
- **Roof is elevated**
  - Camber not needed
  - Roof pitch via post length
  - No bracing from diaphragm
- **Major nodes have posts**
- **Some intermediate nodes have posts**



Structural System



ROOF PURLIN
FRAMING



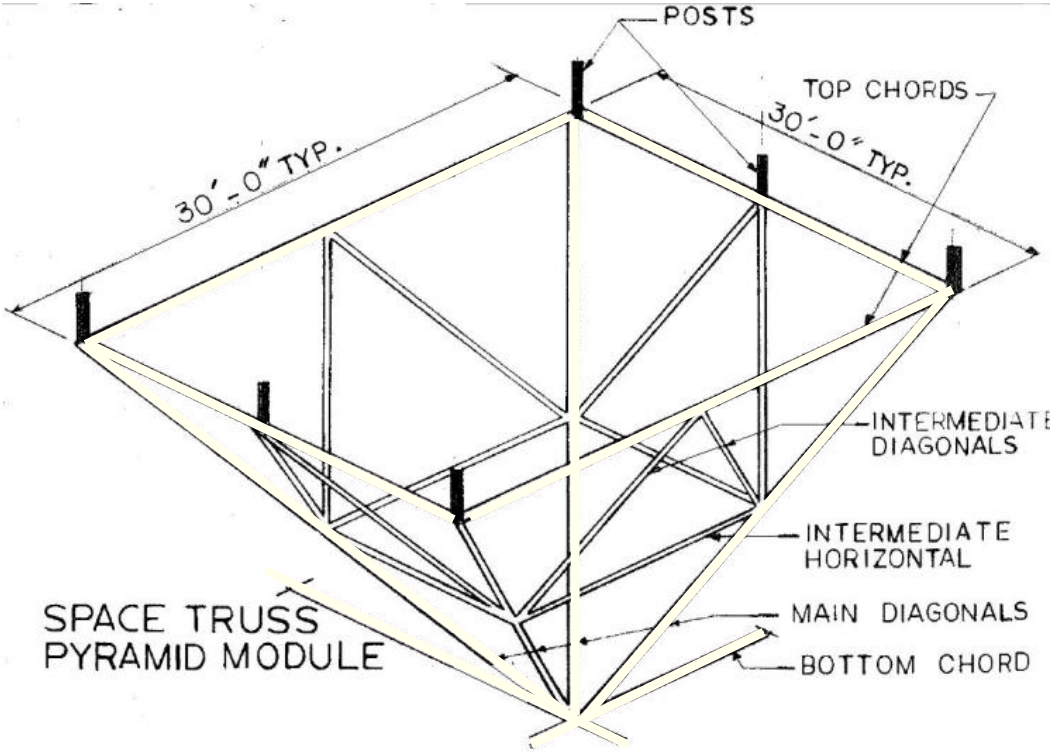
SPACE TRUSS

Design

- Early use of STRUDL, on IBM 360 (1971)
- Only included main space truss members
- Output axial forces

Designer Assumed:

- Fully braced at midpoint
- Pinned connections
- No bending



Cruciform Main Members

- Easy to connect
- Can be bolted
- Weak flexurally
- Weak torsionally

Connection Design

For Horizontal

- Bolted
- No single working point
- Flexibility

For Diagonal

Assembled at Ground Level

Lifted

Final Position

Inspection

- **Agency hired by city for space frame**
- **Hired after space frame was assembled**
- **Daily inspections**
- **Not required to be engineers**
- **Were not engineers**

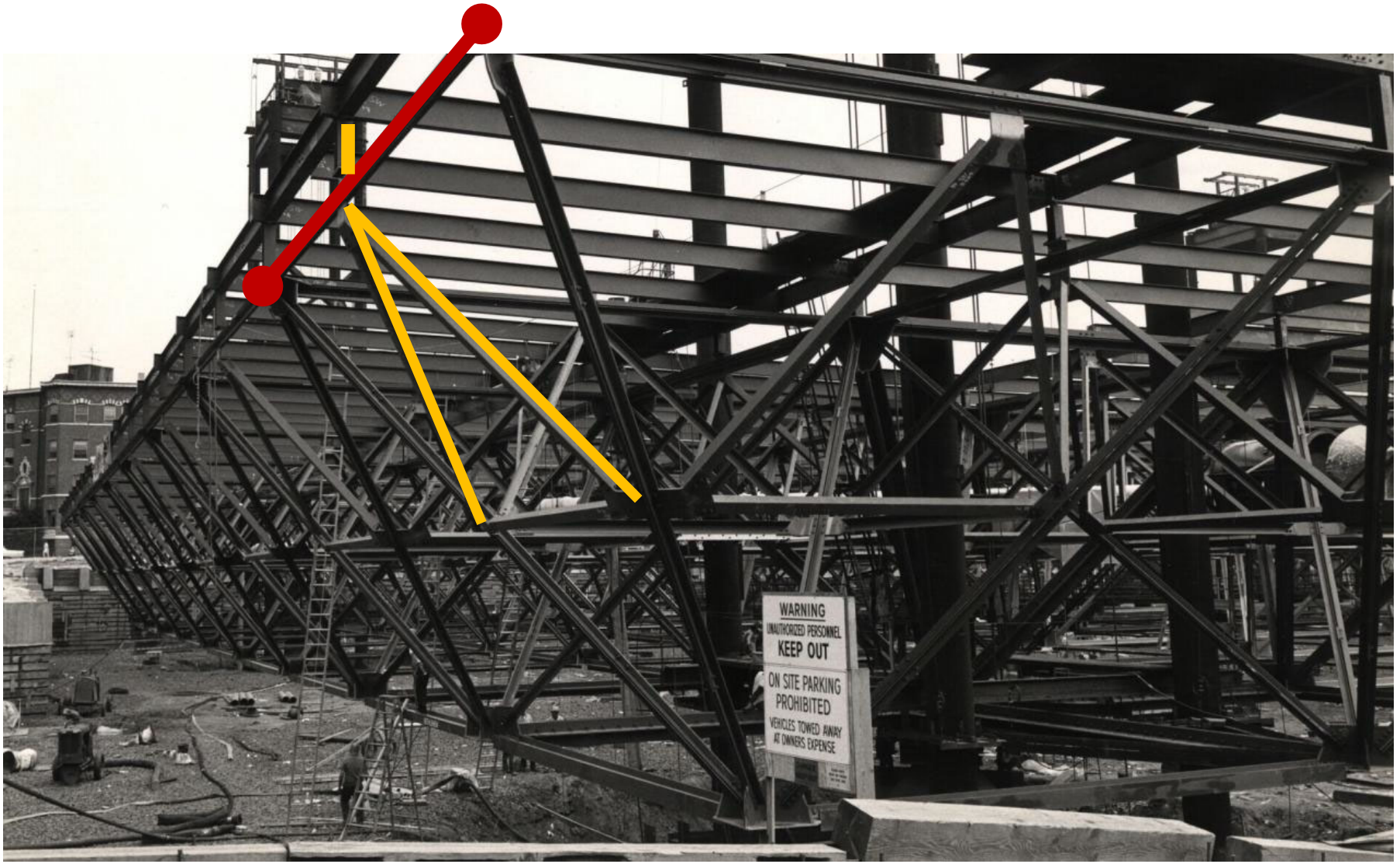
"Final Inspection of the space frame reveals that to date no distortion or warpage of steel members is evident"

Warnings

- During assembly, the engineers were notified that the roof seemed to deflect excessively
- Bowing evident in photographs
- Siding contractor had difficulty installing at perimeter
- When in its final position, the engineers were told that the roof deflection was twice the computed values.
- A year after completion, a citizen notified the engineer that he observed an unsafe dip in the middle.

Five Years Later…Collapse

Unbraced Length? Bending?

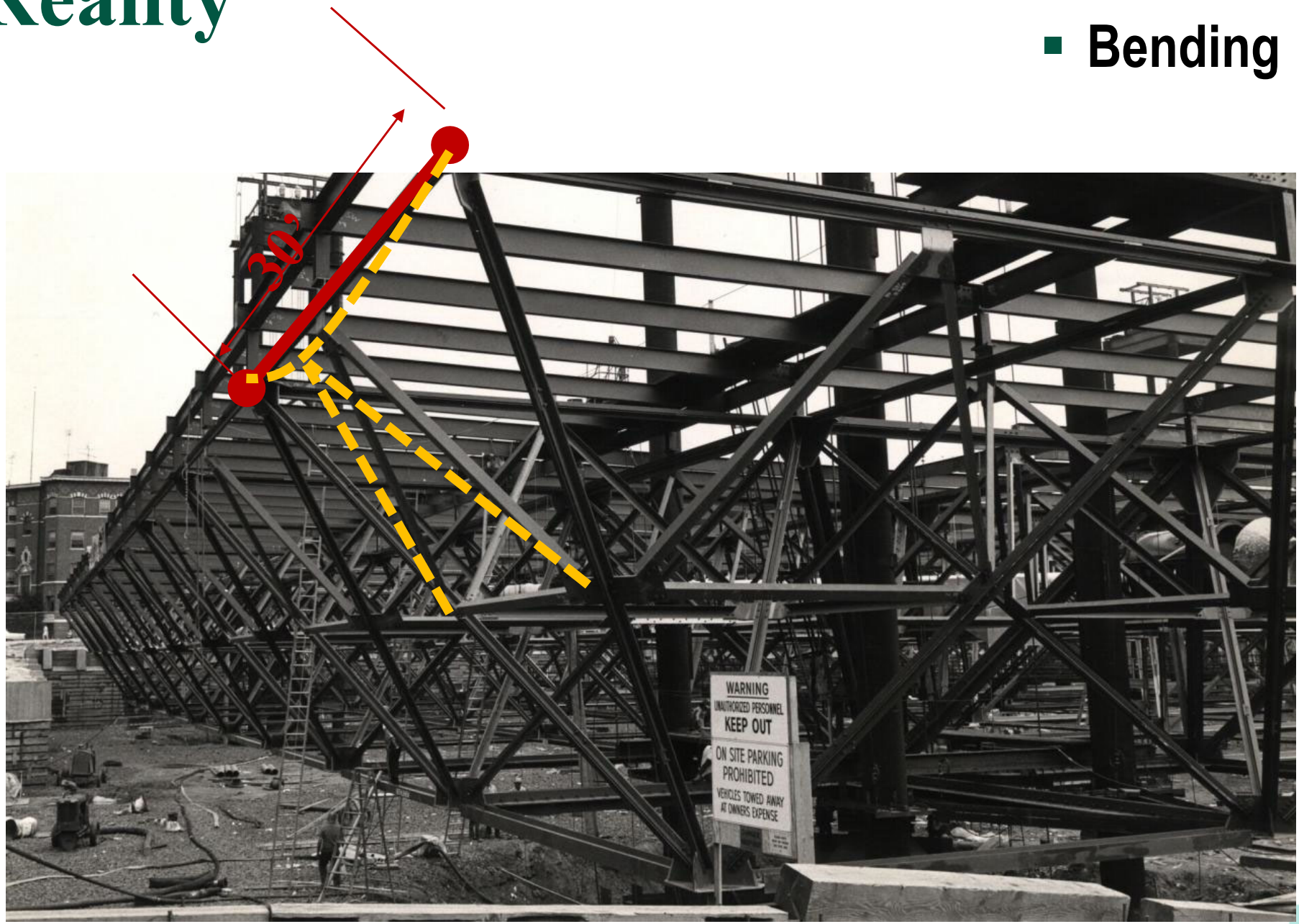


Assumptions

- Braced at midpoint
- No Bending

Reality

- Unbraced length 2X assumption
  - Bending

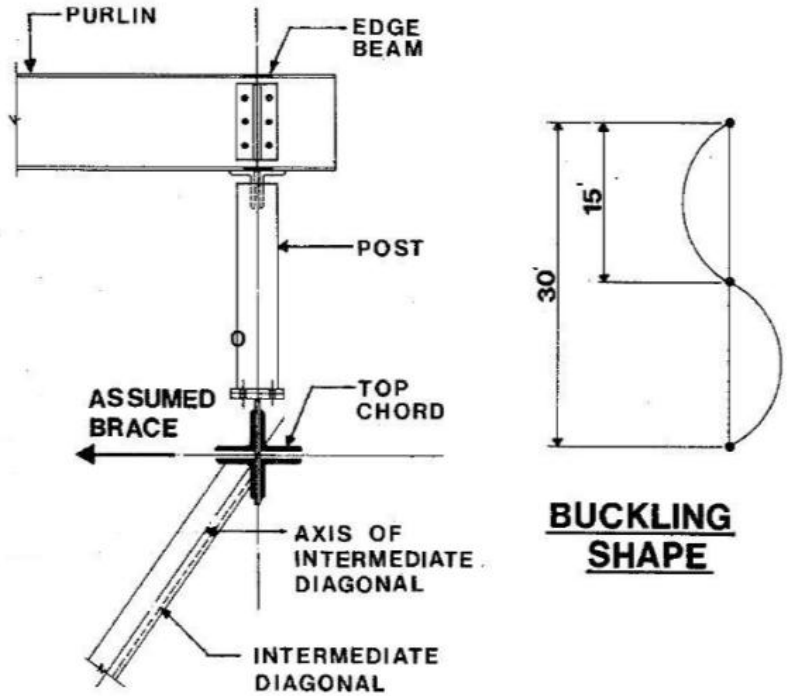


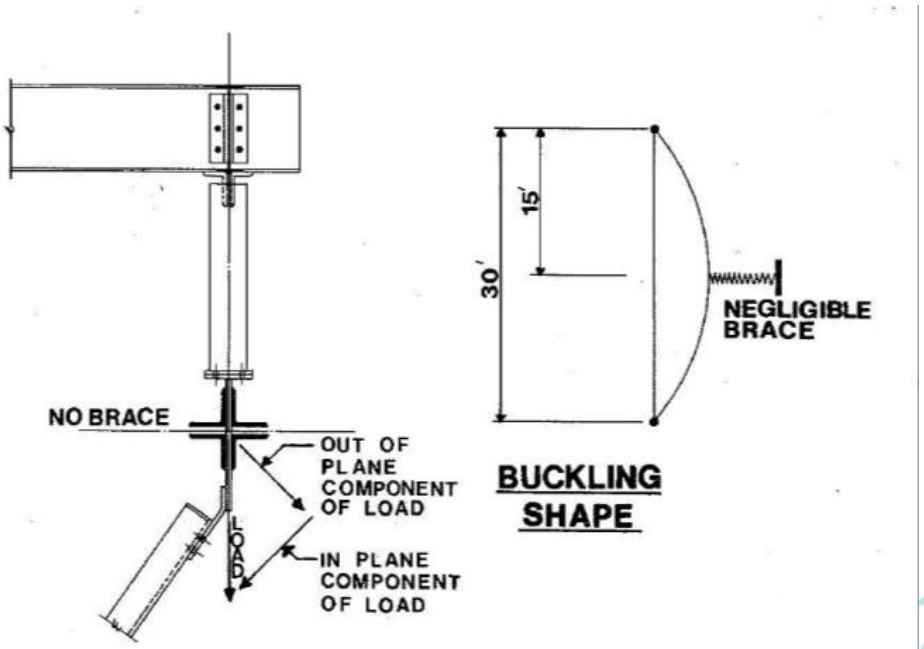
Perimeter—with Post

Overstress: 857%

- **Design Assumption**
  - 160 kip allowable compression
  - No Moment

- **Actual**
  - 15 kip allowable compression
  - Moment

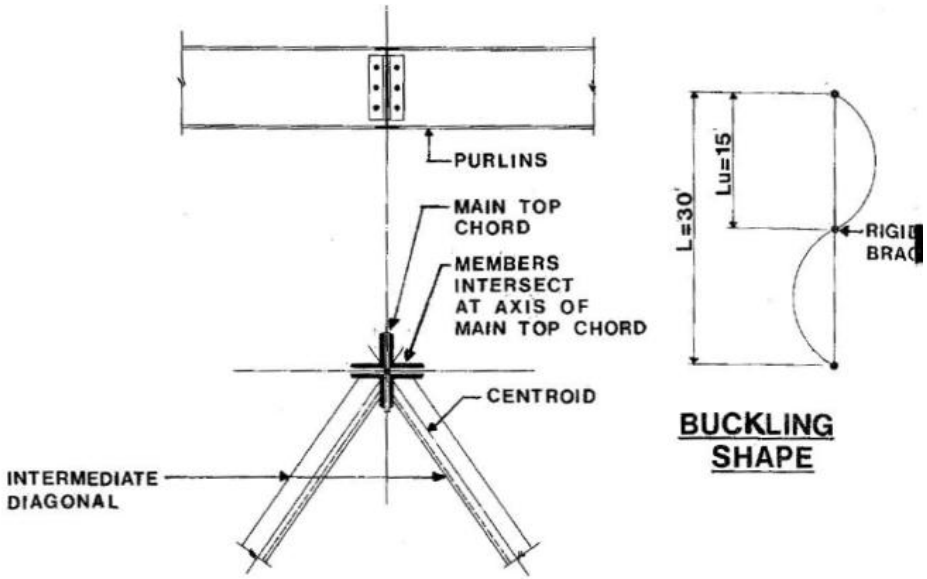


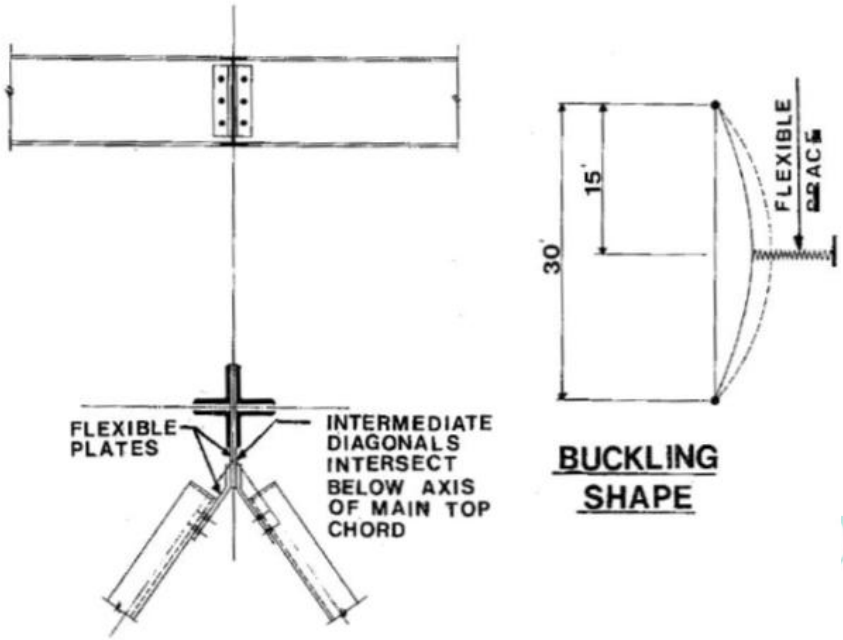


Interior—No Post
Overstress: 107%

- **Design Assumption**
  - 635 kips allowable Compression

- **Actual**
  - 362 kips allowable compression





Analysis Findings

- Snow on roof was 15-18 psf [1]
- Largest load roof had experienced

- Design based on full braces at midpoints
- Actual ultimate live load capacity was 15-20 psf [2]
- Actual dead load was 21% larger than design dead load (roofing, steel framing weight)

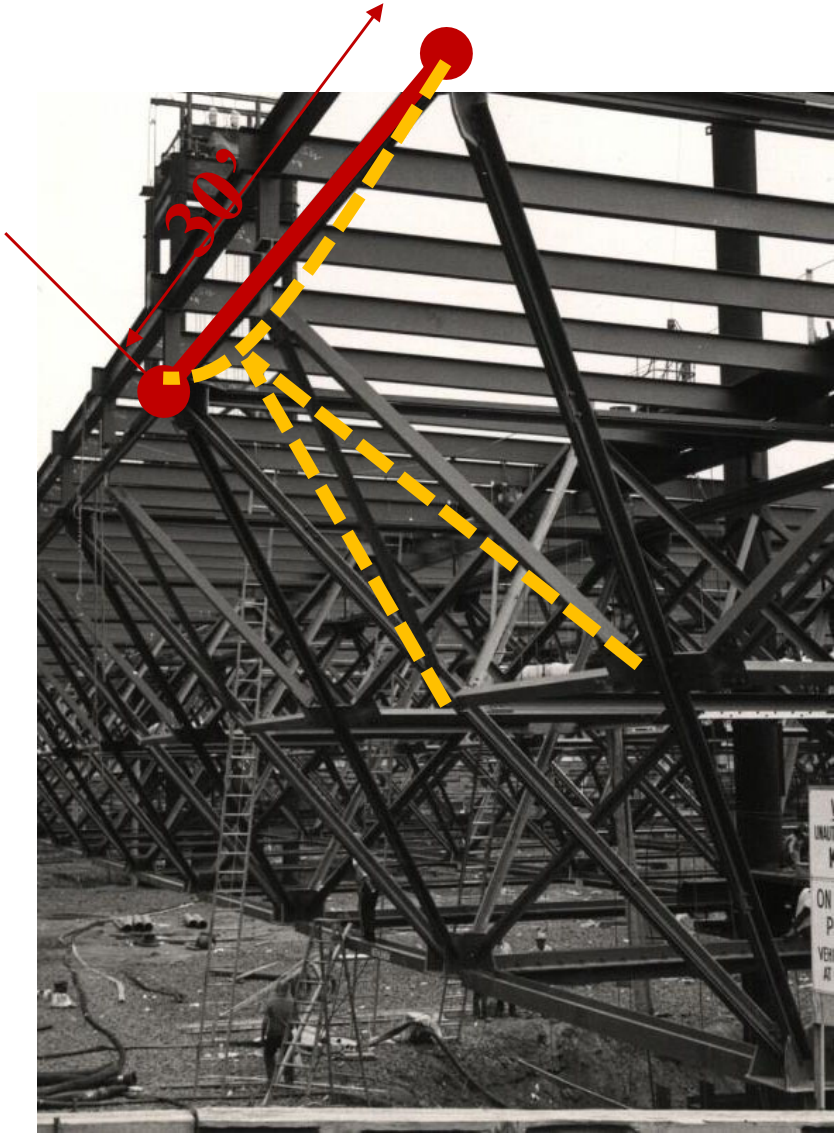
1 Report by US Army Cold Regions Research and Engineering Laboratory
2 Lev Zetlin Associates, report to City of Hartford, June 1978

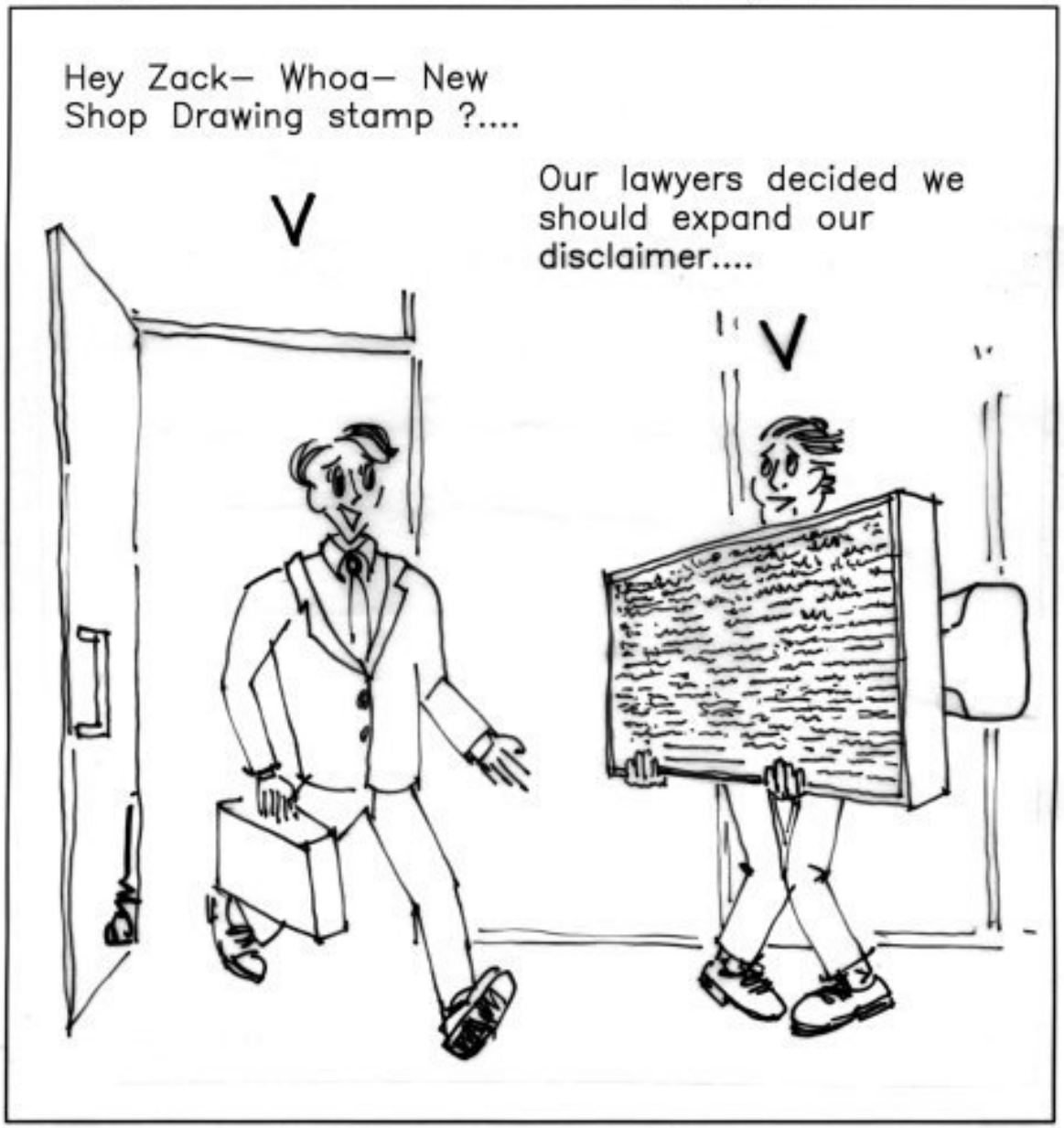
Lessons Learned

- **Caused by Design error**
  - Buckling (wrong unbraced length, soft braces)
  - Did not recognize bending

Contributing Factors

- **Failure to heed warnings**
- **Low caliber inspection**
- **Underestimation of dead load**
- **Lack of peer review**





A Shop Drawing is worth a Thousand Words

Metal Deck Collapse

Worchester, MA

- December 13, 1988
- During construction
- Five workmen fell 40 feet
- Serious injuries
- $ 4 Million Settlement

Building Description

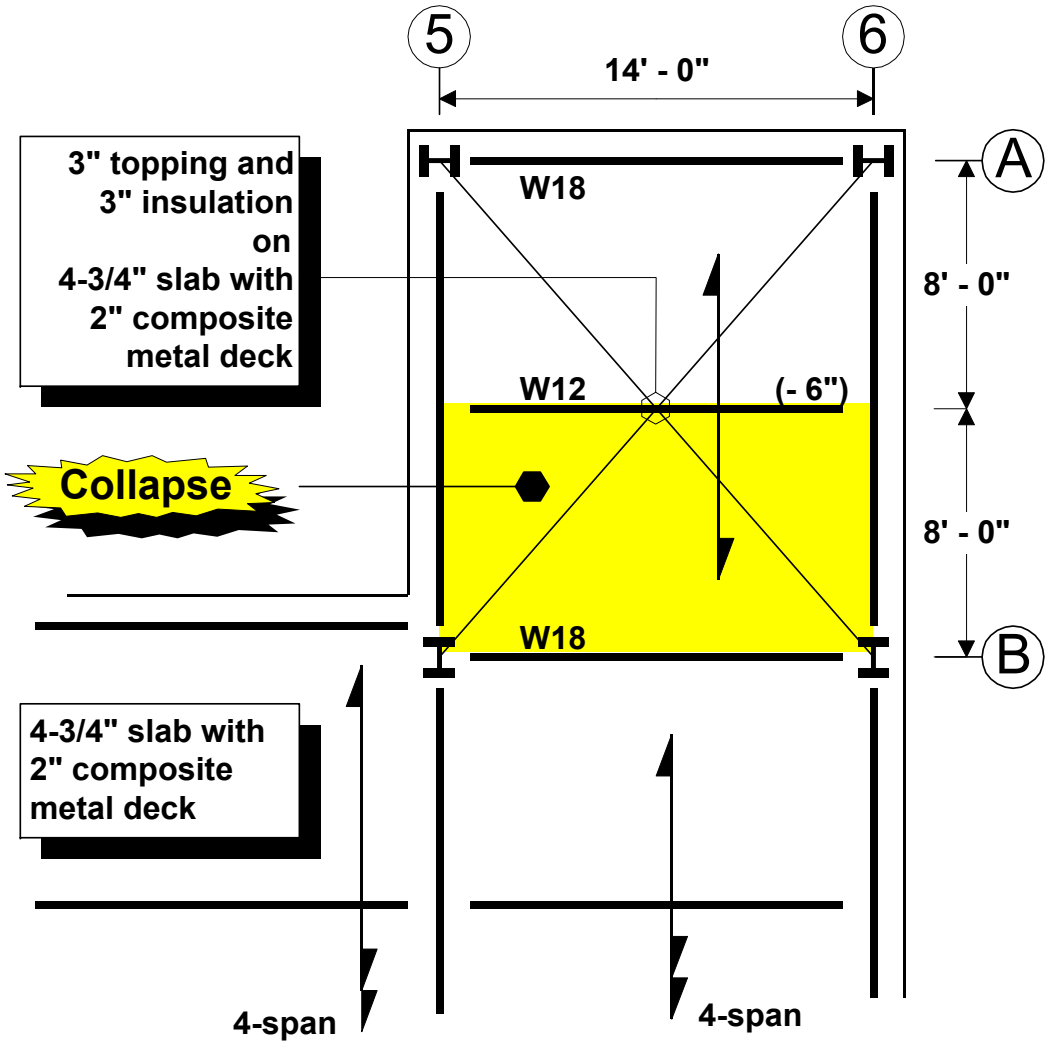
- Laboratory building
- Two levels
- 46,000 sf
- Steel framed
- Composite beams
- Composite metal deck and concrete slabs

Typical Slab Construction

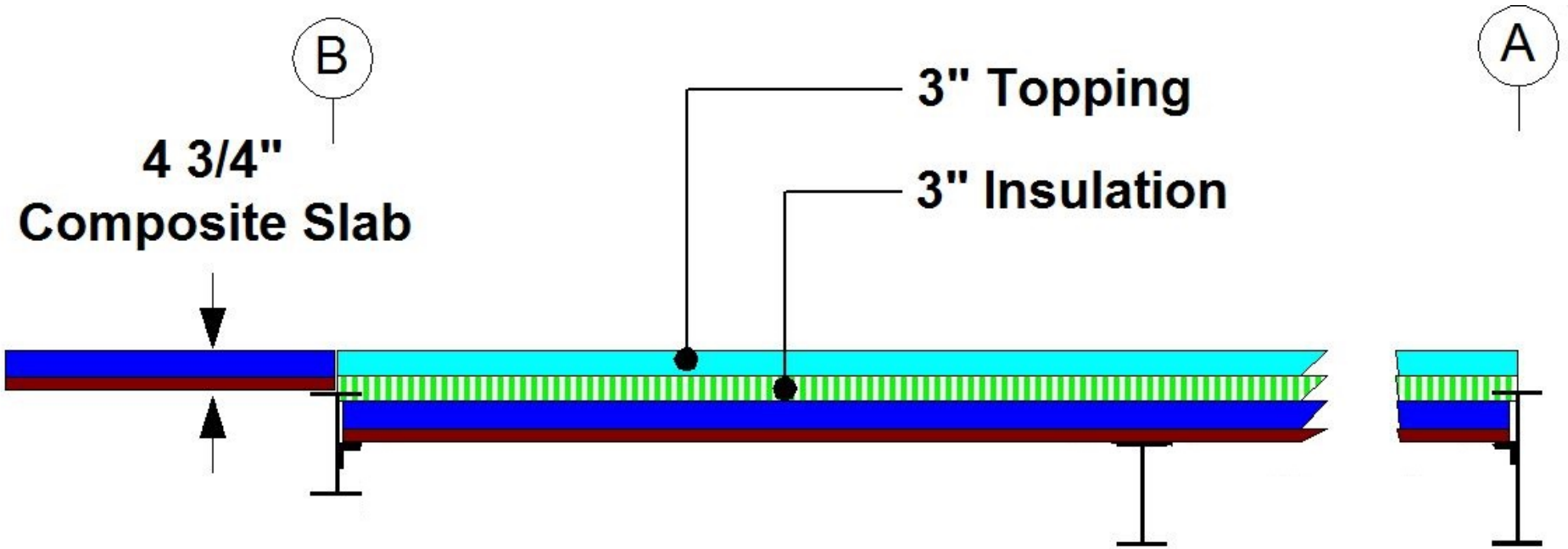
- Composite metal deck/concrete
- Overall thickness: 4-¾”
- 2-inch deep, 22 gauge deck
- Normal weight concrete
- Three and four spans typical

Framing Plan

- Non typical
- 2nd floor “canopy”
- Insulation
- Concrete topping
- Depressed deck
- Two spans



Section



Engineer Used Standard Contract

AIA Document C141, "Standard Form of Agreement Between Architect and Engineer."

The Engineer shall not have control or charge of, and shall not be responsible for, construction means, methods, techniques, sequences or procedures, for safety precautions and programs in connection with the Work,

Shoring Responsibility

- **Project specifications**

"Shop drawings shall indicate locations where shoring of metal deck is required"

Shop Drawing Review

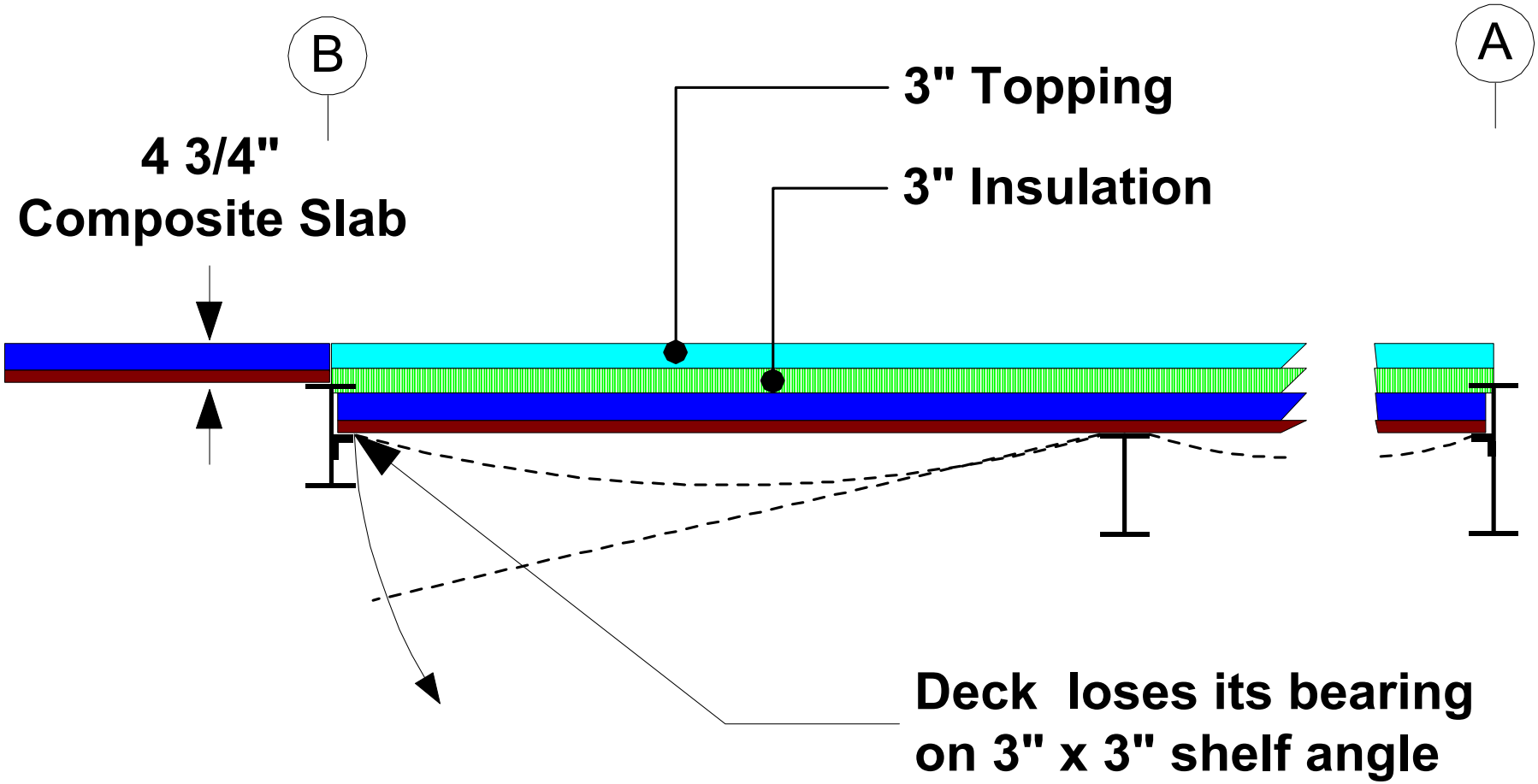
- Engineer reviewed metal deck shop drawings and "gratuitously" pointed out two spans that needed shoring
- There were actually three areas that needed shoring
- The third area collapsed

Telephone Call

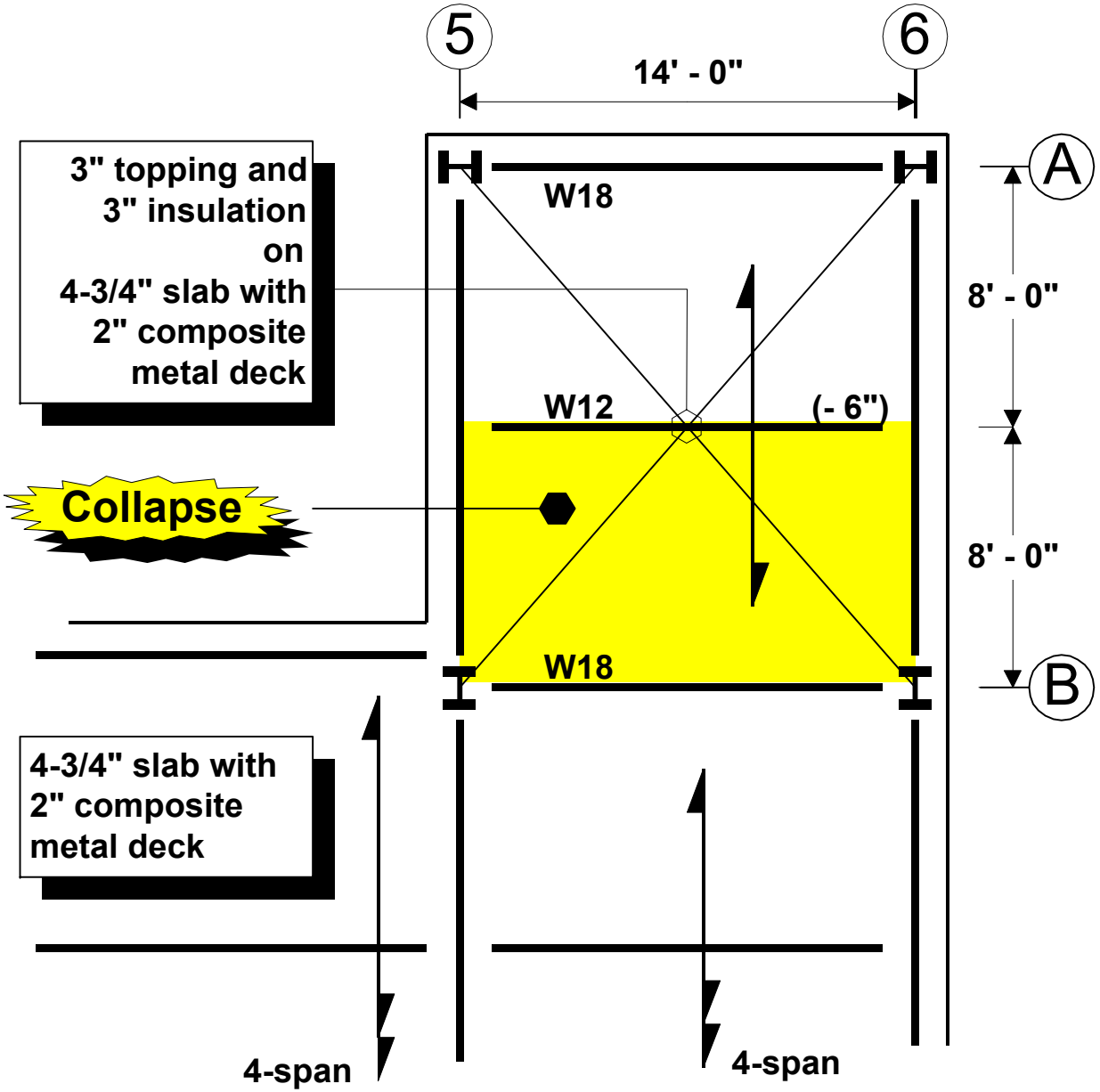
- Morning of accident
- Superintendent calls Engineer
- Asked if he could place topping same day
- Mentions that there was about ½ inch deflection in other areas
- No discussion of shoring
- Engineer checks deflections and says,

"There should be no problem."

Collapse Mechanism

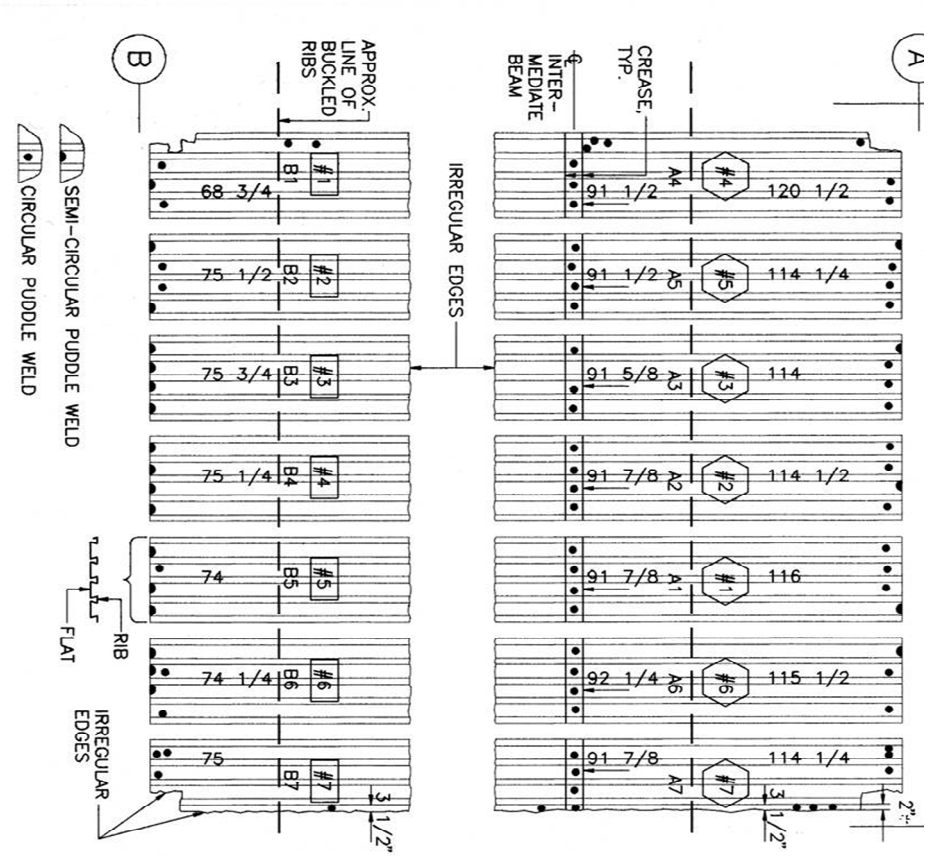


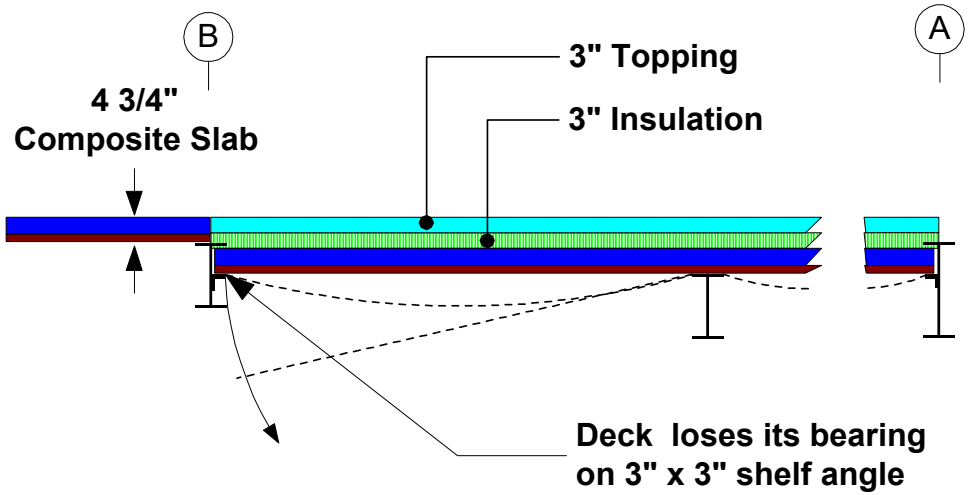
Collapse Area



Observations

- Buckled ribs at midspan
- Crease at intermediate beam
- “Half moon” puddle welds
- No sidelap connections
- Few side welds
- No puddle weld washers





OSHA Court Finding

"…we find that, because the defendant did not assign any of its employees to the construction site, the site was not a 'place of employment' which the defendant had a duty under the OSH Act to protect."

U.S. Court of Appeals, August 1993

Causes

Trigger

- **Added weight of concrete**

Technical Cause

- **Premature loading of uncured composite slab**

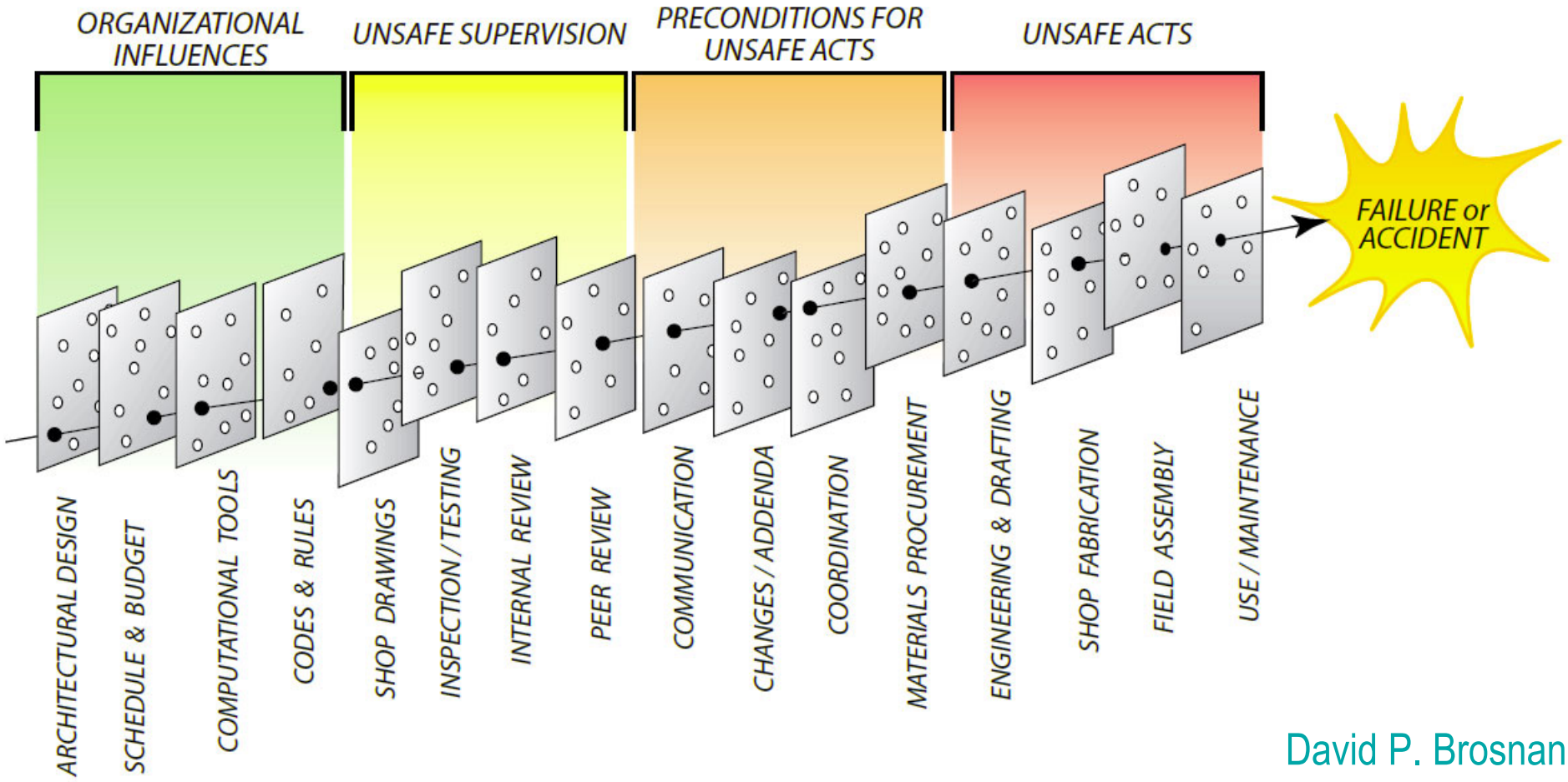
Contributing Factors

- Constructability issues
- Lack of shoring
- Poor workmanship
- Poor inspection

Lessons Learned

- Actions should be consistent with written agreement
- Constructability must be considered by designer
- Non-typical areas require additional attention in all phases by all parties
- Avoid taking responsibility for means and methods
- Follow up verbal instructions with written memorandum immediately
- Competent inspection is crucial

Swiss Cheese Model



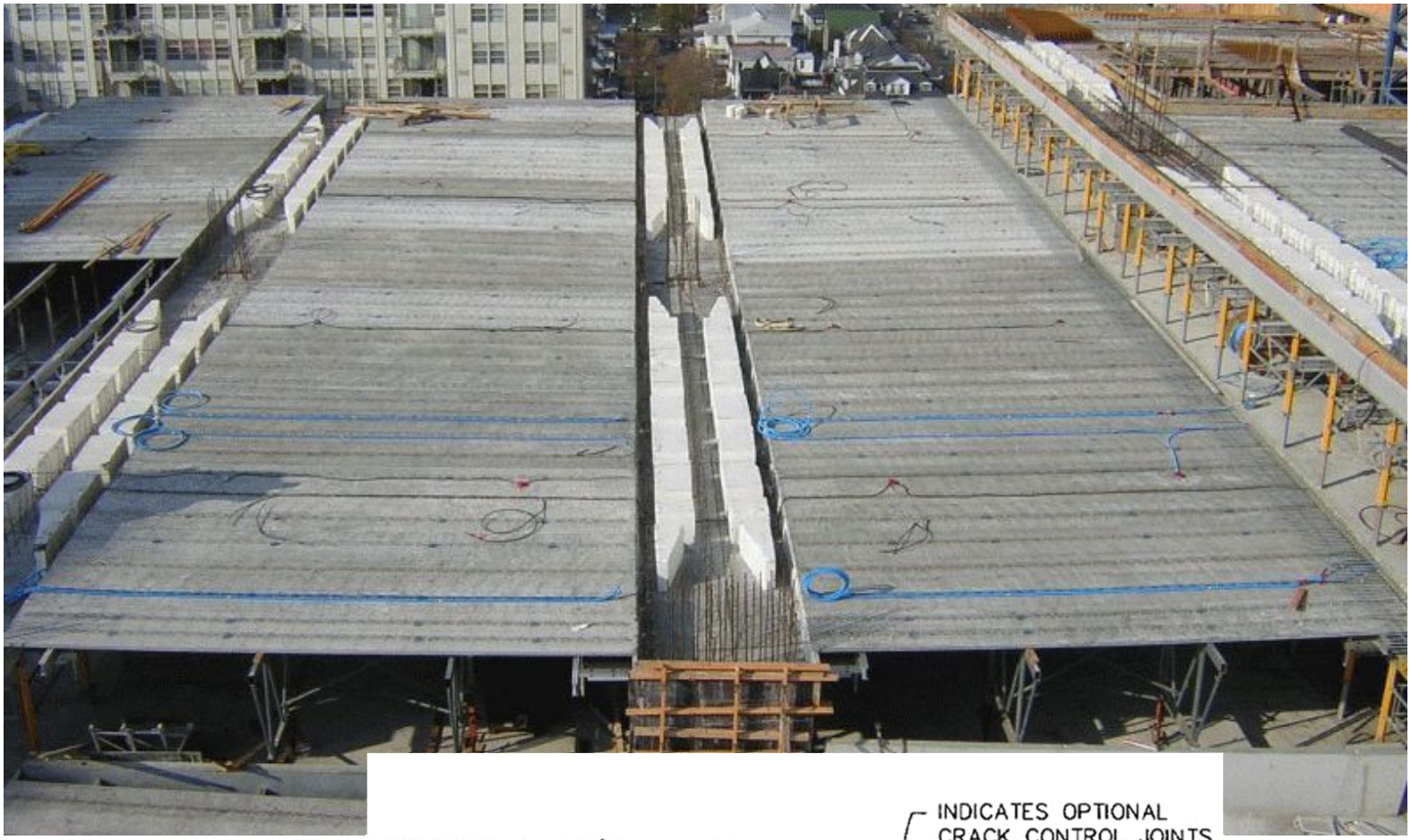
Swiss Cheese Model for Error Propagation in Structural Engineering.

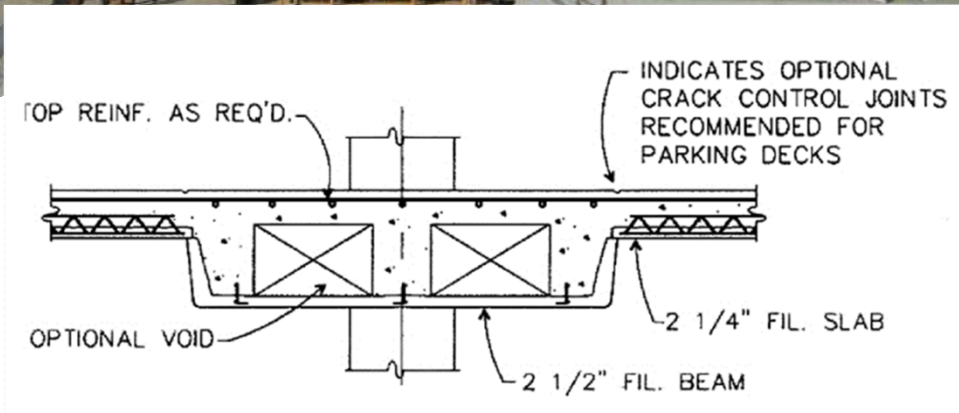
David P. Brosnan
Structure Magazine, 2008

Tropicana Garage Collapse

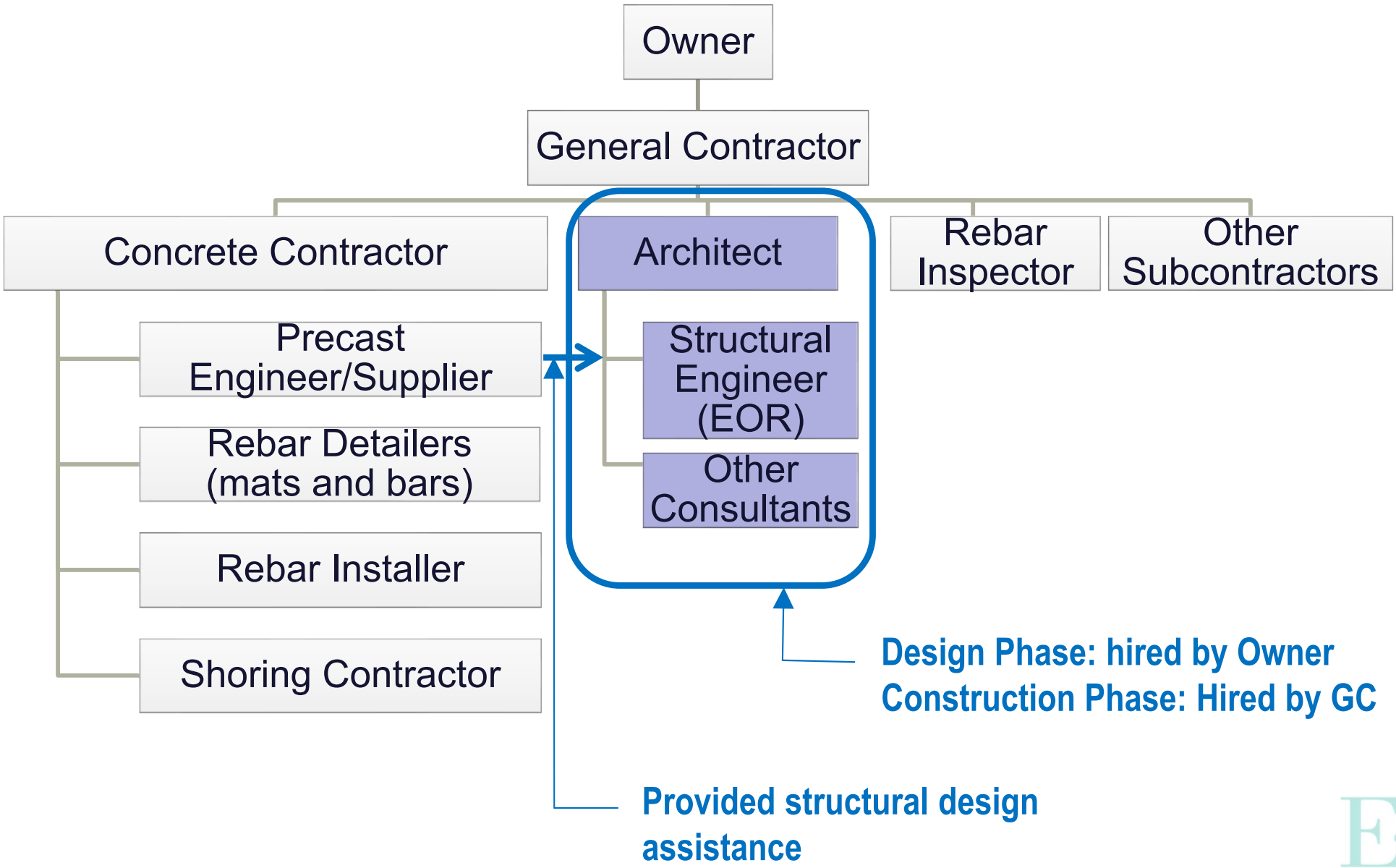
- Atlantic City, NJ
- October 30, 2003
- During construction
- 4 fatalities, 21 injuries
- Settled for $101 Million
- OSHA fines of $119K

Proprietary Structural System

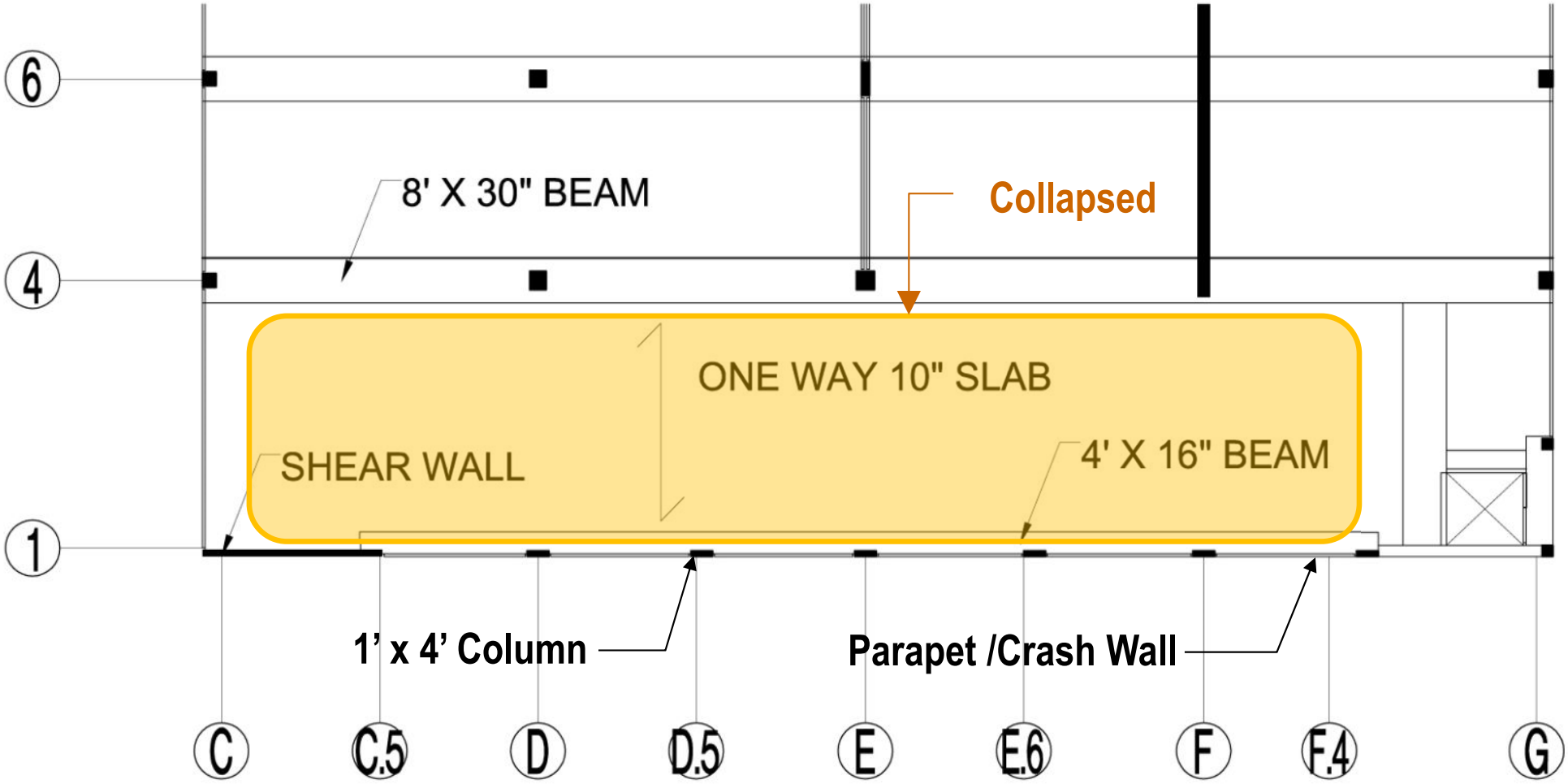




Organization Chart



Structure Plan in Collapse Area



Collapse Configuration

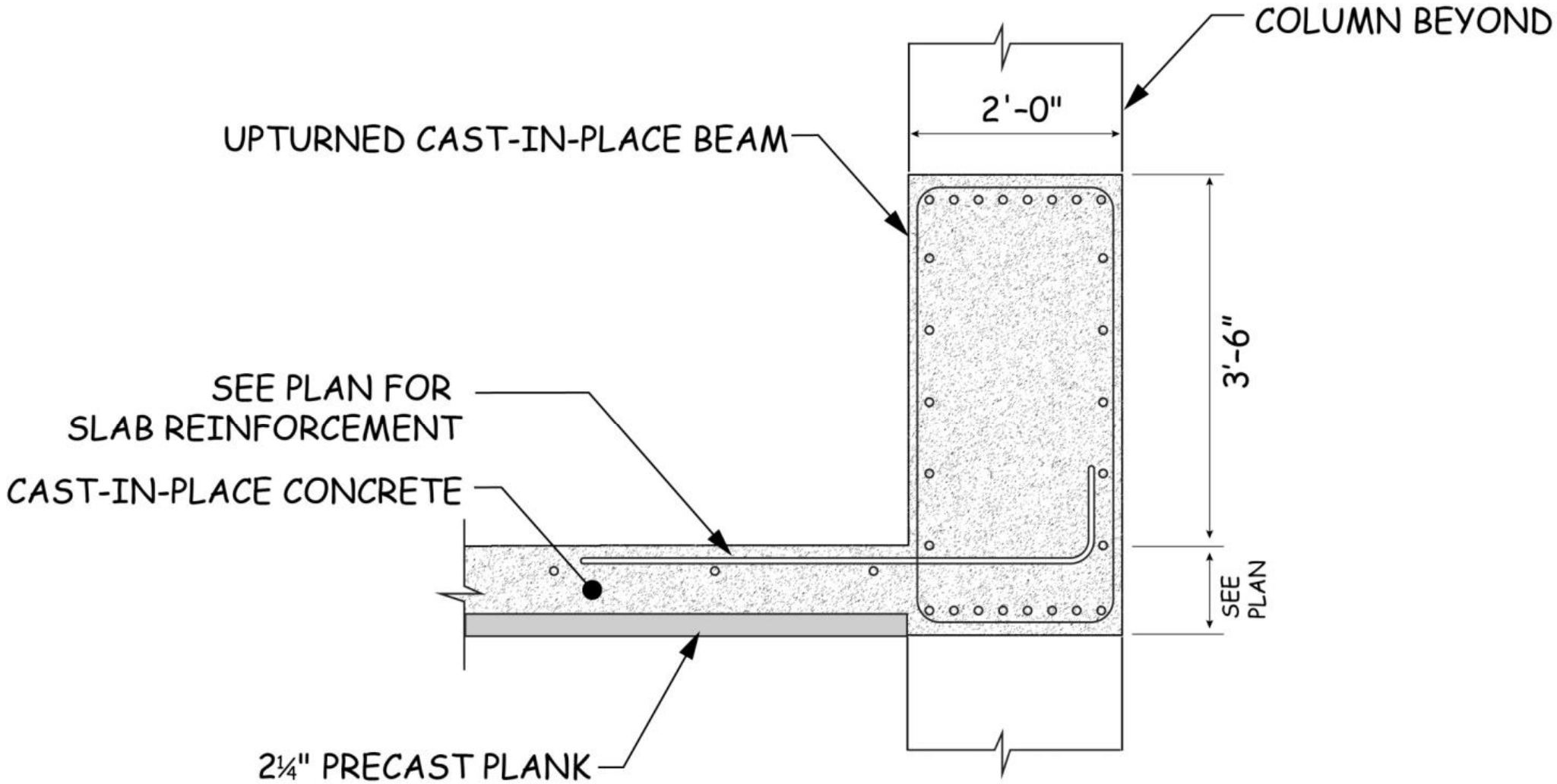
Collapse Configuration

Slab-to-Shearwall Connections

Slab-to-Column Connections

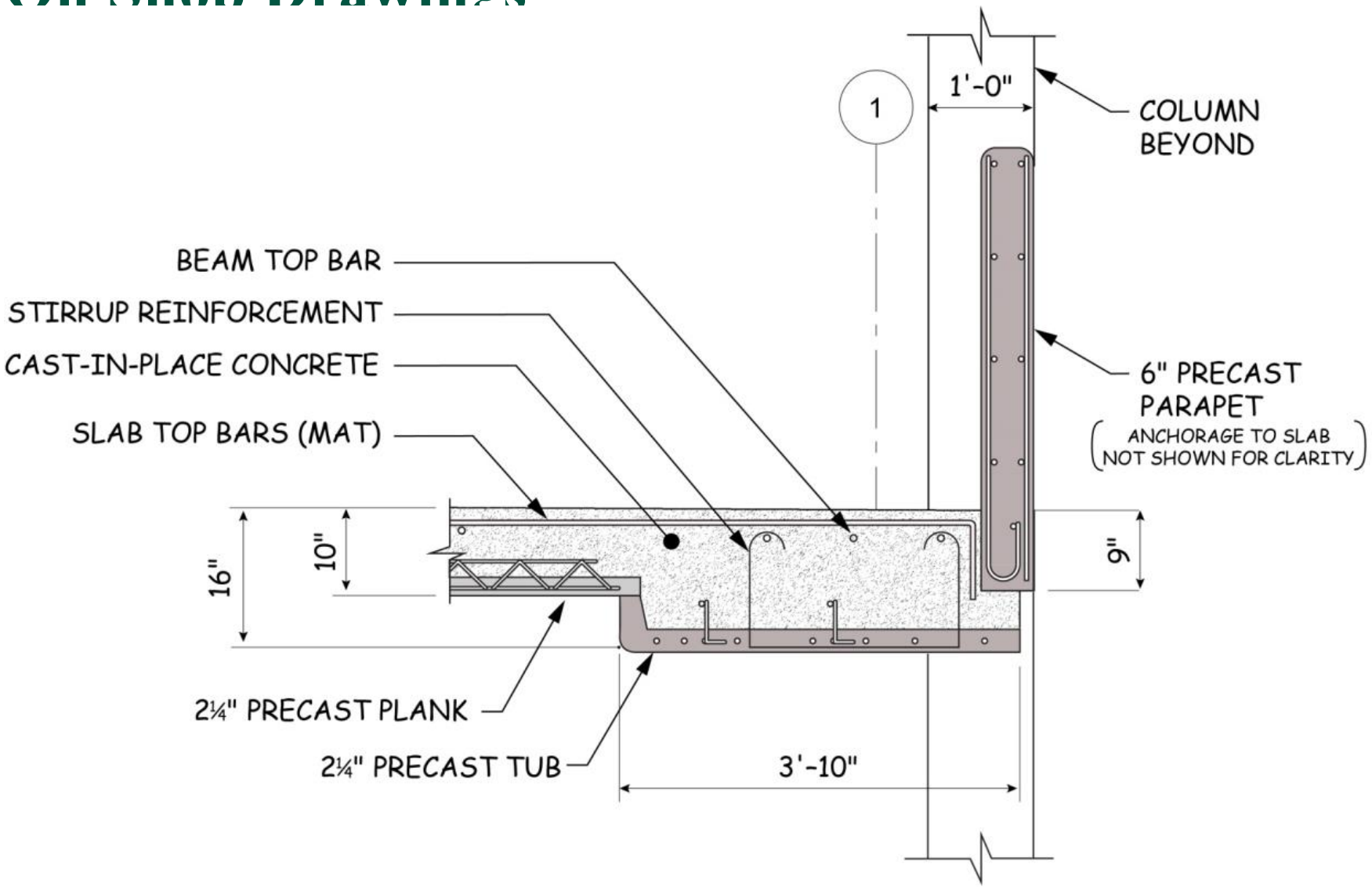
Original Design—Spandrel

on EOR's drawings



Revised Design—Section

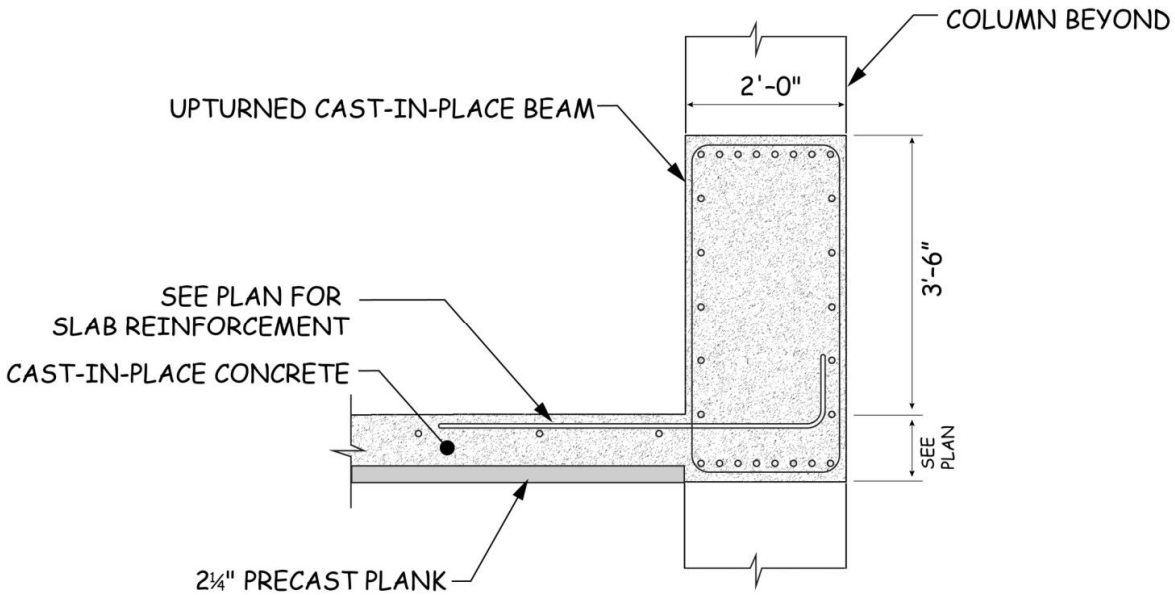
On Shop Drawings



Comparison

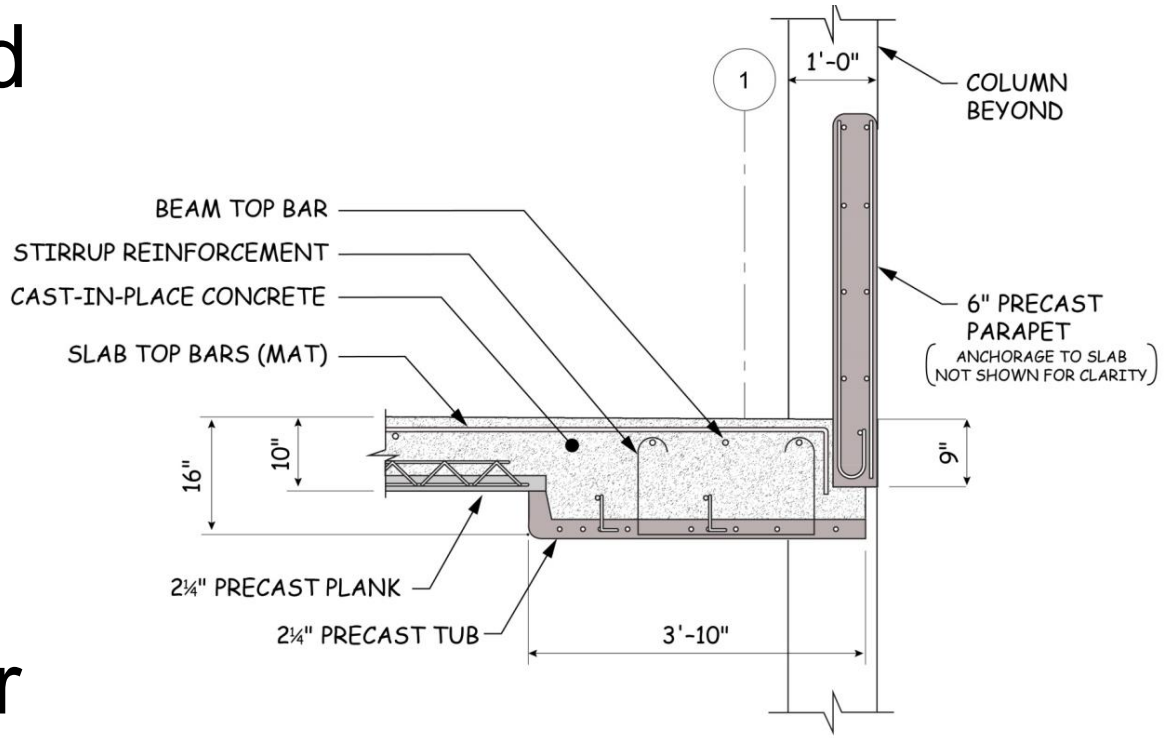
Original Design

- Narrow beam
- Wide column
- Concentric load



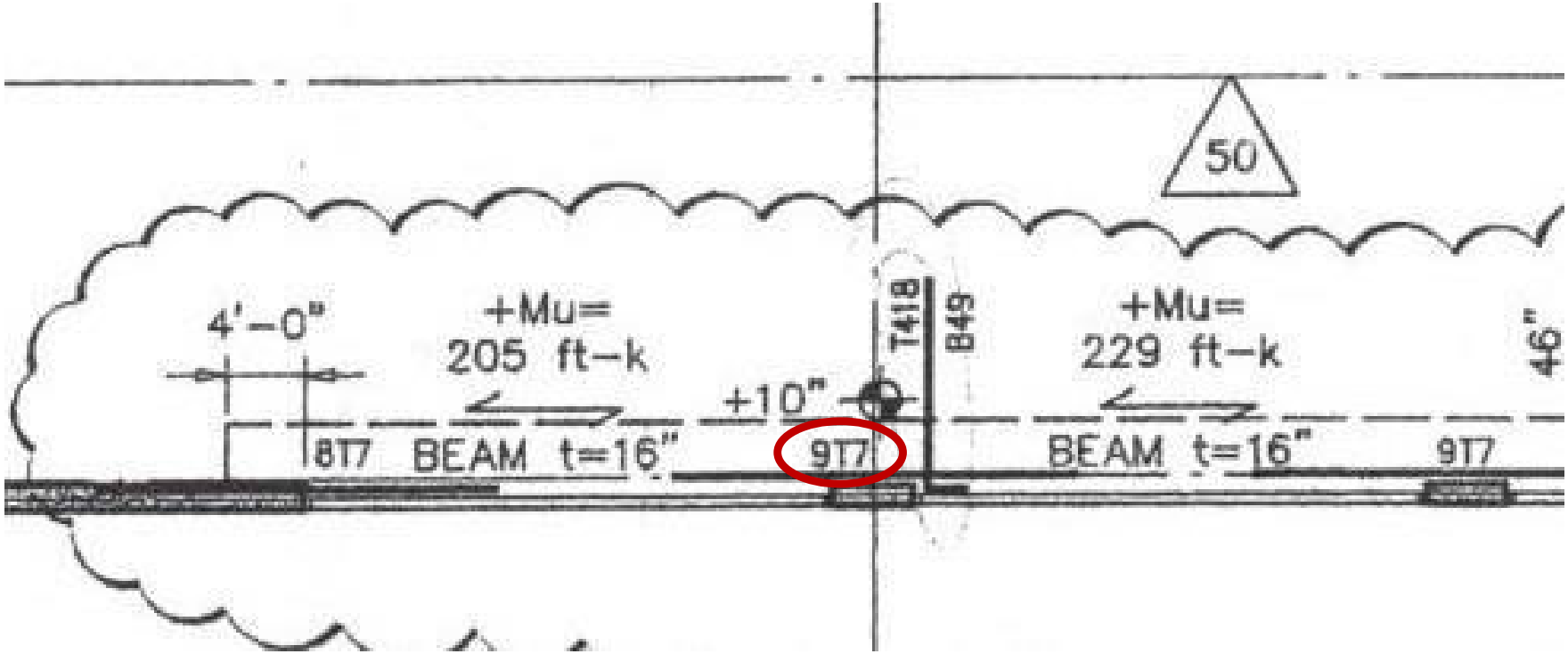
Revised Design

- Wide beam
- Narrow column
- Eccentric load
- Punching shear



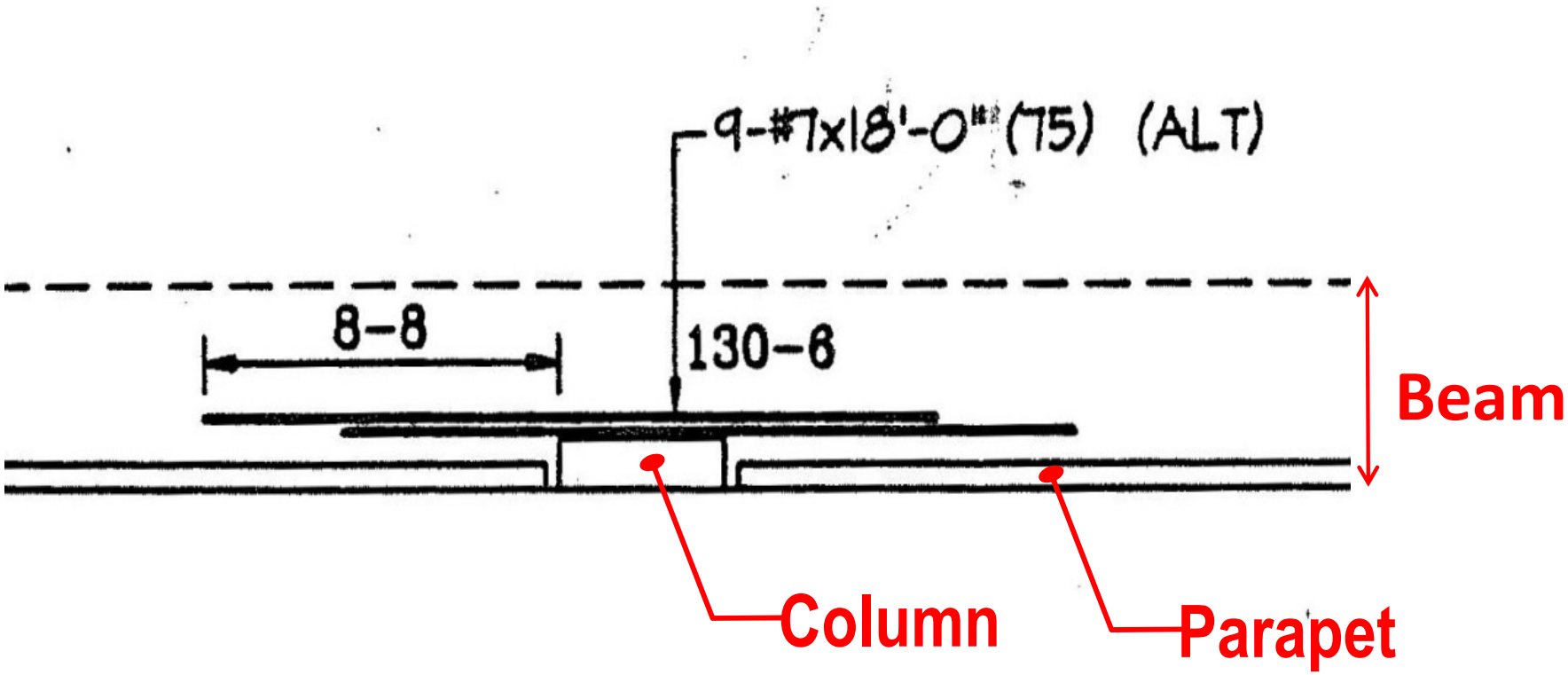
Design Drawings—Beam Bars

- Info provided to EOR by Precast Engineer
- Nine #7 bars Top, typical
- Diagrammatically shown next to column



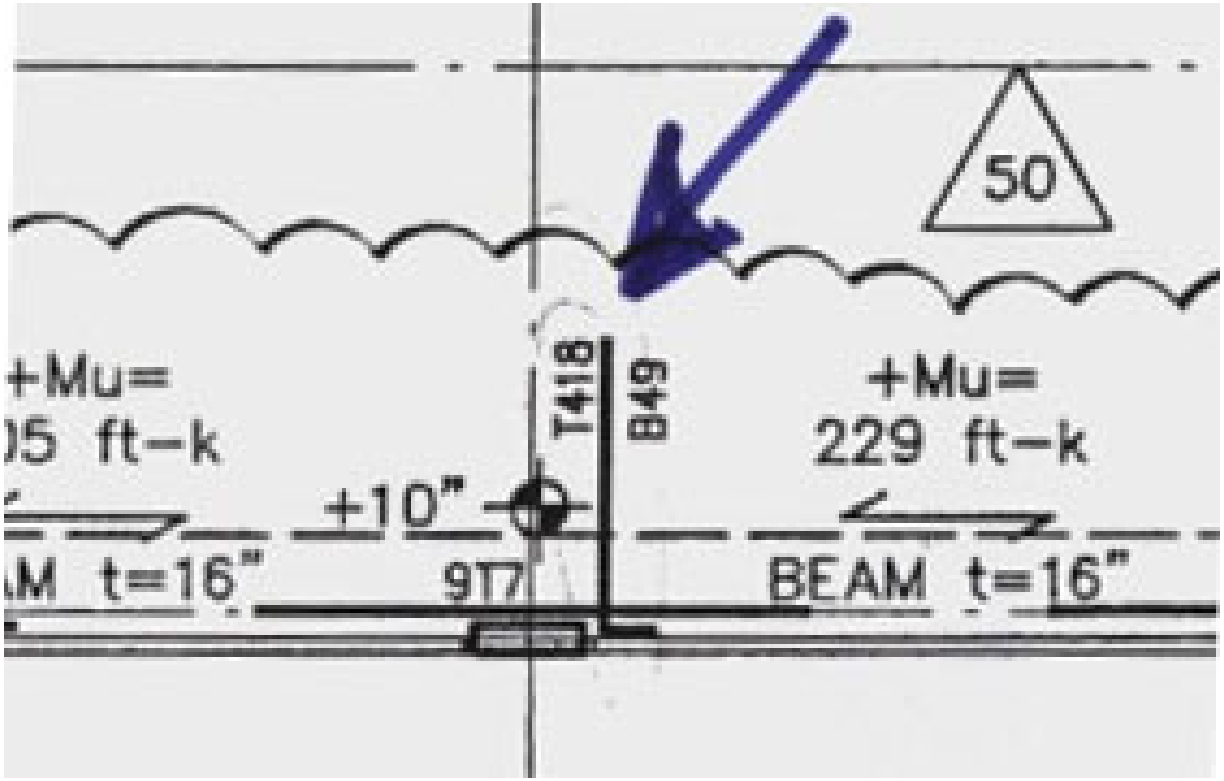
Shop Drawings—Beam Bars

Shown diagrammatically next to columns



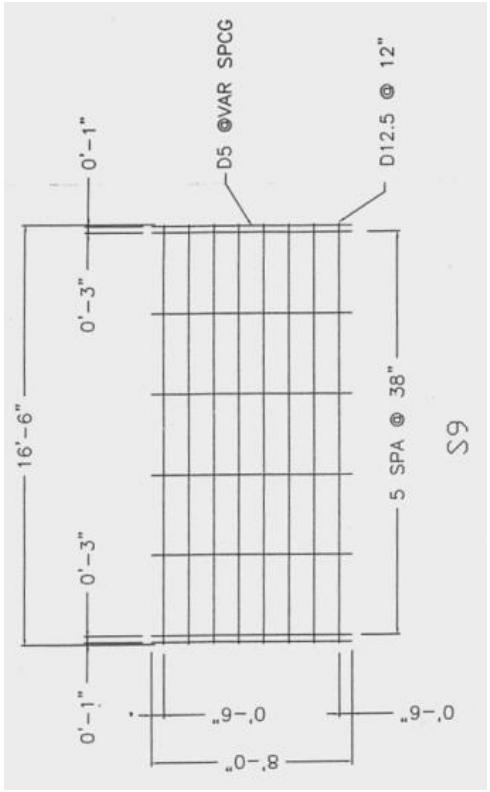
Design Drawings—Slab Bars

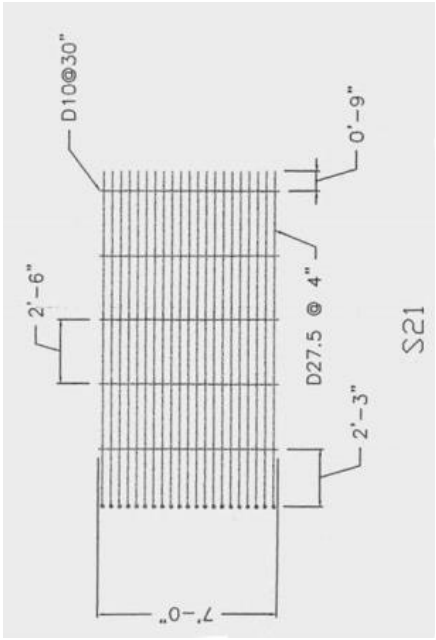
- Design provided to EOR by Precast Engineer
- T418 (#4 top at 18”, hooked)
- B49 (#4 bottom at 9”, hooked)

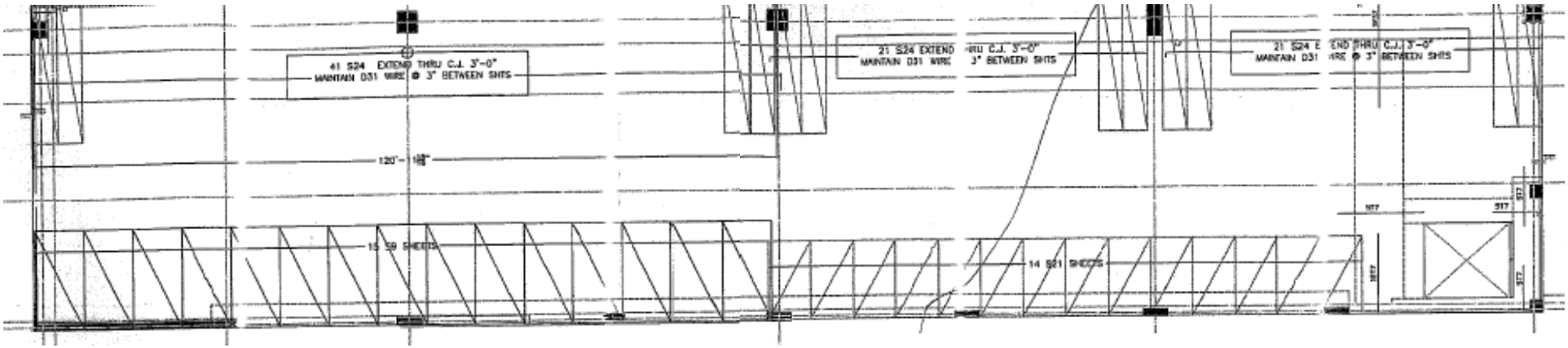


Shop Drawings—Slab Bars

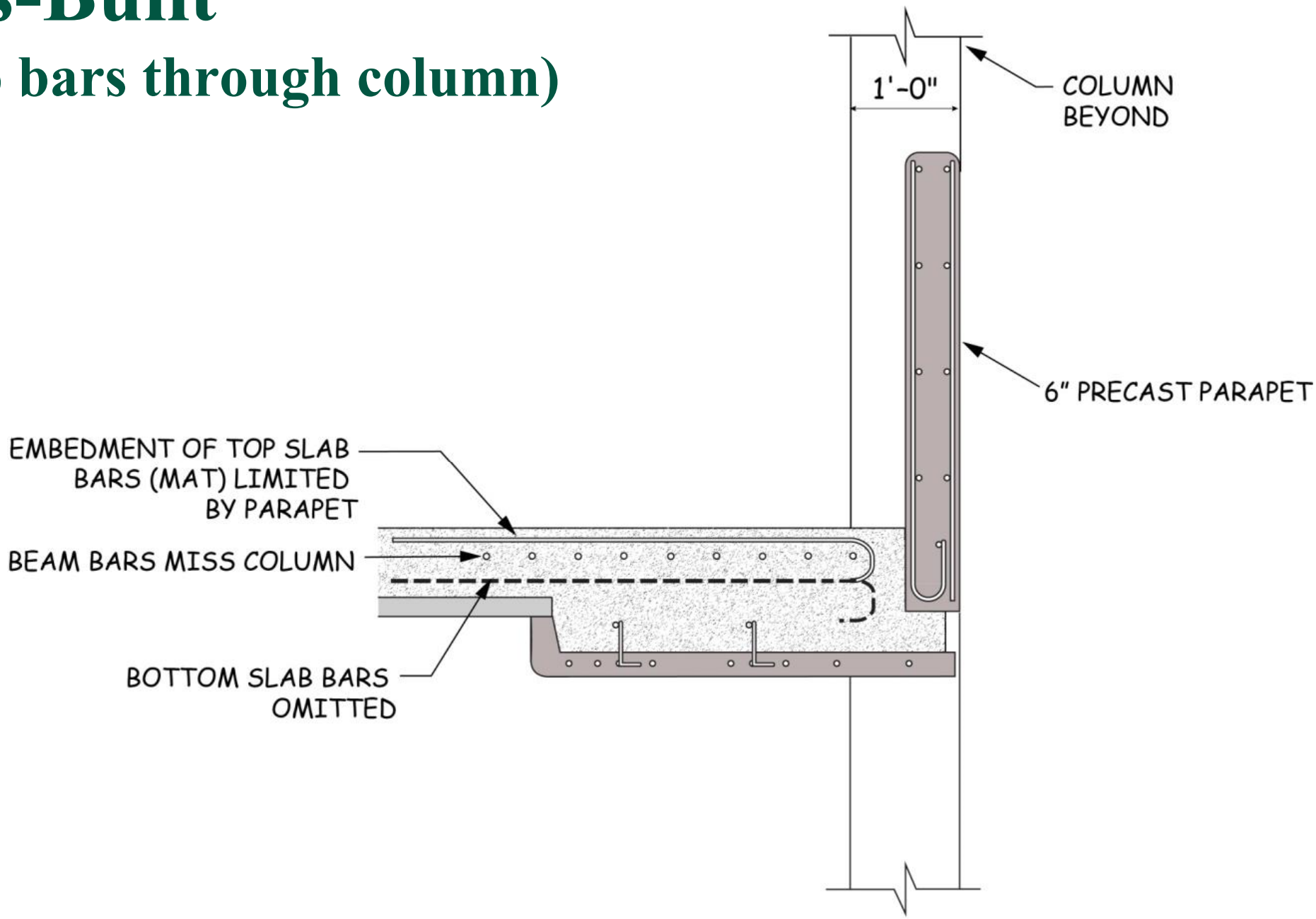
- Mats were used for top bars







As-Built
(no bars through column)

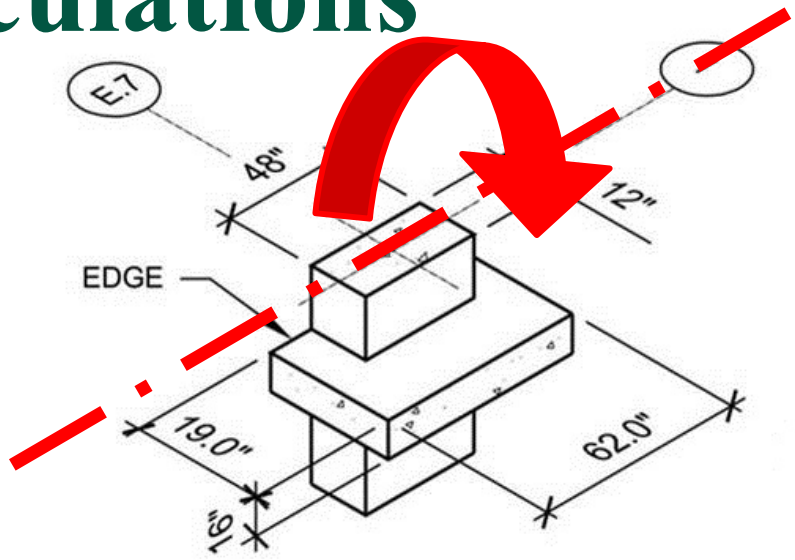


Cracks

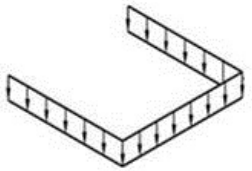
- **Four employees of Concrete Contractor observed cracks on underside, along Column Line 1**
  - Wide enough to insert a credit card
  - As much as 1/8” wide
  - Some thru entire slab thickness
- **Some told supervisor**
- **Supervisor inspected. Thought that the cracks were minor. Took no action.**

Punching Shear Calculations

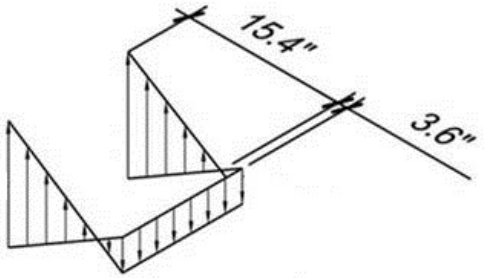
- By Precaster
- Inadequate
- Ignored unbalanced moment
- Significant overload
- Provided to EOR
- Not checked by EOR



TRANSFER OF FORCES AT EDGE COLUMN



DIRECT SHEAR STRESS



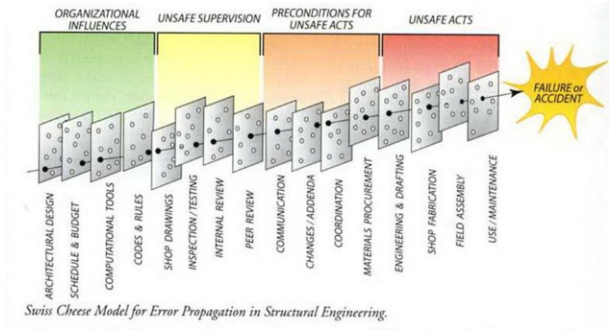
UNBALANCED MOMENT SHEAR STRESS

Proximate Cause

- **Technical**
  - Inadequate punching shear strength
  - Inadequate slab-to-column connections

- **Procedural**
  - EOR relied excessively on Precaster
  - No detail by EOR along spandrel after revision
  - EOR did not check Precaster's calculations
  - EOR transcribed info onto drawings

Error Propagation



Swiss Cheese Model for Error Propagation in Structural Engineering.

- **Precast engineer/supplier—**Changed design, incomplete calculations
- **Structural engineer–** Did not require bars thru columns, did not check precaster's calculations
- **General Contractor–**Did not coordinate subcontractors
- **Concrete Contractor—**Did not report slab cracking
- **Rebar detailer--** Did not detail bars thru columns
- **Rebar installer--** Did not place bars thru columns
- **Rebar inspector—** Did not question no bars thru columns

Lessons

- EOR must thoroughly check all info provided by others
- Non-typical conditions need special attention
- Shop drawings should be unambiguous
- Require concurrent submission of shop drawings for related items
- Inspection by EOR has value
- Inspector should question ambiguous shop drawings
- Risk if EOR is retained by multiple parties

More Info

- **OSHA 2004 Report**

https://www.osha.gov/doc/engineering/2003_10.html

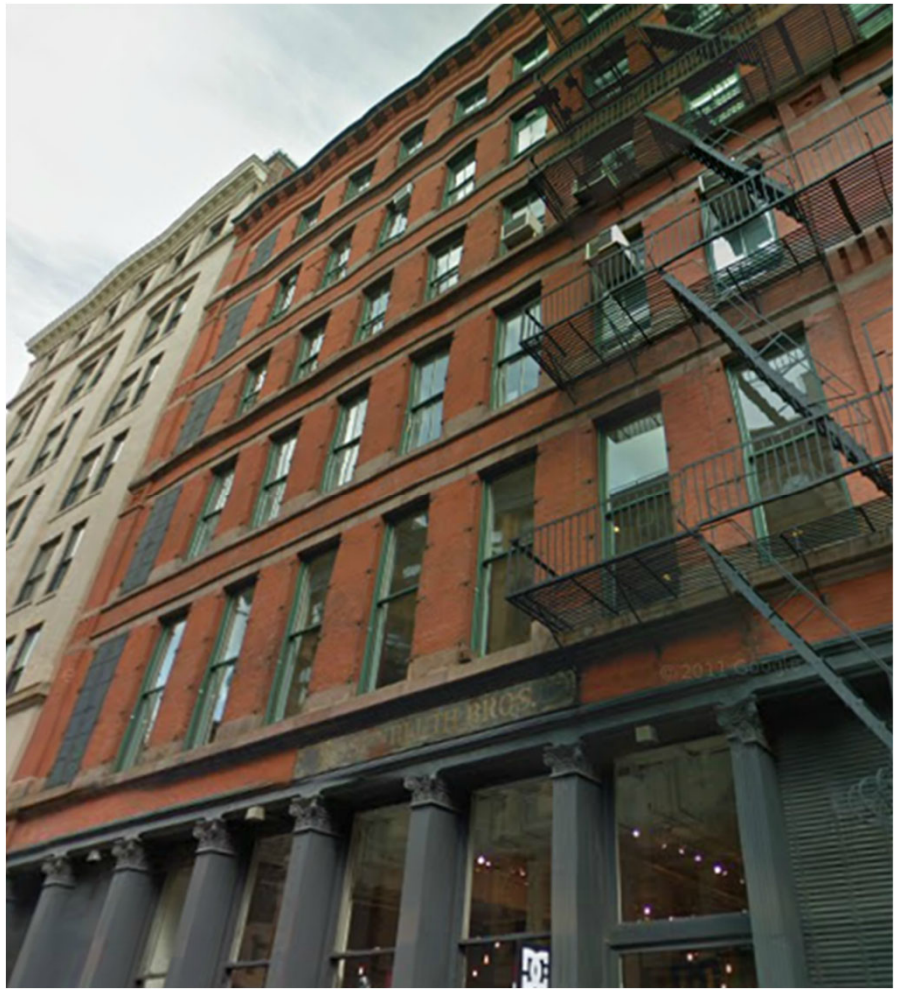
- **Published Paper**

Peraza DB, Tropicana Garage Collapse. Presented at 2019 IABSE Congress and published in Proceedings, New York, NY, September 2019.

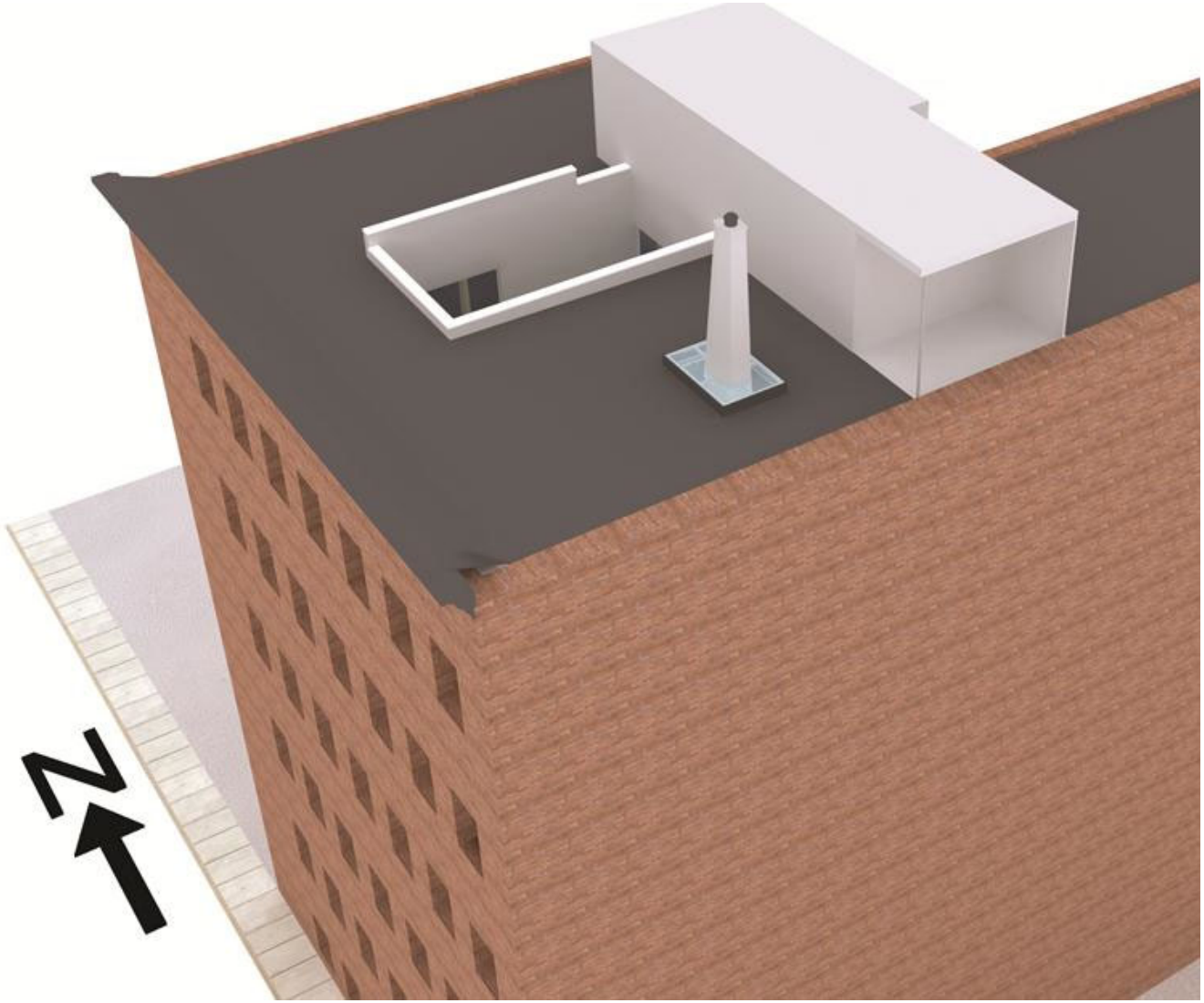
https://www.proceedings.com/50967.html

Renovation in a Vintage Building

- Built 1880
- Light industrial use
- 6 stories
- Cast iron and wood columns
- Converted to residential coops
- Owner of top floor renovates



Aerial View

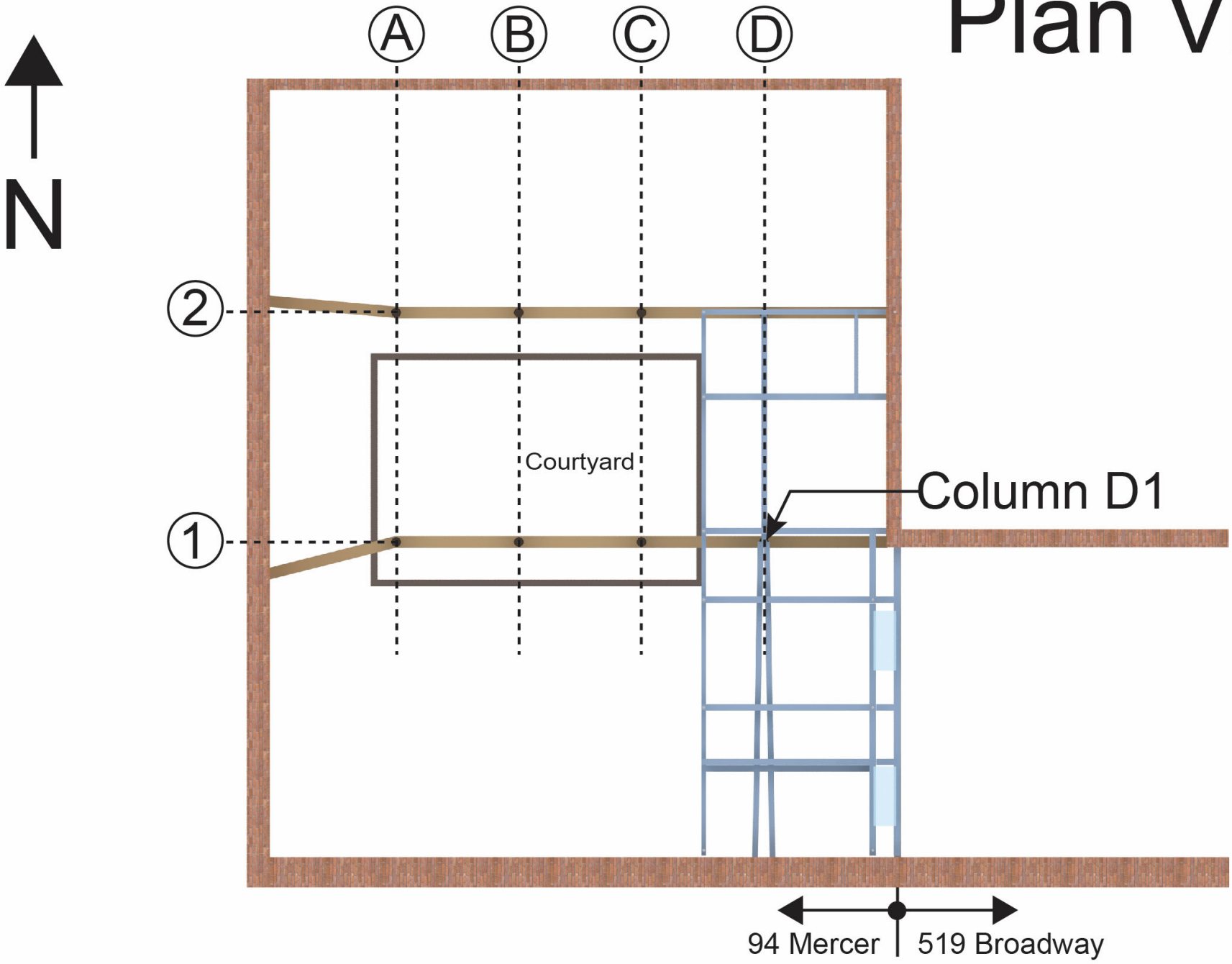


Issues

- Column Overload
- Girder Supporting Fireplace
- Wood Top Plate
- Column Line Stability

- Other Roof Support Issues
- Skylights
- Chimney Stability
- Vibration

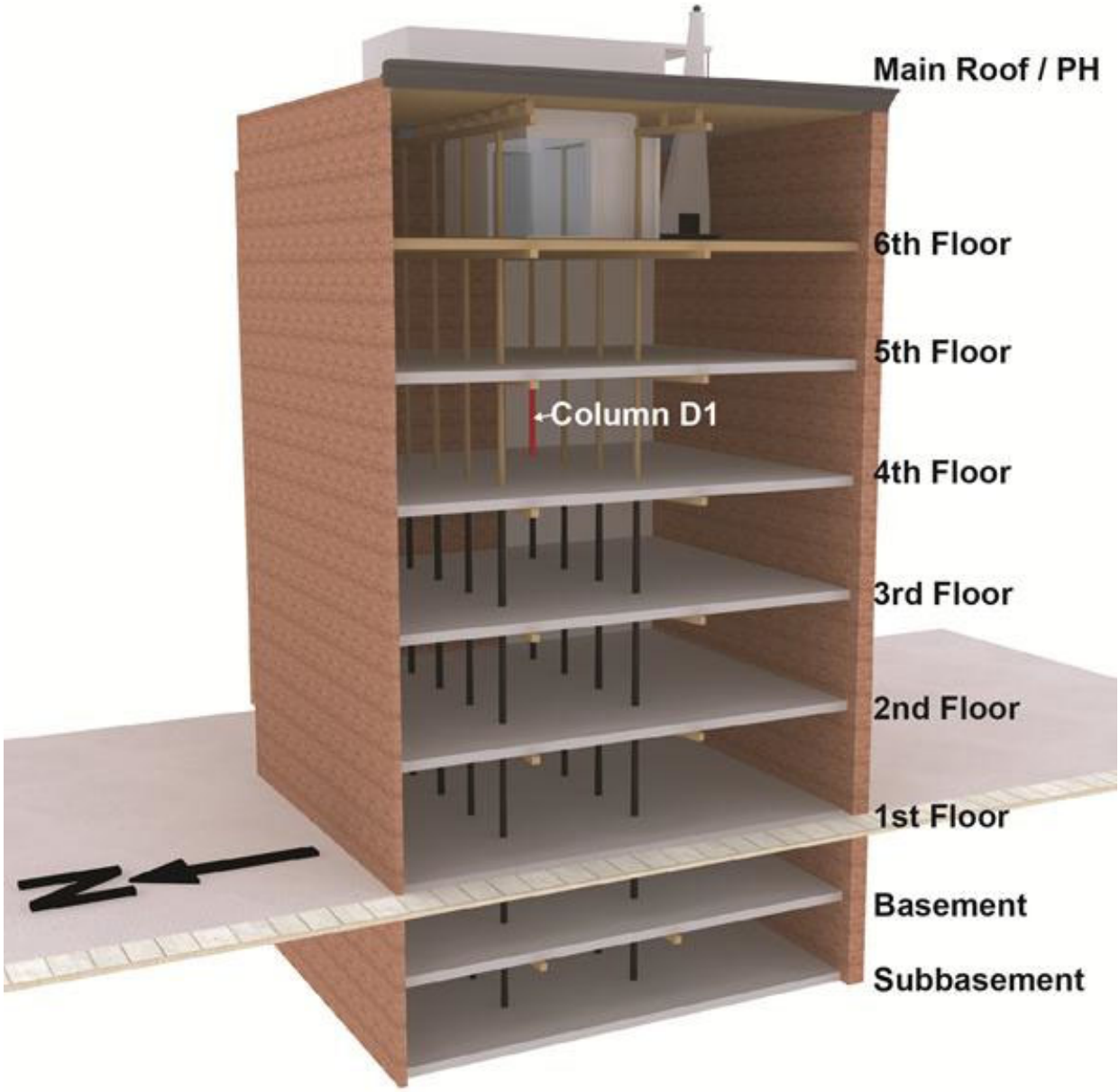
Plan View



Column Overload

- **Problem**
  - Severely overstressed in crushing
  - 79% on 4th floor
  - #2 Dense Southern Yellow Pine
- **EOR Errors/Omissions**
  - Checked columns on 4th floor as if they were cast iron
  - Used wrong diameter (actual area is 60% of BH area)
  - Didn't recognize taper or crushing
  - Didn't have columns graded

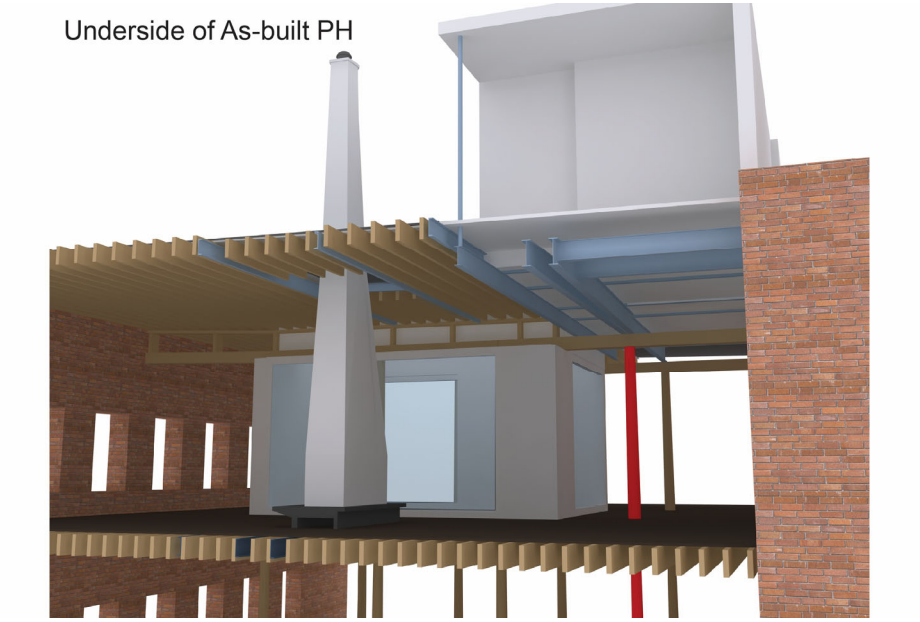
Cross-Section

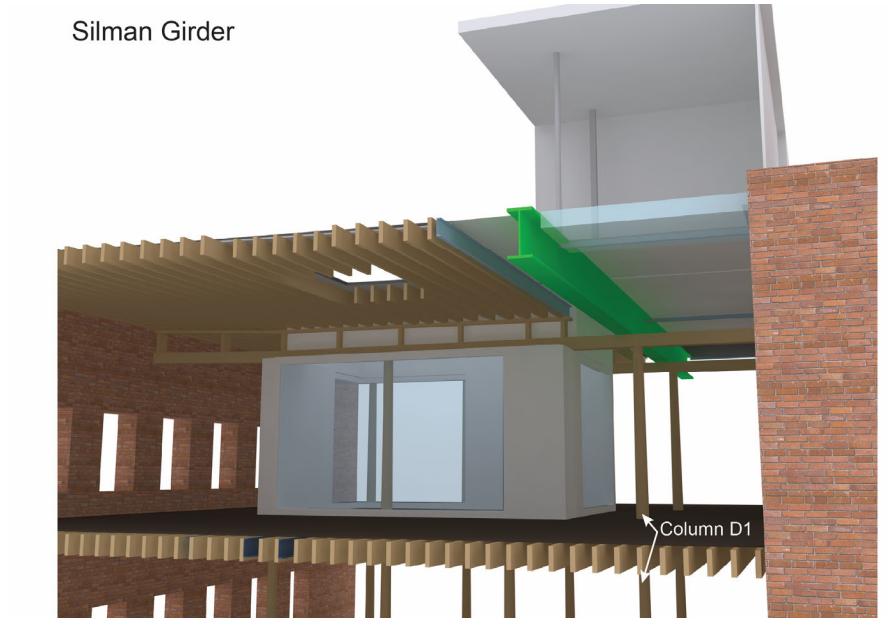


Column Overload

- **Potential Consequences**
  - Collapse of multiple levels
  - Sudden and catastrophic

- **Remedy**
  - Immediately restrict loading
  - Remove penthouse
  - Design new support system for penthouse that bypasses columns





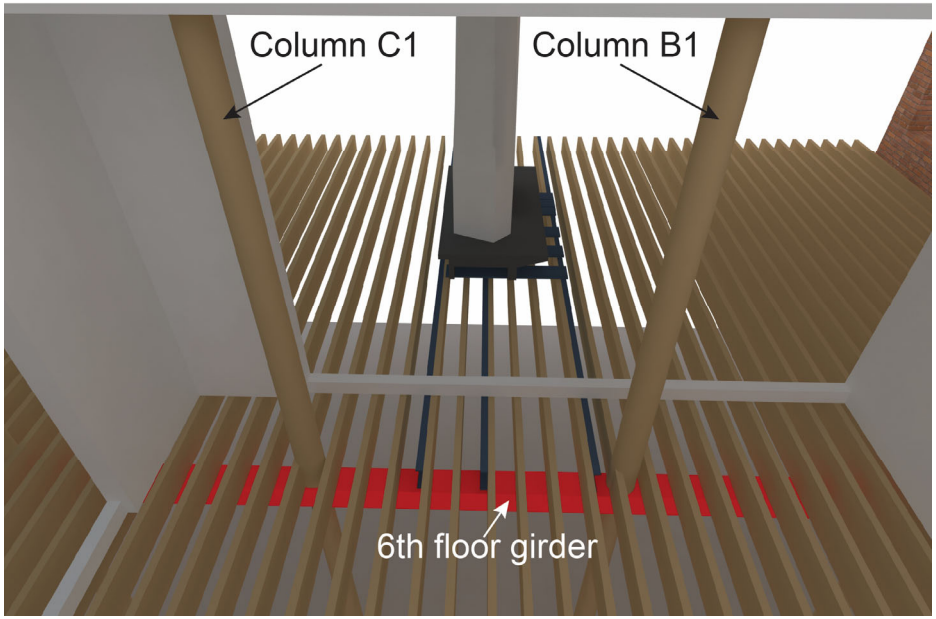
Wood Girder Supporting Fireplace

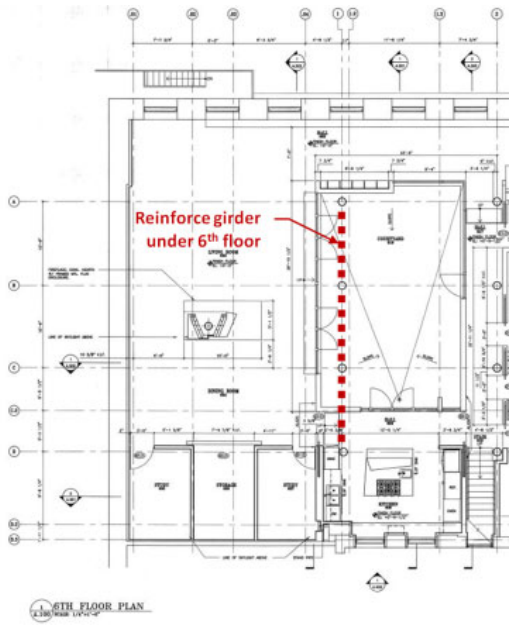
- **Problem**
  - Fireplace girder overstressed 65% in shear
  - Others overstressed 23%

- **EOR Errors/Omissions**
  - Erroneous shear calculations
  - Omitted loads
  - Neglected 2-span

Wood Girder Supporting Fireplace

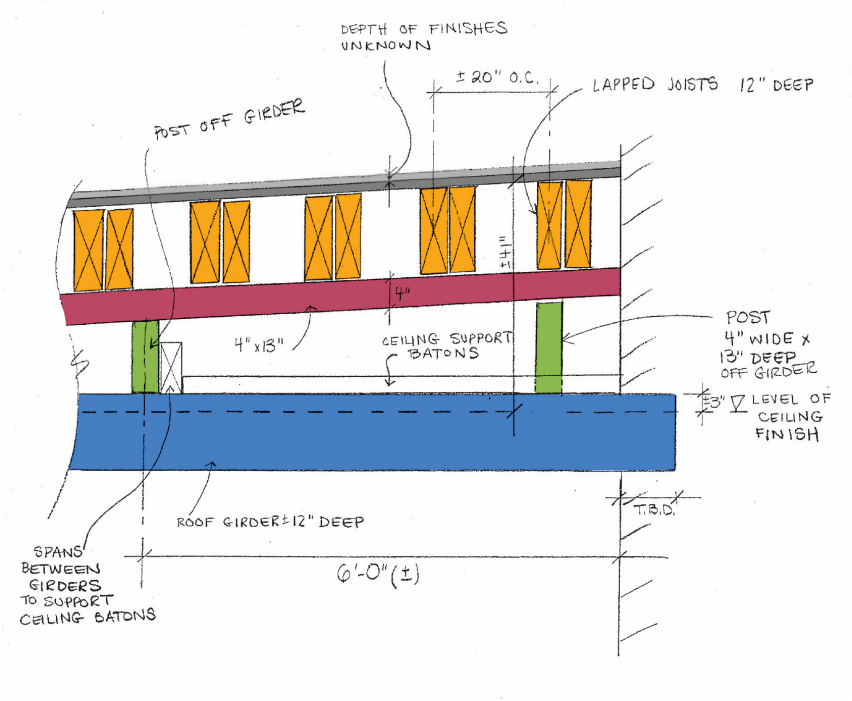
- **Potential Consequences**
  - Collapse of girder and fireplace
  - Overstress of other girders
- **Remedy**
  - Remove fireplace
  - Reinforce girders to safely support courtyard loads





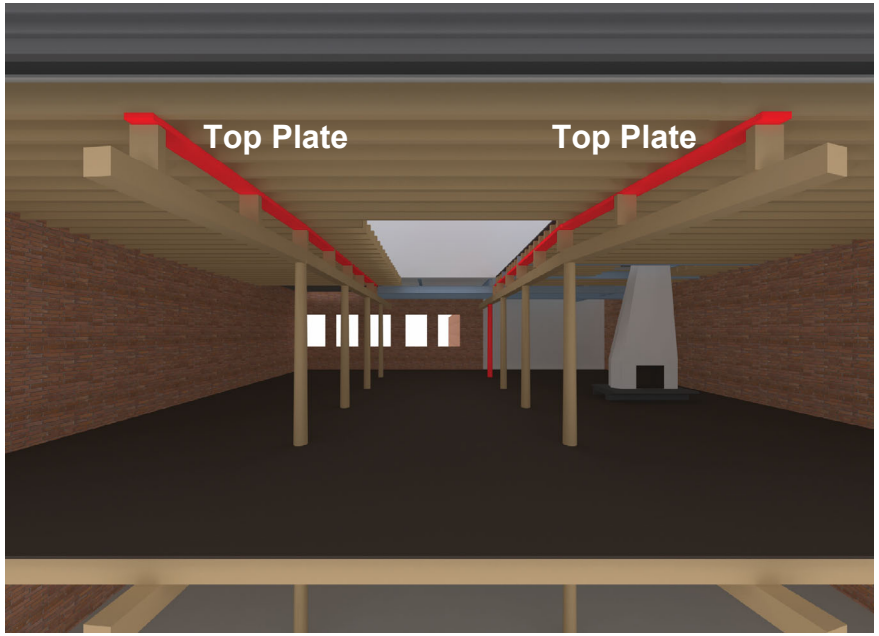
Wood Top Plate

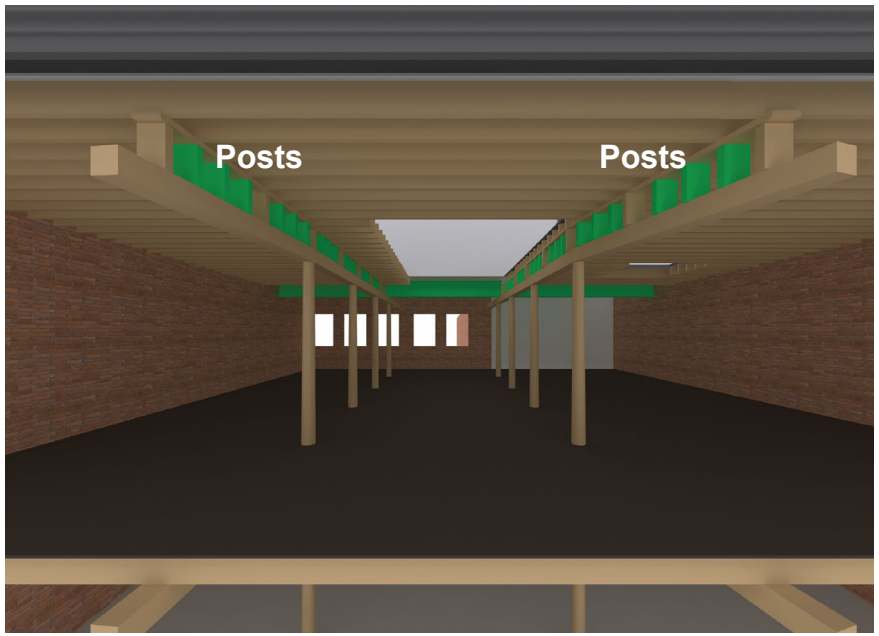
- **Problem**
  - Widely spaced posts
  - Both girder lines
  - Overstressed in bending and shear ~100%
- **EOR Errors/Omissions**
  - Condition forgotten on south
  - Did not recognize on north
  - Did not issue repair sketch for either girder line



Wood Top Plate

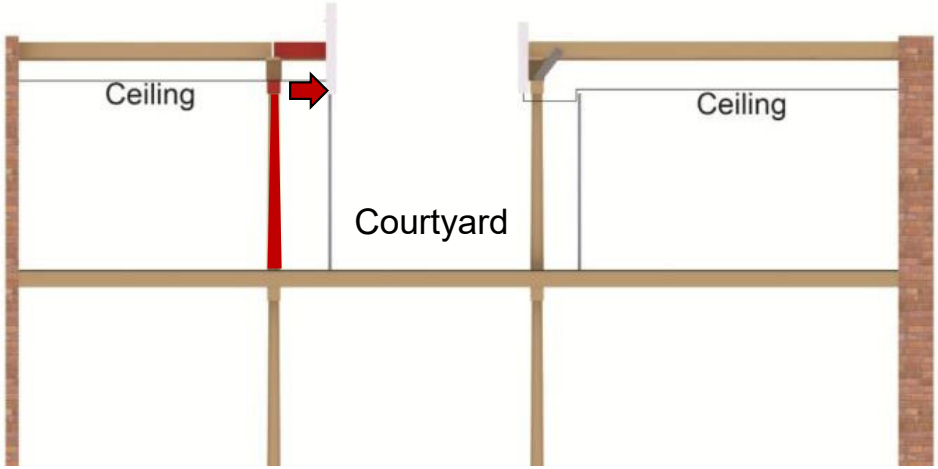
- **Potential Consequences**
  - Partial collapse of roof
- **Remedy**
  - Add posts
  - (Requires ceiling removal)





Column Line Bracing

- **Problems**
  - Column line became unbraced when ceiling joists removed
  - Roof loads and parapet weight on courtyard glass
  - No bracing for wind loads at top of glass



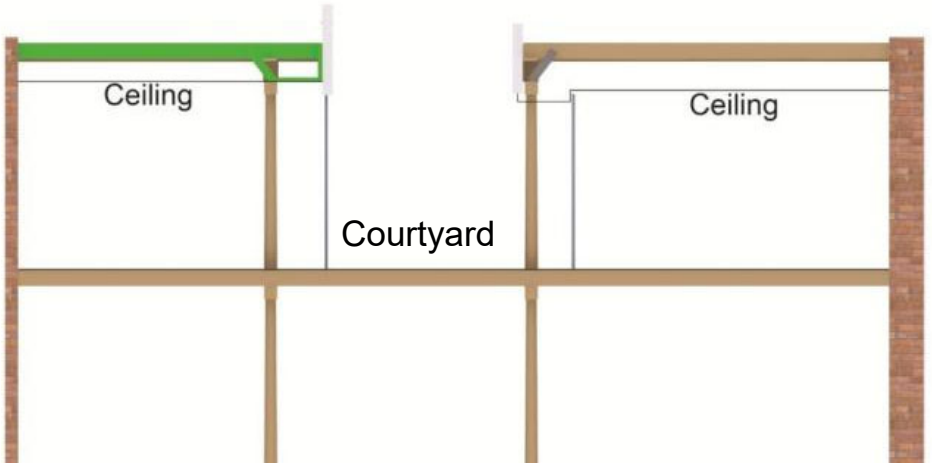
- **EOR Errors/Omissions**
  - Did not recognize conditions

Column Line Bracing

- **Possible consequences**
  - Buckling of column line
  - Damage to courtyard glass wall

- **Remedy**
  - Install knee braces
  - Cantilever joists
  - Brace storefront to girder

  (after removing ceiling)



Lesson Learned

- **Continuity of staff is important**
- **Compatibility of project and firm is important**
  - Project size
  - Project type
- **Quality control is crucial**
- **Site visits may uncover surprises**
- **Skills and technical resources needed are different**

Closing

- Most failures are due to human error
- Often due to an omission
- Quality control is necessary, but not easy
- Few failures due to state-of-the art issues
- Usually there are multiple opportunities, by various parties, to prevent a failure.
- Communication is increasingly important

ASCE Code of Ethics

"Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties."

There is hardly a day that goes by that I don't think about the Hyatt collapse.

My hope is that we, as a profession, can and will continue to learn, practice, disseminate, change, and adopt procedures and policies that will prevent a tragedy like this from occurring again.

Jack Gillum
Engineer of Record
Kansas City Hyatt

University of Minnesota
Driven to Discover®

Structural Engineering
Webinar Series
September 27, 2024

Lessons from Failures for Structural Engineers

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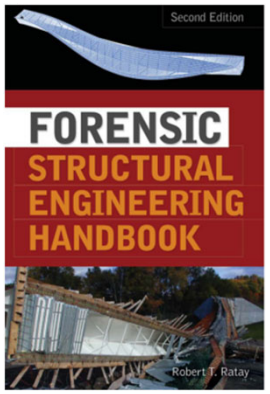
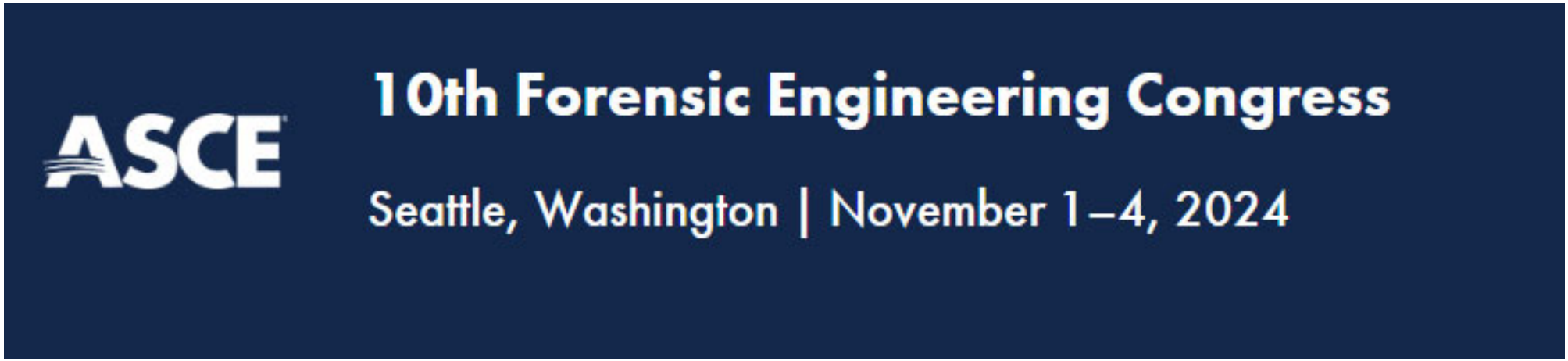


Forensic Structural Engineering Handbook
Edited by Robert Ratay, 2009

Coming Soon



https://www.forensiccongress.org