Failure Literacy: The Landmark Structural Failures You Should Know About

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Structural Engineering

• “The art of moulding materials we do not really understand into shapes we cannot really analyze, so as to withstand forces we cannot really assess, such a way that the public does not really suspect.”
  • E. H. Brown

• Also applied to geotechnical engineering, etc.
Failure

• An unacceptable difference between expected and observed performance
• Involves functional failures as well as collapses
Failure Literacy

- Knowledge of well known failure case histories
- Understanding of causes behind failures
- Recognition of patterns of failures
- Understanding of role of failure in development of design procedures and codes
- Skepticism
Engineering Design

- Selecting materials, systems, and configurations in order to ensure satisfactory performance over the projected lifetime of the facility
Delatte’s Simplified Definition

• Anticipate everything that can possibly go wrong
• Make sure it doesn’t happen
• But remember... engineering is the art of doing for $1 what any idiot could do for $2
New ASCE Code of Ethics

- New version approved by the ASCE Board of Direction on October 26, 2020
- Hierarchical - 1. Society
  1 a. first and foremost, protect the health, safety, and welfare of the public;
  c. express professional opinions truthfully and only when founded on adequate knowledge and honest conviction;
  h. consider the capabilities, limitations, and implications of current and emerging technologies when part of their work; and
  i. report misconduct to the appropriate authorities where necessary to protect the health, safety, and welfare of the public.
New ASCE Code of Ethics

3. Profession
   a. uphold the honor, integrity, and dignity of the profession;
   b. practice engineering in compliance with all legal requirements in the jurisdiction of practice;
   c. represent their professional qualifications and experience truthfully;
   g. continue professional development to enhance their technical and non-technical competencies.
New ASCE Code of Ethics

• 4. Clients and employers
  • a. act as faithful agents of their clients and employers with integrity and professionalism;
  • b. make clear to clients and employers any real, potential, or perceived conflicts of interest;
  • c. communicate in a timely manner to clients and employers any risks and limitations related to their work;
  • d. present clearly and promptly the consequences to clients and employers if their engineering judgment is overruled where health, safety, and welfare of the public may be endangered;
  • f. perform services only in areas of their competence; and
  • g. approve, sign, or seal only work products that have been prepared or reviewed by them or under their responsible charge.
New ASCE Code of Ethics

- 5. Peers
- c. foster health and safety in the workplace;
- d. promote and exhibit inclusive, equitable, and ethical behavior in all engagements with colleagues;
- h. comment only in a professional manner on the work, professional reputation, and personal character of other engineers; and
- i. report violations of the Code of Ethics to the American Society of Civil Engineers.
12 Cases - BSCES Lecture 2005

- Quebec*
- Tacoma Narrows
- Point Pleasant
- Ronan Point*
- 2000 Commonwealth Ave*
- Bailey’s Crossroads

- Hartford Civic Center*
- Willow Island
- Harbor Cay Condominium*
- Hyatt Regency
- Mianus River Bridge
- L’Ambiance Plaza
<table>
<thead>
<tr>
<th>Year</th>
<th>Case</th>
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<tbody>
<tr>
<td>1907</td>
<td>Quebec Bridge (Canada)</td>
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<tr>
<td>1940</td>
<td>Tacoma Narrows Bridge</td>
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<tr>
<td>1967</td>
<td>Point Pleasant/ Silver Bridge</td>
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<tr>
<td>1968</td>
<td>Ronan Point</td>
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<td>1971</td>
<td>2000 Commonwealth Avenue</td>
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<td>1973</td>
<td>Skyline Plaza/ Bailey’s Crossroads</td>
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<td>1978</td>
<td>Hartford Civic Center</td>
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<td>1978</td>
<td>Willow Island power plant cooling tower</td>
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<tr>
<td>1981</td>
<td>Harbour Cay Condominium</td>
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<td>1981</td>
<td>Hyatt Regency walkways</td>
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<td>1983</td>
<td>Mianus River Bridge</td>
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<td>1987</td>
<td>L’Ambiance Plaza</td>
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</table>
New Cases

- Minneapolis I-35 bridge collapse
- Laval Quebec de la Concorde bridge collapse
- Genoa Morandi bridge collapse
- FIU pedestrian bridge collapse
- Sadly, always new material...
The Collapse of the Quebec Bridge - 1907

Developed by Cynthia Pearson and Norb Delatte
Introduction

- Throughout 19th and early 20th centuries, new bridges critical for economic development
- Collapse on August 29, 1907, killed 75 workers
- Quebec Bridge would have been the longest cantilever structure of its day
Design and Construction

• Quebec Bridge Company formed in 1887
• Financially troubled
• Cooper hired as project consulting engineer, attempted to supervise project from New York
Theodore Cooper

- Independent consultant from New York, 60 years old, poor health
- Wrote award winning paper pioneering use of steel for bridges
- Prepared specifications for iron and steel bridges
- Developed widely used method of accounting for railroad loads
Design and Construction

• Cooper selects Phoenix Bridge design as “best and cheapest”
• Increases span from 1,600 to 1,800 ft. to reduce pier cost, also will make bridge world’s longest cantilever
• Cooper allowed high tensile and compressive stresses
Allowable Stress Comparison

24,000 – 100 (l/r) psi

- Modern ASD steel specification - A36
- Cooper
- ASD steel specification with 33 ksi steel
Member Cross-Section

1’-10 ¾”   10”   1’-10 ¾”

The Compression Chords

Each rib made of 4 15/16” plates

Overall dimensions about 5.5 by 4.5 ft., 4 inch plates
Design and Construction

- Financial constraints a constant concern
- Very limited testing, limited design work
- Dead loads were not adjusted
- Cooper stayed in New York, left on site supervision to inexperienced engineers
- Cooper defeated an attempt to review design
- Compression members showed increasing distortion
<table>
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<th>Date of Observation</th>
<th>Deflecting Chords</th>
<th>Amount of Deflection</th>
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<tbody>
<tr>
<td>June 15</td>
<td>A5L &amp; A6L</td>
<td>1/16” to 1/4”</td>
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<tr>
<td>June</td>
<td>A3R &amp; A4R</td>
<td>1/16” to 1/4”</td>
</tr>
<tr>
<td>June</td>
<td>A7R &amp; A8R</td>
<td>1/16” to 1/4”</td>
</tr>
<tr>
<td>June</td>
<td>A8R &amp; A9R</td>
<td>1/16” to 1/4”</td>
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<tr>
<td>June</td>
<td>A8L &amp; A9L</td>
<td>3/4”</td>
</tr>
<tr>
<td>August 6</td>
<td>7L &amp; 8L</td>
<td>3/4”</td>
</tr>
<tr>
<td>August</td>
<td>8L &amp; 9L</td>
<td>5/16”</td>
</tr>
<tr>
<td>August 20</td>
<td>8R</td>
<td>bent</td>
</tr>
<tr>
<td>August</td>
<td>9R &amp; 10R</td>
<td>-------</td>
</tr>
<tr>
<td>August 23</td>
<td>5R &amp; 6R</td>
<td>1/2”</td>
</tr>
<tr>
<td>August 27</td>
<td>A9L</td>
<td>2-1/4”</td>
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</tbody>
</table>
Collapse

- By August 27, member A9L had bowed 2 ¼ inches
- Cooper informed, cabled to stop work on August 29
- Bridge collapsed that afternoon
Locations of Members After Collapse

Royal Commission
Quebec Bridge Enquiry.

Drawing No 16.
Feb. 20th 1908.

Diagram showing in plan & elevation the relative positions of panel points before & after accident (East truss.)

Elevation of East Truss and East Truss System.
Looking West.
Original position shown dotted.

Plan of Bottom Chord System in Wreck.

South    North
Cause of Failure

• Technical cause was failure of compression chords A9L and A9R
• Failure either by rupture of latticing or shearing of lattice rivets
• Weight of material delivered to site exceeded dead load estimates
<table>
<thead>
<tr>
<th>Order No.</th>
<th>Description</th>
<th>Figured Weight</th>
<th>Total.</th>
<th>Actual Weight</th>
<th>Total</th>
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<td>Anchorage eyebars and pins</td>
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<td>Anchor arm pins</td>
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<td>11,581,072</td>
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<td>1,767,972</td>
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<td>1,778,546</td>
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<td>Centre posts and bracing</td>
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<td>2,708,560</td>
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<td>614</td>
<td>Shoes and pedestals</td>
<td>385,810</td>
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<td>Centre post system</td>
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<td>3,485,673</td>
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<td>Cantilever arm trusses</td>
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<td>Cantilever arm eybards</td>
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<td>280,435</td>
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<td></td>
<td>Cantilever arm floor system</td>
<td></td>
<td>12,399,311</td>
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<td>631</td>
<td>Suspended span trusses</td>
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<td>3,379,293</td>
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<td>633</td>
<td>Suspended span eybards</td>
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<td>343,280</td>
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<td>635</td>
<td>Suspended span pins</td>
<td>35,710</td>
<td>35,460</td>
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<td>637</td>
<td>Suspended span truss system</td>
<td>1,197,385</td>
<td>1,214,905</td>
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<tr>
<td>For one-half of the bridge</td>
<td>36,858,262</td>
<td>37,059,841</td>
<td></td>
<td>37,079,872</td>
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<tr>
<td>The whole bridge</td>
<td>73,312,504</td>
<td>74,079,832</td>
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</table>

Actual weight in excess of weight estimated from drawings, 767,373 pounds.
Percentage of error, 1.08 per cent.
Actual weight is 101.03 per cent of figured weight.
Figured weight is 98.96 per cent of actual weight.

September 25th, 1907.
Comparison of Actual and Assumed Dead Loads

<table>
<thead>
<tr>
<th>Element</th>
<th>Assumed Dead Load</th>
<th>Actual Dead Load</th>
<th>Inc.</th>
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<tbody>
<tr>
<td></td>
<td>kN</td>
<td>lb.</td>
<td>kN</td>
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<tr>
<td>Half suspended span</td>
<td>21,538</td>
<td>4,842,000</td>
<td>25,328</td>
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<td>Cantilever arm</td>
<td>58,740</td>
<td>13,205,200</td>
<td>70,300</td>
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<tr>
<td>Anchor arm</td>
<td>59,240</td>
<td>13,317,600</td>
<td>77,034</td>
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</table>
Professional and Procedural Aspects

• Royal Commission of Inquiry assigned blame to Cooper, consulting engineer, and Szlapka, design engineer

• Errors cited by commission
  • Cavalier attitude toward site inspection
  • Unusually high allowable stresses
  • Inaccurate dead load calculation
  • Lack of research and testing for an unprecedented span
Ethical Aspects

• Cooper retained control, although his health and the inadequate fee paid did not allow adequate supervision

• Conflicts between cost and safety resolved in favor of cost

• Origin of Canadian Ritual of the Calling of an Engineer
The Order of The Engineer

- The Obligation of an Engineer
- The Engineers Ring
- To Be an Engineer
- Ceremony
- Governors
- List of Links
- Forms

Ohio

Cleveland State University
Link: 1
Date Chartered: 5/10/75
Last Update: 2/15/01
Status: Active
Epilogue

- Canadian government took over project, provided finances, hired team of experienced engineers
- Redesigned bridge collapsed a second time, in 1916, as center span was installed
- Still longest cantilever bridge in the world
The Second Bridge Collapse
The Quebec Bridge Today
Design and Construction

- 1970 - Innovative design proposed for 300 by 360 foot space frame roof, 83 feet above arena
- Two main layers in 30 by 30 foot grid, 21 feet apart
- 30 foot members braced by midpoint diagonals
Hartford Civic Center Roof

From LZA report
Unusual Elements

- Four angles arranged in cross, not I or tube shape - low buckling strength, but easy to connect
- Top horizontal members did not directly intersect diagonals
- Roofing panels on top of short posts
- Supported on pylon legs
- Space frame not cambered
Compression Member Configurations

- **CROSS**
- **TUBE**
Use of Computers

• Too complex for hand analysis
• Early use of “state-of-the-art” computer analysis
• Deflection predictions - 12 inches down at center, 6 inches up at corners
Construction

• Roof assembled on the ground
• Excessive deflections found at some nodes - engineers notified
• Roof jacked up onto pylons - deflections twice as much as predicted
• Subcontractor had difficulties attaching fascia panels
• Pattern - large, unanticipated deflections
Collapse

- Roof collapsed under snow load at 4:19 a.m. on January 18, 1978
- Evening before, arena had been packed for a basketball game
- No loss of life, no injuries
From Feld and Carper, *Construction Failure*, 1997
Cause of Failure - LZA

• Roof began failing as soon as completed, due to design errors
• Dead loads underestimated by 20 %
• Three design errors - top layer compression members
  • Some overloaded by 852 %
  • Other members overloaded by 213 %
  • Interior members overloaded by 72 %
Bracing, Buckled Shapes, and Capacities

From LZA report
## Connection A

<table>
<thead>
<tr>
<th>Original</th>
<th>As-built</th>
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<tbody>
<tr>
<td><img src="image1" alt="Original Diagram" /></td>
<td><img src="image2" alt="As-built Diagram" /></td>
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<td>Capacity 160,000 lb.</td>
<td>Capacity 15,440 lb.</td>
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</table>
## Connection B

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<td><img src="image1.png" alt="Original Diagram" /></td>
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<td>Capacity 185,000 lb.</td>
<td>Capacity 59,000 lb.</td>
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Connection C

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<td><img src="image" alt="Original Diagram" /></td>
<td><img src="image" alt="As-built Diagram" /></td>
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<tr>
<td>Capacity 625,000 lb.</td>
<td>Capacity 363,000 lb.</td>
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Other Findings

• Roof posts also applied bending stress, not considered in design
• Spacer plates for built up members too far apart - violated AISC slenderness ratio
• Some members had bolt holes > 85 % of cross section, violated AISC
• Some misplaced diagonal members
Other Investigations

• Loomis and Loomis, Inc. - blamed torsional buckling, not lateral buckling
• Hannskarl Bandel, for architect’s insurance company - blamed faulty weld connecting scoreboard to roof
Legal Repercussions

- Parties reached out-of-court settlement six years after collapse
- No definitive ruling on the cause of collapse
Professional and Procedural Aspects

- Five subcontracts coordinated by construction manager
- Construction manager refused to hire a structural engineer to inspect project
- After collapse, construction manager disclaimed all responsibility
- LZA report - inspection and/or QC inadequate, poorly handled
Professional and Procedural Aspects

- Visible distortion and bowing of structure should have been a red flag
- Connecticut requires peer review of certain buildings, but did not for this building
Ethical Aspects

• Excessive deflections brought to engineer’s attention
• Engineer provided assurances, without rechecking work
• Workers knew building was a death trap (Philadelphia Inquirer, May 28, 1978)
Conclusions

• Need to check whether computer results make sense - hand calculations, knowledge of structural behavior
• Need field inspection
• Unexpected deflections must be explained
• Avoid confusion in project responsibility
• Computers have enabled people to make more mistakes faster than almost any invention in history, with the possible exception of tequila and hand guns - Mitch Ratcliffe
Parallels - Quebec and Hartford

- Daring structures, pushing the limit
- New, improved, optimized structural analysis
- Lack of on-site engineering
- Did not react appropriately to structural deformations
- Parts did not fit together
- Buckling and connections
Design and Construction

- Larsen-Nielson System - Denmark, 1948
- Precast Large Panel Concrete
- 22 floors high - 5 flats per floor - total 110
- Took less than 2 years to complete (July 25, 1966-March 11, 1968)

Precast Large Panel Construction
(Levy and Salvadori, Why Buildings Fall Down, 1992, p. 103)
System Building

• Need for new housing stock after WW II
• Shortage of skilled construction workers
• New method needed for
  • Speed of construction
  • Minimum building footprint (high-rise)
  • Simplified construction methods
Collapse

- Southeast corner collapsed 5:45 a.m.
- Initiated by gas explosion on 18th floor
- All exterior walls load bearing
• Collapsed in 2 phases
• Collapse sheared off living room section of the apartments
• 4 fatalities/17 injuries
Causes of Failure

- Substandard brass nut fractured
- Relatively small explosion - less than 10 psi
- Tests show that walls could be laterally displaced at 2.8
- Lack of structural redundancy

(Joint H4)
Joint between interior wall and floor slabs
Remedial Actions Taken

- Southeast corner was rebuilt
- Building reinforced with blast angles
- Gas banned from Ronan Point
Joint Details

Schematic Design of Joint

- Outside wall
- Washer
- Nut
- 3/8" Ø MS lifting rod
- Inside wall panel
- Dry mortar pack
- Floor panel
- Bolt
- Steel tie plate
- 1" bars
- Open joint fin.
  w/ lime mortar
- Hardboard pads

(H2 Joint)
Horizontal joint between floor slab and flank wall

As Built Joint

- Outside wall
- Inside wall panel
- Void filled with rubbish
- Ties not attached
- Voids and rubbish
- Blast angles added after collapse
- Screw not tightened properly

(H2 Joint)
Horizontal joint between floor slab and flank wall
Technical Concerns

• Fire and/or strong wind could have similar effect on building
• Designed to withstand 63 mph wind
• 105 mph wind at 200 ft. up was expected to occur within life of building
• System was not intended for more than 6 floors
• Poor workmanship
Building Demolition

- May 1986
- Architect Sam Webb insisted on dismantling floor by floor
- Allowed study of joints
Webb: “I knew we were going to find bad workmanship - what surprised me was the sheer scale of it. Not a single joint was correct. Fixing straps were unattached: leveling nuts were not wound down, causing a significant loading to be transmitted via the bolts: panels were placed on bolts instead of mortar. But the biggest shock of all was the crucial H-2 load-bearing joints between floor and wall panels. Some of the joints had less than fifty percent of the mortar specified.” (Wearne, 2000).
Building Code Changes

• Fifth amendment - 1970
• Structure must remain stable (with reduced safety factor) with member removed
• Must resist specified pressure from any direction
• Termed “robustness” provision in UK
Conclusions

• Flawed in design and execution
• Existing building codes inadequate for this structure
• Lacked alternate load paths to redistribute forces
• Poor workmanship at critical connections
2000 Commonwealth Avenue

Suzanne King,
Roger Williams University
Faculty Advisor: Dr. Norbert Delatte

January 25, 1971
The Building

• Sixteen story high-rise apartment building
• Cast-in-place reinforced concrete
• Flat slab construction
• Central elevator shaft
• Penthouse mechanical room with a 5 ft. crawl space
• Excavation began in fall of 1969
• Most of work subcontracted
• At time of collapse, construction almost complete
• Brickwork up to 16th floor and work started in individual apartments
Collapse

- Phase 1: Punching Shear Failure in the Main Roof at Column E5
- Phase 2: Collapse of Roof Slab
- Phase 3: General Collapse
Phase 1: Punching Shear

- About 3:00 pm workers take break from placing concrete for the mechanical room floor slab
- Placement started at the west edge and proceeded east
- Shortly after break there was a drop in the floor slab
- Punching shear was noticed around column E5
Phase 2: Collapse of Roof Slab

- After hearing a warning, most workers managed to get out of the way
- Roof slab began to form the shape of a belly
- Roof collapsed onto sixteenth floor
- Reinforcing steel was being placed, so workers were forced to cross over to the west side of the building
Phase 3: General Collapse

- Progressive collapse occurred 20 minutes after roof collapsed
- Weight of the roof caused the 16th floor to collapse onto 15th and so on down to the ground
- Two thirds of the building was gone
- Four workers died
Extent of Collapse

- Column E5
- Shaded Area Represents Extent of Collapse
- Construction Elevator
- Elevator Core
- West Side Roof Slab

Dimensions:
- 68'6" in height
- 8' in depth
- 72'10" in width
- 180'10" in length
Punching Shear

Force Acting on Slab

View of Column and Slab Before Punching Shear Failure Occurs.

Force Acting on Slab

View of Column and Slab After Punching Shear Failure Occurs.
Causes of Punching Shear

- Concrete strength was well below required 3,000 psi
- Inadequate shoring under the roof slab
- Construction equipment and two boilers were on the roof
Design/Construction Flaws

• Insufficient length of rebar
  • bars did not extend far enough into columns
• Incorrect placement of bars
  • confusion with deliveries
  • design around columns did not meet ACI codes
Procedural/Construction Flaws

- Lack of proper building permit and field inspection
- Premature removal of formwork
- Lack of construction control
Harbour Cay Condominium

- Building collapsed while under construction in Cocoa Beach, FL, March 27, 1981
- Yet another punching shear failure
- Designed by a retired NASA engineer, hired another retired NASA engineer to do calculations
ASSUMED STATE OF CONSTRUCTION
AT THE TIME OF THE COLLAPSE

≈ 3:00 P.M. 3/27

Flying forms
Reshores

Construction joints
Numbers in structure indicate age in days at time of collapse
Potential Causes (NIST)

- Low concrete strength
- Weak coarse aggregate - low tensile strength concrete
- Inadequate reshoring
- Impact loading during concrete placement
Critical Omissions

- No checks for deflection or minimum slab thickness
- No punching shear or beam shear checks
- No checks for column reinforcement spacing
- No calculation of effective depth of slab flexural reinforcement
Structural vs. Shop Drawings

Structural

Shop
CRITICAL SECTION FOR COMPUTING PUNCHING SHEAR CAPACITY OF SLAB

AREA OF CRITICAL SECTION = \[2d(C_1+C_2+2d)\]
Insufficient punching shear capacity

• Omission of punching shear check during design of floor slabs
• Incorrect placement of top steel in column strips
Structural engineering is not rocket science.

It is evidently much more difficult.
Discussion and Conclusions

• Important to investigate failures thoroughly to improve engineering practice
• In the U.S. systems are uneven - much better for bridges and tunnels
• OSHA covers buildings under construction, but not completed buildings in service
Discussion

• Investigations in support of litigation
  • Results may be published, or not
  • May be limited in scope
  • Client may require confidentiality

• U.K. CROSS is an excellent system

• Better system needed for the U.S.
Conclusions

- Failure literacy vital for engineers
- Important element of engineering education
- Engineering progress often comes from failures
- Professional and ethical issues in addition to technical issues
- Errors in communication and management
Closing Comments

• Failures have many causes
  • Technical - innovative systems, forgotten mechanisms, pushing the envelope
  • Communications - disconnects between designer, builder, inspector
  • Maintenance and operations
  • Materials and deterioration

• We can learn from each failure
• We can learn from patterns of failure
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Questions?