STRUCTURAL BACKGROUND

STRUCTURE – A SYSTEM OF CONNECTED PARTS USED TO SUPPORT A LOAD

EXAMPLES:
- BRIDGES
- BUILDINGS
- TOWERS
- TANKS
KEY COMPONENTS FOR DESIGN

- MATERIALS
- LOADS
MATERIALS

- STRENGTH
- DEFLECTION
LOADS

- DEAD
  - WEIGHT OF MATERIALS
  - WEIGHT OF PERMANENT FIXTURES
- LIVE (use)
  - PEOPLE
  - CONTENTS
- LIVE (environment)
  - WIND
  - RAIN, SNOW
  - EARTHQUAKES
STRUCTURAL ELEMENTS

- BEAMS/GIRDERS
- COLUMNS
- TIE RODS
STRUCTURE TYPES

- TRUSSES

- CABLES AND ARCHES
FRAMES

SURFACE (SHELLS)
STRUCTURAL DESIGN

MATCH LOADS TO MATERIAL CAPABILITIES

CODES PROVIDE LIMITS

ITERATIVE PROCESS

CONNECTIONS ARE CRITICAL
BRIDGES

ARCH

TRUSS

SUSPENSION

BEAM AND PIERS
BRIDGE FAILURES

- QUEBEC – 1907, 1916
- TACOMA NARROWS – 1940
- KINGS BRIDGE – 1962
- POINT PLEASANT – 1967
- MIANUS I-95 – 1983
- SCHOHARIE – 1987
QUEBEC BRIDGE COLLAPSES
1907 and 1916

- PLANNED AS STEEL TRUSS WITH CANTILEVER CENTER SPAN 1500’ LONG
- DESIGNED BY PROMINENT ENGINEER
1907 FAILURE

- PARTLY COMPLETED CENTER SECTION COLLAPSED KILLING 80.
- EXCESSIVE DEFLECTION NOTED DAY BEFORE
- ENGINEER IN NEW YORK AND DIDN’T GET ADVICE BACK TO SITE IN TIME
CAUSES

- DESIGN PUSHED UP ALLOWABLE STRESS
- LOADS WERE UNDERESTIMATED
- STRUCTURE OVERSTRESSED
- INADEQUATE BRACING
- ARROGANT ENGINEER OUT OF TOUCH WITH SITE AND CONSTRUCTION
- PERSONNEL ON SITE NOT KNOWLEDGEABLE OF DESIGN
LESSONS LEARNED

- THOROUGH CHECKING OF DESIGN CALCULATIONS AND LOAD ASSUMPTION NEEDED
- TESTING NEEDED IF WANT TO EXCEED ACCEPTED STRESS LEVELS
1916 COLLAPSE

- Bridge redesigned by different engineers
- But – still used assumptions of stresses above normal
- Different method to install center span used – lift into place
- During lifting, span came apart and fell into river, killing 11
1916 CAUSE

- CAUSE ATTRIBUTED TO OVERSTRESS IN LIFT SPAN MEMBERS.

- AGAIN – STUDIES SHOWED THAT MATERIALS IN SPAN WERE OVERSTRESSED.

- 1917 – REDESIGNED AND COMPLETED
QUEBEC IMPACTS

- LED TO MORE DETAILED CODES AND STANDARDS
- LED TO INCREASING ACCEPTANCE OF THE AMERICAN SOCIETY FOR TESTING MATERIALS (ASTM) FOR MATERIAL STANDARDS.
- ENGINEERS BEGAN TO DO MORE MATERIAL TESTING.
TACOMA NARROWS - 1940

- SUSPENSION BRIDGE 2800’ SPAN
- DESIGNED BY EXPERIENCED ENGINEERS
- PUSHED ENVELOPE TO CREATE “STREAMLINED” APPEARANCE
- RESULT WAS A THIN, LIGHT SPAN
THE FAILURE

- WINDS CAUSED BRIDGE TO BUCK AND TWIST
- ROLL TAPE!
CAUSE

- OBVIOUSLY WIND CREATED EXCESSIVE MOVEMENT AND STRESS.
- ONE CABLE SLIPPED OUT OF PLACE CAUSING THE FINAL COLLAPSE BY ALLOWING TWISTING INSTEAD OF UP AND DOWN
IMPACTS

- BRIDGE NOT REPLACED TIL 1950
- LED TO DEVELOPMENT OF AERODYNAMICS AS ENGINEERING DISCIPLINE
- LED TO WIND TUNNEL TESTING OF MODELS FOR ALL LARGE BRIDGES
KINGS BRIDGE, MELBOURNE AUSTRALIA - 1962

- A CONCRETE DECK ON HIGH-STRENGTH WELDED PLATE GIRDERS
- 2300 FOOT LONG BRIDGE
- COMBINED SIMPLE SPANS WITH CANTILEVER SPANS
- USE OF HIGH-STRENGTH STEEL NOT COMMON THEN AND WELDING OF THE STEEL USED WAS UNTRIED
FAILURE

- OCCURRED ON VERY COLD NIGHT
- TWO SPANS DROPPED 1 FOOT BUT ADJACENT WALLS PICKED UP LOAD AND PREVENTED TOTAL COLLAPSE.
- NO DEATHS OR INJURIES DUE TO NIGHT
CAUSE

- Cracking at welds found at most connections.
- Cracks occurred immediately after welding and were not detected by inspection techniques.
- Cracks grew with time.
- Cold weather contributed to brittle fracture.
- Inspection of girders in service prevented by walls.
- The steel used did not meet material requirements for toughness needed for the type of construction. Not tested for toughness.
TOUGHNESS

Ductility transition temperature at 15 ft-lb., say 17° F

Transition temperature at steepest slope, say +30° F
IMPACTS

- LED TO MORE TESTING REQUIREMENTS FOR MATERIALS WHEN USING NEW TECHNIQUES
- POINTED OUT NEED FOR HIGHER LEVEL OF INSPECTION AND TESTING WHEN USING NEW APPROACHES
- LED TO REQUIREMENTS FOR BRIDGE COMPONENTS BEING ACCESSIBLE TO INSPECTION.
POINT PLEASANT - 1967

- SUSPENSION BRIDGE BUILT IN 1926
- 1460 FEET LONG
- USED EYE-BAR CHAINS INSTEAD OF TYPICAL WIRE STRAND FOR CABLES
FAILURE

- COLLAPSED IN RUSH HOUR TRAFFIC
- 46 KILLED
CAUSES

- ONE EYEBAR CRACKED AND BROKE
- FATIGUE DUE TO HIGH-STRENGTH STEEL WHICH IS MORE BRITTLE
- CORROSION ACCELERATED BY STRESS
- INSPECTIONS NOT DONE (LAST BEFORE FAILURE WAS IN 1951)
IMPACTS

LED TO A NATIONWIDE BRIDGE INSPECTION PROGRAM MANDATED BY FEDERAL HIGHWAY DEPARTMENT
MIANUS I-95 - 1983

- BRIDGE BUILT IN 1958
- CONVENTIONAL DESIGN
- GIRDERS USED PIN HANGAR CONNECTION
FAILURE

- A 100-FOOT SPAN OF ONE LANE COLLAPSED KILLING 3
- CAUSED MAJOR TRAFFIC DISRUPTION
CAUSE

- CORROSION OF PIN HANGARS
- POOR MAINTENANCE
  - LACK OF CLEANING ALLOWED CORROSION
- INADEQUATE INSPECTION
  - PROBLEMS COULD HAVE BEEN SEEN
  - LACK OF STAFF AND MONEY
- DEFICIENT DESIGN CLAIMED, BUT NOT PROVEN
IMPACTS

- HIGHER PRIORITY GIVEN TO INSPECTION AND MAINTENANCE
- INSPECTIONS OF OTHER SIMILAR BRIDGES FOUND SIMILAR PROBLEMS.
- STRENGTHENING DONE ON OTHER BRIDGES
SCHOHARIE BRIDGE - 1987

- CONVENTIONAL CONCRETE DECK AND STEEL GIRDER BRIDGE BUILT IN 1952
- FIVE SPANS CARRIED BY FOUR PIERS, TWO IN CREEK BED
- WELL MAINTAINED
- INSPECTED IN YEAR BEFORE COLLAPSE
FAILURE

- FAILED DURING HEAVY RAIN
- CENTER SPANS COLLAPSED INTO CREEK FIRST FOLLOWED BY END SPANS
- 10 PEOPLE KILLED
CAUSE

- NOT A STRUCTURAL FAILURE
- RIVER BED SCOUR REMOVED SUPPORT FOR THE FOOTINGS SUPPORTING THE PIERS
- UPSTREAM FLOOD CONTROL DAM RELEASED WATER IN ADDITION TO RAIN
- ORIGINAL FILES HAD REPORT WARNING OF SCOUR POTENTIAL
- INSPECTIONS DID NOT CHECK FOR SCOUR
IMPACTS

- ALTHOUGH SCOUR KNOWN AS A RISK, ITS IMPORTANCE HIGHLIGHTED BY THIS FAILURE.
- LED TO REQUIREMENT OF SCOUR ANALYSIS FOR ALL BRIDGES CROSSING CREEKS.
- LED TO INCLUDING UNDERWATER EXAMINATION IN INSPECTIONS
SUMMARY FOR BRIDGES

MAJOR CAUSES

– DESIGN ERRORS
– PUSHING LIMITS WITHOUT ENOUGH STUDY OR TESTING
– CORROSION OF MATERIALS
– POOR MAINTENANCE
– INTERACTION WITH NATURE (SCOUR)
– POST CONSTRUCTION ACCIDENTS NOT A TECHNOLOGY FAILURE
BUILDING FAILURES

- HISTORICAL FAILURES - TAPE
- BOSTON MOLASSES TANK – 1919
- SKYLINE PLAZA – 1973
- HARTFORD CIVIC CENTER - 1978
- KEMPER ARENA – 1979
- HYATT REGENCY WALKWAYS – 1981
- L’AMBIANCE PLAZA - 1987
BOSTON MOLASSES TANK - 1919

- TANK WAS 90’ DIAMETER AND 50’ HIGH
- MADE OF STEEL PLATES RIVETED TOGETHER SUPPORTED ON CONCRETE FLOOR
- COMPLETED IN 1916 AND TESTED BY RUNNING 6” OF WATER INTO IT
- NEVER FILLED TO MAXIMUM BEFORE FAILURE
FAILURE

- TANK BURST OPEN RELEASING FLOOD OF MOLASSES 2-STORIES HIGH AND 160 FEET WIDE.
- DESTROYED BUILDINGS, ELEVATED RAIL LINES
- KILLED 21, INJURED >150
- TOOK MONTHS TO CLEAN UP MOLASSES
MOLASSES FLOOD
CAUSE

- STUDY FOUND STEEL PLATES THINNER THAN CALLED FOR ON DESIGN PLANS SUBMITTED.
- RIVETED JOINT IN SECOND RING PLACED ABOVE A CUTOUT IN FIRST RING, INCREASING STRESS
- MANHOLE CUTOUT NOT REINFORCED
- IMPROPER DESIGN, NO CHECK OF CALCULATIONS BY ENGINEER
- POOR CONSTRUCTION
IMPACTS

- CALCULATIONS REQUIRED TO BE SUBMITTED BY BOSTON
- DRAWINGS SUBMITTED TO BE SIGNED BY ENGINEER
- INFLUENCED ADOPTION OF ENGINEERING LICENSING LAWS AND REQUIREMENTS FOR SUBMITTING DRAWINGS STAMPED AND SIGNED BY REGISTERED ENGINEER
SKYLINE PLAZA - 1973

- CAST-IN-PLACE CONCRETE APARTMENT BUILDING COLLAPSED DURING CONSTRUCTION
- DESIGN COMMON, AND CONSTRUCTION METHOD COMMON
- EXAMPLE OF THIS TYPE OF CONSTRUCTION CAN BE SEEN DOWNTOWN TODAY
- ONE OF SEVERAL BUILDINGS PLANNED; OTHERS COMPLETED OK
- PLACING CONCRETE FOR 24th FLOOR WHEN FAILED
POST FAILURE PHOTO

NOTE SLAB SECTIONS HANGING DOWN
FAILURE

CONSTRUCTION SEQUENCE IS PLACE ONE FLOOR THEN COLUMNS. FORM FOR SECOND FLOOR. USE METAL OR WOOD SUPPORT FOR SECOND FLOOR TIL CONCRETE STRONG ENOUGH.

24TH FLOOR BEGAN SAGGING WHILE PLACING CONCRETE, AS DID 23RD FLOOR WHICH WAS ONLY 4-DAYS OLD.

COLLAPSE ALLOWED WET CONCRETE TO IMPACT FLOOR BELOW, BREAKING THROUGH AND SUCCESSIVELY THROUGH THE FLOORS BELOW.

14 KILLED AND 34 INJURED.
CAUSE

- PREMATURE REMOVAL OF SHORING BELOW THE 23RD FLOOR
- PLACING 24TH FLOOR TOO SOON, BEFORE 23RD FLOOR CONCRETE HAD REACHED ENOUGH STRENGTH
- SHORING SYSTEM POORLY DESIGNED AND INSTALLED
- SPEEDING UP CONSTRUCTION
ALTHOUGH POINTED OUT SOME BASIC FLAWS IN CONSTRUCTION PROCESS, FEW CHANGES HAVE BEEN MADE.

CONTRACTOR IS RESPONSIBLE FOR SHORING DESIGN AND INSTALLATION; NO INDEPENDENT INSPECTIONS REQUIRED

CONSTRUCTION COLLAPSES STILL OCCUR, MANY FROM SAME CAUSES
HARTFORD CIVIC CENTER - 1978

- BUILT IN 1972
- ROOF WAS EARLY EXAMPLE OF A SPACE TRUSS AND CONSIDERED AT LEADING EDGE OF DESIGN
- ROOF WAS 21 FEET DEEP AND 300 BY 360 FEET
- EARLY USE OF COMPUTER-AIDED DESIGN
FAILURE

- COLLAPSE OF ROOF UNDER SNOW LOAD
- FORTUNATELY NO ONE KILLED
- GO TO THE TAPE
IMPACTS

- SHOOK PUBLIC CONFIDENCE IN SPACE TRUSS ROOFS
- PRESIDENT FORD ORDERED WATER LOAD TESTING FOR SUCH A ROOF OVER MUSEUM IN MICHIGAN
- TEMPERED ENGINEERS AND ARCHITECTS RELIANCE ON COMPUTER MODELS TO CUT DOWN STRUCTURE TO BARE MINIMUM LEAVING NO REDUNDANCY OR MARGIN FOR ERROR
KEMPER ARENA - 1979

- BUILT IN 1974 AND WON AWARDS FOR DESIGN
- ROOF WAS 324' BY 310' SYSTEM OF SPACE TRUSSES HUNG FROM THREE HUGE SPACE FRAME TRUSSES
- CONNECTIONS WERE BY HIGH-STRENGTH BOLTS
- ROLL TAPE
FAILURE

- FAILED DURING RAINSTORM AND AFTER EVENTS
- MOST OF ROOF STRUCTURE FELL DOWN; SPACE FRAME SUPPORTS NOT DAMAGED.
- NO ONE KILLED OR INJURED
CAUSE

- STUDY POINTED TO FAILURE OF THE HIGH-STRENGTH BOLTS.
- BOLTS WEAKENED BY FATIGUE
- BOLTS MAY NOT HAVE BEEN CORRECTLY TIGHTENED
- EXCESSIVE WATER ACCUMULATED ON ROOF DUE TO LACK OF SUFFICIENT DRAINAGE AND HIGH WINDS CAUSING POOLING
IMPACTS

- NEW ROOF HUNG FROM ORIGINAL SPACE FRAME TRUSSES
- USED PIN CONNECTIONS NOT BOLTS
- DRAINAGE IMPROVED AND ROOF SLOPE INCREASED
- LED TO INSPECTIONS OF STRUCTURES WITH THE HIGH-STRENGTH BOLTS TO SEE IF PROPERLY TIGHTENED
- LED TO GREATER DESIGN CONCERN AND ATTENTION TO HIGH-STRENGTH BOLTS
HYATT REGENCY HOTEL WALKWAYS - 1981

- HOTEL ATRIUM LOBBY CROSSED BY THREE HANGING WALKWAYS CONNECTED TO BALCONIES
- COLLAPSE KILLED 114 AND INJURED ~200
- ROLL TAPE
HYATT DETAILS
CAUSE

- Hangar connection not designed by designer, but by shop fabricator
- Redesign not checked by designer
- Design built was inadequate for loads applied
- One walkway collapse led to overloading of others
- Materials and construction were not at fault
IMPACTS

- TWO DESIGNERS LOST LICENSES
- LED TO BETTER DESIGN AND REVIEW OF CONNECTIONS
- PROBLEMS STILL EXIST WITH RESPONSIBILITY FOR DESIGN OF STEEL CONSTRUCTION.
  STRUCTURAL ENGINEER vs FABRICATOR
L’AMBIANCE PLAZA - 1987

ONE OF TOO MANY EXAMPLES OF CONSTRUCTION FAILURE

APARTMENT BUILDING WITH CONCRETE CONSTRUCTION USING “LIFT SLAB” METHOD

PLANNED FOR 13 STORIES; FAILED WHILE ABOUT 50% DONE
FAILURE

- LIFT SLAB METHOD CALLS FOR POURING CONCRETE SLABS ON TOP OF EACH OTHER ON THE GROUND THEN POST-TENSIONING AND LIFTING UP ALONG COLUMNS TO FINAL POSITION.
- COLLAPSE OCCURRED WITH SLABS AT THE 9TH FLOOR LEVEL.
- PROGRESSIVE FAILURE AS FLOORS FELL.
- 28 KILLED AND 16 INJURED
CAUSE

- Connection of a jack to the slab failed and allowed a bolt to slam into column
- Slab began to deflect and caused progressive failures
- Inadequate design of lifting components
- Formal cause never agreed upon
IMPACTS

- SOME CHANGES IN CONSTRUCTION PROCEDURES MADE
- OSHA MANDATED ADHERENCE TO HIGHER SAFETY FACTORS FOR LIFT SLAB PROJECTS
- NEW STANDARDS WRITTEN FOR EVALUATING STRUCTURAL LOADS DURING CONSTRUCTION
BUILDINGS - SUMMARY

- EARLY 1900’S FAILURES OFTEN DUE TO LACK OF DESIGN KNOWLEDGE OR UNDERSTANDING OF MATERIAL BEHAVIOUR
- LATER, STILL SOME MATERIALS ISSUES
- CONNECTIONS OFTEN A BIG PROBLEM
- CONSTRUCTION IMPLEMENTATION A MAJOR CONTRIBUTOR TO MANY RECENT FAILURES
CURRENT PRACTICE

- STRICT CODES FOR MATERIALS
  - AISC, ACI, ASTM

- REVIEWS AND PERMITTING PROCESSES
  - FEDERAL HIGHWAYS
  - STATE CONSTRUCTION
  - LOCAL BUILDING DEPARTMENTS
CURRENT PRACTICES

- BUILDING CODES REQUIRING MORE INSPECTION
  - NEW NC CODE CALLS FOR “SPECIAL INSPECTIONS”

- STILL PROBLEMS IN CONSTRUCTION IMPLEMENTATION OF DESIGNS
WHEN TECHNOLOGY SUCCEEDS

MOVING THE CAPE HATTERAS LIGHTSTATION