Failure Investigation and Structural Assessment Strategies:

**Methods used for the I-35 Bridge Collapse and the Bonner Bridge and Queen Isabella Bridge Investigations**
Outline and Objectives

- Introduction
- Forensic Evaluations
- Failure, defined
- Investigation of Material Failure
  - Bonner Bridge Causeway
  - Queen Isabella Causeway
- Investigation of Structural Failure
  - I-35 Bridge Collapse
Forensic Evaluation

- Field Investigations
- Condition Assessment
- Service Life Prediction
Forensic Evaluation

- Field Investigations
- Condition Assessment
  What will fail first?
- Service Life Prediction
What constitutes Failure?
Failure, defined

Failure
An unacceptable difference between expected and observed performance

- Overstresses
- Large deflections
- Wide concrete cracks
- Fatigue cracking

- (ASCE Technical Council on Forensic Engineering)
Failure, defined

**Collapse**
Gross movement of major members or a significant portion of the structural system that renders them incapable of supporting the intended loading.

Failure does not imply collapse, but collapse is viewed as a structural failure.
What Qualifies as a Failure?

- Catastrophic structural collapse
What Qualifies as a Failure?

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What Qualifies as a Failure?

- Material Failure?
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- Material Failure?
Investigating Bridge Failures
Bridge Structure Investigations

The Forensic Team
- Field Engineers
- Field Technicians
- Material Scientists

The Equipment
- Super-duper extra-special widget
- Primary Tools
  - Visual Inspection
  - Materials Testing
- Advanced Equipment
Bridge Structure Investigations

Visual Methods (simple)
- Close-up Visual Inspection
- Sounding
- Crack Mapping
- Cover Meter
Visual Inspection – Close-up

- Crack widths
Sounding

- Detecting unsound and deteriorated areas of concrete
- Hammer-tapping to locate boundary of unsound concrete
- Low tech
Visual Inspection – Close-up

- Hands-on
  - Concrete condition
  - Rebar condition
Visual Inspection – Close-up

Carbonation Testing

Young crack

Old crack
Bridge Structure Investigations

Non-Destructive Evaluation (advanced)
- Half-Cell Potential
- Linear Polarization
- Ultrasonic Pulse Velocity
- Dye Penetrant Testing
- Magnetic Particle Testing

Material Sampling
- Concrete Petrography
- Steel Composition
Bridge Structure Investigations

Applying what we know to Investigating Causeway Bridge Structures

- **Local Examples**
  - Martin Point Bridge over the Presumpscot River
    Built 1943, is 1,400 feet
  - Veterans Memorial Bridge over the Danvers River
    Built 1997, is 1,710 feet

- **Larger Structures**
  - Bonner Bridge over Oregon Inlet, North Carolina
    Built 1964, is approximately 2.4 miles long
  - Queen Isabella Memorial Causeway, south Texas
    Built 1974, is approximately 2.5 miles long
Bridge Structure Investigations

The need for Investigation

- Bonner Bridge
  - Routine Investigation
  - Known Material Problems
  - Evaluation of Past Repairs Service Life

- Queen Isabella Causeway
  - Routine Investigation
  - Evaluation of existing corrosion mitigation systems
  - Evaluation of Past Repairs Service Life
Bonner Bridge, North Carolina

- Completed April 1964
- Approximately 4 years to complete
- Total Length = 2.4 miles
- 185 Spans

- Superstructure
  Precast Girders and Structural Steel
- Substructure
  Cast-in-place concrete
Bonner Bridge, North Carolina
Bonner Bridge, North Carolina
Bonner Bridge, North Carolina
Bonner Bridge, North Carolina
Focus of Investigation

- Evaluate Construction materials
  - On-site Concrete production
    - Remote location
- Evaluate performance of repairs
- Evaluate corrosion mitigation program
  - 1986 Implementation
    - Discreet anode cathodic protection systems
      - Pile caps, splash zone regions
Bonner Bridge, North Carolina

- Field Investigation
  - Access
  - Inspection
    - Visual
    - NDE
  - Concrete Samples
Bonner Bridge, North Carolina

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Bonner Bridge, North Carolina

- Concrete Petrography
  - Girders
  - Pile Caps
  - Bridge Deck
Bonner Bridge, North Carolina

- Concrete Petrography
  - Girders
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  - Bridge Deck
Bonner Bridge, North Carolina

- Concrete Petrography
  - Girders
  - Pile Caps
  - Bridge Deck

0.1 in.
Bonner Bridge, North Carolina

- Concrete Petrography
  - Girders
  - Pile Caps
  - Bridge Deck
Bonner Bridge, North Carolina

- Concrete Petrography
  - Girders
  - Pile Caps
  - Bridge Deck
Summary of Findings

- Evaluate Construction materials
  - Poor concrete quality
  - Coral used in original concrete

- Evaluate performance of repairs
  - Concrete repairs did not perform well

- Cathodic Protection
  - Not maintained
  - Non-functional
Queen Isabella Causeway

- Connects Port Isabel to South Padre Island, TX
- Completed April 1974
- Approximately 2 years to complete
- Total Length = 2.5 miles
- 150 Spans

- Superstructure
  Precast Girders and Structural Steel
- Substructure
  Cast-in-place concrete
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Queen Isabella Causeway

- Evaluate construction materials
  - On-site concrete production
    - Remote location
- Evaluate performance of repairs
- Evaluate corrosion mitigation program
  - 2003 Implementation
    - Thermally sprayed cathodic protection systems
      - Pile caps, splash zone regions
Queen Isabella Causeway

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Queen Isabella Causeway

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    - Visual
    - NDE
  - Concrete Samples
Queen Isabella Causeway

- Field Investigation
  - Access
  - Inspection
    - Visual
    - NDE
  - Concrete Samples:
    - Assist NDE
Queen Isabella Causeway

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  - Access
  - Inspection
    - Visual
    - NDE
  - Concrete Samples:
    - Assist NDE
Queen Isabella Causeway

- Field Investigation
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  - Inspection
    - Visual
    - NDE
  - Concrete Samples:
    - Assist NDE
Queen Isabella Causeway

- Lab Investigation
  - Access
  - Inspection
    - Visual
    - NDE
  - Concrete Samples:
    - for petrography
Queen Isabella Causeway

- Lab Investigation
  - Access
  - Inspection
    - Visual
    - NDE
  - Concrete Samples:
    - for petrography

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Queen Isabella Causeway

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Queen Isabella Causeway

- Lab Investigation
  - Access
  - Inspection
    - Visual
    - NDE
  - Concrete Samples:
    - for petrography
Conclusions

Material Performance

- Composition
- Location within structure
- Maintenance & Protection
- Service Life Extensions
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– Composition
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  within structure
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Conclusions

Material Performance

- Composition
- Location
- Maintenance & Protection
- Service Life Extensions

Expected Service Life of Structure
Bonner Bridge vs. Queen Isabella Bridge
Investigation of the I-35W Bridge Collapse

Mark R. Chauvin
Wiss, Janney, Elstner Associates, Inc.
Outline

- Description of Bridge
  - Deck Truss
- Brief History
- Collapse
- Field Work
  - Recovery and Removal
  - Observations
- Structural Analysis
- Conclusions
Description of Bridge
Description of Bridge

- Interstate 35 is a major N-S route thru MN
- Divided into parallel arterials thru metro
  - 35E through St. Paul
  - 35W through Minneapolis
- I-35W crosses Mississippi River adjacent to U of MN campus, just NE of downtown
- 2004 ADT =141,000 vehicles (5640 trucks)
Description of Bridge (cont.)

- Designed in 1965 by Sverdrup & Parcel
- Opened to local traffic in 1967
- Eight 12 ft. wide lanes
  - 3 traffic + 1 acceleration/deceleration N + S
- General construction:
  - 6-1/2 inch thick reinforced concrete deck
  - Two 3-span continuous deck trusses
  - Eleven approach spans (5 south, 6 north)
- Total bridge length = 1907 feet
Deck Truss

- Two parallel steel trusses:
  - Welded box-shaped top and bottom chords
    - 21 inches wide x 28 inches deep (typ.)
  - Welded box-shaped vert. + diag. C members
  - H-shaped vert. and diag. T members
- Connected at nodes with 1/2, 5/8, 3/4 and 1 inch thick steel gusset plates (50 ksi)
  - 7/8 inch diameter rivets
WJE/MnDOT Nomenclature:
Top chord nodes U#, bottom chord nodes L#
Nodes 0 (south end) to 14 (midspan)
Nodes 13’ to 0’ (north end)
Deck Truss (cont.)

CROSS-SECTION
AT
PIER 7
Brief History
History - Work

- 1977:
  - Concrete overlay increased deck thickness from 6-1/2 inches to 8-1/2 inches

- 1998/1999:
  - New median and outside barrier
  - Fatigue retrofits of approach girders
  - Deck de-icing system
  - Painting
2007 - Progressive Contractors Inc. (PCI)
- Patching and overlay work began June 2007
  - Removal and replacement of 2 inch 1977 overlay
- Rotomilling outer 2 NB/SB lanes first
- Aggregate and sand stockpiled near mix equipment beyond end of each placement.
  - Seven placements complete by August 1
  - Preparation for 8th placement underway
    - 2 inside southbound lanes Nodes 0’ to 14
July 18, 2007 (looking southbound)
Construction Material Staging on Center Span Truss

4 Loads of Rock (184,380 lbs) 4 Loads of Sand (198,820 lbs) = 383,200 lbs
3 Loaded Commercial Construction Vehicles, Water Truck D16 (48,200 lbs), Cement Tanker B16 (72,780 lbs), and Concrete Mixer B15 (51,400 lbs) = 172,380 lbs
1 Skidsteer and 5 Scootcrates with associated material and workers = approximately 21,655 lbs
Total Load = 577,235 lbs
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577 kips total

Note: about 2” of deck had been removed from the southbound construction lanes
Mid-afternoon on day of collapse
Collapse
U.S. COE Security Camera
(looking north)
U.S. COE Security Camera
South end clearly enters river first

U.S. COE Security Camera
Collapse

- Occurred at 6:05pm on August 1st, 2007
  - Temperature: 92.1°F
    - Peak of 92.9°F at 4:30pm
  - Light to moderate winds 10 to 18 mph
- 4 of 8 lanes closed to traffic for PCI work
- Approx. 110 vehicles on bridge
  - Including construction materials and equipment
- 13 fatalities, 145 people injured
Field Work
Field Work

- NTSB lead federal investigative agency
- WJE retained by MnDOT on Aug. 3rd
- Field tasks included:
  - Post-collapse documentation
  - Member identification, marking and tracking
  - Demolition assistance
  - Monitoring recovery and removal operations
  - Material sampling
Field Work –
Summary of Observations

- River span essentially dropped straight down into river, very little twist or rotation
  - Primary failure regions on north and south ends of submerged section were symmetric
  - Essentially intact between 12 and 10’
- Similar failure modes at all four U10 nodes
  - Gussets separated into multiple sections
- No evidence of collapse initiation at other locations
Structural Analysis
Structural Analysis

- Loads at time of collapse:
  - Self-weight
  - Construction materials and equipment:
    - Located in SW quadrant of river span
    - Placed on bridge 2-3 hours prior to collapse
  - Vehicle traffic in 4 open lanes

- Findings:
  - Forces in most severely loaded deck truss members nearly equal to design service loads
Most critically loaded main truss member was L9W-U10W; at ≈ 102% of the original design service load on 8/1/07.
Node U8

2 Spl. Pls. 27 1/2" x 1/2" (A.S.)

Close Joint

Diaphragm "A"

(2-7/16 Fills)

M.N.S.

U10

let A.

L4 x 4 x 3/8 N.S.

2-1/2 Pls. (A.S.)

M.N.S.

U10 Node Design Detail
U10 Node; plane of known horizontal shear
Simple Initial Calculation

- Check shear only
  - Ignore the normal stresses which also exist at this plane
- Assume shear uniformly distributed along entire plane
- Assume loading is equal to original design dead load $\times 1.15$ (1977 overlay)
- No traffic or construction load considered
Initial Calculation Results

- Sum of horizontal forces in web elements (and in chords) = 2343 k
- Plate gross area = 104 sq. in.
- Avg. shear stress = $\frac{2343}{104} = 23$ ksi
  - Allowable (1964 AASHO) = 15 ksi
  - Yield $\approx 0.6 \times F_y = 30$ ksi
- Close
U10 Node section equilibrium check at yield
- Shear and normal forces acting together
- Magnitude governed by Von Mises yield criteria along entire section
- Internal forces in equilibrium with external forces for each "section"
- Loading proportional to dead load distribution

"Section" for L9-U10

U10 Node section equilibrium check at yield
Initial Analysis (cont.)

- Maximum sustainable compression load in L9-U10 = 2300 kips at measured steel yield strength (51 ksi)
- Estimated load in L9 - U10 at time of collapse (including all loads) = 2340 kips
- Avg. shear stress along horizontal plane = 28 ksi
- L11 gusset also found to be undersized (1/2 inch)
U10 Finite Element Analysis

- Analysis of Node U10 and associated members
  - Apply loading proportionally as indicated in finite element model of entire structure
  - Steel properties determined from testing
  - Material and geometric nonlinearities
  - Initial plate distortion evaluated
    - 2003 URS photos
- Light green corresponds to Von Mises yield level stress
- Strain hardening only in small areas near top of L9-U10 and around lowest row of chord rivets (circle)
- Ultimate strength $\approx 2470$ kips with flat plates
- Ultimate strength $\approx 2390$ kips with initial plate edge distortion similar to that observed in pre-collapse photos
Conclusions
Conclusions

- Construction of deck truss was consistent with design documents
- As-built capacity of U10/10’ and L11/11’ gusset plates roughly half of capacity that required by governing design code
  - These plates had not experienced significant damage or deterioration prior to collapse
- U10 gusset plates were the most critically loaded elements in the deck truss on 8/1/07
Bridge collapse initiated by failure of the improperly designed U10 gusset plates
- As-built ultimate capacity of U10 in vicinity of L9-U10 compression diagonal essentially identical to demands at time of collapse
- Failure mode of U10 gusset predicted by non-linear FEM consistent with the condition of the actual plates after collapse
- U10 became unstable when L9-U10 loading created yield mechanism in gussets