Today's Speakers

Ted Kniazewycz, P.E., F.ASCE
Tennessee Department of Transportation
Director | Structures Division

Aaron Stover PE, SE
Michael Baker International
Regional Bridge Lead

Daniel Baxter, PE, SE
Michael Baker International
Technical Manager – Bridge

Today's Agenda

• Immediate Response
• Phase I – Stability of Structure
• Modeling and Analysis
• Phase II – Long Term Repair of Fracture
• Phase III – Re-Opening to Traffic
• Forensic Evaluation
• Lessons Learned
And so the story begins…

**Bridge History**

- Hernando de Soto
- Constructed 1967-1973
  - Opened August 2, 1973
- Two Span Continuous Tied Arch Bridge
  - 2 – 900ft spans
  - 109ft above the water
  - Designed by Hazlett and Erdall

**Regional Importance**
Agenda - Swift and Critical Decisions

- Immediate Closure
- Three-Phase Approach
  - Assess/Stabilize the Structure
  - Repair of the Fracture
  - Inspect and Assess the rest of the Tie Girders
- Fracture Analysis
- Lessons Learned

Immediate Response
Early Actions in the days immediately following the critical find

Timeline of Events

- TDOT has responsibilities for repair project development
  - Selected Michael Baker International on Tuesday, May 11th
    - Qualification
    - Related Project Experience (Sherman Minton Bridge on I-64)
    - Availability of Team and Equipment (Inspector Staff on-site)
    - Contractual Relationship with TDOT was already in place
  - Initial task was to evaluate bridge in current state
  - Develop preliminary plan to stabilize structure
  - Work with CM on approach to complete fracture repair
- TDOT and ARDOT collaborated on a three-phase approach
  - Evaluate for resumption of river traffic
  - Evaluate and complete repairs for initial fracture
  - Evaluate existing bridge tension members and complete any repairs needed to open bridge

We Make a Difference
**Critical Startup Activities**

- Communication IS Critical
  - 9:00 AM - Detailed design call
  - (DOT Engineers, Consultants, Contractors)
  - 1:00 PM - Media and Social Media updates issued
  - 3:00 PM – Project status call
    - (DOT leadership, USCG, design and contractor)
  - 3:30 PM – Traffic update call
    - local EMS, USCG, DOT
  - 4:00 PM – Engineering & Construction update
    - with partner agencies
- Daily Work Summaries

**Timeline of Events**

- TDOT & ArDOT supplied bridge data to MBI
  - Plans, Shop Drawings & Weld Inspection Report (TDOT)
  - Inspection Reports (ArDOT)
  - Approved development of Phase 1 plating plans & model development

**Impact on Traveling Public**

- Interstate Traffic
  - 60,000 vehicle ADT
  - 2-3 hour backups
  - Estimated $2.4M/day impact to trucking industry
- Mississippi River
  - 470,123 short tons of freight every day
  - soybeans, distillate fuel oil and corn
Propagation of Fracture

- TDOT did not ask for recommendations on safety/risk.
- MBI provides FEA model results to TDOT
  - TDOT does a risk assessment using model data, historic photos & former staff
  - Construction photos suggest favorable sequence of loading during construction
- TDOT provides risk evaluation to USCG who opens river to traffic

Media Attention on Inspection

- Reports of Prior Fracture
- Traffic Snarls
- TDOT Media Coordination

Fracture Details

- Day 2
- Day 3

Phase 1 Repairs

Stabilizing the Structure
Critical Startup Activities

- Gathering Data
  - Bridge Plans, Shop Drawings, Inspection Reports, Models, Test Data...
- Mobilize Engineering Staff and Teams
  - Analysis team
    - Phase 1 Repairs
    - Phase 2 Repairs
- Other activities
  - Project Management
  - Communication / Meetings
  - BIM Modeling

Day 0

Engineering Teams

QC/QA

Design Team

Strengthening

Analysis

Post-Tensioning

Phase I - Plating
- Stabilize
- Constructability
Phase II - Plating
- Strength the fractured tie
Phase III - Plating
- NDT
- Local strengthening
Post - Tension
- Analysis
- Design
- Operations

Hernando de Soto – Mobile Command Center
How Bad is it?

- T1 steel = 100 ksi (+)
  - P/A design = 38ksi
- Fracture 113 in² → 51.5 in² (45%)
  - P/A after fracture = 83ksi
- Eccentric Loading
  - Refined Analysis
- Unknowns
  - Actual force in the tie
  - Redistribution of Load
  - Transient loads
- Strength of Materials
  - Condition of Welds

Hernando de Soto – Combined RA & UAS Live Feed

- May 13: Analysis for safety
- Multiple MiFi devices
- Riverbank for line of sight

Hernando de Soto – UAS Live Feed Inspection
Phase 1: Stabilize the Structure

How do you fix it?

- Tie w/ 4,500 kips +/-
- Displaced laterally and rotated
- Limited reserve capacity

And...
- Time is of the Essence

Permanent Fix
- Duration too long

Shoring Towers
- Navigation / Duration

Temporary PT
- High loads
- Long lead time / fabrication

Adjacent Splice
- Distortion of the box

Lengthen Splice
- Showed promise
Phase 1: Stabilize the Structure

Availability
- Initial contact with several fabricators looking for plate availability
- HPS 70W in stock and able to be used for the repairs
- 2" Thickness? Length?
- You can’t install what you can’t get!

Stupp Bridge in Bowling Green, KY

Phase 1 Preliminary Plans

• 5/14 – Draft Plans Available, TDOT Advertises for CM/GC

CM/GC Procurement

• Repair Project – CM/GC Contractor Selection Process
  o Advertised on Friday - May 14th
  o 8 Contractors were invited to provide submit interest packages
  o Preliminary plating plans were provided as part of the invitation
  o Selection of CM/GC was based on the following
    • Qualification
    • Related Project Experience
    • Availability of Team and Equipment
    • Approach on Repair Options
CM/GC Procurement

- Repair Project – CM/GC Contractor Selection Process
  - Qualification-Based – not awarded to low bidder
    - Phase 1 work based on Force Account (Time & Materials)
    - Phase 2 work was bid / negotiated
    - Phase 3 work was determined based on NDT Inspection Results
  - Awarded to Kiewit Infrastructure Group on Monday - May 17th

CM/GC Benefits

- Contractor selection driven mostly by qualifications selection
- Promotes discovery and resolution of key risks prior to construction
- Provides upfront value engineering and wisdom leading to smoother and more reliable construction phase expectations
- Optimizes schedules
- Enhances collaboration
- Fosters innovation driven by Construction Manager insights
- Allows flexibility
- Improves cost control and certainty
- Allows for fewer change orders and overruns
- Enhances design quality
- Improves constructability

Phase 1: Stabilize the Structure

CM/GC

- Reduce Risk:
  - Add capacity
  - low impact operations (drilling not bolt removal)
  - No attempt to straighten the tie

Day 6
Phase 1: Fabrication

Fabrication
- DAY 6 - Design Finalized 5/18
- DAY 8 - Shop drawings created and approved 5/20
- DAY 10 - Fabrication began 5/21
- DAY 11 - TDOT maintenance picked up the steel 5/22

Loading of the Bridge

Tie Axial Influence Line @ Fracture
- Contractor requested options for construction from the deck of the bridge rather than from a barge on the river
- Loading in Span 1 results in minimum axial load
- Loading in Span 1 near Pier B results in some beneficial compression
- No loads in Span 2

Phase 1: Work Platform

Kiewit Infrastructure installed a specially designed work platform and chain hoists instead of barges from the river. This was a lower risk and less impact option.
**Phase 1: Stabilize the Structure**

**Construction**
- Trucks come from west end of the bridge
- Use chain fall to move plates on Span 2 and into place
- No work barges or river access was used during the duration of the project

---

**Phase 1: Plate Installation**

- Kiewit Infrastructure began installing the plates Saturday, May 22th.
- Phase 1 plate installation was completed on Tuesday, May 25th.
- Completing Phase 1 allowed for starting the Phase 3 inspection work

---

**Phase 1: Stabilize the Structure**

**Construction**
- Outboard plate placed w/ 3" of fill plates
- Eliminate any interference or straightening of the tie.
- Inboard plate required hole cut into the floorbeam web.
- Anchored beyond the girder twist as measured in the field
Phase 1: Stabilize the Structure

- Eccentric connections highly loaded would try to crush box
- Thin cover plates attached with poor welds
- External frame added to account for moment developed by eccentricity

Phase 3: Inspect & U/T all welds

- 484 tie girder weld locations + statistical sample of welds on high truss.
- Phased Array and single beam UT were used – required paint removal.
- More details later

Modeling and Analysis

Assessing the Structural Stability
Model Development

Analysis Team

- MIDAS
- LARSA 4D
- Other

Global Modeling
- 3D Model
  - MIDAS Civil

Local Modeling
- Shell Element of the fracture area

Other
- QC team
- Pier model
- 2003 seismic retrofit design

Global Modeling
- 3D Model

Local Modeling
- Modeled T22 and T23 upstream tie with shell elements
- Connected using rigid links
- Capacity and stability assessment of the current condition – needed for Phase 1 repair activities

Fine mesh in fracture region

Detailed modeling region connected to tie beam elements with rigid links at panel points
Model Development

Local Model – Material Nonlinear Analysis

- 1” square mesh in fracture region – fracture modeled with 1” gap
- Compromise between analysis speed and accuracy
- Elastic-perfectly plastic material model
- Von Mises initial uniaxial yield stress of 100 ksi
- Load incremented in steps of 0.05 up to 1.25 times the service dead load

Model Development

Local Model Results

- Remaining bottom flange was fully yielded through the plate due to dead load

Model Development

Local Model Results

- Inboard web was fully yielded on the inner face of the plate under dead load
Local Model Results

- Inboard web had not reached yield on the outer face of the plate under dead load – web did not entirely yield
- Provided resistance to live load after fracture prior to bridge closure
- Resistance during Phase 1 repairs

Actual Deflected Shape Versus Model

Actual Deflected Shape Versus Model

Actual Deflected Shape Versus Model
Model Development

QC Process
- Checklists used for efficient verification of Midas Civil model
- Each updated version of the model was checked again

LARSA 4D FEA Model
- Independent model with independent team
- Comparable results

Where did the Load go?
- Alternate Load Paths?
  - Sensitivity Analysis
  - Stiffness of the structure
  - Field Observations

Analysis Summary

Phase 1
- Safe Load evaluation
- Stabilizing plate analysis
- Construction support

Phase 2
- PT analysis
- PT cookbook
- Additional construction support

Phase 3
- Moving load analysis

Post Phase 3
- Load Rating
- Redundancy Analysis
Questions?

10 Minute Break

Phase 2 Repairs
Long term remediation of the fractured section
Phase 2 Repair Design

Initial Calc 8:44 PM on 5/11

Design Philosophy
• Preserve capacity of original tie
• How much post-tensioning?
• How much of the gap do we need to close?
• Effects on Secondary Members?
• How effective will the Post-Tensioning actually be?

Multiple concepts considered
• Ultimately, load path to the tie girder dictated design

Tie Girder Complete Replacement

• Initial direction: completely remove the old/fractured tie
• End Result: Cut out Fracture and Plate back to connections

Post-Tensioning System Design

P/T System
• 8 - Cold-rolled 150 ksi 3" diameter PT bars
• Allowance for fitment/eccentric loads
• Staged PT
• Monitoring Plan including direct force measurement
Post-Tensioning System Design

Anchorage
- Designed to remain elastic
- Self-Reacting – Don’t crush the box
- Constructability Coordination
- Fabrication Coordination
- Cheese PL, with Double nut bolts

Sequence
- Install anchorage (walers, struts etc)
- Install Bars
- Disconnect/Remove Lateral bracing
- Post-Tension
- Remove Phase I Plating
- Install Phase II Plating

3D Model

- Detailed Model used to find conflicts

Post-Tensioning System Design
Phase 2 - Plating Design

Original ASD Design:
\[ f_{w,\text{allowable}} = 0.45 f_y \]
\[ f = 0.9 \text{DL} + (\text{LL}+\text{IM}) + \text{Wind} \]

Retrofit Design LRFD: Gross and net sections checks

Phase 2 – Design Philosophy

- Target design resistance
  - Existing Tie STR (Pex = 10396 kips)
  - Fracture Net Section AS/NZS controls
  - \( A_g = A_n \)
  - Yield: \( 0.9 \times 100ksi = 90ksi \)
  - Fracture: \( 0.8 \times 115ksi = 92ksi \)

- Any reduction in x-sect area → Proposed Capacity < Existing Capacity

- Design strategy (Do no harm)
  - Use of Existing Holes
  - Splices at Tie Joints

Phase 2 – Critical Design Assumptions

- Proposed Tie Capacity
  - Inboard Existing Web PL 1 3/8” [A514]
  - 2 Proposed Web PL (GR70)

- Plating installed under PT loading
  - Repair effective for
    - DL = PT load
    - LL
    - Future Loading
  - \( 32” \) high x 2.25” thk

- Passes Yield on Gross and Net Section, so far so good...
Phase 2 – Connection Design

- Check bolt shear on side w/web intact
  - Utilize Existing Holes
  - Avoid Conflicts (Less 8 Bolts)
  - Single Shear
  - 0.76 Fill Plate Reduction Factor
- # Bolts Available Insufficient
  - Need 7 more EF
  - Added 2 columns of 6

Phase 2 – Connection Design

- Net Section Capacity w/8 holes @ Joint = 3366 k
- Net Section Capacity w/6 holes elsewhere = 3749 k

**We can’t fully develop strengthening plate for composite tie due to limited capacity @ Joint**

Therefore, increase plate thickness to 2.5”
Why was FEA NX used?

- Non-linear geometry
  - Need to include large deformation theory to capture buckling – PT force applied to an asymmetric cross-section
- Non-linear material
  - Need to include metal plasticity with hardening to capture yielding
- Incremental analysis
  - Need to include construction/retrofit sequence

Unloading effects on Tie

Model Summary: Geometry

- Geometry originally developed in Midas Civil then imported in FEA NX
- Geometry comprised:
  - Tie segment between L24 and T20
  - Including internal stiffening plates
  - Diag. bracing @ T22 incl. conn. plates
  - Plating installed during fracture retrofit
- Boundary conditions:
  - Fixed @ L24
  - Translational constraints to model effect of floorbeams and brace framing
Model Summary: Mesh

- All elements are:
  - Shells used to model plates
  - Elastic links to model bolts
    - Linear elastic with stiffness representative of bolt shear stiffness
- Mesh size based on 8 elements across tie height and width
- Mesh aspect ratio less than 5
- Detailed mesh around fracture:
  - 1" x 1" elements
  - Collapsed mesh around crack tips

Effect of Retrofit Operations

- Incorporate different alternatives considered in retrofitting
  - Removing gusset plates connections
  - Cutting diagonals, etc.
- Main use was to estimate local effect of unbalanced PT forces
  - Effects are negligible

Final Retrofit Sequence Modeling
Phase 2: PT Weldment Fabrication

- Each weldment is 8 foot tall and 20,000 pounds
- Fabricated by G&G Steel in Russellville, Alabama
- Weldments were delivered to the job site June 11th

Cheese Plate & Double Nut

Day 32

Post Tensioning Anchorage
Phase 2: PT System

Day 39

- PT jacks and hydraulics pumps were delivered and installed

Day 42

Stressing

PT Stressing began Sunday, June 20th and was completed June 22nd.

PT Monitoring

Strain Gauges

Dyna Force Sensors
“Drag” Force

Force in the Tie outside the limits of the PT

Actual Drag Force vs Compression in Tie

As-Built Conditions

- Plate stresses fractured section:
  - Post Fracture: 100 ksi
  - After PT: 75 ksi
  - Current: 80 ksi
- New plates ALONE installed can handle full LRFD Design loading
- Conclusion: There is a large reserve capacity in these members
- Crack tip brought together and removed
- Geometry partially restored
Removing the Fracture  Day 43

Phase 2: Final plating fabrication

- Plating fabrication by W&W / AFCO in Little Rock, Arkansas
- 70 ksi material with A325 bolts
- Partial submittals / approvals for speed of fabrication
- Last Plate installed and torqued on Saturday, July 2nd

Squaring of the Box

Day 43

Day 51
Phase 2 Summary

Day 51

• Phase 2: Final plating fabrication and installation complete

Phase 2 - PT Unloading

Day 52

• PT work by DSI completed on July 2nd
• PT bridge monitoring by WJE

Phase 2 Completion

• Final Painting
• Phase 2 Complete
Questions?

10 Minute Break

IT'S INTERMISSION TIME!
Visit Our Snack Bar!!

Phase 3 Repairs
Inspection, Testing, and Repair for long-term reliability
Phase 3 – Inspection

Day 15 - Day 59

- Full Penetration Butt Weld detail typical throughout structure
  - Potential for similar defects
  - Prevent future failure
- Arch Tie Members and Hanger Pins (Approx. 500 welds)
  - HNTB contracted CAN-USA
  - June 1st to June 23rd
- Arch Truss Members (Sampling)
  - MBI contracted Fickett
  - June 7th to June 11th and June 23rd to 25th

Phase 3 – Inspection Methods

- Visual
- Eddy Current (EC)
  - Near Surface Defects for MP Verification
  - Exact Location of Butt Welds for PAUT
- Magnetic Particle (MP)
  - After EC, prior to Paint Removal for PAUT
  - Utilized to verify EC indication findings
- Phase Array Ultrasonic Testing (PAUT)
  - Paint Removal
  - Embedded Indications

Phase 3 – PAUT Recalibration

- WJE Examination of Fracture
  - Verify CAN-USA system setup sensitivity as QA/QC measure
  - Utilize confirmed defects from extracted fractured section for PAUT data reinterpretation
  - Not much data available for ASTM A514 Steel
- WJE concluded CAN-USA original setup accurate for data collection
- CAN-USA identified additional 17 rejectable welds for a grand total of 46
Phase 3 – Repair Summary

Phase 3 – Design Philosophy

- Target design resistance debate continues
  - Recurring Yield on Gross vs. Fracture on Net Section
  - What is “good enough”?
  - Feasibility/Economics of existing capacity
- EXT-I (50% LL) & STR-I Load Combo
- Effective only for future loading or after additional fracture
- Standardization for Present & Future

Phase 3 – Design Aspects

- Plate Chamfer
  - “Incremental Loading” – 8 bolt holes max
  - All splice ends with holes into thin web
  - Req’d for double plating but utilized for single plating in case of future plating
Phase 3 – Constructability Aspects

- Contractor Input on Constructability
  - Even Joint – 4 bolts to remain
  - Odd Joint – Floorbeam/Tie Connection

Phase 3 – Design/Constr. Aspects

- Dogbone detail for potential crack arrest

Phase 3 – Repair Types (Typical Odd)

- Plating with "Dogbone" (17 locations)
- Core & Plate (8 locations)
- Grinding (21 locations)
Fracture Analysis

Figure 1. Sample under white light showing MT filings at crack locations.

Figure 2. Sample under black light during wet fluorescent MT inspection with four MT indications (red circles).

Figure 10. Repair operation with the location of the repair work indicated. (Weld repair indicated with red arrow)

Figure 39. Primary preexisting crack weld profile.

Figure 40. Core Sample SA008 weld profile.
Fracture Analysis

Figures obtained from WJE Fracture Investigation Report

Primary Pre-existing Crack
Secondary Pre-existing Crack
Fracture Event #1
Fracture Event #2
Fracture Event #3

Lessons Learned

Keys to success
Lessons Learned

- Collaboration
  - Everyone with a Common Goal
- Communication
  - Internal and Externally
  - Many moving pieces and parts
- CM/GC Benefits
  - Risk Reduction
  - Improved Constructability
  - Material Procurement / Schedule
  - Contractor Risk Sensitivity

Lessons Learned

- Ensuring Quality is Critically Important!
  - Multiple Teams working simultaneously
  - Appropriate staff expertise
  - Check and Re-Check – checklists are valuable
  - No time to back track
- Be Prepared for Challenges and Setbacks
  - Don’t assume field conditions = plans
  - Always revisit your assumptions!
- Check your Ego at the door
  - Many opinions, some of them are right
  - All ideas have value
- Keep Calm

By the Numbers

- **Total Repair Cost = $9.7M**

**PHASE 1**
- 30,000 LBS of structural steel redundancy plating to stabilize the Tie Girder
- 448 Temporary bolts required to install the plates

**PHASE 2**
- 108,000 LBS of structural steel redundancy plating added to the Tie Girder
- Over 4,400 Permanent bolts used to connect the plates
- 4,484 Feet of 3” diameter high strength Post tensioning rods utilized in the repair procedure
- Over 4,000 Permanent bolts used to connect the plates
- 1,202 ft of welds inspected and tested in the 472 but welds of Tie Girders

**PHASE 3**
- 17 Welds were plated for a total of 78,000 LBS of structural steel
- Over 4,000 Permanent bolts used to connect the plates
- 1,202 ft of welds inspected and tested in the 472 but welds of Tie Girders

29 Additional weld defects ground or cored out