WRA has been instrumental in improving society's quality of life with cleaner water, improved roads, bridges and railroads, state-of-the-art buildings for federal, state, local and DOD facilities, modern and improved ship building, and marine facilities. Rich in tradition and values, WRA's focus remains the same. Privately owned and managed by technical professionals, the firm maintains a culture and commitment to delivering high-quality, innovative, cost-effective solutions to our clients. WRA strives to build mutually beneficial partnerships with our clients and our commitment extends beyond a project's completion. This philosophy is exemplified by the long-term relationships the firm has established with many government agencies and private businesses

STRUCTURAL STEEL RETROFIT FOR INFINITE FATIGUE LIFE

Interstate Delta Frames: Structural Steel Retrofit and Restoration to Essentially Infinite Fatigue Life, Part II - Structural Response under Service Loading Conditions and Rehabilitation Monitoring

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American Society of Civil Engineers (ASCE) – Richmond, Virginia
September 26, 2018

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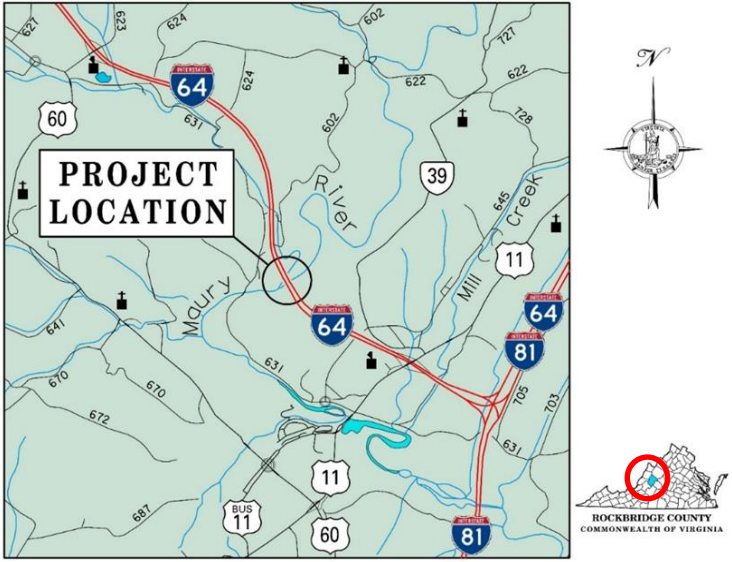
Project Location

- Rockbridge County, Commonwealth of Virginia
- I-64 (EBL & WBL) over Maury River and Kerr's Creek
- Approximately 2.7 miles west of I-81 near Lexington, Virginia



I-64 Delta Frame Bridges

General Elevation View of the Delta Frame Bridges (2017)

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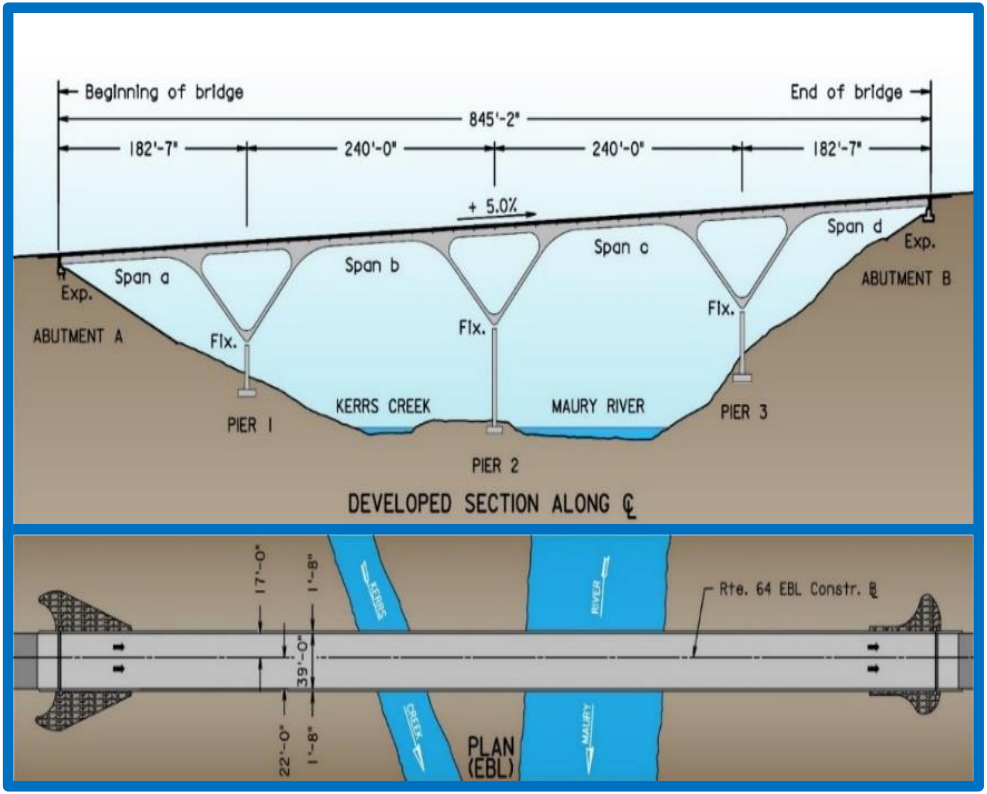
I-64 Delta Frame Bridges

Primary Supporting Elements

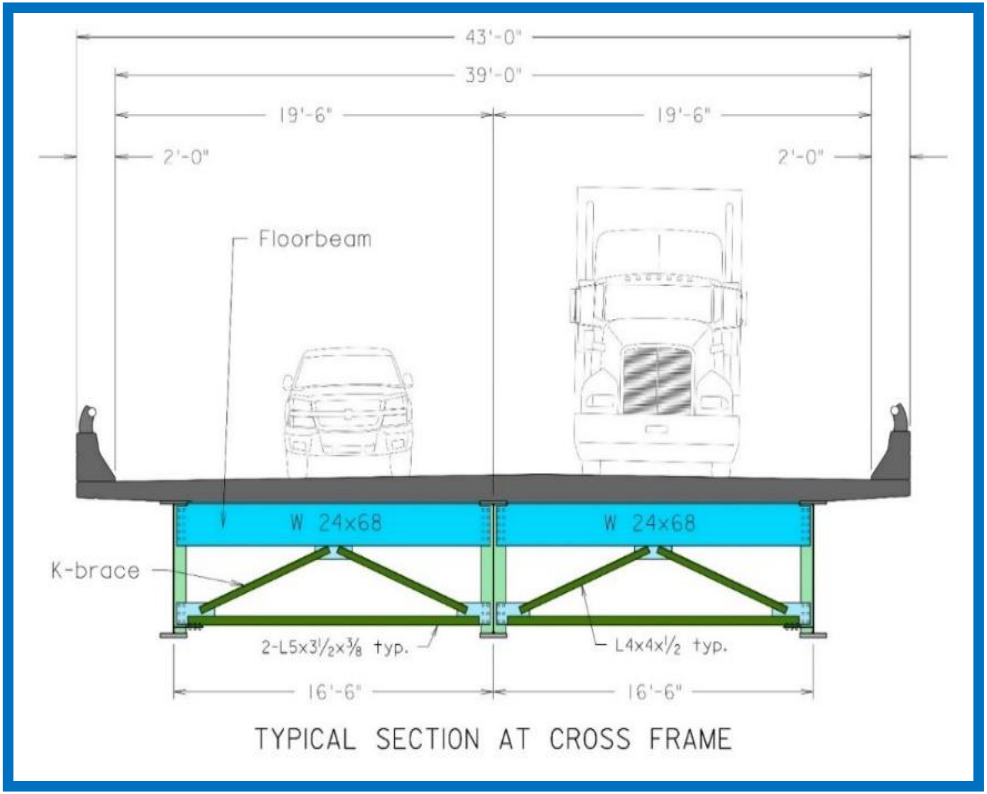
- Two structures over Maury River and Kerr's Creek
- Twin steel superstructure delta frame bridges built in 1976
- Three (3) steel delta girders spaced at 16'-6"
- Four (4) continuous spans (182'-7", 240'-0", 240'-0", 182'-7")
- Reinforced concrete deck (4000 psi) with a minimum thickness of 9 ¾"
- ASTM A36 steel girders

I-64 Delta Frame Bridges



General Plan and Elevation (EBL)

I-64 Delta Frame Bridges



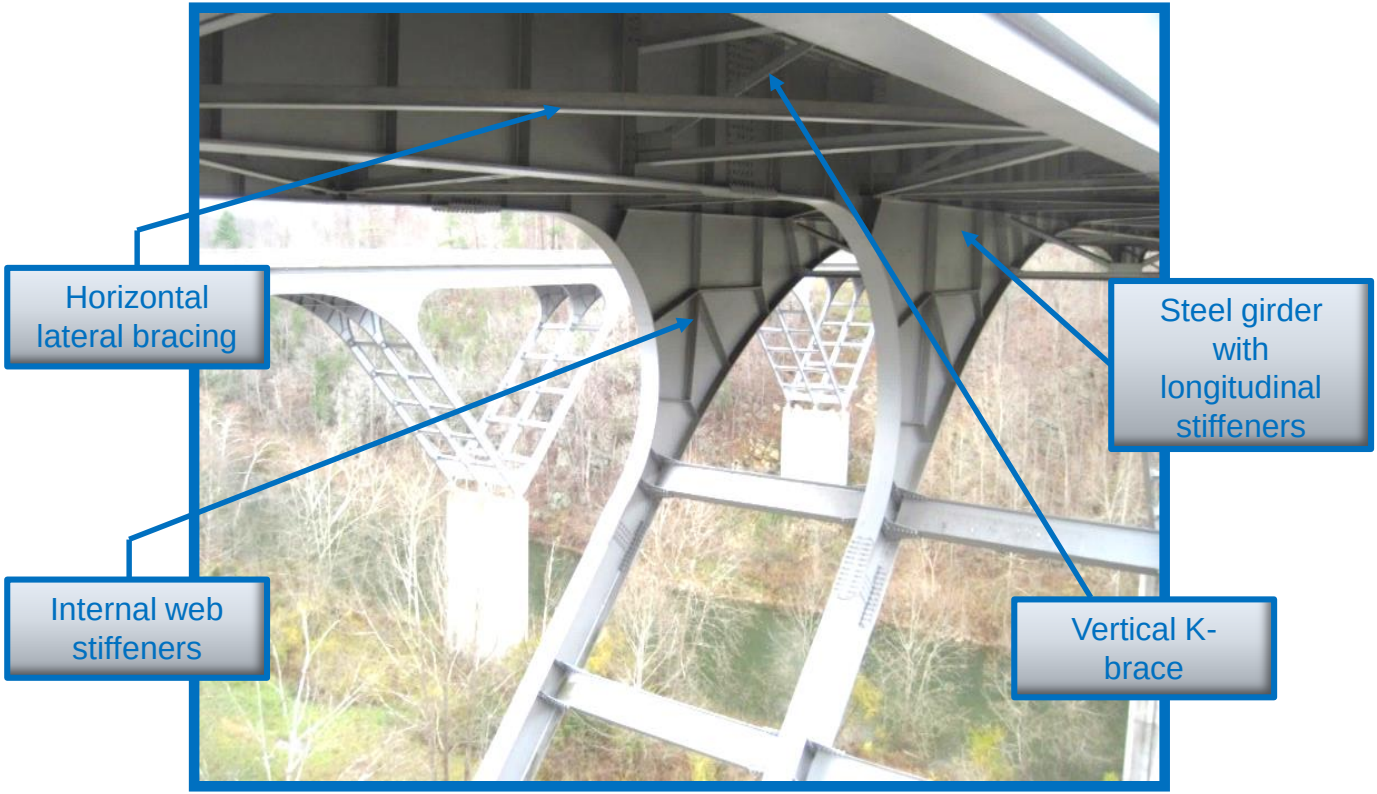
Original Typical Section at Cross-Frame

I-64 Delta Frame Bridges

Secondary Supporting Members and Stability Elements

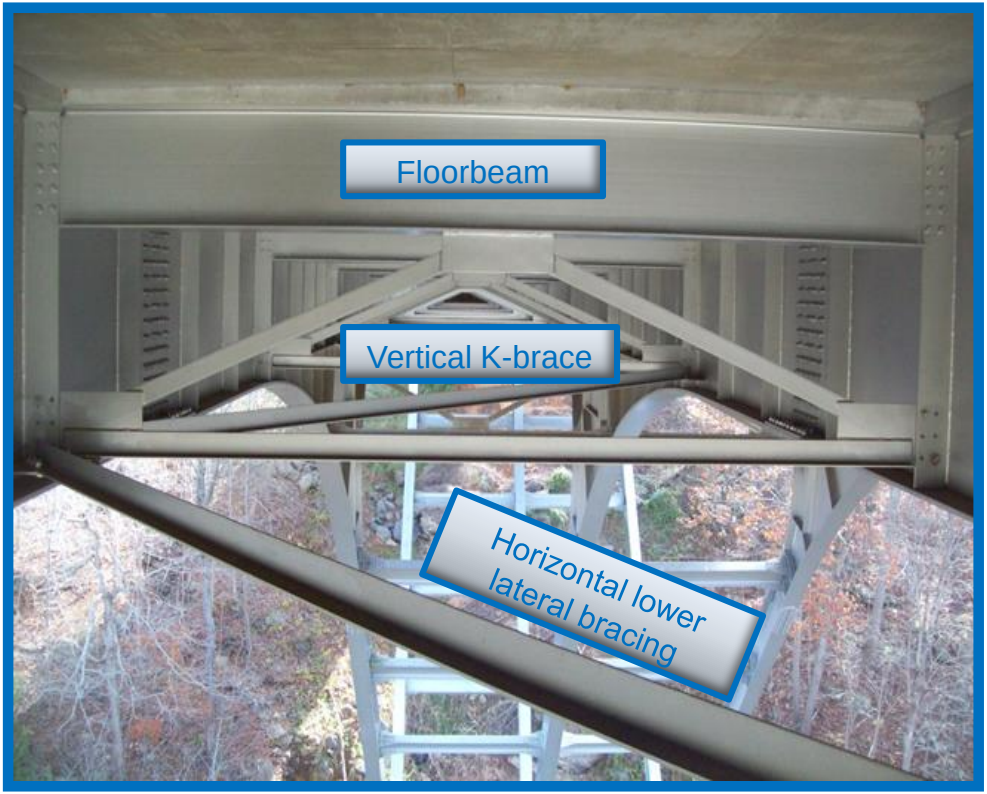
- Cross-frames consisting of floorbeam and vertical K-brace spaced at 20’-0”
- Horizontal lower lateral cross-bracing
- Lateral supporting beams at the delta legs for portal frame action
- Longitudinal and transverse stiffeners along the girders
- Multiple bearing stiffeners at base of delta frames

I-64 Delta Frame Bridges



Lateral Bracing and Web Stiffeners at the "Knuckle" Area

I-64 Delta Frame Bridges



I-64 Delta Frame Bridges

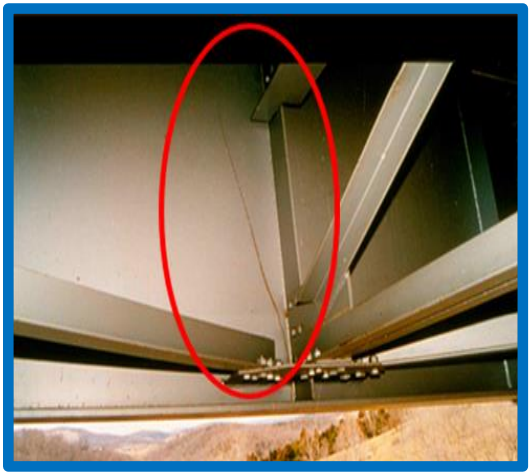
Portal Frame and Bearing Stiffeners

I-64 Delta Frame Bridges

SO WHAT WAS THE PROBLEM WITH THIS BRIDGE !!!

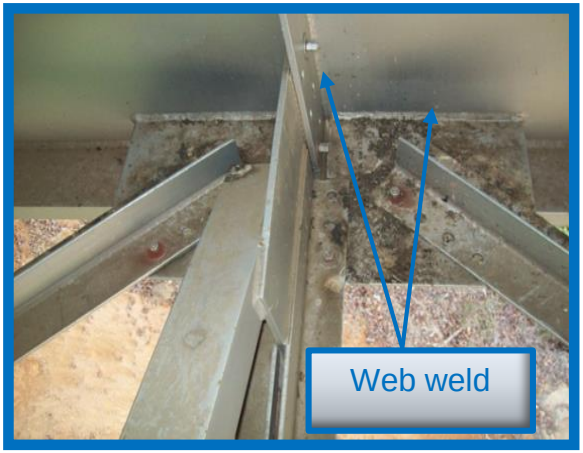
Cracks and Retrofits (1991)

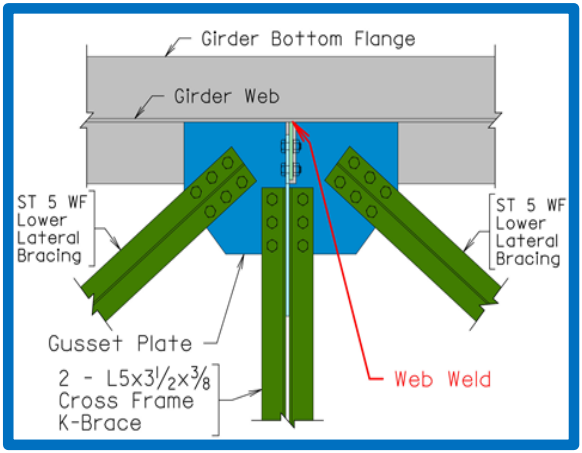
- In early 1991, a web crack was discovered in the outer girder of the EBL structure
- The crack was immediately constrained using splice bolted plates



Cracks and Retrofits (1991)

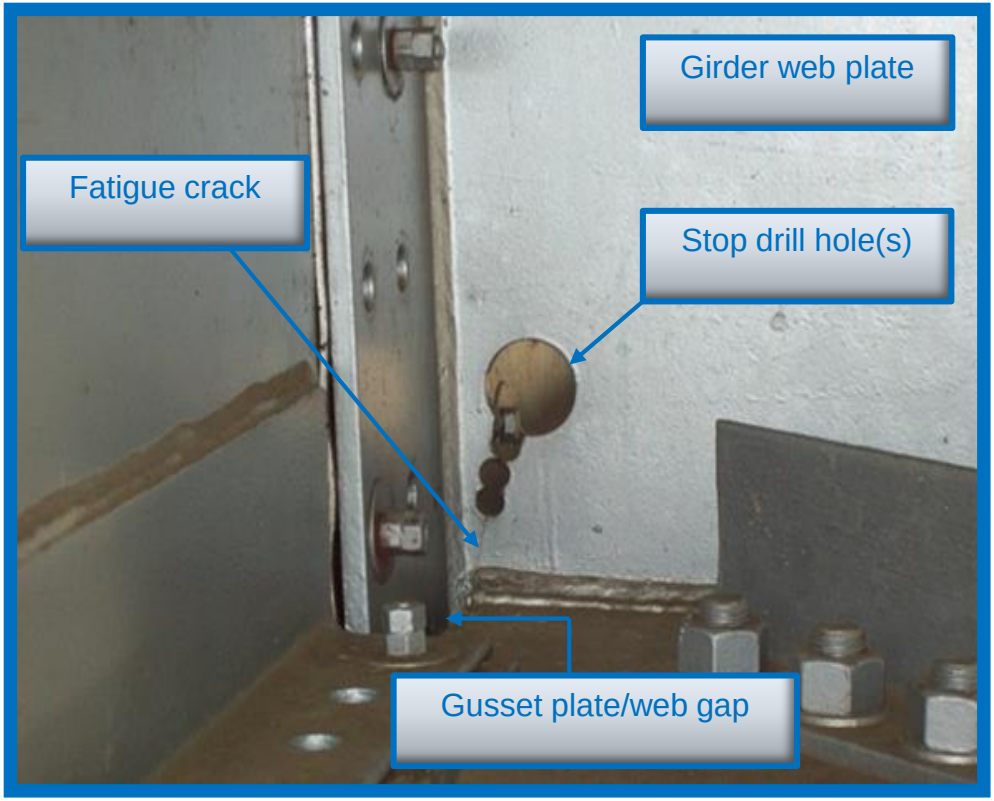
- In mid 1991, three additional cracks were found in the WBL interior girder
- Cracks were also found in the web near the weld at the gap between the vertical connector plate for the K-brace and the horizontal lower lateral bracing gusset plate





Crack at the Web Near Weld

Cracks and Retrofits (1991)



Intersecting weld gap crack path arrest

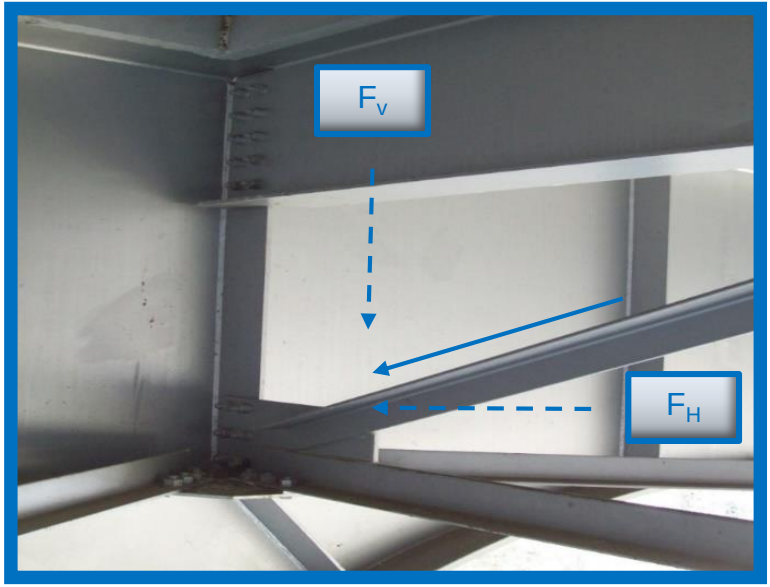
Crack in the Web Near Weld

Cracks and Retrofits (1991)

- Initially cracks were classified as ***distortion-induced fatigue cracks***

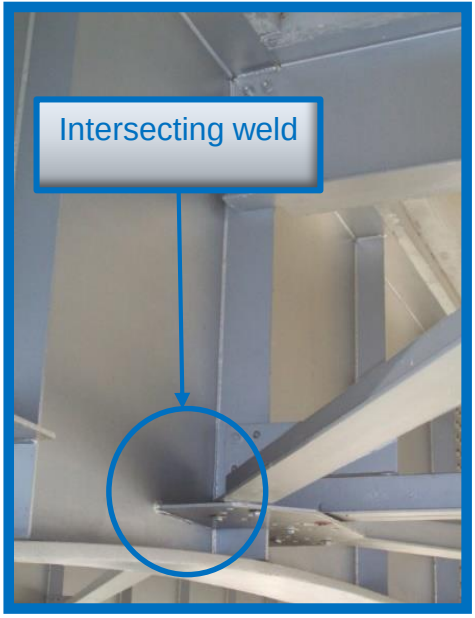
- Thought to be due to the horizontal force component (F_H) introduced by the K-brace members

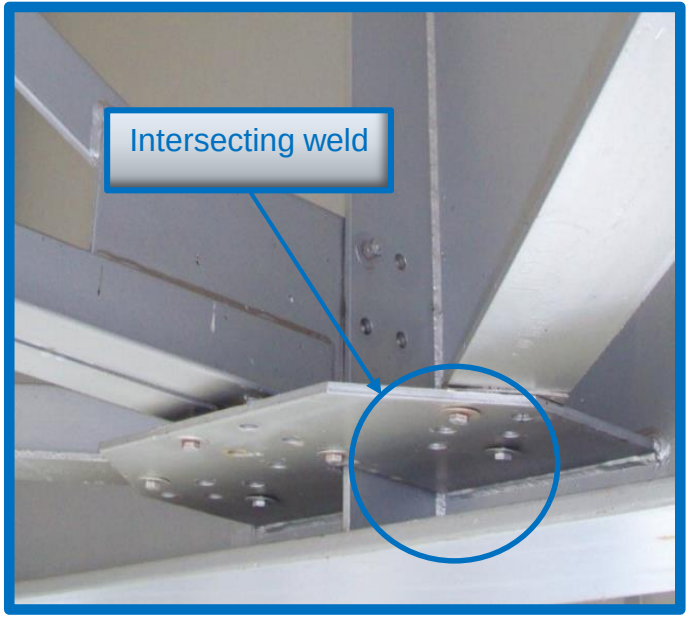
Horizontal force (F_H) of K-brace causing out-of-plan bending



Cracks and Retrofits (1991)

- Later the distortion-induced fatigue cracks were re-classified as ***constraint-induced fracture cracks*** at the close-proximity weld intersection



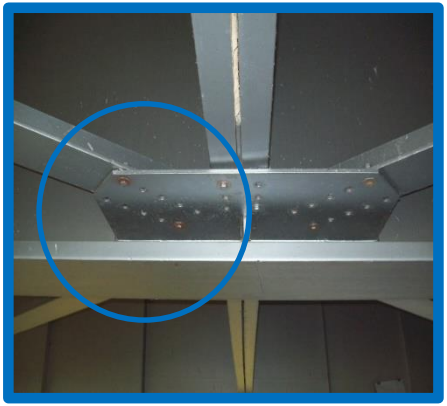


Retrofits (1994)

- Decrease restraint between the girder web connection to the K-brace and the lower lateral bracing

- Achieved by ‘disconnecting’ the lower K-brace connection and the lower lateral bracing except at **negative moment regions**

Loosely connected K-brace and lower horizontal bracing

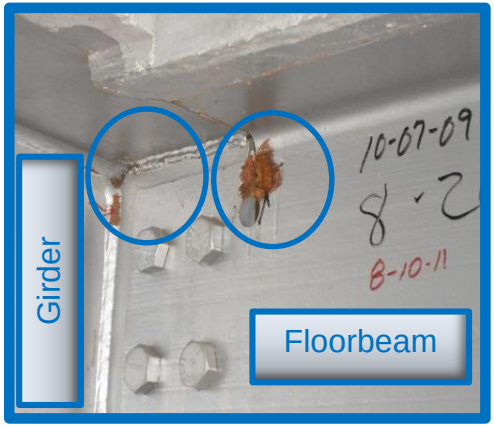


New Cycle of Fatigue Cracks (2009)

- New pattern of fatigue cracking at several locations in the EBL & WBL

- Cracks were found at the ends of the floorbeams:
  - In the girder web to floorbeam connector plate weld
  - In the upper floorbeam cope at the girder connector plate

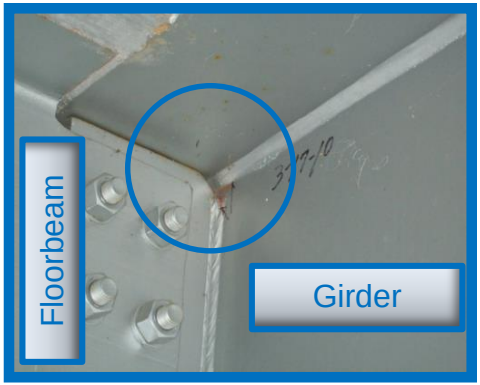
Fatigue cracks at Girder/Floorbeam connection



New Cycle of Fatigue Cracks (2009)

- Analysis performed by VTRC concluded that the cracks were caused by thermal differential between the concrete deck and the steel superstructure
- The floorbeams were non-composite while the girders were composite with the deck
- Differential thermal movement induced unresolved lateral loading at floorbeam ends resulting in formation of fatigue cracks

Fatigue cracks at Girder/Floorbeam connection



Analytical Approach

and

Fatigue Retrofit Recommendations

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Outline

- Analytical Studies and Approach
  - Purpose
  - Findings
  - Retrofit recommendations
- Retrofit Implementation Strategies
- Field Retrofit Implementations
- Retrofit at Fatigue-Prone Areas (connections)
- Health Monitoring System and Thermoelastic Stress Analysis (TSA)
- Bridge Current Status
- Conclusions

Analytical Studies and Fatigue Retrofit Recommendations

Purpose

- Retrofit existing delta frame bridges to provide a long service life
- Study the ongoing fatigue cracking
- Conduct in-depth research studies (VTRC/VDOT) to determine the actual cause of cracking and to develop safe repair/retrofit methods
- Restore the structure to essentially infinite fatigue life

Analytical Studies and Fatigue Retrofit Recommendations

Findings

- The bridges were structurally adequate and did not require replacement

- The fatigue and cracking problems were attributed to specific deficiencies in connection details

- The retrofit methods focused on the following areas:
  - The deck to floorbeam composite behavior
  - The fatigue-prone connection details between different elements of the bridge structure (K-brace, lateral bracing, etc.)

Analytical Studies and Fatigue Retrofit Recommendations

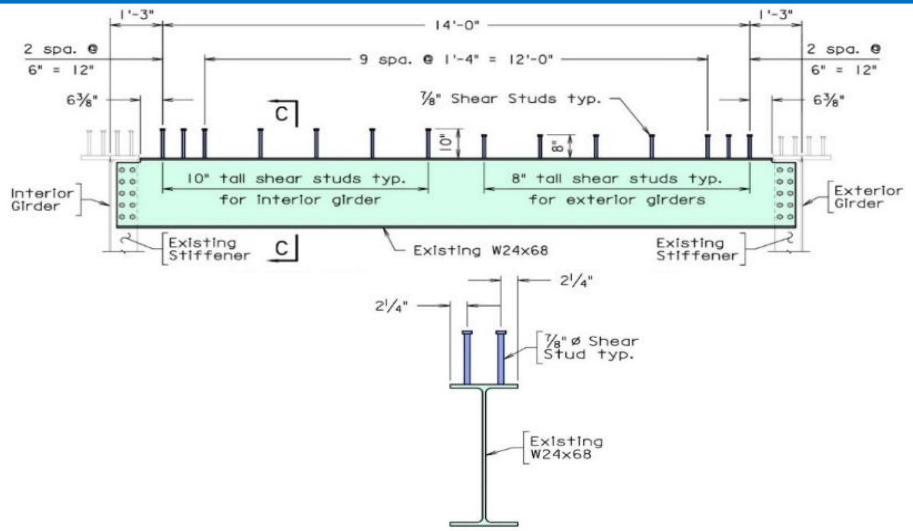
Recommendations

- Establish two-way composite behavior between the concrete deck, the longitudinal girders and the transverse floorbeams through complete deck replacement (light weight concrete)
- Remove the horizontal lower lateral bracing members in the positive moment region, while reconnecting the loose bracing members in the negative moment region
- Improve the fatigue category details of the constraint-induced fracture connections
- Retrofit the floorbeam cope cuts to increase fatigue resistance and improve fatigue detail category

Retrofit Recommendations

- Establish two-way composite behavior between the deck, girders and the floorbeams

Remove deck and install transverse shear studs along the top flange of the floorbeams for full composite action

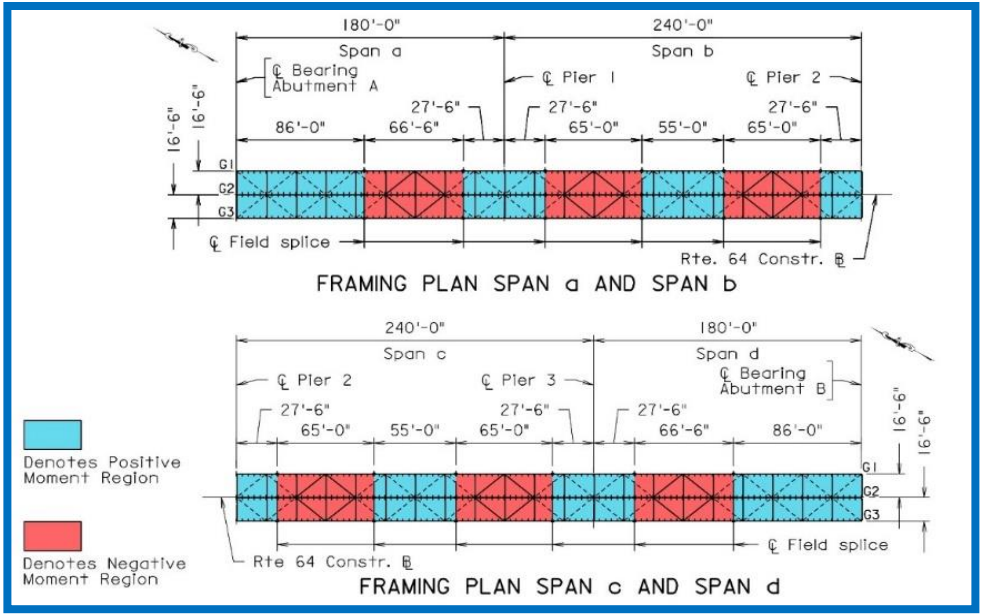


Section C-C

Retrofit Recommendations

- Remove the horizontal lower lateral bracing members in the positive moment region

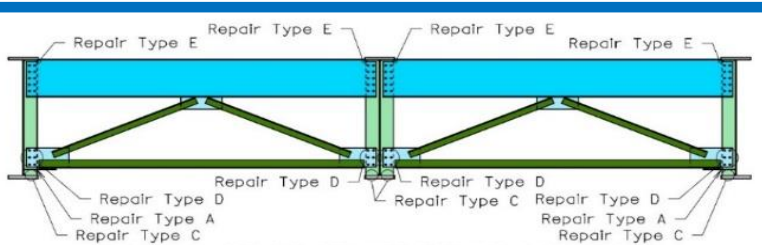
Re-connect horizontal lower lateral bracing in the negative moment region



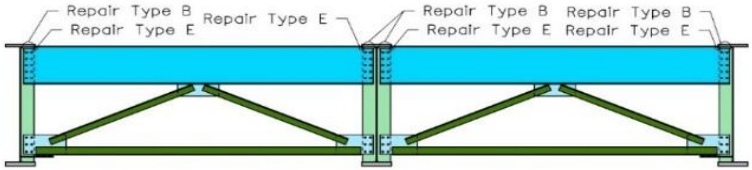
Retrofit Recommendations

- Improve the fatigue category details of the constraint-induced fracture connections in both the positive and the negative moment regions

Various fatigue-prone connection repair types (A, B, C, D, E, F) To improve fatigue performance category



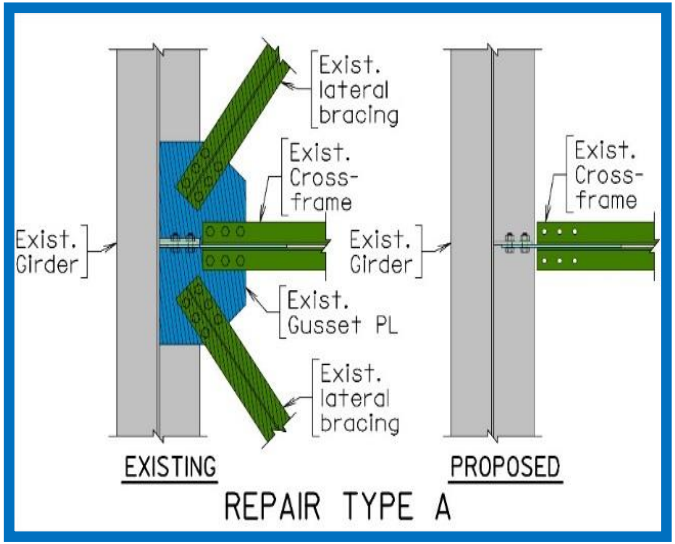
TYPICAL CROSS FRAME REPAIR LOCATIONS IN POSITIVE MOMENT REGIONS

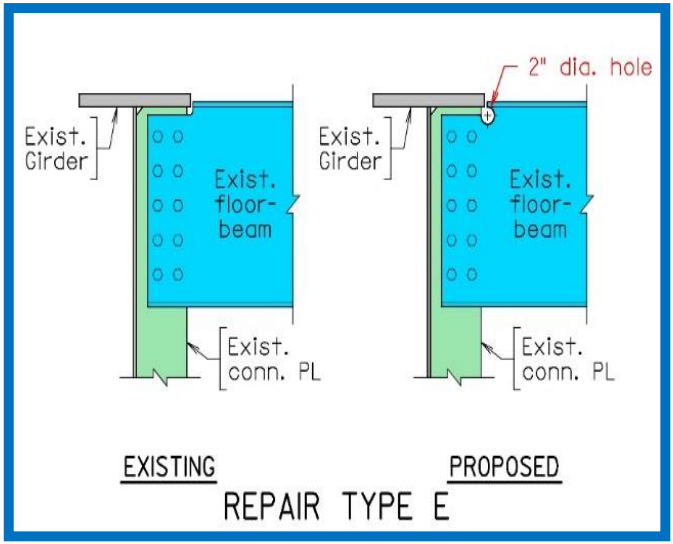


TYPICAL CROSS FRAME REPAIR LOCATIONS IN NEGATIVE MOMENT REGIONS

Retrofit Recommendations

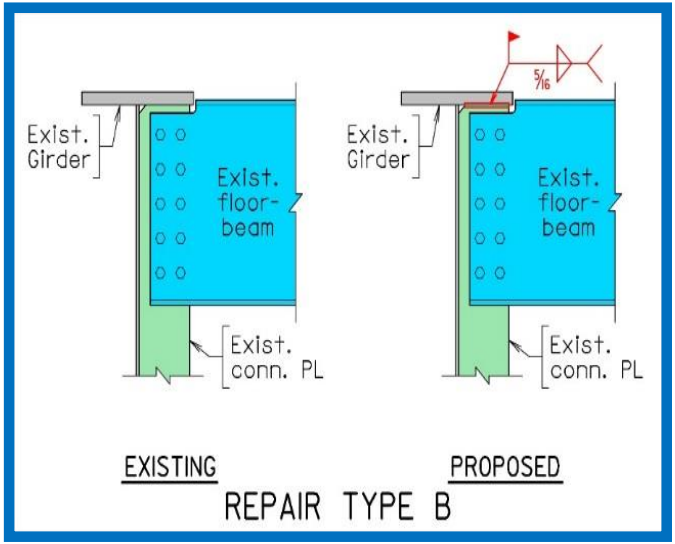
- Examples of Improved fatigue category details in ***positive moment*** region

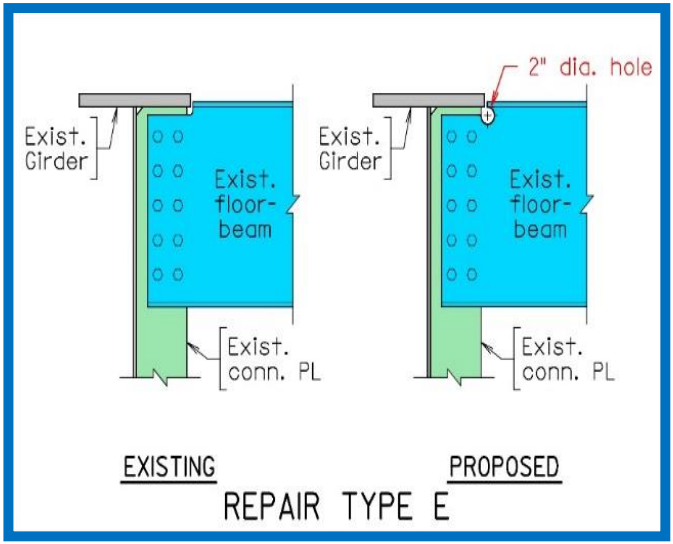




Retrofit Recommendations

- Examples of improved fatigue crack performance in ***negative moment*** region





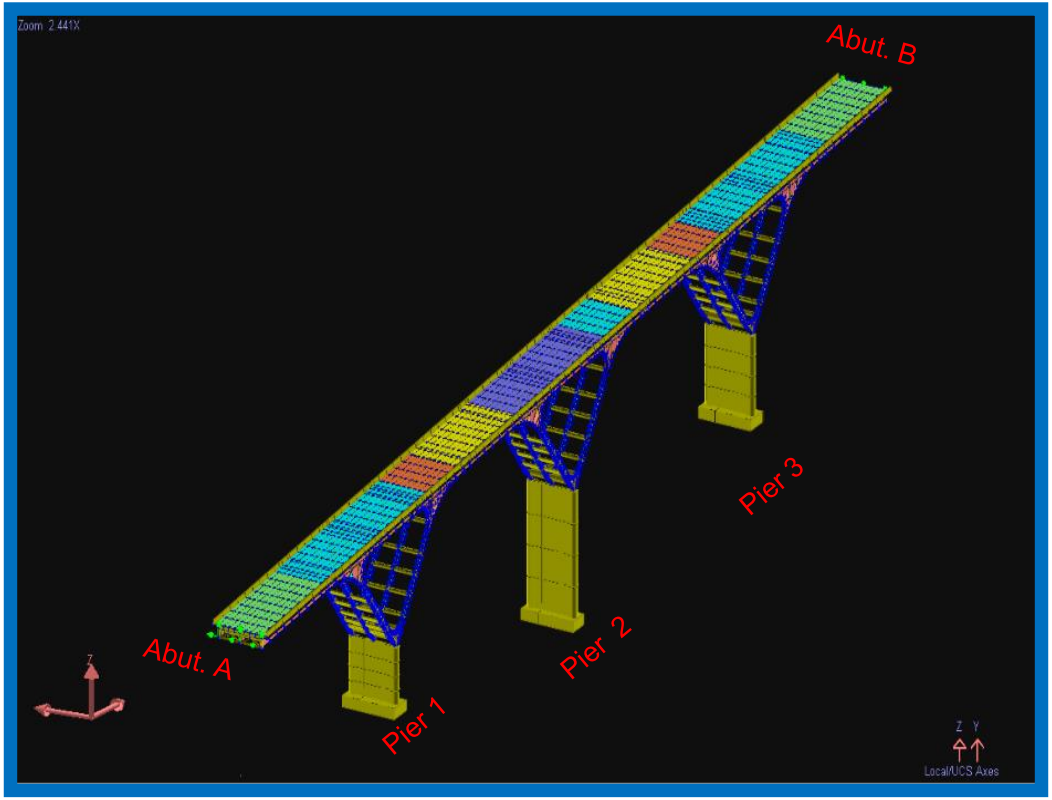
Retrofit Implementation Strategies

Tasks

- A detailed 3-D computer model was developed to model the overall structural response during the prescribed stages of retrofit construction and to ensure the structures' lateral stability
- VDOT Staunton District Bridge Section awarded contract to implement the retrofit/rehabilitation plans provided by WRA
- The bridge abutments were replaced by the Virginia Alternate Abutment configuration including bearing replacement
- A health monitoring system was installed during construction; the actual structural behavior was correlated with the results of the 3-D computer model

3-D Computer Model LARSA-4D

- Three dimensional finite element model
- As-built structure
- **Staged construction**
- **Time dependent analysis for creep and shrinkage effects**
- 7,750 joints
- 2,633 beam elements
- 6,452 plate elements



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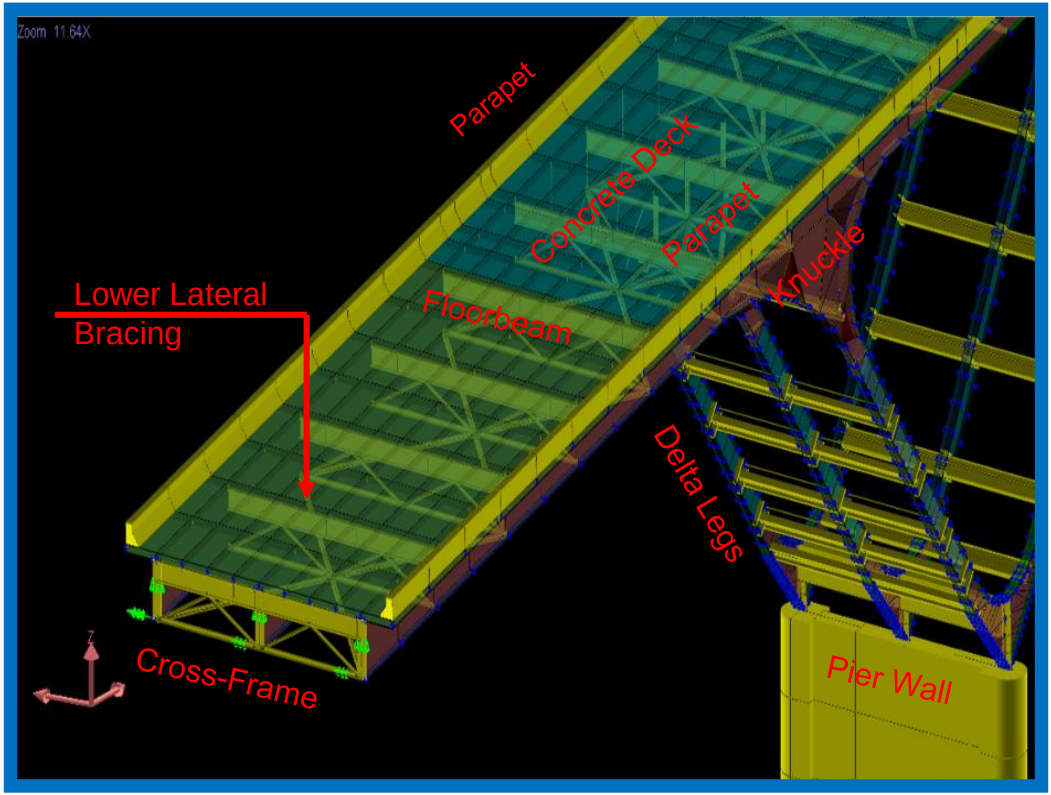
3-D Computer Model LARSA-4D

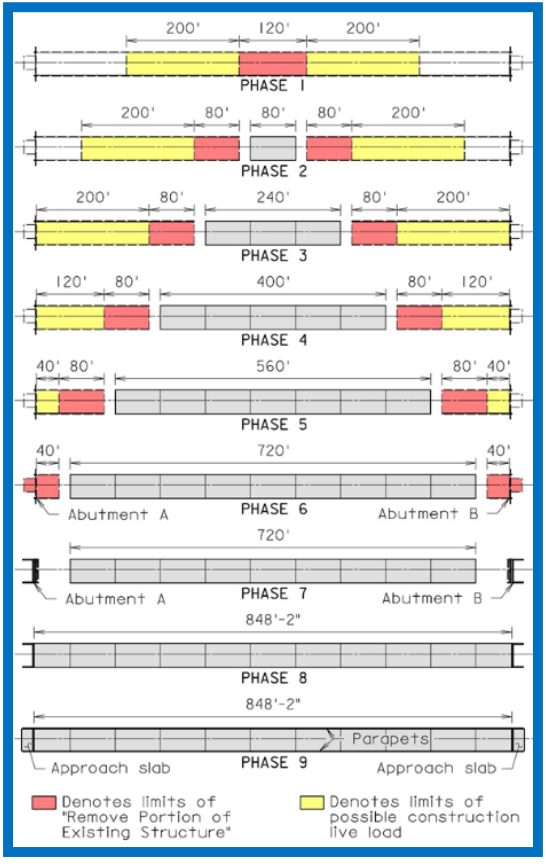
All primary structural elements were modeled:

- Delta girders
- Floorbeams
- Concrete deck
- Lateral bracings
- K-bracing
- Portal bracing



Concrete Deck Demolition and Construction Sequence

- Different deck replacement scenarios were considered
- The scenario that resulted in the lowest stress conditions was chosen
- **Maintained reasonable construction schedule**



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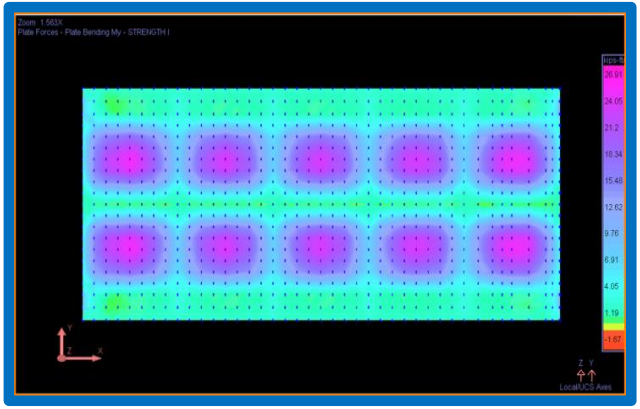
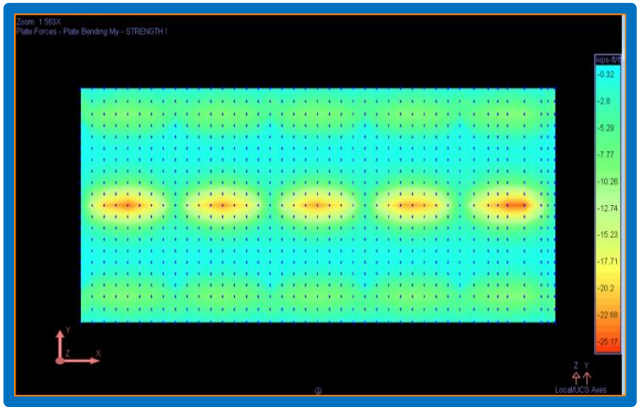
Replacement Deck Two-Way Bending Behavior



Distribution of Positive Moments



Distribution of Negative Moments

Field Retrofit Implementation

- Replaced concrete deck using light weight concrete in stages
- Installed shear studs on top of floorbeams to establish two-way composite action
- Implemented the recommended retrofit at both positive and negative moment regions
- Improved connection fatigue categories
- Replaced existing bearings at abutment
- Modified existing abutment to construct Virginia Alternate Abutment, eliminating joints

Field Retrofit Implementation

Phase (2) Construction Sequence - Deck Removal (EBL)

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Field Retrofit Implementation

Phase (2) Construction Sequence - Deck Replacement (EBL)

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Field Retrofit Implementation

Looking along Floorbeam Showing New Studs

Floorbeams Prior to Installation of Shear Studs

Retrofit at Fatigue-Prone Areas

- Repair Type A
- **Positive moment region**
- Removal of horizontal bracing and gusset plate
- Improved fatigue detail to Category (C)

Before

After

Retrofit at Fatigue-Prone Areas

- Repair Type D
- **Positive moment region**
- Reconnected loose vertical K-brace
- Welded bottom flange girder to connector plates

Before

After

Retrofit at Fatigue-Prone Areas

- Repair Type E
- **Positive moment region**
- Improved coping detail at floorbeam/girder connection by grinding the cope smooth
- Drilled 2”-diameter hole to prevent crack propagation

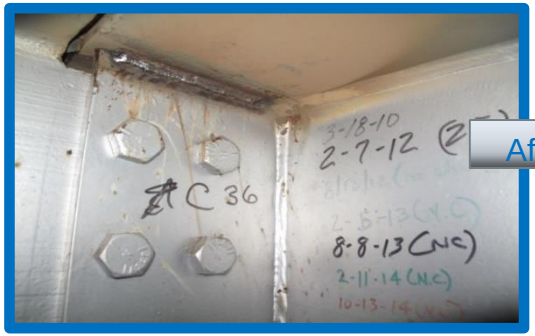
Before

After

Retrofit at Fatigue-Prone Areas

- Repair Type B
- **Negative moment region**
- Increased stiffness of connectivity between floorbeams and girders
- Installed 5/16” weld on both sides of connector plates

Before



After

Retrofit at Fatigue-Prone Areas

- Repair Type F
- Retrofitted general diagonal crack floorbeam coping
- Terminated crack propagation at the tip with 2”-diameter drill
- Installed bolted splice plate to restore element strength capacity

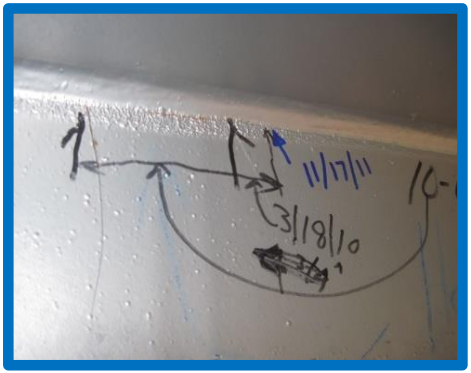
Before

After

Retrofit at Fatigue-Prone Areas

General existing fatigue cracks

Before



Before

Retrofit at Fatigue-Prone Areas

- Repair Type G
- Installed stop drill hole to terminate general existing fatigue cracks
- Applied along web/flange weld or within girders' web
- Introduced to cracks and prevent future propagation

Structural Health Monitoring System

- Due to the sensitivity of the structures' response to loadings and to ensure stability during construction, several instrumental systems were installed by VTRC.

- The monitoring systems included:
  - Visual monitoring
  - Thermoelastic Stress Analysis (TSA) monitoring
  - Strain monitoring
  - Movement detection monitoring

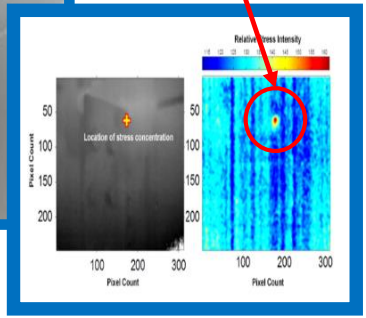
Visual Monitoring

- Provided streamline video monitoring of all construction activities
- Snapshots were taken **every hour** for specific construction activities
- Photos of the overall bridge site were taken **every four hours**

Thermoelastic Stress Analysis (TSA) Monitoring

- Measured small surface temperature changes associated with localized stresses at fatigue prone connections
- Temperature change is directly related to change in sum of the principal stresses under live load

Documented high level stress at fatigue-prone connection due to instantaneous live load application (before retrofit)



Virginia Alternate Abutment

- Provides a Deck-Extension, Twin-Backwall Abutment Detail that delivers a truly jointless bridge solution
- Reference Civil Engineering Magazine June 2018 Issue – the Virginia Difference – for further Detail

2018 Bridge Structural Response and Retrofit Performance

- All retrofit recommendations have been implemented and completed for the EBL & WBL structures
- The concrete decks of the EBL and WBL structures have been replaced
- Both EBL and WBL structures are currently open to traffic
- The 3-D computer model predicted bridge behavior close to that reported by the health monitoring system
- The Thermoelastic Stress Analysis (TSA) system monitored the fatigue stresses developed in the retrofitted connection at the EBL structure and reported substantial reduction of developed stresses

2018 Bridge Structural Response and Retrofit Performance

- Both structures (EBL & WBL) are now subjected to a stringent inspection program by VDOT with increased frequency to ensure successful retrofit
- Inspection reports (2017 and 2018) confirmed the original fatigue cracks were confined; no additional cracks have formed
- The superstructure General Condition Rating (GCR) has been upgraded from level (4) to level (5) and will be increased to level (6) after 4 years of inspection with no additional cracking found
- Bridge structure load rating using LFR method showed significant capacity increase resulting from this structural retro-fit

Conclusions

- All retrofit recommendations for the bridge structure rehabilitation to infinite fatigue life have been successfully implemented

- Recent bridge safety inspections confirmed adequate structural behavior with no indication of additional crack formations

- Thermoelastic Stress Analysis show significantly lower stresses at a retrofitted connection

- Retrofits and deck joint elimination have successfully extended the future service life of the structures while reducing future maintenance costs

Thank You - Questions

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