Important Information for the Assessment of Fatigue

- **Background** – What is Fatigue
- **Details** – What details should be noted during inspections or when reviewing plans
- **Criteria** – When should a Fatigue Analysis / Retrofit be performed on a bridge
- **Analysis** – What does a Fatigue Analysis Involve
- **Repair** – If a repair is warranted, what are common methods of repairing/retrofitting.
Background

What is Fatigue

- Described in IDM 412-4.03(04) – Fatigue Analysis
- “Fatigue is the tendency of a member to fail at a stress level below the elastic limit when subjected to cyclical loading” – NHI Fracture Critical Inspection Techniques for Steel Bridges
- To further simplify – Although a bridge is designed to be strong enough to support a heavy truck driving over the bridge. When millions of trucks over the life of the structure drive over the bridge, fatigue can cause a member to fail at a lower load than it was designed for.
- Fatigue can cause steel members to crack and fracture.

Fatigue is caused by the stress range experienced by the component / detail due to applied cyclic live loading combined with:

- Stress concentrations at weld toes in poorly designed details
- Internal defects and heat affected zones in welded connections
- Detail configurations that simulate a large initial pre-crack
- Out-of-plane distortion of girder web gaps due to unaccounted secondary lateral forces.
- Structural components and welded details have inherent flaws or defects, which serve as initial cracks
Background

• What is Fatigue
  • There are 3 Stages of Fatigue
    • Crack Initiation
    • Crack Propagation
    • Brittle Fracture
  • Fatigue Life is the time from the first truck loading (cycle) until brittle fracture
  • A cycle is not necessarily one cycle per truck. AASHTO LRFD T.6.6.1.2.5-2 defines “n” as the number of cycles per truck passage. It is based on span length and distance from support.

There are two types of Fatigue

• Load-Induced Fatigue is due to the in-plane stresses in the steel plates that comprise bridge member cross-sections.
  • Stresses can be calculated with line girder analysis and are accounted for in design.
Background

• There are two types of Fatigue
  • Distortion-induced Fatigue is that due to secondary stresses in the steel plates that comprise bridge member cross-sections (diaphragms or lateral bracing frames).
  • Stresses can only be calculated with very refined methods.
  • These are more readily classified as “good details” and “bad details”

Background

• What Characteristics Influence Fatigue
  • Structural Details – Over the years the design code has evolved to identify details which are more prone to fatigue. Several of these details were common practice in the past.
  • Material Properties – Research has lead to “tougher” steel which is not as brittle and less likely to fracture.
  • Temperature – Steel is more brittle in colder temperatures (not as critical with the composition of today’s structural steel).
  • Loading – A bridge that sees “more cycles” of truck loads is more susceptible to fatigue than a low volume road bridge.
Background

- Why is Fatigue Important – Cracks happen.

NOTES REPORT

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<th>Date</th>
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<th>By</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/24/2008</td>
<td>General</td>
<td>Sherwood Garrison</td>
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Comment:
Completed a Special In-Depth Inspection with the UB-40 Reach-along and with a Routine Biennial visual inspection. No condition ratings were changed to any bridge inspection elements from what was reported two years ago.

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<thead>
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<tr>
<td>11/25/2008</td>
<td>Permits</td>
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Comment:
Due to the crack that developed in the I-70 WBL Bridge over the Wabash River, that was found in May, 2008, a Restriction List of Steel Bridges with special Details that may be subject to fatigue or fractures has been developed by INDOT’s Steel Inspection Engineer and reviewed by INDOT’s District Bridge Inspection Engineers for completeness.

This bridge is one of the bridges on the Restriction List. The main details that this bridge has that caused it to be on this list are: STEEL GUSSET PLATES WELDED TO THE GIRDER WEB, WITH LATERAL BRACES ATTACHED TO THE GUSSET PLATES. This note has been added to the Bridge Inspection Report, and Bridge Item #001.04 Overload Data has been coded as = 4 = NO Over Load Vehicles Allowed, and Bridge Item #001.02 Load Restriction has been coded as = 3 = YES, Combination of slowing down and positioning the vehicle when crossing the bridge.

Background

- Why is Fatigue Important – Brittle Fracture Happens

Images of the Hoan Bridge showing the cracked span (top) and the sagging segment from a distance (bottom), courtesy of the Northwestern University, Infrastructure Technology Institute.
Details

- **BLN Bridge Evaluation**
  - The first step in any bridge Evaluation is to review the available information
    - Plans
    - Inspection Reports
    - Photographs
  - This information can give you a very good indication on whether problematic areas will be found.
  - For a bridge evaluation where Fatigue is a concern, examination of plan details is a very good first step.

- Plan details should be checked against AASHTO LRFD T.6.6.1.2.3-1.
  - Not all details in AASHTO are bad, typically focus on details D, E & E'. However, a E’ detail in a well designed bridge can be less likely to crack than a B detail in a poorly designed bridge. It is all about location.
Details

- **Common Details**
  - Welded Cover Plate Narrower than Flange
  - E or E' Detail based on Flange Thickness
  - Load Induced Fatigue

- **Common Details**
  - Welded Cover Plate Wider than Flange
  - E' Detail
  - Load Induced Fatigue
Details

- Common Details
  - Intermittent Diaphragm Welds
  - C' for weld of diaphragm web
  - E or E' for weld of diaphragm flange
  - Load Induced Fatigue

- Common Details
  - Tri-axial Constraint
  - Distortion Induced Fatigue
Criteria

When is an Analysis/Retrofit Required?

- Illinois Policy – Memo 96.7 (12/1/1996)
- Existing Welded Coverplate Retrofitting Policy

Retrofit Required:
- Known Fatigue Cracks found
- Bridge subject to unusually heavy loads (quarry loads, landfills, etc.)
- Significant number of permit loads

Retrofit should be considered:
- ADTT > 1500 trucks
- Mean Fatigue Life < 50 years
- If one location is retrofitted, all locations should be retrofitted
- Bridges not meeting the above do not require fatigue evaluation
Criteria

- When is an Analysis/Retrofit Required?
  - Indiana Policy – Rehabilitation Chapter
  - Analysis should be used where cracks found by visual inspection are believed to be either caused by fatigue or are progression-prone under transient loading.
  - Analysis should be used if members are known to have a low fatigue life.

Analysis

- What Does a Fatigue Analysis Involve?
  - Fatigue Analysis performed in accordance with the AASHTO Manual for Bridge Evaluation Chapter 7
  - Performed on Load Induced Fatigue Details Only
  - Not used for Distortion Induced Fatigue
Analysis

• What Does a Fatigue Analysis Involve?
  • Identify the Load Induced Fatigue-Prone Details
  • Identify if deck is composite with steel beams (composite decks dampen vibrations)

• What Does a Fatigue Analysis Involve?
  • Determine Moments from Dead Load and Fatigue Live Load
  • Fatigue Truck is 75% of an HS-20 Design Truck
What Does a Fatigue Analysis Involve?

- Using Section Properties at Each Location, determine stresses from Dead Load and factored Fatigue Load ($\Delta f$) at location of Fatigue-Prone Detail.
- Areas which are subjected to Tension are the only critical fatigue areas.

- Determine the Effective Stress Range from Fatigue Truck

$$\Delta f_{\text{eff}} = R_s \Delta f$$  \hspace{1cm} (MBE 7.2.2-1)

- $R_s$ is determined based on how rigorous of an analysis is performed. If a refined finite-element analysis is performed with actual representative truck weights, $R_s$ value is adjusted.
- $R_s$ is a partial load factor composed of two variables
  - $R_{sa} = \text{Analysis Method Partial Load Factor}$
  - $R_{st} = \text{Truck Weight Partial Load Factor}$
  - $R_s = R_{sa} * R_{st}$
- Typically a line girder analysis and a Fatigue Truck is used which results in $R_s = 1.0$
Analysis

- What Does a Fatigue Analysis Involve?
  - Two checks are performed to determine if the Remaining Fatigue Life needs to be calculated

1. Check if the detail is considered “Fatigue Prone” – Does the location of the detail see enough tension from live load to overcome any compression from dead load. This Code Check is not dependent on the type of detail (cover plate, intermittent weld, etc.), just the stresses

\[
2R_g (\Delta f)_{\text{tension}} > f_{\text{dead load compression}} \quad \text{(MBE 7.2.3-1)}
\]

2. Check if the detail has infinite life. This Code Check compares the stresses that the detail sees with what AASHTO states is the maximum allowable stress range for that detail.

\[
(\Delta f)_{\text{max}} \leq (\Delta F)_{TH} \quad \text{(MBE 7.2.4-1)}
\]

\[
2 \cdot (\Delta \sigma)_{\text{eff}} \leq (\Delta F)_{TH}
\]

\[(\Delta f)_{\text{max}} = \text{maximum stress range expected at detail}\]

\[(\Delta F)_{TH} = \text{constant-amplitude fatigue threshold given in T6.6.1.2.5-3}\]
Analysis

• What Does a Fatigue Analysis Involve?

\[(\Delta F)_{TH} = \text{constant-amplitude fatigue threshold given in T6.6.1.2.5-3}\]

<table>
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<th>Detail Category</th>
<th>Threshold (ksi)</th>
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<tr>
<td>A</td>
<td>24.0</td>
</tr>
<tr>
<td>B</td>
<td>16.0</td>
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<tr>
<td>B'</td>
<td>12.0</td>
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<td>C</td>
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<td>C'</td>
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<tr>
<td>D</td>
<td>7.0</td>
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<td>E</td>
<td>4.5</td>
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<tr>
<td>E'</td>
<td>2.6</td>
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<tr>
<td>M 164 (A 325) Bolts in Axial Tension</td>
<td>31.0</td>
</tr>
<tr>
<td>M 253 (A 490) Bolts in Axial Tension</td>
<td>38.0</td>
</tr>
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If in both checks, the fatigue load stress range exceeds the allowable value, the Remaining Fatigue Life should be determined.

Fatigue Life = \[Y = \frac{R_R \times A}{365 \times n \times (ADTT)_{SL} \times (\Delta f)_{\text{eff}}}\] (MBE 7.2.5.1-1)

\[R_R = \text{Resistance factor for evaluation, minimum or mean}\]

\[A = \text{Detail- category constant}\] (LRFD T.6.6.1.2.5-1)

\[n = \text{number of stress cycles per truck}\]

\[(ADTT)_{SL} = \text{ave. number of trucks per day in a single lane averaged over the fatigue life}\]

\[(\Delta f)_{\text{eff}} = \text{effective stress range}\]
Analysis

- What Does a Fatigue Analysis Involve?
  - Remaining Fatigue Life is calculated by subtracting the current age of the bridge from the Fatigue Life of the bridge (Y).
  - However, as seen in the Fatigue Analysis of I-70 in 2010, this calculation can be very conservative (remaining life was calculated as -40 years)
  - This can be adjusted by adjusting $R_R$
    - Minimum Life – Conservative Design Fatigue Life
      1.0 for “E” Detail
    - Evaluation Life – Conservative Evaluation Fatigue Life
      (usually this value is used)
      1.3 for “E” Detail
    - Mean Fatigue Life – Most Likely Fatigue Life
      1.6 for “E” Detail

- Lastly, as seen with the 2010 Fatigue Analysis of the I-70 Bridges, in-field instrumentation can be used to determine the actual stresses in the beams (more accurate data).
  - At a bottom cover plate termination point, the calculated stress range was 5.4 ksi, however, the measured stress range from the actual traffic measured throughout one week was 2.74 ksi which could be further reduced because of a more refined analysis ($R_a$)
  - The distribution of the forces throughout the structure and the weight of the actual traffic influences the stress
Repair and Retrofit for Fatigue and Fracture

NOT WHAT WE ARE GOING TO DISCUSS...

Common Approaches

- Most retrofit concepts relatively straightforward
- Most common
  - Grinding
  - Hole drilling
  - Connection repair
  - Reduction in stress
  - Improving detail category
  - Weld toe improvement
Before Retrofitting

- Must determine cause of cracking
- Look into published documents on retrofitting
  - FHWA Manual (2013)
  - Other references
- Many “bad” retrofits out there…
  - BE SURE IT WILL WORK
  - CONSIDER PROTOTYPES

Grinding

- Very effective method for “shallow” surface cracks and defects
- Common tools required
- Essential to remove entire crack
- Must inspect closely to ensure removal
  - Cracks will “smear”
  - Suggest using MT
- May not be effective if cracks are very deep
  - >0.5 inches…can’t get it all
  - BUT…ground radius always better than a crack
Typical Tools

Milling and Grinding Surface Defect
Need to Ensure Smooth Stress Flow

Hole Drilling

- Must capture crack tip
- Can be done with basic tools
  - Mag drill (sometimes hand drill)
  - Core barrel
  - May insert a fully pre-tensioned bolt
    - Improves fatigue life
- Should grind surface smooth if possible
- Inspect to ensure crack is captured
- Drilling a hole is always better than leaving a crack
Hole Placement

Idealized crack

Crack tip

The above demonstrates the worst possible case for hole drilling. To ensure that the crack tip has been contained, drill as follows:

Either center the hole over the crack tip

Or the best solution is to position the bit such that the outer diameter just intercepts the crack tip

Hole Drilling
Hole Drilling in Combo with Bolted Splice

Don’t be Afraid of Large Dia. Holes
(Especially for out-of-plane cracks)
Detail Improvement

- Grinding to remove weld toe on CJP
  - Increase from Cat C to B
  - May need to perform NDE to verify internal weld quality if unknown
- Replacing rivets with HS bolts
  - Increase from Cat D to B
- Bolted Splice across cover plate
  - Increase from Cat E to B
Bolting over a Cover Plate Termination

Weld Toe Improvement

- Peening
  - Air Hammer
  - Ultrasonic Impact Treatment (UIT)
    - Proprietary
- Grinding
- Weld toe remelting
  - Gas-Tungsten Arc (GTA)
  - Requires highly skilled technician
Weld Toe Improvement

Hammer Peening

Weld Toe Improvement

Air Hammer Peening
Grinding of Weld Toe

- Disk or burr grinders typically used
  - Burr grinders easier to handle
- Need to have moderate skill level
- Need to follow good procedures
  - Don't over grind
- Best to finish with a stone wheel after burr grinder
Grinding of Weld Toe

Example of Burr Grinding Weld Toe
ANY QUESTIONS?

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Dr. Robert Connor