FCM Designation and Consequences

• Fracture-Critical Member (FCM): Steel tension member/component which failure results in collapse/loss of serviceability
• FCM involves fabrication per AASHTO/AWS D1.5 Section 12
  • Fracture Control Plan = Base metal, process, consumable, inspection reqs.
  • One time expense
  • These have been successful in PREVENTING brittle fractures
• FCM involves Fracture-Critical Member Inspection (NBIS)
  • 24-month default interval, hands-on along the length of the member
  • FCM Inspection is expensive through the life of the bridge
  • These might not be effective in DISCOVERING signs of future fracture
Issues with FCM Inspection

- What do you get from FCP + NBIS? **MORE INSPECTIONS**
- Differences between bridges are not factored in
- Hands-on inspections are not uniform/reliable/homogeneous
  - Human eye looking for hairline indications

Redundancy: Are all FCMs “Critical”?

- FCM fracture is rare, collapse due to FCM fracture is most rare
- Most of the bridges the underwent FCM failures provided service
  - Exc: Silver Bridge hanger fracture led to collapse (1967)
- Most FCM failures would not have been detected by inspection
  - Exc: Lafayette St Bridge (St Paul, MN) fracture stemmed from a fatigue crack
- Fracture triggers (CIF, poor welds, brittle steel) are not allowed
- We take advantage of redundancy:
  **Assume the failure happens and check capacity in the faulted state.**
Research Projects in Steel Bridge Redundancy

- Two main types of redundancy
  - Member-level redundancy
    - Failure of a component of a structural member does not prevent serviceability of the member
  - System-level redundancy
    - Failure of a primary structural member does not prevent bridge serviceability
- TPF-5(253): Member-level Redundancy in Built-up Steel Members

TPF-5(253): Research Program

- Multiple fracture tests
  - Flexural Members
  - Axial Members
- Fatigue after fracture
  - Only flexural
- Load-transfer test
  - Truss Chord
- Dozens of FEA models to develop provisions
TPF-5(253): Fracture Tests

- Notch a component
  - Controlled location (angle/cover plate)
  - Not looking at initial fatigue life – already documented
  - Crack growth through fatigue to critical length (LEFM)
- Cool beam → ensured lower shelf behavior
  - Warmest was -60F….some as cold as -120F
  - Eliminates “but you had good steel” comment
- Apply load to induce a fracture
  - And then….nothing happened
  - Needed to drive a “wedge” into the crack!!

NCHRP 12-87A: Research Program

- Research stems from FHWA 2012 Memo: SRM vs. FCM
- Develop advanced analysis methods (FEA) applicable to inventory:
  - Old and new, two-girder bridges to tied-arch bridges
  - Benchmarked with available data from actual FCM failures:
    - Neville Island Bridge, Hoan Bridge, etc.
- Load combinations for evaluation of redundancy:
  - Take into consideration that the bridge is in the faulted state
- Performance criteria in the faulted state
- Published as NCHRP Report 883
Load Combos for Redundancy Evaluations

- Structures built to the FCP
  - Redundancy I* \((1 + DA_R)(1.05 \, DC + 1.05 \, DW + 0.85 \, LL)\)
  - Redundancy II** \(1.05 \, DC + 1.05 \, DW + 1.30 \, (LL + IM^{***})\)

- Structure not built to the FCP
  - Redundancy I* \((1 + DA_R)(1.15 \, DC + 1.25 \, DW + 1.00 \, LL)\)
  - Redundancy II** \(1.15 \, DC + 1.25 \, DW + 1.50 \, (LL + IM^{***})\)

* Applies to SRMs only  ** Applies to SRMs and IRMs  *** 15%

IRM Guide Specification: Fundamentals (I)

- Existing members and new designs (riveted or bolted)
- Flexural and axial members
- Strength criteria to assess internal redundancy
- Fatigue criteria to determine inspection interval (not FCM inspection)
- Provisions “keep you in a box” in terms of:
  - General criteria
  - Member proportions AND condition
  - Must have remaining fatigue life in “unfaulted condition”
  - Faulted condition = one component failed
IRM Guide Specification: Fundamentals (II)

• Not all members will meet provisions
• Passing member classification: Internally Redundant Member (IRM)
• Easy application based on P/A, Mc/I type calculations
  • Stress amplification
  • Or addition of secondary moments
• Determine interval for “Special Inspection of IRMs”
  • Objective to identify broken components
  • Depth of Special Inspections determined by owner
• Routine safety inspections are not changed
• **Not** intended to be used to justify leaving a broken component in place for extended period

IRM Spec: Application

• Simple analysis methodology
  • P/A, Mc/I type of calculations
  • Spreadsheet might be all needed
• Specific provisions for different member types:
  • Flexural vs. axial
  • Multi- vs. two-component
  • Numerous illustrations
• Application examples
IRM Spec: Impact on Inspection Intervals

- **Case I members:**
  - Infinite unfaulted fatigue life
  - Ia: Infinite faulted fatigue life
  - Ib: Finite faulted fatigue life
  Calculate $Y_{REM}$ in faulted state ($N_i$)

- **Case II members:**
  - Finite unfaulted fatigue life
  \[ N_f = Y_f (1.0 - N_u/Y_{uu}) \]

<table>
<thead>
<tr>
<th>Calculated Remaining Minimum Fatigue Life $N_i$ (Years)</th>
<th>Maximum Permitted Interval (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_i &lt; 20$</td>
<td>Larger of 2 years or $0.5N_i$</td>
</tr>
<tr>
<td>$N_i \geq 20$</td>
<td>10</td>
</tr>
</tbody>
</table>

*The calculated inspection interval may be rounded up to the next even year interval.

IRM Spec: The Real Major Advantage

- Inspection is targeting broken (cut, severed) components
- No need to look for hairline minuscule crack = higher detection rates
- Inspection effort on par with potential consequences

Instead of looking for this, We are looking for this
SRM Guide Specification: Fundamentals

- Existing bridges and new designs
- Applies to the majority of the inventory:
  - Girder (I-, tub-, through-), truss, tied-arch
- Strength evaluation in the faulted state (two load combinations)
- If member is SRM there is no need to perform any “special” inspection
- Provisions “keep you in a box” in terms of:
  - General criteria
  - Bridge condition
  - Must not have details known to be problematic
  - Faulted condition = one member failed

SRM Guide Specification: Application

- Analysis requires use of advanced FEA tool
  - Originally Abaqus, but other software packs are being evaluated
- Guidance for material models, meshing, analytical procedures, failure scenarios, interaction (contact) modeling, connections, etc.
  - Shear stud tensile behavior research
- Performance criteria in the faulted state tailored for FEA results
  - Ex: Effective slab width in composite section in faulted state?
- The application of the guide specification is complex but

WISCONSIN DOT GOT 20+ BRIDGES OF THE FCM INSPECTION LIST!!!
Moving Forward

• Both Guide Specifications have been approved by AASHTO SCOBS
  • Supporting documents are available too
  • WisDOT has already utilized Guide Specs
• We can design/evaluate for fracture
  • Rational decisions supported on available data and analysis
  • There are no buckling critical members!
• Approaching an integral/unified approach to fracture
  • Better allocation of bridge owner’s resources
  • Encourage good practices against fracture (HPS, built-up members, etc.)
  • Allow to focus on potential problems

Redundancy is not New

• Two-winged aircraft are acceptable as failure RISK is low
  • Consequence high
  • Likelihood low

• Modern steel bridges?
  • Likelihood low (FCP)
  • Consequence low (IRM/SRM)
S-BRITE

• Steel Bridge Research, Inspection, Training, and Engineering Center

Questions?

Thank you very much!