Proposed IRM

Specification Provisions

Robert J. Connor, PhD – Purdue University
Francisco Martin, PhD – Purdue University
Cem Korkmaz – Purdue University
Matthew H. Hebdon, PhD, PE – Virginia Tech
Research Objectives

- Determine how to assess internal redundancy of built-up members

- Can partially failed built-up members support design loads at some target reliability?

- Evaluate remaining fatigue life in faulted state
  - How long until next component fails?
  - Critical for setting future inspection interval
Experimental Testing

- Fracture resilience
Experimental Testing

- Fracture resilience

TPF 5(253)
Member-level Redundancy of Built-up Steel Girders

Purdue University

PI - Robert Connor
Graduate Research Assistant - Matt Hebdon
Poorly Proportioned Girder
Moving the Results of TPF-5(253) into Practice

- Proposed to be published as stand-alone Guide Specifications
- Applies to both existing members and new designs
- Inspection interval for “hands-on” inspections explicitly calculated
  - Specific to identify broken components
  - Other reasons may exist to perform hands-on inspection more frequently
- Not intended to be used to justify leaving a broken component in place for extended period
What is Included in the Proposed Specs?

- Strength and fatigue criteria to demonstrate member possesses adequate internal redundancy
- Provisions “keep you in a box” in terms of:
  - General criteria (Article 1)
  - Member proportions
  - Must have remaining fatigue life in “unfaulted condition”
    - Faulted condition = one component failed
- Not all members will meet provisions (this is a good thing)
- New member classification “Internally Redundant Member”
  - “IRM”
- Presently only applies to flexural members
  - Research for axial members well underway
Guide Specification Flow-Chart

Infinite Remaining Faulted Fatigue Life?

Yes

Routine: 2 yr.
Hands-on: 10 yr.

No

Routine: 2 yr.
Hands-on: Per Table 3-1 (faulted state)

IRM

FCM

Routine: 2 yr.
Hands-on: Per Table 3-2 (faulted state)

IRM

FCM

Hands-on inspection interval ≤ 2 years?

No

Did routine inspection find severe corrosion, impact damage, or fatigue cracks?

No

IRM

Yes

FCM

FCM

Yes

FCM

Did hands-on inspection find severe corrosion, impact damage, or fatigue cracks?
For these provisions to apply, the built-up flexural member shall satisfy the following requirements in the as-built, or unfaulted state:

- At least one cover-plate shall be present along the entire length of the tension flange except as follows:
  - Within a distance of 1.5d from the end of a member at an abutment of a simple or continuous span where ‘d’ is the depth of the web plate;
  - Within a distance of 1.5d at an internal support of simple span (e.g., a pier supporting a simple span) where ‘d’ is the depth of the web plate.

This region, where only flange angles are present, need not be evaluated using the provisions contained herein or alter the inspection interval calculated for the member in Article 3.
The web plate(s) shall be mechanically fastened to the tension-flange cover-plates with angles and high-strength bolts or rivets;

Welds shall not be used to fasten the web(s) to the tension flange angles or to fasten the cover-plates together or to the flange angles. Tack welds commonly found on existing members shall be deemed acceptable and not reason to disqualify the member from being evaluated by these provisions;
In new designs, the compression flange may be welded to the web, as shown in Figure C1-1. In continuous spans, regions subjected to net stress reversal shall be built-up and mechanically fastened together;

All components comprising the portion of the tension flange shall be adequately fastened together with high-strength bolts or rivets, satisfying all strength, stitch and seating requirements in effect at the time of the design;

Members shall be proportioned to meet all of the applicable strength requirements;

- Existing members to be evaluated shall possess remaining fatigue life in the unfaulted state; New members shall be designed to satisfy the Fatigue I limit state in the unfaulted state.
- Any single tension flange component, i.e., flange angle or cover-plate, shall not exceed 60% of the total tension-flange gross area;
For existing bridges, members to be evaluated shall have undergone a hands-on inspection within the past 24 months with no cracks in the components comprising the tension flange identified.

For existing bridges, members to be evaluated shall not exhibit severe corrosion, impact damage, or other forms of damage in the regions being evaluated by these provisions.

For new designs, the cover plates shall be fabricated using grades of steel meeting the CVN requirements for non-redundant members. The flange angles and web need only meet the CVN requirements for redundant members.
Live Load Model in Faulted State

- New Load Combo – “Internal Redundancy”
  - Level of live load that could be expected during the interval between when the failure occurs and the time the damage is discovered
  - Will likely change the name to facilitate implementation

- Essentially Strength I Operating from the MBE
  - Consider load combo for new members designed to these provisions….inherently higher reliability

- Proposed to utilize HL-93
  - Load all lanes but apply LL reductions factors
  - No Dynamic amplification due to fracture
    - No movement!
Load Combinations

1.1 Applied Load in Faulted State
In the faulted state, the factored moment in the member, $M_u$, shall be calculated as follows:

$$M_u = \gamma_{p1}M_{DC} + \gamma_{p2}M_{DW} + \gamma_{LL}M_{LL+IM} \quad (1.1-1)$$

where:

- $M_{DC}$ = Bending moment due to dead load of structural components and nonstructural attachments (kip-in).
- $M_{DW}$ = Bending moment due to dead load of wearing surfaces and utilities (kip-in).
- $M_{LL+IM}$ = Bending moment due to vehicular live load and dynamic load allowance (kip-in).
- $\gamma_{p1}$, $\gamma_{p2}$, $\gamma_{LL}$ = Load factors for the Internal Redundancy load combination specified in Table 1.1-1.

Table 1.1-1 - Load Factors for Internal Redundancy Load Combinations

<table>
<thead>
<tr>
<th>Load Combination</th>
<th>$\gamma_{p1}$</th>
<th>$\gamma_{p2}$</th>
<th>$\gamma_{LL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Redundancy</td>
<td>1.25</td>
<td>1.50</td>
<td>1.35</td>
</tr>
</tbody>
</table>

The applied live load shall be the HL-93 design vehicular live load specified in LRFD Design Article 3.6.1.2.1. The dynamic load allowance, IM, shall be taken as 15%, and shall not be applied to the design lane load. The design truck or design tandem shall be positioned longitudinally and transversely such that the load effects are maximized in the faulted state. When

C1.1
Equation 1.1-1 presents the basic concept associated with the addition of total moment in the girder. It can be directly applied for noncomposite sections. For composite sections, the effects of locked-in dead load moment applied to the noncomposite section must be differentiated from those applied to the composite section (i.e., live load moment applied to the composite section). How to treat composite and noncomposite sections is addressed in Article 2.

The Internal Redundancy load combination in Table 1.1-1 represents the loads that may be expected in the faulted state and that the member must withstand prior to being detected. The Internal Redundancy load factors were calibrated to the Strength I limit state at a target reliability index of 2.5 and are consistent with load factors presented in the Manual for Bridge Evaluation. This level of reliability is deemed acceptable in the faulted state and corresponds to the same reliability associated with typical Operating Rating levels.

In order to include possible dynamic amplification associated with the passage of traffic, the lower dynamic load allowance, IM, of 15% utilized in the fatigue load
Strength Checks

- Basic gross and net section checks on “faulted” section
- Non-composite and composite sections treated differently
### 2 Performance in the Faulted State

#### 2.1 Calculated Stress in the Faulted State

**2.1.1 - Noncomposite Sections**

For the purpose of determining the location of the neutral axis and section moduli of the member in the faulted state at the cross-section where the fault is presumed to occur, the severed component shall be neglected.

The factored flexural stress acting on the net and gross section of the faulted member shall be calculated. Equations 2.1-1 and 2.1-2 shall only be considered applicable to the component immediately adjacent to the failed cover-plate and shall not be considered applicable when calculating the stresses in any other components of the cross-section.

For the component immediately adjacent to the severed cover-plate, the factored flexural stress acting the net and gross section shall be computed as follows:

\[
f_{AFN} = \beta_{AF} \frac{M_{ul}}{S_{x,AFN}} \tag{2.1.1-1}
\]

\[
f_{AFG} = \beta_{AF} \frac{M_{ul}}{S_{x,AFG}} \tag{2.1.1-2}
\]

in which:

\[
\beta_{AF} = 1 + 0.2 \left(1 + \frac{N}{4}\right) \tag{2.1.1-3}
\]
2.2—Strength Criteria

Gross section yielding and net section fracture shall be checked for existing members and prevented during the design of new members using Eq. 2.2-1 and 2.2-2 to ensure that the member has sufficient strength in the faulted state.

The factored stresses in the faulted condition, calculated in accordance with Article 2.1, shall satisfy the following:

\[ f_{AFG} \leq \phi_y F_y \]  \hspace{1cm} (2.2-1)

and:

\[ f_{AFN} \leq \phi_u F_u \]  \hspace{1cm} (2.2-2)

where:

- \( F_u \) = specified minimum tensile strength of the flange component under consideration (ksi)
- \( F_y \) = specified minimum yield strength of the flange component under consideration (ksi)
- \( \phi_u \) = resistance factor for fracture on the net section of tension members (LRFD Design Article 6.5.4.2)
- \( \phi_y \) = resistance factor for yielding on the gross section of tension members (LRFD Design Article 6.5.4.2)

C2.2

Due to the presence of damage in the faulted state, the factored stresses are conservatively and intentionally limited to the elastic capacity. The amplified factored flexural stress, to account for localized stress redistribution, is limited to \( \phi_y F_y \) on the gross section and \( \phi_u F_u \) on the net section in the faulted condition.

Resistance factors of \( \phi_y \) and \( \phi_u \) are used in the evaluation of tension flanges of built-up members because the individual flange components of a flexural member have little stress gradient and act essentially as an axially loaded member.
Fatigue Checks in Faulted State

- Two Cases
  - Case I
    - Infinite life prior to failure of component
      - Case IA – Infinite life in faulted state
      - Case IB – Finite life in faulted state
  - Case II
    - Finite life prior to failure of component
    - Obviously finite life in faulted state
Future Hands-on Inspection Interval

- All Case I Members
  - Infinite life prior to component failure

- All Case II members with remaining fatigue life of 25 years or greater in faulted state

Table 3-1 – Maximum Hands-on Inspection Intervals for Case I Members

<table>
<thead>
<tr>
<th>Calculated Remaining Minimum Fatigue Life $N_f$ (Years)</th>
<th>Maximum Hands-on Inspection Interval (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_f &lt; 20$</td>
<td>Larger of 2 years or $0.5N_f^*$</td>
</tr>
<tr>
<td>$N_f \geq 20$</td>
<td>10</td>
</tr>
</tbody>
</table>

*The calculated inspection interval may be rounded up to the next even year interval.*
Future Hands-on Inspection Interval

- More conservative intervals for Case II members when less than 25 years of life remaining in faulted state
- Some life exhausted prior to failure
  - Still positive life

### Table 3-2 – Maximum Hands-on Inspection Intervals for Case II Members

<table>
<thead>
<tr>
<th>Calculated Remaining Minimum Fatigue Life $N_f$ (Years)</th>
<th>Maximum Hands-on Inspection Interval (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_f \leq 10$</td>
<td>Smaller of 2 years or $0.5N_f^*$</td>
</tr>
<tr>
<td>$10 &lt; N_f &lt; 20$</td>
<td>$0.5N_f^*$</td>
</tr>
<tr>
<td>$N_f \geq 20$</td>
<td>10</td>
</tr>
</tbody>
</table>

*The calculated inspection interval may be rounded up to the next even year interval.*
It is recognized that hands-on in-depth inspections may be desirable for other reasons, such as detecting corrosion. Thus, the Owner may wish to consider such inspections at shorter intervals than permitted herein.

Rounding to the next even year interval is acceptable since the remaining minimum fatigue life calculated corresponds to a 97.5% probability that additional cracking will not be observed even in the faulted state. For example, if the minimum fatigue life $N_f$ is calculated to be 8.8 years, $0.5N_f$ yields an inspection interval of $0.5(8.8)$ or 4.4 years for a member designated as a Case I member. Thus an additional factor of safety is applied to the fatigue life based on the 97.5% probability of survival.
Major Advantage of this Approach

- Future inspection objectives different than today
  - Need to find completely broken component, not a small crack

- Much higher Probability of Detection (POD)
  - Very low POD finding small cracks at any one of tens of thousands of rivets

- Integrated Fracture Control Plan
We miss this

We can find this
Summary

- Internal Redundancy of built-up members can be reliably quantified and exploited
  - Similar to what other industries already do!
- Easy-to-use AASHTO ready provisions for flexural members developed
  - Propose a 2018 ballot item

- First attempt at an integrated FCP
  - Inspection interval is tied to consequence of component failure, limit state of interest, & inspection capabilities
- Result is increased reliability for fatigue and fracture limit state w.r.t. inspection
What about axially loaded members?

- Trusses
- Tied Girders
Built-up Axial Members

- 2,000 kip test frame built
- Analytical and experimental evaluation of built-up truss members well underway
Axial Test #2

Outer Plates 1/2x17
Inner plate 1½ x 21
Summary 2\textsuperscript{nd} Test

- Peak load @ fracture 980 kips
- Temp = -60F (lower shelf)
- Gross area before fracture 39.125 in\textsuperscript{2}
- Gross area after fracture = 13.25 in\textsuperscript{2}
- Net section stress immediately after fracture = 74 ksi
- Static net section stress after fracture 56.6 ksi

- Fracture did not propagate to outer plates (as expected)
QUESTIONS