CALIBRATION OF THE SERVICE LIMIT STATES IN AASHTO LRFD – STEEL DESIGN
SHRP R19B

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Modjeski and Masters, Inc.
General Calibration Process

• The selection of the target reliability index is a function of the reliability index inherent in existing structures and the consequences of “failure”.

• Failure is defined as the factored loads exceeding the factored resistance.
General Calibration Process

For the Strength limit state:

• The consequences of loads exceeding the resistance are relatively clear and typically make the bridge unsafe for use.

• The frequency of exceedance should be kept to an extreme minimum.
General Calibration Process

For the Service limit state:

• The consequences of the loads exceeding the resistance are not well defined. (exceeding deflection limit, wider cracks in RC, exceeding stress limit in PSC, ..etc.)

• Limit states may be exceeded but the acceptable frequency of exceedance is not known.
• Strength limit state was statistically calibrated for most load combinations

• Service limit state was not statistically calibrated. Rather, limits on stresses, deflections, crack widths, ..etc. were selected such that, when applied in conjunction with the LRFD loads, give answers similar to those determined using AASHTO Standard Specifications in effect at the time the AASHTO LRFD was developed.
Special Challenges - SLS

• Criteria – What matters?
• Significance of selected limit state
• How often can it be violated?
• Correlated loads and resistance
• Time variance of loads
• Deterioration modeling
• Resistance related to geography/environment
• Role of workmanship
• Paucity of data
Efforts to Calibrate Service Limit States

SHRP R19B:
Bridges for Service Life beyond 100 Years:
Service Limit State Design

NCHRP 12-83:
Calibration of LRFD Concrete Bridge Design Specifications for Serviceability
Research Teams

Modjeski and Masters, Inc.: John Kulicki, Ph.D., P.E. (PI, SHRP R19B)
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University of Nebraska: Andy Nowak, Ph.D.
NCS Consultants: Naresh Samtani, Ph.D., P.E. (R19B only)
Rutgers University: Hani Nassif, Ph.D., P.E. (NCHRP 12-83 only)

TRB/SHRP 2 : Monica Starnes/ Mark Bush/ Jerry DiMaggio
TRB/NCHRP : Dr. Waseem Dekelbab
SHRP R 19B and NCHRP 12-83

- R19B
  - Framework
  - Most of Live Load development
  - General SLS
  - Steel, foundations, bearings, joints
- 12-83 deals with concrete SLS only and R19B inherited results
- Fatigue – joint
- Loads - joint
Review of Live Load Model Development

- Truck WIM data was obtained from the FHWA and NCHRP Project 12-76
- Some data obviously incorrect, several filters were applied to eliminate erroneous records
- Total number of records about 60 million - about 35 million used
- Eliminated records included erroneous records, light vehicles, a site that has a large number of extremely heavy vehicles and one state that used different format.
Multiple presence analysis

- Simultaneous occurrence of trucks on the bridge:
  - Filter based on time of a record and speed of the truck
  - Distance from the first axle of first truck to the first axle of the second truck maximum 200 ft

Two cases of simultaneous occurrence
Conclusions for Multiple Presence

• Vehicles representing the extreme tails of the CDF’s need not be considered to occur simultaneously in multiple lanes.

• For the SLS’s, only a single-lane live-load model need be considered on the load side of the calibration.
Conclusion For Non-Fatigue SLS

- Not necessary to envelope all trucks – SLS expected to be exceeded occasionally
- Scaled HL-93 looks reasonable
- Site/region specific live load should be accommodated
- Some states with less weight enforcement may have to have additional consideration
Overview of Calibration

• Design process: number of loaded lanes unchanged

• Calibration typically used 1 lane loaded on the load side, multiple lanes allowed on the resistance side (i.e. components designed for the controlling case single or multiple lanes loaded)

• Most SLS used annual probability

• $\beta$ typically ranged 0.5 to 1.5 (probability of exceedance in one year 31\% & 7\%, respectively) with one exception for Service II
LL-Deflections in AASHTO LRFD

• Humans do not feel deflections, they feel the accelerations associated with the deflections and vibrations
• Deflection limits were first used by railroads then found their way to highway design
• AASHTO limits on deflections are a fraction of the span length
LL-Deflections – Service I (V??)

- Recommending consideration of the Canadian Code (CHBDC) criteria with load factor = 1.5

Note frequency required
LL Deflections - Comparisons

Deflection Limitations for Highway Bridge Superstructure Vibration

- Existing Spread Box Girders
- Existing Adjacent Box Girders
- Existing I-Girders
- Existing Steel Girders

- without sidewalks
- with sidewalk, occasional pedestrian use
- with sidewalks, frequent pedestrian use

Simulated Steel Bridges Designed to Satisfy AASHTO LRFD Deflection Limits Only
Simulated Steel Bridges Designed to Satisfy AASHTO LRFD Specifications

Deflection Limitations for Highway Bridge Superstructure Vibration

- Acceptable
- Unacceptable

first flexural frequency, Hz

static deflection, mm
LL Deflections

- Canadian (CSA) criteria more inclusive of basic factors
- But----current AASHTO provides similar trends
- Change would require calculations not normally done for routine bridges, but software readily available and approximations available in literature.
LL Deflections

• Proposed revisions for consideration include:
  ○ Introduction of the deflection-frequency graph in 2.5.2.6.2—Criteria for Live Load Response
  ○ Introduction for Service V limit state which will be used to investigate LL deflections and vibrations
  ○ Proposed load factors are 1.0 for permanent loads and 1.5 for live load
Overload Provisions for Steel to Control Permanent Deformations – Service II

- Premature yielding in girders
- Slip of friction bolts
- Now linking to WIM data
- Can this still control design? – experience says often controls girder design.
Basis for Current Service II For Steel

\[ \text{Test stress} = \frac{6}{F_y} \]

Permanent set at midspan, in.  vs. Test stress

Composite bridges
Noncomposite bridges

\(~500,000\) cycles of same load
Service II - Overload Calibration

- Performed under Service II. Load factor for live load 1.3
- Applicable to steel bridges
- Intended to minimize the potential of yielding under service loads
Service II – Overload

- Annual average load occurrence from WIM data – scaled to ADTT = 2500 for all sites:
Service II-Overload

• Previously received SCOS input
• Conclusions from WIM data alone:
  – Not too much basis to lower load factor
  – Site specific evaluation of unique sites warranted
  – Design for single lane loaded is warranted
  – Use of single lane MPF hard to justify FOR THIS LIMIT STATE.
Overload Calibration

• Single lane on load side, multiple load on resistance side
• 41 steel bridges used
• LFD $\beta$ about 1.6 – 2.0, COVs about 0.32 – 0.92
• Using R19B bias and COV on HL-93 and current load factors resulted in mean $\beta$ of 1.8 but bias of only 0.09.
• If we are happy with current $\beta$, even though high for a SLS, calibrated results will yield similar behavior but with more consistency.
Overload Calibration

- Proposed revisions: Add description of the WIM Data Study to the commentary to the definition of Service II load combination
WIM Data Analysis for Fatigue Limit State

• Fatigue I, infinite life: Applicable to structural steel, concrete and reinforcement

• Fatigue II, finite life: Applicable for structural steel. Number of cycles per truck selected to produce same level of fatigue damage.
Fatigue I

• Usually assumed that CAFL can be exceeded by 1/10,000 of the stress cycles
• 99.99% inclusion of normal random variables requires mean plus 3.8 standard deviations
### Fatigue II – Design Cycles Per Truck

<table>
<thead>
<tr>
<th>Longitudinal Members</th>
<th>Span Length</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 40 ft</td>
<td>≤ 40 ft</td>
<td></td>
</tr>
<tr>
<td>Simple Span Girders</td>
<td>1.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Continuous Girders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>near interior support</td>
<td>1.5</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>elsewhere</td>
<td>1.0</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

**Current**

**Proposed**

<table>
<thead>
<tr>
<th>Longitudinal Members</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Span Girders</td>
<td>1.0</td>
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<td>1.5</td>
</tr>
<tr>
<td>elsewhere</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Fatigue - Resistance

• Database for structural steel fatigue test results existed in a Lehigh University report from the 1970’s. No copies could be found.

• An electronic copy was obtained from the original researcher but did not include any headings

• Some of the records included information in only few columns. Other information appeared missing.

• Forensic investigation using bits of information from other published reports

• The research team was able to reconstruct the fatigue resistance database
Fatigue – Resistance Side and Calibration

With help from Drs. Keating, Fisher, Yen, Connor and Roy

S-n Curves → Probability Paper → COV, Bias

β
### Current Reliability Indices for Steel Members

<table>
<thead>
<tr>
<th>Detail Category</th>
<th>$\beta$</th>
<th>Fatigue I</th>
<th>Fatigue II</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.2</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.1</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>B'</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1.2</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>C'</td>
<td>1.2</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>2.0</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.9</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>E'</td>
<td>1.7</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>
Calibration For Fatigue In Steel

Uniform reliability can be achieved using variable resistance factor or change in constants used in calculations

<table>
<thead>
<tr>
<th>Detail Category</th>
<th>Current Constant A $\times 10^8$</th>
<th>Proposed Constant A $\times 10^8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>B</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>B′</td>
<td>61</td>
<td>67</td>
</tr>
<tr>
<td>C</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>C′</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>D</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>E</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>E′</td>
<td>3.9</td>
<td>4.7</td>
</tr>
</tbody>
</table>
## Calibration For Fatigue In Steel

<table>
<thead>
<tr>
<th>Detail Category</th>
<th>Current Constant-Amplitude Fatigue Threshold (ksi)</th>
<th>Proposed Constant-Amplitude Fatigue Threshold (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>B’</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>C’</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>D</td>
<td>7.0</td>
<td>6.7</td>
</tr>
<tr>
<td>E</td>
<td>4.5</td>
<td>5.0</td>
</tr>
<tr>
<td>E’</td>
<td>2.6</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Fatigue

- From the WIM data study, proposed live load load factors:

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Mean</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue I</td>
<td>2.0</td>
<td>0.12</td>
</tr>
<tr>
<td>(currently 1.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue II</td>
<td>0.8</td>
<td>0.07</td>
</tr>
<tr>
<td>(currently 0.75)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Does This Increase Make Sense?

![Bar Chart: Number of Truck Combinations vs Year from 1965 to 2008]

- X-axis: Year (1965 to 2008)
- Y-axis: Number of Truck Combinations (0 to 2,500,000)

The chart shows an increase in the number of truck combinations from 1965 to 2008.
Does This Increase Make Sense?

Percent Change

Truck Weight

1992-1997
1992-2002
Does This Increase Make Sense?

COMPARISON OF GROWTH IN VOLUME AND LOADINGS ON THE RURAL INTERSTATE SYSTEM

PERCENT CHANGE SINCE 1970

YEAR


Rural Average Daily Load

Rural Average Daily Traffic

Source: Truck Weight Study

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Experience great bridges.
The Way Forward

• The work performed under SHRP R19B and NCHRP 12-83 is the start of statistically calibrating the service limit states.

• Work sufficiently complete to consider agenda items which were drafted in the project reports – could be distributed.

• Propose to formalize for consideration at August T-14 meeting – Text ready.
Thank you for listening

Questions?