Bridge Superstructure Tolerance to Total and Differential Foundation Movements

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Current AASHTO LRFD Guidance Related to Tolerable Support Movement

- Guidance provided by AASHTO LRFD Bridge Design Specs found in commentary:
  
  “...studies indicate that angular distortions between adjacent foundations greater than 0.008 rad. in simple spans and 0.004 rad. in continuous spans should not be permitted in settlement criteria”

  (AASHTO LRFD Bridge Design Specifications C10.5.2.2)

- Based on research conducted by Moulton et al. (1985) and Barker et al. (1991)

- In practice, the large tolerable movements provided by this criterion run contrary to designer sensibilities and it is not uncommon for bridge designers to use arbitrarily small values of angular distortions.
Research Objectives

Overarching Goal: Develop a comprehensive understanding of the levels of differential support movements that bridges may tolerate without performance problems.

Specific Objectives:

1. Develop (simple) analytical procedures to determine the acceptable levels of bridge foundation movements (Phase II)

2. Propose revisions to the AASHTO LRFD Bridge Design Specifications that provide rational guidance for foundation movement limits (Phases III and IV)
Phase II Objectives & Workflow

1. Develop estimates of tolerable support movements for both strength and service limit states for common bridge types

2. Identify the critical parameters that influence tolerable support movements

3. Develop simple expressions to estimate the level of tolerable support movement based on the identified influential parameters

4. Conduct parametric analyses on a secondary group of structures to “spot check” if the findings of the primary study were applicable to other, less common, superstructure types.
## Sampled Parameters to Develop Notional Bridge Population

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bounds</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discrete Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridge Type</td>
<td>Steel and PS Concrete Multi-girder</td>
<td>These bridge types were selected as they represent the most commonly designed and built structures</td>
</tr>
<tr>
<td>Bridge Continuity</td>
<td>Simple, 2-Span, Continuous, 3-Span Continuous</td>
<td>These levels of superstructure continuity allow for no continuity, continuity at one end of each span, and continuity at both ends of a span, respectively</td>
</tr>
<tr>
<td>Span Length</td>
<td>40 ft to 160 ft</td>
<td>Typical span lengths for multi-girder bridges.</td>
</tr>
<tr>
<td><strong>Continuous Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Girder Spacing</td>
<td>5 ft to 12 ft</td>
<td>Typical bounds of girder spacing for multi-girder bridges.</td>
</tr>
<tr>
<td>Skew</td>
<td>0° to 60°</td>
<td>Note that larger skew angles require advanced analytical methods.</td>
</tr>
<tr>
<td>Bridge Width</td>
<td>36 ft to 72 ft</td>
<td>Approximately 2 to 4 lanes. This nominal bridge width will be adjusted based on girder spacing.</td>
</tr>
<tr>
<td>Span-to-Depth Ratio</td>
<td>20 to 30</td>
<td>These represent typical bounds on girder depth and govern the relationship between girder strength and stiffness.</td>
</tr>
</tbody>
</table>
Sampling Approaches

Hybrid Full Factorial & Latin Hypercube Approach

- Discrete parameters uncoupled from continuous parameters to allow for finer sampling of the latter.

Latin Hypercube Sampling

- Method divides each parameter range into \( n \) number of bins with equal probability density.
- LHS draws a random sample from each bin, and then randomly pairs samples from different parameters.
- More efficient than traditional MC methods (McKay et al. 1979)

<table>
<thead>
<tr>
<th>LHS Sampling of Continuous</th>
<th>DoE Sampling of Discrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divide Continuous Parameters into ( n ) intervals</td>
<td>Generate a full-factorial sample (i.e. all possible combinations of discrete parameters)</td>
</tr>
<tr>
<td>Draw a random sample from each interval for each parameter</td>
<td>2 Bridge Types x 3 levels of Continuity</td>
</tr>
<tr>
<td>Randomly combine samples from each parameter to generate ( n ) sets of continuous parameters</td>
<td>6 Samples of Discrete Parameters</td>
</tr>
</tbody>
</table>

Pair each sample of continuous parameters with each sample of discrete parameters

Total number of samples within Bridge Suite = \( 6^n \)
Automated Member Sizing

- Member actions are obtained using the commonly employed SLG model.

- AASHTO LRFD Bridge Design procedures are followed to obtain the proper cross-section “design” for steel and pre-stressed concrete girders.

- For steel, an optimization algorithm constrained by the provisions of AASHTO LRFD Bridge Design Specifications is utilized to size components of steel plate girders.

- For pre-stressed concrete, a step function constrained by the provisions of AASHTO LRFD Bridge Design Specifications is utilized to select the proper PCBT cross-section and pre-stressing.

  - Capacities associated with shear and negative moment demands are highly dependent on the harping or de-bonding patterns, stirrup placement and other reinforcement design decisions, which are at the discretion of the designer.
  - These capacities were not calculated.
  - Instead, the shear and negative moment capacities were set equal to the design demands.
Limit States Evaluated

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Evaluated For</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength I</strong></td>
<td>Steel Multi-girder, Pre-stressed Concrete Multi-girder, Open and Closed Steel Box-girder</td>
<td>Flexure and shear limits under strength load combinations</td>
</tr>
<tr>
<td><strong>Service II</strong></td>
<td>Steel Multi-girder, Open and Closed Steel Box-girder</td>
<td>Flexure limits intended to control yielding of steel under service load combinations</td>
</tr>
<tr>
<td><strong>Service I &amp; III</strong></td>
<td>Pre-stressed Concrete Multi-girder, CIP Concrete Multi-cell Box-girder</td>
<td>Compression/tension limits under service load combinations</td>
</tr>
</tbody>
</table>
Estimating Maximum Tolerable Support Movement

\[
\Delta_{tol} = \frac{\phi R - \gamma D}{S_1}
\]

- \(\Delta_{tol}\) = tolerable support movement
- \(\phi R\) = factored resistance for the limit state
- \(\gamma D\) = factored demand force effects for the limit state
- \(S_1\) = force effects per unit support movement

* Units of R, D, and \(S_1\) depend on limit state being evaluated, but units of \(\Delta_{tol}\) are length (in.).

- Similar to the load rating methodology in which capacity is evaluated against the demands for each limit state.
- Demand force effects (D) associated with DL, SDL, and LL are simulated using the finite element model.
- Demand force effects due to a unit support movement (\(S_1\)) are simulated using finite element model.
- Resistance is computed as per AASHTO LRFD
Support Movements Studied

<table>
<thead>
<tr>
<th>Support Movement</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal-Differential Support Movement (LD)</td>
<td>![LD Diagram]</td>
</tr>
<tr>
<td>Transverse-Differential Support Movement (TD)</td>
<td>![TD Diagram]</td>
</tr>
</tbody>
</table>

- LD and TD support movements evaluated at all supports.
- Horizontal movements in the longitudinal direction are assumed to be limited by the tolerance of the movement systems (joints and bearings).
Controlling Locations

Movement @ Abutment

Movement @ Pier

Potential controlling location for TD

Increased negative moment and shear over the pier

Increased shear

Increased positive moment
Tolerable Support Movements Governed by Strength and Service Limit States

Steel Multi-Girder Bridges
Sample Results – Controlling Limit State

Three-Span Continuous Steel Multi-girder Bridges

LD Movement

@ Abutment

@ Pier

TD Movement
Sample Results

Tolerable Support Movement for the Strength I Flexural Limit State of Three-Span Continuous Steel Multi-girder Bridges

LD Movement at Abutment
Smaller girder spacing lends to greater tolerance.

- For flexure limits only.
- Girder spacing explains some of the variance observed in the data.
- Likely because LRFD distribution factors overestimate live load distribution for smaller girder spacing lending to reserve capacity.
- LRFD distribution factors become less conservative (more accurate for larger girder spacing.)
Higher tolerance in positive bending regions.

- Observed relatively higher positive flexure tolerance to movements than induce positive bending (e.g. movements that occur at the pier).
- Due to the implications of the Fatigue limit state on the design of composite sections in positive bending.
- Design for the Fatigue limit State introduces conservatism in the form of additional capacity for the Strength and Service limit states.
- This additional capacity provides bridges with the ability to tolerate movements that induce positive bending.
Outcomes for Steel Multi-girder Bridges

- Maximum tolerable support movements found to exceed current AASHTO guidance in some cases.
- Current guidance generally provides a conservative estimate of tolerable LD movements under flexural limits.
- Becomes less applicable for TD movements and for the Strength I shear limit state for highly skewed bridges.
- Three potential options for predicting tolerable support movements:

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Guidance</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retain current model and specify range of applicability</td>
<td>0.004L</td>
<td>for LD within two-span continuous bridges with span length greater than 100 ft and skew less than 20°</td>
</tr>
<tr>
<td>Update current model and specify range of applicability</td>
<td>0.003L</td>
<td>for LD within three-span continuous bridges with span length greater than 100 ft and skew less than 20°</td>
</tr>
<tr>
<td>Develop a new model for estimating tolerable support movements</td>
<td>$\Delta = f \left( \frac{S}{L} \right)$</td>
<td>for LD support movements, all limit states, and any bridge configuration</td>
</tr>
</tbody>
</table>
Tolerable Support Movements Governed by Strength and Service Limit States

Prestressed Concrete Multi-Girder Bridges
Sample Results – Controlling Limit State

Three-Span Continuous PS Concrete Multi-girder Bridges

LD Movement

1. @ Abutment
   - Strength I Flexure: 20%
   - Strength I Shear: 20%
   - Service: 54%

2. @ Pier
   - Strength I Flexure: 0%
   - Strength I Shear: 0%
   - Service: 100%

TD Movement

1. @ Abutment
   - Strength I Flexure: 14%
   - Strength I Shear: 45%
   - Service: 41%

2. @ Pier
   - Strength I Flexure: 0%
   - Strength I Shear: 9%
   - Service: 91%
Sample Results

Tolerable Support Movement for the Strength I Flexural Limit State of Three-Span Continuous PS Concrete Multi-girder Bridges

LD Movement at Abutment

100 ft Spans
Sample Results

Tolerable Support Movement for the Service III Limit State of Three-Span Continuous PS Concrete Multi-girder Bridges

*LD Movement at Pier*

100 ft Spans
Outcomes for Pre-stressed Concrete Bridges

- Maximum tolerable support movements found to be much smaller than current AASHTO guidance suggests.
- This is especially true for the Service III limit state.
- Three potential options for predicting tolerable support movements:

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Example Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specify constant level of tolerable support movement to account for low tolerance under the Service III limit state</td>
<td>$\Delta \leq 0.5$ inches for all movements and all limit states</td>
</tr>
<tr>
<td>Retain the current model and specify range of applicability (i.e. for specific movements or limit states)</td>
<td>0.004L for LD movements occurring at the abutment for two-span continuous bridges.</td>
</tr>
<tr>
<td>Develop a new model for predicting tolerable support movements and specify range of applicability (i.e. for specific movements or limit states)</td>
<td>$\Delta = f \left( \frac{S}{L} \right)$ for LD support movements under the Strength I Flexure limit state</td>
</tr>
</tbody>
</table>
Functionality Concerns: Ride Quality

- There is little direct guidance on the nature of bridge support movement and rideability concerns outside of the relation of differential movement between bridges and approach slabs and pavements.

- A review of previous research concerning ride quality produced the following recommendations limiting support movements:

<table>
<thead>
<tr>
<th>Movement Case</th>
<th>Limits for Ride Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>For movements occurring at the abutment of simply supported bridges</td>
<td>$\frac{\delta}{L_a} + \frac{\delta}{L_s} &lt; \frac{1}{250}$</td>
</tr>
<tr>
<td>For movements occurring at the abutment of continuous bridges</td>
<td>$\frac{\delta}{L_a} + \frac{2\delta}{L_s} &lt; \frac{1}{250}$</td>
</tr>
<tr>
<td>For movements occurring at the pier of multiple-span simply-supported bridges</td>
<td>$\frac{2\delta}{L_s} &lt; \frac{1}{250}$</td>
</tr>
<tr>
<td>For movements occurring at the pier of continuous bridges</td>
<td>$\frac{2\delta}{L_s} &lt; \frac{1}{250}$</td>
</tr>
</tbody>
</table>

Where:
- $\delta$ = absolute approach settlement
- $L_a$ = length of approach slab
- $L_s$ = length of span
Summary of Findings

- A large parametric study was carried out to estimate the tolerable support movements associated with common bridge types (multi-girder steel and PS concrete).

- Other steel and PS concrete bridge types were spot checked based on the findings of the primary parametric study.

- Results suggest that separate criteria for steel and PS concrete bridge is needed due to the different design limit states and mechanisms present.

- A series of simplified expressions for each bridge type were identified and will be further refined and examined during Phase III of this project.

- Functionality criteria for ride-quality was developed and limitations related to clearance, the tolerance of movement system, and utilities were recognized.

- A procedure to compute tolerable support movements for bridges that fall outside the limits of this study was formalized.
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