Effect of Curved Alignment and Skewed Supports on Bridge Response

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Outline

- Motivation
- Code Procedure
- Study Results
- Conclusions
- Questions
Curve Effect and Skew Effect

The support forces at the end of skewed and curved bridges vary along the bridge width.

Curve Effect – Effect of curving a bridge horizontally on the bridge reactions (support forces)

Skew Effect – Effect of skewing a bridge on the bridge reactions
Issues Caused

Effects cannot be accurately predicted in 2D models

Girders can be under-designed for shear

Bearings receive overload or uplift

Additional moments on substructure
Code Procedures

- **AASHTO LRFD 6th**
  - 2D analysis limits for curved bridges
  - Skew shear correction factors for Live Load only

- **Caltrans Amendments to AASHTO**
  - Skew shear factors changed for some bridge types and applications.
  - Skew shear factors applied to all loads for T-beam and box-girder bridges
No clear guidance concerning Skew and Curve Effects on:

- How to account for torsion in reaction response (Rigid Beam Analogy?)
- Distributing reaction forces to substructure (non-monolithic)
- Bearing design
- Varying post-tensioning
- Uplift in acute corners
Code Procedures: Curve Limits

- Ignore curve for central angles < 12 degrees (L/R=0.2)
- Model as curved spine model for central angles between 12 and 34 (L/R=0.6)
- Full 3D analysis for central angles > 34
Code Procedures: Skew

- Dead Loads
  - No skew correction in AASHTO LRFD 6th
  - Caltrans Amendment provides a correction factor for exterior girders for Box Girder Bridges

\[
Correction\ Factor = 1.0 + \frac{\theta}{50}
\]

- This factor is only dependent on skew angle, \( \theta \), and yielded non-conservative results for most models in this study.
Example: West Llagas Pedestrian Bridge (Gilroy, CA)
-9 + 2 + 17 + 92 = 102 kips Total Reaction
Reaction Distribution for Torsion: Rigid Beam Analogy

\[ V = \frac{T}{10 \times S} \]
Analysis Results

-9 kips

2 kips

17 kips

92 kips

-9% 2% 17% 90%

-9 + 2 + 17 + 92 = 102 kips Total Reaction

Simplified Procedure w/Skew Correction & Torsion Distribution

14 kips

22 kips

34 kips

57 kips
Analysis Study

- **Scope**
  - Over 800 4-Cell Box-Girder Bridges
  - Single-span
  - Bridge models were varied between 0 and 60 degree skew angle and -48 to 48 degree central angle
  - Varied bearing stiffness
Features of Characteristic Plot

Aspect Ratio 1.0, $K_{bearing} = 500,000$ k/in

- Aspect Ratio is Length to Width (L/W)
- Dashed Line is Skew Corrected Value
- Line with dotted markers is straight bridge
- Grey lines are curved bridges with L/R noted on legend
- $R_o$ is the % of abutment reaction at obtuse corner girder
# Sample of Bridge Models

<table>
<thead>
<tr>
<th>Bridge Model – Plan View</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Bridge Model" /></td>
<td>Aspect Ratio = 4.0</td>
</tr>
<tr>
<td></td>
<td>Central Angle = 0°</td>
</tr>
<tr>
<td></td>
<td>Skew Angle = 0°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><img src="image2.png" alt="Bridge Model" /></th>
<th>Aspect Ratio = 4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central Angle = -48°</td>
</tr>
<tr>
<td></td>
<td>Skew Angle = 0°</td>
</tr>
</tbody>
</table>
Sample of Bridge Models

Aspect Ratio = 4.0
Central Angle = 0°
Skew Angle = 30°
Aspect Ratio 1.0, $K_{\text{bearing}} = 500,000$ k/in
Aspect Ratio 1.0, $K_{\text{bearing}} = 500,000 \text{ k/in}$

40% of reaction to obtuse corner (included for reference)

Notes:
1. Straight bridge matches skew correction factor up to about 40 degree skew.
2. Curve effect significantly increases exterior girder reaction
The Curve Effect is more pronounced for negative central angles than for positive central angles.

The top curve (36°) starts at 28%, the middle curve (0°) starts at 18%, and the bottom curve (-36°) starts at 6%.

The distance between the lower curves (18 – 6 = 12) is greater than the distance between the upper curves (28 – 18 = 10).
Aspect Ratio 2.0, $K_{\text{bearing}} = 500,000 \text{ k/in}$

- % Abut. Rxn. @ Obtuse Corner
- Abutment Skew [deg]

Design curves for different skew angles.
Notes:
1. Skew effect increases while design curve remains unchanged.
2. Skew factor severely underestimates reaction after 10 degree skew.
3. Mild coupling of skew and curve effects
Aspect Ratio 4.0, $K_{bearing} = 500,000$ k/in

% Abut. Rxn. @ Obtuse Corner vs. Abutment Skew [deg]
Notes:
1. Skew effect continues to increases while design curve remains unchanged.
2. Skew factor severely underestimates reaction.
Skew Effect for Varying Aspect Ratios

% of Abut. Rxn. @ Obtuse Corner

Abutment Skew [deg]

- Design
- AR = 1.0
- AR = 2.0
- AR = 4.0
- AR = 8.0
Skew Effect for Varying Aspect Ratios

**Design**

- AR = 1.0
- AR = 2.0
- AR = 4.0
- AR = 8.0

% of Abut. Rxn. @ Obtuse Corner vs. Abutment Skew [deg]
Curve Effect for Varying Aspect Ratios

% of Abut. Rxn. @ Obtuse Corner

Central Angle [deg]

AR = 1.0
AR = 2.0
AR = 4.0
AR = 8.0
Empirical Formulas

- At small skew angles and small central angles:
  - Curve effect is not dependant on skew angle
  - Skew effect is not dependant on central angle

- Outside Corner
  \[
  SkewCurve\ Correction\ Factor = 1 + \frac{\theta}{50} \ast AR^{0.9} + \frac{\alpha}{100} \ast AR
  \]

- Inside Corner
  \[
  SkewCurve\ Correction\ Factor = 1 + \frac{\theta}{50} \ast AR^{0.9} + \frac{\alpha}{50} \ast AR^{0.4}
  \]
Proposed Correction Formulas Compared to 3D Model Response

% of Abut. Rxn. @ Obtuse Corner

AB = 1.0
AR = 2.0
AR = 4.0

Pred: AR = 1.0
Pred: AR = 2.0
Pred: AR = 4.0

Abutment Skew [deg]
Summary and Conclusions

- Aspect ratio (length to width ratio) influences skew effect on reaction forces and, therefore, also influences shear forces.

- Aspect ratio influences curve effect.

- Aspect ratio influences coupled skew-curve effect.

- Bearing pad stiffness (support stiffness) influences skew effect, curve effect, and skew-curve effect.

- Spine model analysis with code modifications may not yield conservative reaction forces for skewed and curved bridges with high aspect ratios (> 1.0).
Future Work

- Shear Force and Bearing Reactions:
  - Effect of Bearing Position
  - Other Bridge Types and Configurations
  - Multi-Span Bridges
  - Effects of Prestressing
  - Lab Experimentation

- A fuller perspective of the differences in 2D spine model analysis vs. 3D shell model analysis
Work in Progress

- Caltrans Structural Analysis Committee (Chair: Toorak Zokaie, PE)

- Curved Bridge Superstructure Response
  - Dead Load, Live Load, and Post-tensioning responses
    - Girder End Shear
    - Girder Stress
    - Column response
      - Longitudinal Moment
      - Transverse Moment
Results: Dead Load Abutment Shear ... 1-Span

Dead Load Abutment girder Shears 100'-span

Dead Load Abutment girder Shears Ratios 100'-span

Dead Load Abutment girder Shears L/R and 3D 100'-span
Dead Load Mid-span Bottom Stress … 1-Span
Work in Progress: Preliminary Findings

- Superstructure Study Work in Progress
  - DL, PS and LL moments increase slightly with L/R, 2D analysis is slightly under 3D
  - DL shear & normal stress increase greatly with L/R, 2D gives acceptable accuracy
  - PS stresses do not change much with L/R
  - DL bent shear has same accuracy regardless of curvature but could be low due to section geometry
Questions or Comments?