Curved Steel Girders

Ed Wasserman, P.E.
Civil Engineering Director
Tennessee DOT
Ramp B Over I-40
Field Investigation

Field Instrumentation and Summary of Preliminary Results

August 13, 2010

(Sponsored by the State of Tennessee)
Ramp B over I40
Bridge Summary

- Curved I-girder bridge
- Eight spans, total of 1516 ft, $R_{\text{min}} = 750$ ft
- Five 68 inch deep girders
- 43 ft wide deck
NCHRP Project 12-79

Guidelines for Analytical Methods & Erection Engineering of Curved & Skewed Steel Deck-Girder Bridges

Don White, Georgia Tech
August 2010
1. Guidelines
   – When are simplified 1D or 2D analysis methods sufficient?
   – When are 3D methods necessary?
     for assessing constructability
     & for predicting the constructed geometry

2. Recommendations
   – Level of analysis
   – Plan detail
   – Submittals
Sample of Bridges Studied to Date
Bridges Studied to Date

Suite 1, I-Girder Bridges

- FHWA I-Girder Test Bridge (EISCR1)
- SR8002 Ramp A-1, King of Prussia, PA (EISCS3)
- NHI Example Bridge, 2007 (XICSS5)
- Ramp B over Robertson Ave & I-40, Davidson County, TN (EICCR22a)
Suite 1, Tub-Girder Bridges

NCHRP 12-52 Tub-girder curved example (XTCCR8)

NHI Design Example Straight Tub Girder (XTCSN3)
Suite 3, I-Girder Bridges

MN/DOT bridge No 27998, Minneapolis, MN (EICCS10)

I-235 EB over E. University Ave., Polk Co., IA (EICSS2)

R 0581 Section A01, Cumberland Co., PA (EISSS5)

Ford City Bridge, Ford City, PA (EICCR11)
Bridges Studied to Date

Parametric I-Girder Bridges

(NISCR7), Suite P1
(NISCR2), Suite P1
(NISSS13), Suite P3
(NISCR5), Suite P2
(NISSS16), Suite P3
Data Synthesis & Findings

• Effects of neglecting girder warping torsion
  o Vertical deflection predictions
  o Girder layover predictions
• Significance of using cross-frames without top chords
• Influence of type of cross-frame detailing on straight I-girder bridges
• Cases where one should be wary of global 2nd-order amplification
Vertical Displacements – Effect of Neglecting Warping Torsion, Curved I-Girder Bridges

NHI 2010 Example Bridge (XICCS7)

$L_b/R = 0.031; L_b/L_{as} = 0.137$
Girder Layovers – Effect of Neglecting Warping Torsion, Curved I-Girder Bridges

NHI 2007 Example Bridge (XICCS7)

\[ \frac{L_b}{R} = 0.031; \quad \frac{L_b}{L_{as}} = 0.137 \]
For “well connected” curved bridges... The girder layover is predicted accurately at the cross-frame locations.

Straight skewed bridges are less sensitive to limitations in the modeled torsional stiffness.
Significance of using Cross-Frames without Top Chords in I-Girder Bridges
I-Girder Bridges having Cross-Frames without Top Chords

Bridge on SR 1003 (Chicken Road) over US 74, Robeson Co., NC (EISSS3)

\[ L = 133 \text{ ft}, \; w = 30.1 \text{ ft}, \]
\[ \theta_{\text{left}} = \theta_{\text{right}} = 46.2^\circ, \]
4 girders

Total Dead Load Deformations scaled x10
Cases where one should be wary of global $2^{nd}$-order effects
On-going Research

• Detailed studies of existing bridges
  • Walk through of findings with design engineers on key bridges
  • Field measurements & observations
• Additional studies of parametric bridges
• Thoroughly examine & quantify the conditions where different methods of analysis lose accuracy or fail to predict the bridge responses
Ramp B Over I-40
Field Investigation

Field Instrumentation and Summary of Preliminary Results
August 13, 2010
(Sponsored by the State of Tennessee)
Objectives of this Research

- Instrument selected girders and monitor stresses throughout the bridge
- Track deformations at two key spans
- Track thermal effects
- Compare results with those from analytical work on NCHRP 12-79 to assess the ability of different techniques to predict the behavior during construction
Research Team

• PIs:
  – Roberto Leon
  – Donald White
  – Jochen Teizer

• URAs:
  – Julie Dykas
  – Kevin Mayer
  – Fabio Molina

• GRAs:
  – Towhid Bhuyan
  – Andres Sanchez
  – Cagri Ozgur
  – Juan Jimenez

• Applied Geomechanics:
  – Naia Suszek
  – Jeff Keller
Collaborators

• Bell and Associates Construction:
  – Jeremy Mitchell, Project Manager
  – Dennis Howell, Project Superintendent
  – Joe Howell
• Powell Steel Erection:
  – David Horton, Project Manager
  – Mike Trent, Project Superintendent
  – Harold West, Project Foreman
• Parsons Brinckerhoff:
  – Bryan Estock
  – Mathew Smith
  – Mike Sage
• PDM Steel (Palatka, FL)
  – Chris Price
  – Jeremy Duckett, Project Manager
  – Ben Bristol, Plant Manager
• HDR (via NCHRP Project 12-79)
  – Domenic Coletti
  – Brandon Chavel
• High Steel
  – Bob Cisneros
• TN DOT:
  – Tim Huff, Bridge Designer
  – Ed Wasserman, Civil Engineering Director
Ramp B Field Instrumentation
Instrument Selection

• Long-term stability:
  – Low or no drift
  – Low probability of zero shifts

• Robustness:
  – Survive erection
  – Insensitive to wide temperature and humidity changes

• Simple field installation

• Automated data acquisition
Vibrating wire gauges

- Simple and rugged device consisting of a tensioned wire anchored to two blocks welded to girder
- Changes in length (i.e., strain) are measured as changes in vibration frequency of the wire
- Includes a thermistor to correct for temperature variations
- Not a current or voltage device, so it can be connected and disconnected at will
- Limited range (± 1500 με)
- Static measurements only
Clinometers

• Simple and rugged device consisting of an electrolytic fluid and several contact points
• Changes in rotation are measured as changes in resistance of the fluid
• Includes a thermistor to correct for temperature variations
• The transducer is excited and read by stable, low-noise electronics
• Wide range (± 25 degrees)
• Referenced to gravity
• Static measurements only
Typical Installation

- Six vibrating wire gauges, four at flange tips and two at third point on web
- Two clinometers, one at center of web and one at flange tip
Total Station

• Combines:
  • angle measurement,
  • distance measurement,
  • automatic target recognition

• Accuracy:
  • 0.6 mm + 1 ppm to prism
  • 2 mm + 2 ppm to any surface

• Automated storage of data
Laser Scanner

- Generates a point cloud – a leap forward in terrain and environment understanding
- Both distance and intensity data are measured
- Detailed 3D processing
Instrument Locations

Displacements Scaled 50x
Completion of Bridge Deck Placement
Bridge Deck Not Shown

Girders 1, 2 & 5 instr. @ midspan & near pier 1
Girders 2 & 5 instr. @ midspan & near piers 1 & 2
Girders 2 & 5 instr. near pier 2
Girder 1 instr. @ midspan & near piers 3 & 4
Girder 1 instr. @ midspan & near piers 4 & 5
Girder 1 instr. @ midspan & near piers 5 & 6
Girders 1 & 5 instr. @ midspan & near pier 7
Instrument Locations

Cross-section view showing location of different sensors
Typical Installation

Gage alignment jig

Welded blocks
Data Acquisition

- Six boxes, each with up to 32 gauges and 10 clinometers
- Data downloaded by radio communication
- Powered by solar panels

DACQ System Diagram
Typical Installation

Connecting boxes after erection

Installation of data acquisition boxes
Crane Placement, Start of Stage 1
Stage 1, Placing 2nd Girder over Pier 1
Stage 1, Placing 3rd Girder over Pier 1
Laser-Scan Image, End of Stage 1
Overview of Erection Procedure & Construction Stages Targeted for Study (Plan Sketches and Corresponding Photos)
1- Cribbing on G1 @ 13.7 ft away from the closest CF to the West (6th CF from Abutment 1)
2- Holding Crane on G1 @ 1 ft away from the closest CF to the West (5th CF from Abutment 1)
3- Lifting Crane on G1 @ 5.2 ft away from the closest CF to the West (8th CF from Abutment 1)
4- Lifting Crane on G1 @ 3.8 ft away from the closest CF to the West (2nd CF from Bent 1)

Reference Photo @ top of p-26 of App 3 of QPR

Central

Stress # 4

Figure 22 A

105A1 & 110A2 in place
1. Cribbing on G1 @ 13.7 ft away from the closest CF to the West (5th CF from Abutment 1)
2. Lifting Crane on G2 @ 20 ft away from the closest CF to the West (3rd CF from Abutment 1)
3. Lifting Crane on G2 @ CF location (4th CF from Abutment 1)

Reference Photo @ bottom of p32 of App 3 of QPR

104B1 in place with CF attached
1. Cribbing on G1 @ 13.7 ft away from the closest CF to the West (5th CF from Abutment 1)
2. Lifting Crane on G2 @ 7.7 ft away from the closest CF to the West (9th CF from Abutment 1)
3. Lifting Crane on G2 @ 3.8 ft away from the closest CF to the West (2nd CF from Bent 1)

Reference Photo @ top of p-37 of App 3 of QPR
1. Lifting Crane on G1 @ 20.2 ft away from the closest CF to the West (5th CF from Bent 5)
2. Lifting Crane on G1 @ 4.6 ft away from the closest CF to the West (7th CF from Bent 5)

Reference Photo @ bottom of p-134 of App 3 of QPR

ECCR214

169B14 in place with all CF attached
1-Lifting Crane on G1 @ 11.7 ft away from the closest CF to the West (7th CF from Bent 6).
2-Lifting Crane on G1 @ 5.9 ft away from the closest CF to the West (10th CF from Bent 6).

Reference Photo @ pp-151&152 of App 3 of QPR
Reference Photo @ bottom of p-162 of App 3 of QPR

Stage # 9

All spans fully erected
Summary of Preliminary Results

Lifting of Girder G170A14
Girder layover during lifting

GIRDER 170A14 - Holding Crane

Layover (in.)

-6.00 -4.00 -2.00 0.00 2.00 4.00 6.00
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

6.5 in. (predicted)
8.4 in. (measured)

Normalized Length

- u1-bf-nonlinear - u1-tf-nonlinear - u1-rel-nonlinear - u1-Measured
Stresses:
(11:36AM-12:00PM, 3 min readings)

GIRDER 1 - BOTTOM FLANGE

GIRDER 1 - TOP FLANGE
Lifting of Girder 170

Rotation of Girder 170

- Beam in the air
- Splices and cross-frames being placed
- Steady state

Approx. 5.5° of layover recovered as beam is being placed

Approx. 6.7° of layover during lifting

Time:
- 3/7/10 10:57
- 3/7/10 11:57
- 3/7/10 12:57
- 3/7/10 13:57
Girder 170, Line 20

Microstrain vs Temperature (°C) over time for various locations on Girder 170, Line 20.
Summary of Preliminary Results

Comparison of Analysis Methods
Comparison of Simplified vs. 3D FEA Results

GIRDER 1 - TOP FLANGE

Normalized Length

f_b (ksi)
Comparison of Simplified vs. 3D FEA Results

GIRDER 2 - TOP FLANGE

Normalized Length

$ f_t \text{ (ksi) }$

FEA-NL  ····  1D-Max  MDX-Max  LARSA-Max  FEA-Max
Comparison of Simplified vs. 3D FEA Results

GIRDER 1

Vertical Displacement (in.)

Normalized Length

- u3-FEA-NL
- u3-1D
- u3-MDX
- u3-LARSA
Comparison of Simplified vs. 3D FEA Results

**GIRDER 1**

<table>
<thead>
<tr>
<th>Radial Displacement (in.)</th>
<th>Normalized Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

- **FEA-Nonlinear**
- **LARSA**
Summary

• The comparisons show that the simplified 1D and 2D methods are sufficient to match the expected response of the bridge, as predicted by the 3D FEA.

• Major-axis bending stresses are accurately captured, even at Span 7, where the girder is subject to negative moment along its entire length.

• Flange lateral bending stress predictions based on the V-Load method equation have the same trend as the 3D prediction... The V-load method vertical displacements are a less accurate in Span 8.
Summary (cont.)

• The vertical displacement predictions are reasonably accurate for all the methods... The limitations of the 2D grid models in representing the torsional stiffness of the I-girders does not affect the response

• Radial displacements (layover) are accurately predicted by the 2D grid model at the cross-frame locations... At these positions the response of the group predominates over the response of each individual girder... The 2D model is able to capture this behavior.

• Within the unbraced length (i.e., between cross-frames), the layover prediction is inaccurate... The reason is the absence of warping stiffness contributions in the computer formulation of the 2D grid elements
On-Going Research

- Live load testing of completed structure
- Additional analyses of construction stages and of live load testing
- Final report (December 2010)
Live Load

• Heavy, short wheelbase vehicles (fully loaded tri-axle dump trucks)
• 10 trucks
• Each truck, approx. 72 kips, truck plus aggregate
• 20 positions on the bridge
Load Position B8
G1, Loading B8, Vertical Displacement

Vertical Displacement (in.)

Normalized Bridge Length

With Parapets
Without Parapets
Field Measurements
G5, Loading B8, Vertical Displacement

![Graph showing vertical displacement over normalized bridge length with and without parapets, along with field measurements.](image-url)
G1, Loading B8, Bottom Flange Stress

Normalized Bridge Length

f_\ell \text{ (ksi)}

Normalized Bridge Length

With Parapets

Without parapets

Field Measurements
Summary

• Unique set of data being developed – distribution of thermal stresses for example
• Robust and comprehensive measurements capable of giving a complete picture of system behavior
• Successful measurements during different stages of construction
• Good initial correlation between analytical and experimental values
Partial/Preliminary Findings

• Second Order Amplification of the Overall Torsional Displacements and Flange Lateral Bending Stresses can be large when the structural system is relatively narrow, compared to span length
• Overall overturning instability and high 2\textsuperscript{nd} Order Amplification of the girder responses are independent phenomena.
• Concrete slab placement on narrow stages in phased construction can be problematic.
• Basic beam or frame elements commonly available in analysis and design packages can give rater poor predictions of displacements in cases involving the following attributes, or some combination thereof:
  - More highly curved alignments
  - Girders connected with fewer cross-frames
  - There are fewer number of girders in the bridge cross-section (final or intermediate stages)
  - Girders have more narrow flanges and/or thinner plates
Partial/Preliminary Findings (Cont.)

• Common analysis models in software packages do not include torsional stiffness quantification associated with the warping response (flange lateral bending) of I-girder bridges, leading to poor displacement predictions.

• Generally, flange lateral bending stresses in positive bending regions in many curved girders can be reasonably estimated with the basic equations in the AASHTO LRFD commentary. In the negative bending regions, these stresses are significantly less accurate. This is because the cited equations presume uniform bending, whereas the bending moment gradient in negative bending is quite steep.
• The effect of sequential deck concrete placement on overall bridge response appears to be rather minor compared to the responses obtained from an idealized one-step deck placement, particularly if the positive moment areas are placed first and negative moment areas are placed last.