Evaluation of Reserve Shear Capacity of Bridge Pier Caps Using the Deep Beam Theory

Presented by: Pappu Baniya
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Introduction

- Pier caps transfer the load from girder to piers

- In Ohio – 28,000 bridges
Problem Statement

When analyzed, most bridge pier caps are found to be shear overloaded.

When inspected in the field, they look just fine.

Is the analysis method not appropriate for pier caps?

What is the riddle???
Problem Statement

- Most of the bridge pier caps are found to be overloaded
- Limited funding for repair and rehabilitation
Objective

• To determine a practical and accurate analysis methodology for bridge pier caps.

• To develop a solution algorithm/computer program based on the suitable method → STM-CAP.

• To verify the developed solution procedure (STM-CAP).

• To compare the results of STM-CAP with conventional analysis method.
• Kani performed shear tests in 1964;
Solution Approach

- **Beam**
  - **Shear Span-to-Depth Ratio (a/d) <2.0**
    - **No**
      - **Slender Beam**
        - **Sectional Method**
    - **Yes**
      - **Deep Beam**
        - **Strut-and-Tie Method**
        - **Non-Linear Analysis**
Methodology

- Strut and Tie Model (STM)
  - Considers strut action for deep pier cap.
  - Conceptual truss model to give a definite load-path.
Methodology

- **Girder Loads**
- **Nodes**
- **Strut**
- **Tie**
- **Columns**

Ties $\rightarrow$ Tension for Rebar & Stirrup

Struts $\rightarrow$ Compression for Concrete
Methodology

- STM is a complex method for daily design and analysis tasks.

- Explore innovative strategies to reduce the complexity of the STM to a level comparable to the sectional method.

- **STM-CAP**, stands for Strut and Tie Method for pier CAPs.
STM-CAP

- About 14 modules and 4000 lines of code.
- Embedded into spreadsheet.
Overview of STM-CAP

Input Geometry Details

3. Geometry Details

<table>
<thead>
<tr>
<th>Distance from start of the pier cap to center of first column (C1)</th>
<th>7 ft</th>
<th>6 in</th>
<th>90 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from center of first column to center of second column (C2)</td>
<td>14 ft</td>
<td>6 in</td>
<td>174 in</td>
</tr>
</tbody>
</table>

6. Check whether the Pier Cap is Deep

<table>
<thead>
<tr>
<th>Region</th>
<th>Shear span (a)</th>
<th>a/d ratio</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>60.33 in</td>
<td>1.40</td>
<td>Deep Region</td>
</tr>
<tr>
<td>R2</td>
<td>0.00 in</td>
<td>0.00</td>
<td>Zero Region</td>
</tr>
<tr>
<td>R3</td>
<td>81.67 in</td>
<td>1.89</td>
<td>Deep Region</td>
</tr>
<tr>
<td>R4</td>
<td>71.00 in</td>
<td>1.64</td>
<td>Deep Region</td>
</tr>
<tr>
<td>R5</td>
<td>0.00 in</td>
<td>0.00</td>
<td>Zero Region</td>
</tr>
</tbody>
</table>

This pier cap is deep. Please continue with Section 7.
Overview of STM-CAP

START

Input Geometry Details

Input Factored Load Details (girder load, girder spacing)

Deep or Slender? (a/d ratio)

Deep (a/d < 2.0)

Input Material Properties
($f'c$, $f_y$, rebar diameter, stirrup bar area)

Input Reinforcement Details
(Area and centroid of longitudinal rebar, area and spacing of stirrup)

Input Resistance Factors
($\varphi_c$, $\varphi_s$, node multiplier)

<table>
<thead>
<tr>
<th>Region</th>
<th>Top Steel (in², in)</th>
<th>Bottom Steel (in², in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area ($A_t$)</td>
<td>Centroid ($C_t$)</td>
</tr>
<tr>
<td>R1</td>
<td>13.97</td>
<td>6</td>
</tr>
<tr>
<td>R2</td>
<td>13.97</td>
<td>6</td>
</tr>
<tr>
<td>R3</td>
<td>13.97</td>
<td>6</td>
</tr>
<tr>
<td>R4</td>
<td>13.97</td>
<td>6</td>
</tr>
<tr>
<td>R5</td>
<td>13.97</td>
<td>6</td>
</tr>
</tbody>
</table>

Top bar
Layer 1: 7 nos. #10
Layer 2: 4 nos. #10
Total Area: 13.97 in²
Centroid: 5.95 in

Bottom bar
Layer 1: 7 nos. #9
Total Area: 7 in²
Centroid: 4 in
Overview of STM-CAP

- Strut and Tie Method (STM)

- Capacities are based on Clause 5.6.3.1 of AASHTO LRFD 2014.
Overview of STM-CAP

Utilization Ratio = Force/Capacity

<table>
<thead>
<tr>
<th>Member Code</th>
<th>Load (k)</th>
<th>Capacity (k)</th>
<th>Utilization Ratio</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-F</td>
<td>533</td>
<td>754</td>
<td>0.71</td>
<td>PASS</td>
</tr>
<tr>
<td>E-K</td>
<td>95</td>
<td>754</td>
<td>0.13</td>
<td>PASS</td>
</tr>
<tr>
<td>2-6</td>
<td>-533</td>
<td>-771</td>
<td>0.69</td>
<td>PASS</td>
</tr>
<tr>
<td>5-8</td>
<td>37</td>
<td>378</td>
<td>0.10</td>
<td>PASS</td>
</tr>
<tr>
<td>8-12</td>
<td>-95</td>
<td>-680</td>
<td>0.14</td>
<td>PASS</td>
</tr>
<tr>
<td>B-1</td>
<td>-</td>
<td>-</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>F-5</td>
<td>261</td>
<td>547</td>
<td>0.48</td>
<td>PASS</td>
</tr>
<tr>
<td>H-7</td>
<td>-</td>
<td>-</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>A-2</td>
<td>-627</td>
<td>-826</td>
<td>0.76</td>
<td>PASS</td>
</tr>
<tr>
<td>F-6</td>
<td>-386</td>
<td>-923</td>
<td>0.42</td>
<td>PASS</td>
</tr>
<tr>
<td>E-5</td>
<td>-386</td>
<td>-937</td>
<td>0.41</td>
<td>PASS</td>
</tr>
<tr>
<td>E-8</td>
<td>-149</td>
<td>-782</td>
<td>0.19</td>
<td>PASS</td>
</tr>
</tbody>
</table>
Overview of STM-CAP

- Determines the overload type and probable location.

If $>1$, Flexure Overload  
If $>1$, Shear Overload  
If $>1$, Compression Overload

- Plan load limit (load rating) for the bridge pier cap.
- Right funding at right place.
- Very fast analysis (10 to 30 minutes) for a single pier cap.
- No specialized knowledge about STM is required.
CAST Verification

- CAST (Computer Aided Strut-and-Tie)
  - Research-based, general purpose strut-and-tie software.
  - Uses ACI formulations (modified for AASHTO)

STM-CAP

CAST

- Eight (8) bridge pier caps were modeled with STM-CAP and CAST
- Accuracy within ±5%
Nonlinear FEM Verification

VecTor2

- 2D continuum finite element model
- Based on Modified Compression Field Theory
- Smeared rotating crack model
- Second order material behaviors
Nonlinear FEM Verification

- Existing Cap Beam
Nonlinear FEM Verification

- Existing Cap Beam

```
DL+LL  DL+LL  DL+LL
 |     |     |
 |     |     |
 |     |     |
```
Nonlinear FEM Verification

• Existing Cap Beam
• Nonlinear FE Model

<table>
<thead>
<tr>
<th>245 491 491 245</th>
<th>DL+LL</th>
<th>DL+LL</th>
<th>DL+L 245 491 491 245</th>
</tr>
</thead>
</table>

- Beam: 0.7% stirrups
- Beam: 0.3% stirrups
- Beam: 0.1% stirrups
- Column
- Concrete Cover
Determination of Utilization Ratios

1. Stresses at failure load
2. Critical region marked
3. Same region marked at factored load
4. Average stresses at each region at factored load
5. Divided by capacity
6. Utilization Ratio
Nonlinear FEM Verification

Comparison of Utilization Ratios

Utilization ratios are 40% of STM-CAP results. Behavior matches.
Nonlinear FEM Verification

Higher capacity from Nonlinear FEM but more analysis time.
The trend of capacities, for different a/d ratio, is similar from both methods.
Comparison with Sectional Method

- Not a valid/appropriate method for deep pier caps.

<table>
<thead>
<tr>
<th>Sections</th>
<th>a/d ratios</th>
<th>Sectional Method (UR)</th>
<th>STM-CAP (UR)</th>
<th>Sectional Method (UR) STM – CAP (UR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-A</td>
<td>0.69</td>
<td>0.54</td>
<td>0.22</td>
<td>2.45</td>
</tr>
<tr>
<td>B-B</td>
<td>1.72</td>
<td>0.60</td>
<td>0.55</td>
<td>1.09</td>
</tr>
<tr>
<td>C-C</td>
<td>2.80</td>
<td>0.25</td>
<td>0.3</td>
<td>0.83</td>
</tr>
<tr>
<td>D-D</td>
<td>2.29</td>
<td>0.53</td>
<td>0.38</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Shear Utilization Ratio (UR) Comparison at Different Sections
Comparison with Sectional Method

Capacity $\propto \frac{1}{\text{Utilization Ratio}}$

Shear span-to-depth ratio (a/d)

- Sectional Method
- STM-CAP (Optimized)
- Nonlinear FEM
Conclusion

• Developed a specialized Strut-and-Tie analysis tool for pier cap, STM-CAP.
• STM-CAP uses VBA coding to provide graphical solution.
• Modeling + Analysis time (10 minutes to 30 minutes).
• Does not require any specialized knowledge about Strut and Tie Method (STM).
• Validated the accuracy of STM-CAP using CAST and NLFEA.
• Demonstrated that the Sectional Method underestimates the shear capacity of a pier cap (up to 3 times).
Conclusion

• STM-CAP is more accurate than the sectional method and an easier platform than nonlinear FEM (a good compromise between complexity and accuracy).

• STM-CAP can determine if a pier cap require rehabilitation. If so, it indicates O/L type and location.

• STM-CAP allows ranking overloaded cap beams so that limited resources can be used for the most urgent ones.
Acknowledgements

Review Panel
Ms. Andrea Parks, PE
Mr. Matthew Blythe, PE
Ms. Michelle Lucas
THANK YOU!

Questions?
• Right funding → Right place

Cost Saving

Reduced Congestion

Reduced Safety Risk
• Pier cap of bridge MOT-075-6.36

Width of D-region = h

R1  R2  R3
• Elements of STM
  • Struts
  • Ties
  • Nodes

<table>
<thead>
<tr>
<th>Element</th>
<th>Nature</th>
<th>Represents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strut</td>
<td>Compression Member</td>
<td>Concrete</td>
</tr>
<tr>
<td>Tie</td>
<td>Tension Member</td>
<td>Reinforcement</td>
</tr>
<tr>
<td>Node</td>
<td>Connection (Joint)</td>
<td>Concrete</td>
</tr>
</tbody>
</table>
• Use of Vertical Tie in STM

Without Vertical Tie

With Vertical Tie
• Hand Calculation for Thirteen (13) Sample Bridges.
  - Using two models
    a. Without vertical ties
    b. With vertical ties
- Eight (8) bridge pier caps → modeled with STM-CAP and CAST
- Accuracy within ±5%

<table>
<thead>
<tr>
<th>Bridge Name</th>
<th>Model</th>
<th>STM-CAP</th>
<th>CAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOT-075-0666R</td>
<td>Tension Ties</td>
<td>0.71</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.76</td>
<td>0.75</td>
</tr>
<tr>
<td>MOT-075-1979</td>
<td>Tension Ties</td>
<td>1.02</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.83</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>MOT-075-1881</td>
<td>Tension Ties</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>AUG-075-1234</td>
<td>Tension Ties</td>
<td>0.48</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>MOT-075-0306</td>
<td>Tension Ties</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>MOT-075-0075</td>
<td>Tension Ties</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.55</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>MOT-075-1433 (left southbound)</td>
<td>Tension Ties</td>
<td>0.33</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.39</td>
<td>0.39</td>
</tr>
<tr>
<td>MOT-075-1433 (right southbound)</td>
<td>Tension Ties</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Horizontal Struts</td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Inclined Struts</td>
<td>0.48</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Applicability of STM:

Sectional Method

Bernoulli Hypothesis

Strain Distribution Linear

B-region
• First introduced, 1994 as appendix

• From 2007, compulsory for D-region and Deep member

• Most bridge designers have not embraced the strut and tie model due to the unfamiliarity with the design procedure
Strut and Tie Method:

Ties → Tension for Rebar & Stirrup

Struts → Compression for Concrete

Nodes → Compression or Tension
• Deep beams
  – The beams with shear span-to-depth ratio \( \frac{a}{d} \) less than 2.0 are classified as Deep Beams.
    \[
    \frac{a}{d} < 2.0
    \]
    \[a < 2 \times d\]
  – The distance between load and reaction should be less than 2 x depth of beam

Centroid of tension reinforcement
• Kani performed shear test in 1964;

Kani's Shear Test

Shear Strength/$f'_c$

Shear-Span Ratio ($a/d$)

Experiment
Strut and Tie Method
Sectional Method

Some other literatures:
- Ferguson and Liao (1966)
- Rogowsky et al. (1983)
- Denio et al. (1995)
- Young et al. (2000 & 2002)
- Higgins et al. (2008)
- Cunningham, L.S. (2000)
- Milde et al. (2005)