Evaluation of Damaged Prestressed Bridge Girders

Azam Nabizadeh
Habib Tabatabai

University of Wisconsin-Milwaukee

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Two primary modes of accidental damage to prestressed bridge girders:

- Impact due to over-height vehicles (primarily at the bottom flange)
- Damage during deck removal processes (top flange)

Substantial prior information available on damage due to over-height vehicles.

Earlier studies do not address:

- Changes in service stresses
- User tools to assess damage, design repairs, and assess repaired strength.
Objectives

- **Overall Objective**
  - Develop recommendations and guidelines for the inspection, evaluation, repair, or other needed safety and operational response related to damaged prestressed concrete girders.

- **Specific objectives**
  - Develop guidance on inspections
  - Develop recommendations on determining and categorizing extent of damage
  - Develop tools for assessing effects of damage on strength and serviceability
  - Develop recommendations regarding types of repairs and repair procedures.
Scope

- Comprehensive review of literature
- Field assessments
- Damage Categorization (top and bottom flange)
- Inspection and repair procedures (top and bottom damage)
- Procedures for service stress calculations (undamaged, damaged, and repaired)
- Procedures for strength calculations (undamaged, damaged, and repaired)
- PreBARS software (for Wisconsin sections/practices)
- Case studies
- Recommendations
## Damage Categories

### Bottom Flange Damage

<table>
<thead>
<tr>
<th>Damage Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>Concrete nicks, gouges, scrapes, and cracks that are less than 0.006 in wide, without any exposed or partially exposed strands.</td>
</tr>
<tr>
<td>Moderate</td>
<td>Cracking and spalling of concrete that exposes at least one strand, but no severed strands.</td>
</tr>
<tr>
<td>Significant</td>
<td>Cracking and spalling of concrete and less than 15% of all strands severed at the area of maximum damage.</td>
</tr>
<tr>
<td>Serious</td>
<td>Cracking and spalling of concrete; severed strands are more than 15% and less than 25% of all strands.</td>
</tr>
<tr>
<td>Severe</td>
<td>Cracking and spalling of concrete; severed strands are more than 25% of all strands.</td>
</tr>
</tbody>
</table>

### Top Flange Damage

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<th>Damage Category</th>
<th>Description</th>
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<tbody>
<tr>
<td>Minor</td>
<td>Concrete nicks, gouges, scrapes, and cracks that are less than 0.006 in wide. Spalled area less than 25% of top flange area; no cracking near supports due to girder uplift; girder sweep &lt;1/8-in over 10 ft length; no damage to interface shear reinforcement.</td>
</tr>
<tr>
<td>Moderate</td>
<td>Spalled area more than 25% and less than 50% of top flange area; no cracking near supports due to girder uplift; girder sweep &lt;1/8-in over 10 ft length; little to no damage to interface shear reinforcement.</td>
</tr>
<tr>
<td>Significant</td>
<td>Spalled area more than 50% of top flange area; or cracking near supports due to girder uplift; or girder sweep &gt;1/8-in over 10 ft length; or extensive damage to interface shear reinforcement.</td>
</tr>
</tbody>
</table>
Early repair methods
- Crack injections
- Patching (with or without preload)
- Splicing
- Attachment of steel plates
- Post-tensioning (with corbels)

Current methods
- Crack injections
- Patching (with or without preload)
- Splicing
- CFRP application (bottom of flange [soffit] or two faces of webs)
A comprehensive software program has been developed:

- **Prestressed Bridge Assessment, Repair, and Strengthening (PreBARS)**
  - PreBARS assesses serviceability and strength of PS girders under undamaged, damaged, and repaired conditions
  - Standard Wisconsin I-girders and adjacent box sections
  - Up to 3 continuous or simply-supported spans with each span up to 160 ft long
  - Strand patterns used in Wisconsin

PreBARS is developed within Microsoft Excel® using its VBA (visual basic application) capability.

The program calculates:

- Bridge loads (HL-93) including truck, tandem and lane loads
- Distribution factors (interior and exterior)
- Prestress losses (approximate and refined)
- Preload moments (when used)
- Service stresses
- Section strength
- All calculations at 1-ft increments
PreBARS

- Considers top and bottom flange damage cases
- Procedures developed to calculate changes in section properties, service stresses, and flexural strength under undamaged, damaged, and repaired conditions
- The effects of patching, internal strand splices, external carbon fiber reinforced polymer (CFRP) reinforcement, as well as a combination of these methods, are considered for repair.
- Calculation of Strength I, Service III, Service I, Extreme Event II, ACI 440.2R limit for CFRP application, ...
- Choice of 0.8 or 1.0 for the service III load factor
- Consideration of non-symmetrical section as a result of damage.
- Bottom damage cases include strength calculations, inventory and operating rating, stress checks, etc.
- Top damage calculations include stress checks under non-composite condition, strength of non-composite girder, rating factor for non-composite girder, and strength of composite section.
Representation of Section in Excel
Damage Introduced by Deleting Cells
Repairs

- Girder concrete
- Undamaged strand (black)
- Spliced strand (brown)
- Severed strand (white)
- CFRP sheet
- Patch
Stress change due to damage

Change in stress due to the effect of prestressing force:

$$\sigma = \frac{P}{A} + \left( \frac{(Pe)_y}{l} \right)_x + \left( \frac{(Pe)_x}{l} \right)_y$$

$$\Delta \sigma = \frac{\Delta PA - \Delta AP}{A^2} + \frac{(\Delta Pe_y y + P(\Delta e_y y + \Delta y e_y)) I_x - \Delta I_x Pe_y y}{l_x^2} + \frac{(\Delta Pe_x x + P(\Delta e_x x + \Delta x e_x)) I_y - \Delta I_y Pe_x x}{l_y^2}$$

Change in stress due to the external moment from dead load and transient loads:

$$\sigma = \frac{M_y I_x - M_x I_y}{I_x I_y - I_{xy}} x + \frac{M_x I_y - M_y I_{xy}}{I_x I_y - I_{xy}} y$$

$$\Delta \sigma = \left( \frac{BD - EA}{B^2} \right)_x + \left( \frac{BF - EC}{B^2} \right)_y$$

$$A = M_y I_x - M_x I_{xy}$$

$$B = I_x I_y - I_{xy}^2$$

$$C = M_y I_y - M_y I_{xy}$$

$$D = x[\Delta M_y I_x + M_y \Delta I_x - \Delta M_{xx} I_{xy} - M_x \Delta I_{xy}] + \Delta x A$$

$$E = \Delta I_x (I_y) + I_x (\Delta I_y) - 2I_{xy} (\Delta I_{xy})$$

$$F = y[\Delta M_x I_y + M_x \Delta I_y - \Delta M_{yy} I_{xy} - M_y \Delta I_{xy}] + \Delta y C$$
Strength Calculations

- Based on strain compatibility (AASHTO 5.6.3.2.5)
- Strain limit in concrete: 0.003
- Stress-strain behavior of concrete, prestressing steel and CFRP
- Position of neutral axis at the strength limit state is determined.
- Equilibrium of forces is maintained and failure moment is calculated.
- Strain at centroid of steel and CFRP is checked.
- Failure curvature is calculated
Case Studies

Two structures:
• 146 ft span with Wisconsin 72W girders
• 50 ft span with 36” AASHTO girder

Two types of damage:
• Bottom damage
• Top damage

Extent of damage:
• Bottom damage: 0, 10%, 15%, 20%, 25% loss of strand
• Top damage: 0, 10%, 20%, 30%, 40%, 50% loss of top flange area
Strength – Bottom Damage

146 ft span

50 ft span
Maximum Soffit Stress – Top Damage

Max Stress - Bottom of Girder - Non-Composite Under Self Weight

146 ft span

Max Stress - Bottom of Girder - Non-Composite Under Self Weight

50 ft span
<table>
<thead>
<tr>
<th>Damage category</th>
<th>Definition</th>
<th>Bottom Damage Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Damage</td>
<td>Nicks, gouges, scrapes, cracks (less than 0.006 in wide), and/or limited spalling without any exposed or partially exposed prestressing strands</td>
<td><img src="image1.png" alt="Undamaged bottom flange" /> <img src="image2.png" alt="Damaged bottom flange/no severed strand" /></td>
</tr>
<tr>
<td>Moderate Damage*</td>
<td>Cracking and spalling that would partially or fully expose at least one prestressing strand. Strands with damaged, deformed, or kinked wire(s) should be considered severed</td>
<td><img src="image3.png" alt="Exposed strands" /></td>
</tr>
<tr>
<td>Significant Damage</td>
<td>Cracking and spalling of concrete within the impact zone, not more than 15% of all strands severed</td>
<td><img src="image4.png" alt="Less than 15% severed strands" /></td>
</tr>
<tr>
<td>Serious Damage</td>
<td>Cracking and spalling of concrete within the impact zone, more than 15% and less than 25% of all strands severed</td>
<td><img src="image5.png" alt="15% to 25% severed strands" /></td>
</tr>
<tr>
<td>Severe Damage</td>
<td>Cracking and spalling of concrete within the impact zone, more than 25% of all strands severed</td>
<td><img src="image6.png" alt="More than 25% severed strands" /></td>
</tr>
</tbody>
</table>

* In cases where there are no severed strands but at least 25% of concrete in the flange and/or web is missing, higher condition categories should be considered.
# Damage Categories – Top Flange

<table>
<thead>
<tr>
<th>Damage category</th>
<th>Definition</th>
<th>Top Damage example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Damage</td>
<td>Nicks, gouges, scrapes, cracks (less than 0.006 in wide), localized loss (less than 25% of the area of top flange), no damage to the interface shear reinforcement, no cracking near the supports, girder sweep (at the top flange) that is not more than 1/8 in per 10 ft.</td>
<td><img src="image" alt="Undamaged top flange" /> <img src="image" alt="Minor Damage to top flange" /></td>
</tr>
<tr>
<td>Moderate Damage</td>
<td>Localized loss of between 25% and 50% of the cross section of the top flange, no damage to the interface shear reinforcement, no cracking observed near the supports due to girder vertical deformation, and girder sweep (at the top flange) that is less than 1/8 in per 10 ft.</td>
<td><img src="image" alt="Moderate Damage to top flange" /></td>
</tr>
<tr>
<td>Serious Damage</td>
<td>Localized loss of greater than 50% of the cross section of the top flange, extensive damage to the interface shear reinforcement, or out-of-tolerance sweep of the top flange of the girder.</td>
<td><img src="image" alt="Serious Damage to top flange" /></td>
</tr>
</tbody>
</table>
# Repairs – Bottom Flange

<table>
<thead>
<tr>
<th>Damage category</th>
<th>Inspection and Assessment</th>
<th>Repair methods</th>
</tr>
</thead>
</table>
| Minor Damage       | • Conduct close visual inspection.  
• Record bridge information and location of damaged girder (exterior or interior).  
• Evaluate condition of concrete (including spalled and loose concrete).  
• Note cracking (including crack widths) and map orientation of all cracks including those in the web, deck slab, diaphragms, and barrier walls.  
• Record any girder sweep (out-of-plane deformation).  
• Record location of damage and size/extent of spalls and loose concrete.  
• Provide a sketch of the cross section with the largest loss of section.  
• Measure out-of-plane deformation.  
• Inspect bearings for any signs of damage.  
• Provide detailed pictures (with accompanying explanations) from all affected areas.  
• An engineer should carefully examine the information obtained during inspection.  
• Reevaluate the damage category based on analysis of data. | • Use only hand tools in removing any loose concrete.  
• Delineate the limits of patch area using a shallow saw cut.  
• Avoid damage to strands or stirrups.  
• Use low-modulus epoxy material for nicks and gouges.  
• When patching, use higher modulus patch materials.  
• Investigate bond properties of patch material to avoid debonding in the future.  
• Follow patch manufacturer’s recommendations and sound industry practices for substrate surface preparations. |
| Moderate Damage    | In addition to items listed for minor damage:  
• Evaluate and record condition of exposed strands including dents, cracks, distortions, and corrosion.  
• Review all field data and analyze the structure.  
• Assessment should be made regarding the application of preloading.  
• In case of pre-loading application, use a patching material with modulus of elasticity compatible with the substrate concrete. | In addition to items listed for minor damage where applicable:  
• Remove concrete around exposed strands (3/4” gap) to allow full encasement of the exposed strand with the patch material.  
• Inject all cracks that exceed a width of 0.006 with epoxy. Treat other cracks with a sealer.  
• Epoxy application should be after the application of preload (where applicable) and prior to patching. |
<table>
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<tr>
<th>Damage Level</th>
<th>Recommendations</th>
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</table>
| **Significant Damage** | - Investigate if repairs can address the problem in case of out-of-plane sweep of girder (that is a result of the impact) exceeding the specified tolerance  
- Use CFRP U-wraps over the entire patch area if patch area is not small (above the minor category).  
- If repairs cannot address the out of plane sweep, replace the girder.  
- In addition to items listed for minor and moderate damage;  
  - Identify the location and exposed lengths of all severed strands.  
  - Analyze the structure and check service and strength limit state conditions.  
  - Calculate the AASHTO-specified design forces for the damage location.  
  - Assess service stresses before and after patching with preload, if applicable.  
  - The software tool (PreBARS) can assist in the analyses.  
  - Assess structural condition and repairs at damage location and point of maximum moment, damage at or near the tie-down location.  
  - Investigate loss of concrete above the harped strands in the tie-down location.  
  - Evaluate structural repair options to restore member strength and serviceability to the required/wanted level.  
  - Use of internal strand splices  
  - Use of longitudinally oriented carbon fiber composites (CFRP)  
  - Application of preloading (if required) before patch that remains in place until the patch material has gained sufficient strength and stiffness.  
  - Use of post-tensioning systems  
  - Coating CFRP materials with a protective coating for outdoor use as suggested by the manufacturer  
  - Patching with internal strand splices or a combination of splices and CFRP application  
  - Attaching steel plates to the bottom flange or the web. |
| **Serious Damage** | - In addition to applicable items listed for minor, moderate, and significant damage;  
  - Record the vertical (loss of camber) and horizontal (sweeping) deformations of the girder.  
  - Record any cracking of the deck.  
  - Check service stresses in the concrete and strain at the centroid of prestressing steel.  
  - Investigate the need for temporary traffic restrictions above and/or below the bridge.  
  - In addition to items listed for minor and moderate damage, consider the following where applicable;  
  - A combination of internal strand splices and external CFRP reinforcement  
  - Preloading (recommended)  
  - Application of external CFRP reinforcement after patch installation is complete and sufficiently aged  
  - Use of CFRP U-wraps (with CFRP fabric in wet layup process)  
  - Application of CFRP protective coating per manufacturer’s recommendations. |
| **Severe Damage** | - In addition to applicable items listed for minor, moderate, and significant damage;  
  - Any repair in lieu of replacement should be considered experimental and carefully examined. |
• Consider safety and stability issues.
• Design for the removal and replacement of damaged girder.
• Consider safety and durability for the design of new girder.
• Evaluate joint condition between the old barrier and the new deck at or near the curb.
• Consider the potential for future impacts unless steps are taken to address any clearance shortfalls that may exist.

*For a complete list, see the full description in Chapter 9.
Detailed information on the project are provided in a research project report to the Wisconsin Department of Transportation (Tabatabai and Nabizadeh, 2019).