Extending the Life of Prestressed Concrete Bridge Infrastructure

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Two Stories...

Following the 2005 collapse of the Lake View Drive Bridge, Dr. Harries made a [bold] statement: 

*This girder/bridge was repairable*

The demonstration of this conclusion was developed through:

- two PennDOT-funded projects
- NCHRP Project 20-07/307
- two independent studies
- one industry-funded investigation
- and NCHRP Project 12-95

Resulting in:

- seven refereed journal articles
- three international conferences presentations (Canada, Korea, UK)
- four publically available technical reports
- one international research award
Motivation

Unknown existing condition issues with precast concrete bridge girders...

Charlotte NC
May 2000

Washington PA
December 2005

... and impact damage...

Laval Qc
October 2006
Impact damage

Lake View Drive collapse onto I-70. Impact damage led to significant strand loss, subsequent corrosion and eventual collapse under girder self-weight.

Impact damage to facia beam of McIlvaine Road over I-70. Entire bridge was demolished within 24 hours.

Bridge over I-26 north of Columbia SC showing evidence of significant vehicle impact.

Crawford Lane over I-70 showing relatively minor impact damage
Damage Assessment: Cracking and Strand Loss

**Typical damage from vehicle impact**

Splitting-like cracks from a variety of sources

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**125% Rule**

When considering strand loss, consider adjacent strands:

125% of observable strand loss when extent of corrosion *is* explored

150% when extent is *not* explored.
Damage Assessment: Strand ‘Redevelopment’

Typically, the contribution of severed and corroded strands will be neglected in load rating *along the entire span*.

However, the strand transfer length is ‘redeveloped’ through the Hoyer effect and strand-to-concrete bond.

Away from the damage, the strand remains fully developed and may be relied upon for capacity.

The Hoyer effect enhances prestress transfer through the diametric expansion of the strand.

Loss of or absence of shear key and/or transverse tie rods result in individual girders acting independently

*Increase in loads on girders:*

Barrier wall loads not distributed to interior girders resulting in *eccentric loading* conditions on exterior girders

Live load increases approximately 66% based on AASHTO distribution factors.

Shear key details are presently the subject of newly awarded NCHRP Project 12-95 (PI: Dr. Brent Phares at Iowa State).
Damage Assessment: Adjacent Box Girder Bridges

Curb slab/barrier wall construction ultimately results in a composite *asymmetric section* having an *eccentric load*

Impact damage typically affects the exterior soffit corner resulting in additional *asymmetry*

*Asymmetric damage to asymmetric sections loaded eccentrically* results in significant *biaxial flexural effects* which reduce the actual and apparent capacity of the exterior girders.

Despite this, typical engineering assessment is 1D analysis
Analysis of eccentrically loaded box girders

Biaxial nonlinear fiber element section analysis program (XTRACT)

Determines $M_x$-$M_y$ failure surface based on user selected failure strains:

- $\varepsilon_{cu} = 0.003$
- $\varepsilon_{pu} = 0.010$
- $\varepsilon_{su} = 0.100$

Test Girder from Lake View Drive Bridge

Harries, K.A. (2009) Structural Testing of Prestressed Concrete Girders from the Lake View Drive Bridge, ASCE Journal of Bridge Engineering 14(2)
Test Girder from Lake View Drive Bridge

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Test Girder from Lake View Drive Bridge

Analysis of Lake View Drive Exterior Girder

Locate and identify nature and extent of damage along length of beam

Analysis of Lake View Drive Exterior Girder

Perform multiple 2D sections analyses, stitching these together considering ‘redevelopment’ of severed strands.

Analysis of Lake View Drive Exterior Girder

Applied moment

- Moment due to self weight plus 326.5 kN applied load
- 326.5 kN applied axle load
- 111.2 kN applied axle load

Analysis of Lake View Drive Exterior Girder

Observed Failure and Damage

Significant over estimation of capacity using conventional 1D analysis. Underestimation of capacity if only critical section is considered. In this case, 125% rule accounted for additional unseen damage.

Field testing of Prestressed Box Girder

Damaged exterior girder recovered from decommissioned bridge in SW PA

Girder at test site prior to recasting top slab

Applied loading using same set-up as Lake View Drive study

Impact and subsequent deterioration damage documented

Field testing of Prestressed Box Girder

Girder capacity predictions made accounting for eccentricity and strand redevelopment

Instrumentation using innovative fiber optic system based on the principle of microbending and the measurement of intensity modulation.

Field testing of Prestressed Box Girder

High precision data that tracked girder behaviour even at low stress levels.
Outstanding correlation with predictions including measurements not otherwise possible to obtain in situ.
So...where are we?

Following the 2005 collapse of the Lake View Drive Bridge, Dr. Harries made a [bold] statement: *This girder/bridge was repairable*

Improved understanding and execution of *in situ* assessment.
Integration of beneficial effects of strand redevelopment.
Analytic tools that better capture anticipated eccentric behavior of exterior box girders.
Tools for improved SHM of *in situ* structures.

Now we need to establish which girders can be repaired and by which means.
Establishing a ‘Spectra of Repair’

Extensive study involving the design of 541 repairs of 3 prototype girders subject to damage ranging from minor to severe. Each repair was assessed based on *practicality, constructability* and *LRFR rating* and compared to its original ‘as built’ capacity.

Establishing a ‘Spectra of Repair’

Prototype girders (3):
Adjacent and Spread Box Girders and AASHTO I-girders

Impact damage resulting in:
1.8% to over 40% strand loss; residual capacity as low as 40% of as built

Repair techniques (10):

strand splicing

EB-CFRP strip  EB-CFRP fabric
bPT-CFRP  uPT-CFRP
P-CFRP  NSM-CFRP
PT-steel  steel jacket
hybrid  replace girder

Normalized rating factors:

\[
RF_D = \frac{C_D - \gamma_{DC} DC - \gamma_{DW} DW \pm \gamma_P P}{C_0 - \gamma_{DC} DC - \gamma_{DW} DW \pm \gamma_P P}
\]

for which,

\[
C_D \geq 1.1 DC + 1.1 DW + 0.75 (LL + IM) \pm \gamma_P P
\]

Undamaged girder: \(RF_0 = 1.0\)
Damaged girder: \(RF_D < 1.0\)
Repaired girder: \(RF_R > RF_D\)

Objective is to determine whether \(RF_R\) is adequate for continued operation.

Establishing a ‘Spectra of Repair’

**Example:** Exterior AB girder repaired with EB-CFRP

![Graph showing the spectra of repair with various repair factors and damage rating factors.](Image)

Establishing a ‘Spectra of Repair’

**Example:** Exterior AB girder repaired with EB-CFRP

## Limitations of Repair Techniques

<table>
<thead>
<tr>
<th>Repair Technique</th>
<th>Geometric Constraint</th>
<th>CFRP Bond</th>
<th>Limitation of Repair Techniques</th>
<th>Maximum number of strands replaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB-CFRP</td>
<td>soffit: (b_f \leq b)</td>
<td>(\varepsilon_{fd} = 0.083 \sqrt{\frac{f_c'}{nE_f t_f}} \leq 0.9 \varepsilon_{fu})</td>
<td>(n_{max} = \frac{E_f n_t_f b_f \varepsilon_{fd} \alpha H}{f_{pu} A_p \beta H})</td>
<td>bPT-CFRP can also restore lost prestress force:</td>
</tr>
<tr>
<td>bPT-CFRP</td>
<td>soffit: (b_f \leq \approx 0.5b)</td>
<td>(\varepsilon_{fd} = 0.083 \sqrt{\frac{f_c'}{nE_f t_f}} + \kappa \varepsilon_{fu} \leq 0.9 \varepsilon_{fu})</td>
<td>(n_{max-PT} = \frac{E_f n_t_f b_f \kappa \varepsilon_{fu} \beta}{f_{pe} A_p \alpha})</td>
<td></td>
</tr>
<tr>
<td>NSM-CFRP</td>
<td>soffit: (b_f \leq \approx 0.5b)</td>
<td>(\varepsilon_{fd} = 0.7 \varepsilon_{fu})</td>
<td></td>
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<tr>
<td>strand splices</td>
<td>limited to developing 0.85(f_{pu}) in stands 12.7 mm diameter or less; therefore effective number of strands restored by strand splices = 0.85(n_{spliced}) limited to splicing 15% of strands in a girder regardless of staggering</td>
<td></td>
<td></td>
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</tbody>
</table>

\(C_D \geq 1.1DC + 1.1DW + 0.75(LL+IM) \pm \gamma_p P\)

Example:
Exterior IB girder (25% strand loss):

- Damaged rating factor, $RF_D = 0.59$
- Installation of 5 strand splices, $RF_R = 0.79$
- Additional installation of 4 plies EB-CFRP, $RF_R = 0.95$

As-built $RF = 1.0$

Hybrid Repair – Strand Splices and EB-CFRP

Example:
Exterior IB girder (25% strand loss):

- undamaged strand
- repaired with strand splice
- not repaired

- 1 ply CFRP U-wrap
- 4 plies EB-CFRP

So...was Harries right or just a braggard?

First, some history:
The BIV-48 girder had 60 – 3/8” 250 ksi strands. From inspections:
1994: 14 of 60 (23%) strands reported severed $\Rightarrow RF_D \approx 0.77$
2004: 20 of 60 (33%) strands reported severed $\Rightarrow RF_D \approx 0.66$
post collapse: 32 of 60 (53%) strands reported severed $\Rightarrow RF_D \approx 0.47$

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Residual capacity of girder was inadequate – the girder collapsed under its own self weight!

\[ C_D < 1.1DC + 1.1DW + 0.75(LL+IM) \]

Although this could have been remediated by:

- removing wearing surface; replacing with composite deck
- replacing 700 lb/ft barrier wall with steel barrier rail (girder was no behaving compositely with bridge therefore 100% of barrier load carried by exterior girder)
So...was Harries right or just a braggard?

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\[
\text{RF}_D \approx 0.47
\]

Maximum available repairs:

\[
\text{EB-CFRP} \rightarrow \text{RF}_R \approx 0.75
\]

\[
\text{bPT-CFRP} \rightarrow \text{RF}_R \approx 1.08
\]

Strand splicing and NSM-CFRP is not recommended for box girders.

So... technically, the girder was repairable and, being an exterior girder, was perhaps adequate with a rating factor of about 0.75.


Kasan, J. and Harries, K.A. 2010. Repair of Prestressed Concrete Adjacent Box Girder Bridges, *Proceedings of the International Conference on Short and Medium Span Bridges*, Niagara Falls, Canada


Harries, K.A. 2009. Structural Testing of Prestressed Concrete Girders from the Lake View Drive Bridge *ASCE Journal of Bridge Engineering*
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2014 Landis Lecture
Presented by the Department of Civil and Environmental Engineering

Is Structural Engineering Education Sustainable?

Lawrence C. Bank, PhD, PE, FASCE
Professor of Civil Engineering
The City College of New York

February 13, 2014 at 4:00 pm
Frick Fine Arts Auditorium and Cloister
- Reception Follows -