SHEAR STRENGTHENING OF STEEL BRIDGE GIRDERS USING SMALL-DIAMETER CFRP STRANDS

Presenting by:
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North Carolina State University
OUTLINE

1) Introduction
2) Objective
3) Scope
4) Research Program
   • Phase I
   • Phase II
   • Phase III
5) Conclusion
Use of FRP for concrete structures is very well established and used in practice

ACI 440
Design Guideline for Use of FRP in Concrete Structures
The use of FRP for steel structures has been very limited in the past.
Flexural Strengthening of Steel Bridge Girders  
*(HM CFRP Laminates)*

Starting from 2000 at NCSU

David Schnerch, 2004  
Flexural Strengthening of Steel Bridges with High Modulus CFRP Strips

Mina Dawood, 2005  
Strengthening Steel Structures With Carbon Fiber Reinforced Polymer
Flexural Strengthening of Steel Bridge Girders

(*HM CFRP Laminates*)

Dawood 2005
Small-Diameter CFRP Strand
Flexural Strengthening of Composite Beams
(Small-Diameter CFRP Strands)

Salar Tabrizi, 2013

Strengthening of Steel Structures with Carbon Fiber Reinforced Polymer (CFRP)
1) Introduction

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   • Phase I
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5) Conclusion
2) Overall OBJECTIVE

To propose a shear strengthening system to match the flexural strengthening
2) Specific OBJECTIVES

- Evaluate the effectiveness of a proposed CFRP material for shear strengthening of steel girders.
- Select the most effective material stiffness, configuration and reinforcement ratio.
- Develop analytical model to study different parameters not considered in the experimental program.
- Develop design recommendations for shear strengthening of steel girders.
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3) SCOPE

- Experimental Program
- Analytical model
- Design recommendations
OUTLINE

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4) RESEARCH PROGRAM

- **Phase I**: Strengthening for uniaxial compression
- **Phase II**: Strengthening of steel plate for pure shear
- **Phase III**: Strengthening of bridge girder for shear
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Phase I: Uniaxial Compressive Strengthening

Effects of:

• Slenderness ratio \((h/t)\)

• Material stiffness \((HM, IM, LM)\)

• Reinforcement ratio \((1 \& 2 \text{ Layers})\)
Material Properties: CFRP Strands in Tension

<table>
<thead>
<tr>
<th>CFRP Type</th>
<th>Ultimate Strain (%)</th>
<th>Ultimate Strength (Mpa (ksi))</th>
<th>Elastic Modulus (Mpa (ksi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Modulus (LM)</td>
<td>1.68</td>
<td>2350 (340)</td>
<td>140,000 (20,000)</td>
</tr>
<tr>
<td>Intermediate Modulus (IM)</td>
<td>1.04</td>
<td>2200 (320)</td>
<td>214,000 (31,000)</td>
</tr>
<tr>
<td>High Modulus (HM)</td>
<td>0.32</td>
<td>827 (120)</td>
<td>260,000 (37,500)</td>
</tr>
</tbody>
</table>
Phase I: Concept

![Diagram showing test plate dimensions and forces](image)
### Phase I: Test Matrix (32 tests)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Slenderness Ratio</th>
<th>Number of Layers</th>
<th>Strengthening Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slenderness Ratio (14 Tests)</td>
<td>48</td>
<td>1</td>
<td>HM</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>77</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>128</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforcement Ratio Material Stiffness (18 Tests)</td>
<td>77</td>
<td>1</td>
<td>HM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>IM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LM</td>
</tr>
<tr>
<td></td>
<td>154</td>
<td>1</td>
<td>HM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>IM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LM</td>
</tr>
</tbody>
</table>
Phase I: Test Setup

Elevation View

3D Sketch

Sidewiew

Jack

Sleeve

Pin

Plate

Load Cell

HS Bar
Phase I: Instrumentation

CONTROL PLATE

FRONT FACE

BACK FACE

Strain Gauges

STRENGTHENED PLATE

FRONT FACE

BACK FACE

Strain Gauges
Phase I: Instrumentation

Strain Gauge

CFRP Strands Layer
Steel Plate
CFRP Strands Layer
Phase I: Instrumentation

BACK FACE

String Potentiometers
Phase I: Instrumentation

Optotrak Motion Capturing System

IRED @ 75 mm (3 in.)

IRED on Sleeve

IRED on Sleeve
Phase I: Application of Strengthening System

- Sandblasted Plate
- Application of Primer
Phase I: Application of Strengthening System

Polyurea Putty Application

CFRP Application
Phase I: Application of Strengthening System

Sanding of First Layer  
Application of Second Layer
Plate Buckling Behavior

Axial Load, $P$

Axial Deformation, $u$

Lateral Deformation, $\Delta$

$P_b$

Theoretical Behavior

Plate with Imperfection
Phase I: Testing Strengthened Plate (h/t = 154)
Imperfections

1. Residual stress (uneven cooling, welding)
2. Plate initial out-of-straightness
3. Eccentricities
4. Application of CFRP
Phase I: (Effect of Reinforcement Ratio for different Material Stiffness)
High-Modulus CFRP (h/t=77)
Phase I: Effect of

- Reinforcement Ratio
- Material Stiffness
- Slenderness Ratio

IB-24-5/16

IB-48-5/16

$h/t = 77$

$h/t = 154$
Failure of the Strengthening System

\[ (h/t=96) \]
Phase I : (Finite Element Analysis)

(ANSYS Workbench V.16.2)

FEA model was calibrated with experimental program to study parameters not considered in the experimental program.
Element

3D 8-node SHELL281

- 6 degree of freedoms
- Nonlinear analysis with large deformation
- Layered Capabilities
Loading and Boundary Conditions

- **Frictional Contact**
- **Fixed pin**
- **Upward displacement**
- **Fully bonded contact**

**Initial Imperfection (First Mode of Buckling)**

- $\delta$

**EXAMPLE:**

- $\delta = 1/1200 \times 0.02$, $u=0.025$, PL1x1, Pin 1, CFRP = 0.125
- Static Structural
- Time: 2 s
- 9/26/2015 10:58 PM

- Remote Displacement (Top Pin)
- Remote Displacement (Bot Pin)
Calibrated Parameters

<table>
<thead>
<tr>
<th>Friction Factor</th>
<th>0.025</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ</td>
<td>2mm (5/64 in.)</td>
</tr>
</tbody>
</table>
Model Calibration (Control Specimen)

Longitudinal Steel Strain (microstrain)

Applied Load, P (kN)

Applied Load, P (kip)

-300 -200 -100 0 100 200 300

0 2 4 6 8 10 12 14

0 2 4 6 8 10

Control Specimen

Compression

Tension

h/t = 154

EXPERIMENT

FEM

NC STATE UNIVERSITY
Model Calibration (1 Layer Strengthened Specimen)

Applied Load, \( P \) (kN)

Longitudinal Steel Strain (microstrain)

Intermediate-Modulus (1 Layer Strengthened)

Compression

Tension

\( h/t = 77 \)

EXPERIMENT

FEM
Phase I: Parametric Study

Effects of:

- Slenderness Ratio (6 selected numbers)
- Reinforcement Ratio (1, 2, 3 layers)
- CFRP Elastic Modulus (LM, IM, HM)
- Boundary Condition (Pined End, Fixed End)
Phase I: Parametric Study (High-Modulus)


Phase I: Analytical Approach
(Euler Buckling, $K=1$)

$$P_{cr} = \frac{\pi^2 E_s I_t}{(KL)^2}$$

**Transformed Section Properties**

$$I_t = I_s + \sum_{i=1}^{n} \frac{E_{fi}}{E_s} I_{fi}$$

---

**Experimental vs Theoretical Buckling Load**

- **Conservative Estimation Zone**
- **Un-conservative Estimation Zone**

**Graph Details**
- **K=1**
- **Control Plate**
- **Strengthend Plate**

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Phase II: Shear Strengthening

Effect of:

- Reinforcement Ratio
- CFRP Strand Orientation
Phase II : Concept

Steel Shear Panel

[Diagram showing APPLIED LOAD, SPECIMEN, SUPPORT REACTION, and PINNED SUPPORT]
Phase II: Test Setup

- BUILT-UP FRAME
  - Clamped by Pre-stressing Bolts
- Short Plate
- Long Plate
- TEST PLATE
Phase II: Test Setup
Phase II: Application of Strengthening System

1) Application of Primer

2) Application of Putty

3) CFRP Application
Phase II: Test Matrix (9 tests)

(SET #1)

(SET #2)

(SET #3)

HM CFRP

45

90

±45
Phase II : Instrumentation

- **FRONT FACE**
  - Horizontal Strain Gauge
  - Vertical Strain Gauge
  - IRED @ 75 mm (3 in.)
  - Edge IRED

- **Optotrak Motion Capturing System**
Plate Shear Buckling Behavior

The diagram illustrates the behavior of a plate under shear load, comparing a flat plate to an imperfect plate. The graphs show the relationship between load (P) and deformation, with a clear distinction between in-plane deformation (u) and lateral deformation (Δ). The curves for flat and imperfect plates exhibit different behaviors, indicating the effect of plate imperfections on buckling resistance.
Imperfections
Phase II: Test Results

45 Degree (Set#1)
Phase II : Effect of

- CFRP Strand Orientation
- Reinforcement Ratio

Increase in Shear Capacity (%) vs CFRP Strand Orientation (Degree)
Phase II: Effect of

- CFRP Strand Orientation
- Reinforcement Ratio
Phase II: (Finite Element Analysis)

3D 20-node SOLID186
Loading and Boundary Conditions

(a) Support
(b) Bonded Contact

Upward Displacement
Bolt & Nut
Frictional Contact
Loading and Boundary Conditions
(Initial Imperfection)
Model Calibration

45 Degree (Set#1)
Phase II: Parametric Study

Effect of:
- Slenderness Ratio (5 selected numbers)
- CFRP Elastic Modulus (LM, IM, HM)
- Reinforcement Ratio (1, 2 Layers)
Phase II: Analytical Approach

\[ \tau = \frac{VQ}{It} \]

**Transformed Section Properties**

\[ I_t = I_s + \sum_{i=1}^{n} \frac{E_{fi}}{E_s} I_{fi} \]

\[ t_t = t_s + \sum_{i=1}^{n} \frac{t_{fi}}{t_s} t_{fi} \]

![Graph with Experimental and Theoretical Shear Increase](Image)
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Phase III: Shear Strengthening of Bridge Girder (Experimental Program)

Effects of:

- CFRP Strand Orientation
- Reinforcement Ratio
Phase II: Test Matrix

Panel I
- I-Control
- I-0-1HM
- I-0-90-2HM

Panel II
- II-Control
- II-90-1HM
- II-90-2HM

Panel III
- III-Control
- III-45-1HM
- III-45-2HM

Panel IV
- IV-Control
- IV-45-1HM
- IV±45-2HM
Phase II: Test Results

(Set#1)
Phase III: Effect of

- CFRP Strand Orientation
- Reinforcement Ratio
Phase III: Effect of
- CFRP Strand Orientation
- Reinforcement Ratio

![Bar graph showing the effect of CFRP Strand Orientation and Reinforcement Ratio on Increase in Lateral Stiffness.](image-url)
Phase II: Analytical Approach

\[ \tau = \frac{VQ}{It} \]

**Transformed Section Properties**

\[ It = Is + \sum_{i=1}^{n} \frac{E_{fi}}{E_s} I_{fi} \]

\[ t_t = t_s + \sum_{i=1}^{n} \frac{t_{fi}}{t_s} t_{fi} \]
5) Conclusion

• The small-diameter CFRP strands is an effective strengthening system for increasing buckling and shear capacity of the steel plates.
• The system exhibits excellent bond characteristics.
• The effectiveness of the strengthening system increased by increasing the plate slenderness ratio, material stiffness and reinforcement ratio.
• Applying the CFRP strands in direction of principle compressive stresses gives the most effective strengthening orientation.
• To avoid waste of material and labor cost, it is recommended to apply first layer of CFRP material in vertical direction and then attach additional layers orthogonal to the bottom layer.
• Simple analytical approaches can be effectively used to estimate the buckling and shear capacities of the strengthened specimens.
Research Publications at CFL

• Journal Papers


Research Publications at CFL

• Conference Papers


Research Publications at CFL

International Institute
for FRP in Construction

The FRPRCS-12/APFIS2015 Award for BEST PAPER for
Research on FRP Strengthening of Existing Structures
is awarded to

Hamid Kazem, Sami Rizkalla, Rudolf Seracino and Akira Kobayashi

for the paper entitled

Small-diameter CFRP strands for strengthening steel bridge girder

Joint Conference
12th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-12) & 5th Asia-Pacific Conference on FRP in Structures (APFIS2015)
14-16 December 2015, Nanjing, China

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December 2015
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DIRECTOR OF THE NSF I/UCRC - CENTER FOR THE INTEGRATION OF COMPOSITE INTO INFRASTRUCTURE (CICI)

Dr. Sami Rizkalla is the Distinguished Professor of Civil Engineering and Construction, Director of the Constructed Facilities Laboratory (CFL) and Director of the NSF I/UCRC – Center for the Integration of Composite into Infrastructure (CICI) at North Carolina State University in Raleigh, North Carolina.

Dr. Rizkalla is interested in design, construction and performance of reinforced and prestressed concrete structures and bridges.
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Special Thanks To:
Thank You

Question ?