Henderson, KY to Evansville, IN

Bridge on US-41

Roebing Bridge over Ohio River

Field Testing

3-D Accelerometers

Owensboro Bridge

The Maysville Bridge

Field Testing

Bridge over Tennessee River

Field Testing

Field Testing
**Outline**
- Introduction
- High Performance Materials
- Conclusions
- Acknowledgment

**FRP Components**
*FRP = Fiber Reinforced Polymer*

**High Performance Materials**

**Possible Instrumentation Plan**

**I-64 Parallel Bridges over US60**

**BARGE IMPACT ON BRIDGES**

**Instrumentation Plan - US 41N Bridge**

**FRP COMPOSITES**

1. The outer girder on Eastbound I-64 over Eastbound US60 gets hit by trucks exceeding the height restriction due to low clearance at that location.
2. This girder in Span 3 on Westbound I-64 underwent excessive deflection and vibration under truck loading. Cracks had formed on this girder and the adjacent girders.
3. This girder in Span 1 on Westbound I-64 underwent excessive deflection and vibration under truck loading. Cracks had formed on this girder and the adjacent girders.

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Glass FRP Bar

FRP Composite Materials

- **Resins**
  - Thermosetting Polymers
    - Polyester
    - Epoxy
    - Vinylester
    - Commonly used in CE applications
    - Cannot be reversibly softened
    - Thermoplastics
      - Polyurethane
      - Thermoplastic
      - Phenolics
      - Not currently used in CE applications
      - Polymer can be reversibly softened

- **Reinforcements**
  - Carbon
  - Glass
  - Aramid
  - Boron
  - Nylon
  - Polyester
  - Polyethylene

- **Fillers**
  - Calcium carbonate
  - Clay
  - Talc
  - Aluminum trihydrate
  - Silica
  - Microspheres
  - Mica

- **Additives**
  - Catalysts & promoters
  - Inhibitors
  - Release agent
  - Pigments
  - UV absorber
  - Fire retardant

Fabrication Processes

- Hand Lay-Up
- Pultrusion
- Spray-Up Molding
- Other

Function of Fillers

- Improves mechanical properties
- Improves surface finish
- Improves processability
- Lowers mold part cost
- Improves dimensional stability
- Reduces porosity

Function of Additives

- Modifies cure rate
- Extends shelf life
- Prevents shrinkage
- Improves weatherability
- Reduces porosity
- Adds color

Pulltrusion:

- FRP bars, structural sections, plates
FRP APPLICATIONS

2007 Full Carbon Fiber Road Racing Bike Dura Ace

2011 Ducati Diavel Carbon

Audi Carbon Skis

King Cobra Carbon CB Iron-set Golf Club
**Bridge Design Parameters**

- Pedestrian Load of 85 psf ~ 4 kPa
- Live load deflection limit of L/180 (4 inches ~100 mm)

---

**I-Girder Steel Bridge**

- W18x46 Section
- 2 Girders Required
- E = 29,000 ksi ~ 200 GPa

---

**GFRP Beam Requirements**

- 30 GFRP Girders required using 18" (~460mm) deep sections
- E = 2500 ksi ~ 17 GPa (1/12 E steel)

---

**THE CLEAR CREEK BRIDGE**

- Pultruded Hybrid
- Carbon/Glass FRP I-Beams

---

**Sea Shadow Stealth Boat**

**Stealth Submarine**

**Ghost**

**M-14/M1A Rifle**

**Walther P22 Carbon Fiber**

**Frame 3.4" 22LR**
**GFRP Beam Requirements**

- 8 Girders required using 24" (~610mm) sections
- $E = 2500 \text{ ksi} \approx 17 \text{ GPa}$

**Laboratory Testing**

**Bridge Fabrication**

**Bridge Assembly**

**Bridge Construction**
Bridge Construction

Bridge Construction

Load Test

Bridge Construction

Bridge Construction

Bridge Visit By International Researchers

Bridge Construction

Bridge Construction

Bridge Visit By Japanese Researchers

Opening Ceremony
November 14, 1996

Clear Creek Bridge, Kentucky

GFRP Cables
- Longest FRP Girder Bridge
- First application of Inverted Cable Stay
- First Hybrid FRP Bridge

**THE SWINGING BRIDGE**
**PULTRUDED GFRP DECK**
Johnson County, KY
Rebars
- Fiber Reinforced Polymer (FRP)
- Stainless Steel Clad (SS)
- Microcomposites (MMFX)
- Epoxy Coated Steel (ECS)

Stress/Strain Curves of Various Rebars

Clark County Bridge
- First Bridge in the US With CFRP Bars
- Second Bridge in the US With CFRP Bars

Roger's Creek Deck, Kentucky - 1997
- Second Bridge in the US With GFRP Bars

Clark County Bridge, Kentucky - 2002
- First Bridge in the US With CFRP Bars
First Deployment of MMFX Steel Bars in the World

First Deployment of Stainless Steel Clad Bars in the US

US NAVY Platform
Panama City, Florida

FRP & Concrete Piles

FRP & Concrete Piles

FRP & Concrete Piles

FRP & Concrete Piles

MMFX
SSC
MMFX

US NAVY Platform
Panama City, Florida

FRP Piles

FRP Piles

Underwater Weapons Systems Laboratory (UWSL)

Acoustic test pit: 350 ft by 250 ft, 10 ft deep (magnetically clean)
Bridge Decks
- FRP Deck
- Aluminum Deck

FRP Bridge Decks

Placement of FRP Deck
Aluminum Bridge Decks

KY 974 Bridge Over Howard Creek
Clark County, KY

Aluminum Bridge Deck
Fabricated in Holland

Aluminum Deck Placement

KY 974 Bridge Over Howard Creek
Clark County, KY

Deck Connection to Steel Girders

Aluminum Bridge Deck Placement

KY 974 Bridge Over Howard Creek
Clark County, KY

Asphalt Topping

KY 974 Bridge Over Howard Creek
Clark County, KY

Bridge Ready for Traffic
After 2 Hours 07/20/2006

07/26/2006
KY 270 Bridge
Webster County, KY

Aluminum Deck Placement

Bridge Retrofit
- Carbon FRP Fabric
- High Strength Steel Fabric (Hardwire)
- Carbon FRP Laminates

CFRP Fabric

Beam Strengthening

CFRP Fabric vs. Steel

Ultimate Load = 3.25 kip

CFRP Fabric Test Specimens
Bridge on KY 3297 over Little Sandy River
Carter County, Kentucky

Shear Cracks in P/C Box Beams

Original Solution
Replace the Superstructure
- Cost: ~$600,000
- Close Bridge to Traffic

Alternate Solution
Use CFRP Fabric
- Cost: $105,000
  (Design, Repair, and 3-yr Monitoring)
- Bridge Remains Open to Traffic
  (Except for Heavy Trucks)

Step 1:
Surface Preparation

Step 2:
Crack Injection and Filling of Voids

Step 3:
Apply Primer

Step 4:
Apply Carbon Fabric
Step 5: CFRP Fabric on Outside Face Painted to Match Concrete Color

Crack Monitor on Inside Beam Face

No Crack Movement has Occurred Since Repair Was Completed in October 2001

The State Journal, December 2001

Bridge Monitoring (10/01 to 12/06)

Scaffolding Used for Monthly Bridge Monitoring

Crack Monitor on Inside Beam Face

Cost Effective: $105,000 for Repair vs. $600,000 for Replacement

Repair is Effective: No Crack Movement Since Repair was Completed in October 2001

- No Traffic Control or Disruption

Conclusion

The Daily Independent

November, 2001

CFRP Fabric on Inside Faces of the Beams Was Not Painted to Match Concrete Color

Crack Monitor

Associated Press

November, 2001

Engineers taping old bridges with super-strength fabric

Kentucky, USA

I-65 North-South Expressway, Jefferson County
I-65 Elevated Expressway

PIER 6 at Main & Hancock ST

Retrofit Locations

PC spans between Broadway & Chestnut

PIER 4 at Jefferson & Preston ST

PIER I-65 over Muhammad Ali Blvd.

PC spans between Jacob & Gray ST

PC girders

Cracks at piers with fixed restraints.

Bridge deck

Steel rebars

Embedment length of steel rebars

Pier cap

PC girder

Crack

Cracks in prestressed concrete girders near supports

Instrumentation on Span 117, Pier 6, Northern I-65 Expressway

BEAM 6

BEAM 7

L VDT 1 (H)

L VDT 2 (V)

L VDT 3 (H)

L VDT 5 (V)

THERMOMETER

AND DA QU drift

SYSTEM

-10

0

10

20

30

40

50

60

70

80

90

0

400

800

1200

1600

Elapsed Time (Hours)

Relative Horizontal Movement (x 10^-3 in)

LVDT 3 (H) as of May 1, 2004

Beam 7

Span 117

Beam 7

Span 117

LVDT 2 (V) as of May 1, 2004

beam 5

Span 117

PC beam moving downward relative to pier cap

Crack is closing

LVDT 2 (V) as of May 1, 2004:

Beam 6

Span 117

LVDT 3 (H) as of May 1, 2004

Beam 6

Span 117

PC beam moving downward relative to pier cap

Crack is closing
Repair of Pier (I-65 over Muhammad Ali Blvd.)

Bridge Retrofit Using Tri-axial CFRP Fabric in Simpson County, KY
High Strength Steel Fabric (Hardwire)

Retrofit Measures: Hardwire Steel FRP

Strengthening With CFRP Laminates

Second Bridge in the US With Steel Wire Fabric

Testing of Beam Strengthened With CFRP Laminates

Repair Completed

Repair Completed
Louisa-Fort Gay Bridge
Over the Tug Fork and Big Sandy Rivers

Coal Truck Weigh in Motion Data:
225,000 lb (100 Metric Ton)

Tishkovka Bridge
Perm, Russia

Flexural Cracks in RC Spans 4-6-7
Louisa-Fort Gay Bridge

Number of CFRP Laminates Required for Flexural Strengthening

Application of CFRP Laminates to Span 4

Need to Increase Strength of Girder 1 and Girder 5 by 15%

Technology Exchange with Perm, Russia
**Firsts in the Eastern Block Countries**
- Production of CFRP Laminates
- Retrofit Design With CFRP Laminates
- Bridge Retrofitting With CFRP Laminates

**Introduction**
Ultra High Modulus CFRP Plates
(Modulus 450 GPa / 65,250 ksi)

**Takiguchi Bridge, 2008 (Tokyo, Japan)**

**High Modulus CFRP Laminates**
- **Ultra High Modulus:**
  \[ E_{\text{ECFRP}} > 2E_{\text{Steel}} \]  
  \[ E_{\text{ECFRP}} > 400 \text{ GPa (58000 ksi)} \]
- **High Modulus:**
  \[ 0.5E_{\text{Steel}} < E_{\text{ECFRP}} < 2E_{\text{Steel}} \]  
  \[ 14500 \text{ ksi} < E_{\text{ECFRP}} < 29000 \text{ ksi} \]
- **Intermediate Modulus:**
  \[ 0.5E_{\text{Steel}} < E_{\text{ECFRP}} < 2E_{\text{Steel}} \]  
  \[ 7000 \text{ ksi} < E_{\text{ECFRP}} < 200 \text{ GPa (29000 ksi)} \]
- **Low Modulus:**
  \[ E_{\text{ECFRP}} < 0.5E_{\text{Steel}} \]  
  \[ 100 \text{ GPa (14500 ksi)} < E_{\text{ECFRP}} < 100 \text{ GPa (14500 ksi)} \]

**Retrofit of the KY 32 Bridge in Scott County, KY**
Steel Girders Strengthened With Ultra High Modulus CFRP Laminates

**KY 32 Bridge**

**Ultra High Modulus CFRP Laminate**
CFRP Laminate with peel ply Epoxy
Limitations of Current Retrofit Methods

Second Bridge in the World With UHM CFRP Laminates

Lexington Herald Leader April 22, 2010

State Highway 92 Bridge, Pottawattamie County, Iowa
KY32 Bridge over Lytles Creek in Scott County

Louisa-Fort Gay Bridge

Louisa-Fort Gay Bridge

US150 Bridge, Washington County, KY

CatStrong CFRP Rod Panels Developed at U. of KY

CatStrong CFRP Rods
Developed at U. of KY

Fiberglass mesh backing
<table>
<thead>
<tr>
<th>Designation</th>
<th>Diameter, d (in)</th>
<th>Rod area (x10^-3 in²)</th>
<th>Rod Spacing, s (in)</th>
<th>Bars per panel</th>
<th>Weight (lb./panel)</th>
<th>Strength (kip/ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRP70</td>
<td>0.078</td>
<td>4.78</td>
<td>0.25</td>
<td>48</td>
<td>0.66</td>
<td>73.4</td>
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<tr>
<td>CRP90</td>
<td>0.088</td>
<td>6.08</td>
<td>0.25</td>
<td>48</td>
<td>0.81</td>
<td>93.4</td>
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<tr>
<td>CRP110</td>
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<td>7.54</td>
<td>0.25</td>
<td>48</td>
<td>1.00</td>
<td>115.8</td>
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<tr>
<td>CRP145</td>
<td>0.136</td>
<td>14.53</td>
<td>0.375</td>
<td>32</td>
<td>1.30</td>
<td>148.7</td>
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<tr>
<td>CRP195</td>
<td>0.156</td>
<td>19.11</td>
<td>0.375</td>
<td>32</td>
<td>1.71</td>
<td>195.7</td>
</tr>
</tbody>
</table>

**CatStrong Carbon panel placement**

CRP-195 vs. CFRP Fabric

- t_C = 0.156 in
- t_S = 0.28 in
- W_{CFRP} = 11.45 lb/ft
- W_C = 0.43 lb/ft
- Ultimate Load = 195 kip

CRP-195 vs. CFRP Laminate

- t_C = 0.156 in
- t_L = 0.047 in
- W_L = 0.35 lb/ft
- W_C = 0.43 lb/ft
- Ultimate Load = 195 kip

CRP-195 vs. Steel

- t_C = 0.156 in
- t_S = 0.28 in
- W_S = 11.45 lb/ft
- W_C = 0.43 lb/ft
- Ultimate Load = 195 kip

CRP-195 vs. HARDWIRE

- t_C = 0.156 in
- t_H = 0.141 in
- W_H = 1.43 lb/ft
- W_C = 0.43 lb/ft
- Ultimate Load = 195 kip

**CatStrong Field Applications**

**Repair of the KY218 Bridge Over Blue Springs Creek, Hart County, KY**

1. Step 1: Application of resin on concrete girder
2. Step 2: Application of CFRP80 on resin
3. Step 3: Application of resin coat on CFRP80

Type 1 Truck W = 40,000 lbs
Type 2 Truck W = 73,500 lbs
Type 3 Truck W = 81,000 lbs

CRP 195 Strength = 195,700 lbs/ft

Type 1 Truck W = 40,000 lbs
Type 2 Truck W = 73,500 lbs
Type 3 Truck W = 81,000 lbs

Type 1 Truck W = 40,000 lbs
Type 2 Truck W = 73,500 lbs
Type 3 Truck W = 81,000 lbs

CRP-195 vs. Steel

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CRP-195 vs. HARDWIRE

- t_C = 0.156 in
- t_H = 0.141 in
- W_H = 1.43 lb/ft
- W_C = 0.43 lb/ft
- Ultimate Load = 195 kip
Retrofit of Impacted Girder on the Sunnyside-Gotts Road over I-65
Day 1-2: Preparation of Damaged Zone
Day 3: Bonding Agent on Steel and Concrete
Day 4: Patching of Defects
Day 5: Crack Injection
Day 6: Formwork for Repair Mortar
Day 6: Grinding of Crack Injection Ports
Day 6: Sand Blasting of Retrofit Surface
Day 6: CatStrong CRP 195 Application
Day 6: CFRP Fabric Application
Day 6 (Dawn of Day 7): Retrofitted Zone

Retrofitted Girder Stronger Than Original Girder

KY 81 Bridge, McLean County, KY

Removal of Loose Concrete, Rust From Steel, etc. (8/9/12)

Beam Brought Back to Original Shape (8/10/12)

Beam After Repair (9/18/12)

Application of CatStrong (9/17/12)

Application of CFRP Fabric (9/18/12)

Outline
- Introduction
- Space Age Material
- Conclusions
- Acknowledgment

Conclusion
- HP Materials are now viable alternative construction material
- Structural repair is an area where HP Materials
- Health Monitoring
Outline
- Introduction
- High Performance Materials
- Conclusions
- Acknowledgment

Thank You and Have a Nice Day

Personnel 1996 – Present
Structures Group
- 36 Visiting Professors and Scholars
- 14 UK Professors
- 35 Staff
- 12 Ph.D. Students
- 45 M.S. Students
- 37 U.G. Students
- 12 High School Students

Questions?