Thinking Outside the Pipe: Using Composites for Infrastructure Repair

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Basics

- FRPs are externally bonded reinforcement applied to existing concrete, masonry, steel, and timber structures

- FRPs are used to strengthen or retrofit structural members

- FRPs cannot be used everywhere. There are limitations.

- Most, but not all applications require good bond between the FRP and the substrate

- All applications require an engineering design

- 20+ year history (guides and specifications are available)
Infrastructure Nomenclature

FRP = Fiber Reinforced Polymer

In infrastructure repair we refer to “composites” as FRPs

The term “composite” is reserved for “composite action”
Typical Wet Lay-up FRP Systems

Carbon Fiber Fabrics

Unidirectional Fabrics

Saturant Resin

Paste or Putty

Primer
Other FRP Strengthening Systems

Pre-cured Plates

NSM Bars or Strips

Strand Sheets
Why Strengthen or Retrofit?

• Changes in use
  ▪ High density filing systems
  ▪ Slab openings

• Deterioration / Corrosion / Damage

• Design / Construction errors

• Changes in building codes
  ▪ Seismic
  ▪ Wind
  ▪ Higher truck loads

• Protection
Types of Infrastructure

• Buildings
• Parking Garages
• Bridges
• Tunnels
• Tanks/Silos
• Piers/Wharves
• Stadiums
• Pipes
Structural Members

- Beams/Joists
- Stringers
- Trusses
- Slabs (RC and PT)
- Columns
- Walls
- Piling
- Connections
Challenges Addressed by FRPs

- Flexural Strength
  - Positive moment
  - Negative moment

- Shear Strength
  - Beam shear
  - In-plane shear

- Torsional Strength
- Tensile Strength
- Compression Strength
Challenges Addressed by FRPs

- Seismic Retrofit
  - Ductility Enhancement
  - Confinement of Lap Splices
  - Collectors
  - Diaphragms
  - Shear strength
  - Beam-Column joints

- Blast Mitigation

- Stiffness Enhancement
The Competition

- External reinforcement
- Steel plate bonding
- Pipe collars
- Welded plates
- Bolted plates
- Externally bonded FRP systems
- Near surface mounted (NSM) FRP systems
- Etc.

- Section enlargement
- Steel jackets
- Reinforced concrete jackets
- Span shortening
- Knee braces
- Shear collars
- Slotted in reinforcing bars
- External post-tensioning
- Internal post-tensioning

There are many ways to strengthen or retrofit an existing structure! Why use FRP?
Why Choose FRPs?

• **Structural Benefits**
  - Very high strength and stiffness
  - Lightweight

• **Life Cycle Benefits**
  - Corrosion resistant
  - Thin, unnoticeable

• **Economic Benefits**
  - Low installation costs
  - Low “shut-down” costs
Negative Moment Strengthening of a Slab

- Rebar omitted during construction

- Negative moment strengthening of 2-way slab

- Multiple plies were installed on top surface of slab

- Carpeting installed on top of CFRP
Flexural Upgrade of Precast Box Girder

- Pier Complex at NAS Earle, NJ
- Corrosion-related deterioration to bottoms of precast box girders
- Reduction of flexural strength
- Repaired concrete and installed CFRP plies to bottom of box girders
Restoring Strength to Column

• Building under construction

• Lateral steel inadvertently omitted from perimeter columns

• Wrapped carbon fiber plies around the column
Blast Hardening

Photos courtesy of Sika Corporation
Guggenheim Museum

- FRP used to strengthen deteriorated concrete walls of 6th floor rotunda
- Accomplished while museum remained open to public
General Installation Procedure

• Repair substrate
  – Inject cracks
  – repair spalls,
  – fill voids, etc.

• Prepare substrate surface

• Install FRP system

• Remove air voids

• Allow FRP system to cure

• Inspect cured system

Contact-Critical or Bond-Critical?
Wet Lay-up Installation Method

Prime Surface

Fill Voids with Epoxy Paste

Install Carbon Sheets

Roll Out Air
Field Quality Control and Inspections

Rigorous inspections contribute to successful projects

- Tensile tests (witness panels)
- Fabric alignment (< 1”/foot)
- Delaminations
- Cure of resins
- Adhesion strength (for bond-critical)
Engineering Considerations

• Bond-Critical vs. Contact-Critical

• Unique material characteristics of FRPs
  ▪ Brittle vs. Ductile

• Durability

• Mechanics and behavior of FRP strengthened elements
  (too much FRP may not always be good)

• Code considerations (fire, smoke/flame spread)

FRPs are not explicitly covered by the building code
Engineering Considerations

• Selection of FRP Systems
  ▪ Environmental Considerations
  ▪ Loading Considerations

• Strengthening Limits

\[
(\phi R_n)_{existing} \geq \left(1.1 S_{DL} + 0.75 S_{LL}\right)_{new}
\]

• Good detailing

• Competent substrate (f’c > 2000 psi)
Structural Fire Resistance

• Some suppliers tout 1-, 2-, 4-hour ASTM E119 fire ratings

• ASTM E119 does not cover FRPs

• Fire protection materials protect the fire resistance of the existing structure, not the FRP
Rational Fire Resistance

• Use ACI 216 to check structure
• Use reduced material strengths at a given temperature
• NEGLECT CONTRIBUTION OF FRP
• Find the resulting reduced structural capacity
• \[ 1.0DL + 1.0LL < \text{Reduced Strength of Member due to fire} \]
Flexural Behavior

- Heavy FRP Reinf.
- Moderate FRP Reinf.
- Light FRP Reinf.
- Unstrengthened RC Beam

Axes:
- Load
- Strength
- Ductility
- Deflection
Flexural Design Basics

- Most bond-critical applications are controlled by...
  - FRP rupture
  - Concrete failure
  - Debonding of FRP

- The more layers of FRP used, the more likely debonding will control

- The more layers of FRP, the less efficient each layer becomes

**Effect of FRP Stiffness on Bond**

![Graph showing the effect of FRP stiffness on bond](image)
Shear Strengthening

Two-sides: GOOD

U-wrap: BETTER

Fully Wrapped: BEST
Shear Design Basics

• Most bond-critical applications are controlled by...
  - Debonding of FRP
  - Concrete shear failure

• Strain in FRP is limited to 0.004 to prevent loss of aggregate interlock

• The more layers of FRP used, the more likely debonding will control

• The more layers of FRP, the less efficient each layer becomes
Axial Strengthening (Confinement)

• Fibers oriented transverse to the longitudinal axis of the member
  ▪ Contribution of any longitudinal fibers to axial strength are neglected

• FRP wrapping results in an increase in the apparent strength of the concrete and in the maximum usable compressive strain in the concrete

• Passive confinement

• Intimate contact between FRP system and member is critical
Axial Strengthening (Confinement)

• Circular columns work better than rectangular

• FRP must be in intimate contact with concrete (no gaps)

• Improves ductility of column

• Strain in FRP is limited to 0.004 to guard against shear failure

• Practical limit is based on service stress
Axial Strengthening (Confinement)

Compression Behavior of FRP Confined Concrete

Stress (psi) vs. Strain (in/in)

- Circular
- Square
- Rectangular (1:2)
- Unconfined
Helpful References

- ACI 440.2R (Design Guide-Concrete)
- ACI 440.7R (Design Guide-Masonry)
- ACI 440.8R (Material Spec)
- ICRI 330 Guide Specification
Helpful References

- ICC-ES
  - Provides third party review of products not covered by building code
  - Products are evaluated according to an acceptance criteria (AC125)
  - Products meeting the criteria are issued an evaluation service report

- ASTM D3039
- ASTM D7565
- ASTM D7522
Helpful References

• AASHTO FRP Guide*
  • Covers bridge and highway

• AWWA Standard for FRP repairs to PCCP pipe
  • In development

* Use with caution
Thank You!