# Strengthening and Preserving Concrete Bridges using FRP Composites

#### **RIGOBERTO BURGUEÑO, PH.D.**

Associate Professor of Structural Engineering

Department of Civil and Environmental Engineering Michigan State University



## WHAT ARE FIBER REINFORCED POLYMER (FRP) COMPOSITES?

A matrix (polymer) reinforced with stiff synthetic fibers

- Common FRP Constituent Materials for Strengthening Systems
  - Fibers: Carbon, E-Glass, Aramid
  - Resins: Epoxy, Vinylester, Polyester
- Other fiber reinforced composite materials
  - Straw in clay
  - fiber reinforced concrete
  - Natural materials: wood, sea shells, bone
- More conventional composite materials
  - reinforced concrete
  - chopped strand board, plywood



#### Fiber-Reinforced Composites – Fiber







![](_page_2_Picture_4.jpeg)

![](_page_2_Picture_5.jpeg)

![](_page_2_Picture_6.jpeg)

![](_page_2_Picture_7.jpeg)

## **Advantages of FRP Composites**

#### Structural Benefits

- High strength/weight and stiffness/weight properties
- Controllable directional stiffness & strength
- Good fatigue resistance
- Short "development lengths"

#### Life-Cycle Benefits

- Increased corrosion resistance
- Resistance to chemical attack
- Thin (i.e., unobtrusive)

#### Economic Benefits

- Low installation cost
- Fast turn around

![](_page_3_Picture_13.jpeg)

## Comparative Properties of FRP Composites

![](_page_4_Figure_1.jpeg)

![](_page_4_Picture_2.jpeg)

## Factors Affecting Mechanical Properties

- **Type of fiber reinforcement**
- Fiber volume
- Fiber orientation
- Resin type
- Manufacturing process
- Quality control

![](_page_5_Picture_7.jpeg)

## **FRP COMPOSITES – Realistic Properties for Civil Engineering Applications**

- Strength: Values comparable to high strength structural steels can be achieved. However, their non-ductile response limits the range that can be used
- Strain: Failure strains are low and typically limited to 1% for carbon and up to 3% for glass composites
- Modulus: For quasi-isotropic assumptions it ranges from 10% to 30% of steel and for unidirectional composites from 1/3 to 2/3 of the modulus of steel
- <u>Cost</u>: Dominated by the price of the fiber

# Strengthening, Retrofitting & Preservation

#### **Strengthening**

- Flexural Strengthening (beams, slabs, walls, etc.)
- Shear Strengthening (beams, columns, walls, etc.)
- Axial Enhancement (columns, pressure vessels)

#### Retrofitting

- Shear (beams, columns, walls, joints)
- Confinement (beams, columns, joints)
- Lap Splices (beams, columns, joints)

□ Preservation

- Corrosion Inhibition (columns, beams, etc.)
- Shallow Repair Anchorage (columns, beams MICHICAN STATE etc.)

## **Typical FRP Strengthening Systems**

#### Wet-Layup Systems

- Unidirectional fiber sheets
- Multidirectional fiber sheets
- Mechanically applied fiber t

#### Prepeg Systems

- Unidirectional fiber sheets
- Multidirectional fiber sheets
- Mechanically applied fiber to

#### Precured Systems

- Unidirectional sheets
- Multidirectional grids
- Shell elements

#### □ Others

![](_page_8_Picture_14.jpeg)

![](_page_8_Picture_15.jpeg)

![](_page_8_Picture_16.jpeg)

![](_page_8_Picture_17.jpeg)

#### **Flexural Strengthening**

□ Typical increase in flexural strength is 5 – 40%

Increases of 160% have been documented

Positive and negative moment strengthening

Add strength to RC and PC members

Reduce crack widths

Seismic loading

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002

![](_page_9_Picture_8.jpeg)

#### CFRP Overlays for Flexural Strengthening

![](_page_10_Picture_1.jpeg)

![](_page_10_Picture_2.jpeg)

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002.

## **CFRP Strips for Slab Strengthening**

![](_page_11_Figure_1.jpeg)

![](_page_11_Picture_2.jpeg)

![](_page_11_Picture_3.jpeg)

![](_page_11_Figure_4.jpeg)

## **FRP Flexural Strengthening** Failure Modes

![](_page_12_Figure_1.jpeg)

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002

![](_page_12_Picture_3.jpeg)

## **Shear Strengthening**

Increase shear capacity of beams or columns

Amount of increase depends on section geometry, existing reinforcement, and a variety of additional factors.

#### Change failure mode to flexural Typically results in a more ductile failure

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002.

#### **Shear Strengthening**

![](_page_14_Picture_1.jpeg)

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002.

#### **Shear Strengthening Schemes**

![](_page_15_Figure_1.jpeg)

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded RP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002.

## **Confinement Strengthening**

- Increase in member axial compressive strength
- Increase in member axial tensile strength
- Enhance the ductility of members subjected to combined axial and bending forces

#### Mechanism:

- Fibers oriented transverse to the longitudinal axis of the member
- Contribution of any longitudinal fibers to axial strength is negligible
- Results in an increase in the strength of the concrete and in the maximum compressive strain

ACI Committe **149**, **355ive** the **Optimeraent** ction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002

![](_page_16_Picture_9.jpeg)

#### **Confinement Strengthening**

![](_page_17_Picture_1.jpeg)

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002.

#### **Confinement Strengthening Mechanism**

![](_page_18_Picture_1.jpeg)

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02, American Concrete Institute, Farmington Hills, Michigan, July 2002

![](_page_18_Picture_3.jpeg)

### Seismic Retrofitting

![](_page_19_Picture_1.jpeg)

Flexure/Shear Failures Flexural Plastic Hinge Failures

![](_page_19_Picture_4.jpeg)

## CFRP Jacket Shear Retrofit Testing

![](_page_20_Figure_1.jpeg)

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## **Strengthening of Walls and Slabs**

Reduction of shear deformations in structural walls

Retrofitting of shear walls to achieve ductile inplane behavior

Repair of damaged walls to increase in-plane ductility

Retrofitting of out-of-plane unreinforced masonry walls

#### In-Plane Strengthening of Structural Walls

![](_page_22_Figure_1.jpeg)

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Laursen, P.T., Seible, F., and Hegemier, G.A., "Seismic Retrofit and Repair of Masonry Walls with Carbon Overlays, University of California, San Diego, Structural Systems Research Project Report No. SSRP-95-01, January 1995

#### **FRP Overlays for Preservation**

![](_page_23_Picture_1.jpeg)

![](_page_23_Picture_2.jpeg)

![](_page_23_Picture_3.jpeg)

## **Michigan DOT Applications**

#### **Column Confinement**

- Most common use (CFRP wraps)
- M-39/I-96 Interchange
  - Vertical cracking of the columns mainly due to slenderness.
- I-75 Bridge over the Rouge River in Detroit, MI
  - The substructure consists of slag aggregate concrete
  - CFRP used for confinement after the repairs to increase durability of the repair for 30 to 40 years.
  - CFRP applied using wet layup

#### **Beam Shear Strengthening**

- I-696 Plaza Structures in Southfield, MI
  - Side by side box beams developed diagonal tension cracks.
  - CFRP sheets as additional shear reinforcement at beam<sup>5</sup>

### **Michigan DOT Applications**

![](_page_25_Picture_1.jpeg)

![](_page_25_Picture_2.jpeg)

#### **Michigan DOT Applications**

![](_page_26_Picture_1.jpeg)

![](_page_26_Picture_2.jpeg)

![](_page_26_Picture_3.jpeg)

## **Durability Aspects and Related Issues**

**Durability Issues (in order of importance)** 

- Heat
- Humidity
- Ultraviolet Radiation Diesel Fuel
- Alkalinity
- **Quality Issues** 
  - Voids
  - Delaminations
  - Inclusions

Porosity, Fiber/Resin variations

- Performance Issues
  - Creep
  - Relaxation

![](_page_27_Picture_14.jpeg)

- Freeze/Thaw Salt Water

## **Disadvantages of FRP Composites**

- □ Cost
  - High material cost
  - Unfamiliarity can rise cost/bids
- Durability
  - There are debatable positions
  - Uncertainty affects the potential for lower long-term cost
- Material Variability
  - High dependence on raw materials and manufacturing
- Design Guidelines
  - Underdeveloped
- Repair and Inspection
  - Reduced experience and available methods
- **Education** 
  - More complex than conventional materials
  - Still lacking at the technical and professional level

![](_page_28_Picture_16.jpeg)

### **RATIONAL USE OF FRP COMPOSITES**

The use FRP composites for structural rehabilitation is a proven success and can have a prominent role together with our conventional materials.

#### □ However ...

Successful implementation of FRP composites requires understanding that design cannot be done following our approach for metals.

Design decisions for FRP composites are coupled to a high degree with intricate connections and interrelations between materials, configuration,

## Future of FRPs in the Renewal of Civil Infrastructure will depend on

-

□ The solution of issues such as repair, fire behavior, durability, and environmental concerns.

The degree of quality control that can be developed and provided during the manufacturing/installation.

The availability of codes, standards, and guides for design and analysis tools.

![](_page_30_Picture_5.jpeg)

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![](_page_31_Picture_4.jpeg)