DESIGNING AND SPECIFYING FRP MATERIALS FOR THEIR USE IN STRUCTURAL STRENGTHENING OF BRIDGES

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KEY LEARNING OBJECTIVES

01 **DETERMINE WHY STRUCTURES NEED TO BE STRENGTHENED AND TYPICAL STRENGTHENING TECHNIQUES**

02 **DESIGN AND SPECIFICATION CONSIDERATIONS, ALONG WITH AVAILABLE INDUSTRY GUIDELINES, FOR SUCCESSFUL USE OF MATERIALS**

03 **HIGHLIGHT MATERIALS THAT CAN BE USED FOR STRUCTURAL STRENGTHENING ALONG WITH THEIR ADVANTAGES AND DISADVANTAGES**

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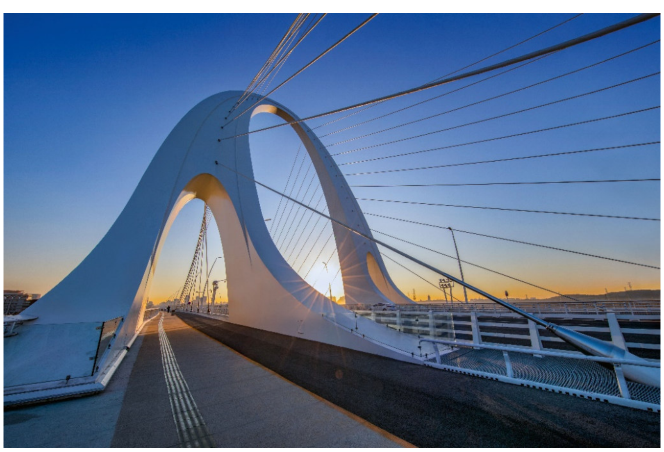
WHAT WE DO – BUILDING TRUST

Sika is a specialty chemicals company with a leading position in the development and production of systems and products for bonding, sealing, damping, reinforcing and protecting in the building sector and motor vehicle industry.



SIKA AT A GLANCE

25,000	EMPLOYEES
100	COUNTRIES
300+	PLANTS WORLDWIDE
6	NEW & EXPANDED PLANTS IN 2020
83	NEW PATENTS IN 2020
1	ACQUISITION IN 2020
7.88 BN	NET SALES IN 2020 (IN CHF)

WE ARE THERE

Our products might not always be visible but the results they achieve bring clear added value to customers and society.

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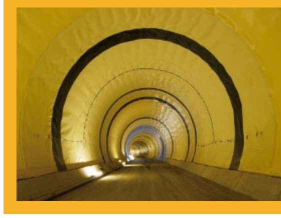
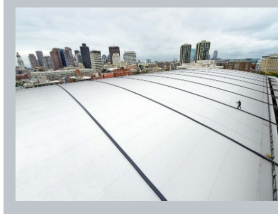
FOCUS ON ATTRACTIVE MARKETS:
CROSS-SELLING, LIFE-CYCLE MANAGEMENT, ONE STRONG BRAND

Concrete

Waterproofing



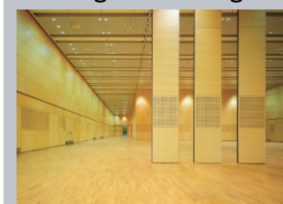
Roofing



Building Finishing

Flooring & Coating

Sealing & Bonding



Refurbishment

Industry

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CONCRETE REPAIR & PROTECTION

Repairing, protecting, and maintaining structures of all types is a necessary and worthwhile investment to extend a structure's usable service life.

Products	Product Families
Bonding Agents	Sika® Armatec®, Sikadur®, SikaLiquid® Weld
Coating & Water Repellents	Sikalastic®, Sikagard®
Concrete Fibers	Fibermesh®, Enduro®, Novomesh®
Corrosion Protection	Sika® FerroGard®, Sika Armatec®
Crack Injection	Sikadur®, SikaFix®, Sika® Inject
Expansion Joints	Wabo®, Emseal® Grouts Sikadur®, SikaGrout® Mortars SikaTop®, SikaQuick®, SikaCrete®, SikaRepair® Multipurpose Epoxies Sikadur® Structural Strengthening Sika Carbodur®, SikaWrap® Traffic Coatings Sikalastic® Deckpro
Grouts	Sikadur®, SikaGrout®
Mortars	SikaTop®, SikaQuick®, SikaCrete®, SikaRepair®
Multipurpose Epoxies	Sikadur®
Structural Strengthening	Sika® Carbodur®, SikaWrap®
Traffic Coatings	Sikalastic® Deckpro

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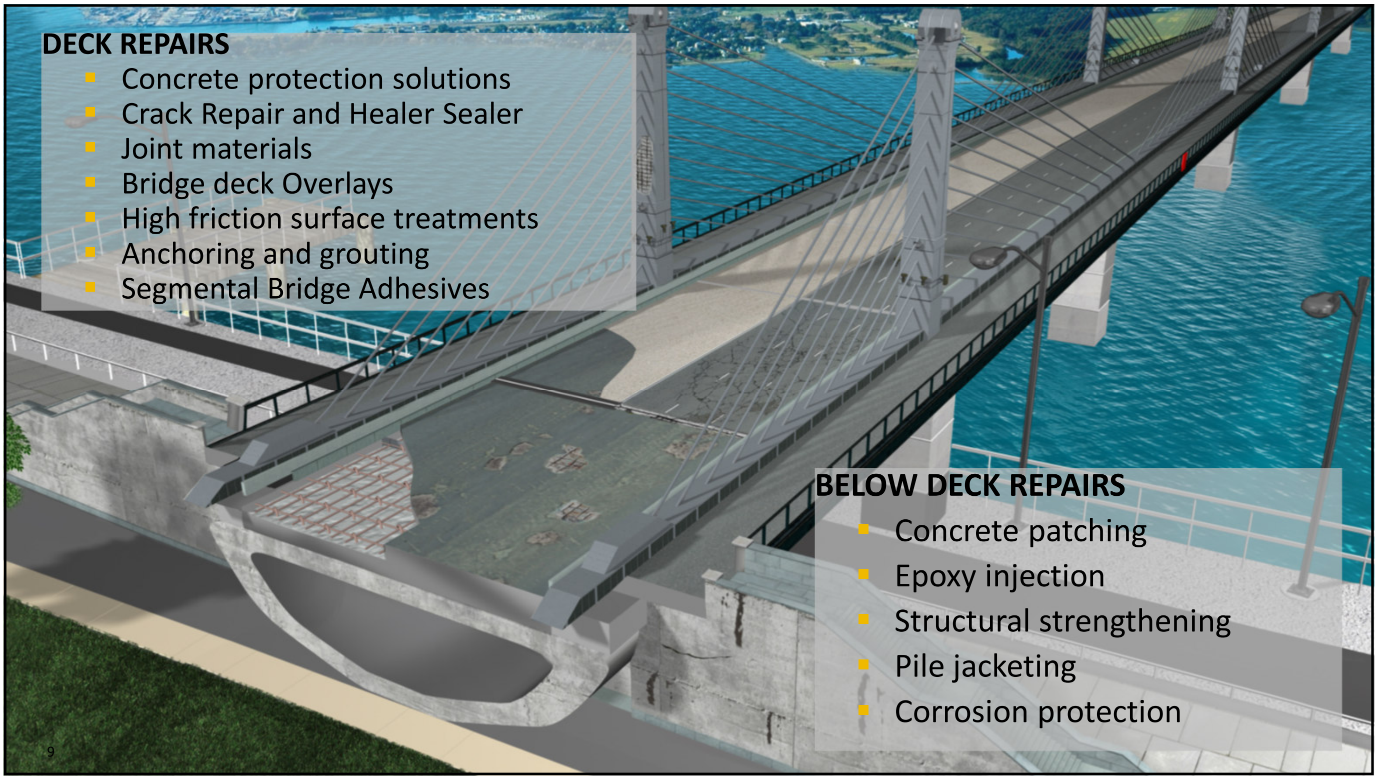

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WHY DO STRUCTURES NEED STRENGTHENING

So that our structures are not zip-tied or strapped together to prevent failure!

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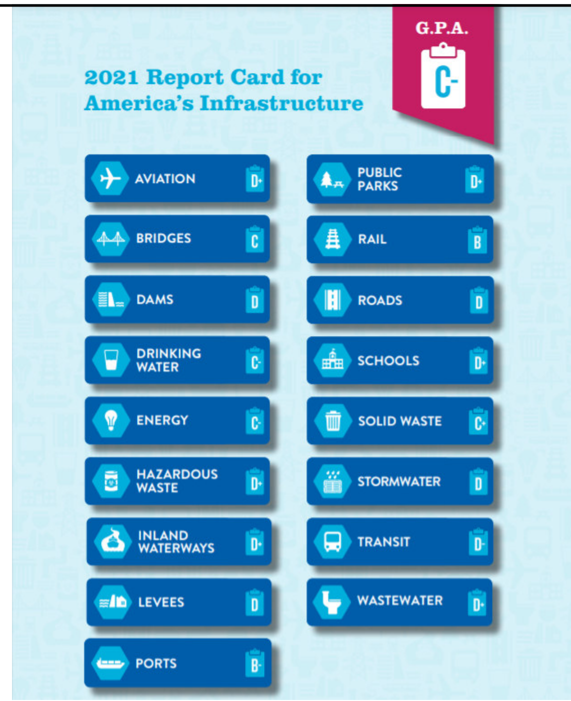
U.S. INFRASTRUCTURE STATE

- American Society of Structural Engineers – Report Card
- Overall grade: C-
- Over 600,000 bridges in U.S.
- 231,000 bridges need repair
- 4 in 10 bridges are 50 years or older
- Total infrastructure needs: $5.94 TRILLION over 10 years



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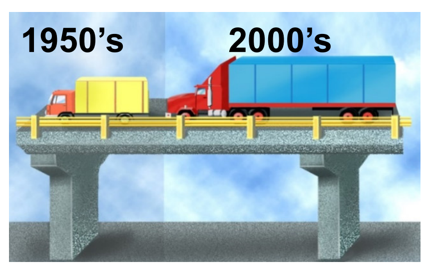
WHY DO STRUCTURES NEED STRENGTHENING?

- Insufficient reinforcement
- Corrosion damage
- Change in use
- Structural damage
- Seismic upgrade



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HOW ARE STRUCTURES STRENGTHENED
TYPICAL STRENGTHENING METHODS

EXTERNALLY BONDED FRP OR STEEL

Traditionally done with steel, most bonded strengthening is nowdays done with FRP

SECTION ENLARGEMENT

Used frequently, this method is intrusive to the structure, adds a lot of weight, and takes longer to implement

EXTERNAL POST-TENSIONING

For cases where high-capacity contribution is required, external PT is great solution. Traditionally done with steel, PT strengthening can also be done with FRP

SUPPLEMENTAL SUPPORTS

Supplemental supports are a great solution, though they take headspace and can be tricky to install.

WHAT ARE FRP SYSTEMS?

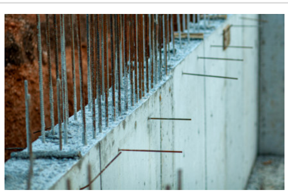
FABRIC

Fabrics are made from glass or carbon fiber.

RESIN

Most used resins to saturate the fabrics are epoxy and more recently PU.

REINFORCED CONCRETE



Reinforced concrete is a composite. Bonding FRP to it creates a complex system. Understanding how to design with it properly is critical for successful strengthening.

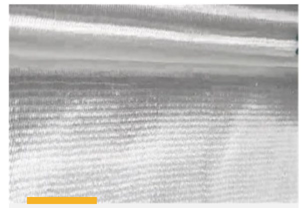
MOST COMMON FRP MATERIALS
GLASS VS CARBON

Carbon Systems (CFRP)

- Damp/wet conditions
- Stiffness driven
- Extreme alkaline conditions

Stronger, stiffer, more durable

CFRP



Glass Systems (GFRP)

- Seismic strengthening
- Dry conditions
- Extreme acidic conditions
- Economical

Economical, used commonly for seismic retrofit

GFRP

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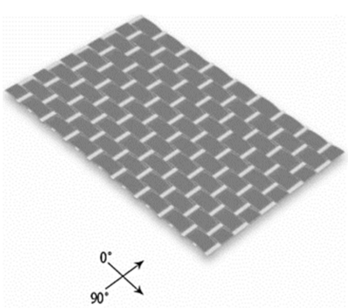
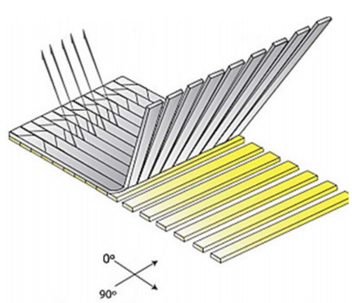
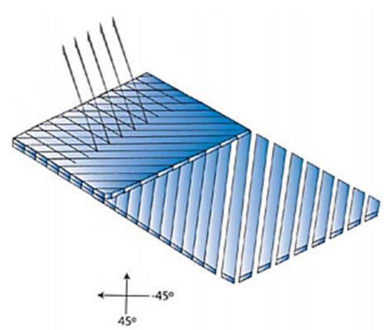
FRP FABRIC TYPES

Uniaxial Fabrics	Biaxial Fabrics	+/-45d Fabrics







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ADVANTAGES OF FRP REPAIRS

- Cost/scheduling benefits
- "Get in, Get out, Stay out!"
  - - FHWA Mantra for accelerated construction
- Reduced maintenance costs
- Light weight materials puts less strain on the structure
- Non-corrosive, designed for long-term performance

LIMITED ACCESS

TYPICAL APPLICATIONS

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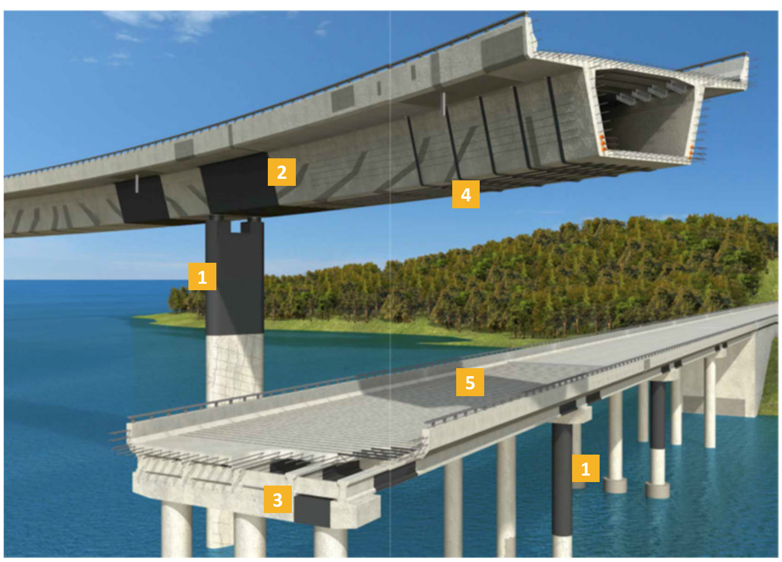
TYPICAL USE
BRIDGE APPLICATIONS



1 **Pier confinement**

2 **Shear strengthening of girders**

3 **Shear strengthening of pier caps**

4 **Flexural strengthening of girders**

5 **Deck Stiffening**

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PIER CONFINEMENT AND PIER CAP SHEAR STRENGTHENING
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GIRDER FLEXURAL STRENGTHENING
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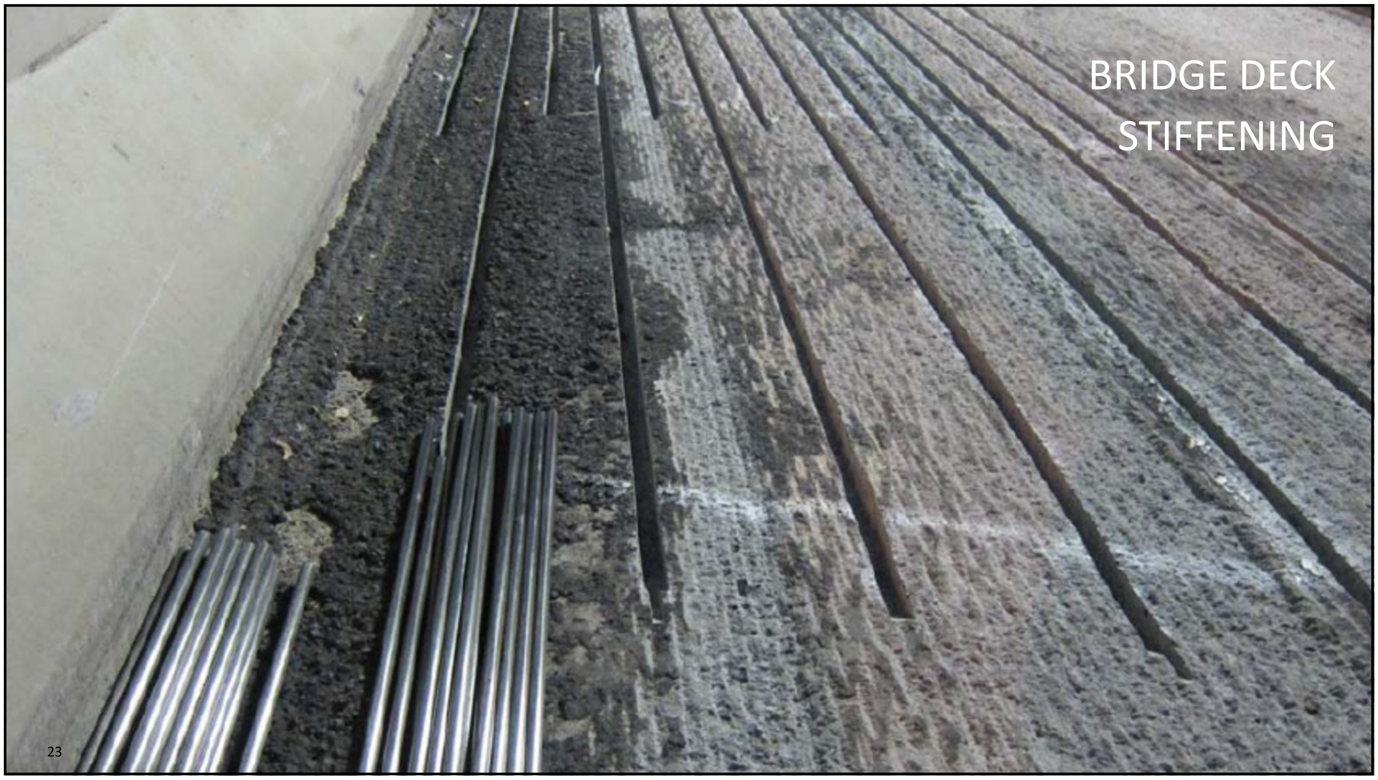

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TYPICAL APPLICATIONS

Parking Structures

- Shear Strengthening
- Corrosion Damage
- Column strengthening
- Corbel Upgrades

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TYPICAL APPLICATIONS

Buildings

- Modifications (wall or slab openings)
- Change in use
- Seismic upgrades
- Wall strengthening

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DESIGN GUIDES AND PRINCIPALS

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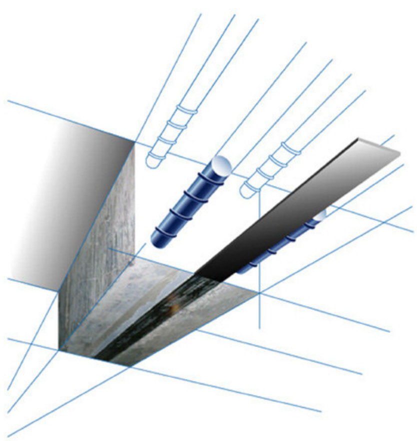
CODES AND STANDARDS

- AASHTO Guide 2nd Ed
  - Guide Specification for Design of Bonded FRP Systems for Repair of Strengthening Concrete Bridge Elements
- ACI 440.2R-17
  - Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

DESIGNING WITH FRP

- Provides secondary reinforcement



FRP Limitations

"SUPPLEMENTAL REINFORCEMENT"

AASHTO STRENGTHENING LIMIT

$$R_r \geq \eta_i\left[(DC+DW)+(LL+IM)\right]$$

ACI 440 STRENGTHENING LIMIT

$$(\phi R_n)_{existing} \geq (1.1S_{DL} + 0.75S_{LL})_{new}$$

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LIVE LOAD LIMIT DURING FRP APPLICATION

$$0.5M_{n,r} \geq (1+IM)M_{LL,r} \qquad (3.4\text{-}1)$$

where:

IM = dynamic load allowance

$M_{LL,r}$ = live load moment during FRP system application and cure (kip-in.)

$M_{n,r}$ = nominal flexural resistance of member prior to application of FRP system (kip-in.)

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MATERIAL REQUIREMENTS

- Environmental reduction factors
  - Material properties (non bond-critical applications
  - Interface strain (bond critical)
- 85% strength retention for various exposures
- Glass transition temperature – 40 degrees higher than max design temp

- *Environmental Exposure Category A*: Environmental Exposure Category A shall apply to overpass bridges and bridges over dry surfaces. Exposure to periodic rain or seasonal de-icing agent spray fall in this category.
- *Environmental Exposure Category B*: Environmental Exposure Category B shall apply to bridges that are continuously or frequently in contact with water or located in high moisture environments. Bridges located in coastal regions, over waterways, or near water bodies fall in this category.

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FLEXURAL STRENGTHENING

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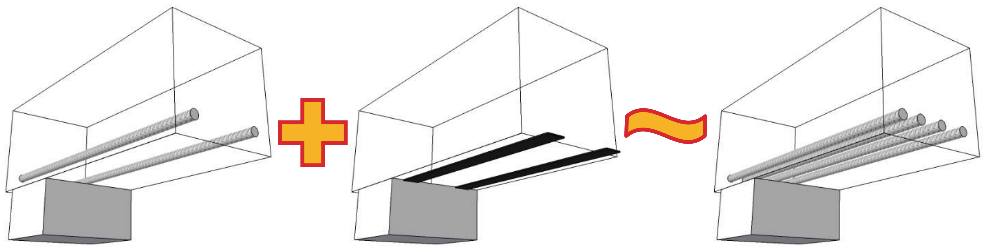
HOW DOES CFRP AFFECTS A REINFORCED BEAM?

FLEXURAL STRENGTHENING



$$M_r = \phi \begin{bmatrix} A_{ps} f_{ps}\left(d_p - \dfrac{c}{2}\right) \\ + A_s f_s \left(d_s - \dfrac{c}{2}\right) - A_s' f_s' \left(d_s' - \dfrac{c}{2}\right) \\ - \alpha_{1f} f_c' (b - b_w) h_f \left(\dfrac{h_f}{2} - \dfrac{c}{2}\right) \end{bmatrix}$$

FRP Contribution $+\phi_f A_f f_{fe}\left(d_f - \dfrac{c}{2}\right)$

$$f_{fe} = E_f \varepsilon_{fe}$$

$$\varepsilon_{fi} = 0.045\sqrt{\frac{f_c'}{nE_f t_f}} \qquad (5.2.1\text{-}2)$$

in which:

$$nE_f t_f \le 1{,}900 \text{ kip/in.} \qquad (5.2.1\text{-}3)$$

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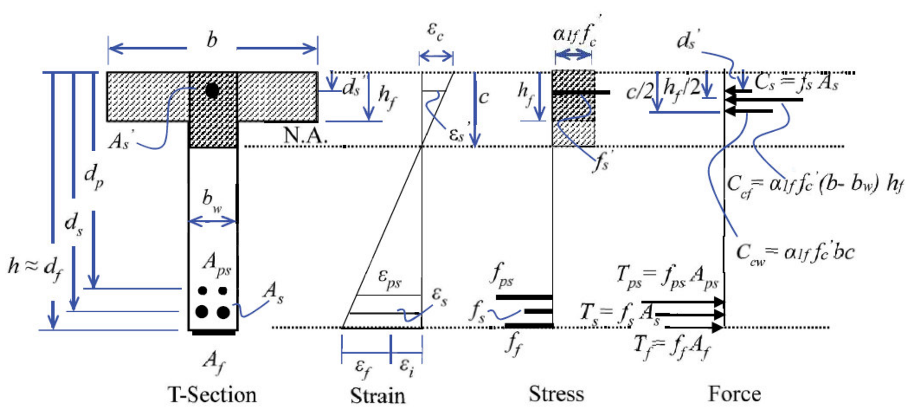

$$c = \frac{A_{ps} f_{ps} + A_s f_s + A_f f_{fe} - A_s' f_s' - \alpha_{1f} f_c' (b - b_w) h_f}{\alpha_{1f} f_c' b_w}$$

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DETAILING REQUIREMENTS

- Check for shear to prevent end debonding. If needed provide:
  - U-wraps
  - Spike Anchors
- If FRP-concrete interface strain is to be increased
  - U-wraps along beam length
  - Spike anchors

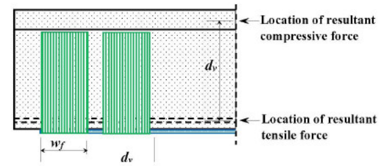

Figure C5.5.2.3-1—U-wrap anchors to prevent end debonding

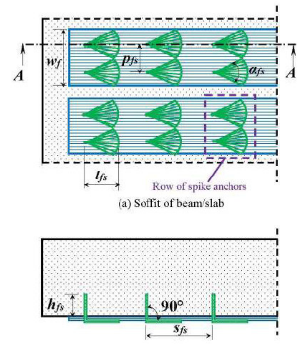

Figure C5.5.3.2-1—Notation and layout of spike anchors along the flexural reinforcement

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SHEAR STRENGTHENING

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COMBINED STRENGTHENING

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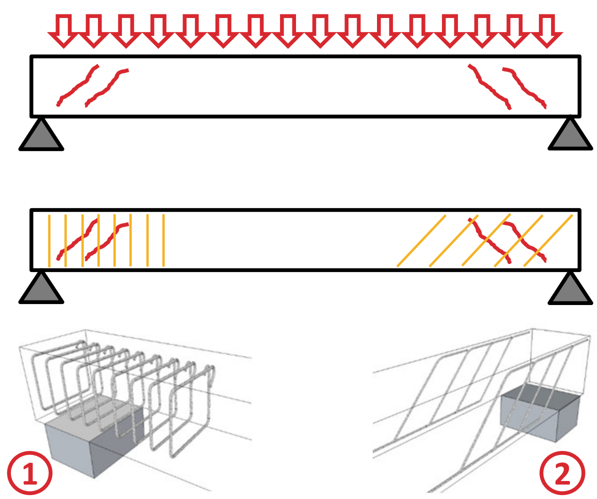
MAIN TYPES OF STRENGTHENING

SHEAR



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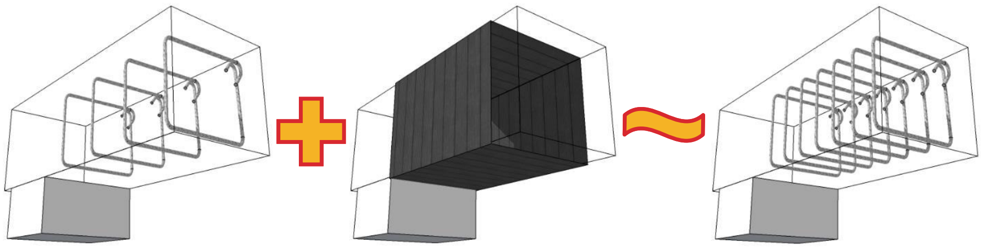
SHEAR STRENGTHENING



$$V_r = \phi\left(V_c + V_s + V_p\right) + \phi_f V_f$$

Steel and concrete Contribution

FRP Contribution

- Members are U-wrapped or fully wrapped
- Can be discrete strips or a continuous strips

$$V_f = \frac{A_f f_{fe} d_{fv} (\sin\alpha_f + \cos\alpha_f)}{s_f} \qquad (6.3.2\text{-}1)$$

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SHEAR STRENGTHENING

$$A_f = 2nt_f w_f$$

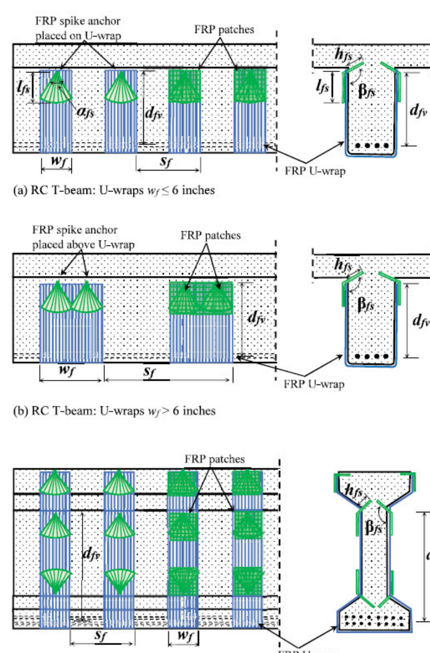
$$f_{fe} = E_f \varepsilon_{fe}$$

- For full anchorage conditions (using complete wrap or U-wrap with properly designed anchors, rupture failure is expected):

$$\varepsilon_{fe} = \phi_{EM}\left(\text{lesser of}\begin{Bmatrix}0.006\\ 0.4\varepsilon_{fu}\end{Bmatrix}\right) \qquad (6.3.2\text{-}4)$$

- For other anchorage conditions (using side bonding or U-wrap, non-rupture failure is more likely):

$$\varepsilon_{fe} = \phi_{Ei}\left(\text{lesser of}\begin{Bmatrix}0.004\\ R_f\varepsilon_{fu}\end{Bmatrix}\right) \qquad (6.3.2\text{-}5)$$



(a) RC T-beam: U-wraps $w_f \leq 6$ inches

(b) RC T-beam: U-wraps $w_f > 6$ inches

(c) PC I-beam: U-wraps $w_f \leq 6$ inches

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STRENGTHENING IN TORSION

$$T_f = \frac{\phi_{EM} n E_f t_f \varepsilon_{fe} d_{fv} \alpha_t x_1 y_1}{s_f}$$

$$\alpha_t = \text{ lesser of } \begin{cases} 0.66+0.33\dfrac{y_1}{x_1} \\ 1.5 \end{cases} \qquad (6.4.2\text{-}2)$$

$$\varepsilon_{fe} = 0.004 + \frac{1}{2}(\varepsilon_{fu} - 0.004) \qquad (6.4.2\text{-}3)$$

$$\varepsilon_{fu} \geq 0.008 \qquad (6.4.2\text{-}4)$$

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TYPES OF STRENGTHENING

CONFINEMENT

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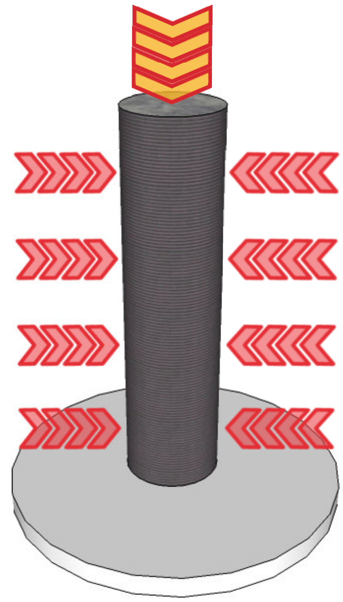
TYPES OF STRENGTHENING
CONFINEMENT

To avoid the lateral expansion, its necessary to ensure a confinement around the element using a rigid material with a high strength such as FRPs.

CFRP strengthening
- Increase in both axial and flexural strength
- Commonly used for seismic retrofitting
- Most efficient reinforcement in circular columns



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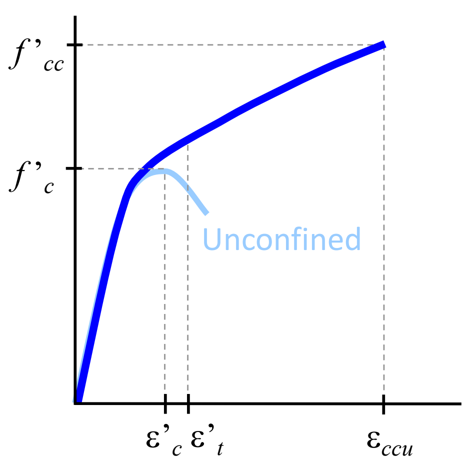
CONFINEMENT DESIGN PER ACI 440



$$P_r = 0.85\phi\left[0.85 f'_{cc}\left(A_g - A_{st}\right) + \left(f_y A_{st}\right)\right]$$

(7.3.1-1)

$$f'_{cc} = f'_c\left(1 + \frac{2\phi_f f_l}{f'_c}\right)$$

$$f_l = \phi_{EM}\frac{2nE_f t_f \varepsilon_{fe}}{D_e}$$

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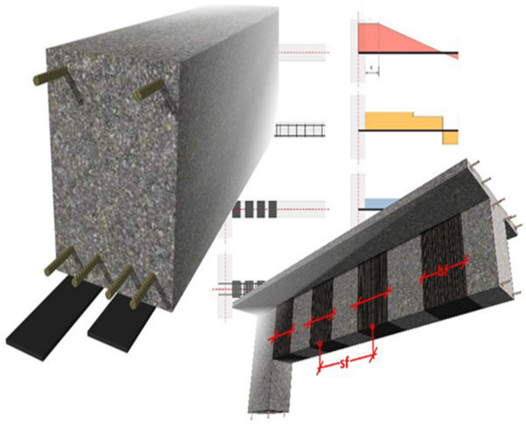
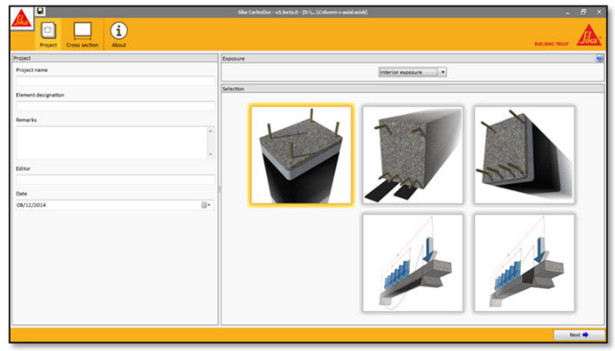
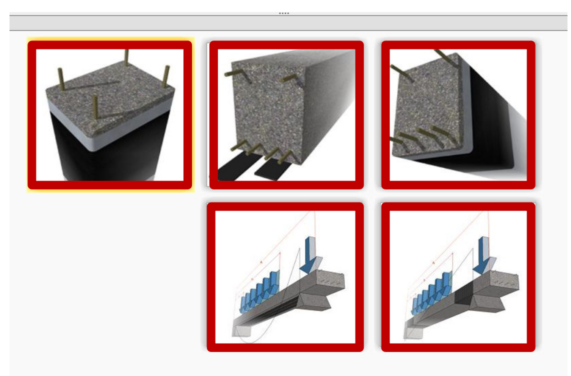
FRP DESIGN SOFTWARE





SIKA® CARBODUR® SOFTWARE

- We have 5 different modules:
- RC section FRP confinement design
- RC section FRP flexural strengthening design
- RC section FRP shear strengthening design
- RC beam FRP flexural strengthening design
- RC beam FRP shear strengthening design



SPECIFYING FRP SYSTEMS

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HOW TO SPECIFY FRP?

- Were strengthening limits checked?
- Who will perform the design?
  - In-house design
    - Specify min material properties req'd
    - Be inclusive
  - Delegate it
    - Geometrical data (size of members and rebar amount and layout)
    - Concrete and steel properties
    - Demand and capacity.

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SPECIFICATION DOCUMENTS

- Spec documents
  - Align drawings and spec documents
- Specifying minimum material properties:
  - Tensile strength, stiffness, and elongation
  - Prevent sole-sourcing - review various manufacturer's PDSs for min requirements

Table 1
FRP Cured Laminate Properties

Property	CFRP	EGFRP
Design Unit Tensile Strength[1, 2]	2.2 k/in/ply	2.8 k/in/ply
Unit Tensile Stiffness[1]	*220 k/in/ply	140 k/in/ply
Design Elongation at failure	1.00%	2.00%
Nominal Fabric Weight	9 oz/yd²	27 oz/yd²

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EXAMPLE 1

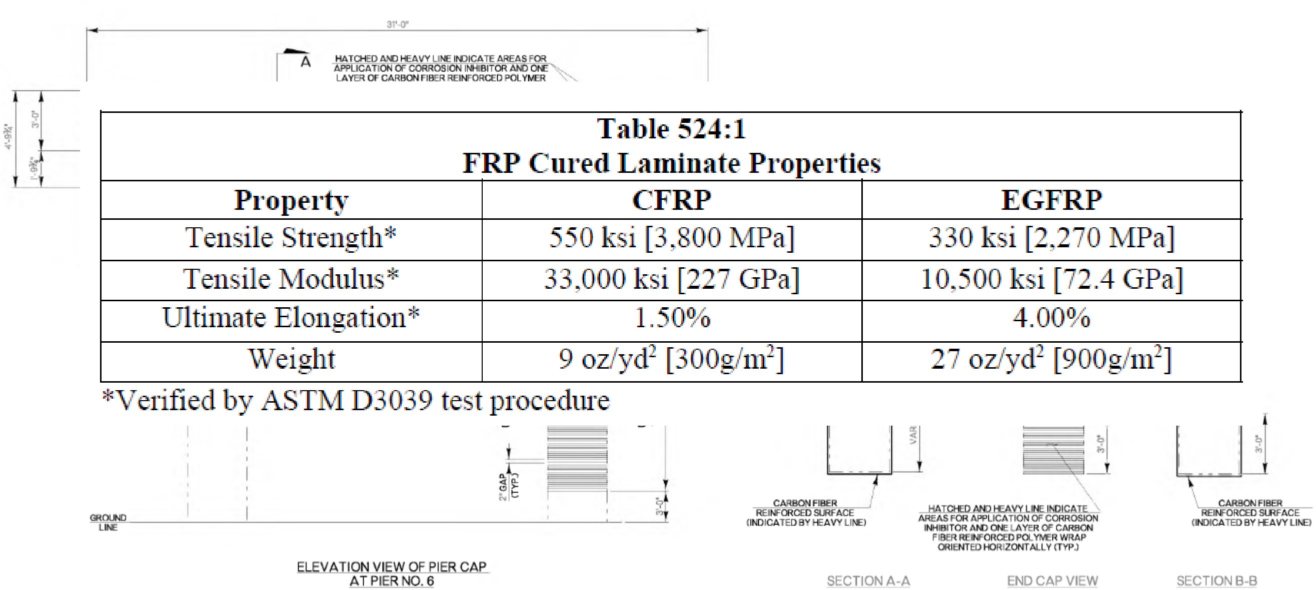

Table 524:1
FRP Cured Laminate Properties

Property	CFRP	EGFRP
Tensile Strength*	550 ksi [3,800 MPa]	330 ksi [2,270 MPa]
Tensile Modulus*	33,000 ksi [227 GPa]	10,500 ksi [72.4 GPa]
Ultimate Elongation*	1.50%	4.00%
Weight	9 oz/yd² [300g/m²]	27 oz/yd² [900g/m²]

*Verified by ASTM D3039 test procedure

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EXAMPLE 2

FRP DESIGN CRITERIA:

(1) REQUIRED NEGATIVE MOMENT FLEXURAL CAPACITY PARAMETERS:

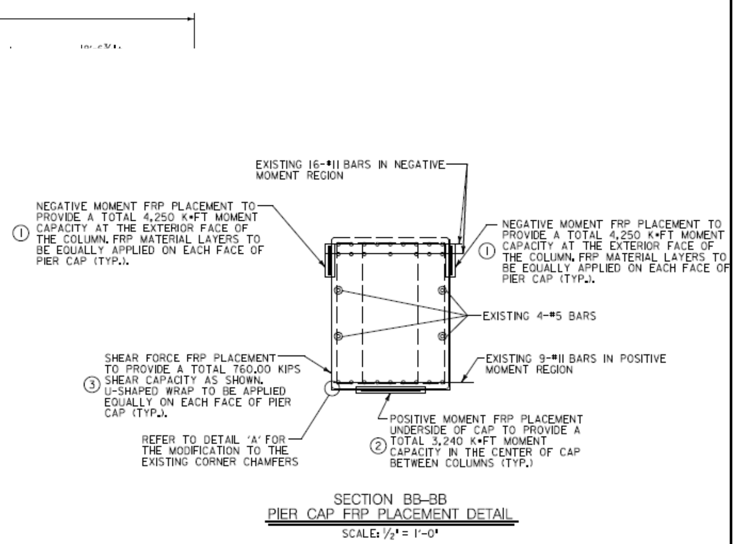
b = 48"	WIDTH OF PIER CAP
h = 61.92"	HEIGHT OF PIER CAP (ASSUMED FOR DESIGN PURPOSES)
clear cover = 2"	CLEAR COVER FOR EXISTING PIER REINFORCING
f'c = 3.0 ksi	SPECIFIED 28 DAY STRENGTH OF EXISTING CONCRETE
fy = 40.0 ksi	SPECIFIED YIELD STRENGTH OF EXISTING REINFORCING STEEL
As = 21.84 in²	EXISTING NEGATIVE MOMENT AREA OF STEEL
ϕMn = 4,250 k•ft	REQUIRED NEGATIVE MOMENT CAPACITY AFTER STRENGTHENING. FRP LAYERS SHALL BE APPLIED EQUALLY EACH FACE.

(2) REQUIRED POSITIVE MOMENT FLEXURAL CAPACITY PARAMETERS:

b = 48"	WIDTH OF PIER CAP
h = 61.92"	HEIGHT OF PIER CAP (ASSUMED FOR DESIGN PURPOSES)
clear cover = 2"	CLEAR COVER FOR EXISTING PIER REINFORCING
f'c = 3.0 ksi	SPECIFIED 28 DAY STRENGTH OF EXISTING CONCRETE
fy = 40.0 ksi	SPECIFIED YIELD STRENGTH OF EXISTING REINFORCING STEEL
As = 19.12 in²	EXISTING POSITIVE MOMENT AREA OF STEEL
ϕMn = 3,240 k•ft	REQUIRED POSITIVE MOMENT CAPACITY AFTER STRENGTHENING

(3) REQUIRED SHEAR CAPACITY PARAMETERS:

b = 48"	WIDTH OF PIER CAP
h = 61.92"	HEIGHT OF PIER CAP (ASSUMED FOR DESIGN PURPOSES)
clear cover = 2"	CLEAR COVER FOR EXISTING PIER REINFORCING
f'c = 3.0 ksi	SPECIFIED 28 DAY STRENGTH OF EXISTING CONCRETE
fy = 40.0 ksi	SPECIFIED YIELD STRENGTH OF EXISTING REINFORCING STEEL
Vc = 311.50 kips	ASSUMED ULTIMATE CONCRETE SHEAR CAPACITY
Vs = 122.52 kips	ASSUMED ULTIMATE REINFORCING STEEL SHEAR CAPACITY
ϕVn = 760.0 kips	REQUIRED SHEAR CAPACITY AFTER STRENGTHENING. FRP LAYERS SHALL BE APPLIED EQUALLY EACH FACE.



SECTION BB–BB
PIER CAP FRP PLACEMENT DETAIL
SCALE: ½" = 1'-0"

SHALL BE COMPLETED AFTER STAGE 2 REMOVAL WHEN STRINGERS NOS. 4 AND 5 HAVE NOT BEEN PLACED. FRP SYSTEM SHALL BE COMPLETELY CURED PRIOR TO THE SETTING OF ANY NEW STRINGERS, DECK FORMING, OR DECK CONCRETE PLACEMENT.

ELEVATION
PIER NO. 1 FRP PLACEMENT DETAIL
SCALE: 3⁄16" = 1'-0"

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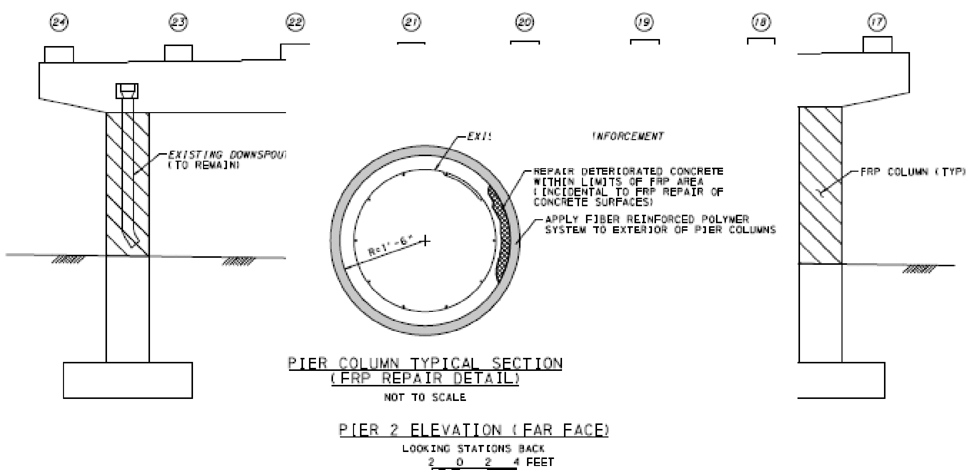
EXAMPLE 3



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PROJECT COMPLETION

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PROTECTIVE COATINGS

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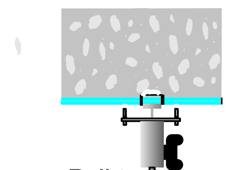
QC ACCEPTANCE CRITERIA

- Delamination
  - Limited to ensure proper bond
- Bond
  - Pull off tests to determine bond strength to concrete
  - Minimum 200 psi (1.4 MPa)
- Laminate tensile Testing
  - Panel making is an art-form
  - Panels must be flat and have smooth finish



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FRP SYSTEMS AT GLANCE

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SURFACE PREP

- All defects repaired using epoxy mortar
- Concrete prepared by sandblasting
- Concrete smoothed out using grinders
- Open pores
- Remove laitance
- Smooth and level
- Corners rounded to ½" min

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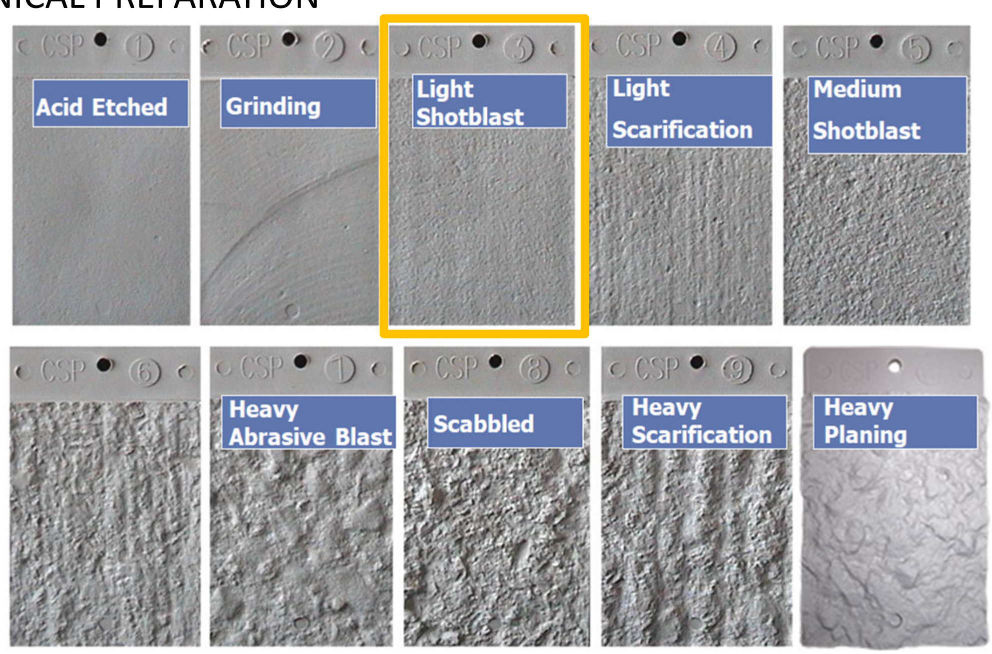
MECHANICAL PREPARATION



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PRIMER APPLICATION FOR FRP SYSTEMS

- Mix & Apply Epoxy Primer

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AVAILABLE FRPS SYSTEMS

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FABRIC BASED FRP SYSTEMS

FIELD SATURATED SYSTEMS AND PRE-SATURATED SYSTEMS

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FIELD SATURATED FRP SYSTEM

- The ORIGINAL FRP system
- Longest in the market and most trusted
- Most common resin used is epoxy
- Durable in various environments
- Saturation is done in the field

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WET LAY-UP INSTALLATION METHOD

- Saturate Fabric with Resin – Table or Saturator

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DRY LAY-UP INSTALLATION METHOD

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FIELD SATURATED FRP SYSTEMS

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FIELD SATURATED FRP SYSTEMS

- Remove air bubbles

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PRESATURATED SYSTEM

- Open foil pouches when ready to apply

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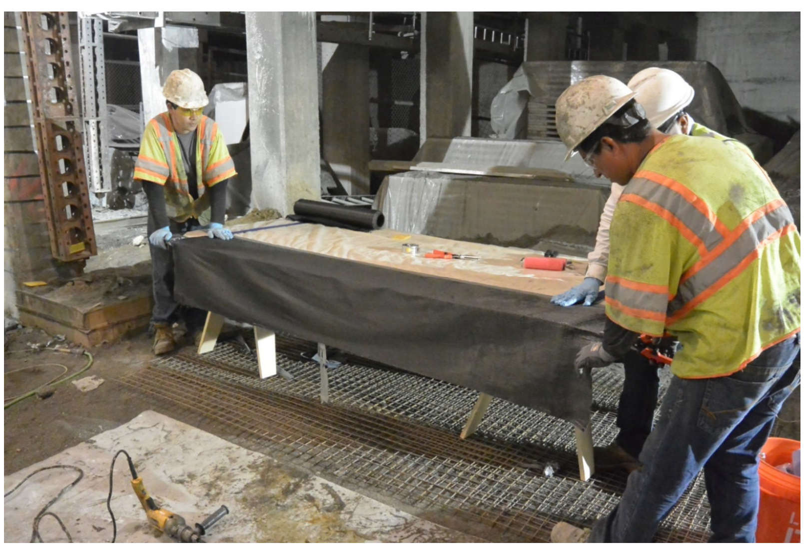
PRESATURATED SYSTEM

- Cut “wet” fabric if necessary



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FRP PLATES AND NSM SYSTEM

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CFRP PLATES

Clean the CFRP strips

Cut the laminate to size

Apply even amount of epoxy to the laminate

Apply and roll the CFRP strip onto concrete

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FRP RODS – NSM REINFORCEMENT

Cut and clean grooves

Place rods in the groove

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NSM REINFORCEMENT

- Fill the groove with epoxy

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POST-TENSION FRP PLATES

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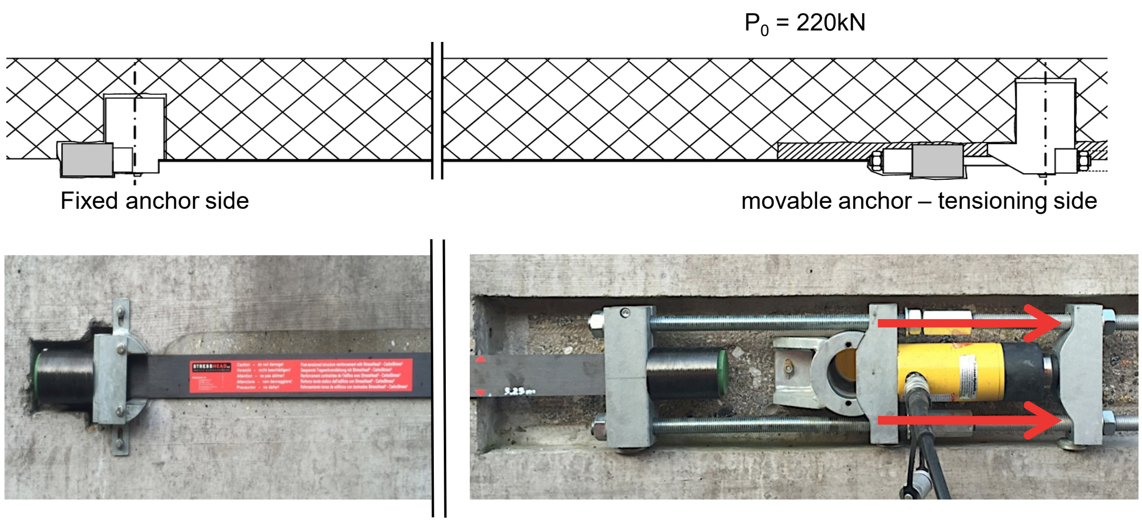
POST-TENSIONING FRP SYSTEM - ANCHORS

- Standard anchor Type III



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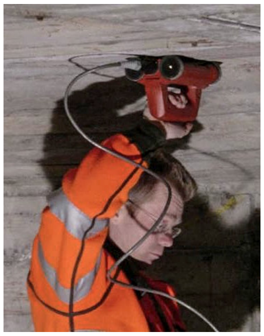
POST-TENSIONING FRP SYSTEM

- Application


Define location


Drilling


Chipping


Installation & injection

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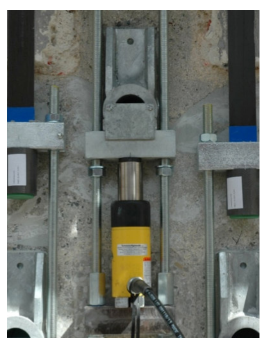
POST-TENSIONING FRP SYSTEM

- Application


Installation of tendon


Apply adhesive
(if bonded)


Tensioning of tendon


Protection (optional)

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CONCLUSIONS

- FRP's are cost and time effective solutions for reinforcement of infrastructure
- Typical FRP strengthening applications in RC include flexural, shear, confinement, and seismic strengthening
- Specifying FRP properly will prevent delays, headaches, and RFI's on projects.
- Proper repair and application is critical to ensure successful and long-lasting reinforcement
- Sika has many resources and tools, including the very powerful design software, to help you with the design and specification process

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THANK YOU FOR YOUR ATTENTION

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