Western Bridge Engineers' Seminar

SEPTEMBER 25 - 28, 2011 | ARIZONA GRAND HOTEL | PHOENIX, ARIZONA

HDR

Fiber Reinforced Polymer (FRP) Strengthening of Concrete Beams

Navigating the Current Design Specifications and Procedures

Robert D. Richardson, PE

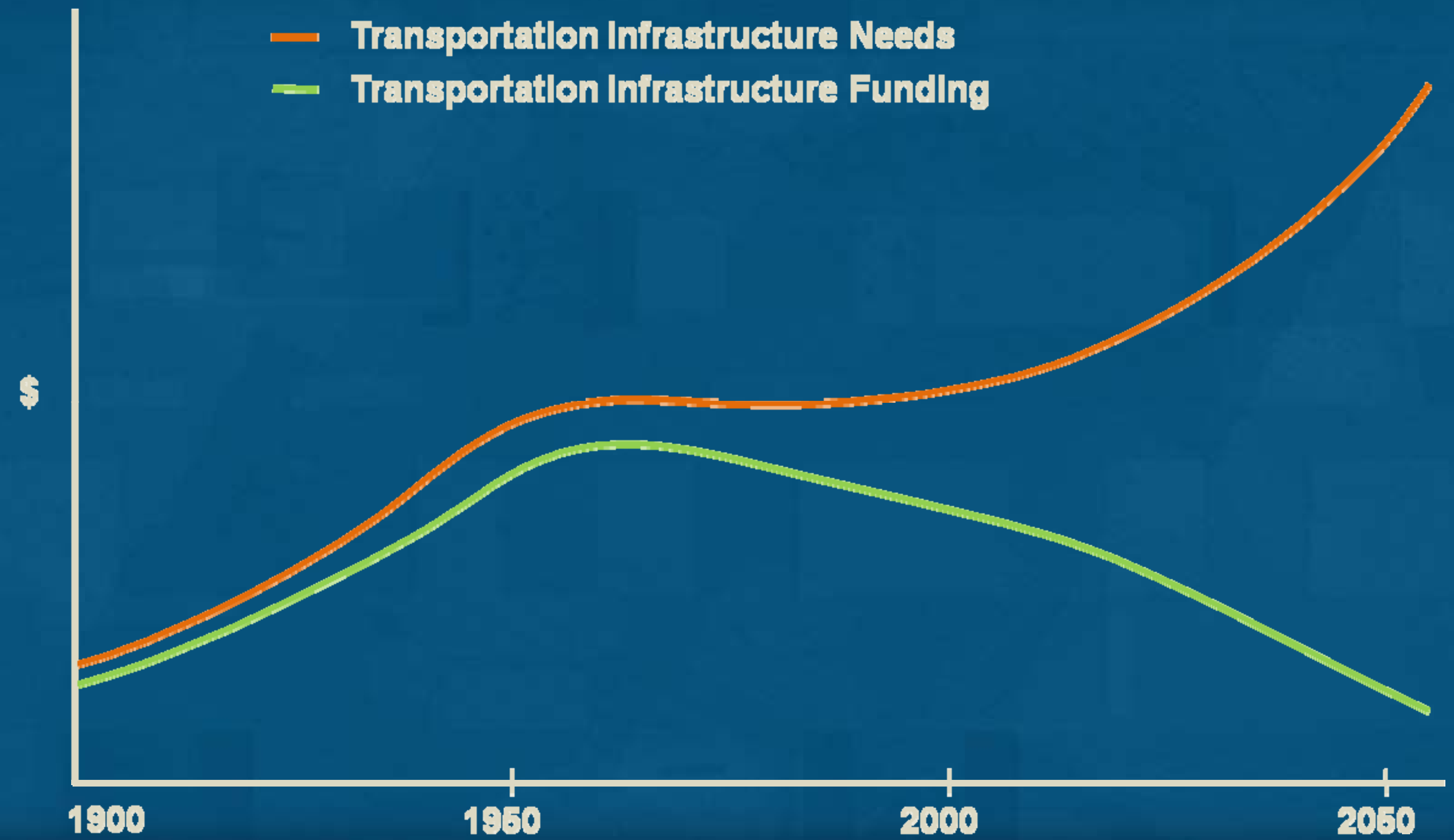
Domenic A. Coletti, PE

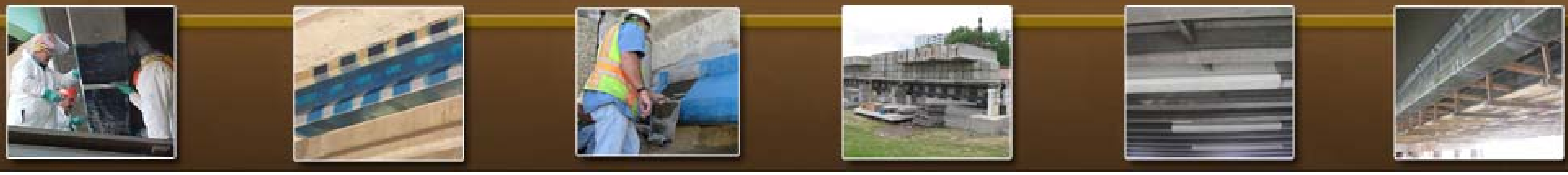
Western Bridge Engineers' Seminar 2011

Phoenix, AZ

General Background

Transportation Infrastructure Funding VS Needs

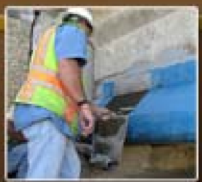


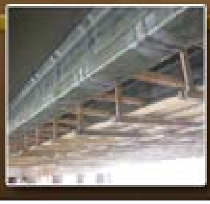


Purpose

- REPAIR DAMAGED CONCRETE GIRDERS
  - Impact
  - Rust
  - Other
- STRENGTHEN OLDER CONCRETE STRUCTURES FOR CURRENT LOADS
  - HL93
  - Remove Load Restrictions

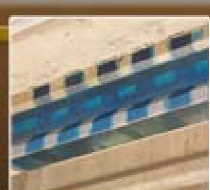
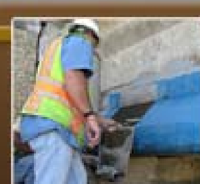


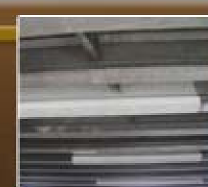
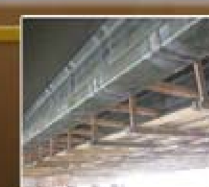


Study Limitations

- CONCRETE BEAMS (Pre-stressed and Conventionally Reinforced)
  - Flexural Strengthening
  - Shear Strengthening
- WET-LAYUP CARBON FIBER REINFORCED POLYMER (CFRP) SYSTEMS
  - NO Near-Surface Mount (NSM) Systems
  - NO Prefabricated Plate Systems

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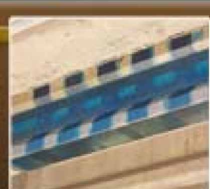
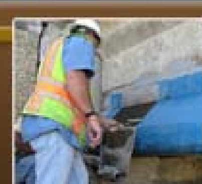
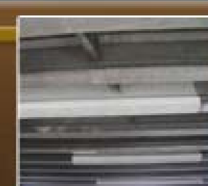
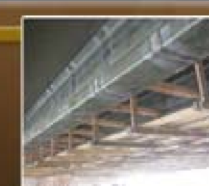
Current Design Spec's

HDR

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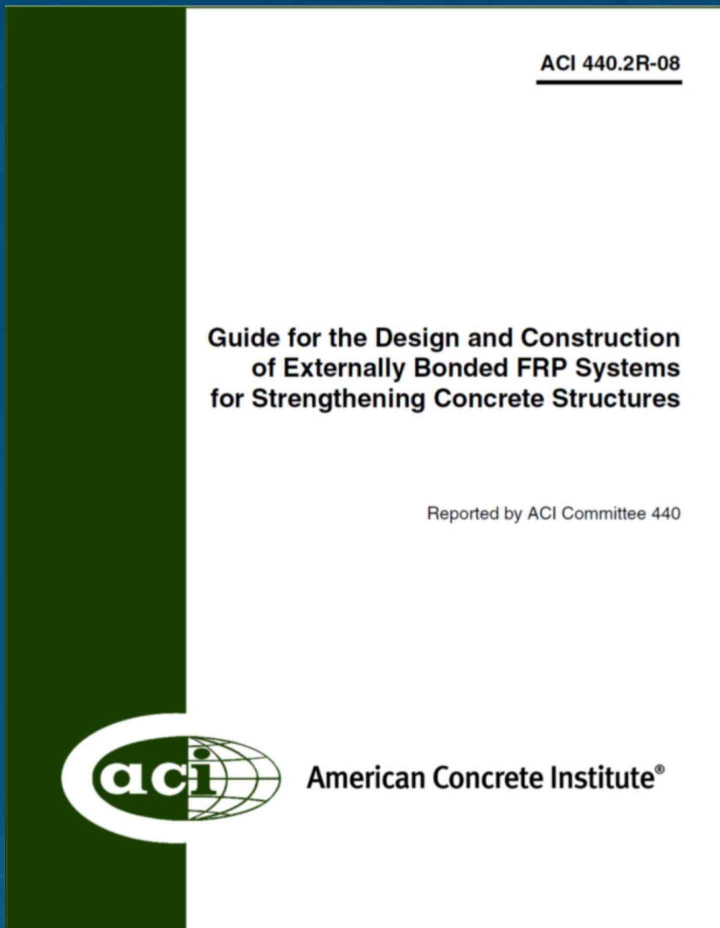

ACI 440.2R-08

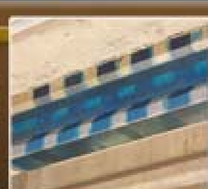
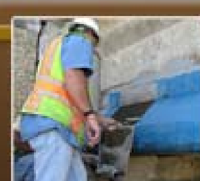
Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

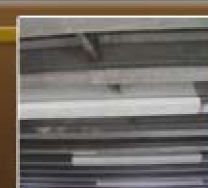
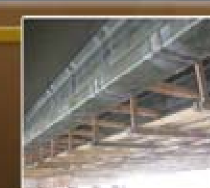
Reported by ACI Committee 440

American Concrete Institute®

ACI 440.2-R08

Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, Revised 2008

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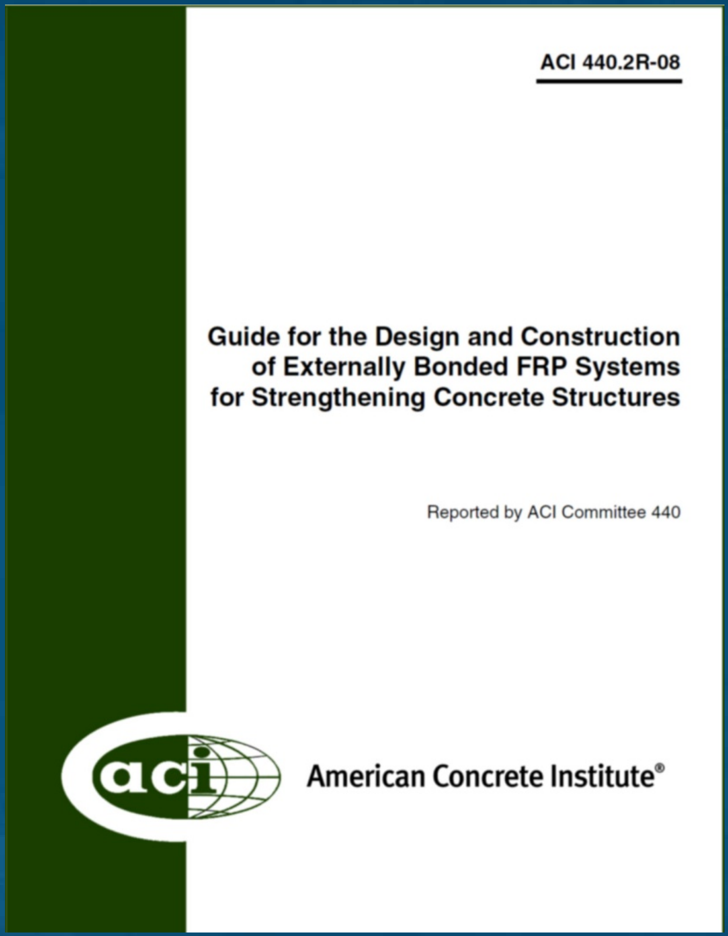


ACI 440.2R-08

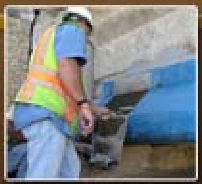
Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

Reported by ACI Committee 440

American Concrete Institute®

- Context and format conform with ACI 318
- Widely used for several years
- Refined treatment of flexural resistance factors related to reinf. steel strain and ductility
- Includes several example design calculations
- No long-term durability testing requirements



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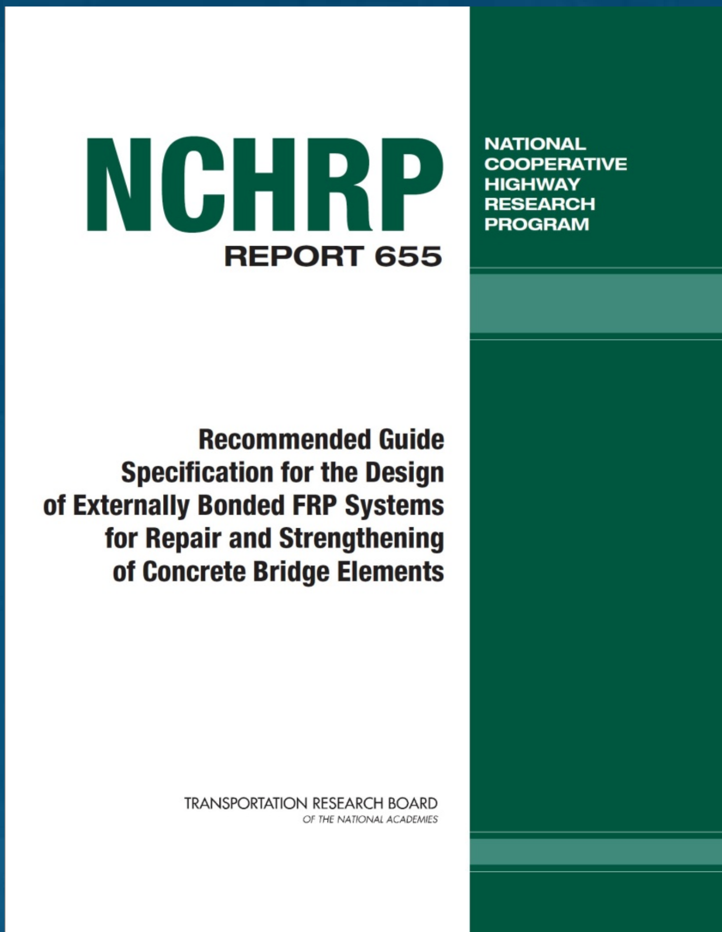
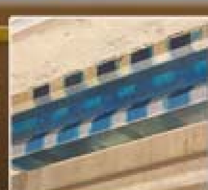
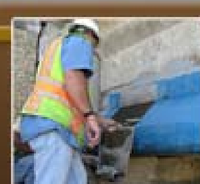
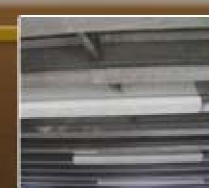
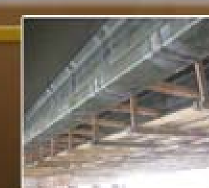

NCHRP
REPORT 655
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NCHRP Report No. 655

Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 2010

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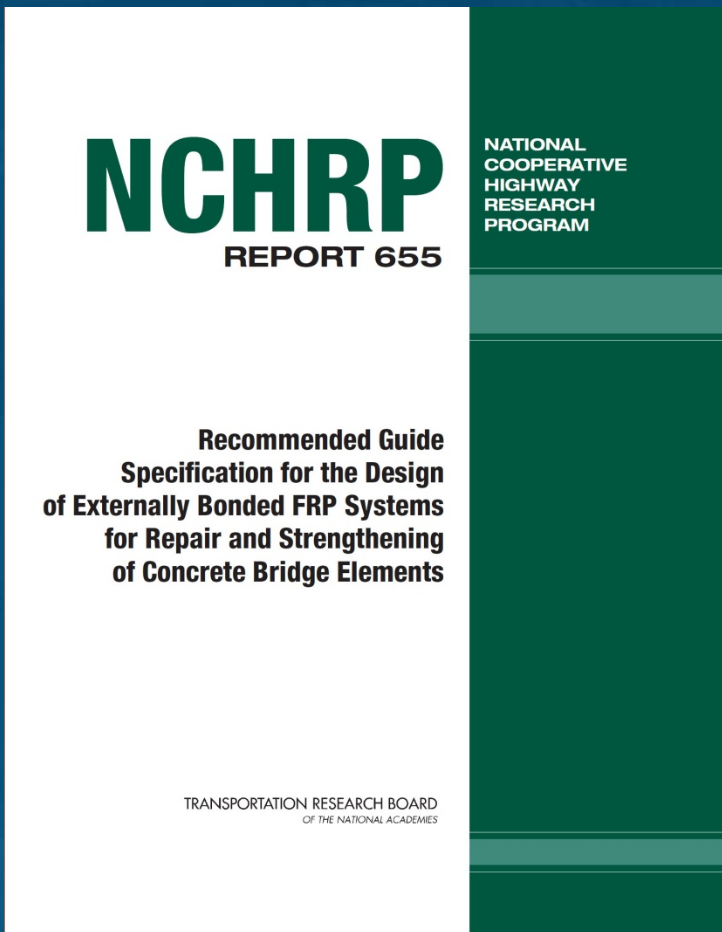
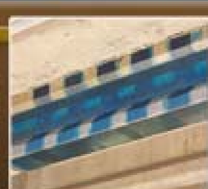
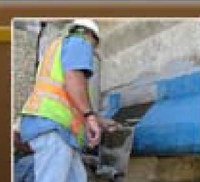

NCHRP
REPORT 655

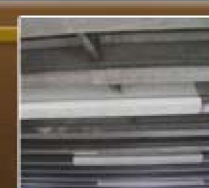
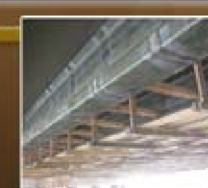
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements

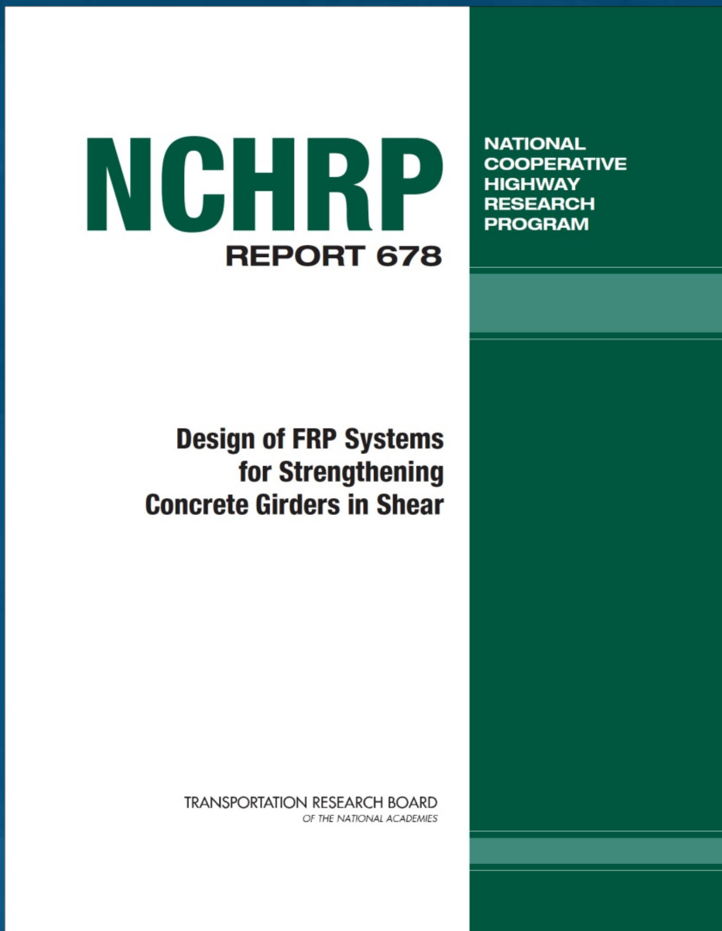
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

- Context and format conform w/ AASHTO LRFD Bridge Design Specifications
- Shear - Includes design examples for both prestressed and non-prestressed beams
- Flexure - Includes design examples for non-prestressed beams only
- Peer reviewed only

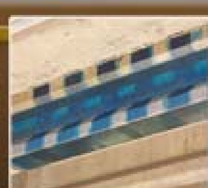
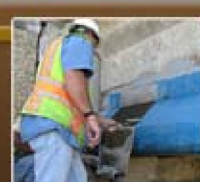



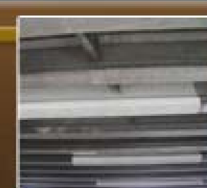
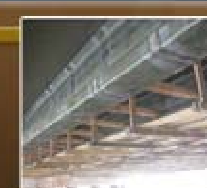
Current Design Spec's


NCHRP
REPORT 678
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Design of FRP Systems for Strengthening Concrete Girders in Shear
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NCHRP Report No. 678

Design of FRP Systems for Strengthening Concrete Girders in Shear, 2011

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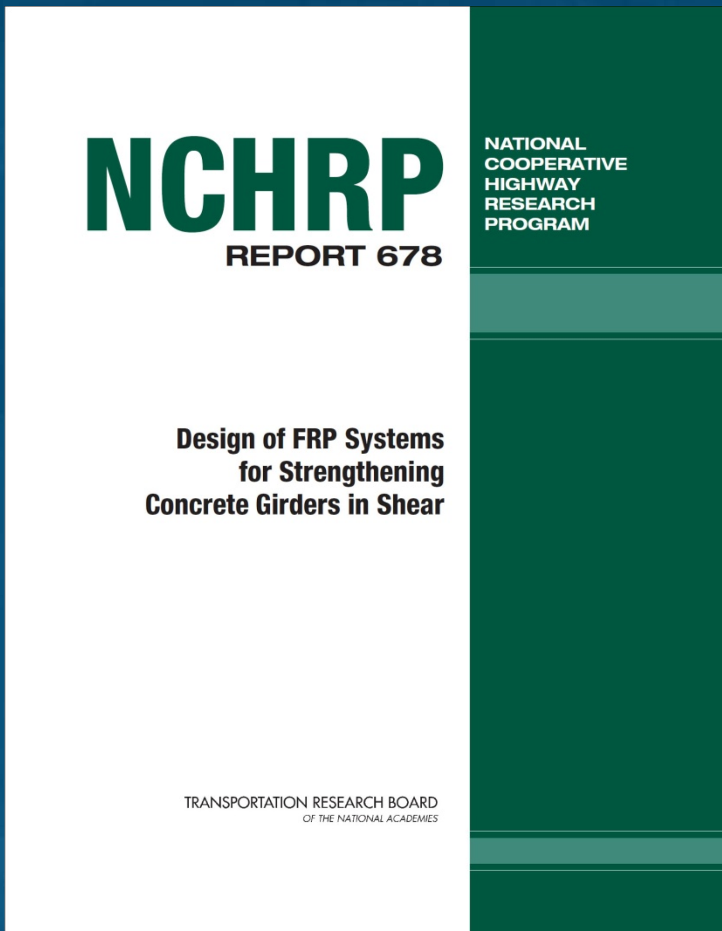
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REPORT 678
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TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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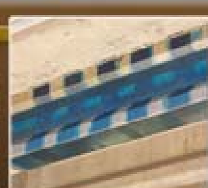
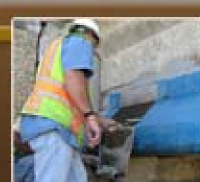
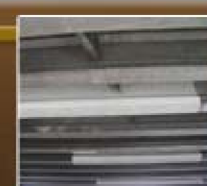
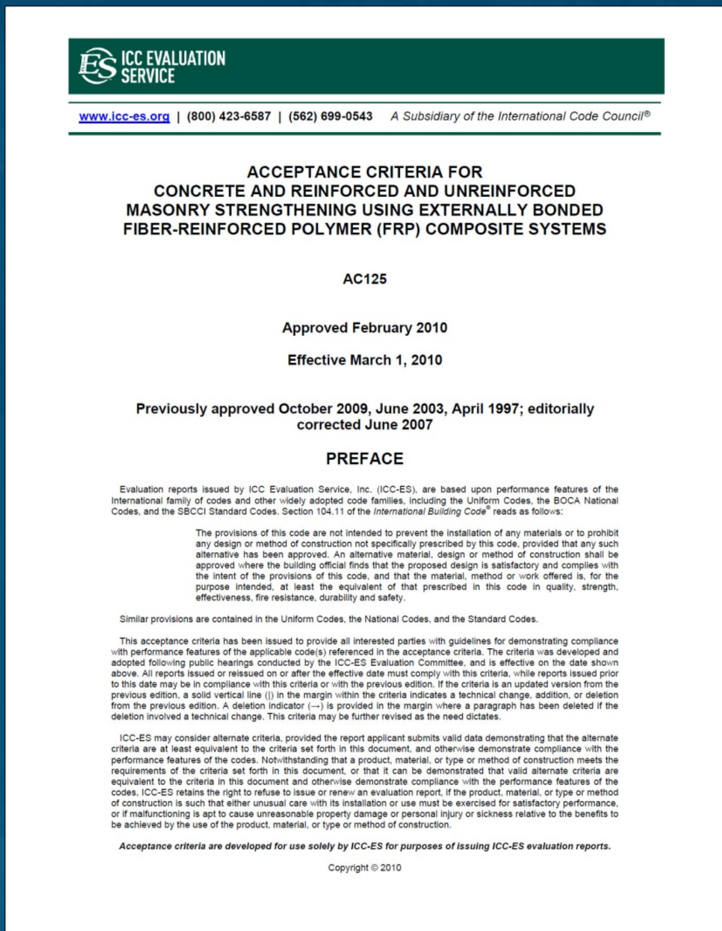
- Includes design examples for both prestressed and non-prestressed beams
- Addresses shear design only
- Peer reviewed only




Current Design Spec's

HDR



ICC EVALUATION SERVICE

www.icc-es.org | (800) 423-6587 | (562) 699-0543 *A Subsidiary of the International Code Council®*

ACCEPTANCE CRITERIA FOR CONCRETE AND REINFORCED AND UNREINFORCED MASONRY STRENGTHENING USING EXTERNALLY BONDED FIBER-REINFORCED POLYMER (FRP) COMPOSITE SYSTEMS

AC125

Approved February 2010

Effective March 1, 2010

Previously approved October 2009, June 2003, April 1997; editorially corrected June 2007

PREFACE

Evaluation reports issued by ICC Evaluation Service, Inc. (ICC-ES), are based upon performance features of the International family of codes and other widely adopted code families, including the Uniform Codes, the BOCA National Codes, and the SBCCI Standard Codes. Section 104.11 of the *International Building Code®* reads as follows:

> The provisions of this code are not intended to prevent the installation of any materials or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety.

Similar provisions are contained in the Uniform Codes, the National Codes, and the Standard Codes.

This acceptance criteria has been issued to provide all interested parties with guidelines for demonstrating compliance with performance features of the applicable code(s) referenced in the acceptance criteria. The criteria was developed and adopted following public hearings conducted by the ICC-ES Evaluation Committee, and is effective on the date shown above. All reports issued or reissued on or after the effective date must comply with this criteria, while reports issued prior to this date may be in compliance with this criteria or with the previous edition. If the criteria is an updated version from the previous edition, a solid vertical line (|) in the margin within the criteria indicates a technical change, addition, or deletion from the previous edition. A deletion indicator (→) is provided in the margin where a paragraph has been deleted if the deletion involved a technical change. This criteria may be further revised as the need dictates.

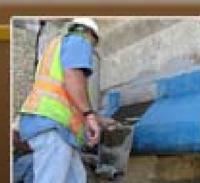
ICC-ES may consider alternate criteria, provided the report applicant submits valid data demonstrating that the alternate criteria are at least equivalent to the criteria set forth in this document, and otherwise demonstrate compliance with the performance features of the codes. Notwithstanding that a product, material, or type or method of construction meets the requirements of the criteria set forth in this document, or that it can be demonstrated that valid alternate criteria are equivalent to the criteria in this document and otherwise demonstrate compliance with the performance features of the codes, ICC-ES retains the right to refuse to issue or renew an evaluation report, if the product, material, or type or method of construction is such that either unusual care with its installation or use must be exercised for satisfactory performance, or if malfunctioning is apt to cause unreasonable property damage or personal injury or sickness relative to the benefits to be achieved by the use of the product, material, or type or method of construction.

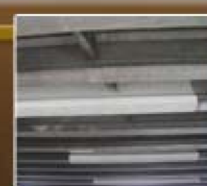
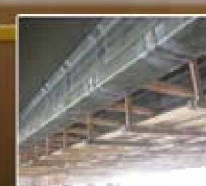
Acceptance criteria are developed for use solely by ICC-ES for purposes of issuing ICC-ES evaluation reports.

ICC AC-125

Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Externally Bonded Fiber-Reinforced Polymer (FRP) Composite Systems, 2010

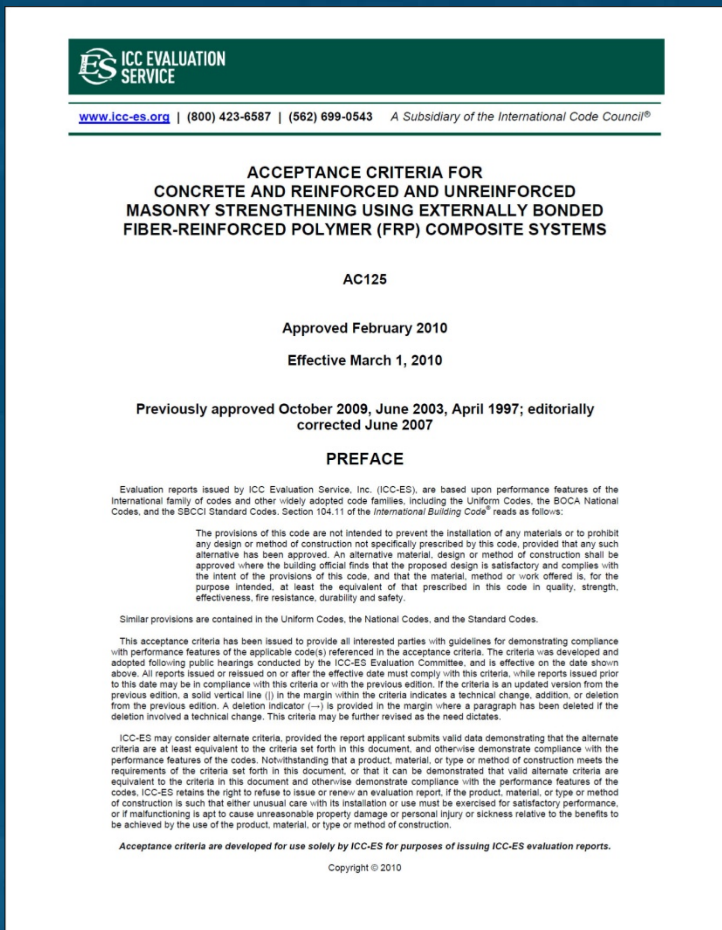




Current Design Spec's

HDR



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AC125

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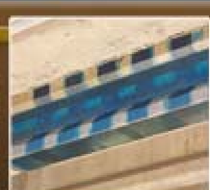
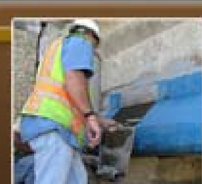
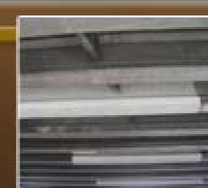
Acceptance criteria are developed for use solely by ICC-ES for purposes of issuing ICC-ES evaluation reports.

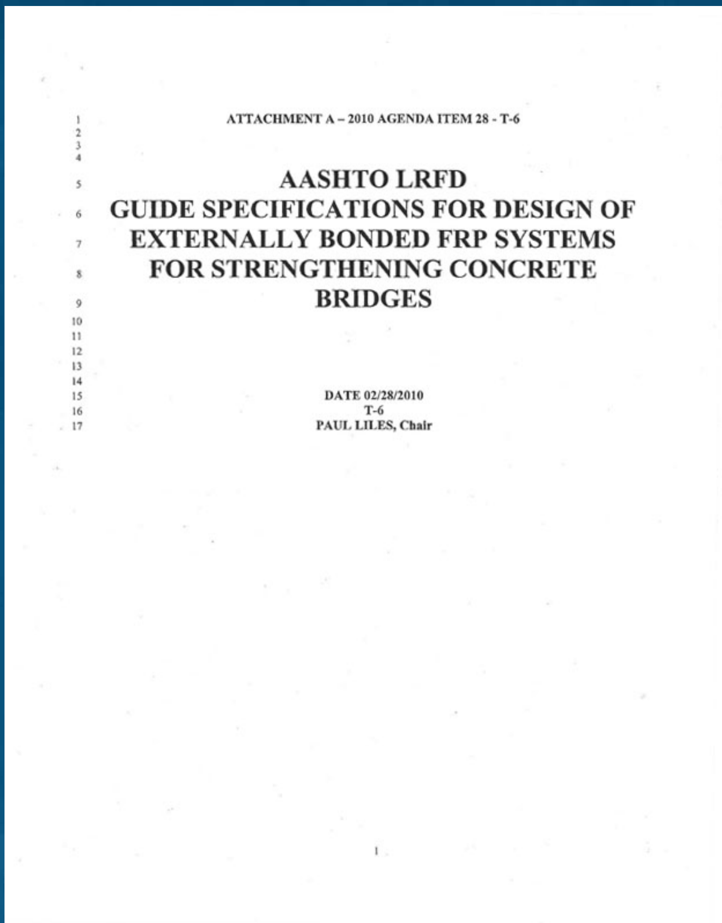
- "Acceptance Criteria" document
- Similar to ACI 440.2R-08
- Includes long-term durability testing requirements similar to NCHRP 655
- Not considered further in the conducted study







Current Design Spec's

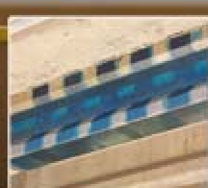
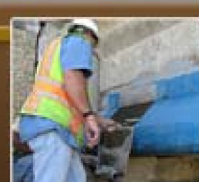

ATTACHMENT A – 2010 AGENDA ITEM 28 - T-6

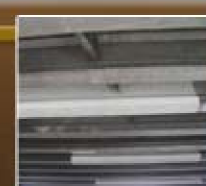
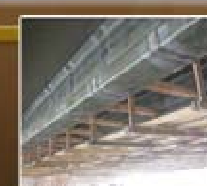
AASHTO LRFD
GUIDE SPECIFICATIONS FOR DESIGN OF
EXTERNALLY BONDED FRP SYSTEMS
FOR STRENGTHENING CONCRETE
BRIDGES

DATE 02/28/2010
T-6
PAUL LILES, Chair

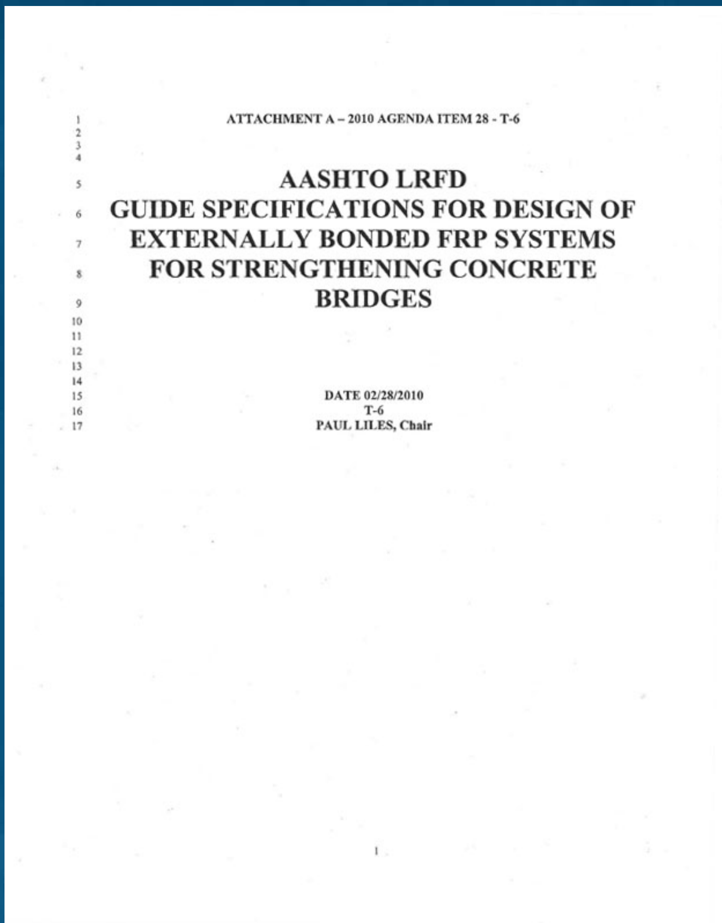
1

Proposed *AASHTO LRFD Guide Specification for Design of Externally Bonded FRP Systems for Strengthening Concrete Bridges*, 2010

Current Design Spec's

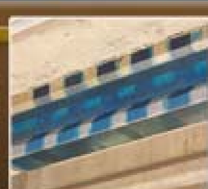
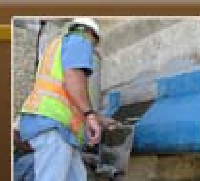

ATTACHMENT A – 2010 AGENDA ITEM 28 - T-6

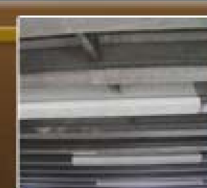
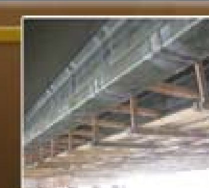
AASHTO LRFD
GUIDE SPECIFICATIONS FOR DESIGN OF
EXTERNALLY BONDED FRP SYSTEMS
FOR STRENGTHENING CONCRETE
BRIDGES

DATE 02/28/2010
T-6
PAUL LILES, Chair

1

- AASHTO LRFD Bridge Design Specifications format
- Refined treatment of flexural resistance factors related to reinf. steel strain and ductility
- Very similar to ACI 440.2-R08 except for shear resistance factors (AASHTO LRFD)
- Inconsistencies in document – not considered further in the study

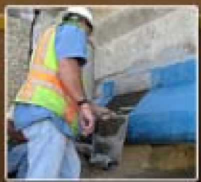




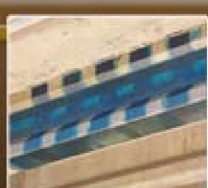
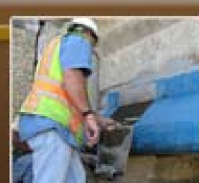
Current Design Spec's

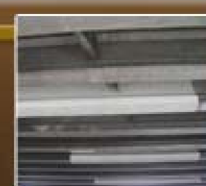
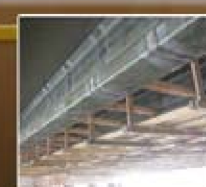
FEATURE	ACI 440.2	NCHRP 655	NCHRP 678
Documentation of Nominal Capacity Design Equations (BASED ON THE LEVEL OF COMPREHENSIVE DOCUMENTATION)	✓		
Experimental Substantiation of Nominal Capacity Equations (BASED ON THE SIZE AND LONGEVITY OF THE TEST POOL DATA)	✓		
Treatment of Strain Limitations (BASED ON THE INCLUSION OF APPLICATION METHOD AND REDUCED DUCTILITY)	✓		
Material Testing Requirements (BASED ON THE LEVEL OF COMPREHENSIVENESS – ESP. LONG-TERM DURABILITY)		✓	
Load Factors (BASED ON STATISTICAL DERIVATION AND COMFORMITY W/ AASHTO LRFD)		✓	
Flexure Resistance Factors (BASED ON STATISTICAL DERIVATION AND INCLUSION OF REDUCED DUCTILITY)	✓		
Shear Resistance Factors ((BASED ON STATISTICAL DERIVATION AND COMFORMITY W/ AASHTO LRFD)	?	?	?






FLEXURAL STRENGTHENING

Flexural Strengthening

ACI 440.2R-08

$$\phi M_n \geq M_u$$

$$\phi M_n = \phi\left[A_s f_s\left(d-\frac{\beta_1 c}{2}\right)+ \psi_f A_f f_{fe}\left(d_f-\frac{\beta_1 c}{2}\right)\right]$$

$$\psi_f = 0.85$$

$0.65 \leq \phi \leq 0.90$ depending on ε_t or ε_{ps}

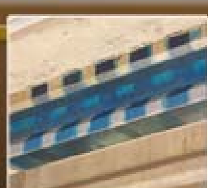
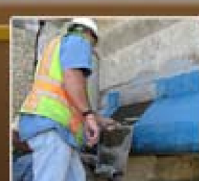
NCHRP 655

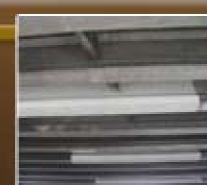
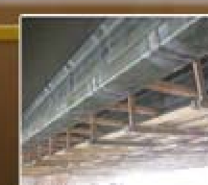
$$M_r \geq M_u$$

$$M_r = 0.9\left[A_s f_s\left(d_s - k_2 c\right) + A_s' f_s'\left(k_2 c - d_s'\right) + \phi_{frp} T_{frp}\left(h - k_2 c\right)\right]$$

$$\phi_{frp} = 0.85$$

$T_{frp} = b_{frp} N_b$ (at 0.5% strain)

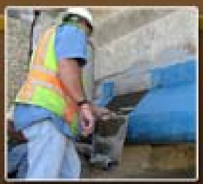



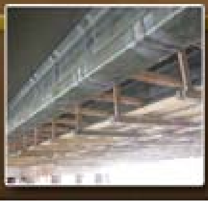
Flexural Strengthening

Assumptions

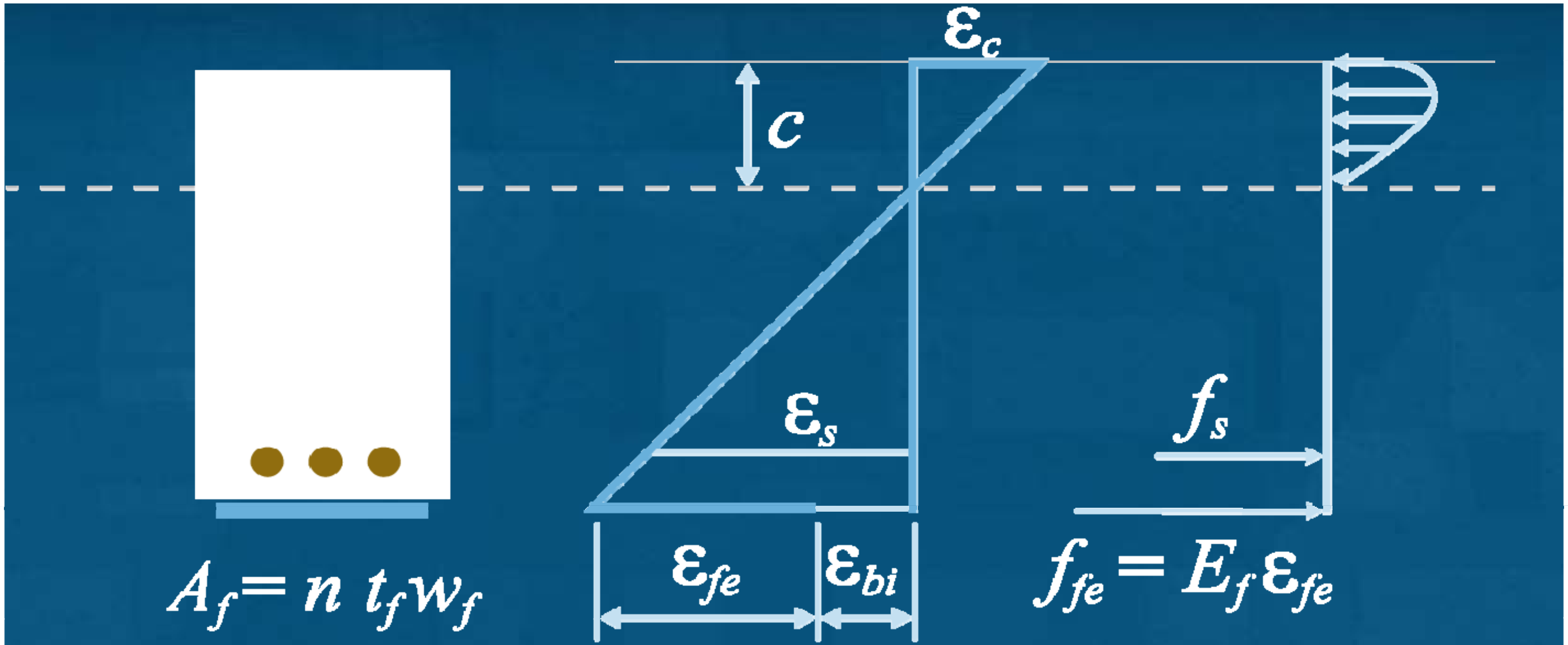
- Design calculations are based on actual dimensions and material properties.
- Plane sections remain plane (including FRP).
- Maximum concrete compressive strain ε_{cu}=0.003
- Ignore concrete tensile strength.
- FRP performs linear-elastically to failure.
- Perfect bond between concrete and FRP (no slip).
- Neglect shear deformation within the adhesive layer.





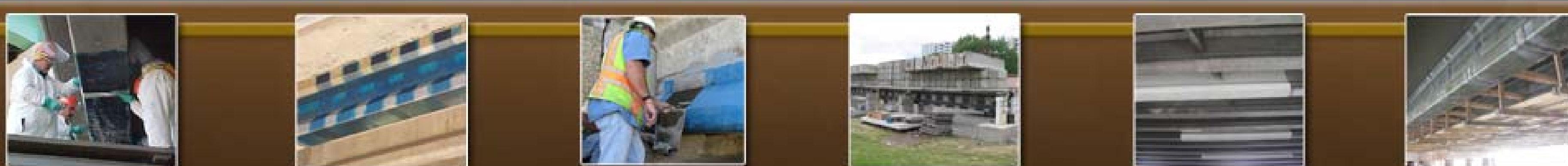



Flexural Strengthening



$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + A_f f_{fe} \left(h - \frac{\beta_1 c}{2}\right)$$

ACI



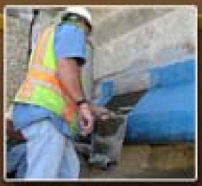
Flexural Strengthening

Failure Modes

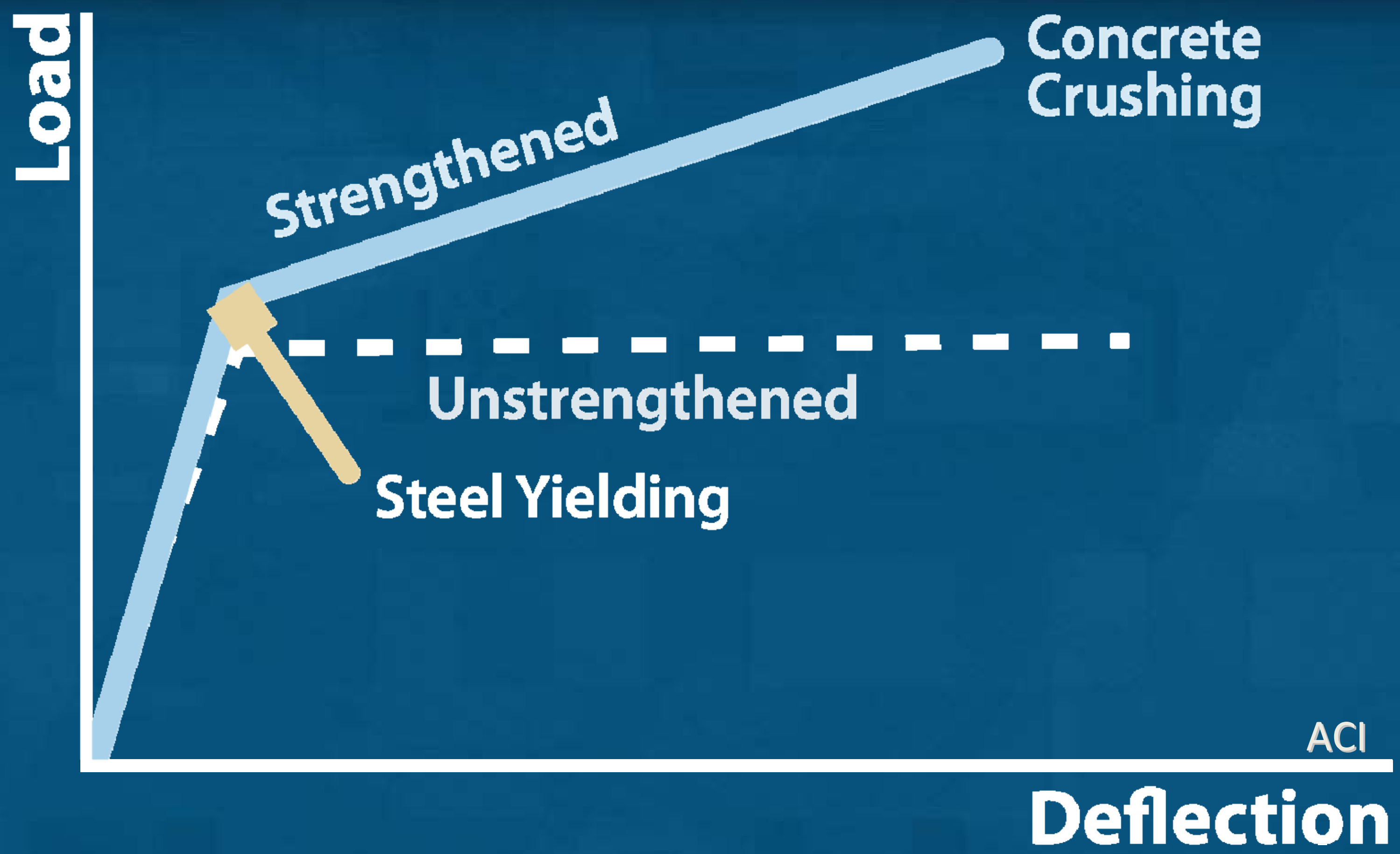
1. Crushing of concrete prior to steel yielding
2. Yield of steel followed by concrete crushing
3. Yield of steel followed by FRP failure
4. Shear or tension delamination in concrete cover
5. FRP debonding from substrate

Modes 2 or 3 are generally the desired failure mode.

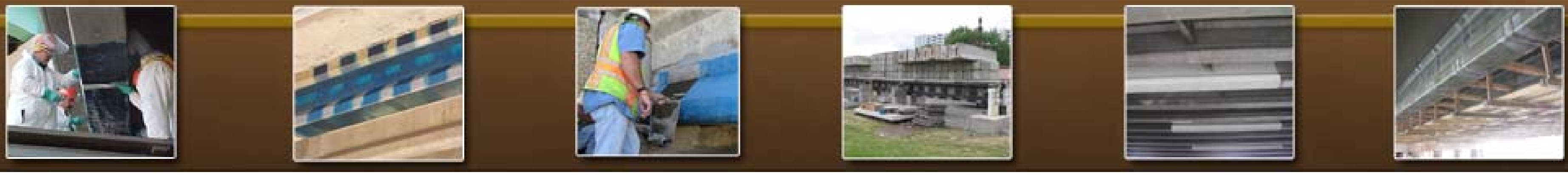





Flexural Strengthening

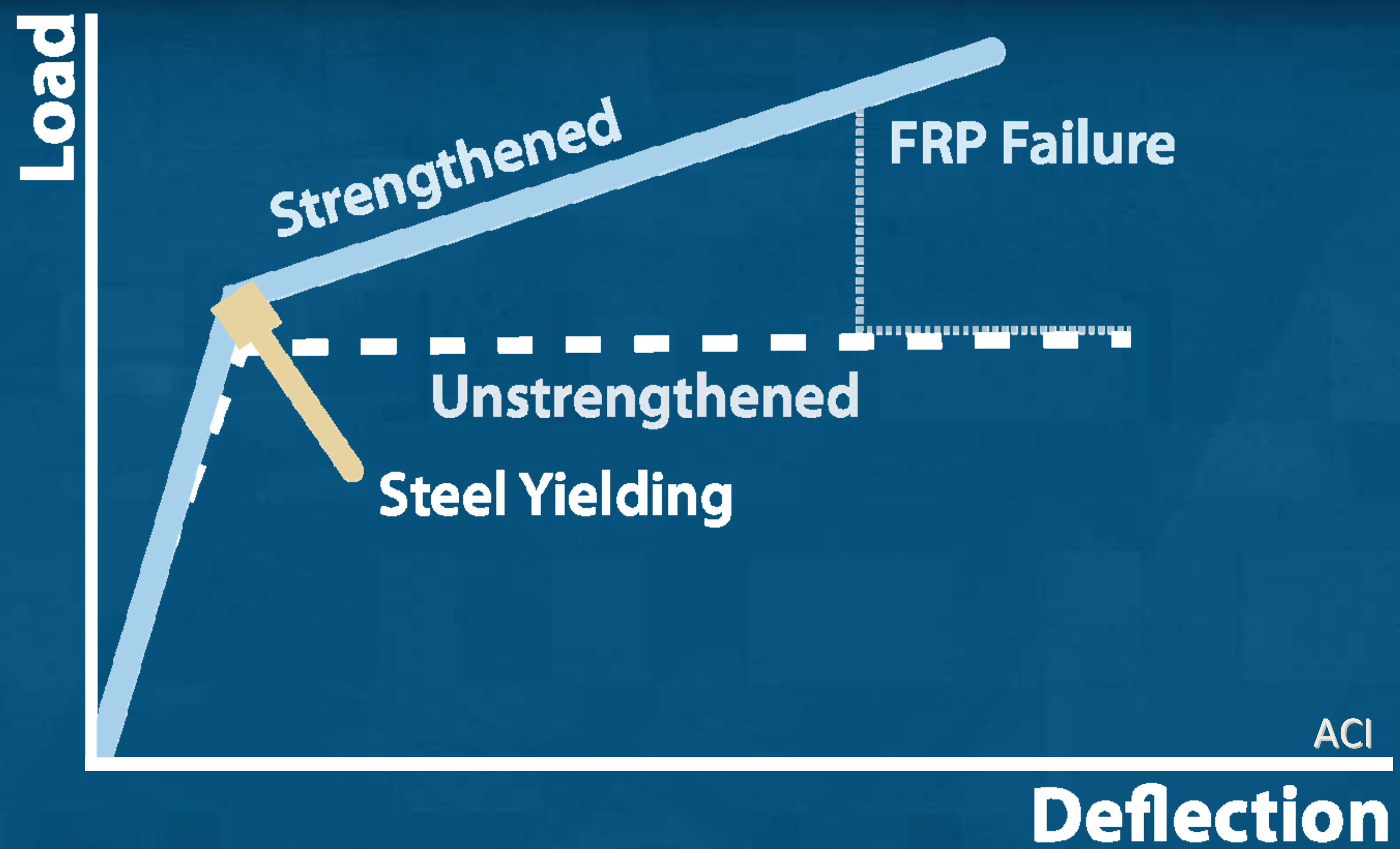


Failure Mode 2 – Steel Yield followed by concrete crushing



Flexural Strengthening

HDR



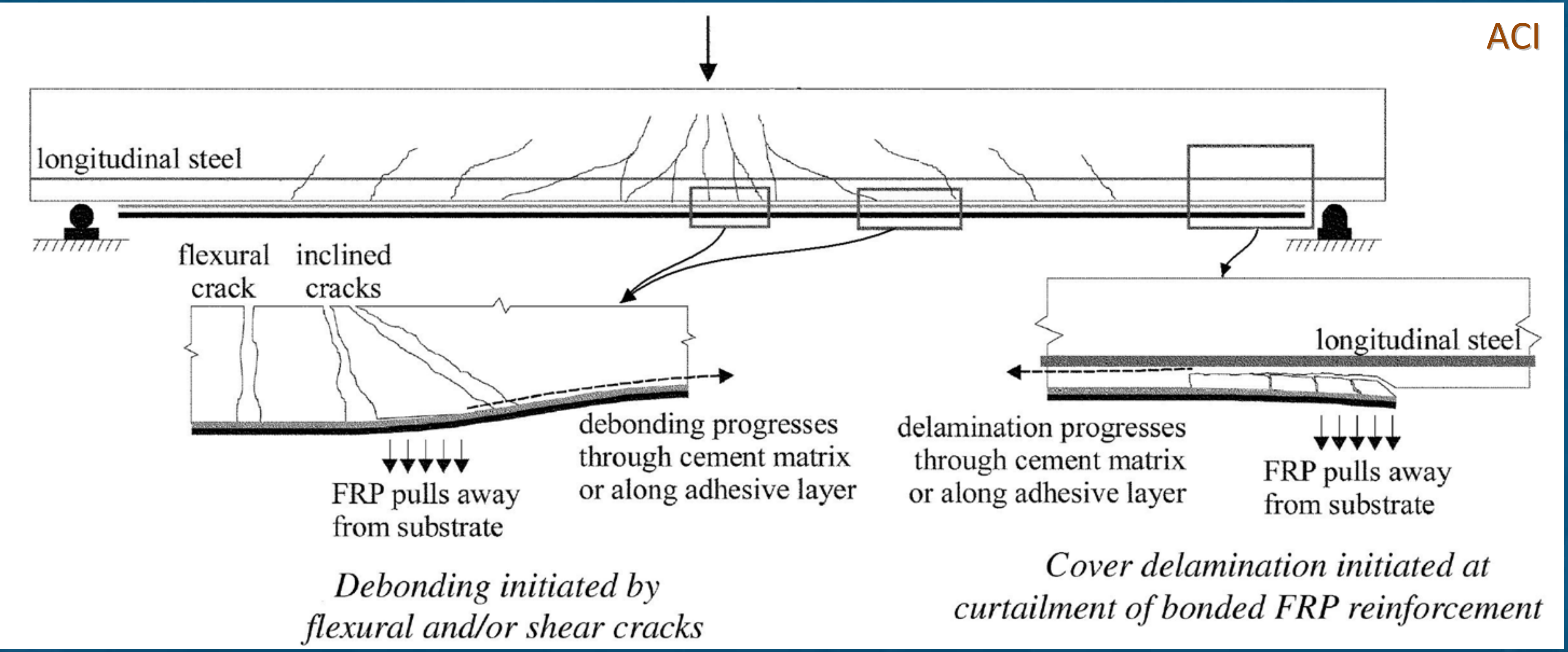
Failure Mode 3 - Yield of Steel followed by FRP failure



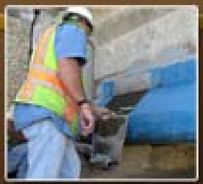



Flexural Strengthening

FRP DEBONDING/PEELING LIMITS








Flexural Strengthening

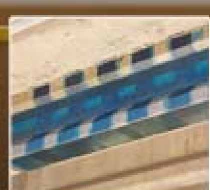
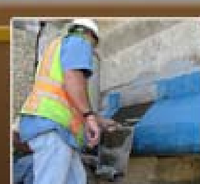
FRP DEBONDING/PEELING LIMITS

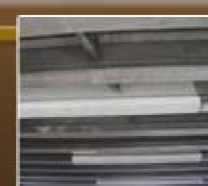
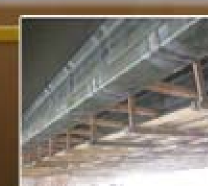
ACI 440.2R-08

$$\varepsilon_{fd} = 0.083\sqrt{\frac{f'c}{nE_f t_f}} \leq 0.9\varepsilon_{fu}$$

NCHRP 655

$$f_{peel} = \tau_{av}\left[\left(\frac{3E_a}{E_{frp}}\right)\frac{t_{frp}}{t_a}\right]^{1/4} \leq 0.065\sqrt{f'_c}$$

Flexural Strengthening

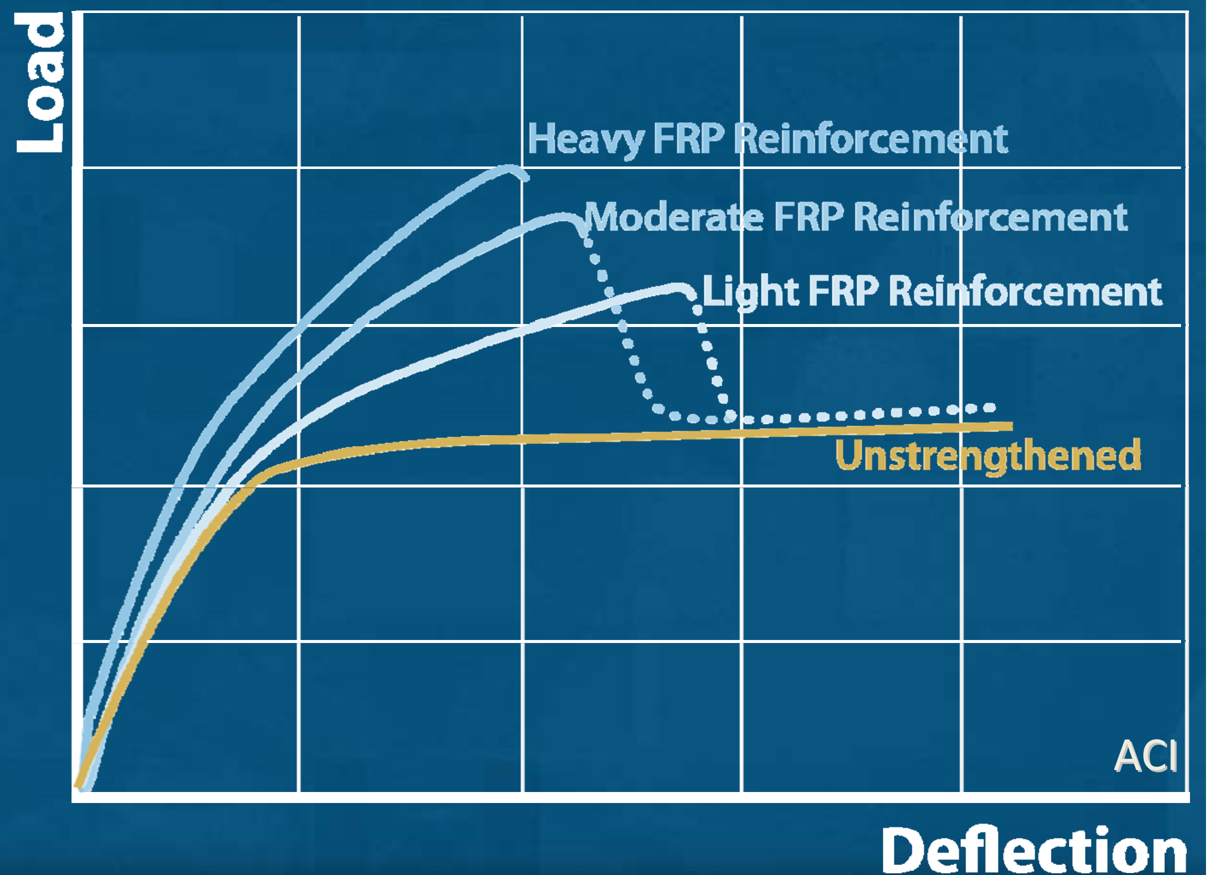
ACI 440.2

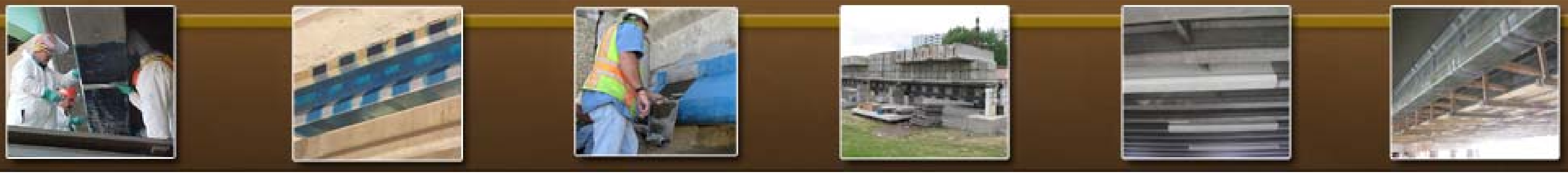
- Reduced ductility addressed with a variable ϕ factor

NCHRP 655

- FRP strain at ultimate limit state ≥ 2.5 x FRP strain at the point where the tension steel yields

FRP is a Non-ductile System

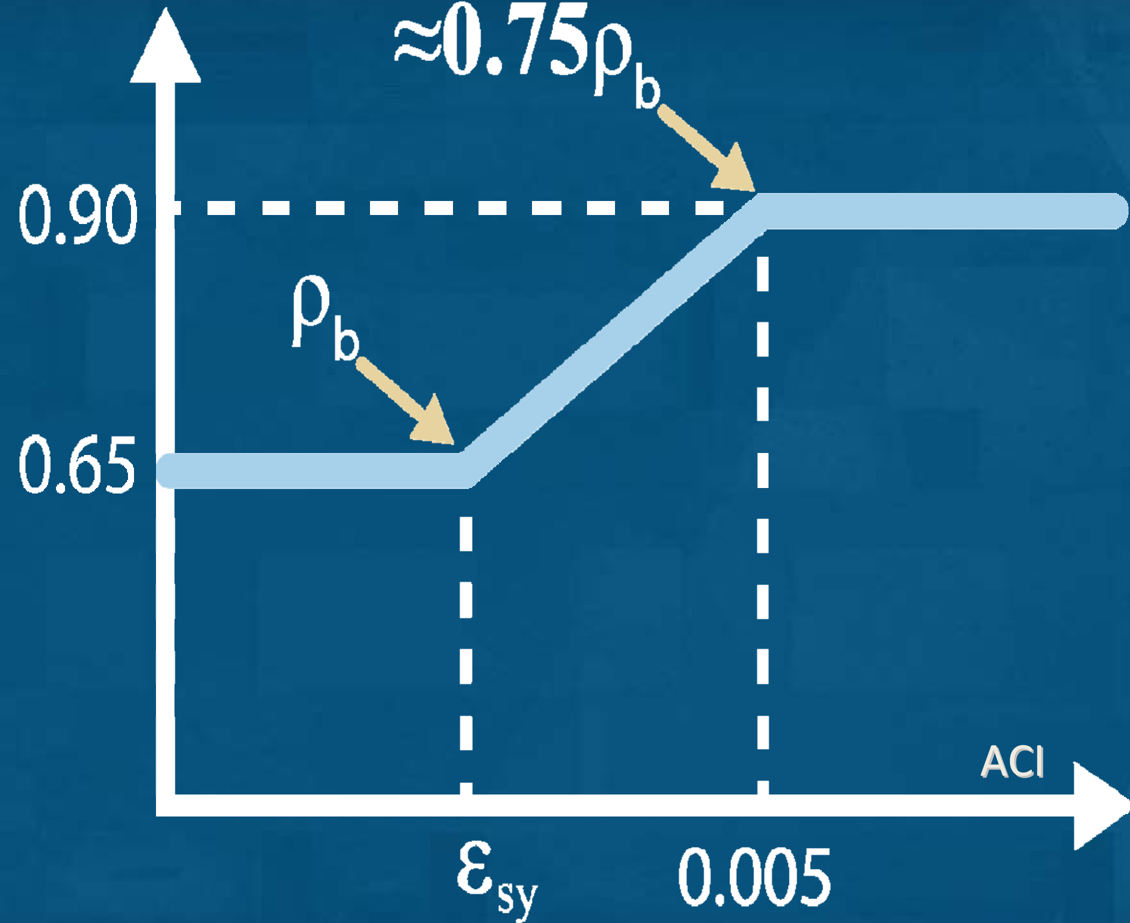


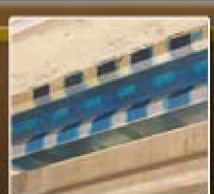


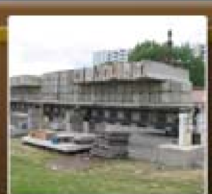
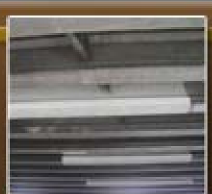
Flexural Strengthening

ACI 440.2-R08

- ϕ is a function of strain in the reinforcing steel.
- Similar for prestressed concrete beams with different strain limits



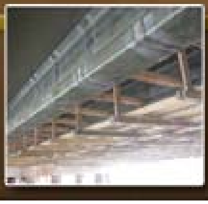




Flexural Strengthening

Section shear capacity must be sufficient to accommodate the shear forces associated with the increased flexural capacity.



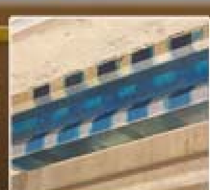
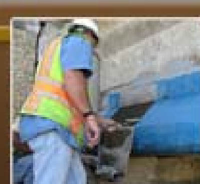


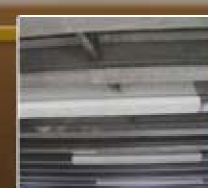



Western Bridge Engineers' Seminar
SEPTEMBER 25 - 28, 2011 | ARIZONA GRAND HOTEL | PHOENIX, ARIZONA

HDR

SHEAR STRENGTHENING




Western Bridge Engineers' Seminar
SEPTEMBER 25 - 28, 2011 | ARIZONA GRAND HOTEL | PHOENIX, ARIZONA

Shear Strengthening

HDR

ACI 440.2R-08

$$\phi V n \geq V u$$

$$\phi V_n = \phi (V_c + V_s + \psi_f V_f)$$

$$\phi = 0.75$$

$$\psi_f = 0.85 \ \text{(3 – sided wrap)}$$

$$V_f = \frac{(A_{fv}\, f_{fe}\, (\sin\alpha + \cos\alpha)\, d_{fv})}{s_f}$$

$$V_s + V_{frp} \leq 8\sqrt{(f'_c)}\, b_w d$$

NCHRP 655

$$V r \geq V u$$

$$V_r = \phi (V_c + V_s + V_p) + \phi_{frp} V_{frp}$$

$$\phi = 0.90$$

$$\phi_{frp} = 0.55 \ \text{(3 – sided wrap)}$$

$$V_{frp} = \frac{N^e_{frp}\, w_{frp}\, (\sin\alpha + \cos\alpha)\, d_{frp}}{s_v}$$

$$V_s + V_{frp} \leq 8\sqrt{(f'_c)}\, b_w d$$

NCHRP 678

$$\phi V n \geq V u$$

$$\phi V_n = \phi (V_c + V_s + V_f + V_p)$$

$$\phi = 0.90$$

$$V_f = \frac{A_f\, f_{fe}\, d_f}{s_f} (\sin\alpha_f + \cos\alpha_f)$$

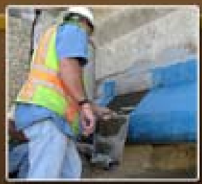
$$f_{fe} = R_f \varepsilon_{fu}$$

$$R_f = 0.066 \leq 3(\rho_f E_f)^{-0.67} \leq 1.0$$

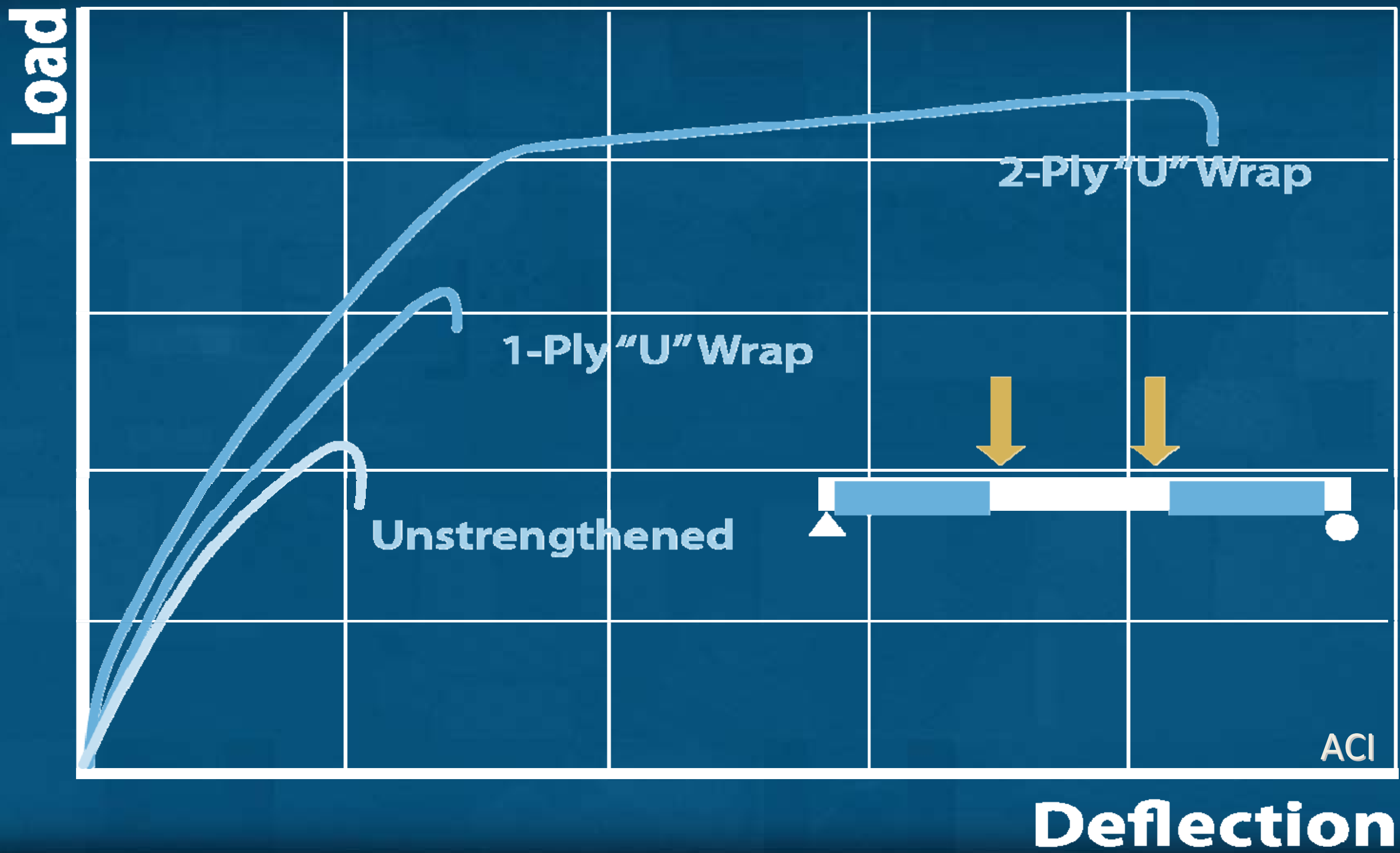
(2 or 3 - sided wrap)

$$Vn \leq 0.25(f'_c\, b_v d_v) + V_p$$

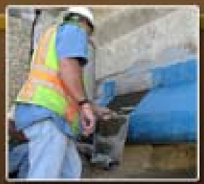





Shear Strengthening








Shear Strengthening

Standard Arrangement

Strips

Excellent Choice for use with Anchors

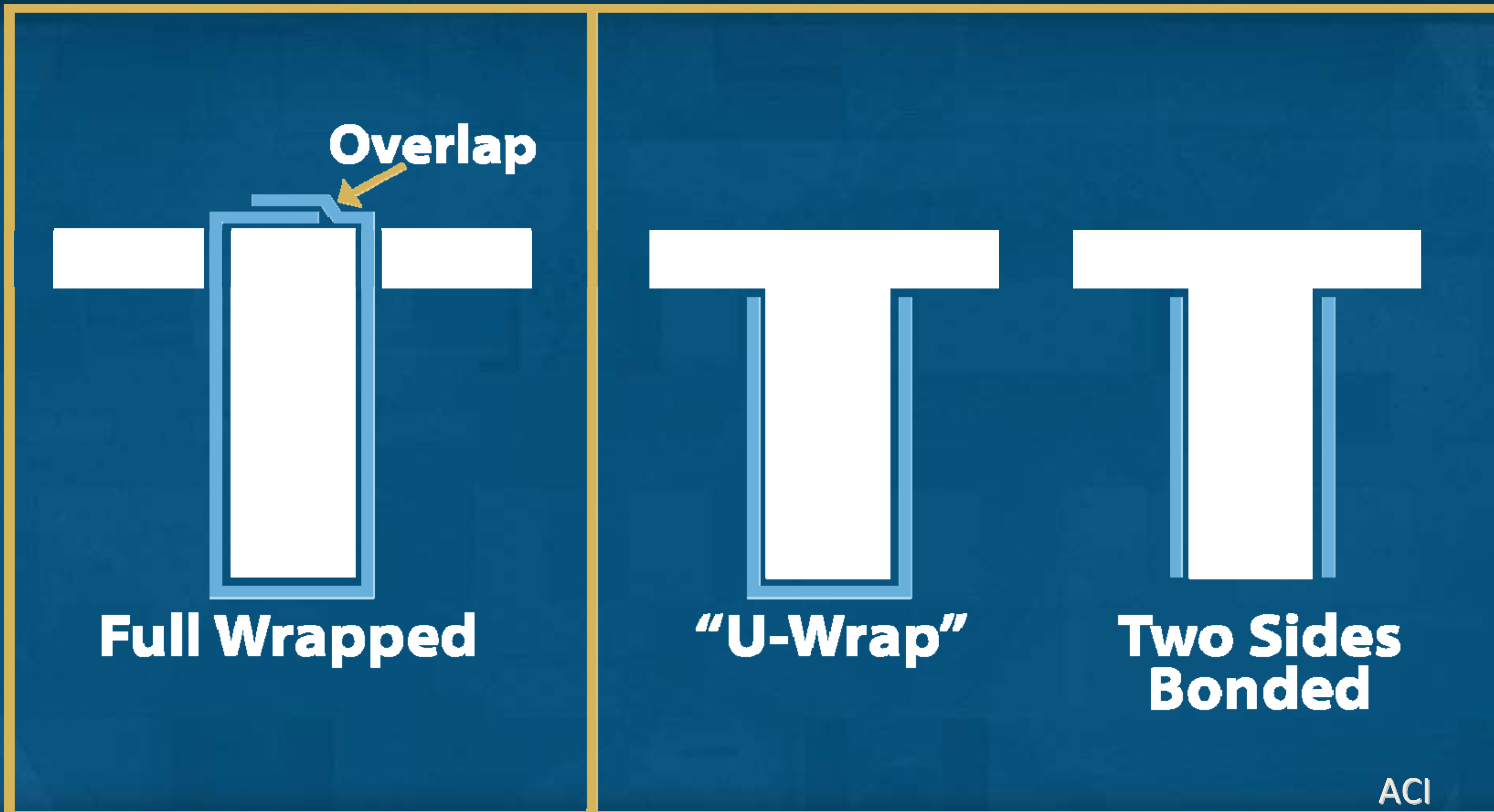
Continuous

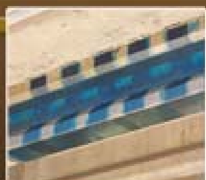
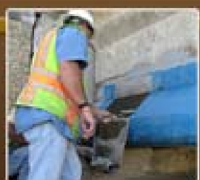
Not Recommended – Constructability

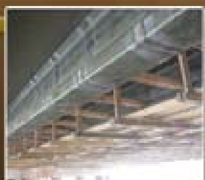
Inclined

ACI

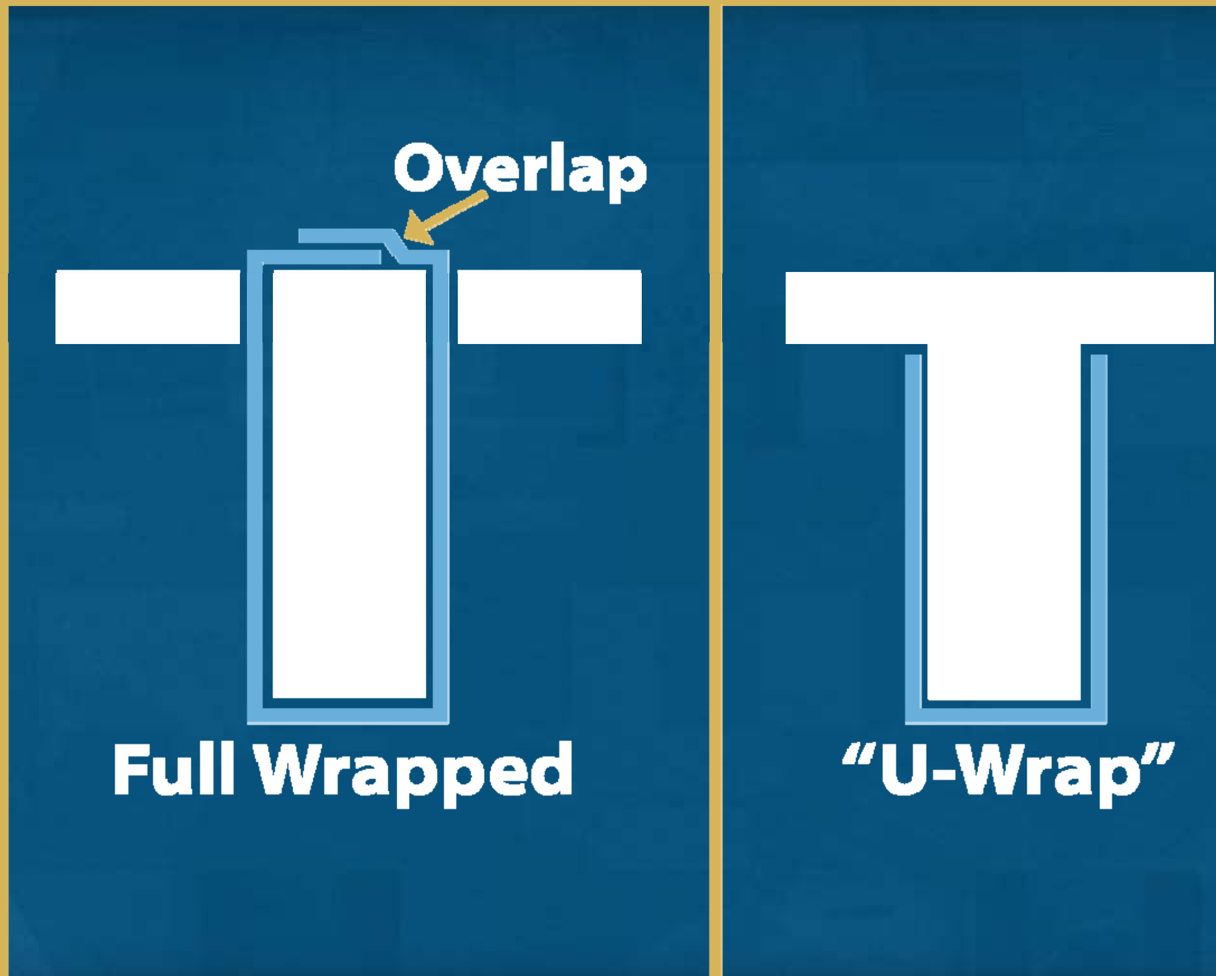
Shear Strengthening

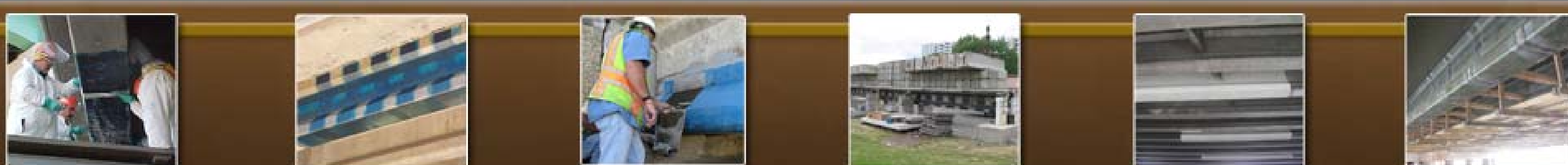


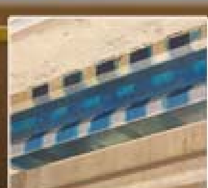
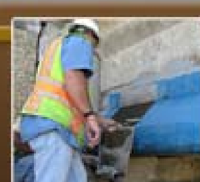
Shear Strengthening

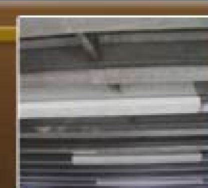




Shear Strengthening

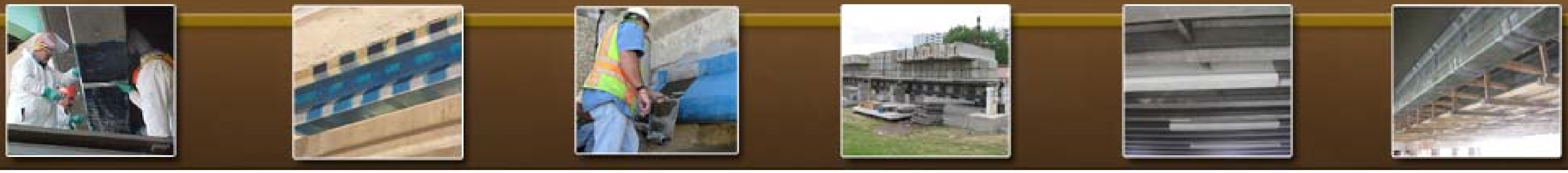
Debonding failure of CFRP U-wrap shear strengthening

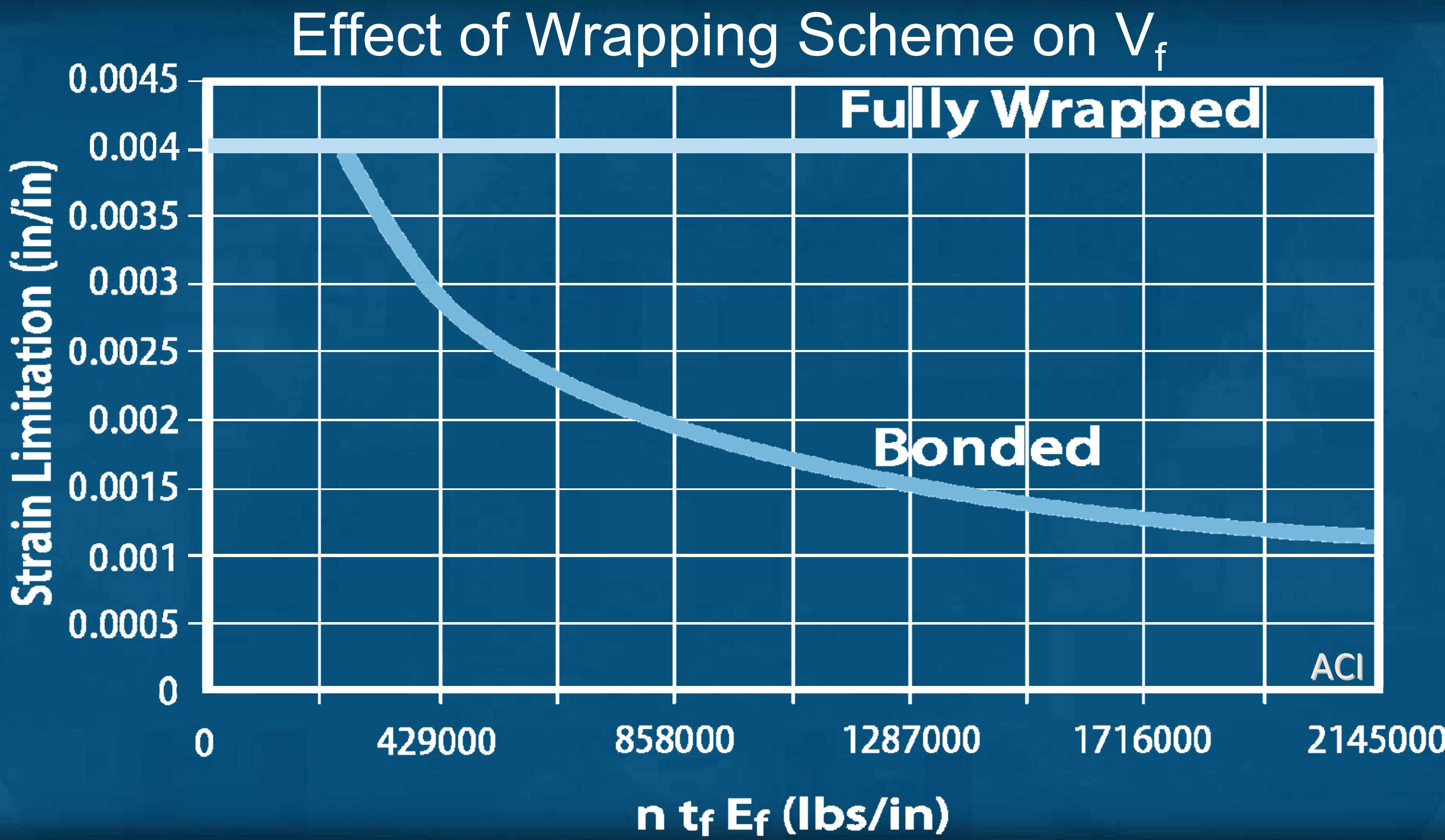



Shear Strengthening

Debonding failure of CFRP U-wrap shear strengthening

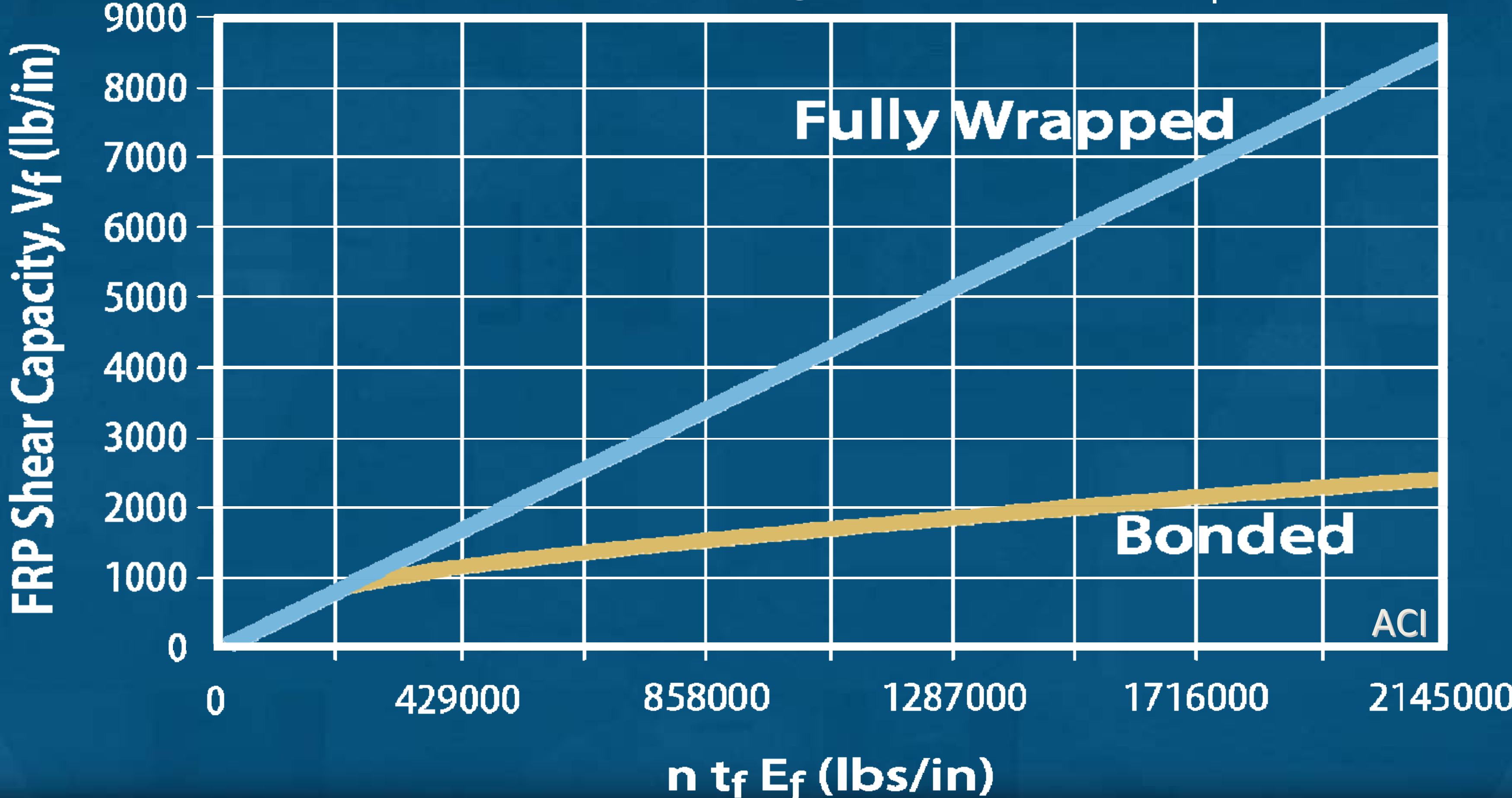


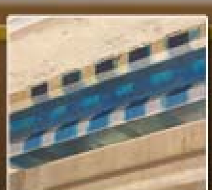
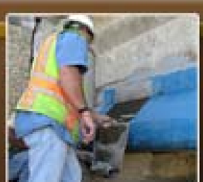
Shear Strengthening

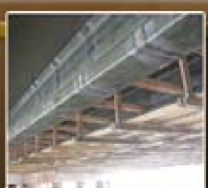


Shear Strengthening

Effect of Wrapping Scheme on V_f



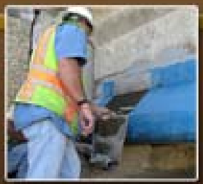
General Requirement

Recommended Minimum Capacity of Existing Structural Members to "Qualify" for FRP Strengthening

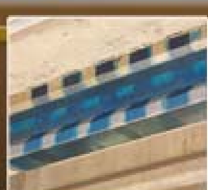
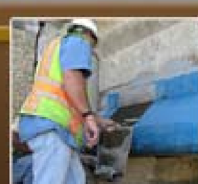
$$(\phi R_n)_{existing} \geq (1.1S_{DL}+0.75S_{LL})_{new}$$

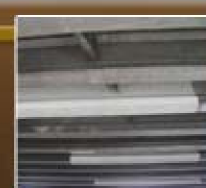
(ACI 440.2R-08 Equation 9-1)



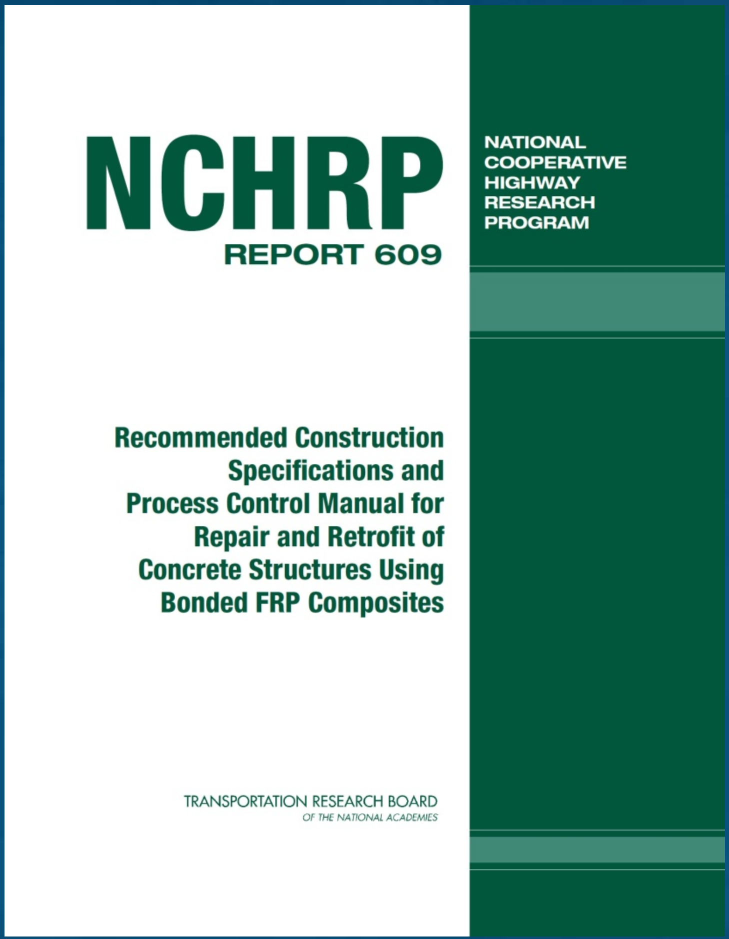



CONSTRUCTION SPECIFICATIONS




Construction Spec's

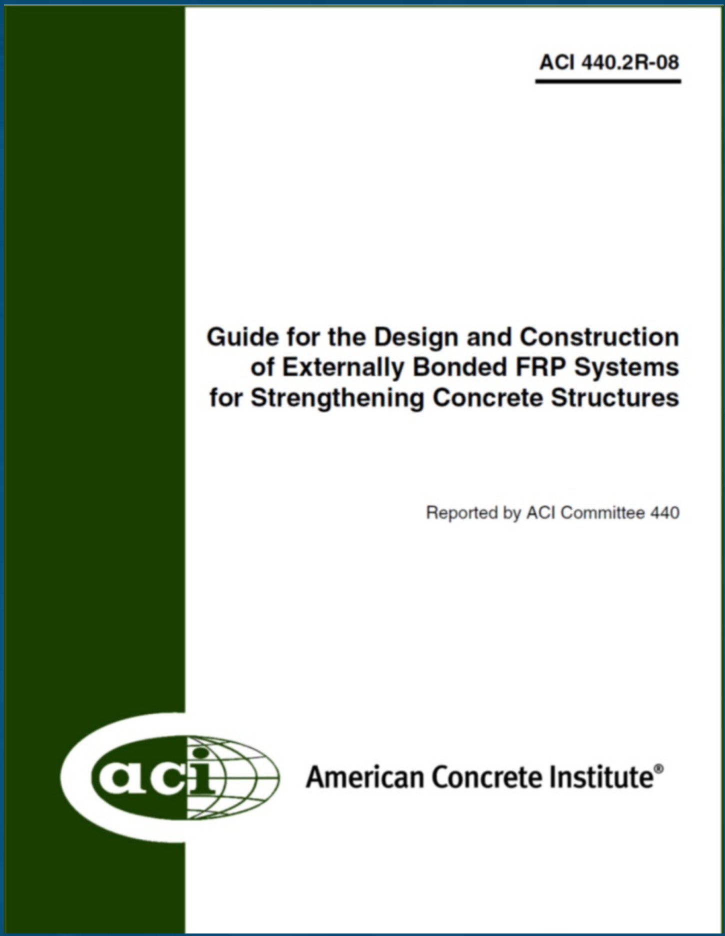


NCHRP
REPORT 609

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

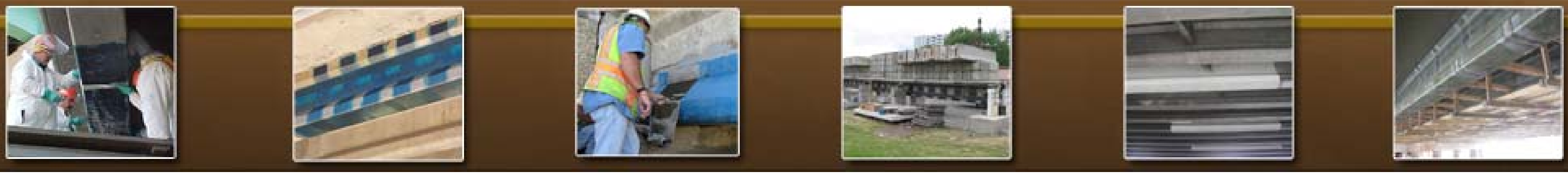


ACI 440.2R-08

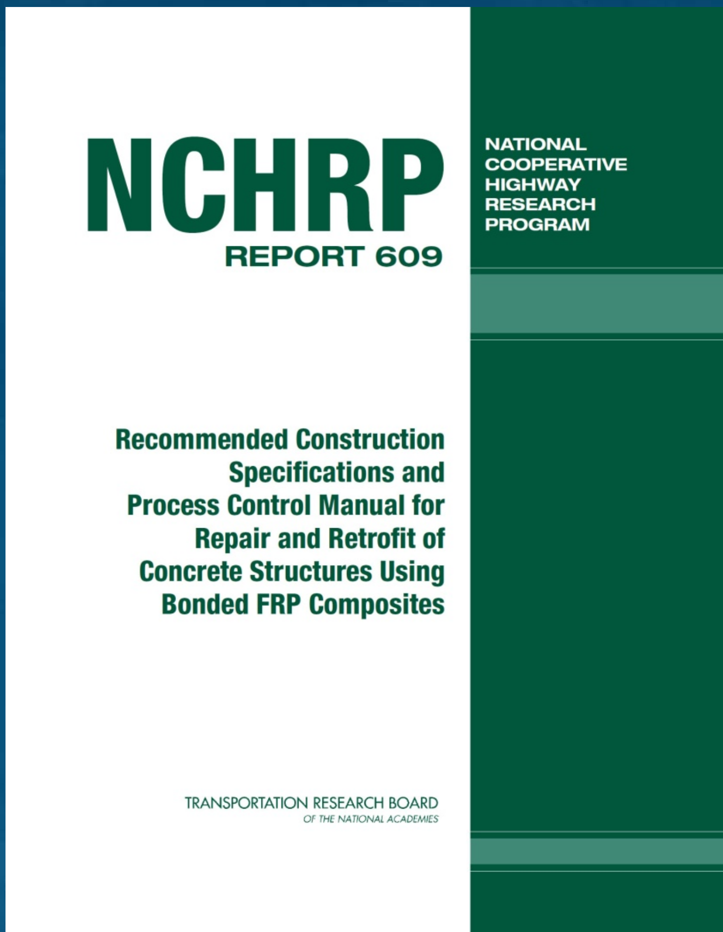
Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

Reported by ACI Committee 440

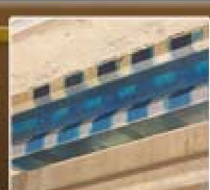
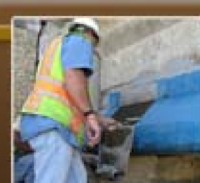
American Concrete Institute®

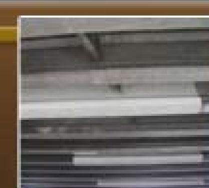
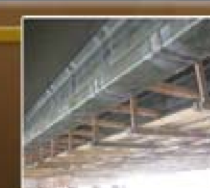


Construction Spec's



NCHRP Report No. 609
Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites, 2008

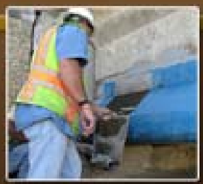




Construction Spec’s

- Proprietary Systems (Manufacture and Installation)
- Performance Specification
  - ✓ Must work in conjunction with Plans
- Repair of Existing Section is Key
  - ✓ Repair Cause of Damage - then Repair Damage
- Surface preparation for FRP Bonding is Key
  - ✓ Quality Control from Start to Finish
- Testing Requirements (ASTM, etc.)
- UV and Fire Protection Coatings






Western Bridge Engineers' Seminar
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Wrap Up

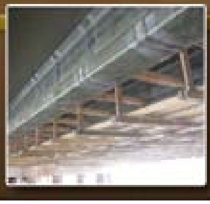
HDR

Thank You!

- BASF Corporation (Mbrace®)
- Fyfe Company (TYFO® and FIBRWRAP®)
- Contech Services Inc.
- QuakeWrap® Inc.
- Prof. Kent Harries – University of Pittsburgh
- Mr. Paul Liles, P.E.





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QUESTIONS?