The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Carbon Fiber-Reinforced Polymer Systems for Concrete Structures

Tuesday, November 12, 2019
2:00-3:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Provide a summary of the findings from the National Cooperative Highway Research Program (NCHRP)'s Research Report 907: Design of Concrete Bridge Beams Prestressed with Carbon Fiber Reinforced Polymer (CFRP) Systems

Learning Objectives

At the end of this webinar, you will be able to:

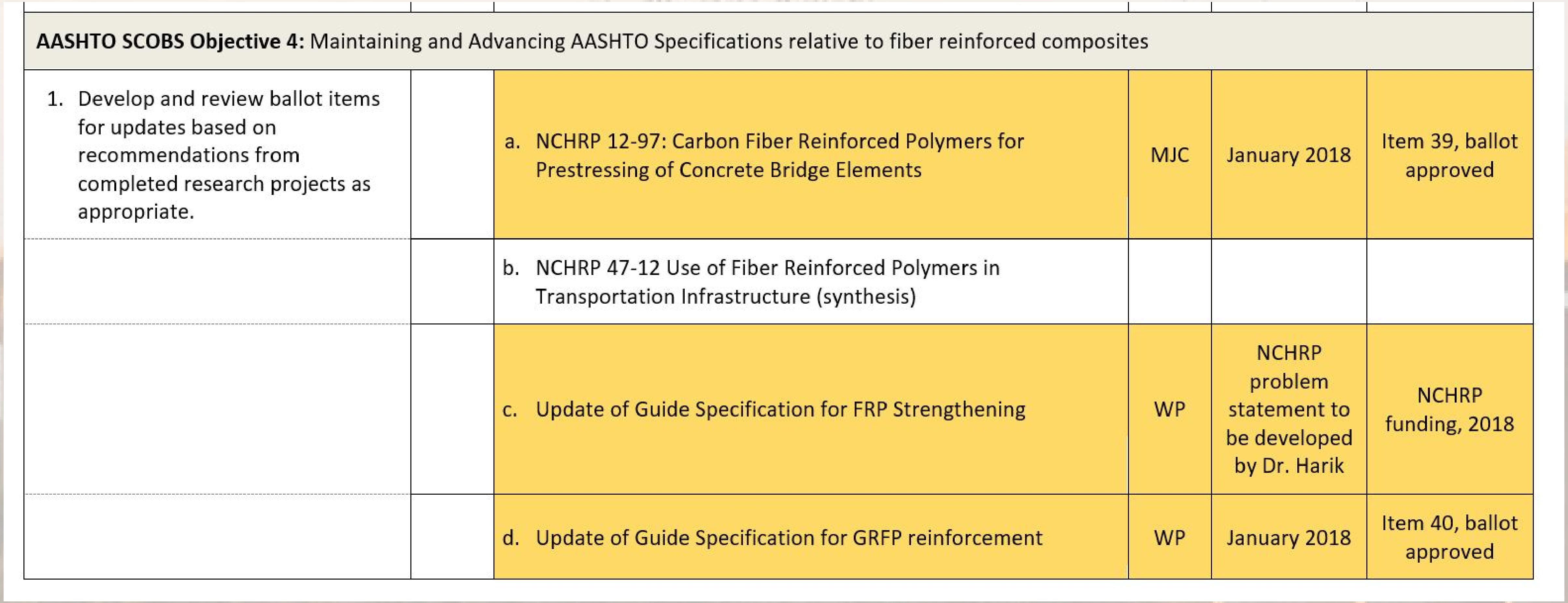
- Describe the mechanical properties of carbon fiber-reinforced polymer (CFRP) bars and cables
- Describe the flexural design procedures of concrete beams prestressed with CFRP systems
- Apply the AASHTO-LRFD design specifications using the CFRP systems
- Discuss the step-by-step design examples for use of CFRP for prestressing

NCHRP 12-97, and resulting AASHTO LRFD Guide Specification

Webniar

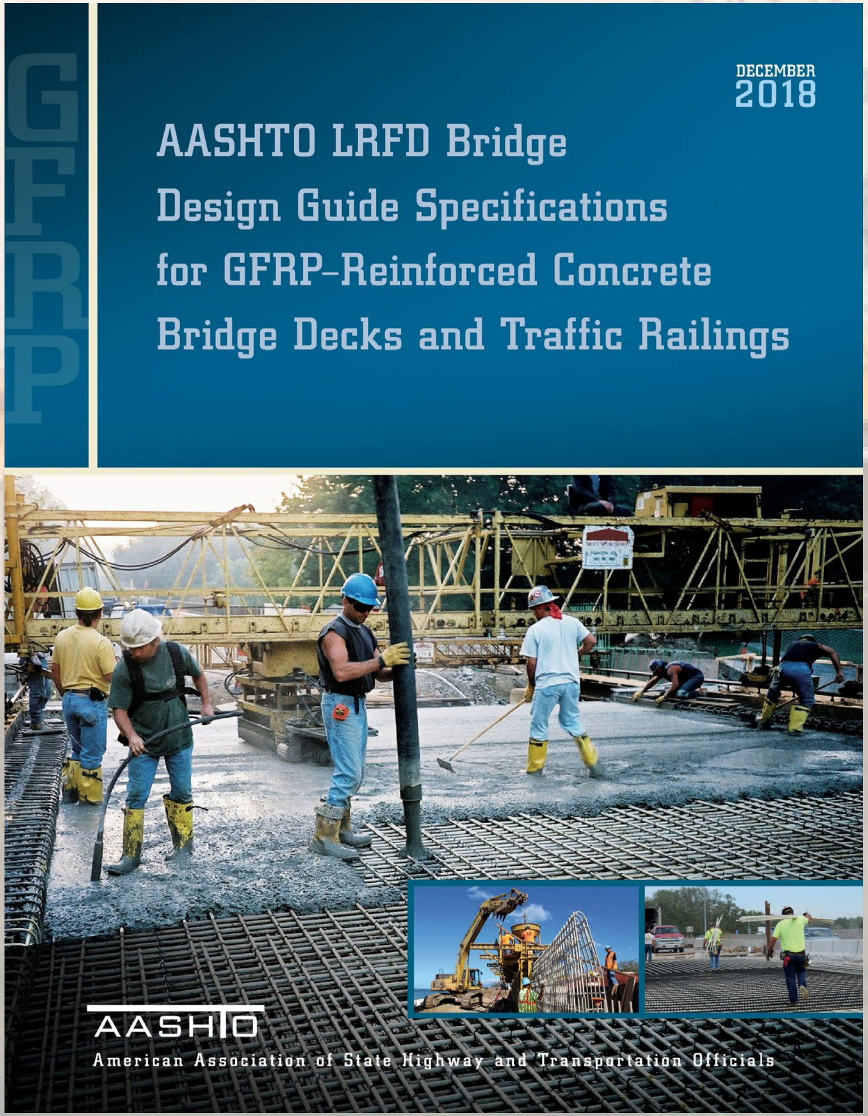
Matthew Chynoweth, PE – Chief Bridge Engineer,
Director, Michigan DOT Bureau of Bridges and Structures

AASHTO T-6 Strategic Plan



AASHTO SCOBS Objective 4: Maintaining and Advancing AASHTO Specifications relative to fiber reinforced composites					
1. Develop and review ballot items for updates based on recommendations from completed research projects as appropriate.		a. NCHRP 12-97: Carbon Fiber Reinforced Polymers for Prestressing of Concrete Bridge Elements	MJC	January 2018	Item 39, ballot approved
		b. NCHRP 47-12 Use of Fiber Reinforced Polymers in Transportation Infrastructure (synthesis)			
		c. Update of Guide Specification for FRP Strengthening	WP	NCHRP problem statement to be developed by Dr. Harik	NCHRP funding, 2018
		d. Update of Guide Specification for GRFP reinforcement	WP	January 2018	Item 40, ballot approved

FRP Composite Specifications

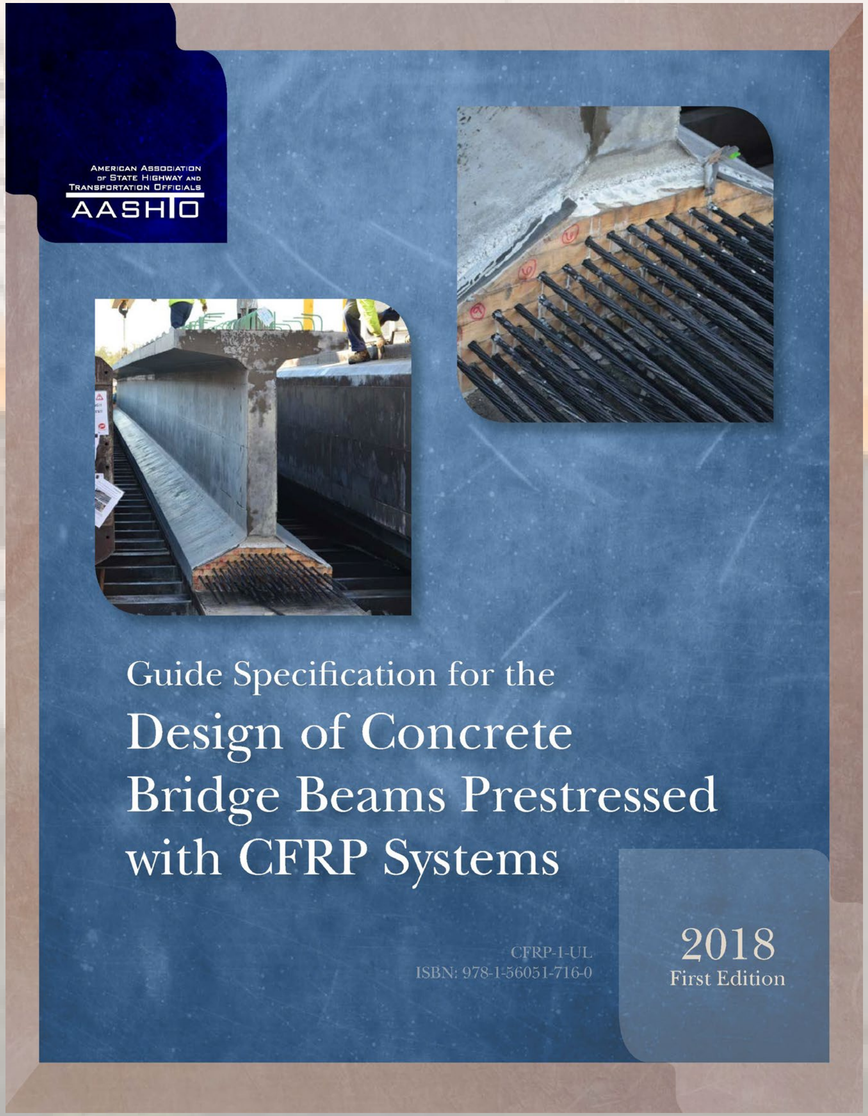


GFRP

DECEMBER
2018

AASHTO LRFD Bridge
Design Guide Specifications
for GFRP-Reinforced Concrete
Bridge Decks and Traffic Railings

AASHTO
American Association of State Highway and Transportation Officials



American Association
of State Highway and
Transportation Officials
AASHTO

Guide Specification for the
Design of Concrete
Bridge Beams Prestressed
with CFRP Systems

CFRP-1-UL
ISBN: 978-1-56051-716-0

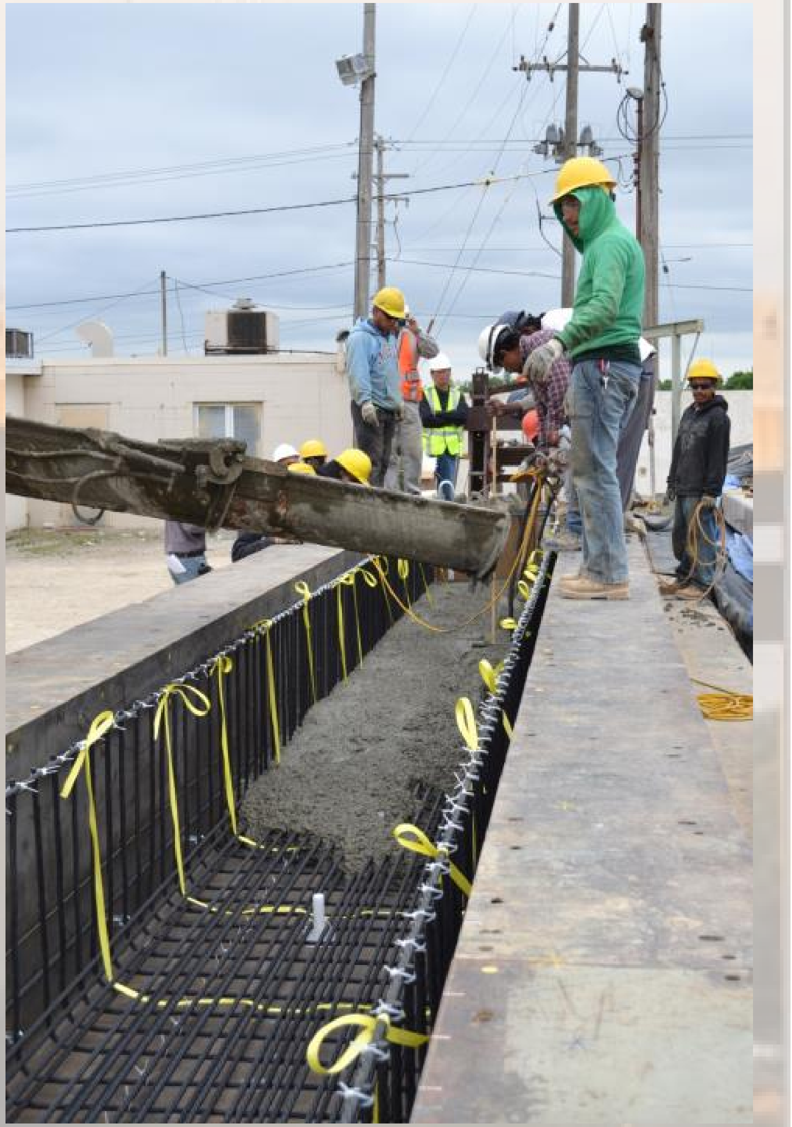
2018
First Edition

MDOT CFRP Post Tensioning Deployments

- Pembroke Ave over M-39 (2011)
- M-50 over NS Railroad (2012)
- I-94 EB & WB over Lapeer Road (2014)

MDOT CFRP Prestressing Deployments

- M-102 EB and WB over Plum Creek (2013 – 2014)
- M-100 over Sharp Drain (2015)
- M-66 over West Branch River (2015)
- M-86 over Prairie Creek (2016)
- I-75 SB over Sexton-Kilfoil Drain (2017)
- M-3 over I-94 (2018)
- Brush Street over I-94 (2019)
- Cadillac Ave over I-94 (2020)



NCHRP 12-97

National Cooperative Highway Research Program

Design of Concrete Bridge Beams Prestressed with CFRP Systems

Abdeldjelil Belarbi, PhD, PE, FACI, FASCE, FSEI
Distinguished Professor
University of Houston
belarbi@uh.edu

TRB Webinar
November 12, 2019

1. *INTRODUCTION*

2. *NCHRP 12-97 AND DELIVERABLES*

3. *DESIGN MATERIAL PROPERTIES*

4. *PRESTRESS LOSSES*

5. *FLEXURAL DESIGN & SERVICEABILITY LIMITS*

6. *DESIGN EXAMPLE*

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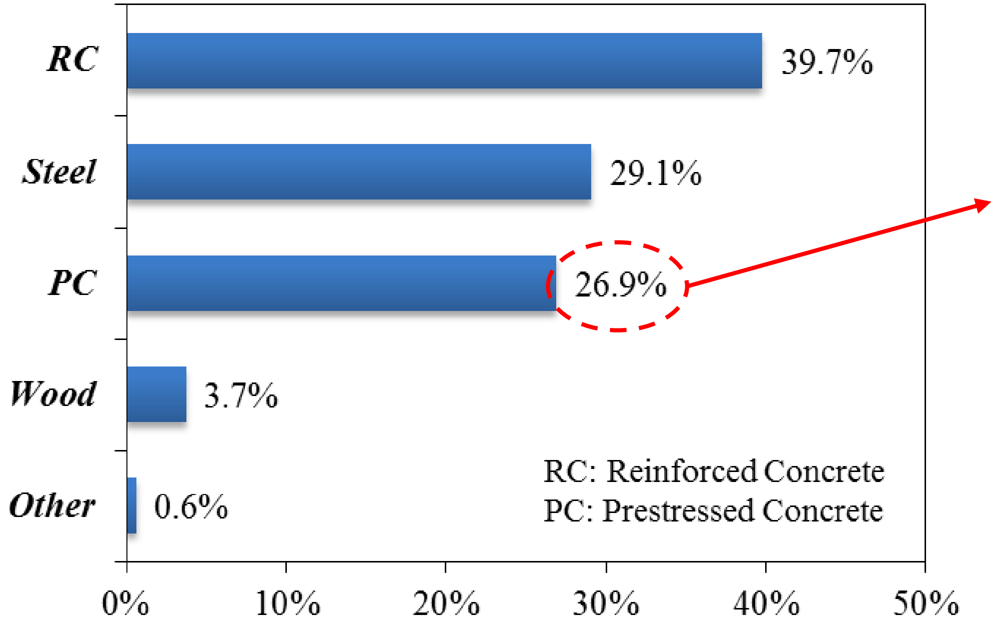
AASHTO T6 Members

Precast Plants and Material Suppliers

Precast/Prestressed Concrete Institute
Heldenfels Enterprises, Inc.
East Texas Precast
Tokyo Rope, Inc.
Pultrall Inc.

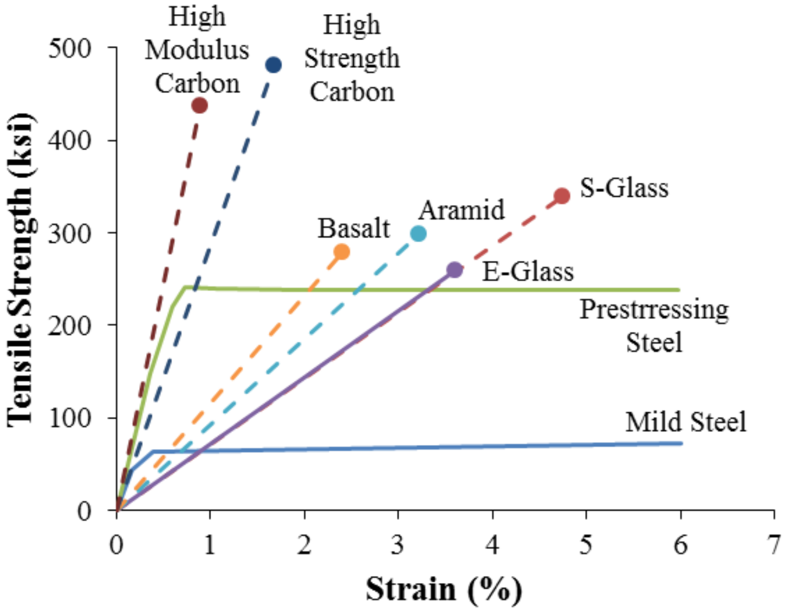
1. INTRODUCTION

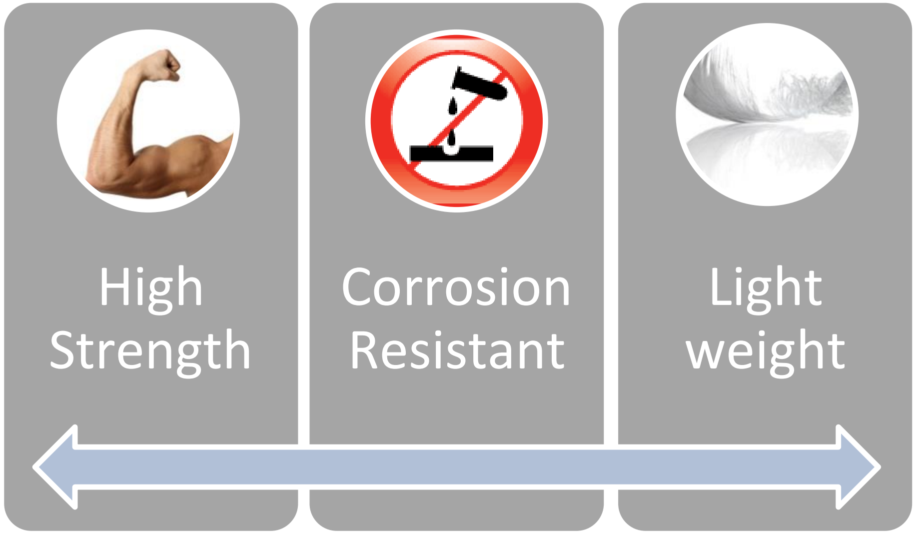


http://www.lafargeprecastedmonton.com/anthony-henday-ring-road/img_0983/
www.fhwa.gov
https://www.alibaba.com/product-detail/post-tension-concrete-prestressing-steel-pc_60677672453.html

1. INTRODUCTION

Carbon Fiber Reinforced Polymers (CFRP)





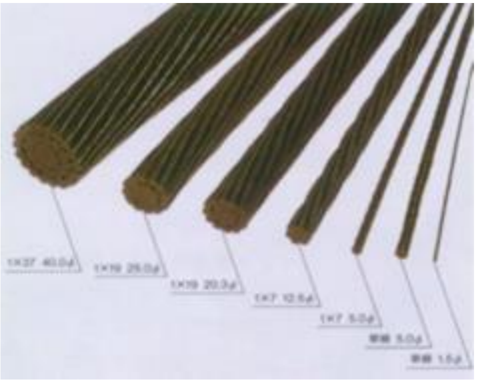
High Strength

Corrosion Resistant

Light weight

1. INTRODUCTION

Commercially available CFRP types



CFRP Cable

CFRP Bar

CFRP sheets

Internal (reinforcing) and external (strengthening) application

external (strengthening) application

Tokyo rope product sheet
www.google.com/images

1. INTRODUCTION

Advantage of CFRP prestressing

20 years

Steel prestressed bridge

20 years

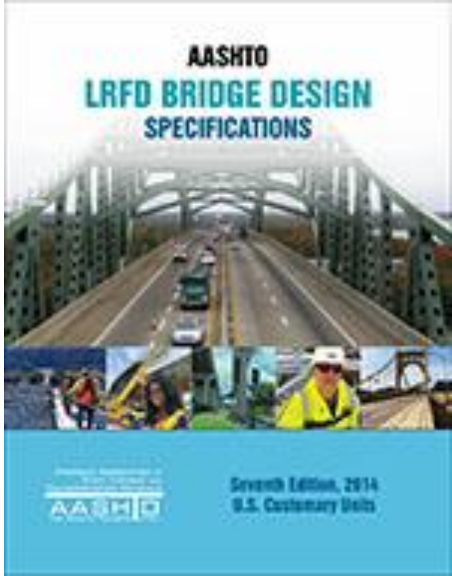
CFRP prestressed bridge

(Enomoto et. al., 2011)

2. NCHRP 12-97 AND DELIVERABLES

Project Objective

To develop a proposed guide specification, in AASHTO LRFD format, for the design of concrete beams prestressed with CFRP systems for bridge applications for both pretensioning and post-tensioning.



AASHTO
LRFD BRIDGE DESIGN
SPECIFICATIONS

Seventh Edition, 2014
U.S. Customary Units

2. NCHRP 12-97 AND DELIVERABLES

Major Research Tasks

Experimental Research Program

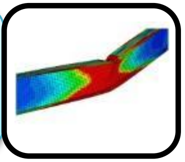
CFRP Properties

Small-scale Prisms

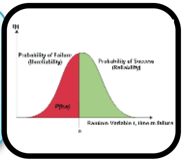
Large-scale Girders

Analytical Research Program

Numerical Simulations & FEM Modeling



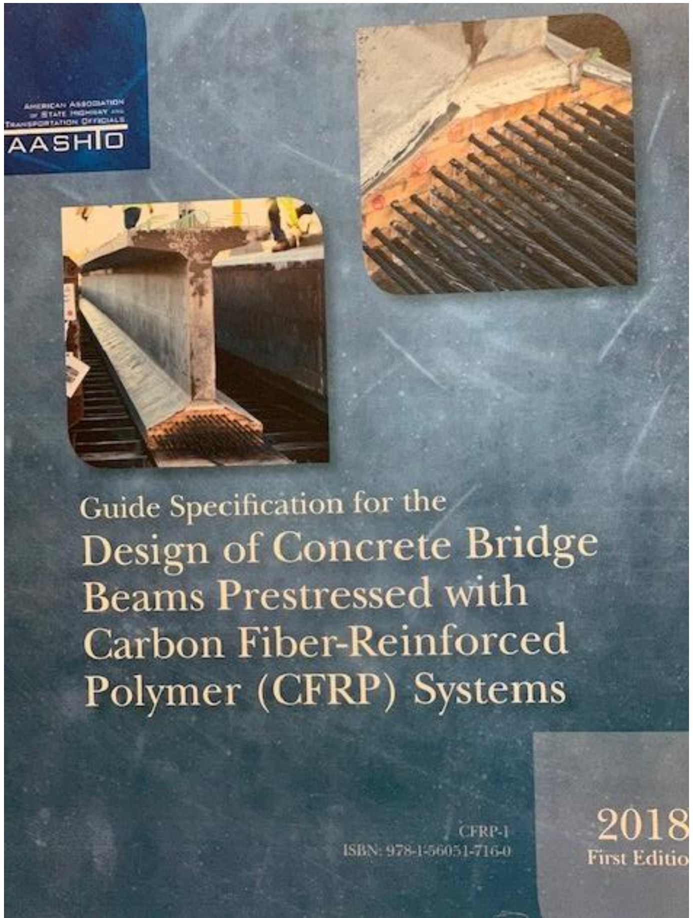
Parametric Study & Reliability Analysis



2. NCHRP 12-97 AND DELIVERABLES

Project Deliverables

1. Design Guide Specifications
2. Material Specifications



American Association of State Highway and Transportation Officials

AASHTO

Guide Specification for the

Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems

CFRP-1

ISBN: 978-1-56051-716-0

2018

First Editio

2. NCHRP 12-97 AND DELIVERABLES

Project Deliverables

3. Final Research Report

(NCHRP Report 907)

http://www.trb.org/main/blurbs/179653.aspx

(Supporting Appendices)

http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP12-97_Appendices.pdf

NCHRP

RESEARCH REPORT 907

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Design of Concrete Bridge Beams Prestressed with CFRP Systems

2. NCHRP 12-97 AND DELIVERABLES

Project Deliverables

4. Design Examples

http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_907AttachmentB.pdf

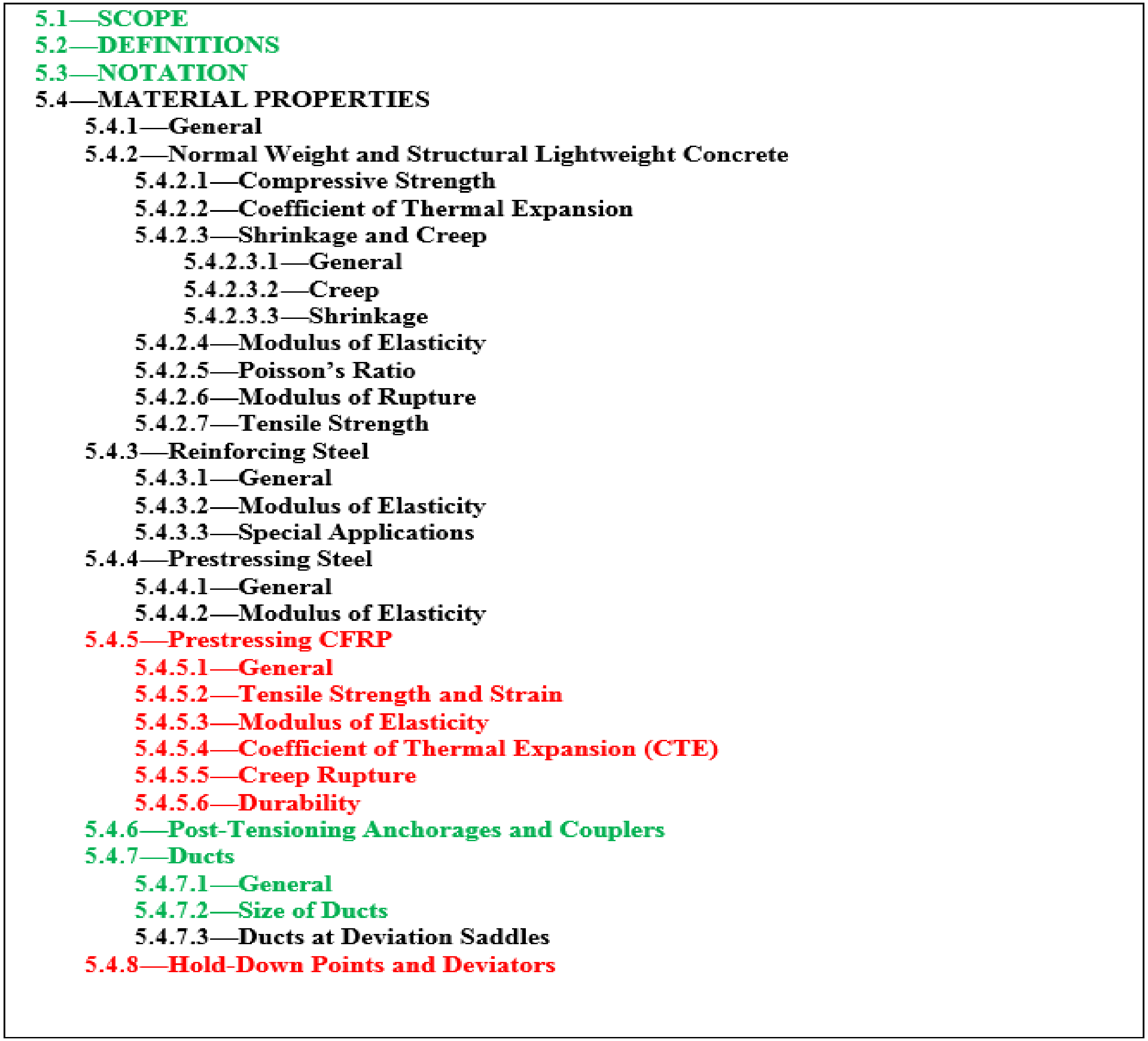
ATTACHMENT B

Design Examples
The following five design examples illustrate the use of the design guide specifications prepared in this project and subsequently published by AASHTO (AASHTO Guide Specifications, 2018):

Example B-1: Design of a rectangular beam pretensioned with straight CFRP cables
Example B-2: Design of a Decked AASHTO pretensioned girder with straight CFRP cables
Example B-3: Design of a Decked AASHTO pretensioned girder with harped CFRP cables
Example B-4: Design of a rectangular beam post-tensioned with straight CFRP cables
Example B-5: Design of a Decked AASHTO post-tensioned girder with draped CFRP cables

2. NCHRP 12-97 AND DELIVERABLES

Design Guide Specifications



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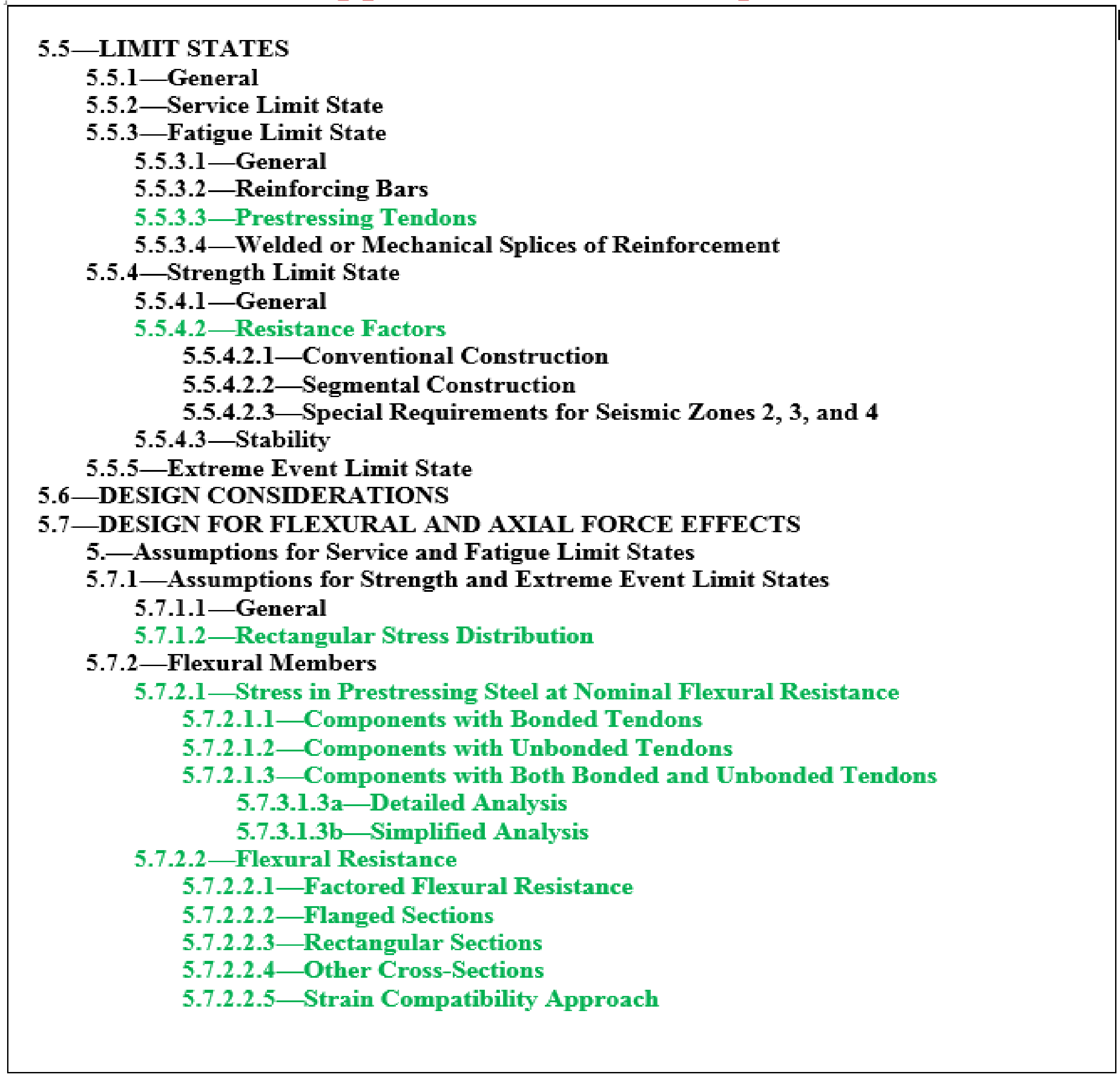
🟥 New Provisions

🟩 Revised Provisions

2. NCHRP 12-97 AND DELIVERABLES

Design Guide Specifications



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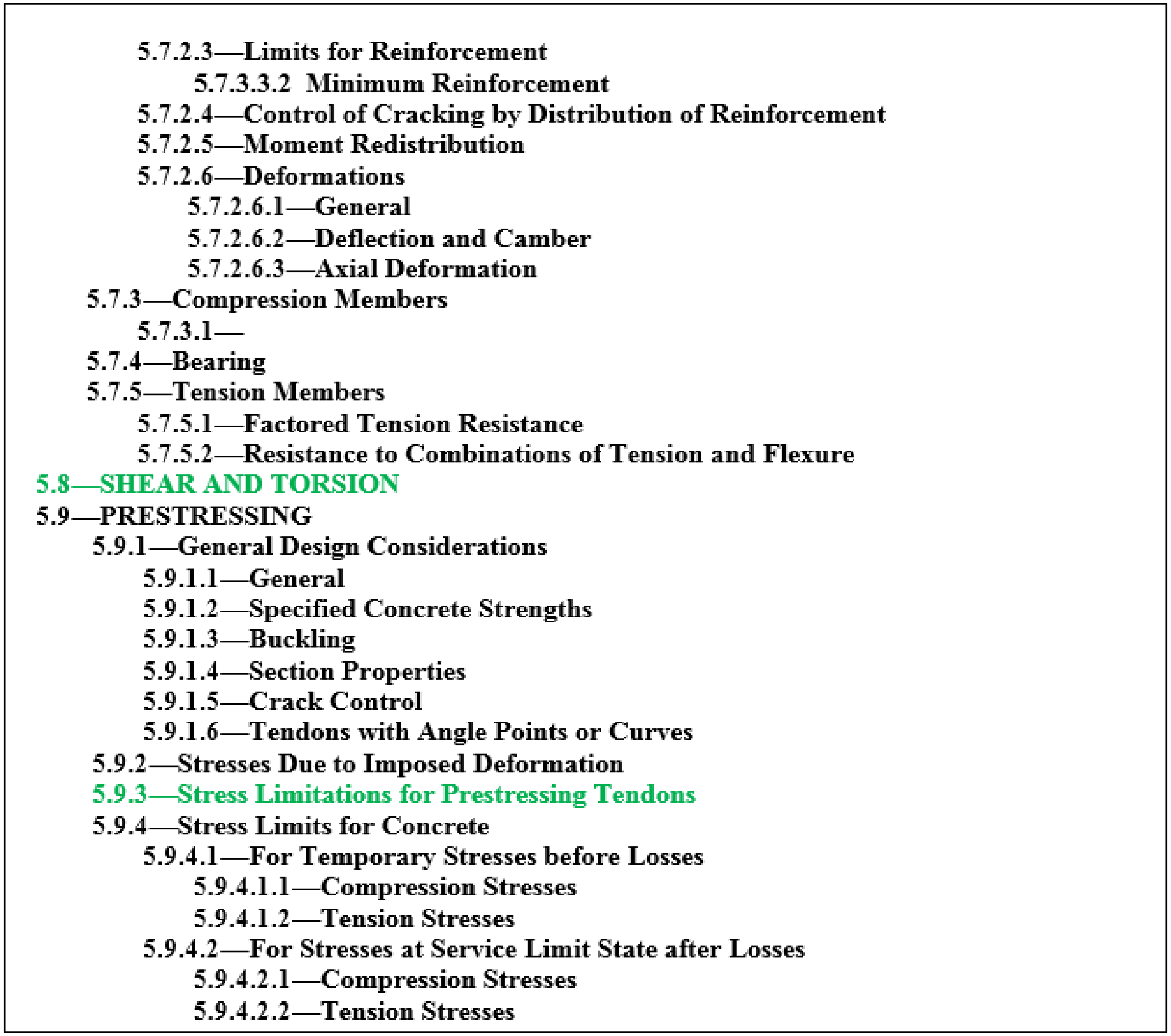
🟥 New Provisions

🟩 Revised Provisions

2. NCHRP 12-97 AND DELIVERABLES

Design Guide Specifications



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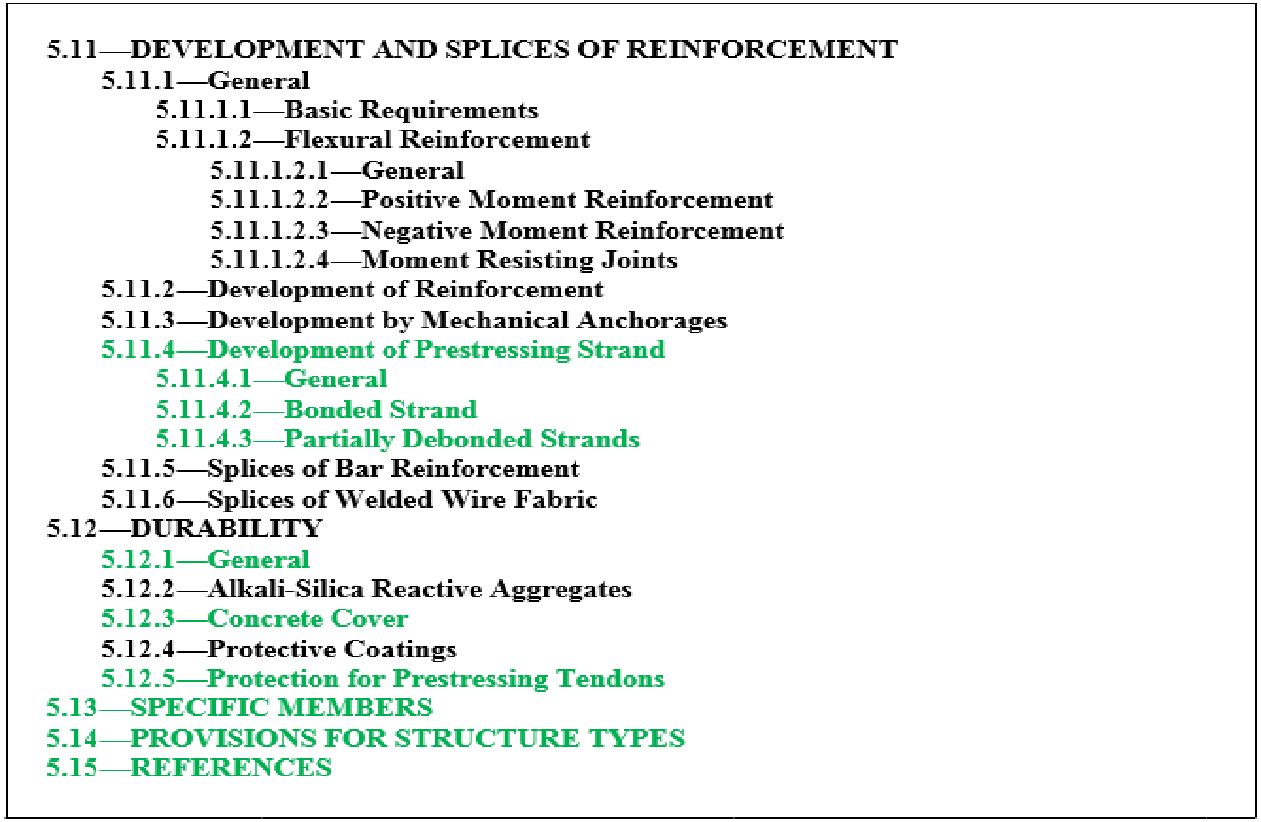
🟥 New Provisions

🟩 Revised Provisions

2. NCHRP 12-97 AND DELIVERABLES

Design Guide Specifications



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- 5.14—PROVISIONS FOR STRUCTURE TYPES
- 5.15—REFERENCES

🟥 New Provisions

🟩 Revised Provisions

2. NCHRP 12-97 AND DELIVERABLES

Design Guide Specifications

SCOPE:

- Concrete compressive strengths from 4.0 ksi to 15.0 ksi.
- Pretensioned concrete beams
- Bonded and unbonded internally post-tensioned concrete beams.
- Steel transverse reinforcement only.

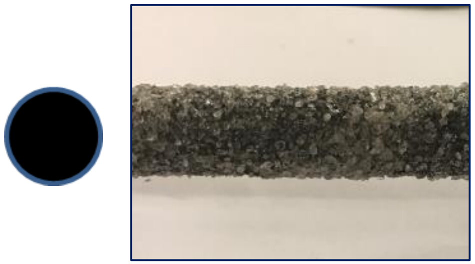
Provisions for unbonded post-tensioned beams may be applicable to beams that are strengthened with external CFRP post-tensioning.

LIMITATIONS:

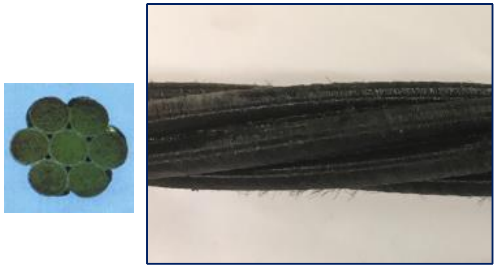
- Anchorage detailing for external CFRP post-tensioned strengthening systems
- Partially prestressed concrete beams except that partial prestressing is allowed for beams with unbonded post-tensioning.
- Segmental construction and prestressed concrete bridge beams curved in plan.
- Design for torsion.

2. NCHRP 12-97 AND DELIVERABLES

Type of prestressing reinforcement used



CFRP bars
(dia = 0.5 in.)



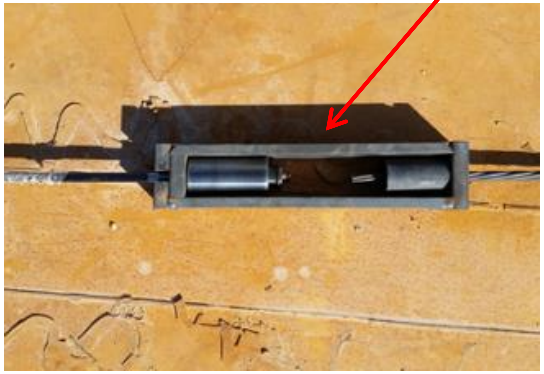
CFRP cable
(dia = 0.6 in.) (pre-tension)
(dia = 0.76 in.) (post-tension

2. NCHRP 12-97 AND DELIVERABLES

CFRP prestressing system characteristics

CFRP System = FRP Bars/Cables + Anchors + Couplers

Couplers



CFRP Bar

CFRP Cable

Pre-tensioning application

Post-tensioning application

2. NCHRP 12-97 AND DELIVERABLES

Major Design Issues/Common Questions Asked

- Anchorage Characterization
- Environmental Reduction Factor/Durability
- Allowable Stresses at Jacking/Transfer
- Creep Rupture for CFRP
- Strength Reduction Factor
- Unbonded Construction
- Other Design Provisions….

3. DESIGN MATERIAL PROPERTIES

Useful Definitions

A_f = area of prestressing CFRP (in.^{2})

E_f = modulus of elasticity of prestressing CFRP (ksi)

f_{pu} = design tensile strength of prestressing CFRP (ksi)

ε_{pu} = design tensile strain of prestressing CFRP (in./in.)

- ✓ Improper calculation of area (A_f) affects the determination of E_f and f_{pu}
- ✓ Design calculations using these E_f and f_{pu} will be affected, accordingly,

  However the Prestress force will not be affected

Prestressing CFRP Types and Sizes

AASHTO Material Specifications

2.5.4—Prestressing CFRP Types and Sizes

- *The prestressing CFRP can be utilized in two forms: bars or cables. Only CFRP bars with monolithic, prismatic cross-section (typically circular), and CFRP cables with seven twisted wires are allowed.*
- *The size of prestressing CFRP bars shall be consistent with standard sizes for steel reinforcing bars given in AASHTO M 31M/M 31 (ASTM A615/A615M.*
- *The size of prestressing CFRP cables shall be consistent with standard sizes for steel prestressing strands as given in AASHTO M 203M/M 203 (ASTM A416/A416M).*
- *The nominal diameter and area of a prestressing CFRP cable to be used for designation and design shall be provided by the manufacturer.*

3. DESIGN MATERIAL PROPERTIES

	Provisions	Test Methods	Limitations
MECHANICAL PROPERTIES	**Tensile Strength**	ASTM D7205/ D7205M	N/A
	Tensile Modulus of Elasticity	ASTM D7205/ D7205M	The tensile modulus of elasticity of CFRP bars and cables based on the cross-sectional area, as specified in Article 2.5.4, **shall be at least 17,000 ksi.**
	Shear Strength (Transverse axis)	ASTM D7617/ D7617M	The transverse shear strength of prestressing CFRP **shall be at least 18 ksi.**
	Tensile Strain	N/A	The tensile rupture strain of CFRP cables and bars obtained by this procedure **shall be at least 1.2 percent.**
	Bond Strength	ASTM D7913/D7913M	N/A

3. DESIGN MATERIAL PROPERTIES

AASHTO Guide Specifications

1.4.1.2—Tensile Strength and Strain

The tensile strength and the tensile strain of prestressing CFRP as reported by the manufacturers shall be in compliance with the provisions of Articles 2.6.1 and 2.6.4 of the AASHTO Materials Guide Specification for CFRP Prestressing cables and bars, herein, referred to as AASHTO CFRP Materials Specifications.

The design tensile strength of prestressing CFRP, f_{pu} *,shall be taken as tensile strength, as reported by the manufacturer multiplied by the environmental reduction factor (CE) as specified in Table 1.4.1.2*

Table 1.4.1.2—Environmental Reduction Factors (CE)

Environmental Condition	*CE*
Prestressing CFRP not exposed to environmental effects (internal applications)	*1.0*
Prestressing CFRP exposed to environmental effects (external applications without protection)	*0.9*

3. DESIGN MATERIAL PROPERTIES

AASHTO Material Specifications

2.6.1—Tensile Strength

- *The tensile strength, as reported by the manufacturer for product certification, shall be the load measured according to ASTM D7205/ D7205M at a frequency and number of specimens as specified in Article 2.9.1 and the characteristic value computed according to ASTM D7290 divided by the area of prestressing CFRP as specified in Article 2.5.4. The manufacturer shall report the individual test results.*

ASTM D7290 (2017)

two-parameter Weibull distribution

$$f(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x}{\alpha}\right)^{\beta-1} exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

β = Shape parameter

α = Scale parameter

3. DESIGN MATERIAL PROPERTIES

Steps:

- ✓ *Determine mean ($\bar{x}$) and standard deviation S_{n-1} for the measured material property*

$$\bar{x} = \frac{\left(\sum_{i=1}^{n} x_i\right)}{n}$$

$$s_{n-1} = \sqrt{\left(\sum_{i=1}^{n} (x_i - \bar{x})^2\right) / (n-1)}$$

- ✓ *Calculate Shape parameter (β) by numerically solving the following equation*

$$\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}} \ln(x_i)}{\sum_{i=1}^{n} x_i^{\hat{\beta}}} - \frac{1}{\hat{\beta}} - \frac{1}{n} \sum_{i=1}^{n} \ln(x_i) = 0$$

3. DESIGN MATERIAL PROPERTIES

Steps:

✓ *Calculate Scale parameter ($\hat{\alpha}$) using the following equation*

$$\hat{\alpha} = \left(\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}}}{n}\right)^{\frac{1}{\hat{\beta}}}$$

✓ *Calculate Nominal Strength by*

(5th percentile value!!)

$$x_{0.005} = \hat{\alpha}[0.0513]^{\frac{1}{\hat{\beta}}}$$

✓ *Calculate Characteristics Strength by*

$$x_{char} = \Omega x_{0.005}$$

Data confidence factor
Depends on sample size!!

3. DESIGN MATERIAL PROPERTIES

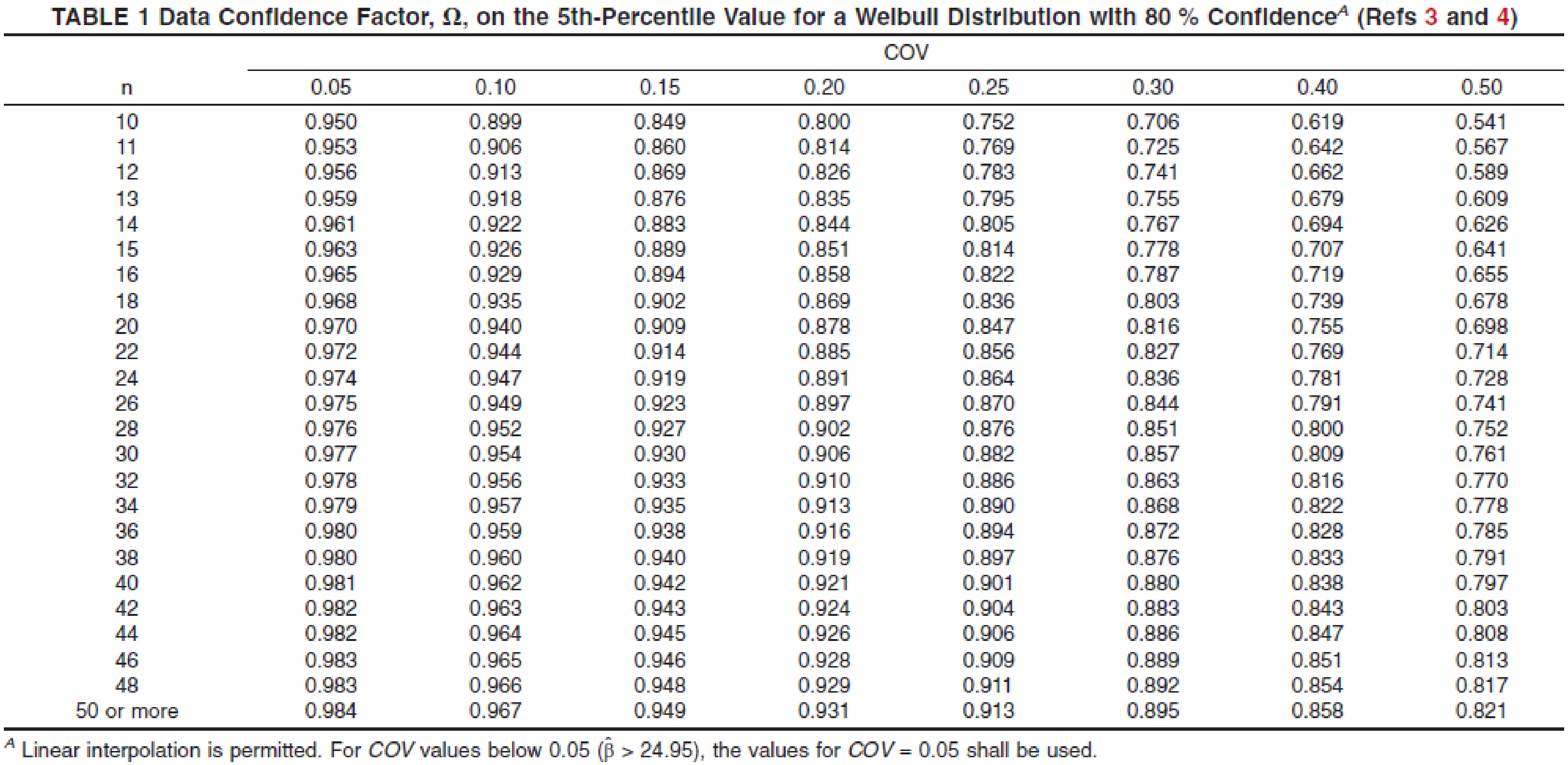


TABLE 1 Data Confidence Factor, Ω, on the 5th-Percentile Value for a Weibull Distribution with 80 % Confidence[A] (Refs 3 and 4)

n	COV 0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.50
10	0.950	0.899	0.849	0.800	0.752	0.706	0.619	0.541
11	0.953	0.906	0.860	0.814	0.769	0.725	0.642	0.567
12	0.956	0.913	0.869	0.826	0.783	0.741	0.662	0.589
13	0.959	0.918	0.876	0.835	0.795	0.755	0.679	0.609
14	0.961	0.922	0.883	0.844	0.805	0.767	0.694	0.626
15	0.963	0.926	0.889	0.851	0.814	0.778	0.707	0.641
16	0.965	0.929	0.894	0.858	0.822	0.787	0.719	0.655
18	0.968	0.935	0.902	0.869	0.836	0.803	0.739	0.678
20	0.970	0.940	0.909	0.878	0.847	0.816	0.755	0.698
22	0.972	0.944	0.914	0.885	0.856	0.827	0.769	0.714
24	0.974	0.947	0.919	0.891	0.864	0.836	0.781	0.728
26	0.975	0.949	0.923	0.897	0.870	0.844	0.791	0.741
28	0.976	0.952	0.927	0.902	0.876	0.851	0.800	0.752
30	0.977	0.954	0.930	0.906	0.882	0.857	0.809	0.761
32	0.978	0.956	0.933	0.910	0.886	0.863	0.816	0.770
34	0.979	0.957	0.935	0.913	0.890	0.868	0.822	0.778
36	0.980	0.959	0.938	0.916	0.894	0.872	0.828	0.785
38	0.980	0.960	0.940	0.919	0.897	0.876	0.833	0.791
40	0.981	0.962	0.942	0.921	0.901	0.880	0.838	0.797
42	0.982	0.963	0.943	0.924	0.904	0.883	0.843	0.803
44	0.982	0.964	0.945	0.926	0.906	0.886	0.847	0.808
46	0.983	0.965	0.946	0.928	0.909	0.889	0.851	0.813
48	0.983	0.966	0.948	0.929	0.911	0.892	0.854	0.817
50 or more	0.984	0.967	0.949	0.931	0.913	0.895	0.858	0.821

[A] Linear interpolation is permitted. For *COV* values below 0.05 ($\hat{\beta} > 24.95$), the values for *COV* = 0.05 shall be used.

3. DESIGN MATERIAL PROPERTIES

Design Strength Comparison

Variable	CFRP cable	CFRP bar
Diameter	0.6	0.5
Shape parameter (β)	28	46
Scale parameter (α)	418 ksi	278 ksi
COV	0.044	0.028
No of samples	10	10
Characteristics value (Tensile Strength)	358 ksi	247 ksi
Calculated Guaranteed Strength $(\mu - 3\sigma)$	371 ksi	255 ksi
Manufacturer Reported Guaranteed Strength	338 ksi	257 ksi

3. DESIGN MATERIAL PROPERTIES

	Provisions	Test Methods	Limitations
MECHANICAL PROPERTIES	**Tensile Strength**	ASTM D7205/ D7205M	N/A
	Tensile Modulus of Elasticity	ASTM D7205/ D7205M	The tensile modulus of elasticity of CFRP bars and cables based on the cross-sectional area, as specified in Article 2.5.4, **shall be at least 17,000 ksi.**
	Shear Strength (Transverse axis)	ASTM D7617/ D7617M	The transverse shear strength of prestressing CFRP **shall be at least 18 ksi.**
	Tensile Strain	N/A	The tensile rupture strain of CFRP cables and bars obtained by this procedure **shall be at least 1.2 percent.**
	Bond Strength	ASTM D7913/D7913M	N/A

3. DESIGN MATERIAL PROPERTIES

AASHTO Material Specifications

2.6.2—Tensile Modulus of Elasticity

- *The tensile modulus of elasticity shall be obtained from specimens tested in accordance with ASTM D7205/D7205M and at a frequency and number of specimens as specified in Article 2.9.1. The manufacturer shall report the individual test results. The tensile modulus of elasticity of prestressing CFRP cables and bars based on the cross-sectional area, as specified in Article 2.5.4, shall be at least 18,000 ksi.*

2.6.4—Tensile Strain

- *The tensile strain shall be calculated for the purpose of product certification by dividing the tensile strength by the tensile modulus of elasticity. The tensile strain of CFRP cables and bars obtained by this procedure shall be at least 1.2 percent.*

4. PRESTRESS LOSSES

Prestress Losses

Pre-tensioned:

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT}$$

Post-tensioned:

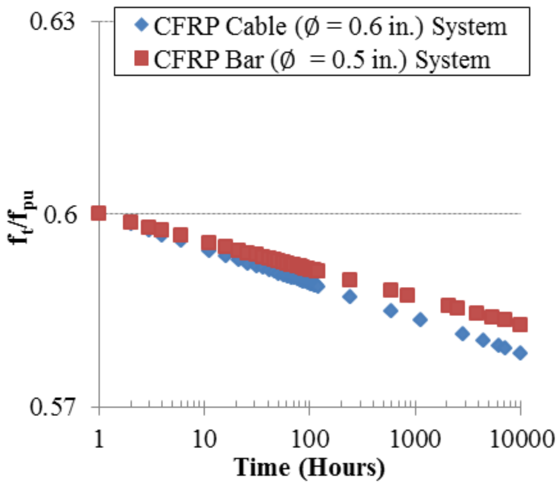
$$\Delta f_{pT} = \Delta f_{pF} + \Delta f_{pA} + \Delta f_{pES} + \Delta f_{pLT}$$

Time dependent losses:

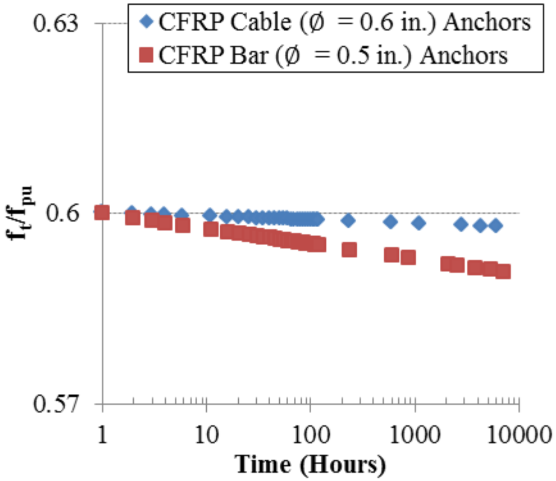
$$\Delta f_{pLT} = \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR} + \boldsymbol{\Delta f_{pTH}}$$

4. PRESTRESS LOSSES

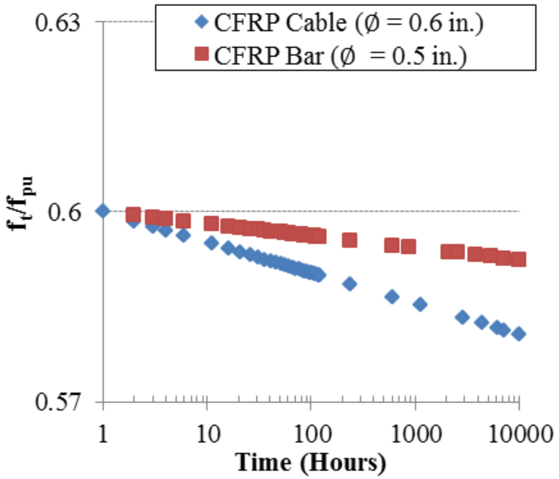
CFRP Prestress Relaxation Losses



CFRP System Losses



CFRP Anchors Losses



CFRP Losses

CFRP Cables (Φ = 0.6 in)

$$\Delta f_{pR} = \left(0.020\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$$

CFRP Bars (Φ = 0.5 in)

$$\Delta f_{pR} = \left(0.016\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$$

CFRP Cables (Φ = 0.6 in)

$$\Delta f_{pR} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$$

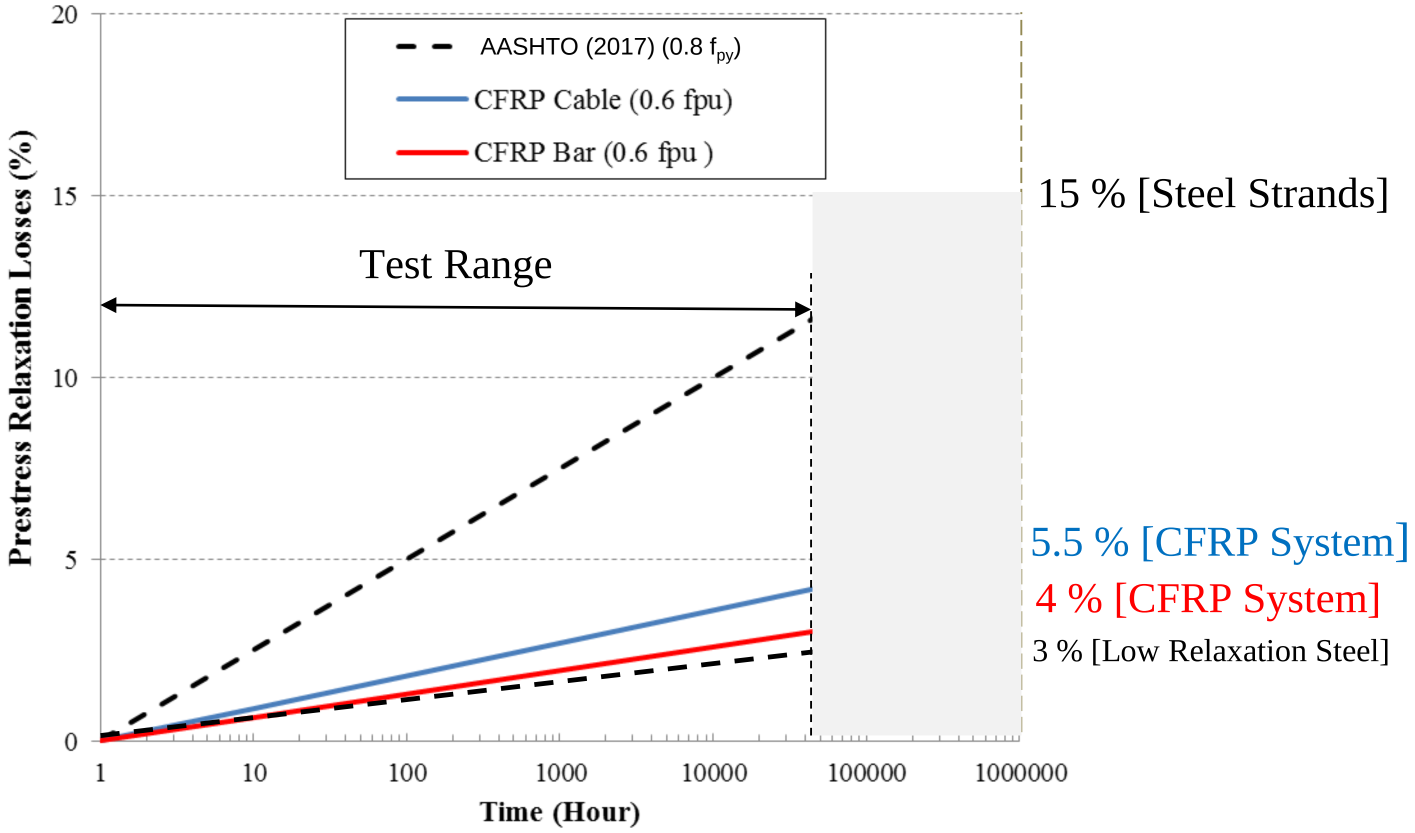
CFRP Bars (Φ = 0.5 in)

$$\Delta f_{pR} = \left(0.013\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$$

4. PRESTRESS LOSSES

CFRP Prestress Relaxation Losses

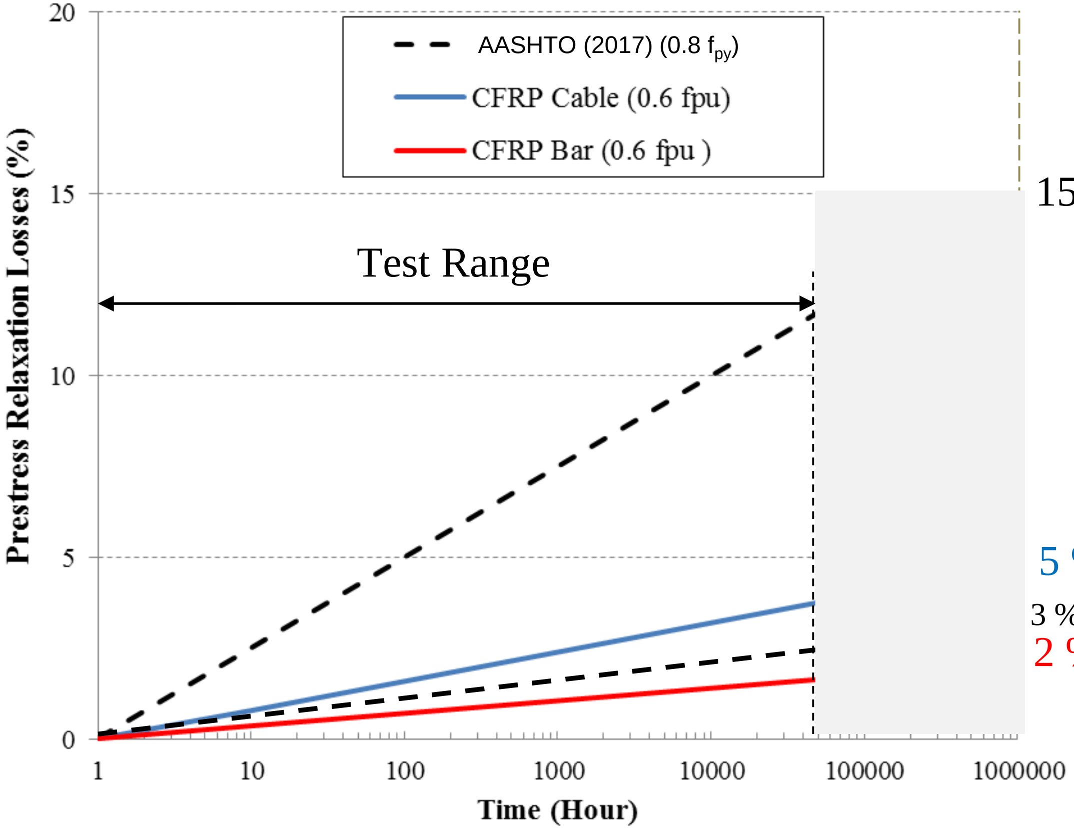
Comparison with AASHTO (2017) Equations



4. PRESTRESS LOSSES

CFRP Prestress Relaxation Losses

Comparison with AASHTO (2017) Equations



15 % [Steel Strands]

5 % [CFRP Only]

3 % [Low Relaxation Steel]

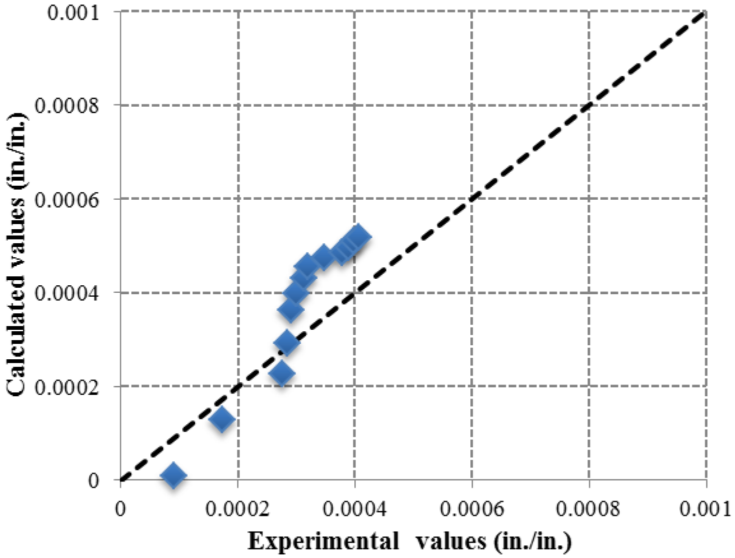
2 % [CFRP Only]

4. PRESTRESS LOSSES

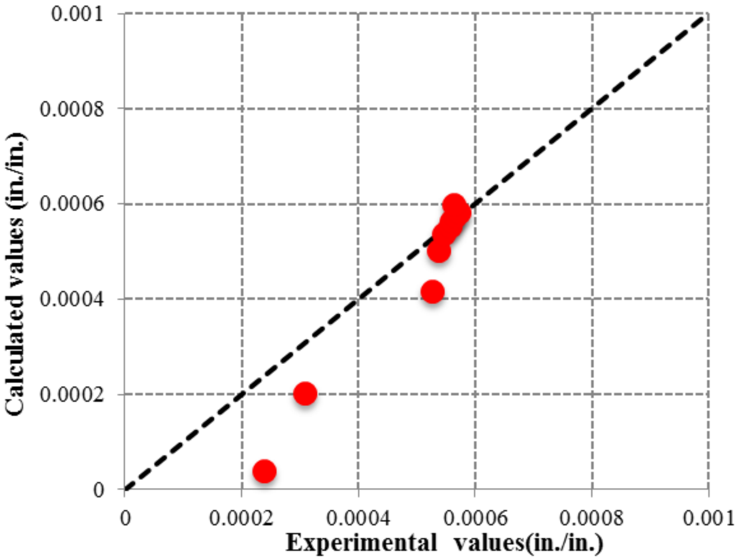
Concrete Creep and Shrinkage Losses

Shrinkage Strains Comparison with AASHTO (2017) Equations

$$\varepsilon_{sh} = k_s \times k_{hs} \times k_f \times k_{td} \times 0.48 \times 10^{-3}$$



Prestressing CFRP Cable (Ø = 0.6 in.)



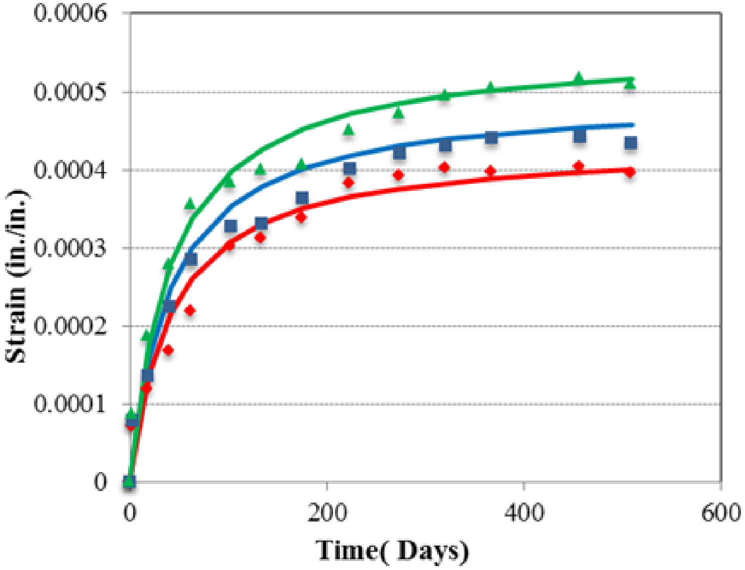
Prestressing CFRP Bar (Ø = 0.5 in.)

4. PRESTRESS LOSSES

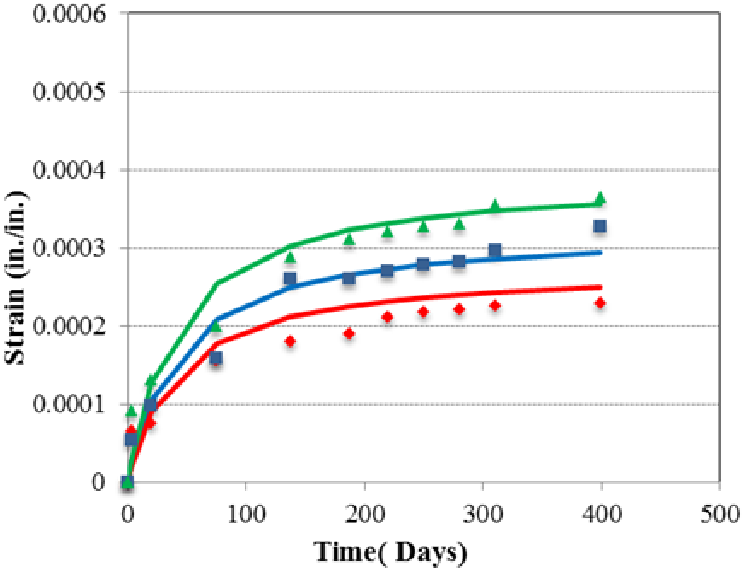
Concrete Creep and Shrinkage Losses

Creep Strains Comparison with AASHTO (2017) Equations

$$\Psi(t,t_i)= 1.9\times k_s\times k_{hs}\times k_f \times k_{td}\times t_i^{-0.118}$$



Prestressing CFRP Cable (Ø = 0.6 in.)

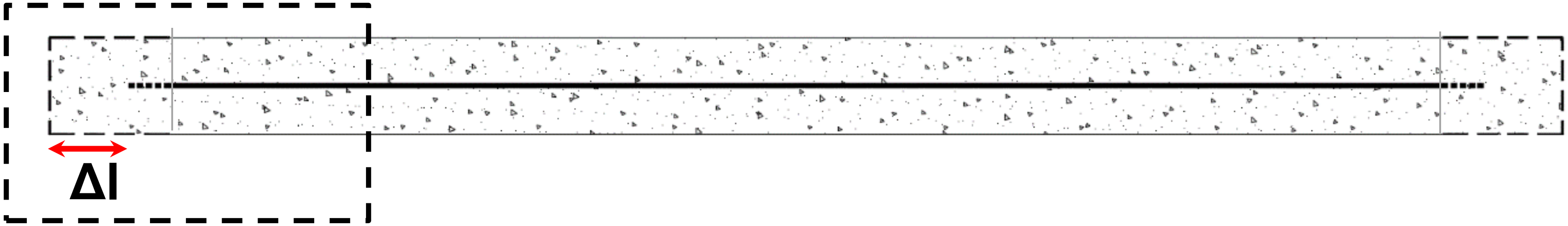


Prestressing CFRP Bar (Ø = 0.5 in.)

4. PRESTRESS LOSSES

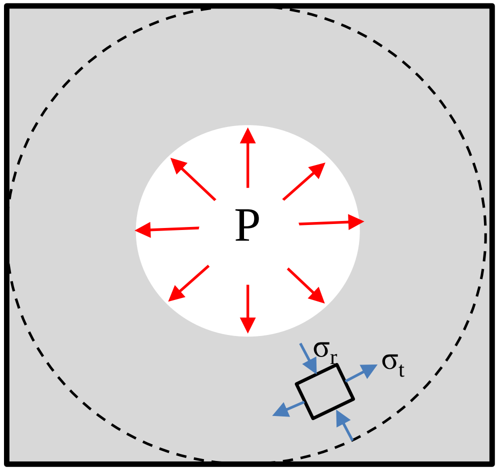
Thermally Induced Losses

Longitudinal effect ($\alpha_{f,l} < \alpha_c$)



Transverse effect ($\alpha_{f,t} > \alpha_c$)

(photo credit: Hany Abdalla)



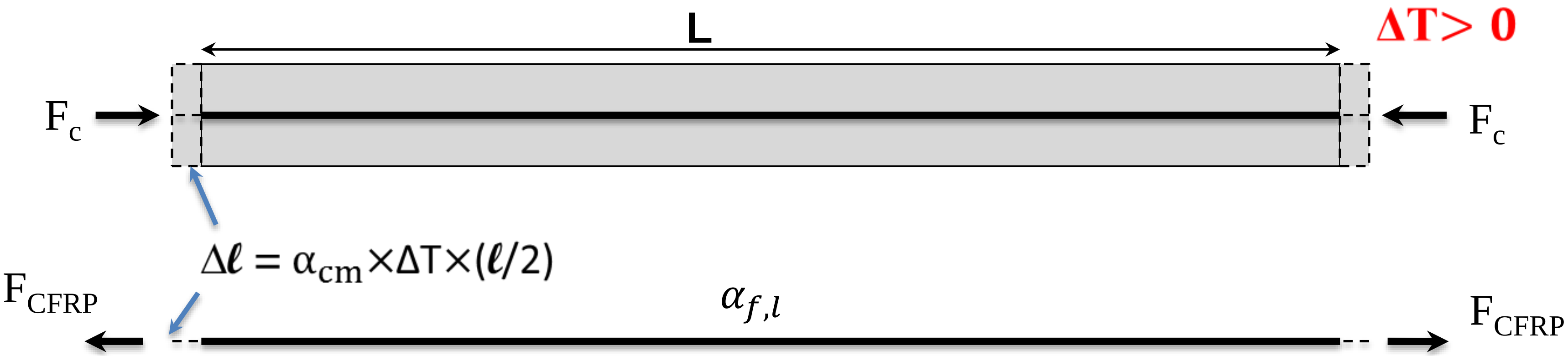
4. PRESTRESS LOSSES

Thermally Induced Losses

Longitudinal effect

Lower longitudinal coefficient of thermal expansion of CFRP than concrete causes thermal induced stresses that cause prestress gain or loss

Longitudinal effect ($\alpha_{frp,l} < \alpha_c$)



1.9.2.4—Losses Due to Temperature Changes

$$\Delta f_{pTH} = \Delta T(\alpha_{cfrp} - \alpha_c)E_f \geq 0$$

ΔT = *temperature change (°F)*

$\alpha_{f,l}$ = *longitudinal coefficient of thermal expansion of prestressing CFRP (1/°F)*

α_c = *coefficient of thermal expansions of concrete(1/°F)*

E_f = *modulus of elasticity of prestressing CFRP (ksi)*

4. PRESTRESS LOSSES

Elastic Shortening

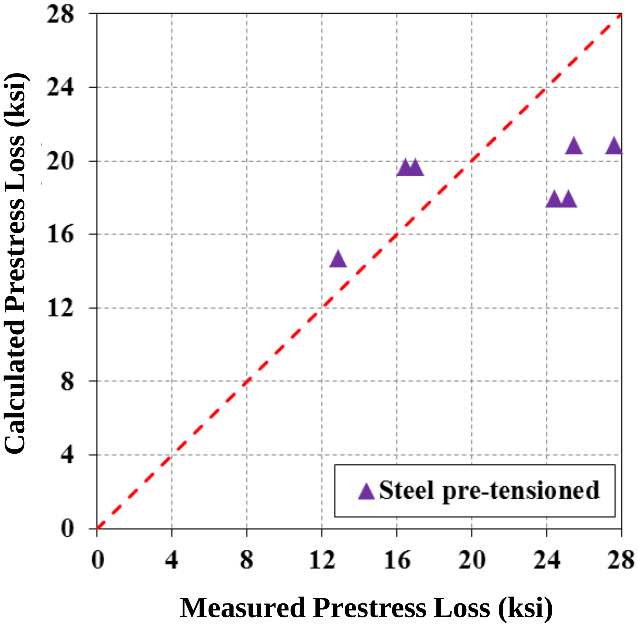
AASHTO Design Guide Specifications

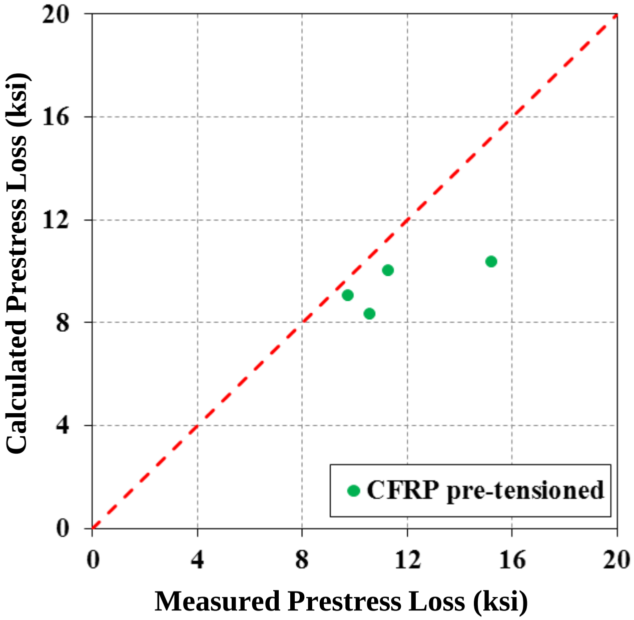
1.9.2.2.3a—Pretensioned Members

The loss due to elastic shortening in pretensioned members shall be taken as:

$$\Delta f_{pES} = \frac{E_f}{E_{ct}} f_{cgp}$$

Use existing AASHTO (2017) equation but replace E_s with E_f





Tadros, M. K. (2003). Prestress losses in pretensioned high-strength concrete bridge girders (Vol. 496). Transportation Research Board.

4. PRESTRESS LOSSES

Elastic Shortening

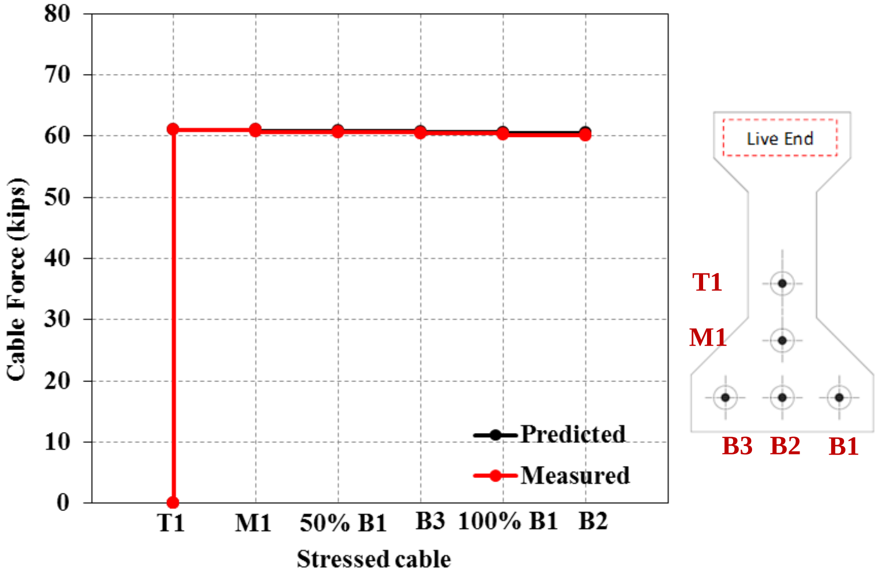
AASHTO Design Guide Specifications

1.9.2.2.3b—Post-Tensioned Members

The loss due to elastic shortening in post-tensioned members may be taken as:

$$\Delta f_{pES} = \frac{N-1}{2N}\frac{E_f}{E_{ct}} f_{cgp}$$

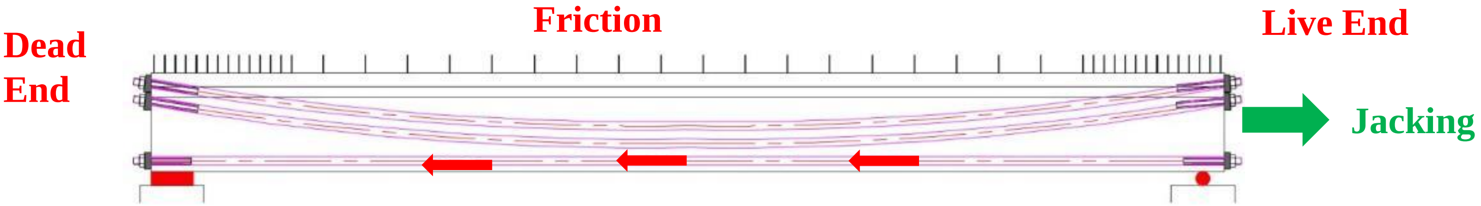
Use existing AASHTO (2017) equation but replace E_s with E_f



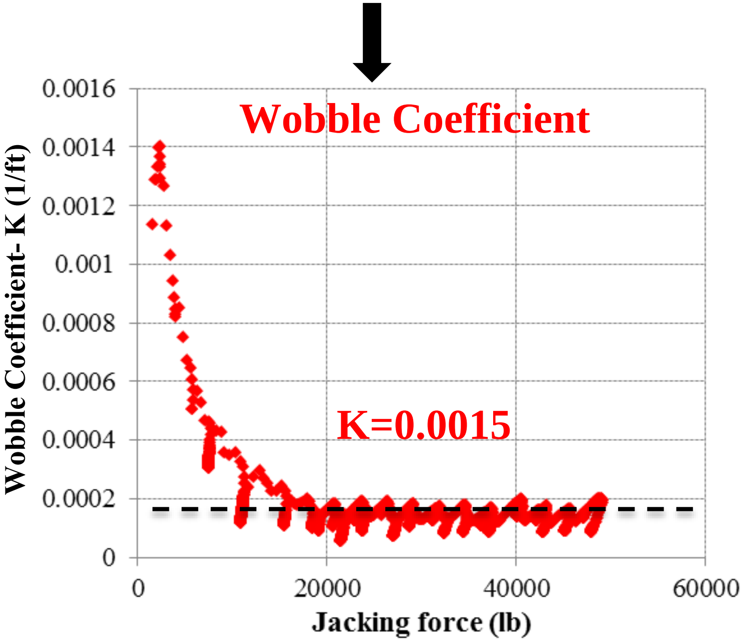
Elastic shortening of cable T1 during the posttensioning sequence

4. PRESTRESS LOSSES

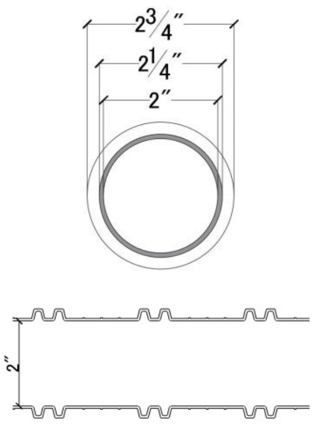
Friction Losses



$$\Delta f_{pF}=f_{pj}\,(1-e^{-(\mu\alpha+Kx)})$$



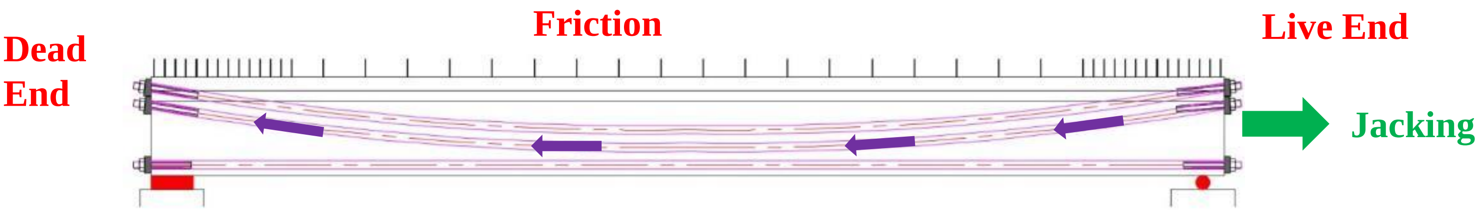
Wobble Coefficient vs. Jacking force



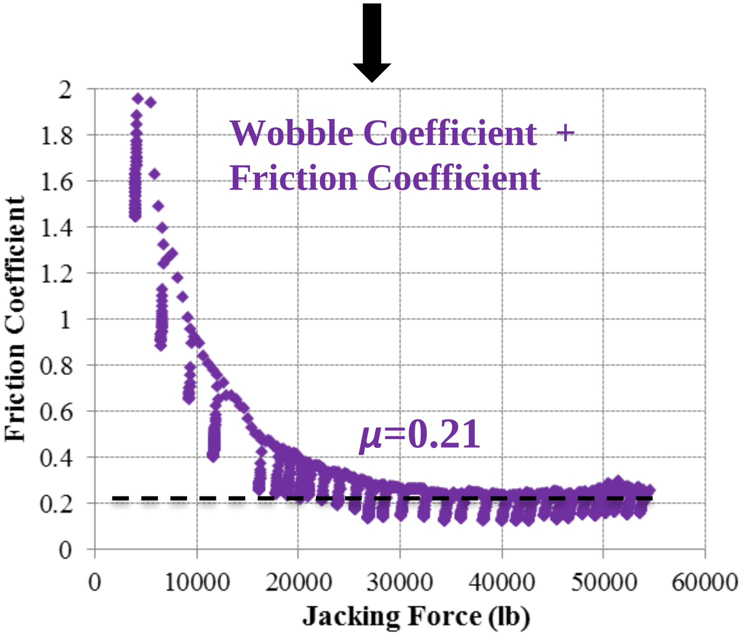
2'' Corrugated plastic duct
Material: Polypropylene

4. PRESTRESS LOSSES

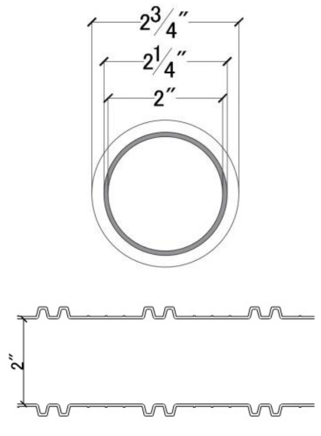
Friction Losses



$$\Delta f_{pF}=f_{pj}\,(1-e^{-(\mu\alpha+Kx)})$$



Friction Coefficient vs Jacking force



2'' Corrugated plastic duct
Material: Polypropylene

4. PRESTRESS LOSSES

Friction Losses

5.9.5.2.2—Friction (AASHTO 2017)

Post-Tensioned Construction:

$$\Delta f_{pF} = f_{pj}\left(1 - e^{-(\mu\alpha + Kx)}\right)$$

μ = coefficient of friction

K = wobble friction coefficient per unit length of tendon (1/ft.)

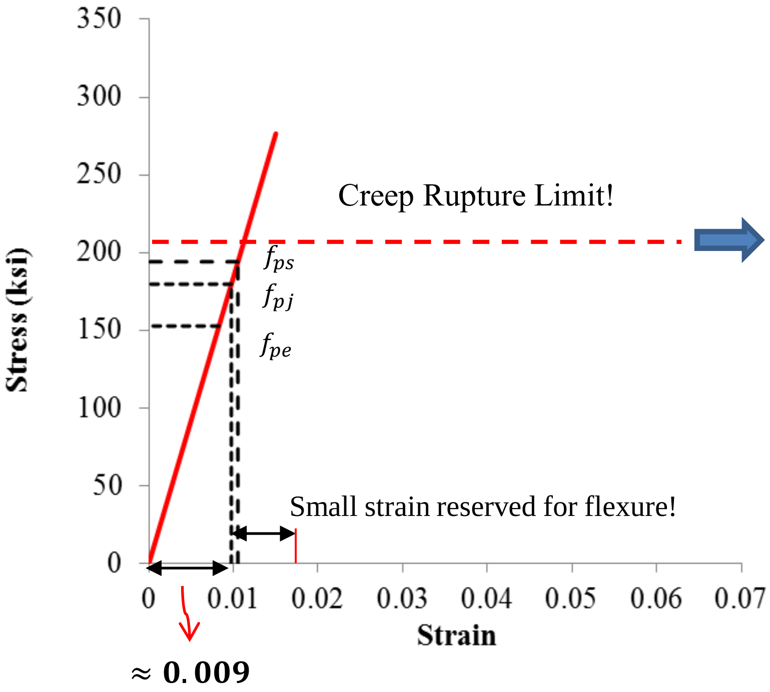
- Values of K and μ should be based on experimental data
- **In the absence of such data**, a value within the ranges of K and μ as specified in Table 1.9.2.2.2b-1 may be used.

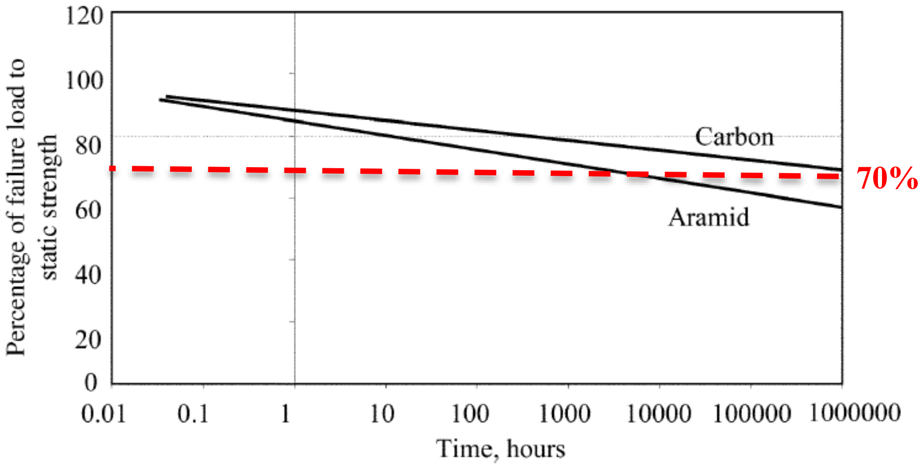
Prestressing Type	Duct Type	*K*	μ
CFRP Cable	PVC	0.00040	0.45
	Polypropylene	0.00022	0.21

4. PRESTRESS LOSSES

Design Requirements		AASHTO (2017)	CFRP Guide Specifications
Prestress Losses	**Relaxation**	Intrinsic relaxation: $\Delta f_{pR}(t,t_i) = \frac{f_{pt}}{K'_L}\frac{\log(24t)}{\log(24ti)}(\frac{f_{pt}}{f_{py}} - 0.55)$	Cables: for post-tensioning $\Delta f_{pR} = \left(0.020\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$ For pretensioning $\Delta f_{pR} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$ Bars: for post-tensioning $\Delta f_{pR} = \left(0.016\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$ For pretensioning $f_{pR} = \left(0.013\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$
	Creep	$\Psi(t,t_i)=1.9\times k_s\times k_{hs}\times k_f\times k_{td}\times t_i^{-0.118}$	Same as AASHTO (2017)
	Shrinkage	$\varepsilon_{sh}=k_s\times k_{hs}\times k_f\times k_{td}\times 0.48\times 10^{-3}$	Same as AASHTO (2017)
	Temperature Effect	N/A	$\Delta f_{pTH} = \Delta T(\alpha_{f,l} - \alpha_c)E_f \geq 0$
	Friction	$\Delta f_{pF}=f_{pj}\,(1-e^{-(\mu\alpha+kx)})$	Same as AASHTO (2017)
	Elastic Shortening	$\Delta f_{pES} = \frac{E_s}{E_{ct}} f_{cgp}$	$\boldsymbol{E_s \rightarrow E_f}$
	Anchorage Set	$\Delta f_{pAS} = \frac{\Delta_{AS}}{l} E_s$	$\boldsymbol{E_s \rightarrow E_f}$

Creep Rupture Stress Limit

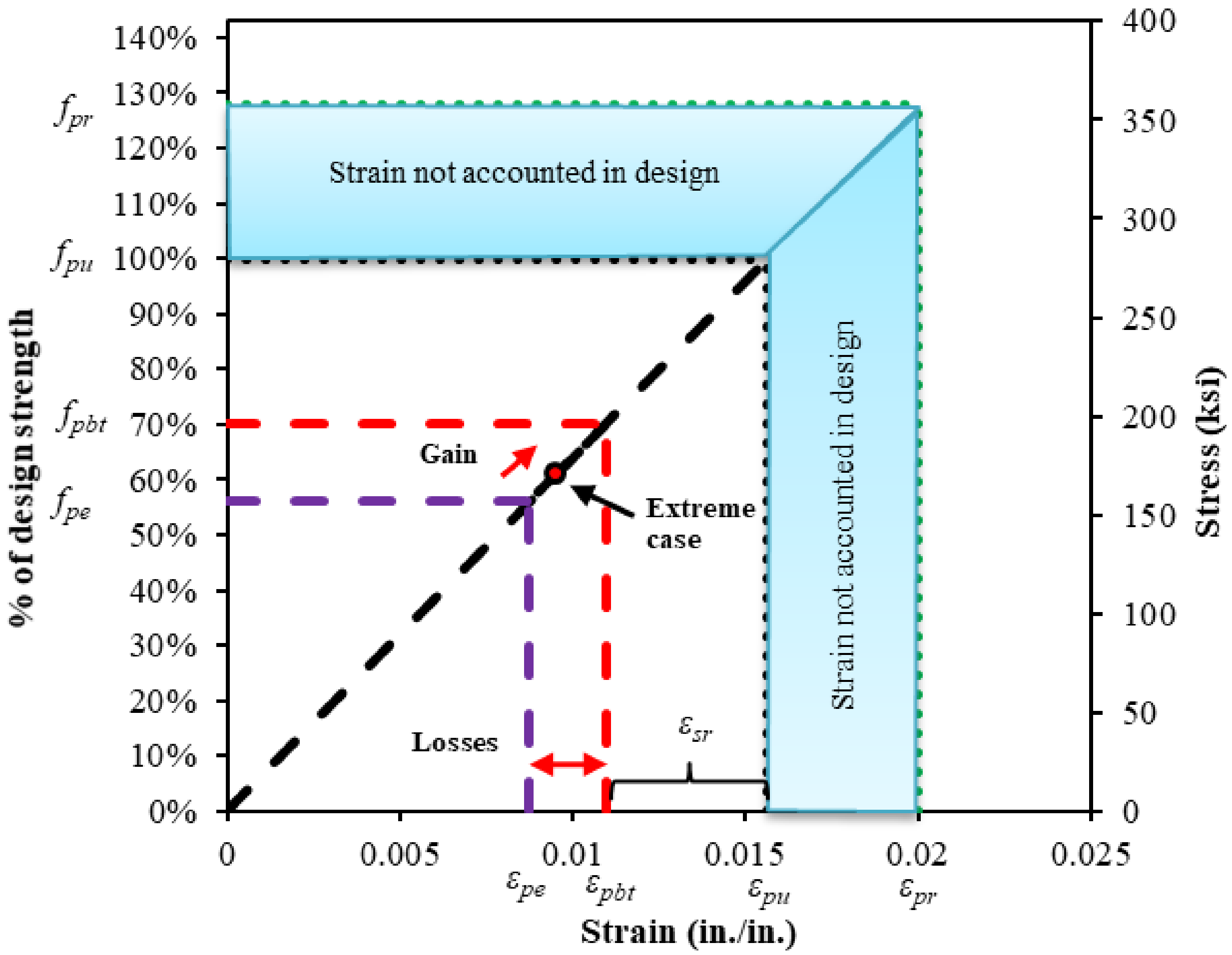




Creep rupture limit for CFRP tendons (ACI440.4R-04)

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Stress Strain Relationship of 0.6 inch diameter cables



ε_{sr} = The reserved tensile strain prior to transfer

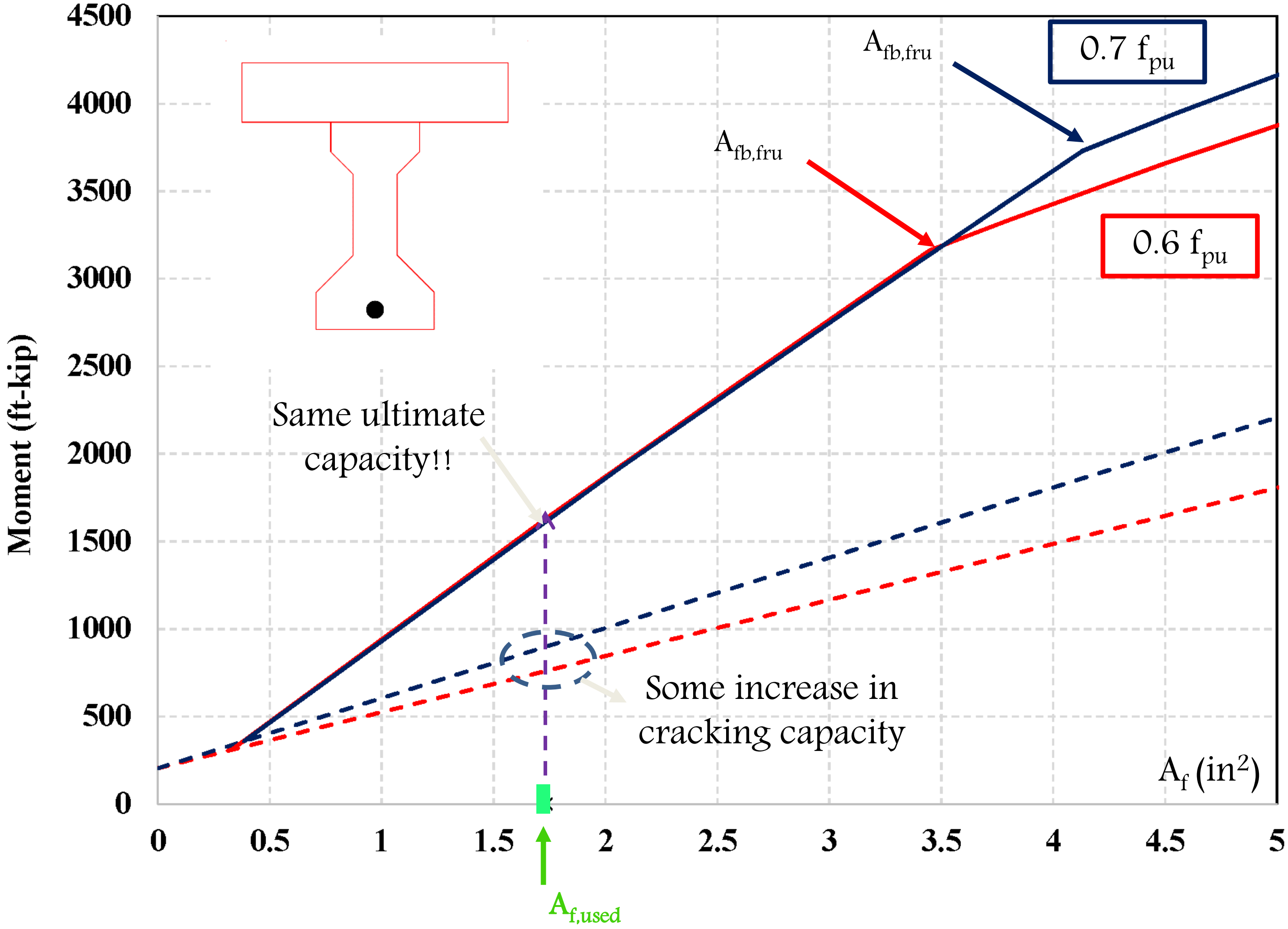
****Extreme case** refers to the occurrence of service load on a cracked girder*

- - - *Stress immediately before transfer*

- - - *Effective prestress after all losses*

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Design Approach: Jacking Stress Effect



1.9.1—Stress Limitations for Prestressing CFRP

Table 1.9.1-1—Stress Limits for Prestressing CFRP

	Cables	***Bars***
Immediately prior to transfer (f_{pbt})	**$0.70\ f_{pu}$**	**$0.65\ f_{pu}$**
At service limit state after all losses (f_{pe})	**$0.65\ f_{pu}$**	**$0.60\ f_{pu}$**

C1.9.1

The stress limitations included in Table 1.9.1-1 are based on the CFRP types evaluated in the NCHRP 12-97 project. It is suggested that the maximum allowable stress immediately prior to transfer (f_{pbt}) *for commercially available CFRP types with different properties may be calculated using the following equation:*

$$f_{pbt} = E_f \times min\left(\varepsilon_{pu} - 0.004, 70\%\ of\ \varepsilon_{pu}\right)$$

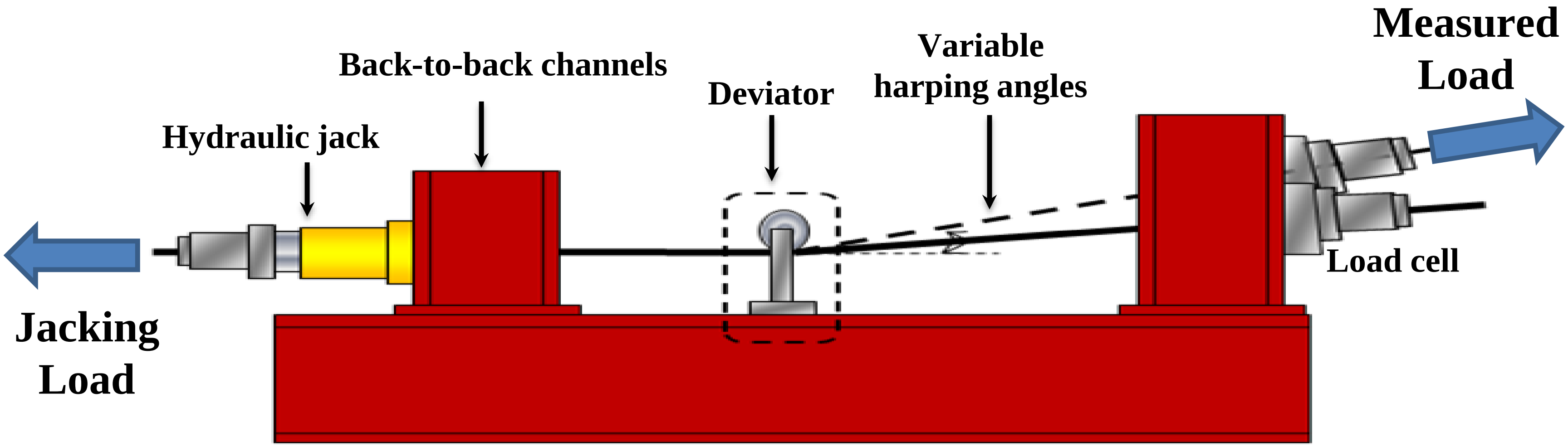
where:

E_f = modulus of elasticity of prestressing CFRP (ksi)
ε_{pu} = design tensile strain of prestressing CFRP (in./in.)

5. Flexural Design & Serviceability Limits

CFRP Harping Properties:

Test-Setup



1 in. Steel

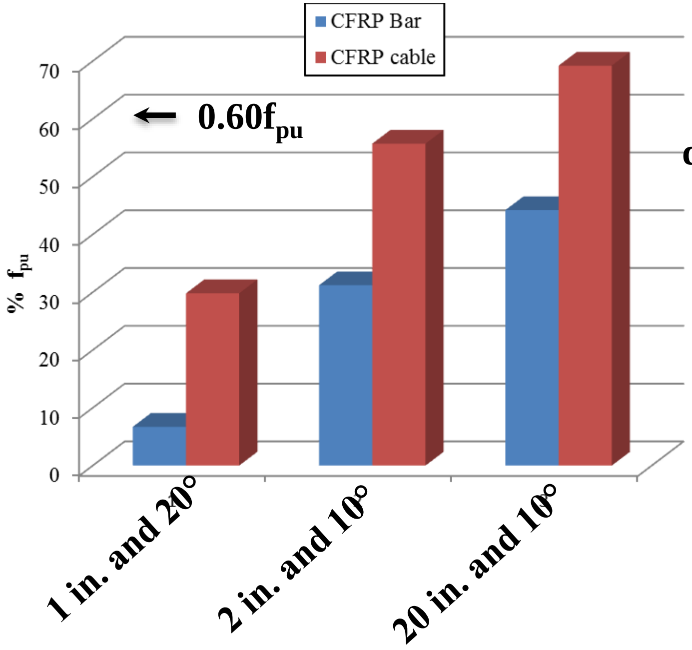
2 in. Teflon

20 in. Steel

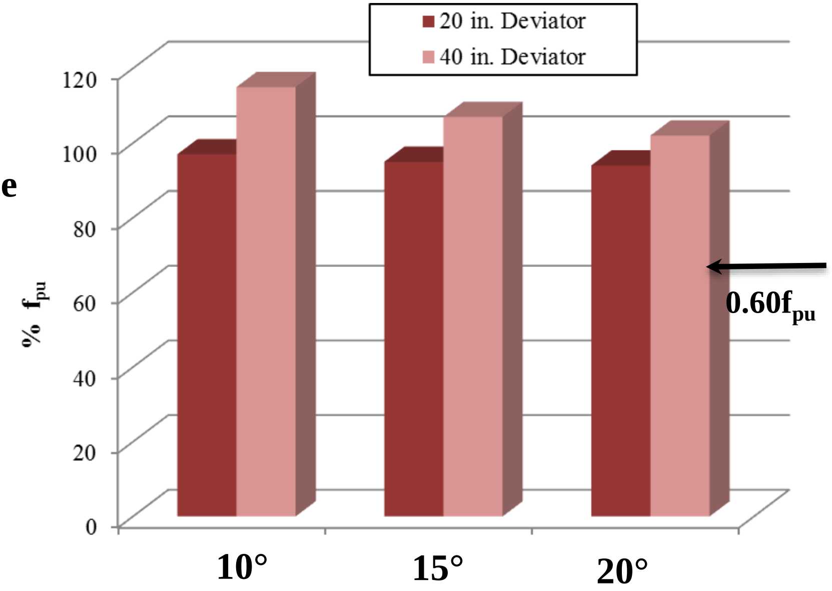
5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

CFRP Harping Properties:

<u>Strength retention under various harping configuration:</u>



Increased deviator size



<u>20 in.</u>

<u>40 in.</u>

- 1 in. and 2 in.-diameter deviators that are available in the industry **will not work**
- CFRP bars are **not recommended** to be harped in bridge girders

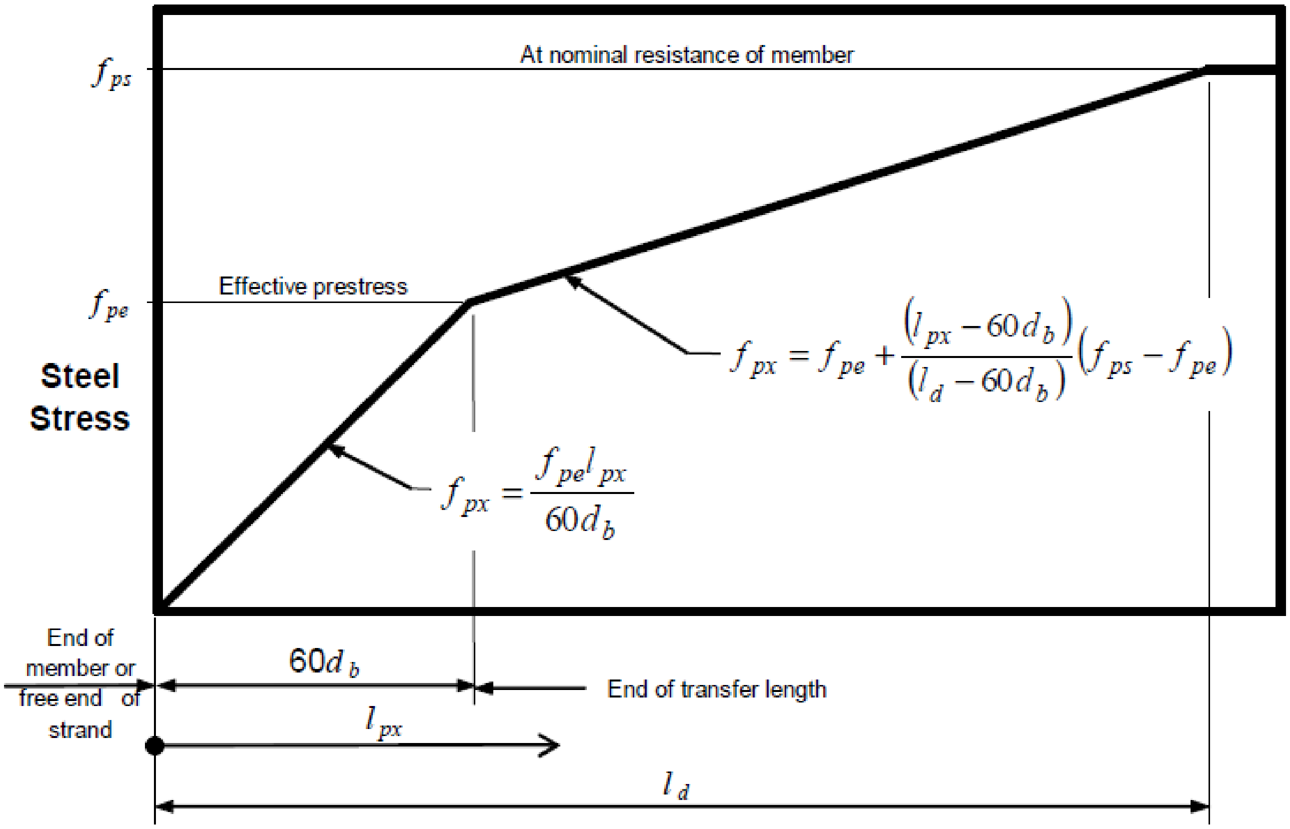
5. Flexural Design & Serviceability Limits

Design Requirements		**AASHTO (2017)**	**CFRP Guide Specifications**
Stress Limit for CFRP Tendons	**Straight Tendons/Bars**	At jacking: Pre-tensioned = 0.75 f_{pu} Post-tensioned = 0.9 f_{py} At service = 0.8 f_{py}	**CFRP Cables:** **Prior to transfer = 0.70 f_{pu}** **At service = 0.65 f_{pu}** **CFRP Bars:** **Prior to transfer = 0.70 f_{pu}** **At service = 0.65 f_{pu}**
	Harped/ Draped	5.4.6.3 Ducts at deviation Saddles	**-Minimum deviator size: 20 in.** **-Strength retention: 100% of f_{pu}**

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

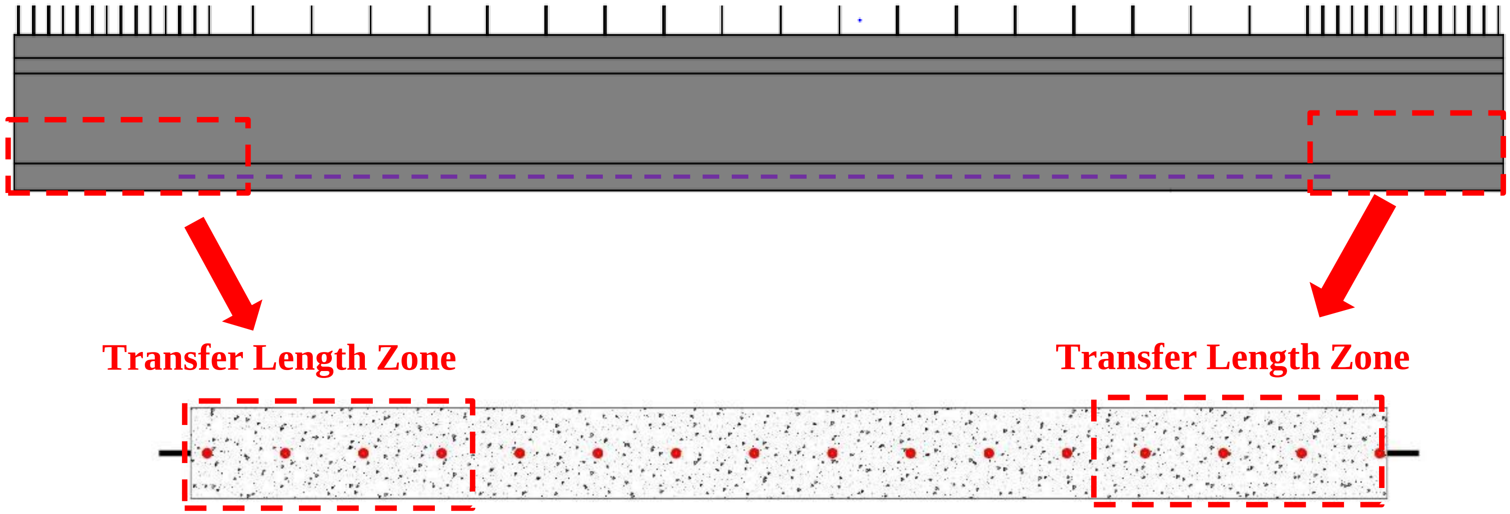
Transfer Length:

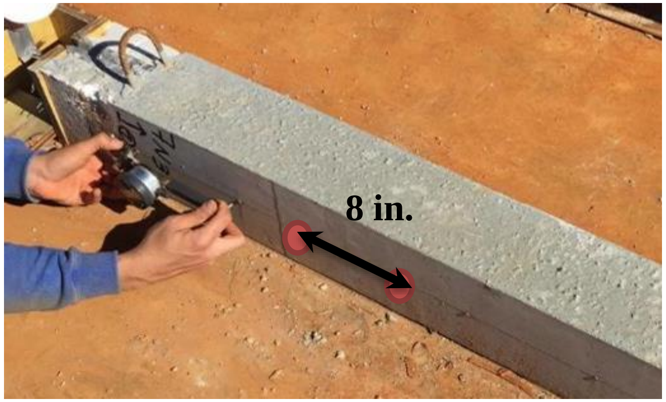
5.11.4—Development of Prestressing Strand (AASHTO 2017)



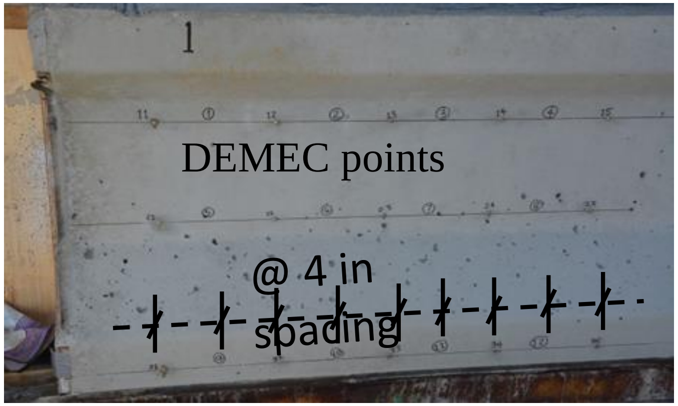
5. Flexural Design & Serviceability Limits

Transfer Length:





Concentrically prestressed prisms

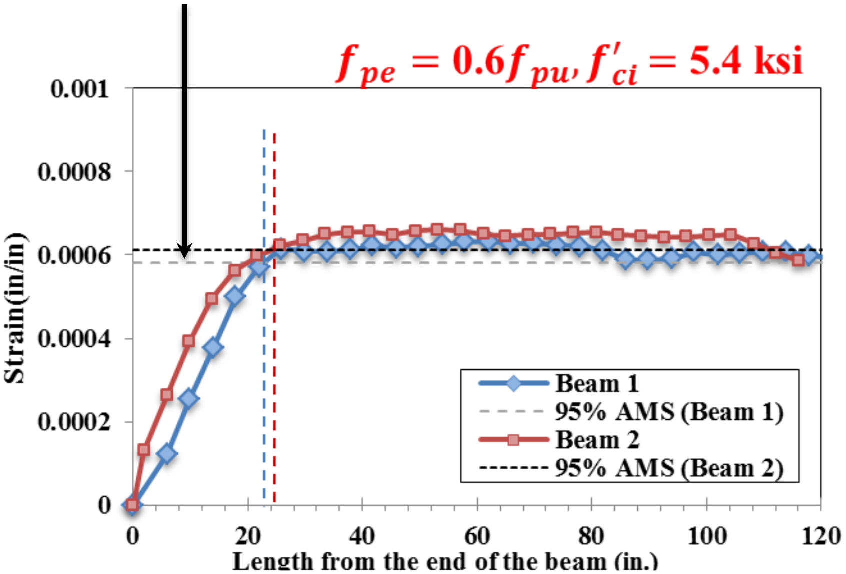


Full-scale girder

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Transfer Length:

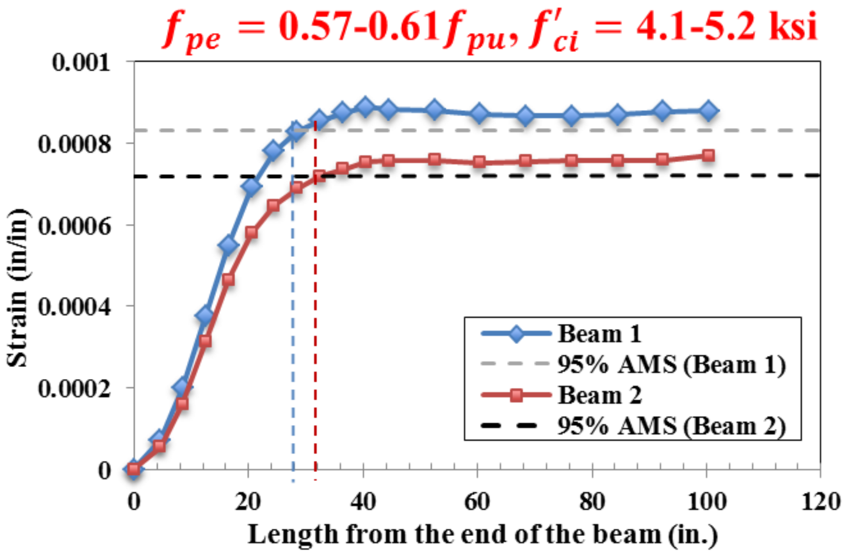
Full-scale Beam Test:



Average Maximum Strain (AMS) line to determine Transfer Length

$f_{pe} = 0.6 f_{pu}, f'_{ci} = 5.4$ ksi

Full-scale Beams -- CFRP Cable (Ø = 0.6 in.)



$f_{pe} = 0.57\text{-}0.61 f_{pu}, f'_{ci} = 4.1\text{-}5.2$ ksi

Full-scale eams --CFRP Bar (Ø = 0.5 in.)

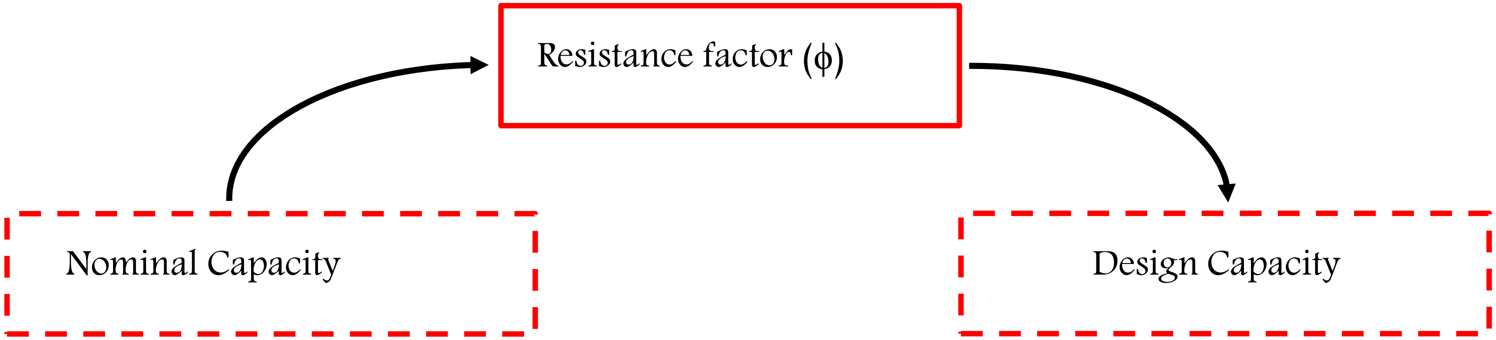
Beam 1: l_t =22 in. ($\cong 37 d_b$)
Beam 2: l_t =25 in. ($\cong 42\ d_b$)

Beam 1: l_t =28 in. ($\cong 56\ d_b$)
Beam 2: l_t =32 in. ($\cong 64\ d_b$)

$$\ell_t = 40 - 60\ d_b$$

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Parametric Study and Reliability Analysis

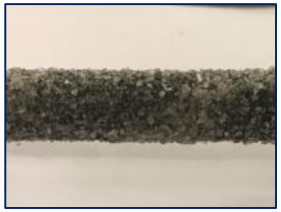


Resistance factor (ϕ)

Nominal Capacity

Design Capacity

→ Ductile (Yield) → ✓



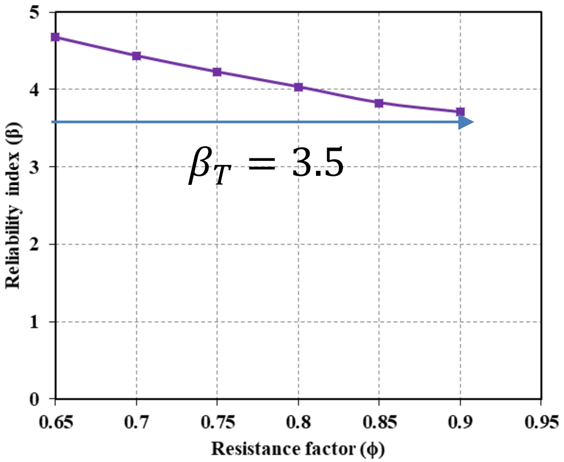
→ Brittle (Rupture) → ⚠

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

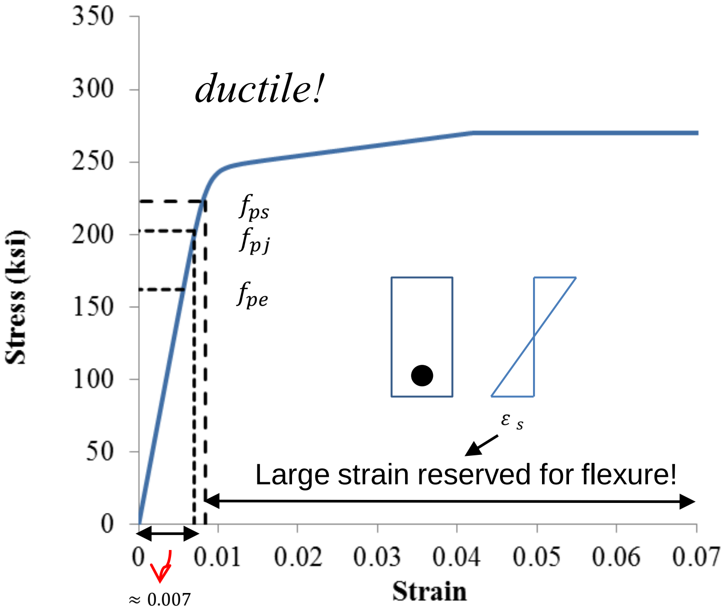
Parametric Study and Reliability Analysis

Reliability index vs resistance factor: Prestressing Steel

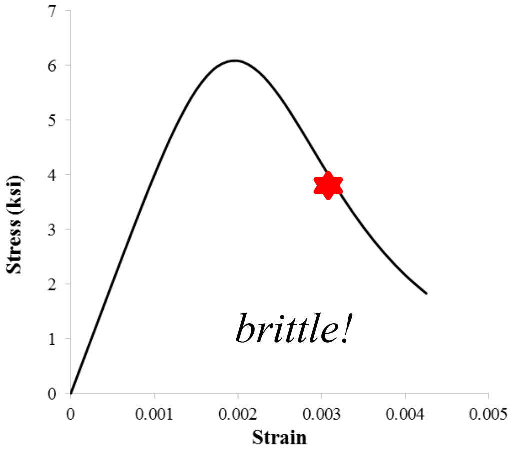
Yielding of prestressing steel is desirable
(Resistance factor for steel **(Φ) = 1.0)**



$\phi = 1.0$



Large strain reserved for flexure!

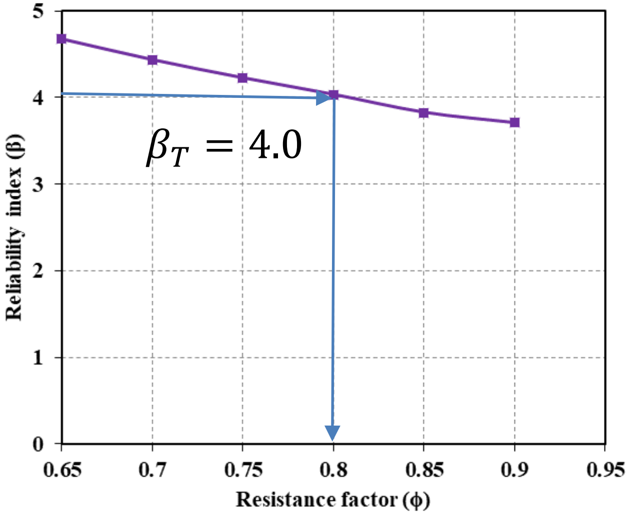


5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

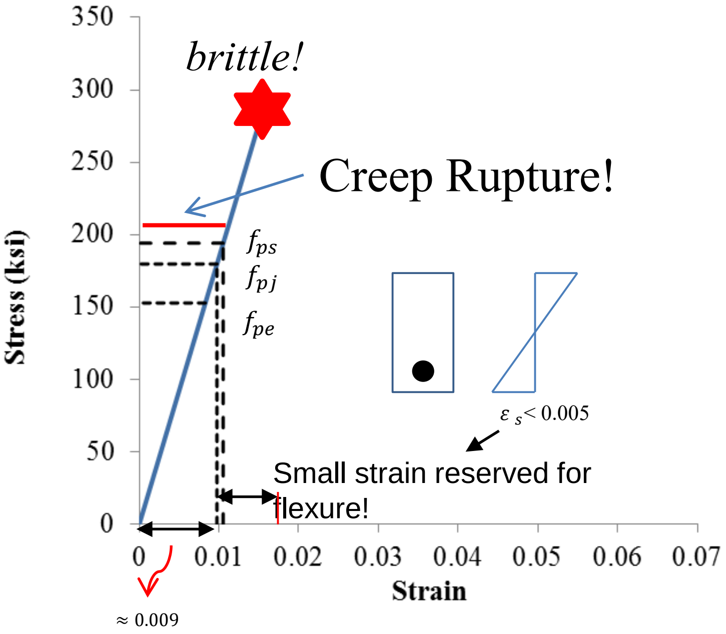
Parametric Study and Reliability Analysis

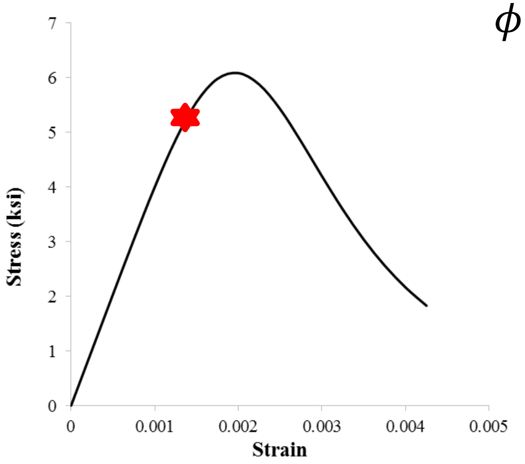
Reliability index vs resistance factor: Prestressing CFRP

FRP rupture is not desirable
FRP rupture is the cost-effective solution
Φ should be lower because of the brittle nature of CFRP



$\phi = 0.8$

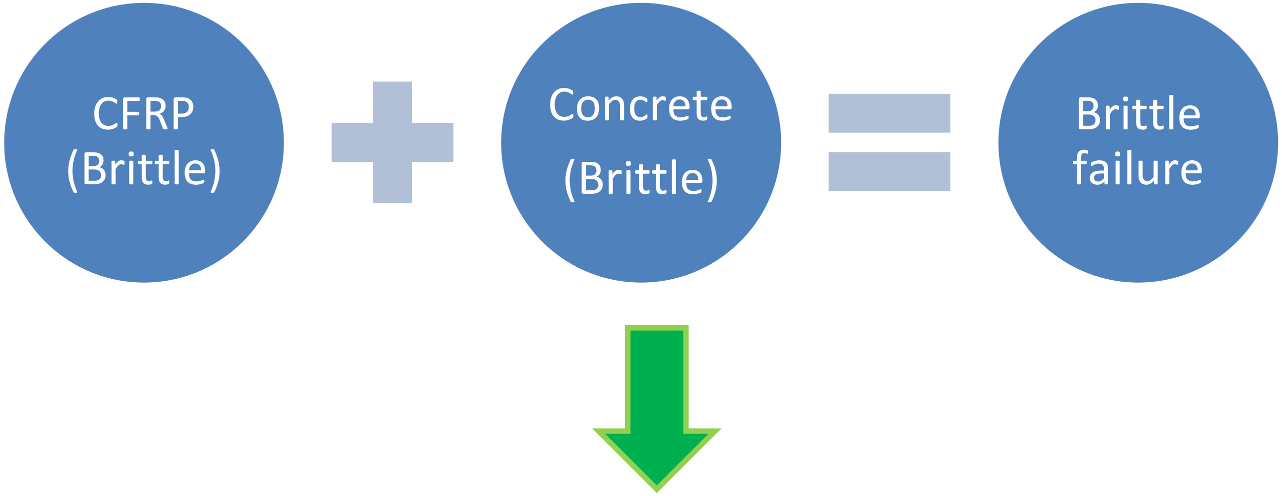




5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

1.5.3.2—Resistance Factors

- *For flexural design, the resistance factor, ϕ, shall be taken as 0.75.*



Recommended $\phi = 0.75$

[*Same as concrete crushing*]

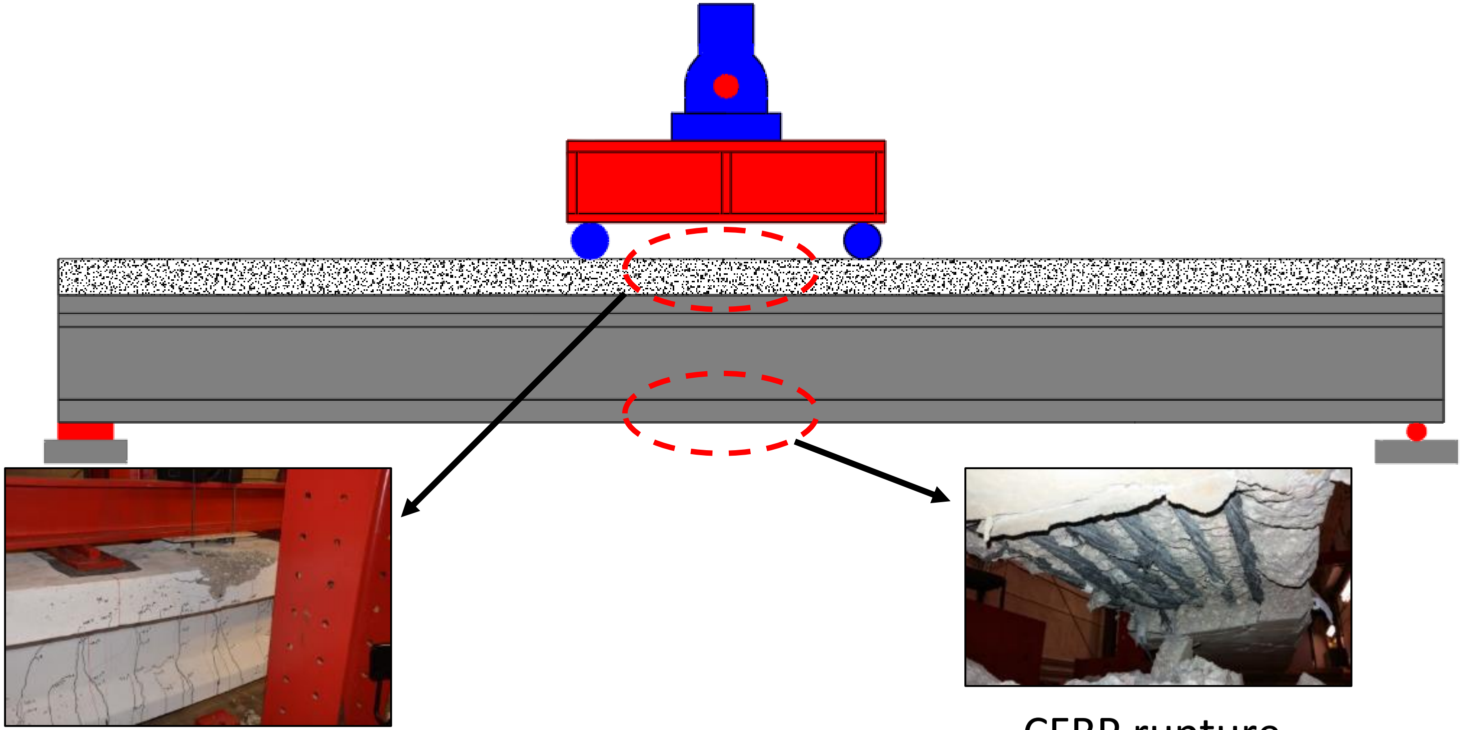
5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

	Provisions	**AASHTO (2017)**	**CFRP Guide Specifications**
Bond, Development Length and Transfer Length	**Transfer Length**	ℓ_t=60 d_b	$\ell_t = \frac{f_{pbt} d_b}{\alpha_t {f'_{ci}}^{0.67}}$ **α_t=1.0 for bars** **α_t=1.3 for cables** **ℓ_t=50d_b**
	Development Length	$l_d \geq k\left(f_{ps} - \frac{2}{3} f_{pe}\right) d_b$	$\ell_b = \frac{(f_{pu} - f_{pe}) d_b}{\alpha_d {f'_{ci}}^{0.67}}$ **α_d=0.5 for bars** **α_d=1.5 for cables** $\ell_d = \ell_t + \ell_b$

	Provisions	**AASHTO (2017)**	**CFRP Guide Specification**
Flexural Design	**Resistance Factor**	For tension -controlled: Ø = 1.0 For compression -controlled: Ø = 0.75	**For tension-controlled: Ø = 0.75** **For compression-controlled: Ø = 0.75**

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Flexural Behavior



Concrete crushing
Compression failure

CFRP rupture
Tension
failure

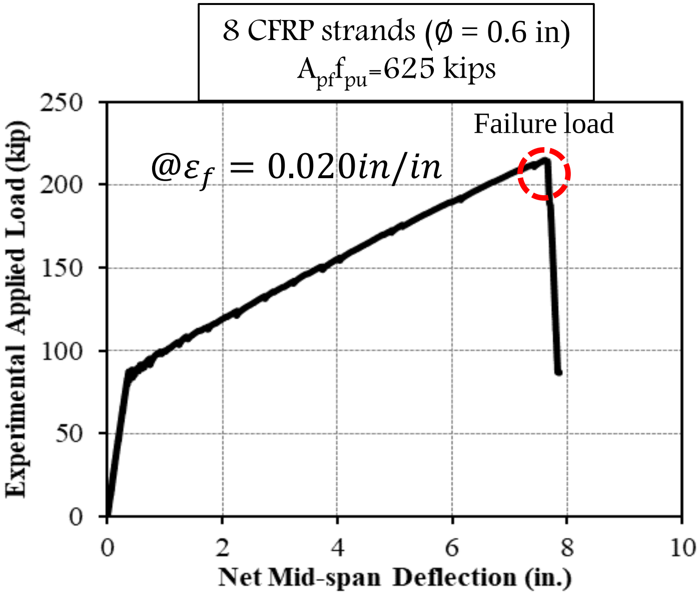
✓

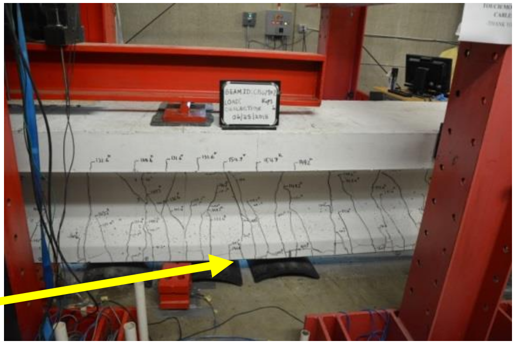
Selected Mode of Failure

Flexural Behavior: Monotonic test results

Load-deflection behavior: (CFRP vs Steel pre-tensioned beam)

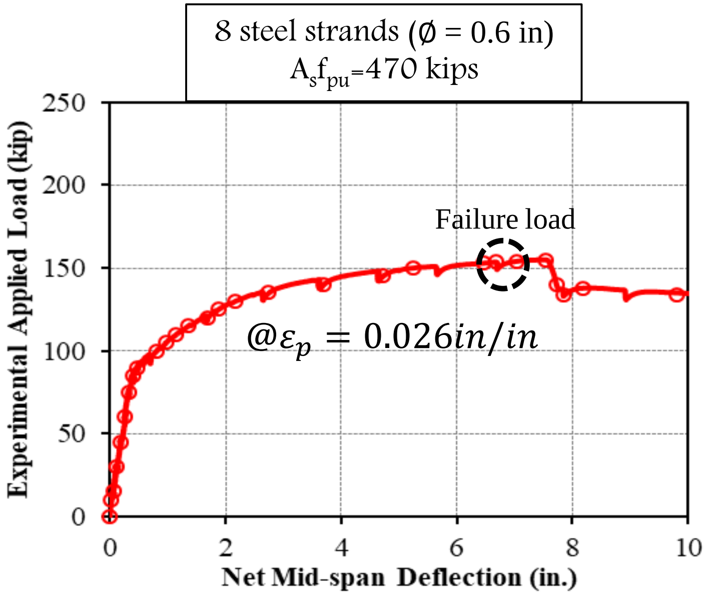
CFRP pre-tensioned beams

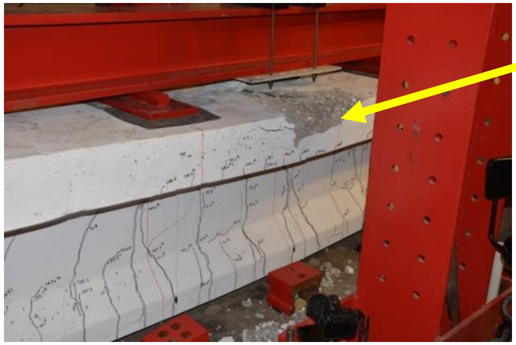




CFRP Rupture

Steel pre-tensioned beams



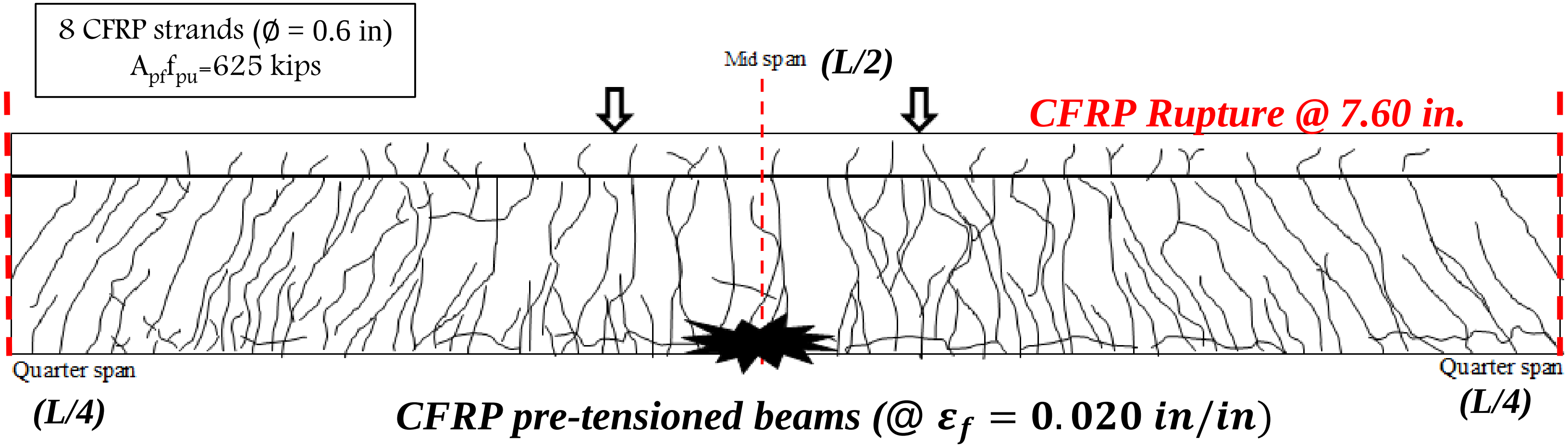


Concrete Crushing

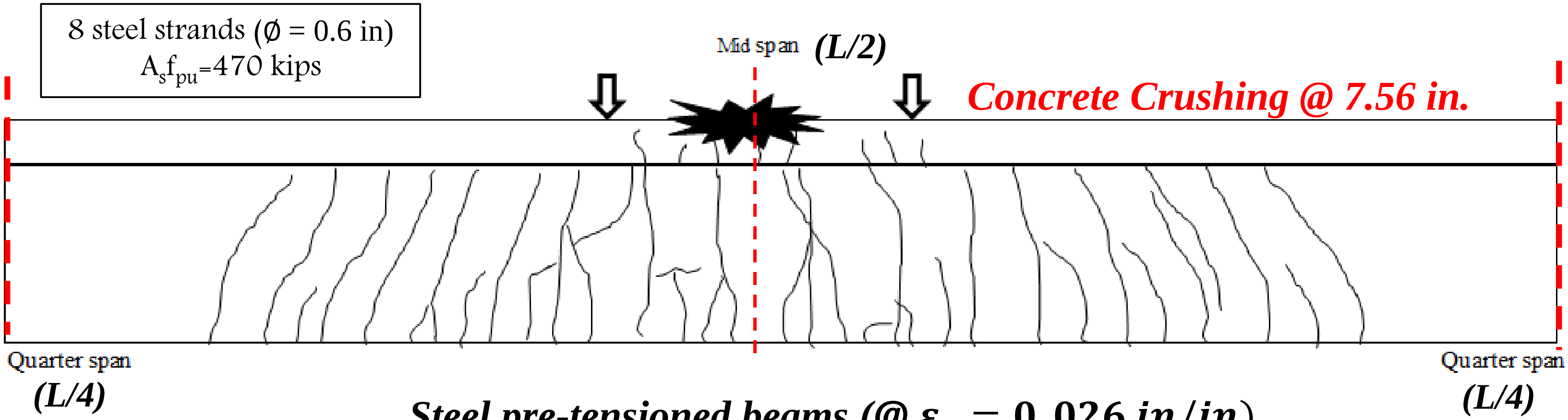
5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Flexural Behavior: Monotonic test results

Crack distribution at failure: (CFRP vs Steel pre-tensioned beam)



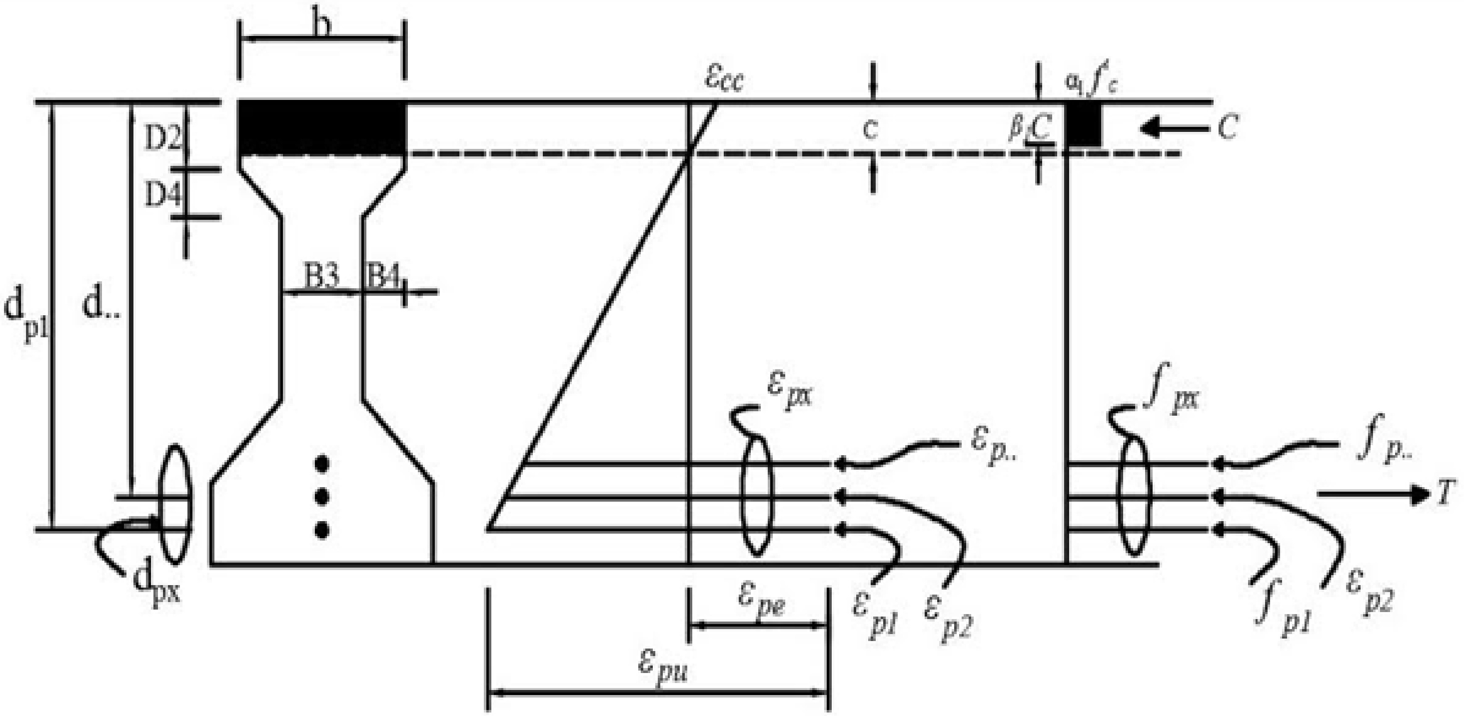
CFRP pre-tensioned beams (@ $\varepsilon_f = 0.020\ in/in$)



Steel pre-tensioned beams (@ $\varepsilon_p = 0.026\ in/in$)

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Flexural Behavior:



5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Analysis of Pretensioned beams:

1.7: Design For Flexural And Axial Force Effects

1.7.3—Flexural Members

1.7.3.1—Stress in Prestressing CFRP at Nominal Flexural Resistance1

1.7.3.1.1—Components with Bonded Prestressing CFRP

for T-section behavior:

$$c = \frac{\sum_{x=1}^{n} A_{px} f_{px} - 0.85 f_c'(b - b_w)h_f}{\alpha_1 f_c' \beta_1 b_w}$$

for rectangular behavior:

$$c = \frac{\sum_{x=1}^{n} A_{px} f_{px}}{\alpha_1 f_c' \beta_1 b}$$

c $\rightarrow$ *Iteration using:*

$$\varepsilon_{px} = \varepsilon_{pe} + \varepsilon_{cc}\frac{d_{px} - c}{c}$$

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

$\rightarrow$ *compression controlled:*

$$\varepsilon_{cc} = \varepsilon_{cu}$$

$\rightarrow$ *tension controlled:*

$$\varepsilon_{p1} = \varepsilon_{pu}$$

$$\varepsilon_{cc} = \varepsilon_{pu}\frac{c}{d_{p1} - c}$$

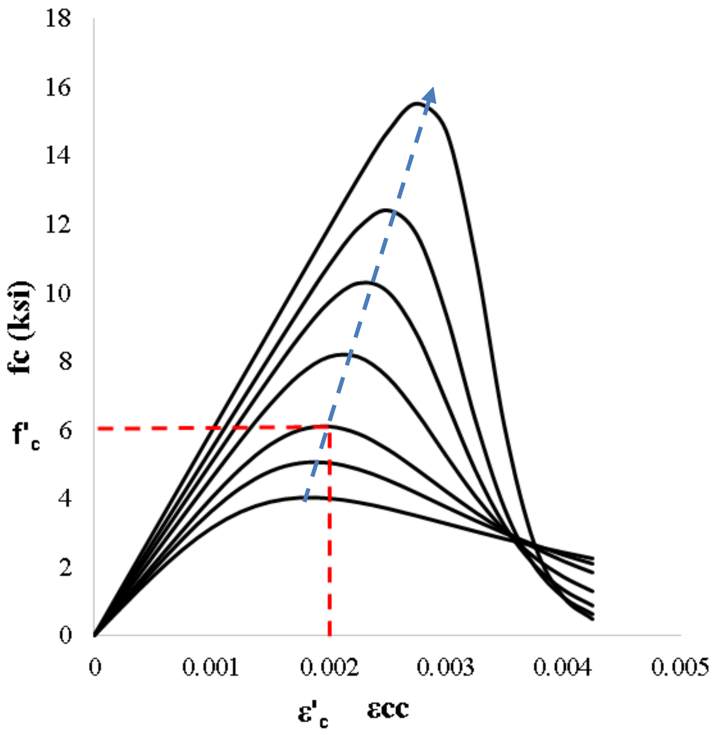
NO YIELD PLATEAU!!

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

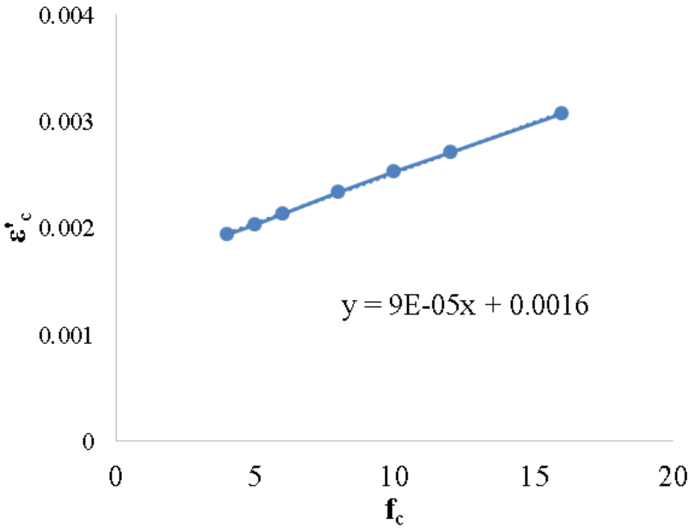
Stress-block factors: ***C1.7.2.1***

When $\varepsilon_{cc} < \varepsilon_{cu}$, *i.e, for tension-controlled section*

$\boldsymbol{\alpha_1}$ *and* $\boldsymbol{\beta_1}$ *for rectangular stress distribution is proposed*



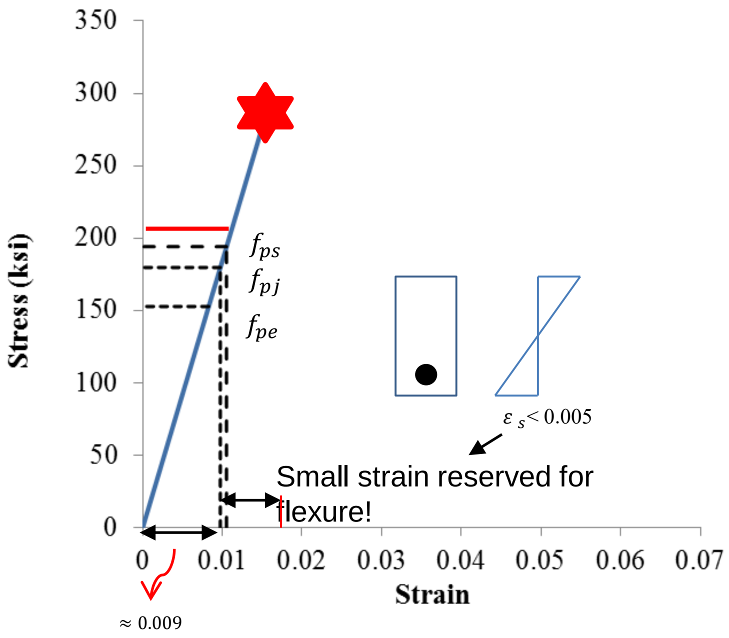
$$\frac{f_c}{f'_c} = \frac{n\left(\frac{\varepsilon_{cc}}{\varepsilon'_c}\right)}{(n-1) + \left(\frac{\varepsilon_{cc}}{\varepsilon'_c}\right)^{nk}}$$



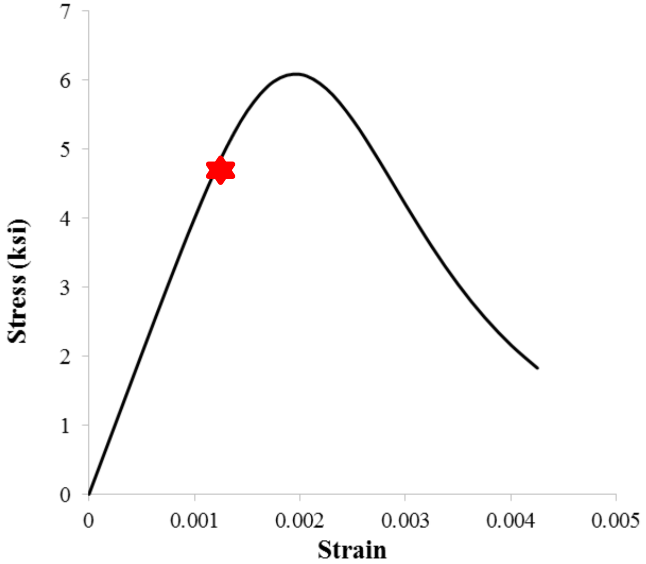
Variation of ultimate strain with concrete strength

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Stress-block factors:

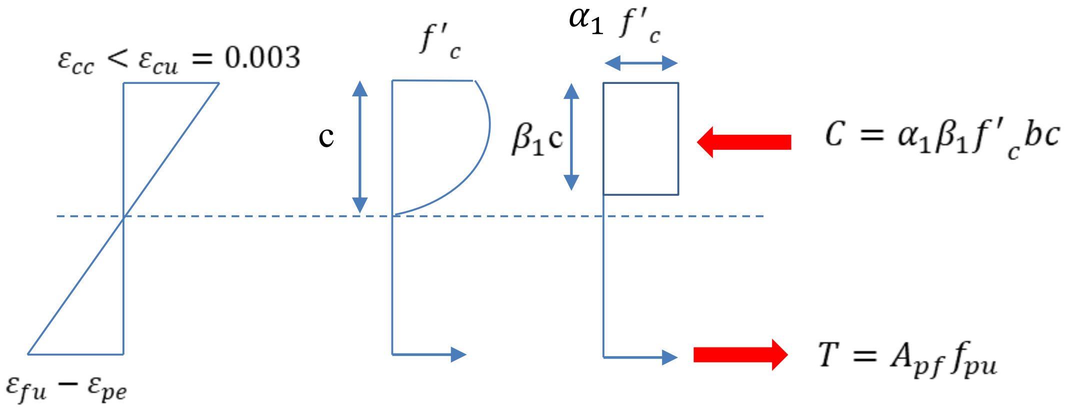


Small strain reserved for flexure!



5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Stress-block factors:



Up to 5 ksi, α_1 and β_1 can be estimated as

(Derived from parabolic stress-strain relationship)

$$\beta_1 = \frac{4 - \frac{\varepsilon_{cc}}{\varepsilon'_c}}{6 - 2\left(\frac{\varepsilon_{cc}}{\varepsilon'_c}\right)} \qquad \alpha_1 = \frac{\left(\frac{\varepsilon_{cc}}{\varepsilon'_c} - \frac{1}{3}\left(\frac{\varepsilon_{cc}}{\varepsilon'_c}\right)^2\right)}{\beta_1}$$

$$\times \qquad\qquad \times$$

From 5 to 15 ksi, α_1 and β_1 can be estimated as

$$\left(-\frac{f'_c}{50} + 1.1\right) \geq 0.65 \qquad \left(-\frac{f'_c}{60} + 1.0\right)$$

Or can be estimated using the AASHTO-LRFD (2017) approach as $\alpha_1, \beta_1 = f(f'_c)$
(The deviation is within 5 % with proposed value being conservative)

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Analysis of Post-tensioned beams:

1.7.3.1.1—Components with Unbonded Prestressing CFRP

for T-section behavior:

$$c = \frac{\sum_{x=1}^{n} A_{px} f_{px} - 0.85 f_c'(b - b_w)h_f}{\alpha_1 f_c' \beta_1 b_w}$$

for rectangular behavior:

$$c = \frac{\sum_{x=1}^{n} A_{px} f_{px}}{\alpha_1 f_c' \beta_1 b}$$

compression controlled:

$$\varepsilon_{cc} = \varepsilon_{cu}$$

Iteration using:

$$c \longrightarrow \quad \varepsilon_{px} = \varepsilon_{pe} + \Omega \varepsilon_{cc} \frac{d_{px} - c}{c}$$

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

tension controlled:

$$\varepsilon_{p1} = \varepsilon_{pu}$$

$$\varepsilon_{cc} = \varepsilon_{pu} \frac{c}{d_{p1} - c}$$

$\Omega = \frac{1.5}{L/d_p}$ *Single point loading*

$\Omega = \frac{3.0}{L/d_p}$ *for two point, uniform loading or a combination of both*

Ω *= strain reduction factor for unbonded prestressing CFRP*

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Proposed

$$f_{px} = f_{pe} + \Omega E_f \varepsilon_{cc} \frac{d_{px} - c}{c}$$

$\Omega = \dfrac{1.5}{L/d_p}$ Single point loading

$$\Omega = \frac{3.0}{L/d_p}$$

for two point, uniform loading or a combination of both

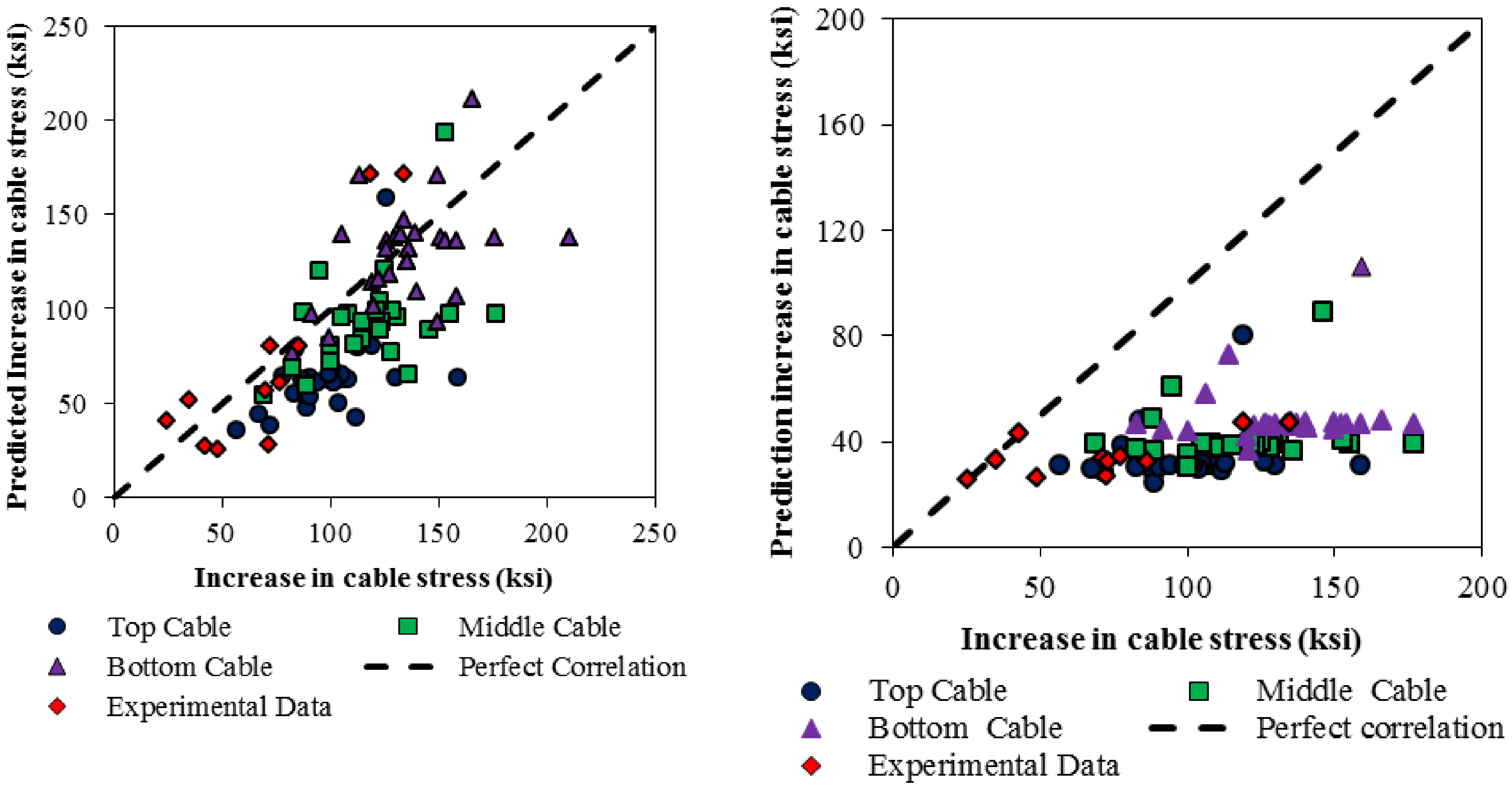
Ω = strain reduction factor for unbonded prestressing CFRP

AASHTO (1996 to 2017)

$$f_{ps} = f_{pe} + 900\left(\frac{d_p - c}{l_e}\right) \leq f_{py}$$

$\boldsymbol{l_e}$ *= Effective length*

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

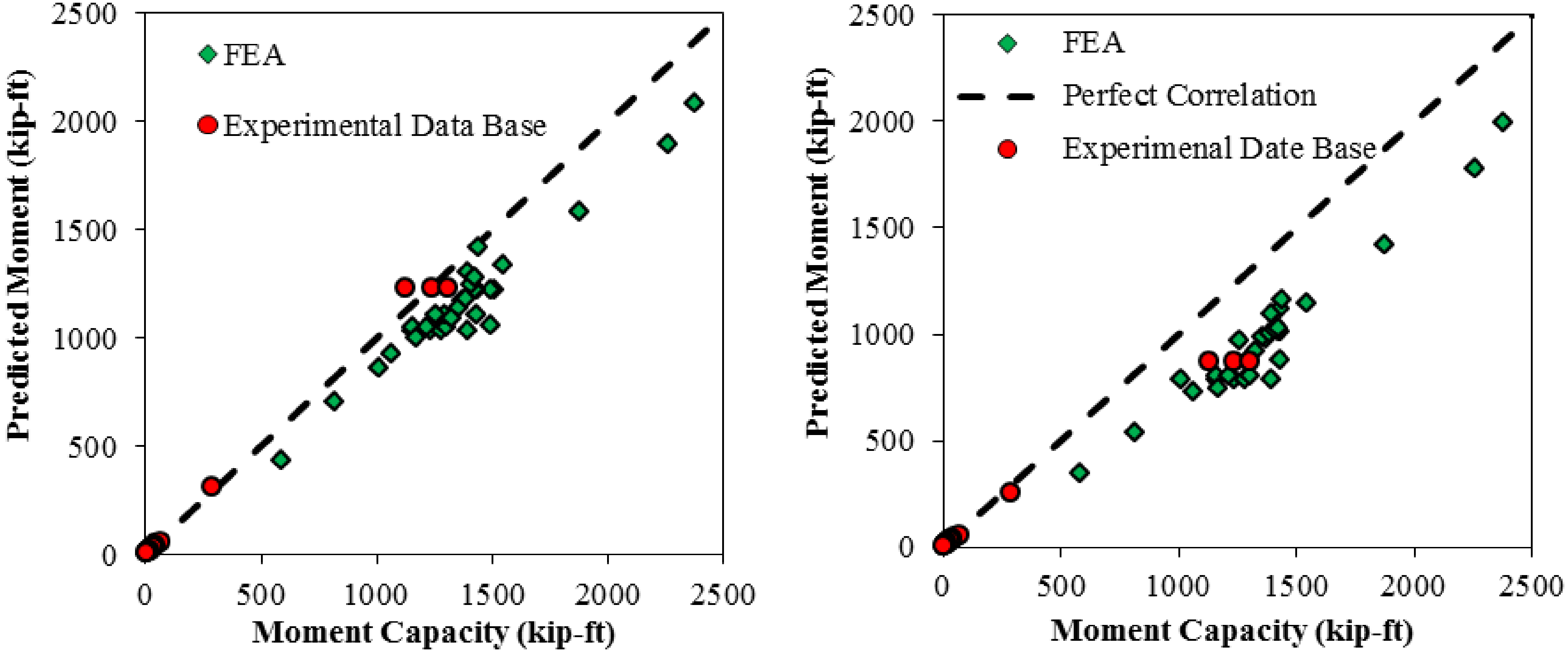


Proposed

AASHTO-LRFD (2017)

Results obtained from FEA or Experimental versus the calculated values

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS



Proposed

AASHTO-LRFD (2017)

Results obtained from FEA or Experimental versus the calculated values

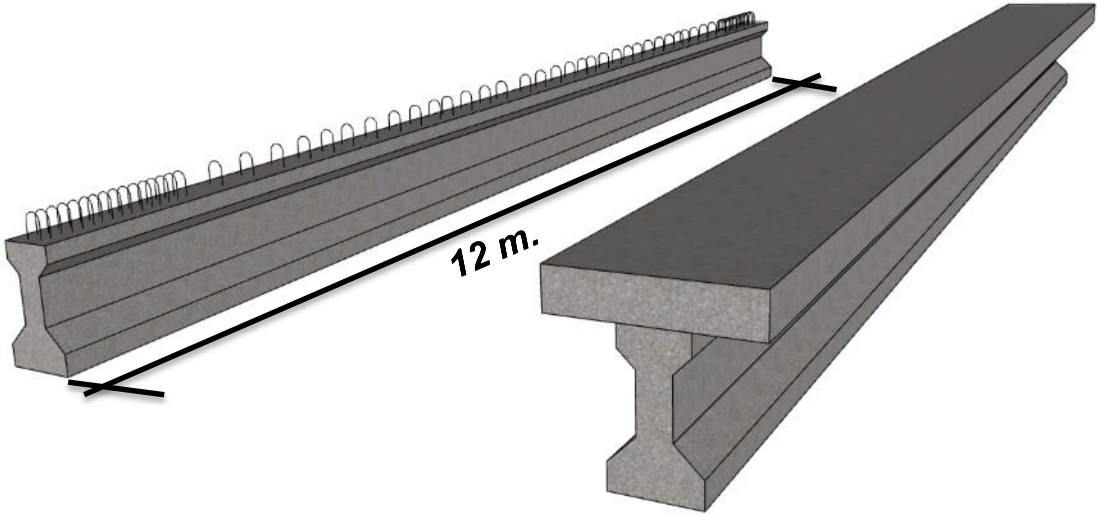
5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

	Provisions	AASHTO (2017)	CFRP Guide Specifications
Flexural Design	**Unbonded Prestressing CFRP**	$f_{ps} = f_{pe} + 900\left(\frac{d_p - c}{l_e}\right)$ $l_e = \left(\frac{2\, l_i}{2 + N_s}\right)$	$\mathbf{f_{px} = f_{pe} + \Omega E_f \varepsilon_{cc} \frac{d_{px} - c}{c}}$ $\mathbf{\Omega = \frac{1.5}{L/d_p}}$ **(single point loading)** $\mathbf{\Omega = \frac{3.0}{L/d_p}}$ **(two point, uniform loading or a combination)**

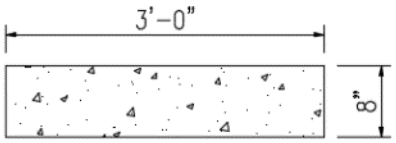
5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

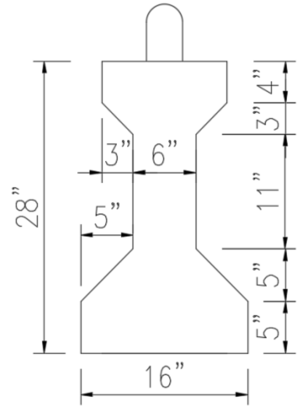
Large-scale Testing

Test specimen:



20 cm composite deck

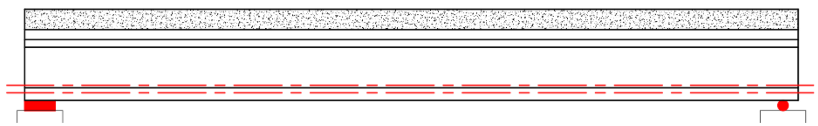




AASHTO Type I

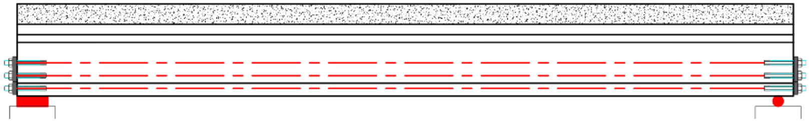
1 in. = 25.4 mm

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS



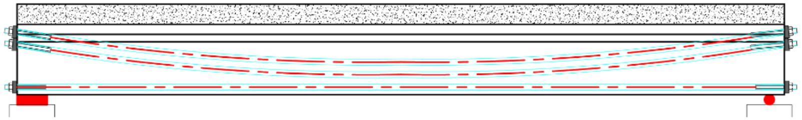
Pre-Tension, Straight Bars/Cables **[7]**

- **Cables** (Ø = 0.6in.) **[3]**
  - Monotonic **[2]**
  - Fatigue **[1]**
- **Bars** (Ø = 0.5in.) **[4]**
  - Monotonic **[3]**
  - Fatigue **[1]**
  - Partially Debonded **[1]**



Post-Tension, Straight Cables **[2]**

- **Cables** (Ø = 0.76 in.) **[2]**
  - Monotonic **[1]**
  - Fatigue **[1]**



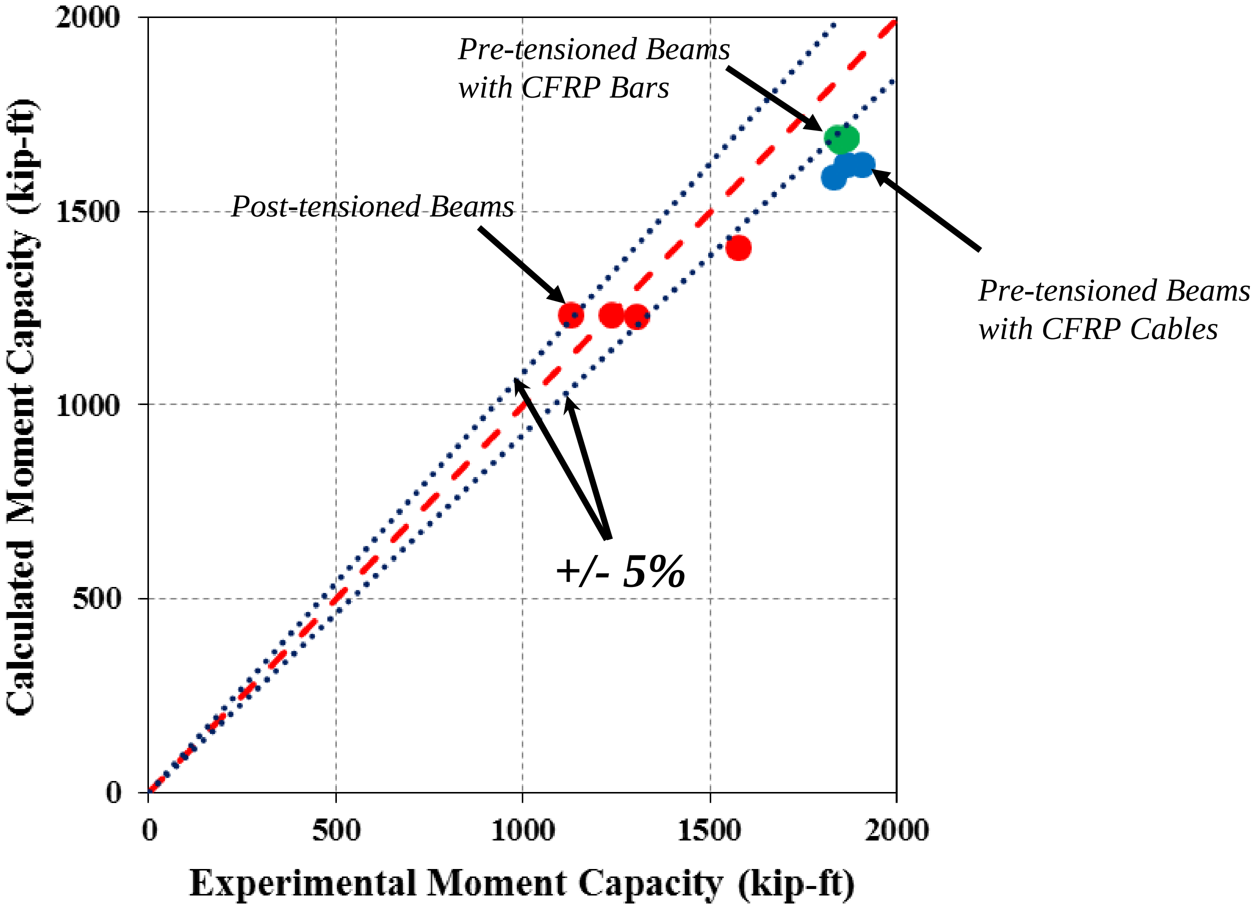
Post-Tension, Draped Cables **[3]**

- **Cables** (Ø = 0.76 in.) **[3]**
  - Unbonded **[1]** → Fatigue **[1]**
  - Bonded **[2]** → Monotonic **[2]**

$\boldsymbol{f_{pi}) = 0.6\, f_{pu}, f'_c = 9 - 12\ ksi}$

$\boxed{\Sigma = [12]}$

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS



Pre-tensioned Beams with CFRP Bars

Post-tensioned Beams

Pre-tensioned Beams with CFRP Cables

+/- 5%

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Flexural Design:

1.7: Design For Flexural And Axial Force Effects

1.7.3—Flexural Members

1.7.3.3—Limits for CFRP Reinforcement

1.7.3.1.1—Minimum Reinforcement

Unless otherwise specified, at any section of a tension-controlled (CFRP rupture) flexural component, the amount of prestressing CFRP shall be adequate to develop a factored flexural resistance, M_r, greater than or equal to the lesser of the following:

- *Factored moment (M_u) required by the applicable strength load combination specified in Table 3.4.1-1 of the AASHTO LRFD Bridge Design Specifications; and*
- $M_{cr} = \gamma_3 \left[\left(\gamma_1 f_r + \gamma_2 f_{cpe}\right) S_c - M_{dnc}\left(\frac{S_c}{S_{nc}} - 1\right)\right]$ *(1.7.3.3.1-1)*

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Short and Long-term Deflections:

1.7.3.4.2—Deflection and Camber

In the absence of a more comprehensive analysis, instantaneous deflections may be computed using the modulus of elasticity for concrete as specified in Article 5.4.2.4 of the AASHTO LRFD Bridge Design Specifications and taking the moment of inertia as the gross moment of inertia, I_g *, or an effective moment of inertia,* I_e *, given by Eq. 1.7.3.4.2-1:*

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta_d I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \leq I_g \qquad (1.7.3.4.2\text{-}1)$$

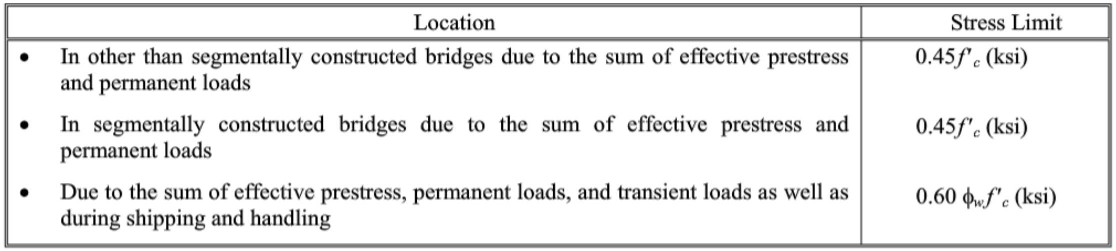
in which β_d is a factor to decrease the effective moment of inertia and is taken as

$$\beta_d = 0.5\left(\frac{E_f}{E_s} + 1\right) \qquad (1.7.3.4.2\text{-}2)$$

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

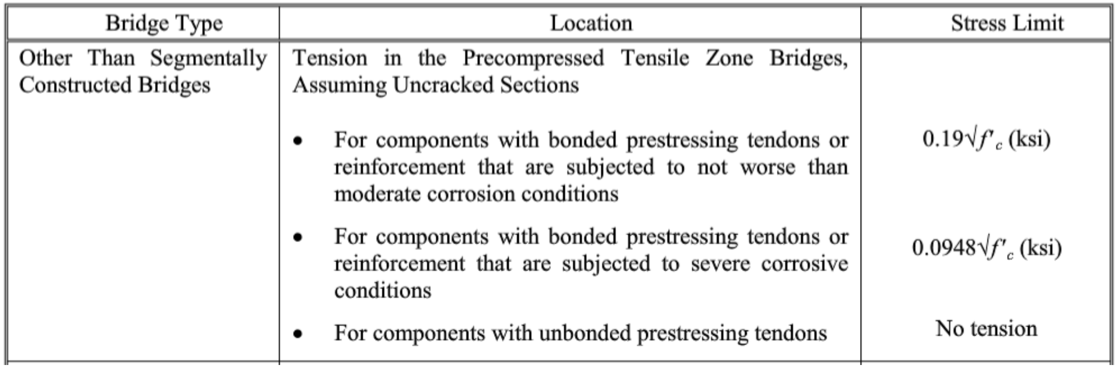
Concrete Stress Limits:

Compressive stress at service after losses (AASHTO 2014)



Location	Stress Limit
• In other than segmentally constructed bridges due to the sum of effective prestress and permanent loads	$0.45f'_c$ (ksi)
• In segmentally constructed bridges due to the sum of effective prestress and permanent loads	$0.45f'_c$ (ksi)
• Due to the sum of effective prestress, permanent loads, and transient loads as well as during shipping and handling	$0.60\ \phi_w f'_c$ (ksi)

Tensile stress limit at service after losses (AASHTO 2014)



Bridge Type	Location	Stress Limit
Other Than Segmentally Constructed Bridges	Tension in the Precompressed Tensile Zone Bridges, Assuming Uncracked Sections	
	• For components with bonded prestressing tendons or reinforcement that are subjected to not worse than moderate corrosion conditions	$0.19\sqrt{f'_c}$ (ksi)
	• For components with bonded prestressing tendons or reinforcement that are subjected to severe corrosive conditions	$0.0948\sqrt{f'_c}$ (ksi)
	• For components with unbonded prestressing tendons	No tension

All applicable!!

Since prestressing CFRP cannot be harped*, strand may be debonded to satisfy the stress limits.

* Unless they retain 100% of the design strength at the deviator points

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

	Provisions	AASHTO (2017)	CFRP Guide Specifications
Flexural Design	**Min Factored Flexural Strength**	• $1.33M_r$ • $M_{cr} = \gamma_3\left[(\gamma_1 f_r + \gamma_2 f_{cpe})S_c - M_{dnc}\left(\frac{S_c}{S_{nc}} - 1\right)\right]$	**Same as AASHTO (2017)**
Service Limit State	**Long-term Deflection**	Multiplying instantaneous deflections by; 4.0 (for I_g) or 3.0 -1.2 (A'_s / A_s) ≥1.6 (for I_e)	Multiplying instantaneous deflections by; 4.0 (for I_g) **Same as AASHTO (2017)**
	Concrete Stresses	Compressive stress limit=0.6f'_{ci}	**Same as AASHTO (2017)**
Fatigue Limit State	**Constant Amplitude Fatigue Threshold**	For fatigue considerations, concrete members shall satisfy: γ (Δf) ≤ (ΔF)TH	**Same as AASHTO (2017)**

5. FLEXURAL DESIGN & SERVICEABILITY LIMITS

Summary:

★ *Most of the current AASHTO provisions are applicable for CFRP*

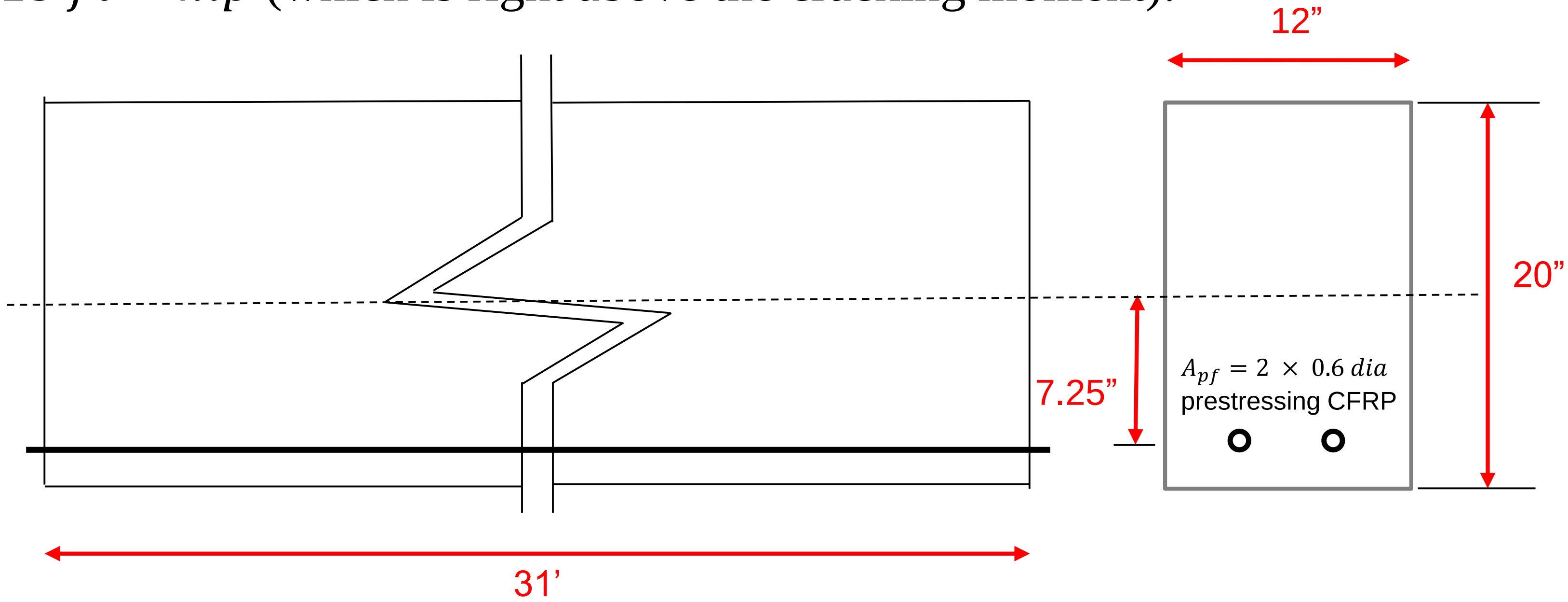
- ✓ *Design approach and methodology*
- ✓ *Creep, shrinkage and elastic shortening losses*
- ✓ *Camber and deflections*
- ✓ *Concrete Stress limits at release and service*

★ *Major revisions included in CFRP Guide Specification*

- ✓ *Harping and draping of Prestressing CFRP*
- ✓ *CFRP prestress relaxation losses*
- ✓ *Jacking stress limits*
- ✓ *Prestress transfer length*
- ✓ *Strength reduction factor*

6. DESIGN EXAMPLE

The following example illustrates the analysis of rectangular beam pretensioned with two prestressing cables of 0.6 inch diameter and a jacking stress of $0.70f_{pu}$. The beam is 31 ft in length and carries a superimposed dead load of 20% of it's self-weight and the live load of 0.35 kip/ft in addition to its own weight. The analysis includes checking all applicable service and strength limit states according to AASHTO-LRFD (2017) and AASHTO Guide Specifications (2018). They are referred in the following example as AASHTO and AASHTO-CFRP respectively. The analysis also includes the computations of deflection corresponding to the moment of 115 $ft - kip$ (which is right above the cracking moment).



6. DESIGN EXAMPLE

Overall beam Length $L_{span} =$ $31\ ft$

Design Span $L_{Design} =$ $30\ ft$

Concrete Properties

Concrete strength at release $f'_{ci} =$ 5.5 ksi

Concrete strength at 28 days $f'_{c} =$ 9 ksi

Unit weight of concrete $\gamma_c =$ 150 pcf

Prestressing CFRP

Diameter of one prestressing CFRP cable $d_b =$ 0.6 in

Area of one prestressing CFRP cable $A_{pf} =$ 0.18 in^2

The design tensile load is the characteristics value of the tensile test data conducted as a part of NCHRP 12-97 project and computed according to ASTM D7290 as recommended by the proposed material guide specification. The design tensile stress is obtained as follows:

Design tensile stress

$$f_{pu} = \frac{64.14}{A_{pf}} = 356.33\ ksi$$

6. DESIGN EXAMPLE

Modulus of elasticity (AASHTO-CFRP Art. 1.4.1.3) $E_f = 22500\ ksi$

Design tensile strain $\varepsilon_{pu} = \dfrac{f_{pu}}{E_f} = 0.016$

Stress limitation for prestressing CFRP (AASHTO-CFRP Art. 1.9.1)

Before transfer (f_{pi} as used in this example) $f_{pbt} = 0.70 f_{pu} = 249.43\ ksi$

At service, after all losses $f_{pe} = 0.65 f_{pu} = 231.62\ ksi$

Beam Section Properties

Width of beam $b = 12\ in$

Height of beam $h = 20\ in$

Cross-section area of beam $A = b * h = 240\ in^2$

6. DESIGN EXAMPLE

Distance from centroid to the extreme bottom fiber of the non-composite precast girder	$y_b =$	$10\ in$
Distance from centroid to the extreme top fiber of the non-composite precast girder	$y_t =$	$h - y_b = 10$ in
Moment of inertia of deck about it centroid	$I_g =$	$8000\ in^4$
Section modulus referenced to the extreme bottom fiber of the non-composite precast girder	$S_b =$	$800\ in^3$
Section modulus referenced to the extreme top fiber of the non-composite precast girder	$S_t =$	$800\ in^3$
Weight of the beam	$w = b * h(\gamma_c) = 0.25\ kip/ft$	

Material Properties for Girder and Deck Concrete:

Modulus of elasticity of concrete (AASHTO Art. 5.4.2.4)	$E =$	$12\gamma_c{}^{2.0} f'_c{}^{0.33}$
At release	$E_{ci} =$	$4631\ ksi$
At 28 days (Girder)	$E_c =$	$5451\ ksi$
Modulus of rupture of concrete (AASHTO Art 5.4.2.6)	$f_{mr} =$	$0.24\sqrt{f'_c}$
At release	$f_{ri} =$	$0.56\ ksi$
At 28 days (Girder)	$f_r =$	$0.72\ ksi$

6. DESIGN EXAMPLE

Number of Strands and Strand Arrangement:

Total number of prestressing CFRP	$n_p = 2$
Concrete cover	$c_c = 2.75\ in$
Depth of prestressing CFRP from the top fiber of the beam	$d_p = 17.25\ in$
Eccentricity of prestressing CFRP	$e_c = 7.25\ in$

Load and Moment on Beam:

Unit weight due to superimposed load	$w_{SD} = 0.2w = 0.05\ kip/ft$
Unit weight due to live load	$w_L = 0.35\ kip/ft$

M_b = unfactored bending moment due to beam self-weight, k-ft

$$M_b = \frac{wL_{design}{}^2}{8} = 28.13\ ft\text{-}kip$$

M_{SD} = unfactored bending moment due to superimposed dead, k-ft

$$M_{SD} = \frac{w_{SD}L_{design}{}^2}{8} = 5.63\ ft\text{-}kip$$

M_L = unfactored bending moment due to live load, k-ft

$$M_L = \frac{w_L {L_{design}}^2}{8} = 39.38\ ft{-}kip$$

Moment at service III [AASHTO Table 3.4.1-1]

$$M_s = M_b + M_{SD} + 0.8M_L = 65.25\ ft\text{-}kip$$

Moment at Strength I [AASHTO Table 3.4.1-1]

$$M_u = 1.25M_b + 1.5M_{SD} + 1.75M_L = 112.5\ ft\text{-}kip$$

Prestressing Loss

Prestressing CFRP stress before transfer $f_{pi} = 0.70 f_{pu} = 249.43\ ksi$

Elastic Shortening

$$\Delta f_{pES} = \frac{E_f}{E_{ct}} f_{cgp}$$

[AASHTO-CFRP Eq. (1.9.2.2.3a-1)]

Where E_f = modulus of elasticity of prestressing CFRP (ksi)
E_{ct} = modulus of elasticity of the concrete at transfer or time of load application (ksi) = E_{ci}
f_{cgp} = the concrete stress at the center of gravity of CFRP due to the prestressing force immediate after transfer and the self-weight of the member at sections of maximum moment (ksi)

6. DESIGN EXAMPLE

AASHTO Article C5.9.5.2.3a states that to calculate the prestress after transfer, an initial estimate of prestress loss is assumed and iterated until acceptable accuracy is achieved. In this example, an initial estimate of 10% is assumed.

$eloss = 10\%$

Force per strand at transfer

$$f_{cgp} = \frac{P_i}{A} + \frac{P_i {e_c}^2}{I_g} - \frac{M_G e_c}{I_g}$$

Where, P_i = total prestressing force at release = $n_p * p$

e_c = eccentricity of strands measured from the center of gravity of the precast beam at midspan

M_G = moment due to beam self-weight at midspan (should be calculated using the overall beam length)

$$M_G = \frac{w {L_{span}}^2}{8} = 30.03\ ft\text{-}kip$$

Solve the following equation for eloss

$$eloss = \frac{E_f}{f_{pi} E_{ci}} \left(\frac{n_p A_{pf} f_{pi} (1 - eloss)}{A} + \frac{n_p A_{pf} f_{pi} (1 - eloss) {e_c}^2}{I_g} - \frac{M_G e_c}{I_g} \right)$$

Therefore, the loss due to elastic shortening $eloss = 0.01$

The stress at transfer $f_{pt} = f_{pi}(1 - eloss) = 246.39\ ksi$

The force per strand at transfer $p_t = A_{pf} f_{pt} = 44.35\ kips$

6. DESIGN EXAMPLE

The concrete stress due to prestress

$$f_{cgp} = \frac{n_p p_t}{A} + \frac{n_p p_t {e_c}^2}{I_g} - \frac{M_G e_c}{I_g} = 646.53\ psi$$

The prestress loss due to elastic shortening $\Delta f_{pES} = \frac{E_f}{E_{ct}} f_{cgp} = 3.14\ ksi$

Total prestressing force at release $P_t = n_p * p_t = 88.7\ kips$

Final prestressing loss including Elastic Shortening

Assume a total prestress loss of 18% [This assumption is based on the average of all cases in the design space considered in the reliability study]

$ploss = 18\%$

$f_{pe} = f_{pi}(1 - ploss) = 204.54\ \ ksi$

Force per strand at service $p_e = A_{pf} f_{pe} = 36.82\ \ kips$

6. DESIGN EXAMPLE

Check prestressing stress limit at service limit state: [AASHTO-CFRP Table 1.9.1-1]

$f_{pe} \leq 0.6 f_{pu}$ *Stress limit satisfied*

Check Stress at Transfer and Service:

Stress at transfer: $P_t = n_p P_t = 88.7\ kips$

Stress Limits for Concrete

Compression Limit: [AASHTO Art. 5.9.2.3.1a]

$0.6 f_{ci} = 3.3\ ksi$

Where f_{ci} is concrete strength at release=5.5 ksi

Tension Limit: [AASHTO Art. 5.9.2.3.1b]

Without bonded reinforcement $-0.0948\sqrt{f'_c}$ =- 0.22 ksi= -0.2 ksi

Therefore, tension limit, $= -0.2\ ksi$

With bonded reinforcement (reinforcing bars or prestressing steel) sufficient to resist the tensile force in the concrete computed assuming an uncracked section where reinforcement is proportioned using a stress of 0.5 fy , not to exceed 30 ksi

$-0.24\sqrt{f'_c}$ =- 0.56 ksi

6. DESIGN EXAMPLE

Stresses at Transfer Length Section

Stresses at this location need only be checked at release since this stage almost always governs. Also, losses with time will reduce the concrete stresses making them less critical.

Transfer length $l_t = \frac{f_{pi} d_b}{\alpha_t f_{ci}^{0.67}}$ **[AASHTO-CFRP Eq. 1.9.3.2.1-1]**

Where, d_b=prestressing CFRP diameter (in.)

$\boldsymbol{\alpha}_t$= coefficient related to transfer length taken as 1.3 for cable

Also can be estimated as l_t=50d_b=30 in.

Moment due to self-weight of the beam at transfer length

$$M_{bt} = 0.5\, w l_t (L_{Design} - l_t) = 8.59 \text{ ft-kip}$$

Stress in the top and bottom of beam:

$$f_t = \frac{P_t}{A} - \frac{P_t e_c}{S_t} + \frac{M_{bt}}{S_t} = -0.31 \text{ ksi} \geq -0.56 \text{ ksi } \textit{[OK]}$$

$$f_b = \frac{P_t}{A} + \frac{P_t e_c}{S_b} - \frac{M_{bt}}{S_b} = 1.04 \leq 3.3 \text{ ksi } \textit{[OK]}$$

6. DESIGN EXAMPLE

Stresses at midspan

Stress in the top and bottom of beam:

$$f_t = \frac{P_t}{A} - \frac{P_t e_c}{S_t} + \frac{M_b}{S_t} = -0.01\ ksi \geq 0.56 \text{ ksi } [OK]$$
$$f_b = \frac{P_t}{A} + \frac{P_t e_c}{S_b} - \frac{M_b}{S_b} = 0.75 \leq 3.3 \text{ ksi } [OK]$$

Stresses at Service Loads

Total prestressing force after all losses $P_e = n_p P_e =$ $73.63\ kips$

Concrete Stress Limits:[AASHTO Art. 5.9.2.3.2a]

Due to the sum of effective prestress and permanent loads (i.e. beam self-weight, weight of future wearing surface, and weight of barriers) for the Load Combination Service 1:

for precast beam $0.45 f_c =$ $4.05\ ksi$

Due to the sum of effective prestress, permanent loads, and transient loads as well as during shipping and handling for the Load Combination Service 1:

for precast beam $0.60 f_c =$ $5.4\ ksi$

6. DESIGN EXAMPLE

Tension Limit: *[AASHTO Art. 5.9.2.3.2b]*

For components with bonded prestressing tendons or reinforcement that are subjected to not worse than moderate corrosion conditions for Load Combination Service III

for precast beam $-0.19\sqrt{f_c} = \quad -0.57\ ksi$

Stresses at Mid-span

Concrete stress at top fiber of the beam

To check top stresses, two cases are checked:

Under permanent loads, Service I:

$$f_{tg} = \frac{P_e}{A} - \frac{P_e e_c}{S_t} + \frac{M_b + M_{SD}}{S_t} = 0.15\ ksi \leq 4.05\ \text{ksi} \quad [OK]$$

Under permanent and transient loads, Service I:

$$f_{tg} = f_{tg} + \frac{M_L}{S_t} = 0.76\ ksi < 5.4\ ksi \qquad [OK]$$

Concrete stress at bottom fiber of beam under permanent and transient loads, Service III:

$$f_b = \frac{P_e}{A} + \frac{P_e e_c}{S_b} - \frac{M_b + M_{SD} + 0.8(M_L)}{S_b} = -4.65 \times 10^{-3}\ ksi > -0.57\ ksi \quad [OK]$$

6. DESIGN EXAMPLE

If the tensile stress is between these two limits, the tensile force at the location being considered must be computed following the procedure in AASHTO Art. C5.9.2.3.1b. The required area of reinforcement is computed by dividing tensile force by the permitted stress in the reinforcement $(0.5 f_b \leq\ 30\ ksi)$

Strength Limit State

Effective prestressing strain

$$\varepsilon_{pe} = \frac{f_{pe}}{E_f} = 0.00909$$

If $\varepsilon_{cc} \leq 0.003$, the stress block factors are given by

$$\varepsilon_{co} = \left[\left(\frac{f'_c}{11\ ksi}\right) + 1.6\right] 10^{-3} = 0.0024$$

$$\beta_1(\varepsilon_{cc}, \varepsilon_{co}) = max\left[0.65, \frac{4 - \left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right)}{6 - 2\left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right)}\left(\left(\frac{f'_c}{50\ ksi}\right) + 1.1\right)\right]$$

[AASHTO-CFRP Eq. C1.7.2.1-3]

$$\alpha_1(\varepsilon_{cc}, \varepsilon_{co}) = \frac{\left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right) - \frac{1}{3}\left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right)^2}{\beta_1(\varepsilon_{cc}, \varepsilon_{co})}\left(\left(\frac{f'_c}{60\ ksi}\right) + 1\right)$$

[AASHTO-CFRP Eq. C1.7.2.1-4]

6. DESIGN EXAMPLE

By using equilibrium and compatibility, the depth of the neutral axis (c) and the strain at top fiber of the beam can be found using following

Constraints:

$\varepsilon_{cc} \leq 0.003$

$\varepsilon_{pe} + \dfrac{d_p - c}{c}\varepsilon_{cc} = \varepsilon_{pu}$

Solve:

$$\alpha_1(\varepsilon_{cc}, \varepsilon_{co}) * f'_c * \beta_1(\varepsilon_{cc}, \varepsilon_{co}) * b * c = n_p A_{pf} E_f\left(\varepsilon_{pe} + \frac{d_p - c}{c}\varepsilon_{cc}\right)$$

Solving:

$c = 2.98\ in$

$\varepsilon_{cc} = 0.0014$

$$\beta_1 = max\left[0.65, \frac{4 - \left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right)}{6 - 2\left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right)}\left(\left(\frac{f'_c}{50\ ksi}\right) + 1.1\right)\right] = 0.65$$

$$\alpha_1 = \frac{\left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right) - \frac{1}{3}\left(\frac{\varepsilon_{cc}}{\varepsilon_{co}}\right)^2}{\beta_1}\left(\left(\frac{f'_c}{60\ ksi}\right) + 1\right) = 0.61$$

Depth of neutral axis $c = 2.98\ in$

Strain at prestressing CFRP at ultimate $\varepsilon_f = \frac{d_p - c}{c}\varepsilon_{cc} = 0.0067$

Total tension force $T_f = n_p A_{pf} E_f \left(\varepsilon_{pe} + \varepsilon_f\right) = 128.28\ kip$

Total compression force $C_c = \alpha_1 f'_c \beta_1 bc = 128.28\ kip$

Tension force = Compression force *[OK]*

The capacity of the section is:

$$M_n = T_f\left(d_p - c\right) + C_c\left(c - \frac{\beta_1 c}{2}\right) = 174.05\ ft\text{-}kip$$

Selection of strength resistance factor:

$\emptyset = 0.75$ [for CFRP prestressed beams] [AASHTO-CFRP Art. 1.5.3.2]

Check for capacity

$\emptyset M_n = 130.54\ ft\text{-}kip \geq M_u = 112.5\ ft\text{-}kip$ *[OK]*

Minimum Reinforcement

NCHRP project 12-94 has revised the minimum reinforcement provisions for prestressed beams and the research results has been published under NCHRP report 906. Therefore, the outcome of the NCHRP 12-94 project may also influence the requirements for CFRP prestressed beams.

At any section of a flexural component, the amount of prestressed and non-prestressed tensile reinforcement shall be adequate to develop a factored flexural resistance, M_r, at least equal to the lesser of:

1.33 times the factored moment required by the applicable strength load combinations

6. DESIGN EXAMPLE

$$M_{cr} = \gamma_3 \left[(\gamma_1 * f_r + \gamma_2 * f_{cpe}) S_c - M_{dnc} \left(\frac{S_c}{S_{nc}} - 1 \right) \right]$$ [AASHTO-CFRP 1.7.3.3.1-1]

Where, $\gamma_1 = 1.6$ flexural cracking variability factor
$\gamma_2 = 1.1$ prestress variability factor
$\gamma_3 = 1.0$ prestressed concrete structures

$f_{cpe} = \frac{P_e}{A} + \frac{P_i e_c}{S_c} - \frac{M_b}{S_c} = 0.55\ ksi$
$f_r = 0.20\sqrt{f'_c} = 0.6\ ksi$
$M_{cr} = 104.5\ ft\text{-}kip$

Check for governing moment:

$gov_{moment} = \min(M_{cr}, 1.33 M_u) = 104.5\ ft\text{-}kip$

Check for minimum reinforcement requirement

$\emptyset M_n \geq gov_{moment}$ *[OK]*

Deflection and Camber [Upward deflection is negative]

Deflection due to Prestressing Force at Transfer

$\Delta_{pt} = \frac{-P_t}{E_{ci} I} \frac{e_c {L_{span}}^2}{8} = 0.3\ in$

Deflection due to Beam Self-Weight

$$\Delta_b = \frac{5 * w * {L_{span}}^4}{384 E_{ci} I}$$

6. DESIGN EXAMPLE

Deflection due to Beam Self-Weight at transfer

$$\Delta_{bt}=\frac{5*w*{L_{span}}^4}{384E_{ci}I}=0.14\ in$$

Deflection due to Superimposed Dead Load

$$\Delta_{SD}=\frac{5*w_{SD}*{L_{design}}^4}{384E_cI}=0.02\ in$$

Deflection due to Live Load

$$\Delta_L=\frac{5*w_L*{L_{design}}^4}{384E_cI}=0.15\ in$$

Using ACI 440 multipliers for long-term deflections

Immediate camber at transfer $\delta_i=\Delta_{pt}+\Delta_{bt}=-0.16\ in$

Camber at erection $\delta_e=1.80\Delta_{pt}+1.85\Delta_{bt}=-0.28\ in$

Deflection at final $\delta_f=1.00\Delta_{pt}+2.70\Delta_{bt}+4.10\Delta_{SD}+\Delta_L=0.31\ in$

Deflection due to Live Load when the Section is Cracked (i.e, for a moment of 115 ft-kip)

Stress at bottom fiber due to the effect of prestress only

$$f_{cpe}=\frac{P_e}{A}+\frac{P_e e_c}{S_c}=0.97\ ksi$$

Tensile strength of concrete

$$f_r=0.24\sqrt{f'_c}=0.72\ ksi$$

6. DESIGN EXAMPLE

Cracking moment of the beam can be computed as:

$$M_{cr} = \left(f_r + f_{cpe}\right)S_c = 112.94 \ \textit{ft-kip}$$

Factor to soften effective moment of inertia (because of the use of prestressing CFRP)

$$\beta_d = 0.5\left(\frac{E_f}{E_s} + 1\right) = 0.89 \quad \text{[AASHTO-CFRP Eq. 1.7.3.4.2-2]}$$

Modular ratio

$$n = \frac{E_f}{E_c} = 4.13$$

Cracked moment of inertia

$$I_{cr} = \frac{bc^3}{12} + bc(c - 0.5c)^2 + nA_{pf}\left(d_p - c\right)^2 = 257.07 \ in^4$$

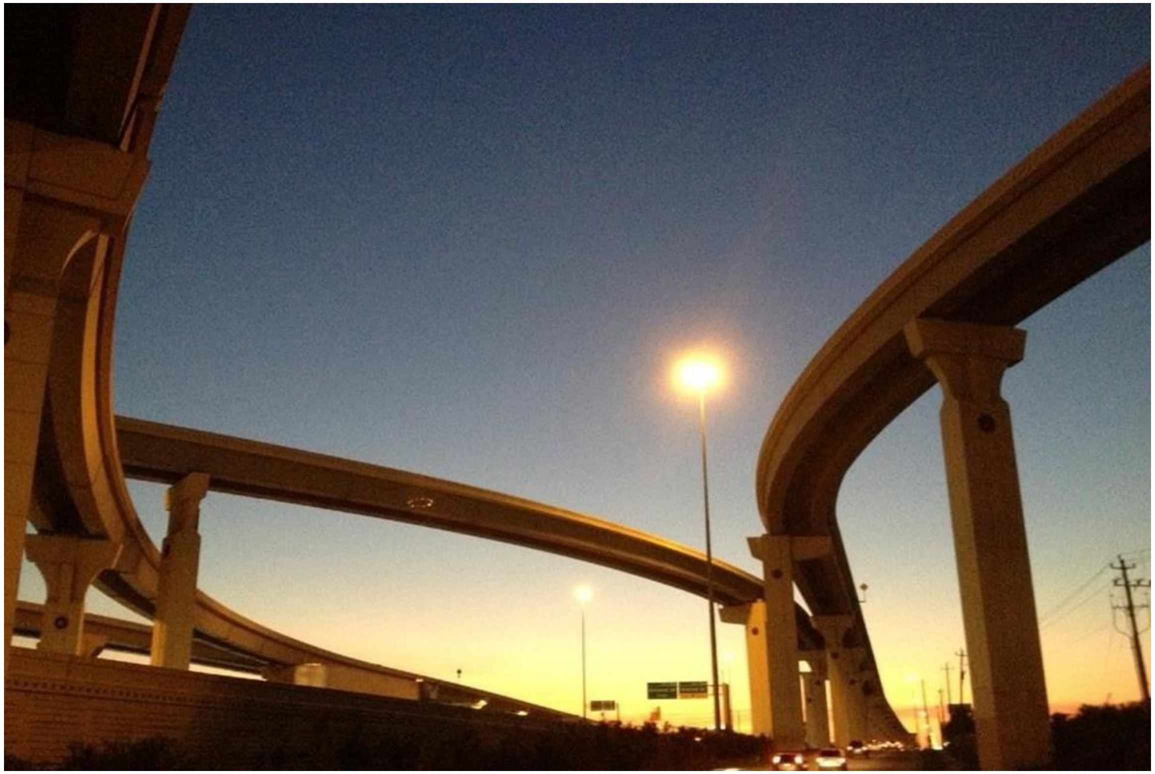
Moment at which deflection is computed $M_a = 115 \ \textit{ft-kip}$

Effective moment of inertia, [AASHTO-CFRP Eq.1.7.3.4.2-1]

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta_d I + \left(1 - \left(\frac{M_{cr}}{M_a}\right)^3\right) I_{cr} = 6757.81 \ in^4$$

Deflection due to live load producing a moment of 115 ft-kip

$$\Delta_L = \frac{5 M_a {L_{design}}^2}{48 E_c I_e} = 0.51 \ in$$



Thank you !

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