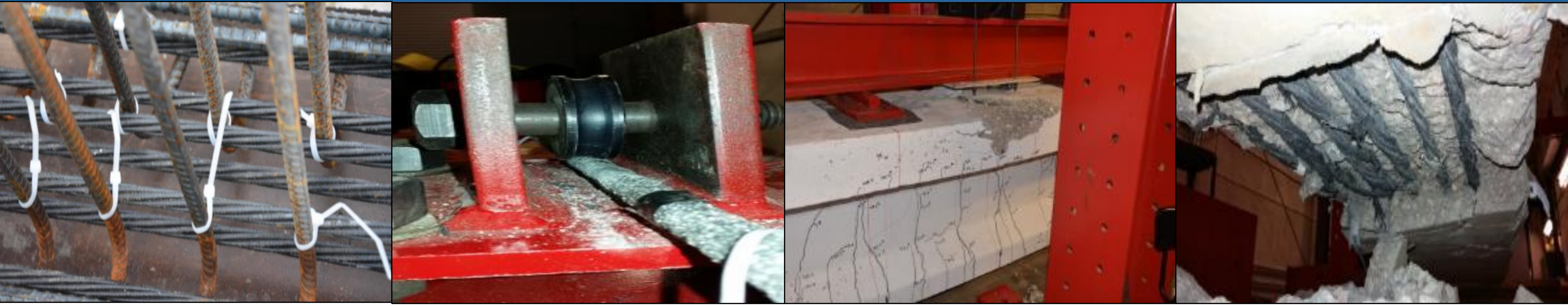
AASHTO CFRP-Prestressed Concrete Design Training Course



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Florida Department of
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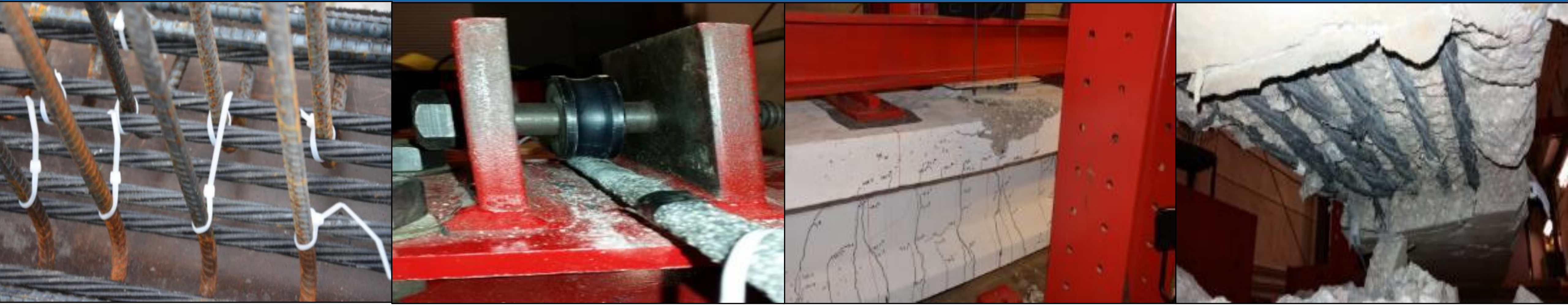
Department of Civil & Environmental Engineering

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



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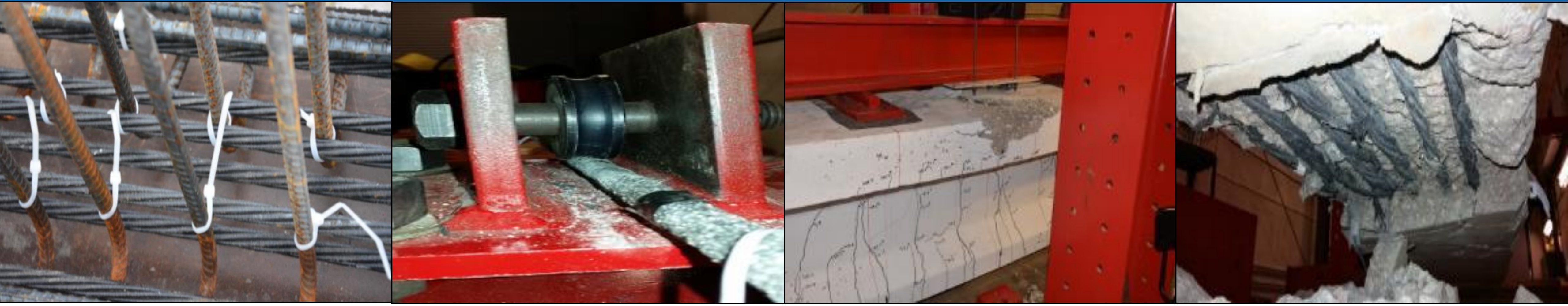
COURSE OUTLINE

1. Introduction & References
2. Prestressing CFRP
3. Flexural Design
4. Shear Design
5. Prestressed Piles
6. Design Examples

2. PRESTRESSING CFRP



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PRESTRESSING CFRP

- **Material Properties of Prestressing CFRP**
  - Types and sizes
  - Mechanical properties
  - Coefficient of thermal expansion
  - Creep rupture

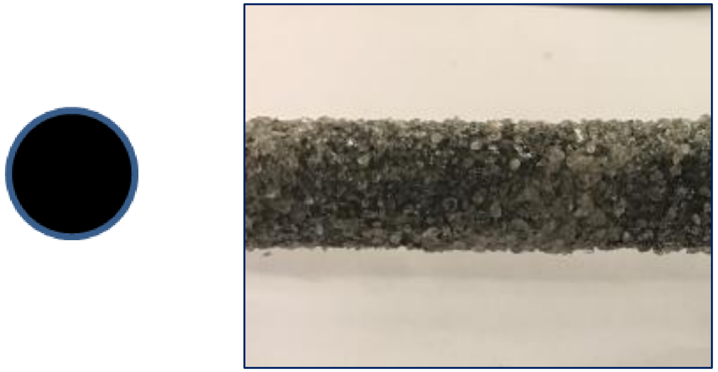
- **Stress Limitations for Prestressing CFRP**

- **Prestress Losses**
  - Total prestress loss
  - Elastic shortening
  - Thermally induced losses
  - Long-term time-dependent losses

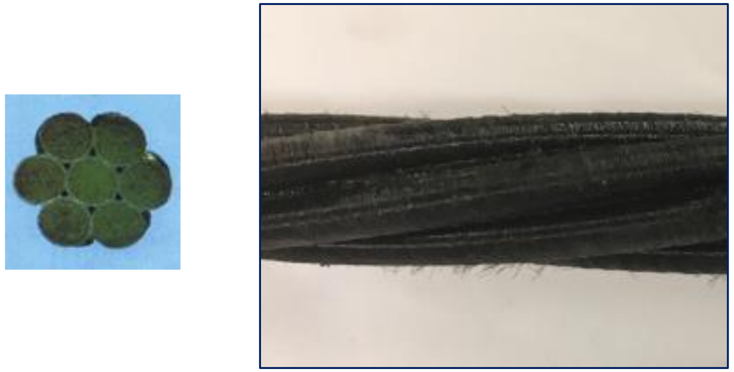
- **Development of pretensioning CFRP tendons**

PRESTRESSING CFRP

Types



CFRP bar



CFRP cable

Sizes

Consistent with
AASHTO M 31M/M 31
ASTM A615/A615M
ASTM D7957/D7957M

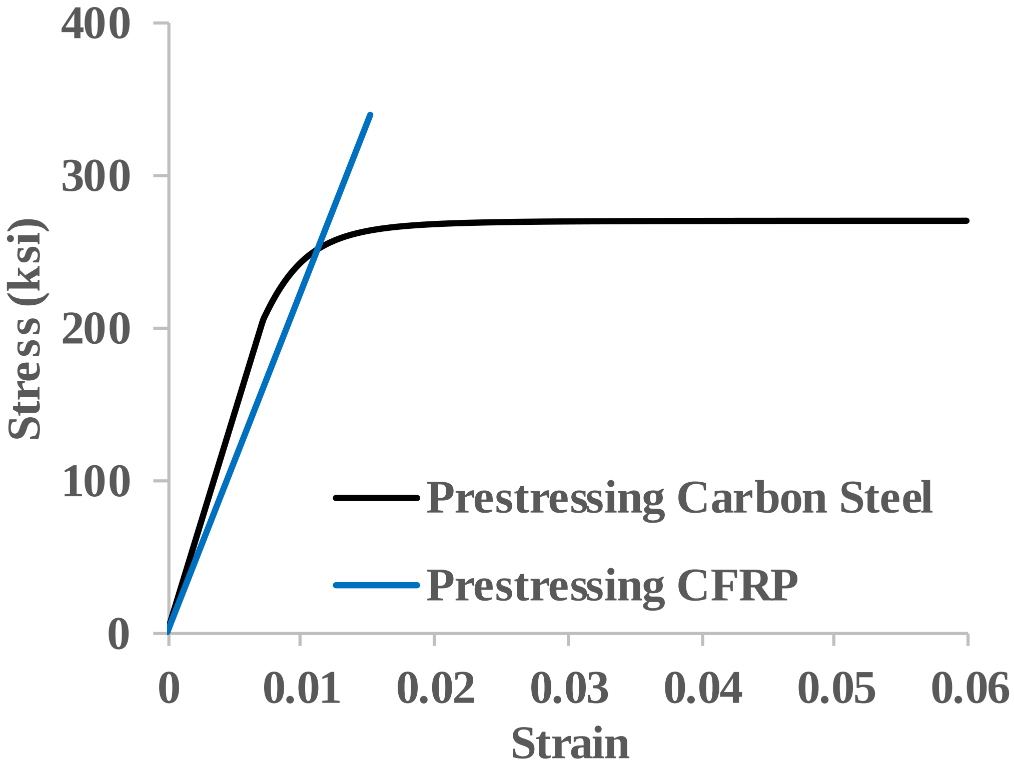
Provided by manufacturer
FDOT Spec 933-1.3

[AASHTO CFRP Material Specifications 2.5.4]

[FDOT Specification Section 933]

PRESTRESSING CFRP

Material Properties: Prestressing CFRP vs. Steel



Material specification	AASHTO M203	AASHTO CFRP
Steel/CFRP type	1080 Carbon Steel	Prestressing CFRP
Grade	250 and 270	340-360
Modulus of elasticity (ksi)	≅ 28,500	18,000-22,500
Total elongation (%)	≥ 3.5	≅ 1.6

PRESTRESSING CFRP

Prestressing CFRP Material Properties

Provisions	Test Methods	AASHTO CFRP Minimums	FDOT Minimums
Tensile Strength	ASTM D7205/ D7205M	N/A	≥ values listed in Table 1-2 in FDOT Spec 933
Tensile Modulus of Elasticity	ASTM D7205/ D7205M	≥ 17,000 ksi	≥ 18,000 ksi for bar ≥ 22,400 ksi for cable
Shear Strength (Transverse Axis)	ASTM D7617/ D7617M	≥ 10 % of tensile strength	N/A
Tensile Strain	N/A	≥ 1.2 %	N/A
Bond Strength	ASTM D7913/D7913M	≥ 700 psi	N/A

[AASHTO CFRP Material Specifications 2.6]   *[FDOT Specification Section 933]*

PRESTRESSING CFRP

Prestressing CFRP Strand [FDOT]

Table 1-2
Typical Sizes and Loads of CFRP Prestressing Strands and Bars

Type	Nominal Diameter (in)	Nominal Cross Sectional Area (in^2)	Nominal Ultimate Load (P_u) (kips)	Nominal Ultimate Tensile Stress (ksi)
Single Strand - 5.0mm Ø	0.20	0.025	9.1	364
7-strand - 7.9mm Ø	0.31	0.048	17.8	370
7-strand - 10.8mm Ø	0.43	0.090	33.1	367
Single Strand - 9.5mm Ø	0.38	0.110	35.0	318
7-strand - 12.5mm Ø	0.49	0.117	43.3	370
Single Strand - 12.7mm Ø	0.50	0.196	59.0	301
7-strand - 15.2mm Ø	0.60	0.179	66.2	369
7-strand - 17.2mm Ø	0.68	0.234	86.6	338

** will be corrected as 370 ksi in January 2021 eBook*

Material properties of prestressing CFRP investigated in NCHRP Report 907

	Cable	Bar
Effective cross-sectional area, in^2	0.179	0.196
Resin type	Epoxy	Vinyl Ester
Fiber volume fraction	0.65	N/A
Longitudinal ultimate load, kip	61	49
Longitudinal tensile strength, ksi	340	250
Longitudinal elastic modulus, ksi	22,480	20,880
Maximum longitudinal strain, %	1.7	1.3

** Note: FDOT limit > NCHRP Report 907 value*

[FDOT Specification Section 933]

[NCHRP Report 907]

PRESTRESSING CFRP

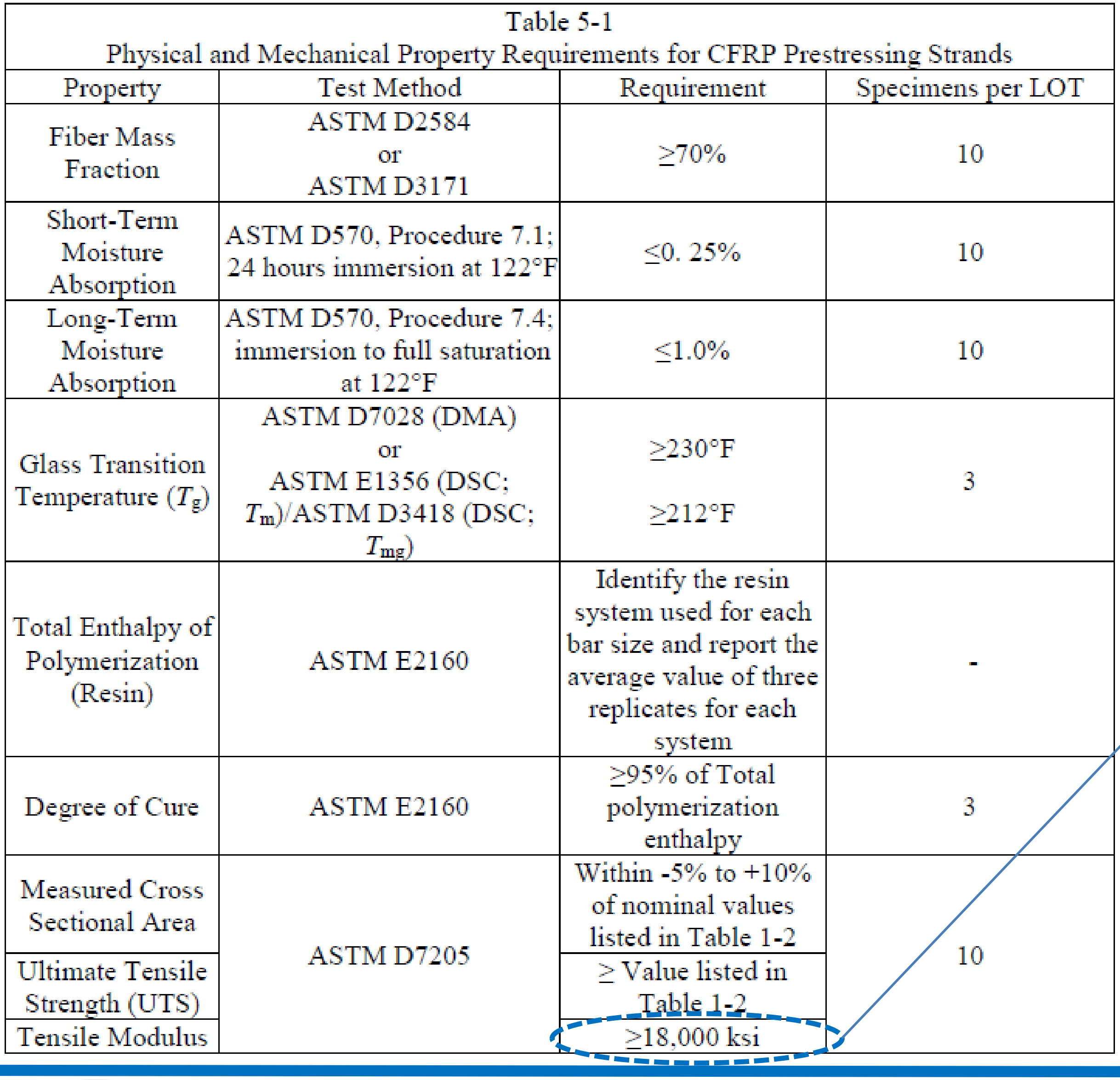


Table 5-1
Physical and Mechanical Property Requirements for CFRP Prestressing Strands

Property	Test Method	Requirement	Specimens per LOT
Fiber Mass Fraction	ASTM D2584 or ASTM D3171	≥70%	10
Short-Term Moisture Absorption	ASTM D570, Procedure 7.1; 24 hours immersion at 122°F	≤0. 25%	10
Long-Term Moisture Absorption	ASTM D570, Procedure 7.4; immersion to full saturation at 122°F	≤1.0%	10
Glass Transition Temperature (T_g)	ASTM D7028 (DMA) or ASTM E1356 (DSC; T_m)/ASTM D3418 (DSC; T_{mg})	≥230°F ≥212°F	3
Total Enthalpy of Polymerization (Resin)	ASTM E2160	Identify the resin system used for each bar size and report the average value of three replicates for each system	-
Degree of Cure	ASTM E2160	≥95% of Total polymerization enthalpy	3
Measured Cross Sectional Area	ASTM D7205	Within -5% to +10% of nominal values listed in Table 1-2	10
Ultimate Tensile Strength (UTS)		≥ Value listed in Table 1-2	
Tensile Modulus		≥18,000 ksi	

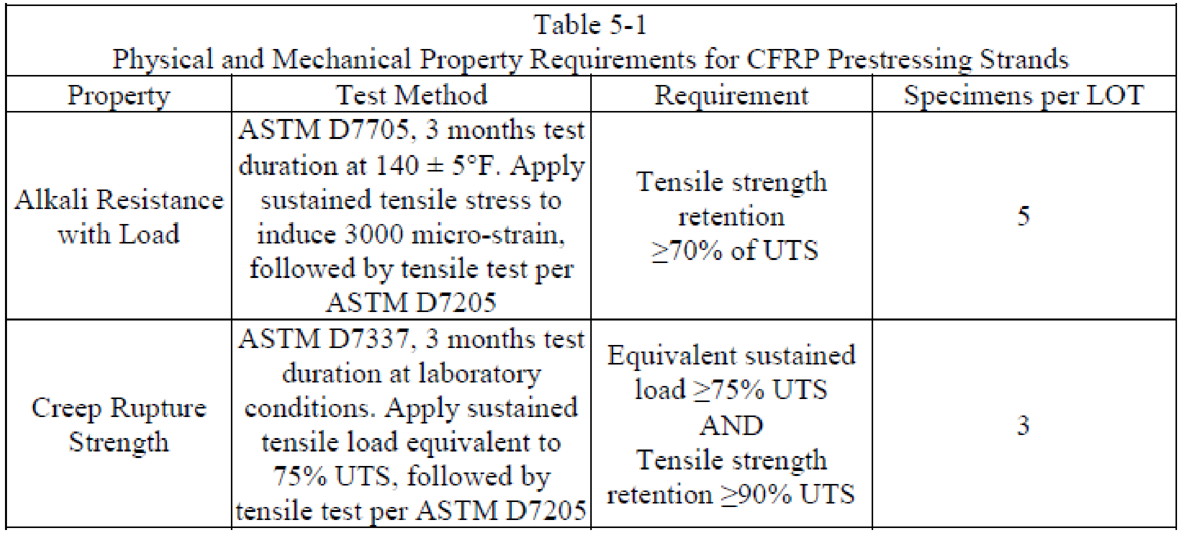


Table 5-1
Physical and Mechanical Property Requirements for CFRP Prestressing Strands

Property	Test Method	Requirement	Specimens per LOT
Alkali Resistance with Load	ASTM D7705, 3 months test duration at 140 ± 5°F. Apply sustained tensile stress to induce 3000 micro-strain, followed by tensile test per ASTM D7205	Tensile strength retention ≥70% of UTS	5
Creep Rupture Strength	ASTM D7337, 3 months test duration at laboratory conditions. Apply sustained tensile load equivalent to 75% UTS, followed by tensile test per ASTM D7205	Equivalent sustained load ≥75% UTS AND Tensile strength retention ≥90% UTS	3

Note: In FDOT Spec (July 2020), the minimum Tensile Modulus is 18,000 ksi, but this is based on single-bar-strand.
For CFRP cables, the minimum Tensile Modulus is 22,400 ksi, this will be updated in FDOT Spec (Jan 2021)

[FDOT Specification Section 933]

PRESTRESSING CFRP

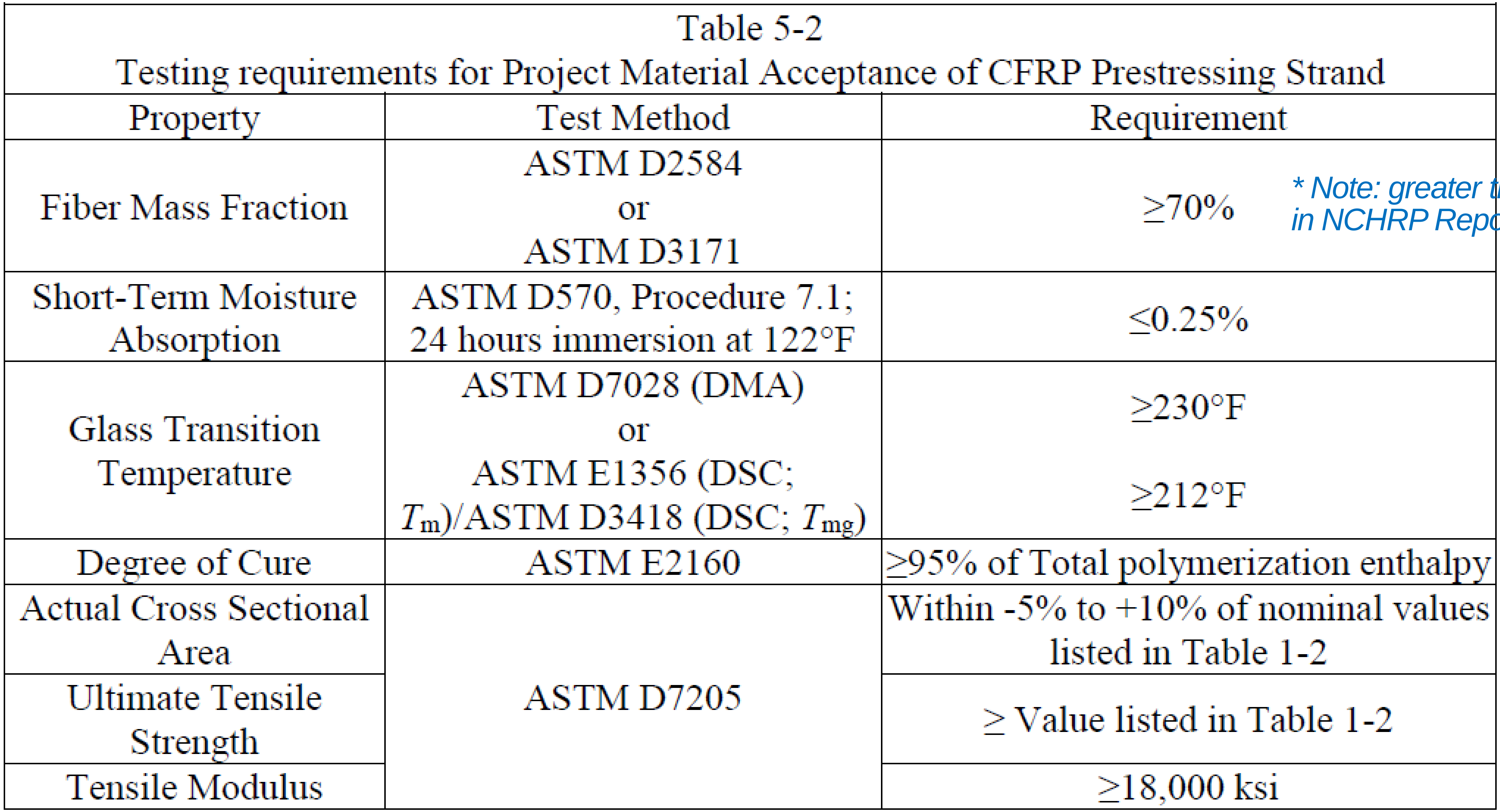


Table 5-2

Testing requirements for Project Material Acceptance of CFRP Prestressing Strand

Property	Test Method	Requirement
Fiber Mass Fraction	ASTM D2584 or ASTM D3171	≥70%
Short-Term Moisture Absorption	ASTM D570, Procedure 7.1; 24 hours immersion at 122°F	≤0.25%
Glass Transition Temperature	ASTM D7028 (DMA) or ASTM E1356 (DSC; T_m)/ASTM D3418 (DSC; T_{mg})	≥230°F ≥212°F
Degree of Cure	ASTM E2160	≥95% of Total polymerization enthalpy
Actual Cross Sectional Area	ASTM D7205	Within -5% to +10% of nominal values listed in Table 1-2
Ultimate Tensile Strength		≥ Value listed in Table 1-2
Tensile Modulus		≥18,000 ksi

** Note: greater than 65% in NCHRP Report 907*

[FDOT Specification Section 933]

PRESTRESSING CFRP

Prestressing CFRP Material Properties

f_{pu} - Design tensile strength of prestressing CFRP

$$f_{pu} = \text{Tensile Strength} \times \text{Environmental Reduction Factor}$$

Table 1.4.1.2—Environmental Reduction Factors (C_E)

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

[AASHTO CFRP Guide Specifications 1.4.2]

PRESTRESSING CFRP

Prestressing CFRP Material Properties

Tensile Strength (*AASHTO CFRP-1*, Material Specification, 2.6.1)

“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 (manufacturer’s guaranteed strength) 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

[*AASHTO CFRP-1 Specifications* 2.6.1]

PRESTRESSING CFRP

Tensile Strength (***AASHTO CFRP-1***, Material Specification)

Two-parameter Weibull distribution

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

Step 1: Determine mean $\bar{x}$ and standard deviation S_{n-1} for the measured material property

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad S_{n-1} = \frac{\sum_{i=1}^{n}(\bar{x} - x_i)^2}{n-1}$$

Step 2: The maximum likelihood estimate $\hat{\beta}$ of the shape parameter β , is calculated by numerically solving the following equation

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

PRESTRESSING CFRP

Tensile Strength (***AASHTO CFRP-1***, Material Specification)

Step 3: The maximum likelihood estimate $\hat{\alpha}$ of the scale parameter α , is calculated by

$$\hat{\alpha} = \left(\frac{\sum_1^n x_i^{\hat{\beta}}}{n}\right)^{\frac{1}{\hat{\beta}}}$$

Step 4: Calculate the coefficient of variation (COV)

$$COV = \frac{\sqrt{\Gamma\left(1+\frac{1}{\hat{\beta}}\right) - \Gamma^2\left(\left(1+\frac{1}{\hat{\beta}}\right)\right)}}{\Gamma\left(1+\frac{1}{\hat{\beta}}\right)}$$

$\Gamma(\quad)$ the gamma function

PRESTRESSING CFRP

Tensile Strength (***AASHTO CFRP-1***, Material Specification)

Step 5: Calculate Nominal Strength by

$$x_{0.005} = \hat{\alpha}(0.0513)^{\frac{1}{\hat{\beta}}}$$

5th percentile value

Step 6: Calculate Characteristics Strength by

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

Ω is data confidence factor depends on sample size

PRESTRESSING CFRP

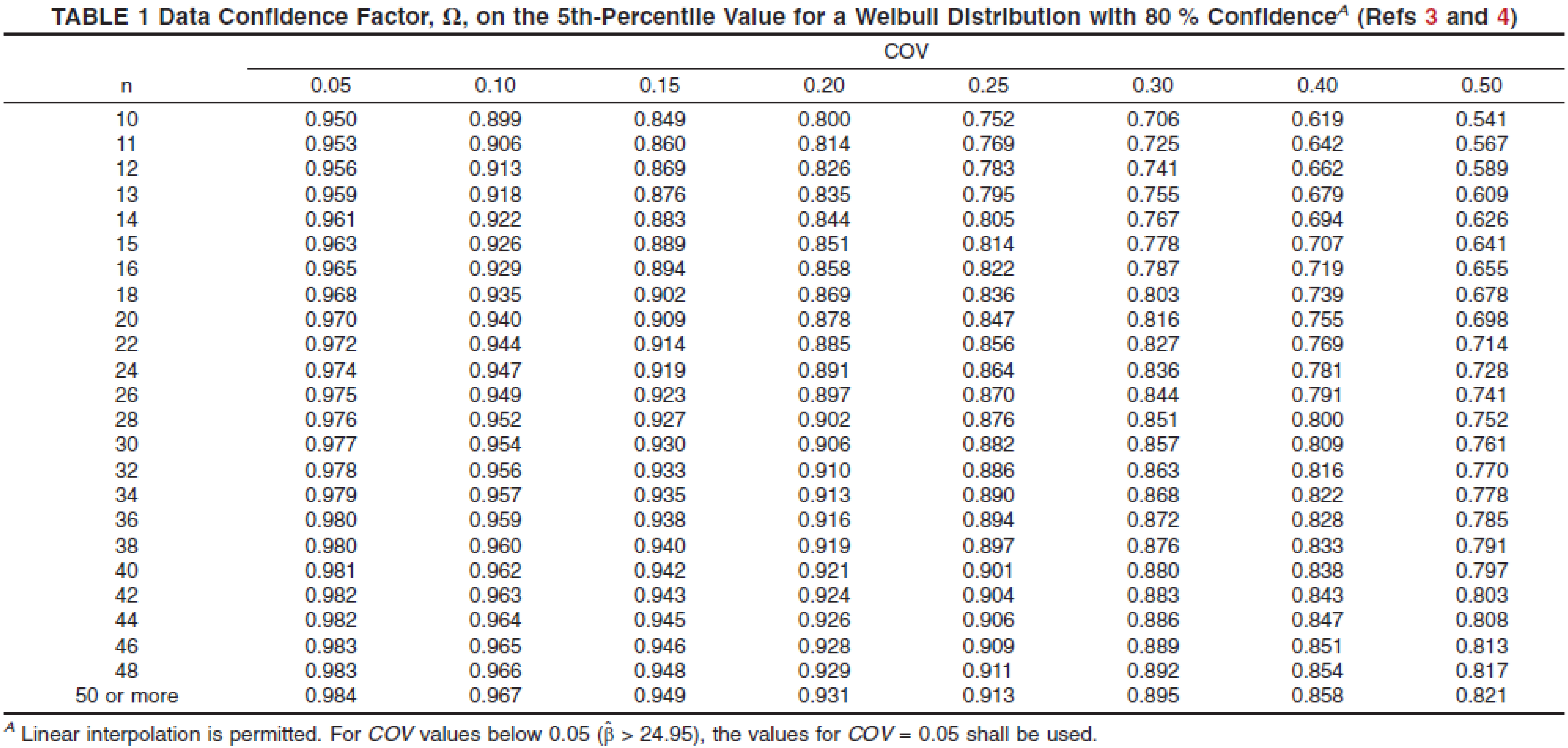


TABLE 1 Data Confidence Factor, Ω, on the 5th-Percentile Value for a Weibull Distribution with 80 % Confidence[A] (Refs 3 and 4)

	COV							
n	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.

PRESTRESSING CFRP

Example: Design Strength

10 tensile test results: 370, 366, 368, 372, 370, 368, 365, 368, 369, 366 ksi

Step 1: $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = 368.2$ $S_{n-1} = \frac{\sum_{i=1}^{n} (\bar{x} - x_i)^2}{n-1} = 4.62$

Step 2: $\hat{\beta} = 119$

Step 3: $\hat{\alpha} = \left(\frac{\sum_{1}^{n} x_i^{\widehat{\beta}}}{n} \right)^{\frac{1}{\widehat{\beta}}} = 369$

Step 4: $COV = 0.005$

PRESTRESSING CFRP

Example: Design Strength

10 tensile test results: 370, 360, 368, 372, 370, 368, 360, 368, 369, 366 ksi

Step 5: $x_{0.005} = \hat{\alpha}(0.0513)^{\frac{1}{\hat{\beta}}} = 360$

Step 6: $\Omega = 0.95$

$x_{char} = \Omega x_{0.005} = 342 \text{ ksi}$

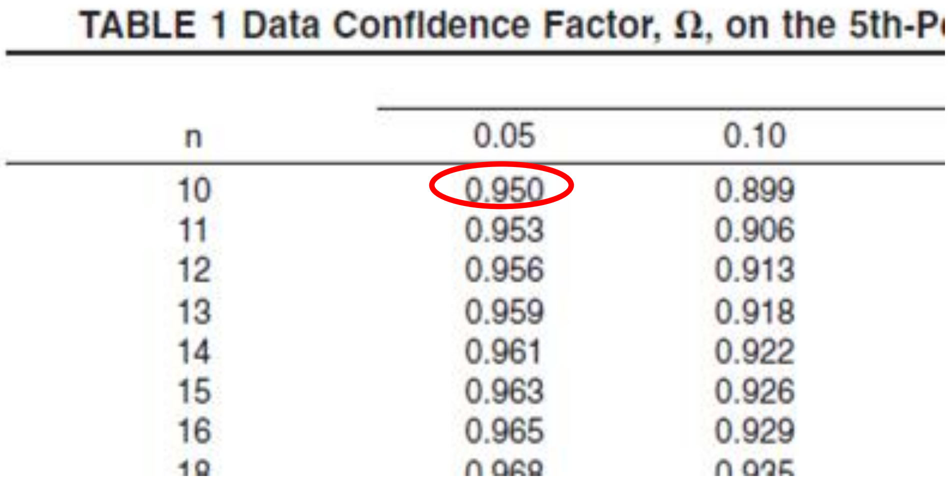


TABLE 1 Data Confidence Factor, Ω, on the 5th-P

n	0.05	0.10
10	0.950	0.899
11	0.953	0.906
12	0.956	0.913
13	0.959	0.918
14	0.961	0.922
15	0.963	0.926
16	0.965	0.929
18	0.968	0.935

PRESTRESSING CFRP

Example: Design Strength

10 tensile test results: 370, 360, 368, 372, 370, 368, 360, 368, 369, 366 ksi

Tensile Strength Comparison

Characteristics Value (Tensile Strength) ***AASHTO CFRP-1 / ASTM D7290 (2017)***	342 ksi
Calculated Guaranteed Strength $(\bar{x} - 3S_{n-1})$ ***ACI 440.2R***	354 ksi

PRESTRESSING CFRP

Coefficient of Thermal Expansion (CTE)

- Shall be measured according to ASTM D696
- CTE depends on:
  - Type of fiber
  - Type of resin
  - Volume fraction of fibers

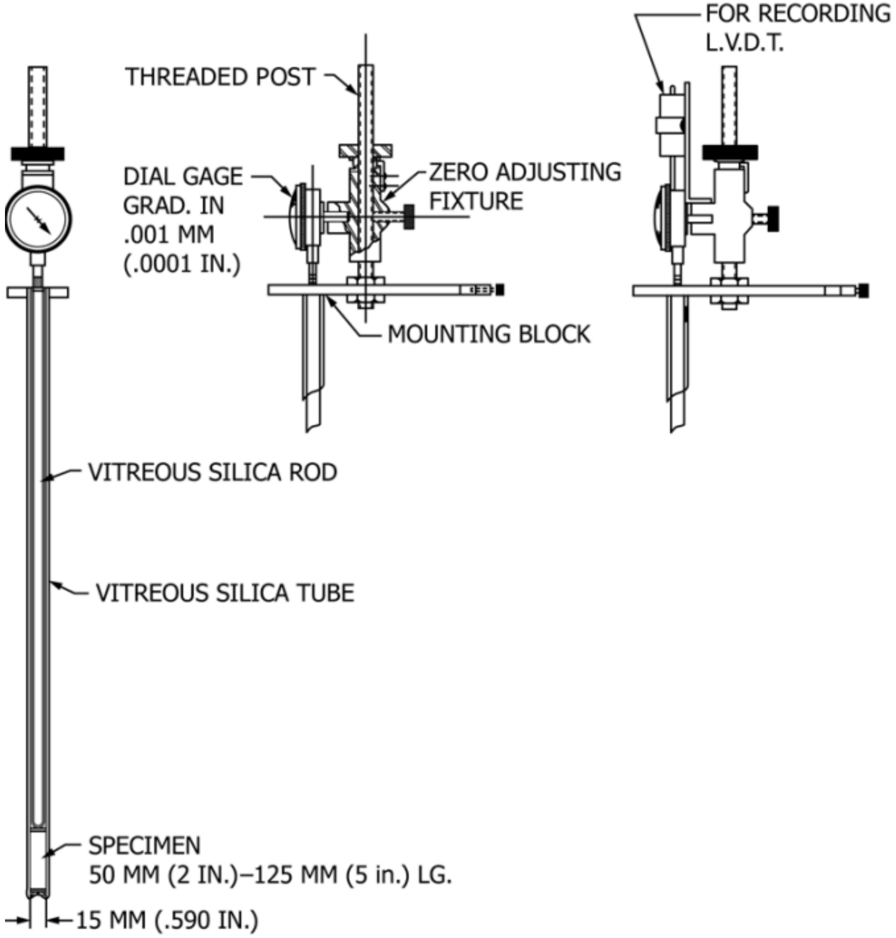
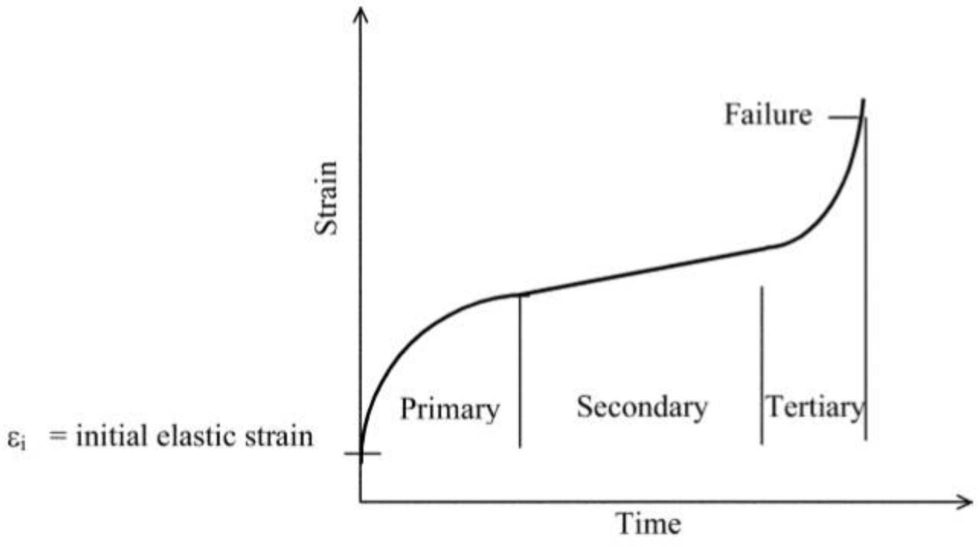


FIG. 1 Quartz-Tube Dilatometer

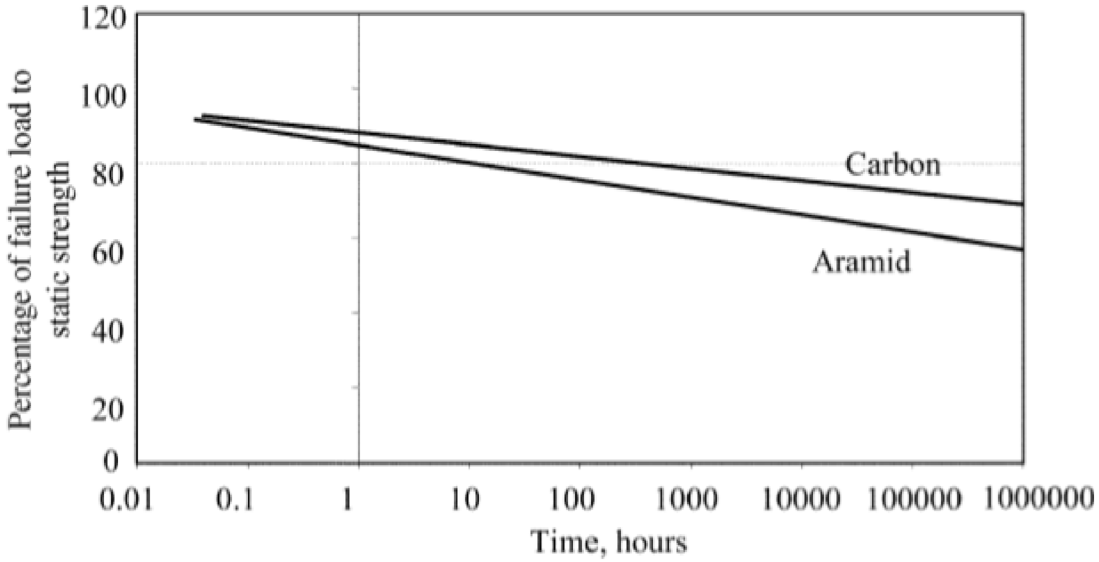
[AASHTO CFRP Specifications 2.5.3] *[ASTM D696-16]*

PRESTRESSING CFRP

Creep Rupture



The three stages of creep deformation



Comparison of creep-rupture curves for AFRP and CFRP rods under environmental exposure

To prevent Creep Rupture failure ⇨ Limit the prestress level in prestressing CFRP

[ACI 440.R-11]

PRESTRESSING CFRP

Stress Limitations for Prestressing CFRP

The tensile strength at the strength and extreme event limit state $\leqslant$ Design tensile strength f_{pu}

The prestressing CFRP stress due to prestress or at the service limit state $\leqslant$ min $\begin{cases} \text{Table 1.9.1-1} \\ \text{Recommended by the manufacturer} \end{cases}$

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}

[AASHTO CFRP Specifications 1.9.1.1]

PRESTRESSING CFRP

Stress Limitations: Prestressing CFRP vs. Steel

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}

Table 5.9.2.2-1—Stress Limits for Prestressing Steel

	Low Relaxation Strand	Plain High Strength Bars	Deformed High Strength Bars
Immediately prior to transfer (f_{pbt})	0.75 f_{pu}	0.70 f_{pu}	-
At service limit state after all losses (f_{pe})	0.80 f_{py}	0.80 f_{py}	0.80 f_{py}

[AASHTO CFRP Specifications 1.9.1.1]

[AASHTO LRFD Specifications 5.9.2.2]

PRESTRESSING CFRP

Prestress Losses

- Total Prestress Losses
- Elastic shortening
- Thermally induced losses
- Long-term losses
    - Approximate Estimation
    - Refined Estimation
        - Prestress losses between transfer and deck placement
        - Prestress losses between deck placement and final time

PRESTRESSING CFRP

Prestress Losses

Total prestress loss in pretensioned members

Prestressing Steel does not have this part

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

Losses/gains due to
- elastic shortening or extension at the time of application of prestress and/or external loads

Losses due to long-term
- shrinkage and creep of concrete
- relaxation of the prestressing CFRP

Loss due to
- temperature change

Instantaneous

$$\underbrace{\hphantom{\text{Losses due to long-term} \quad \text{Loss due to temperature change}}}_{\text{Time dependent}}$$

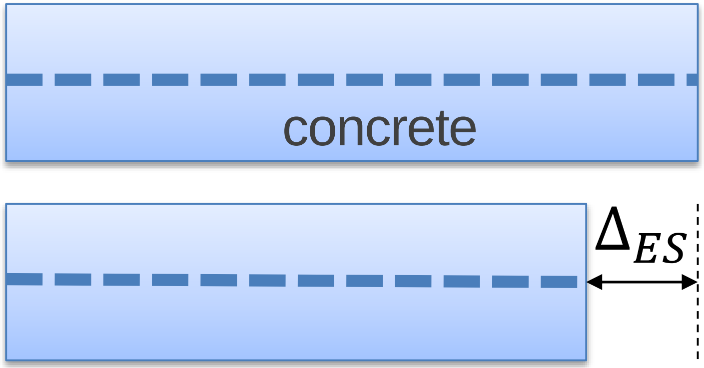
[AASHTO CFRP Specifications 1.9.2.1]

PRESTRESSING CFRP

Prestress Losses

Elastic shortening

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



$$\varepsilon_{ES} = \frac{f_c}{E_c}$$

$$\Delta f_{pES} = E_f \varepsilon_{ES} = \frac{E_f}{E_c} f_c$$

E_f = Modulus of elasticity of prestressing CFRP (ksi)

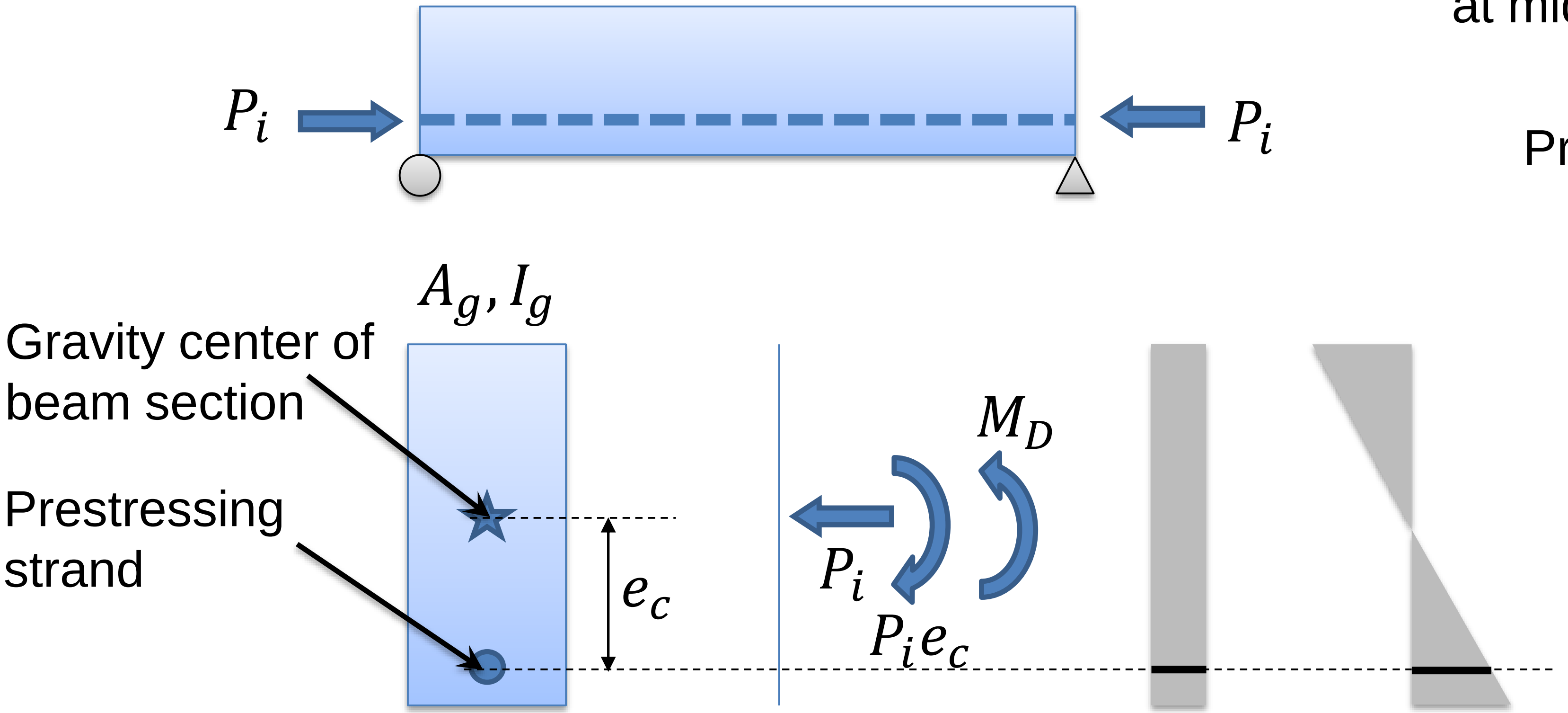
E_{ct} = Modulus of elasticity of concrete at transfer or time of load application (ksi)

f_{cgp} = Concrete stress at the center of gravity of prestressing CFRP due to prestressing force immediately after transfer and the self-weight of the member at the section of maximum moment (ksi)

[AASHTO CFRP Specifications 1.9.2.2.3]

PRESTRESSING CFRP

Beam example



Gravity center of beam section

Prestressing strand

$$\frac{P_i}{A_g} \qquad \frac{P_i {e_c}^2}{I_g} - \frac{M_D e_c}{I_g}$$

Moment due to beam self-weight at mid-span (max moment)

Prestressing force

$$f_{cgp} = \frac{P_i}{A_g} + \frac{P_i {e_c}^2}{I_g} - \frac{M_D e_c}{I_g}$$

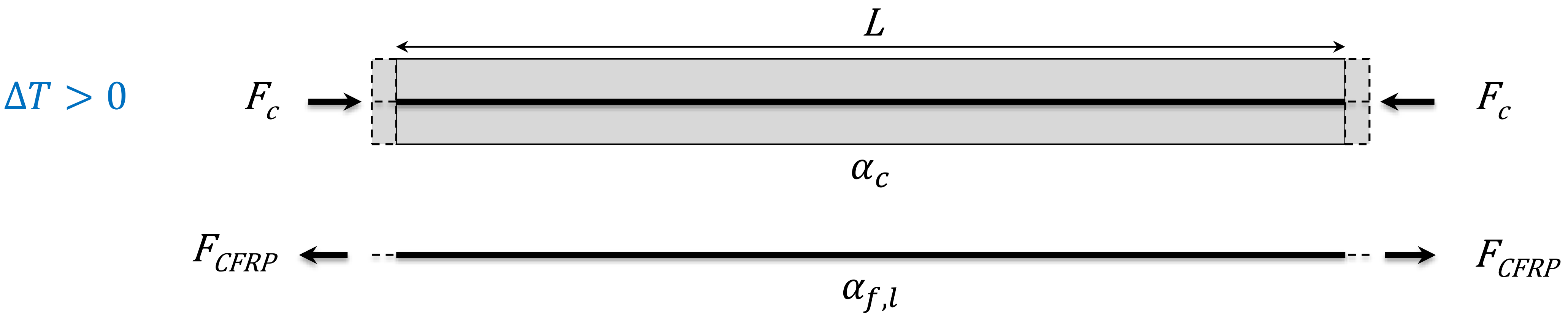
$$\Delta f_{pES} = \frac{E_f}{E_{ct}} f_{cgp}$$

PRESTRESSING CFRP

Prestress Losses: Thermally-Induced Losses

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

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



PRESTRESSING CFRP

Prestress Losses: Thermally-induced losses

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

ΔT = Temperature change (°F)

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

α_c = Coefficient of thermal expansion of concrete (/°F)

E_f = Modulus of elasticity of prestressing CFRP (ksi)

[AASHTO CFRP Specifications 1.9.2.4]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses

- Approximate Estimation

[AASHTO CFRP Specifications 1.9.2.3]

[AASHTO LRFD Specifications 5.9.3.3]

- Refined Estimation

[AASHTO CFRP Specifications 1.9.2.5]

[AASHTO LRFD Specifications 5.9.3.4]

PRESTRESSING CFRP

Prestress Losses

Long-Term Losses (Approximate Estimation)

$$\Delta f_{pLT} = 10.0\frac{f_{pi}\,A_{ps}}{A_g}\gamma_h\gamma_{st} + 12.0\gamma_h\gamma_{st} + \Delta f_{pR}$$

Correction factor for relative humidity

$$\gamma_h = 1.7 - 0.01H$$

Correction factor for concrete strength

$$\gamma_{st} = \frac{5}{1 + f'_{ci}}$$

Estimation of relaxation loss, taken as 2.4 ksi for low relaxation strand and in accordance with manufacturers recommendations for other types of strands

[AASHTO LRFD Specifications 5.9.3.3]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

$$\Delta f_{pLT} = \underset{\substack{\nearrow \\ \text{Shrinkage}}}{\Delta f_{pSR}} + \underset{\substack{\uparrow \\ \text{Creep}}}{\Delta f_{pCR}} + \underset{\substack{\nwarrow \\ \text{Relaxation}}}{\Delta f_{pR}}$$

$$\Delta f_{pLT} = \underbrace{\left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)}_{\substack{\text{Prestress losses between} \\ \text{Transfer and deck placement}}}{}_{id} + \underbrace{\left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)}_{\substack{\text{Prestress losses between} \\ \text{deck placement and the final time}}}{}_{df}$$

[AASHTO CFRP Specifications 1.9.2.5]

[AASHTO LRFD Specifications 5.9.3.4]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between Transfer and deck placement***

- Shrinkage (Girder)

$$\Delta f_{pSR} = \varepsilon_{bid} E_f K_{id}$$

- Creep (Girder)

$$\Delta f_{pCR} = \frac{E_f}{E_{ci}} f_{cpg} \Psi_b(t_d, t_i) K_{id}$$

Same as AASHTO LRFD Specification 5.9.3.4

- Relaxation (CFRP)

$$\Delta f_{pR1} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$$ Cables

$$\Delta f_{pR1} = \left(0.013\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$$ Bars

Modified for CFRP

[AASHTO CFRP Specifications 1.9.2.5.2] *[AASHTO LRFD Specifications 5.9.3.4]*

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between Transfer and deck placement***

- Shrinkage (Girder)

$$\Delta f_{pSR} = \varepsilon_{bid} E_p K_{id}$$

Shrinkage strain of girder

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

Transformed section coefficient (interaction between concrete and bonded tendon)

$$K_{id} = \frac{1}{1 + \frac{E_f}{E_{ci}} \frac{A_{pf}}{A_g} \left(1 + \frac{A_g {e_{pg}}^2}{I_g}\right) [1 + 0.7\Psi_b(t_d, t_i)]}$$

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between Transfer and deck placement***

- Creep (Girder) $$\Delta f_{pCR} = \frac{E_f}{E_{ci}} f_{cpg} \Psi_b(t_d, t_i) K_{id}$$

Creep coefficient $$\Psi_b(t_d, t_i) = 1.9 k_s k_{hc} k_f k_{td} t_i^{-0.118}$$

Transformed section coefficient (interaction between concrete and bonded tendon)

$$K_{id} = \frac{1}{1 + \frac{E_f}{E_{ci}} \frac{A_{pf}}{A_g} \left(1 + \frac{A_g {e_{pg}}^2}{I_g}\right) [1 + 0.7\Psi_b(t_d, t_i)]}$$

t_i: age of concrete at time of initial load application (day)
t_d: age of deck placement (day)

[AASHTO LRFD Specifications 5.4.2.3.2] *[AASHTO LRFD Specifications 5.9.3.4.2a]*

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between Transfer and deck placement***

Factor for the effect of the volume-to-surface ratio of the component

$$k_s = 1.45 - 0.13\left(\frac{V}{S}\right) \geq 1.0$$

Humidity factor for shrinkage

$$k_{hs} = 2.00 - 0.014H$$

Humidity factor for creep

$$k_{hc} = 1.56 - 0.008H$$

Factor for the effect of concrete strength

$$k_f = \frac{5}{1 + f'_{ci}}$$

Time development factor

$$k_{td} = \frac{t}{12\left(\frac{100 - 4f'_{ci}}{f'_{ci} + 20}\right) + t}$$

[AASHTO LRFD Specifications 5.4.2.3.2] *[AASHTO LRFD Specifications 5.4.2.3.3]*

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between Transfer and deck placement***

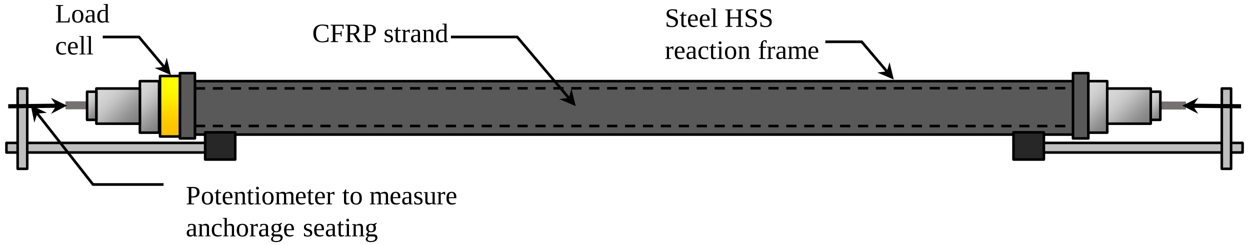
- Relaxation (CFRP)

$$\Delta f_{pR1} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$$ Cables

$t = t_d - t_i$

$$\Delta f_{pR1} = \left(0.013\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$$ Bars

(Based on the experimental program in NCHRP Report 907)



[AASHTO CFRP Specifications 1.9.2.5.2]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between deck placement and the final time***

- Shrinkage (Girder) $\Delta f_{pSD} = \varepsilon_{bdf} E_f K_{df}$
- Shrinkage (Deck) $\Delta f_{pSS} = \frac{E_f}{E_c} \Delta f_{cdf} \left[1 + 0.7\Psi_b\left(t_f, t_d\right)\right]$ *(Prestress Gain)*
- Creep (Girder) $\Delta f_{pCD} = \frac{E_f}{E_{ci}} f_{cpg} \left[\Psi_b\left(t_f, t_i\right) - \Psi_b\left(t_d, t_i\right)\right] K_{df} + \frac{E_f}{E_c} \Delta f_{cd} \Psi_b\left(t_f, t_d\right) K_{df}$
- Relaxation (CFRP) $\Delta f_{pR2} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right) \log(24t) \times f_{pu}$ Cables

$\Delta f_{pR2} = \left(0.013\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right) \log(24t) \times f_{pu}$ Bars

[AASHTO LRFD Specifications 5.9.3.4]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between deck placement and the final time***

- Shrinkage (Girder) $\Delta f_{pSD} = \varepsilon_{bdf} E_f K_{df}$

Shrinkage strain of girder

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

Transformed section coefficient (interaction between concrete and bonded tendon)

$$K_{df} = \frac{1}{1 + \frac{E_f}{E_{ci}} \frac{A_{pf}}{A_c} \left(1 + \frac{A_c {e_{pc}}^2}{I_c}\right) \left[1 + 0.7\Psi_b(t_f, t_d)\right]}$$

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between deck placement and the final time***

- Shrinkage (Deck) $\Delta f_{pss} = \frac{E_p}{E_c} \Delta f_{cdf} \left[1 + 0.7\Psi_b(t_f, t_d)\right]$

Change in concrete stress at centroid of prestressing strands due to shrinkage of deck concrete

$$\Delta f_{cdf} = \frac{\varepsilon_{ddf} A_d E_{c\,deck}}{1 + 0.7\Psi_b(t_f, t_d)} \left(\frac{1}{A_c} - \frac{e_{pc} e_d}{I_c}\right)$$

Shrinkage strain of deck

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

t_d: age of deck placement (day)

t_f: final age (day)

[AASHTO LRFD Specifications 5.9.3.4]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between deck placement and the final time***

- Creep (Girder) $\Delta f_{pCD} = \frac{E_f}{E_{ci}} f_{cpg}\left[\Psi_b(t_f,t_i) - \Psi_b(t_d,t_i)\right]K_{df} + \frac{E_f}{E_c}\Delta f_{cd}\Psi_b(t_f,t_d)K_{df}$

Creep coefficient

$$\Psi_b(t,t_i) = 1.9k_s k_{hc} k_f k_{td} t_i^{-0.118}$$

Transformed section coefficient (interaction between concrete and bonded tendon)

$$K_{df} = \frac{1}{1 + \frac{E_f}{E_{ci}}\frac{A_{pf}}{A_c}\left(1 + \frac{A_c e_{pc}^2}{I_c}\right)\left[1 + 0.7\Psi_b(t_f,t_d)\right]}$$

[AASHTO LRFD Specifications 5.9.3.4]

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses ***between deck placement and the final time***

- Relaxation (CFRP)

$$\Delta f_{pR2} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu}$$ Cables

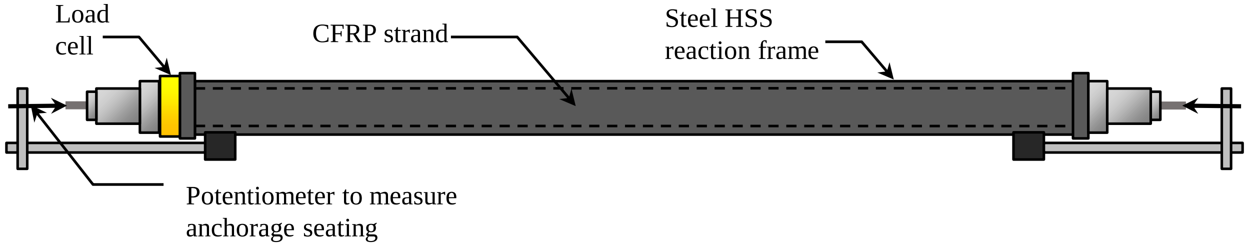
$$t = t_f - t_d$$

$$\Delta f_{pR2} = \left(0.013\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0057\right)\log(24t) \times f_{pu}$$ Bars

for steel

$$\Delta f_{pR2} = \Delta f_{pR1}$$

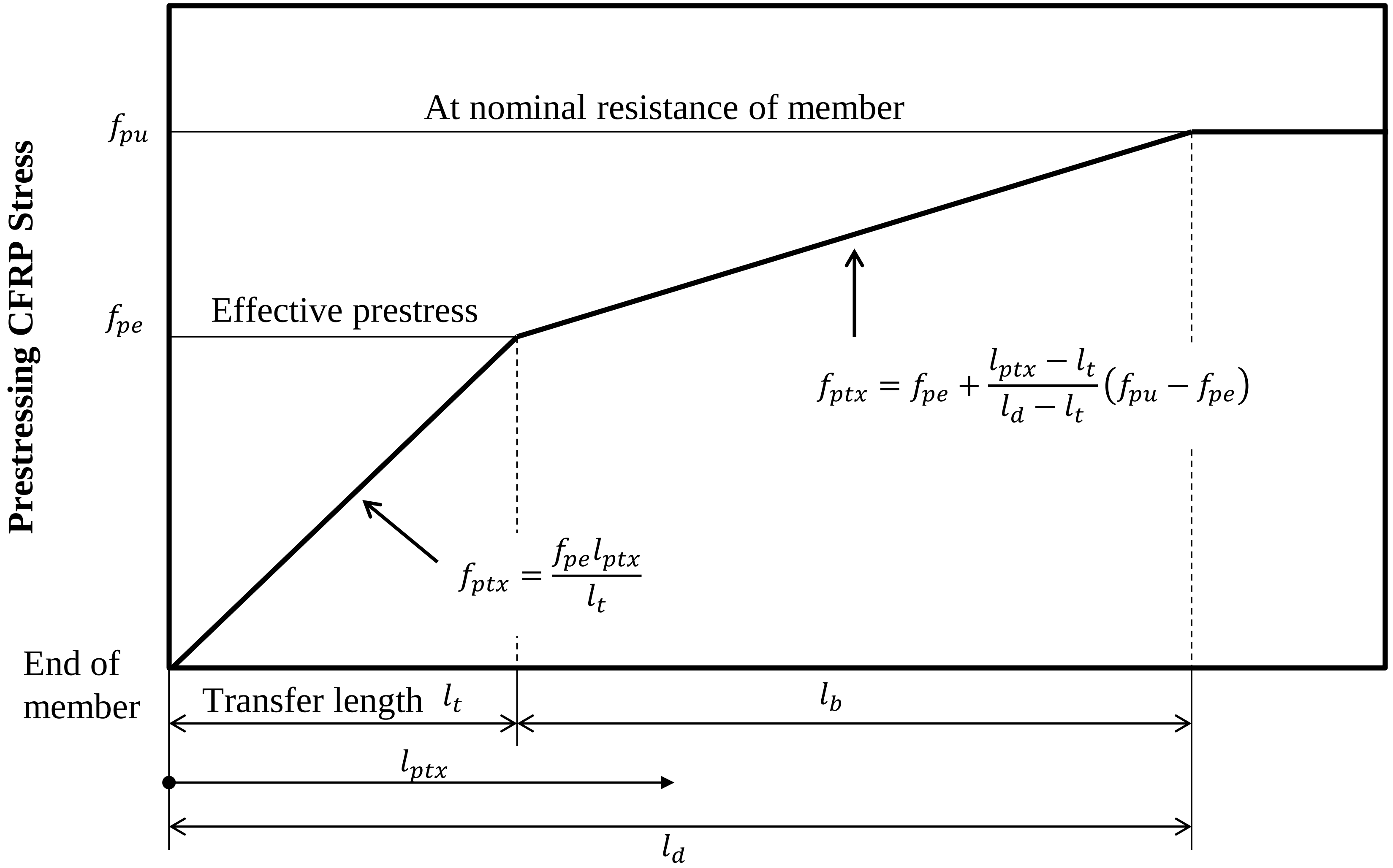
(Based on the experimental program in NCHRP Report 907)



[AASHTO CFRP Specifications 1.9.2.5.2]

PRESTRESSING CFRP

Development of Pretensioning Tendons



[AASHTO CFRP Specifications C1.9.3.2.2]

PRESTRESSING CFRP

Transfer Length

$$l_t = \frac{f_{pbt} d_b}{\alpha_t {f'_{ci}}^{0.67}}$$

for steel

$l_t = 60 d_b$

d_b = Prestressing CFRP diameter (in.)

f'_{ci} = Design concrete compressive strength at time of prestressing (ksi)

f_{pbt} = Stress in prestressing CFRP immediately prior to transfer (ksi)

α_t = Coefficient related to transfer length taken as 1.0 for bar, 1.1 for cable

Alternatively, transfer length can be estimated as $50d_b$ for prestressing CFRP cables and bars

[AASHTO CFRP Specifications 1.9.3.2] *[ACI 440.R-11]*

PRESTRESSING CFRP

Flexural Bond Length for Bonded Prestressing CFRP

$$l_b = \frac{(f_{pu} - f_{pe})d_b}{\alpha_d f_c'^{0.67}}$$

for steel

$$l_d \geq \kappa\left(f_{ps} - \frac{2}{3}f_{pe}\right)d_b$$

$\kappa = 1.0$ (member depth $\leq 24\ in.$)

$\kappa = 1.6$ (member depth $> 24\ in.$)

d_b = Prestressing CFRP diameter (in.)

f_c' = Compressive strength of concrete for use in design (ksi)

f_{pu} = Tensile stress of prestressing CFRP (ksi)

f_{pe} = Effective stress in prestressing CFRP after losses (ksi)

α_d = Coefficient related to flexural bond length taken as 0.53 for bar, 1.48 for cable

[AASHTO CFRP Specifications 1.9.3.2] *[ACI 440.R-11]*

PRESTRESSING CFRP

Development Length for Debonded Prestressing CFRP

Same equation as prestressing steel

$$l_d \geq \kappa\left(f_{pf} - \frac{2}{3} f_{pe}\right) d_b$$

κ = 2.0

d_b = Prestressing CFRP diameter (in.)

f_{pf} = Average stress in prestressing CFRP at the time for which the nominal resistance of the member is required (ksi)

f_{pe} = Effective stress in prestressing CFRP after losses (ksi)

[AASHTO LRFD Specifications 5.9.4.3.3]

Questions?

Florida Department of Transportation

UNIVERSITY of HOUSTON
CULLEN COLLEGE of ENGINEERING
Department of Civil & Environmental Engineering

2. PRESTRESSING CFRP

2.1 Review Questions: Fundamentals

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Florida Department of
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Department of Civil & Environmental Engineering

REVIEW QUESTIONS

2.1.1) The guaranteed tensile strength of prestressing CFRP as provided by the manufacturer is ___________?

a. The characteristic value computed according to ASTM D7290 divided by the area of prestressing CFRP. The manufacturer shall report the individual test results.

b. The mean tensile strength of the sample population

c. The mean tensile strength of the sample population minus two standard deviations

d. None of the above

REVIEW QUESTIONS

Tensile strength of prestressing CFRP

AASHTO CFRP-1 Specifications 2.6.1

“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 (Manufacturer’s guarancted strength) **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.”**

[AASHTO CFRP-1 Specifications 2.6.1]

REVIEW QUESTIONS

2.1.1) The guaranteed tensile strength of prestressing CFRP as provided by the manufacturer is ___________?

a. **The characteristic value computed according to ASTM D7290 divided by the area of prestressing CFRP. The manufacturer shall report the individual test results.**

b. The mean tensile strength of the sample population

c. The mean tensile strength of the sample population minus two standard deviations

d. None of the above

REVIEW QUESTIONS

2.1.2) Prestressing CFRP has _________ than prestressing steel?

a. **Higher** ultimate strength but **lower** elastic modulus

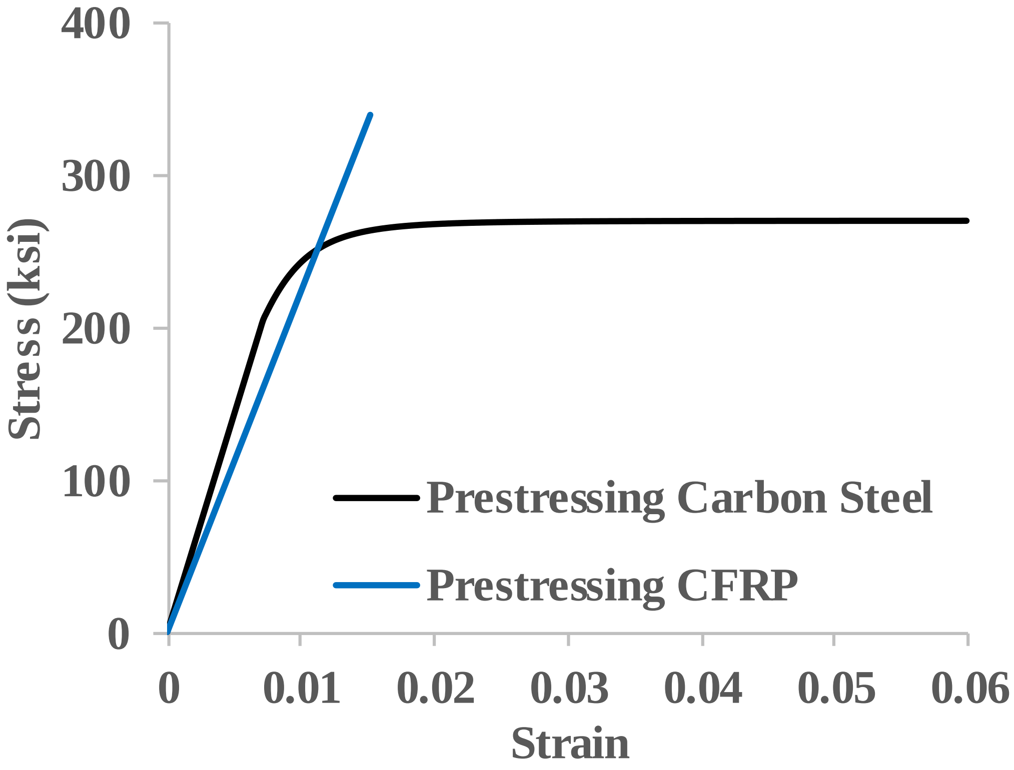
b. **Higher** ultimate strength and **higher** elastic modulus

c. **Lower** ultimate strength but **higher** elastic modulus

a. **Lower** ultimate strength and **lower** elastic modulus

REVIEW QUESTIONS

Material Properties: Prestressing CFRP vs. Steel



Material specification	AASHTO M203	AASHTO CFRP
Steel/CFRP type	1080 Carbon Steel	Prestressing CFRP
Grade	250 and 270	340-360
Modulus of elasticity (ksi)	≅ 28,500	18,000-22,500
Total elongation (%)	≥ 3.5	≅ 1.6

REVIEW QUESTIONS

2.1.2) Prestressing CFRP has __________ than prestressing steel?

a. <u>**Higher ultimate strength but lower elastic modulus**</u>

b. **Higher** ultimate strength and **higher** elastic modulus

c. **Lower** ultimate strength but **higher** elastic modulus

a. **Lower** ultimate strength and **lower** elastic modulus

REVIEW QUESTIONS

2.1.3) Prestress stress limit for CFRP is _________ than low relaxation carbon steel strand at service limit state?

a. Lower

b. Higher

c. Same

REVIEW QUESTIONS

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}

Table 5.9.2.2-1—Stress Limits for Prestressing Steel

	Low Relaxation Strand	Plain High Strength Bars	Deformed High Strength Bars
Immediately prior to transfer (f_{pbt})	0.75 f_{pu}	0.70 f_{pu}	-
At service limit state after all losses (f_{pe})	0.80 f_{py}	0.80 f_{py}	0.80 f_{py}

[AASHTO CFRP Specifications 1.9.1.1]

[AASHTO LRFD Specifications 5.9.2.2]

REVIEW QUESTIONS

2.1.3) Prestress stress limit for CFRP is _________ than low relaxation carbon steel strand at service limit state?

a. **<u>Lower</u>**

b. Higher

c. Same

REVIEW QUESTIONS

2.1.4) Prestress loss due to temperature change should be considered in design for _____?

a. Prestressing CFRP only

b. Prestressing steel only

c. Both prestressing CFRP and steel

d. None of prestressing CFRP and steel

REVIEW QUESTIONS

Total prestress loss in pretensioned members

Prestressing Steel does not have this part

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

Losses/gains due to

- elastic shortening or extension at the time of application of prestress and/or external loads

Losses due to long-term

- shrinkage and creep of concrete
- relaxation of the prestressing CFRP

Loss due to

- temperature change

Instantaneous

Time dependent

[AASHTO CFRP Specifications 1.9.2.1]

REVIEW QUESTIONS

2.1.4) Prestress loss due to temperature change should be considered in design for ______?

a. **<u>Prestressing CFRP only</u>**

b. Prestressing steel only

c. Both prestressing CFRP and steel

d. None of prestressing CFRP and steel

REVIEW QUESTIONS

2.1.5) Which type of prestressing strand requires longer transfer length?

a. Prestressing CFRP requires longer transfer length

b. Prestressing steel requires longer transfer length

c. Same for Prestressing CFRP and steel

REVIEW QUESTIONS

- Transfer Length for Prestressing CFRP

$$l_t = \frac{f_{pbt} d_b}{\alpha_t {f'_{ci}}^{0.67}}$$

Alternatively, transfer length can be estimated as $50d_b$ for prestressing CFRP cables and bars

- Transfer Length for Prestressing steel

$$l_t = 60d_b$$

[AASHTO CFRP Specifications 1.9.3.2] [ACI 440.R-11]

REVIEW QUESTIONS

2.1.5) Which type of prestressing strand requires longer transfer length?

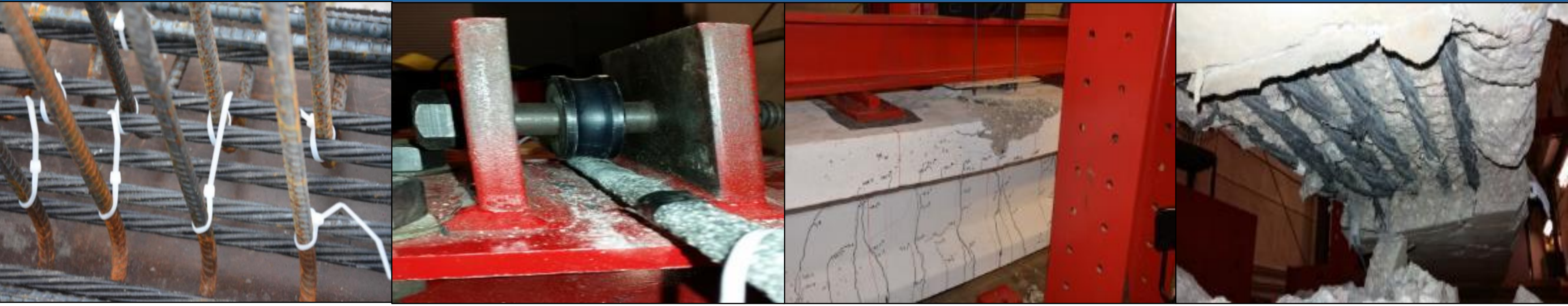
a. Prestressing CFRP requires longer transfer length

b. <u>Prestressing steel requires longer transfer length</u>

c. Same for Prestressing CFRP and steel

2. PRESTRESSING CFRP

2.2 Design Example: Prestress losses



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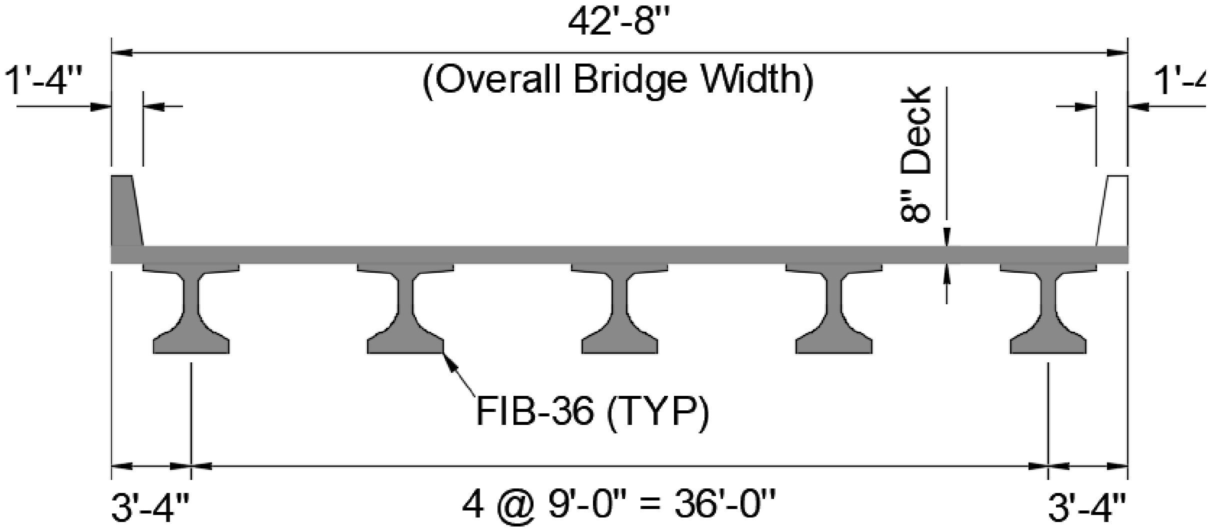
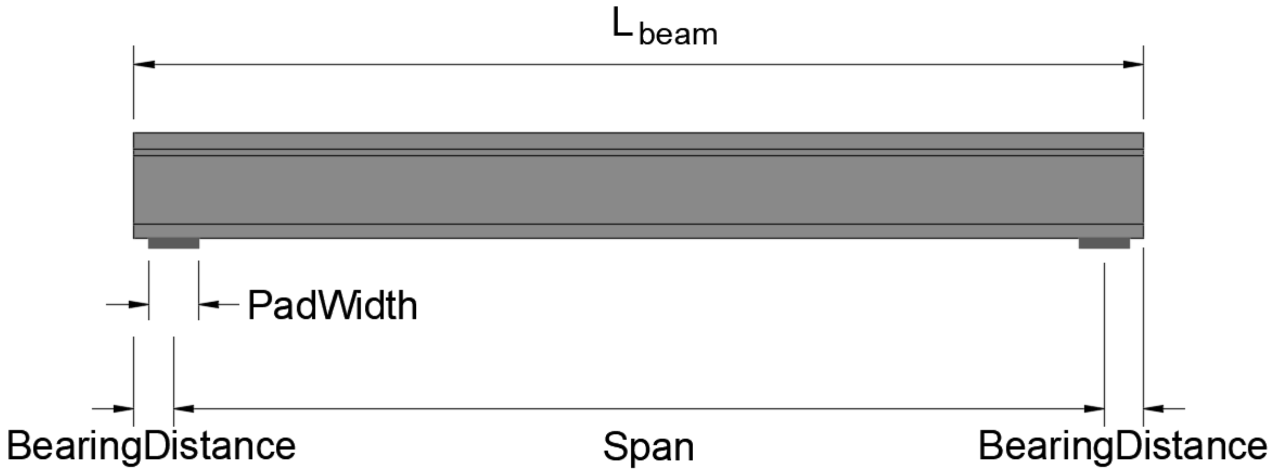
DESIGN EXAMPLE: PRESTRESS LOSS

Geometry





$\text{Beam Span} = 87.667 \text{ ft}$

$\text{BeamSpacing} = 9 \text{ ft}$

$\text{BridgeWidth} = 42.667 \text{ ft}$

$\text{Slab thickness } t_{slab} = 8.5 \text{ in}$

$\text{Beam depth } h_{beam} = 36 \text{ in}$

DESIGN EXAMPLE: PRESTRESS LOSS

Concrete

Beam $f'_{c.beam} = 8.5$ ksi

Beam $f'_{ci.beam} = 6$ ksi

Beam $E_{c.beam} = 5112$ ksi

Beam $E_{ci.beam} = 4557$ ksi

Slab $f'_{c.slab} = 5.5$ ksi

Slab $E_{c.slab} = 4428$ ksi

Unit weight $\gamma_c = \boxed{150 \text{ pcf}}$

Note: 145 pcf is permitted

CFRP strand

Diameter $D_p = 0.6$ in

Effective area $A_{pf} = 0.179 \text{ in}^2$

Elastic modulus $E_f = 22{,}480$ ksi

Design tensile strength $f_{pu} = 341$ ksi

Design tensile strain $\varepsilon_{pu} = 0.015$ ksi

Jacking stress $f_{pj} = 239$ ksi

GFRP rebar

Bar size $= \# 5$

Diameter $d_{GFRP} = 0.625$ in

Elastic modulus $E_{GFRP} = 6500$ ksi

Design tensile strength
$f_{fu.GFRP} = 66.4$ ksi

Bend $\varphi_{bend} = 0.6$

DESIGN EXAMPLE: PRESTRESS LOSS

Prestress losses

Assume 0 in this example

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

Losses/gains due to
- elastic shortening or extension at the time of application of prestress and/or external loads

Losses due to long-term
- shrinkage and creep of concrete
- relaxation of the prestressing CFRP

Loss due to
- temperature change

Instantaneous

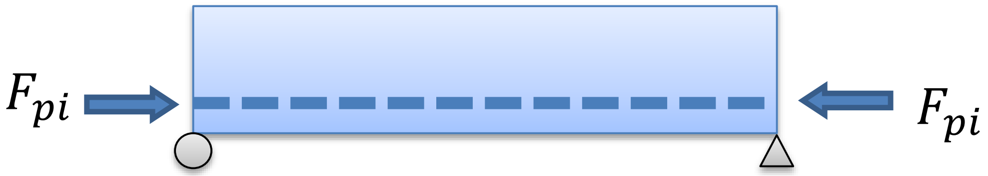
Time dependent

DESIGN EXAMPLE: PRESTRESS LOSS

Prestress loss – Elastic shortening

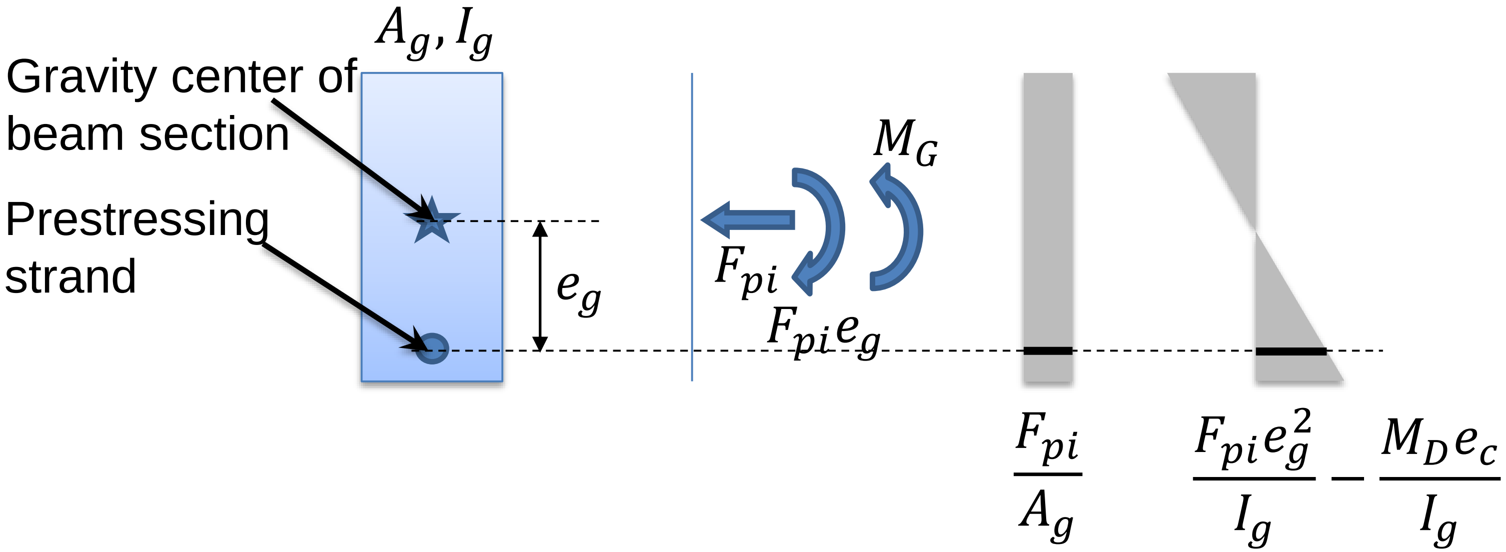
Concrete stress at the center of gravity of prestressing CFRP due to prestressing force immediately after transfer and the self-weight of the member at the section of maximum moment:

$$f_{cgp} = \frac{F_{pi}}{A_{g.tr}} + \frac{F_{pi} e_g^2}{I_{g.tr}} - \frac{M_G e_g}{I_{g.tr}} = 2.894 \text{ ksi}$$



Prestress loss due to Elastic shortening

$$\Delta f_{pES} = \frac{E_f}{E_{ct}} f_{cgp} = 14.277 \text{ ksi}$$



PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

$$\Delta f_{pLT} = \underset{\substack{\nearrow \\ \text{Shrinkage}}}{\Delta f_{pSR}} + \underset{\substack{\uparrow \\ \text{Creep}}}{\Delta f_{pCR}} + \underset{\substack{\nwarrow \\ \text{Relaxation}}}{\Delta f_{pR}}$$

$$\Delta f_{pLT} = \underbrace{\left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)_{id}}_{\substack{\text{Prestress losses between} \\ \text{Transfer and deck placement}}} + \underbrace{\left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)_{df}}_{\substack{\text{Prestress losses between} \\ \text{deck placement and the final time}}}$$

[AASHTO CFRP Specifications 1.9.2.5] *[AASHTO LRFD Specifications 5.9.3.4]*

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses <u>between Transfer and deck placement</u>

- Shrinkage (Beam concrete) $\Delta f_{pSR} = \varepsilon_{bid} E_f K_{id} = 4.924 \text{ ksi}$
- Creep (Beam concrete) $\Delta f_{pCR} = \frac{E_f}{E_{ci}} f_{cpg} \Psi_b(t_d, t_i) K_{id} = 12.508 \text{ ksi}$
- Relaxation (CFRP) $\Delta f_{pR1} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right)\log(24t) \times f_{pu} = 6.953 \text{ ksi}$

In total, $\Delta f_{pLT.id} = \left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)_{id} = 24.385 \text{ ksi}$

[AASHTO CFRP Specifications 1.9.2.5.2] *[AASHTO LRFD Specifications 5.9.3.4]*

PRESTRESSING CFRP

Prestress Losses: Long-Term Losses (Refined Estimation)

Prestress losses between deck placement and the final time

- Shrinkage (Beam concrete) $\Delta f_{pSD} = \varepsilon_{bdf} E_f K_{df} = 6.465 \text{ ksi}$
- Shrinkage (Slab concrete) $\Delta f_{pSS} = \frac{E_f}{E_c} \Delta f_{cdf} \left[1 + 0.7\Psi_b(t_f, t_d)\right] = 1.44 \text{ ksi}$
- Creep (Beam concrete) $\Delta f_{pCD} = \frac{E_f}{E_{ci}} f_{cpg} \left[\Psi_b(t_f, t_i) - \Psi_b(t_d, t_i)\right] K_{df} + \frac{E_f}{E_c} \Delta f_{cd} \Psi_b(t_f, t_d) K_{df} = -0.99 \text{ ksi}$
- Relaxation (CFRP) $\Delta f_{pR2} = \left(0.019\left(\frac{f_{pt}}{f_{pu}}\right) - 0.0066\right) \log(24t) \times f_{pu} = 10.814 \text{ ksi}$

In total, $\Delta f_{pLT.df} = \left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)_{df} = 14.86 \text{ ksi}$

[AASHTO LRFD Specifications 5.9.3.4]

PRESTRESSING CFRP

Total Prestress Losses

Elastic shortening $\Delta f_{pES} = 14.277 \text{ ksi}$

Long-Term Losses $\Delta f_{pLT} = \left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)_{id} + \left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)_{df} = 39.245 \text{ ksi}$

Loss due to temperature change (Assume 0 in this example) $\Delta f_{pTH} = 0$

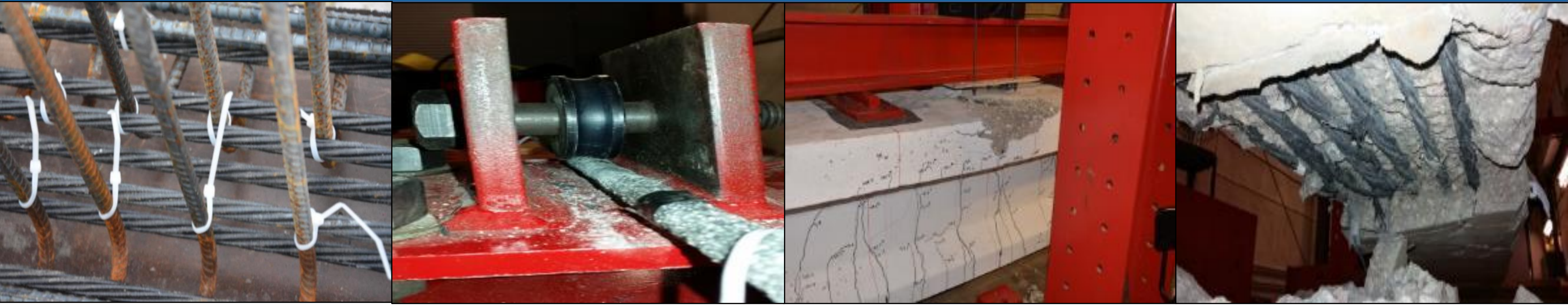
Total prestress loss $\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pTH} = 53.522 \text{ ksi}$ (22.4%)

Effective prestress after all losses

$f_{pe} = 185 \text{ ksi} < f_{pe.limit} = 0.65 f_{pu} = 222 \text{ ksi}$ **OK**

[AASHTO LRFD Specifications 5.9.3.4]

AASHTO CFRP-Prestressed Concrete Design Training Course



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