2014 MAASTO Annual Meeting

Session 6B – Bridges
MDOT Implementation of Carbon Fiber Technology

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July 30, 2014

MDOT CFRP Considerations

•MDOT main interests:

- **Using innovative materials in the pursuit of the 100-year service life bridge**
- **Fostering economic development by using innovative materials**
- **Ensuring the largest benefit, and longest service life using public dollars**

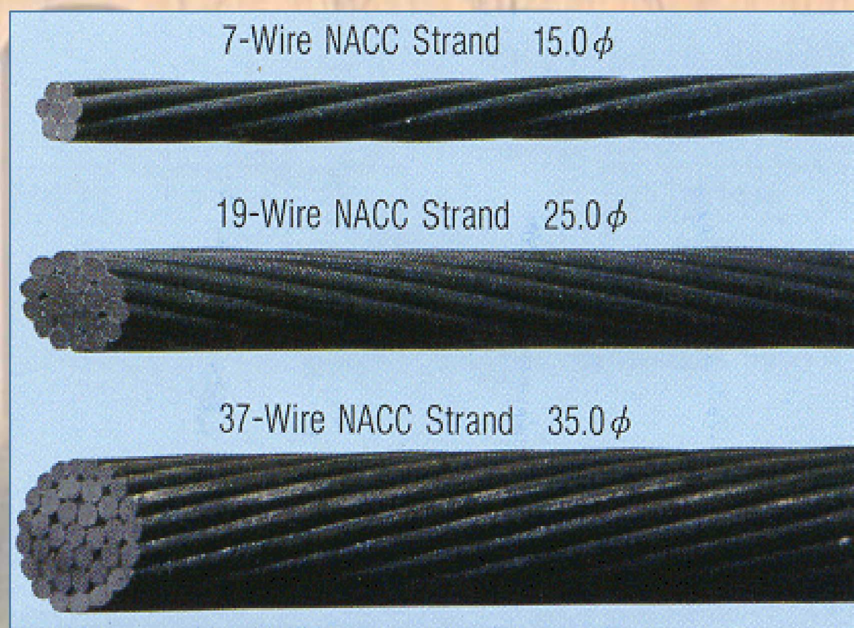
MDOT CFRP Considerations

•MDOT main interests:

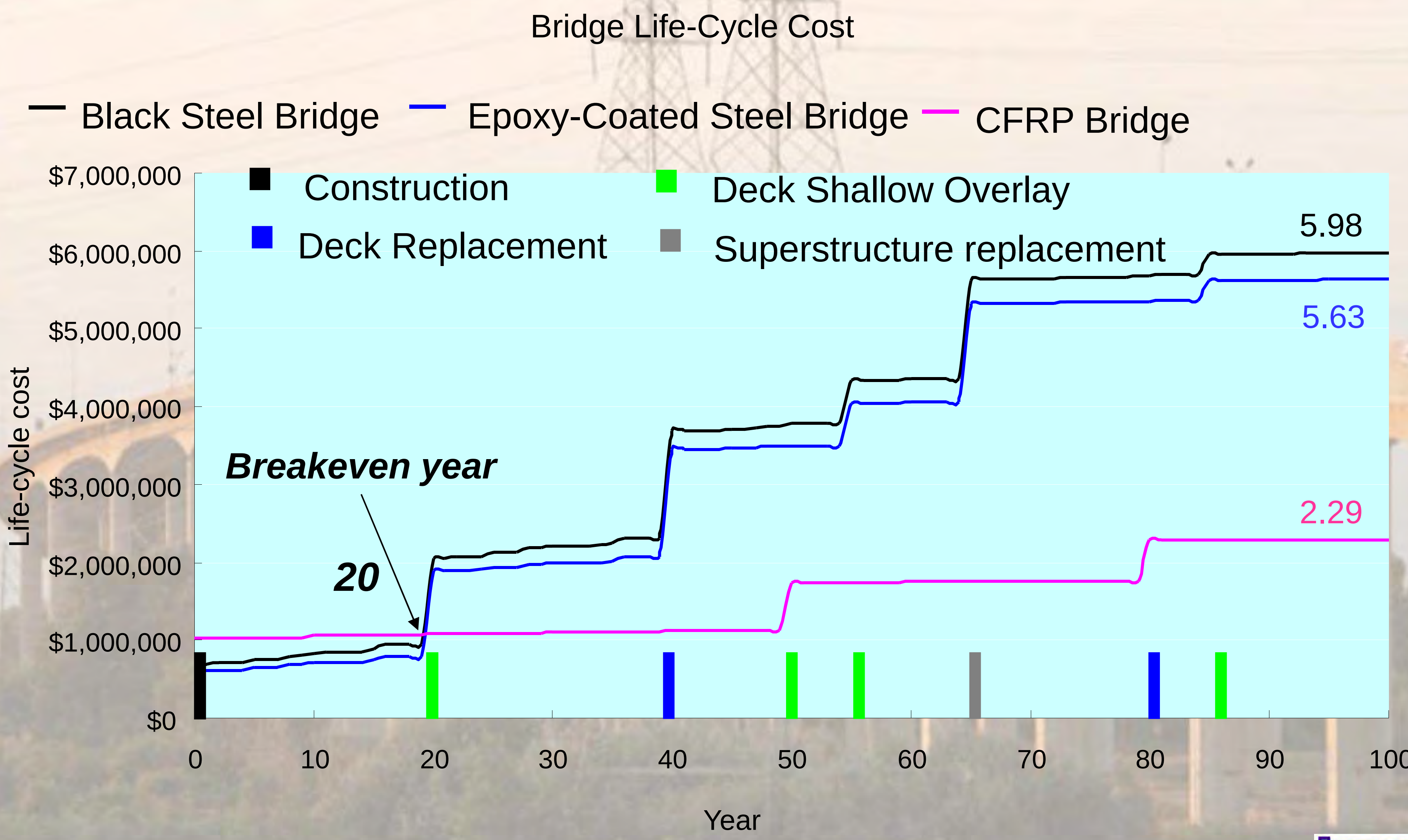
- CFRP prestressing strands, and post tensioning tendons, for transverse PT, no grout is required for duct
- Currently no competitive material to uncoated ASTM A 416, Grade 270 low relaxation high strength strand
- CFRP offers non-corrosive alternate, only major behavioral difference is at ultimate strength, linear failure mode with no yield, and modulus of elasticity is roughly 2/3 that of steel
- Design for no extreme concrete fiber tension

MDOT CFRP Considerations

- **MDOT has been partnering with Lawrence Technological University on CFRP research since 2005**
- **Material specifications, stressing procedures, details and tolerances have been developed**



MDOT CFRP Considerations



MDOT CFRP Considerations

- Based on actual life cycle data for uncoated steel, and epoxy coated steel rebar, and some long term testing of CFRP reinforcement, and theoretical deterioration rates, the life cycle cost to build and maintain these bridges can be quantified and compared

- Based on analysis, the initial cost for CFRP reinforced bridges is higher, however, the “break even” year is after 20 years of service, and for a 100 year service life, the total cost of the CFRP reinforced bridge is expected to be less

MDOT CFRP Considerations

- MDOT was recently named AASHTO Innovation Initiative (formerly TIG) Lead State Initiator for CFRP implementation

- Each year a highly valuable, but not largely recognized innovation in use at least one agency, are proven in use, and will be of significant benefit to other agencies.

- The program actively seeks out proven advancements in transportation technology, investing time and money to accelerate their adoption by agencies nationwide

- Lead State Responsibilities include:
  - Share their states' knowledge about the focus technology, and to advise potential users across the country of the possible benefits available to them
  - Develop a Marketing Plan consisting of:
    - Work Plan
    - Communications Plan
    - Performance Management Plan

AASHTO Innovation Initiative

MDOT CFRP Considerations

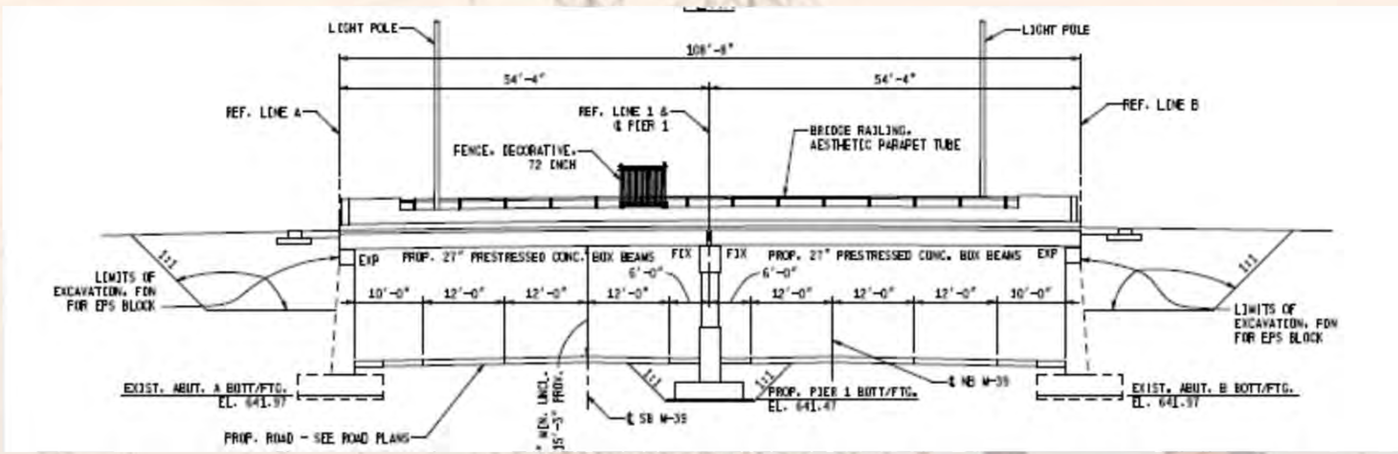
- AASHTO Innovation Initiative activities for CFRP implementation will be starting this calendar year with the formation of the Lead States Team, and development of the Marketing Plan and budget establishment

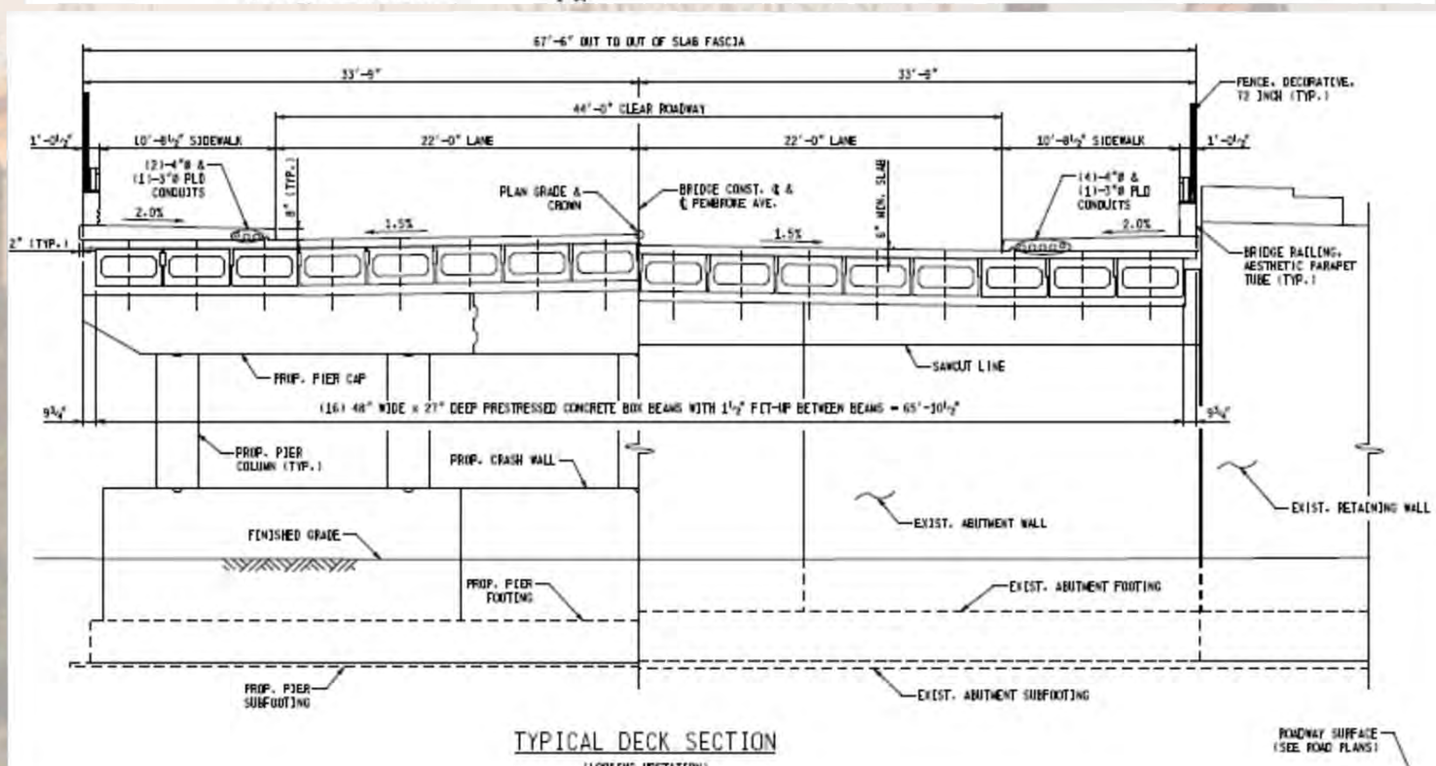
- MDOT has constructed several projects using CFRP prestressing and post tensioning, which will serve as examples of market ready deployments. Examples of these projects are as follows:

MDOT CFRP Deployment

- **Pembroke over M-39 Superstructure Replacement**

MDOT CFRP Deployment





MDOT CFRP Deployment

- **Public outreach to explain the benefits of CFRP materials to customers and stakeholders**

MDOT CFRP Deployment

- **Materials delivered to MDOT**

MDOT CFRP Deployment

MDOT CFRP Deployment

- **Transverse post tensioning cables = 40 mm, 37 wire strand, with a guaranteed breaking load of 269 kips**
- **Cables are socketed into a stainless steel anchorage with a highly expansive material (HEM)**
- **Load from stressing chair is imparted on to anchorage, and nut is locked into position**
- **Transverse PT load = 169 kips, capacity of cable = 269 kips. Actual stress = $0.63*f_{pu}$**

MDOT CFRP Deployment

- Tendons stressed from one end, load measured at dead end via load cell

MDOT CFRP Deployment

- **NEFMAC Grid installation**

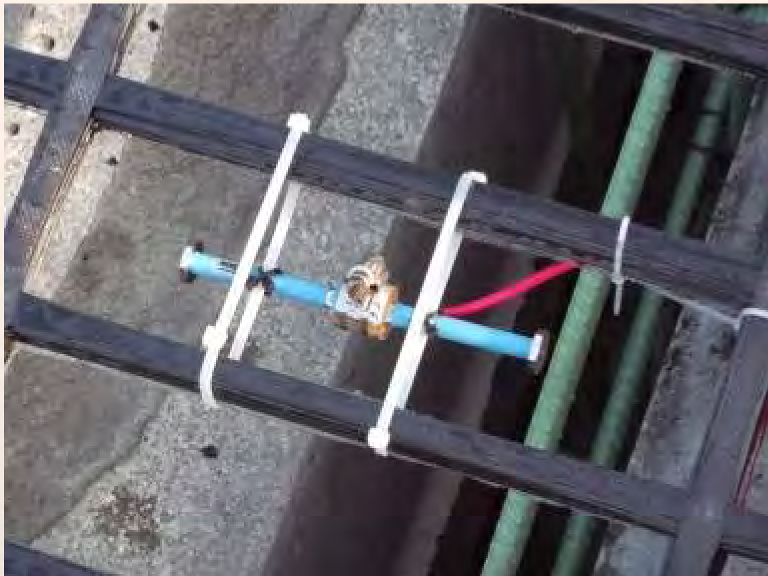
MDOT CFRP Deployment

- **NEFMAC Grid installation**

MDOT CFRP Deployment

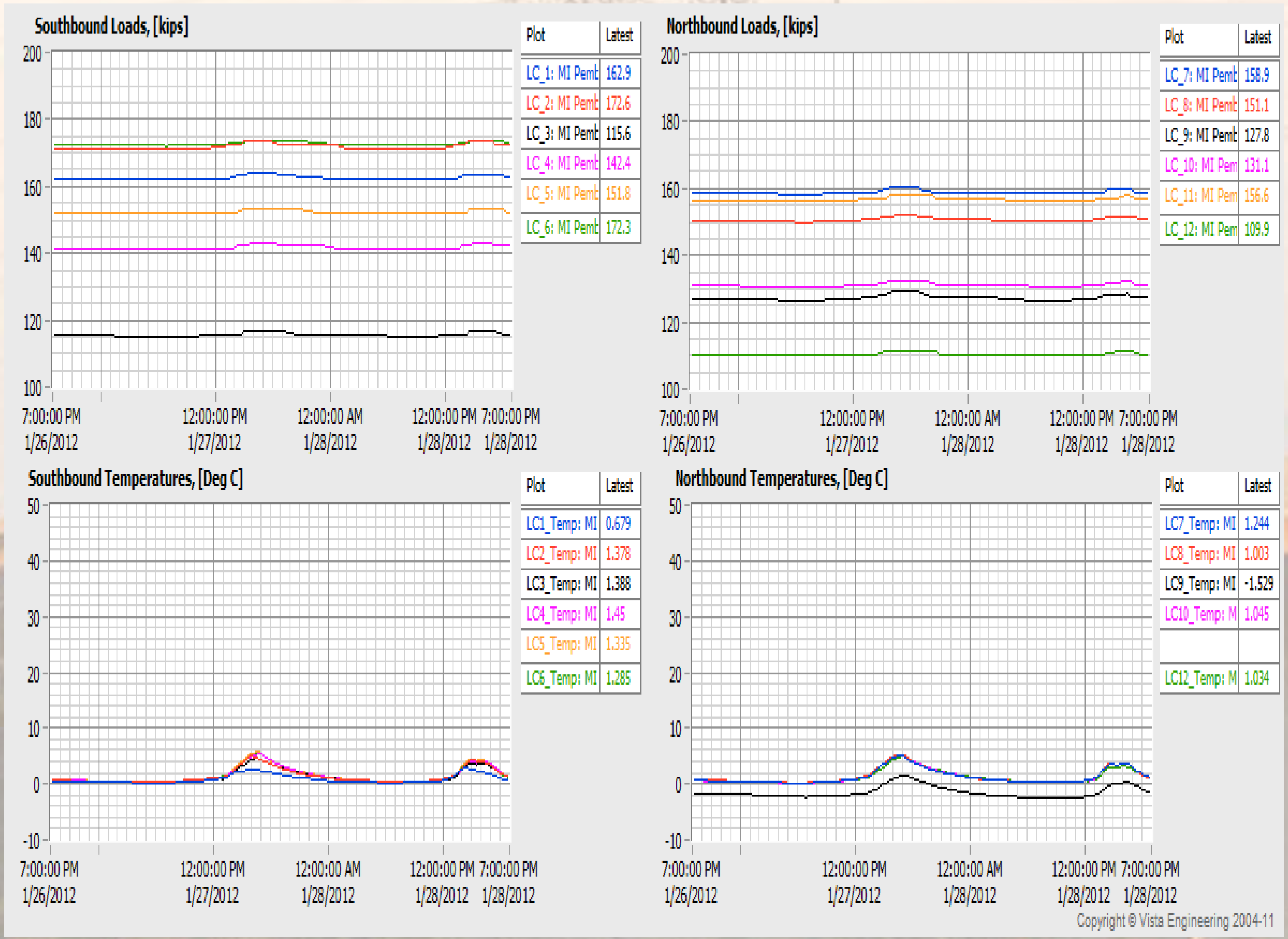
- **NEFMAC Grid installation**

MDOT CFRP Deployment



- **Strain gages, load cells and LVDT deflectometers installed**

MDOT CFRP Deployment



- **Measuring deck deflections, deck strains, and PT tendon loads**

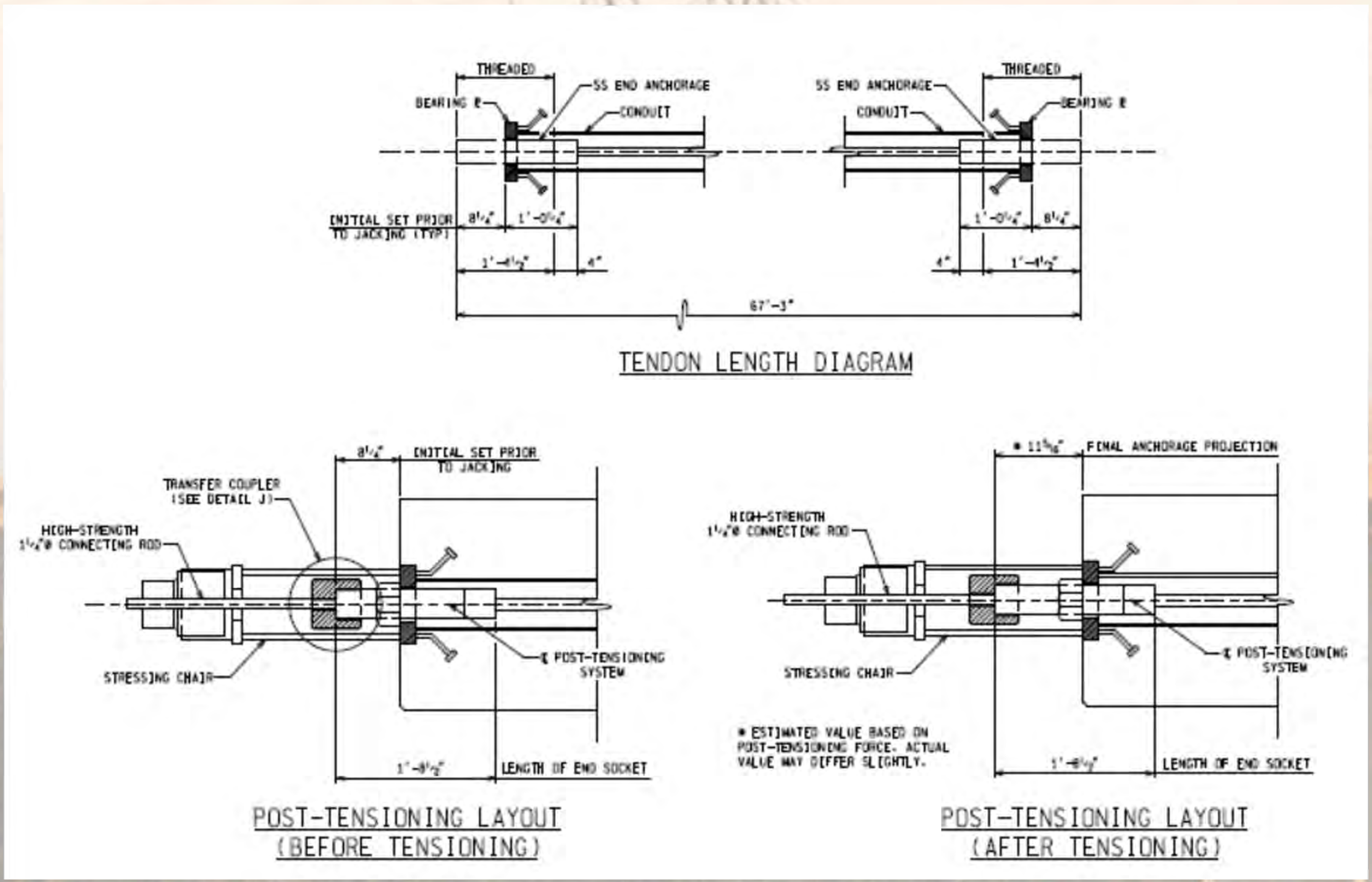
MDOT CFRP Deployment

- **Complete Pembroke Structure**

MDOT CFRP Deployment

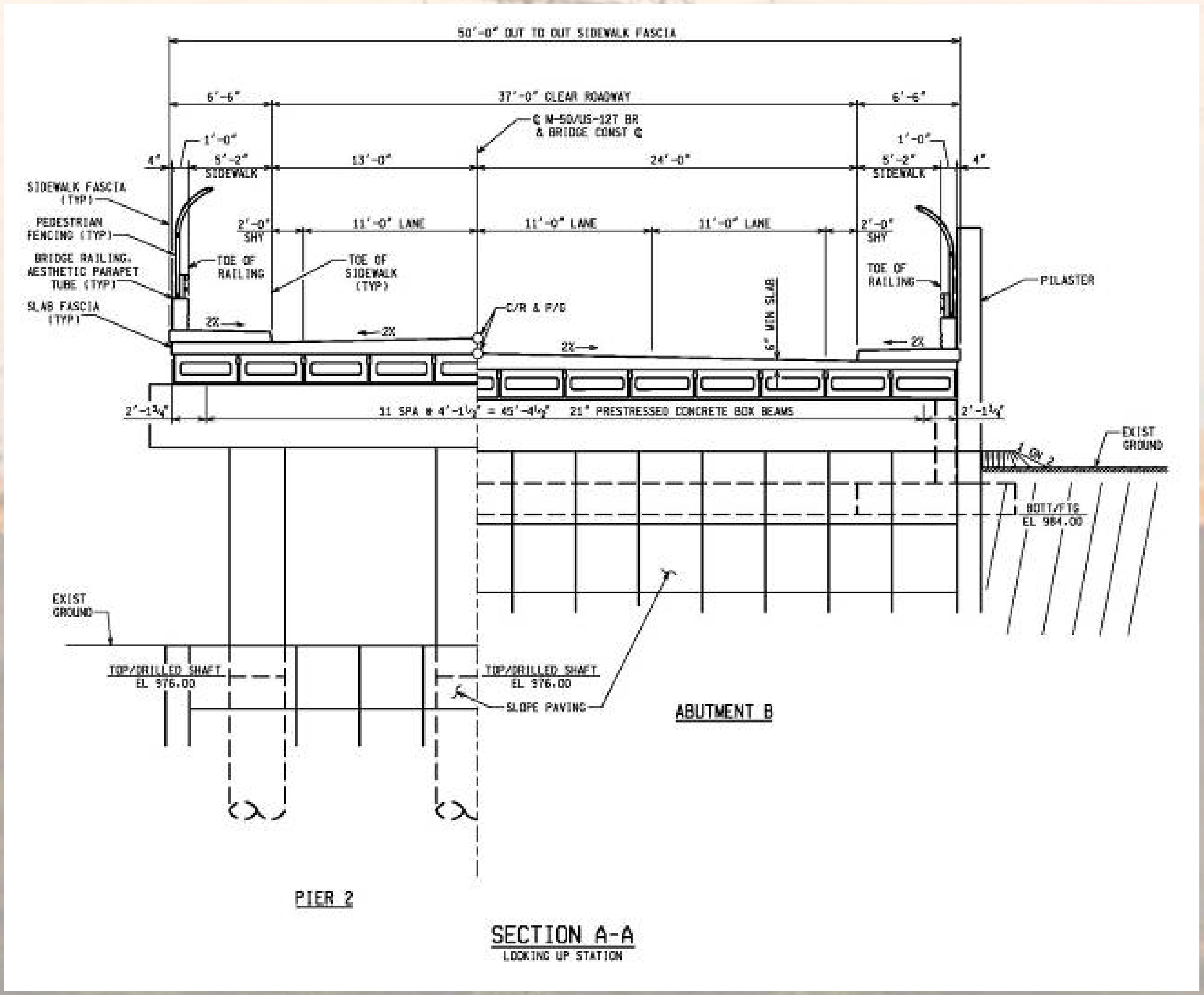
- **M-50/US-127 BR over NS RR Bridge Replacement**

MDOT CFRP Deployment



- **40 mm, 37 wire CFCC post tensioning tendon**

MDOT CFRP Deployment



- **21" side by side prestressed box beams**

MDOT CFRP Deployment

• **Cables were sheathed an fed into 5" PVC conduits**

MDOT CFRP Deployment

• **cable installation**

MDOT CFRP Deployment

- **cable installation**

MDOT CFRP Deployment

- **Stressing chair: cables stressed to 75 kips when superstructure non-composite, then 150 kips once the deck is placed and cured**

MDOT CFRP Deployment

- **Load cells placed on dead end to measure loads**

MDOT CFRP Deployment

CFCC Inspection for M-50 Bridge Over NSRR 5 / 9

Tokyo Rope Mfg.
May 28, 2012

3. CFCC Inspection

Classification Inspection of CFCC 1×37 40.0φ and Transverse Post-Tensioning Cable equivalent

Particular Breaking load of CFCC and Transverse Post-Tensioning Cable equivalent

Date May 28, 2012

Specimen details CFCC 1×37 40.0φ Transverse Post-Tensioning Cable equivalent 3.8m long including terminal fixing by stainless steel sockets; 1pc

Results

Specimen	Lot No. of CFCC	Breaking load		Others
		Specification	Measured	
CFCC 1×37 40.0φ Transverse Post-Tensioning cable equivalent	G56	1,200 or above	2,173.6 kN	-

Witnessed by Dr. Nabil F. Grace, Lawrence ~~Technology~~ Technological University

(signature)

05/28/2012

Mr. Takuji Yoshimoto, Plant Manager, Gamagori CFCC Plant, TCT Division

(signature)

Gamagori CFCC Plant, Tokyo Rope Mfg. Co., Ltd.

Tokyo Rope Mfg. Co., Ltd. Gamagori CFCC Factory 1-1 Nakamura Toyooka Gamagori Aichi 443-0011 Japan Phone +81-533-68-3176 Fax. +81-533-68-0882

CFCC Inspection for M-50 Bridge Over NSRR 9 / 9

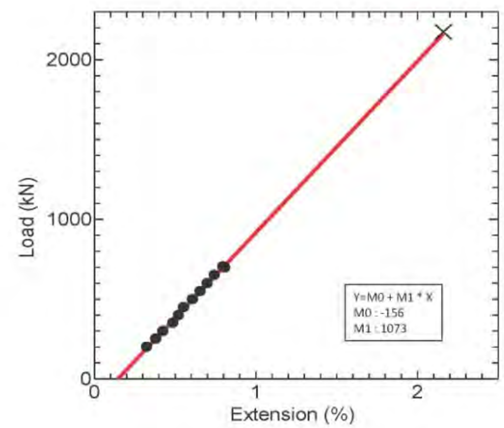
Tokyo Rope Mfg.
May 28, 2012

Tensile Test Result

CFCC Inspection – 40.0 φ

Specimen : No. P-1
(CFCC 1×37 40.0φ)
Transversa Post-Tensioning Cable equivalent

Load-extension curve



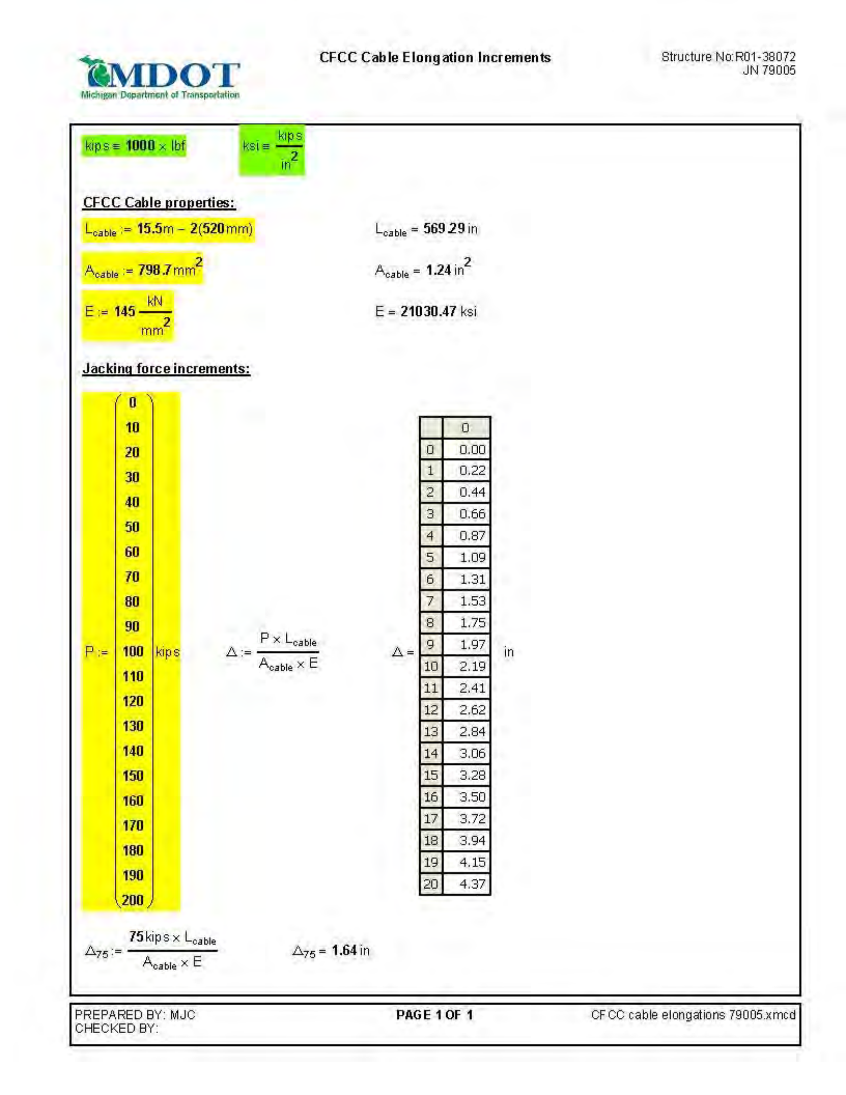
Braking Load = 2173.6 kN
Effective cross sectional area = 798.7 mm^2
Tensile modulus = 134 GPa
Elongation at break = 2.2 %

Tokyo Rope Mfg. Co., Ltd. Gamagori CFCC Factory 1-1 Nakamura Toyooka Gamagori Aichi 443-0011 Japan Phone +81-533-68-3176 Fax. +81-533-68-0882

- **Material properties provided via test reports from manufacturer**

1200 kN = 269 kips
2173 kN = 489 kips

MDOT CFRP Deployment



MDOT Michigan Department of Transportation

CFCC Cable Elongation Increments

Structure No: R01-38072
JN 79005

$kips \equiv 1000 \times lbf$ $\quad ksi \equiv \frac{kips}{in^2}$

CFCC Cable properties:

$L_{cable} := 15.5m - 2(520mm)$ $\quad L_{cable} = 569.29\ in$

$A_{cable} := 798.7\ mm^2$ $\quad A_{cable} = 1.24\ in^2$

$E := 145 \frac{kN}{mm^2}$ $\quad E = 21030.47\ ksi$

Jacking force increments:

$P := (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200)^T\ kips$

$\Delta := \frac{P \times L_{cable}}{A_{cable} \times E}$

$\Delta =$ (in)

	0
0	0.00
1	0.22
2	0.44
3	0.66
4	0.87
5	1.09
6	1.31
7	1.53
8	1.75
9	1.97
10	2.19
11	2.41
12	2.62
13	2.84
14	3.06
15	3.28
16	3.50
17	3.72
18	3.94
19	4.15
20	4.37

$\Delta_{75} := \frac{75 kips \times L_{cable}}{A_{cable} \times E}$ $\quad \Delta_{75} = 1.64\ in$

PREPARED BY: MJC
CHECKED BY:

PAGE 1 OF 1

CFCC cable elongations 79005.xmcd

- **Theoretical elongation calculations were compared to actual elongations and gage pressures**

Taking the next step

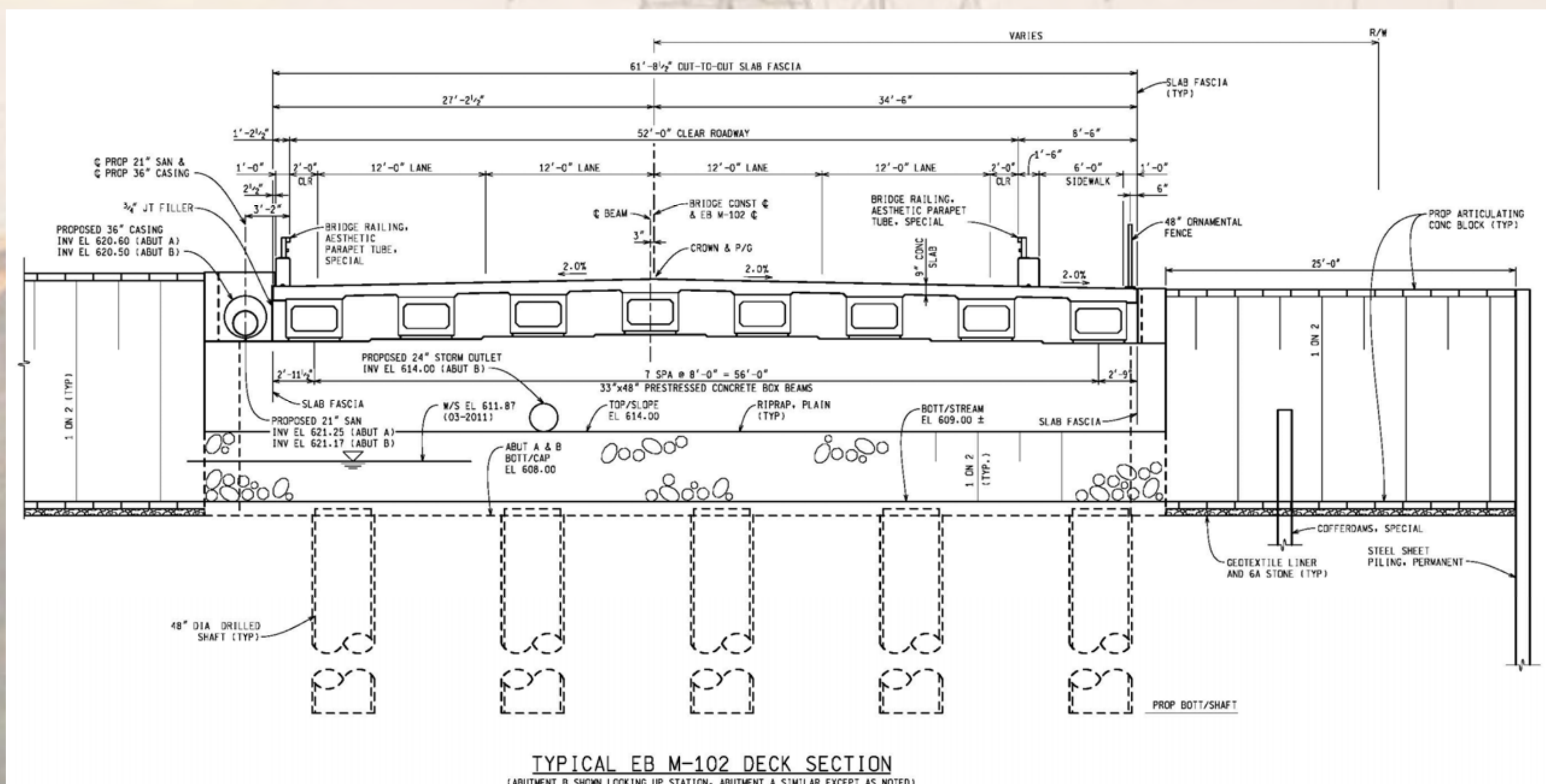
- After successful deployments of CFRP materials on two projects, MDOT decided to move forward with a prestressed application
- MDOT selected an M-route structure with easy access to monitoring equipment, and inspection
- This route takes 4 lanes in each direction in and out of the City of Detroit, and has a very high ADT

Taking the next step

- M-102 over Plum Creek, in the City of Detroit was selected

M-102 over Plum Creek: Design

- Twin 75’ long single span structures, using 33” x 48” side by side box beams prestressed with CFCC



M-102 over Plum Creek: Design

- Determination of number of the theoretical number of CFCC strands based on calculation of excess tension in bottom flange based on Service III limit state:

$$f_b = \frac{M_{DC1}}{S_B} + \frac{M_{DC2} + M_{DW}}{S_{B3n}} + \frac{0.80 \times M_{LL+I}}{S_{Bn}}$$

- Allow for 0 tension in bottom flange at service, as opposed to *0.19√f'c* allowable

M-102 over Plum Creek: Design

- CFCC strand data based on testing:
  - *GUTS* = 60.70 kips
  - A_{strand} = 0.179 in^2
  - f'_{pu} = 339 ksi – calculated ultimate tensile strength
  - C_E = 0.90 – environmental factor per ACI 440.1R-06
  - f_{pu} = 305 ksi – design ultimate tensile strength
  - E_{ps} = 21,000 ksi

M-102 over Plum Creek: Design

- Assume strand eccentricity based on strand center of gravity is between two rows of strands, and equal number of strands in each row:

$$P_e = \frac{f_b}{\left(\frac{1}{A_{beam}} + \frac{e_{strand}}{S_B}\right)}$$

- Strand stress limit prior to transfer:

$$f_t = 0.60 \times f_{pu}$$

M-102 over Plum Creek: Design

- Assume 25% losses, and calculate the number of strands to start, then refine design based on service and strength limit state checks:

$$f_{pe} = A_{strand} \times f_t \times 0.75$$

$$N_{strands} = \frac{P_e}{f_{pe}}$$

M-102 over Plum Creek: Design

- Need to develop jacking forces to stay below creep-rupture curve, while efficiently providing force to offset excess tension due to applied loads

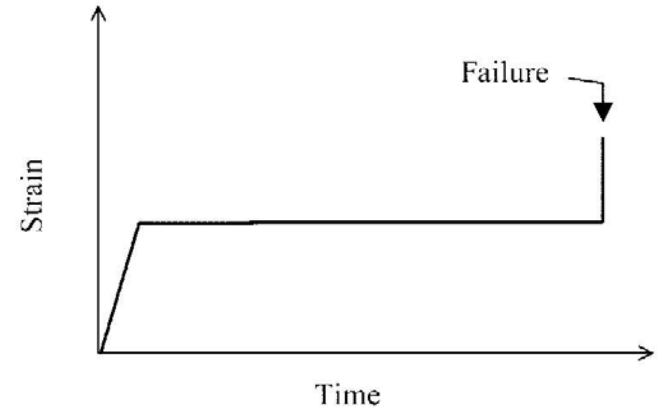


Fig. 3.6—Carbon creep-rupture curve.

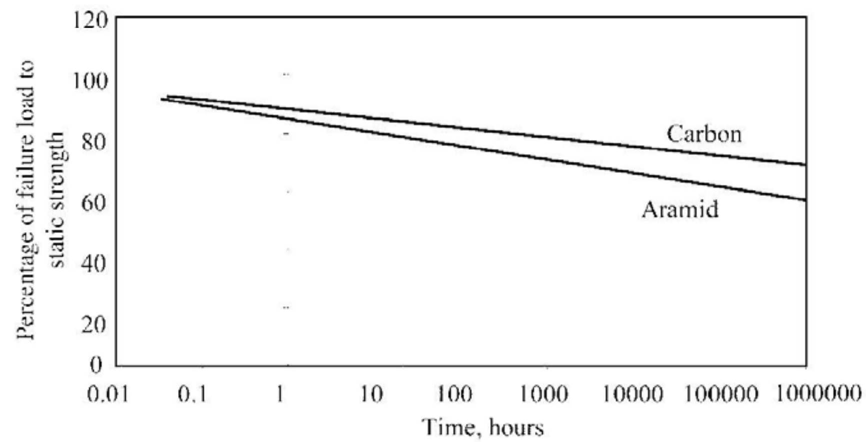


Fig. 3.7—Comparison of creep-rupture curves for aramid and carbon FRP rods under environmental exposure.

M-102 over Plum Creek: Design

- Developed options based on jacking stress and cost of materials:

Stress Immediately Following Transfer	Number of 0.60" Diameter Strands	Length of one Beam (ft)	Total Number of Beams	Total Length of CFCC (ft)	CFCC Cost per Foot ($/ft)	Total CFCC Cost
0.60 fpu	23	58	16	21,344	$ 5.00	$ 107,000.00
0.55 fpu	25	58	16	23,200	$ 5.00	$ 116,000.00
0.50 fpu	28	58	16	25,984	$ 5.00	$ 130,000.00
0.45 fpu	32	58	16	29,696	$ 5.00	$ 149,000.00
0.40 fpu	37	58	16	34,336	$ 5.00	$ 172,000.00

M-102 over Plum Creek: Design

- 0.60*f_{pu} is a good balance between maximizing stress in strands for economic feasibility, while ensuring stress levels well below the creep-rupture threshold

- This allows for sufficient additional CFCC capacity for pseudo-ductility (deformability), ensuring a cracked concrete section, and large deflections prior to failure

M-102 over Plum Creek: Design

- Initial strand losses, and time dependent losses determination:
  - Per ACI 440R, initial losses can be determined from AASHTO material loss equations
  - AASHTO 5.9.5.2.3:

$$\Delta f_{pES} = \frac{A_{ps} \times f_t \left(I_{beam} + e_{strand}^2 \times A_{beam} \right) - e_{strand} \times M_{SW} \times A_{beam}}{A_{ps} \left(I_{beam} + e_{strand}^2 \times A_{beam} \right) + \frac{A_{beam} \times I_{beam} \times E_c}{E_{ps}}}$$

M-102 over Plum Creek: Design

- Time dependent losses based on testing data
  - Relaxation taken as 2.3% of initial pull based on 1,000,000 hours (114 years):
  - AASHTO 5.9.5.3 can be used:

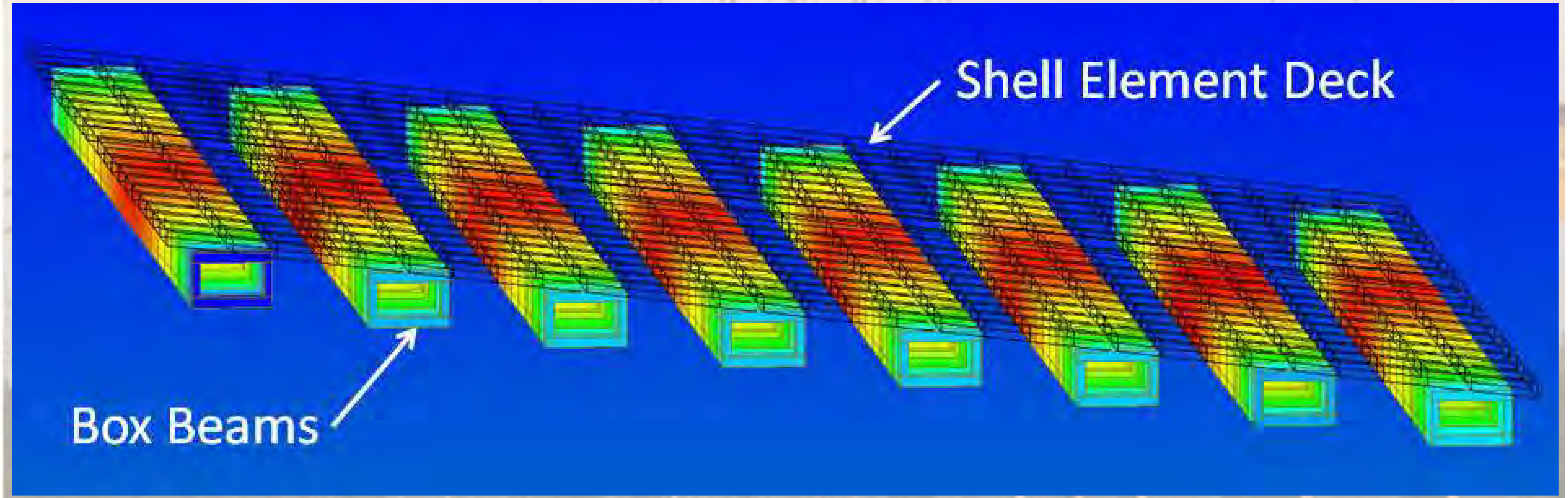
$$\Delta f_{pLT} = 10 \times \frac{f_t \times A_{strand}}{A_{beam}} \gamma_h \gamma_{st} + 12 \gamma_h \gamma_{st} + \Delta f_{pR}$$

$$\Delta f_{pR} = f_t \times 2.3\%$$

  - Elastic gains are conservatively neglected

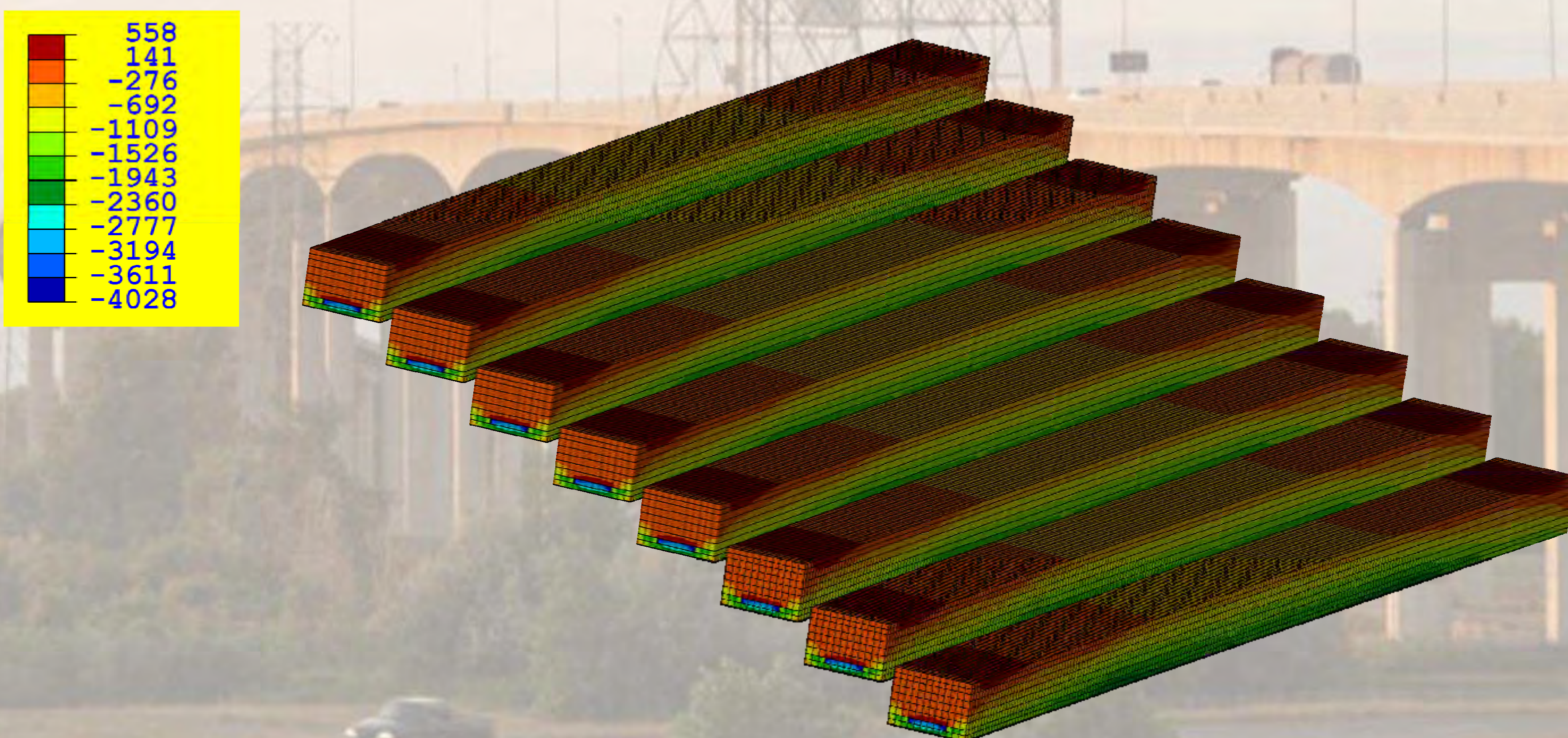
M-102 over Plum Creek: Design

- Design was refined via finite model by designer:



M-102 over Plum Creek: Design

- Design was further refined and checked via finite model by Dr. Nabil Grace:



M-102 over Plum Creek: Design

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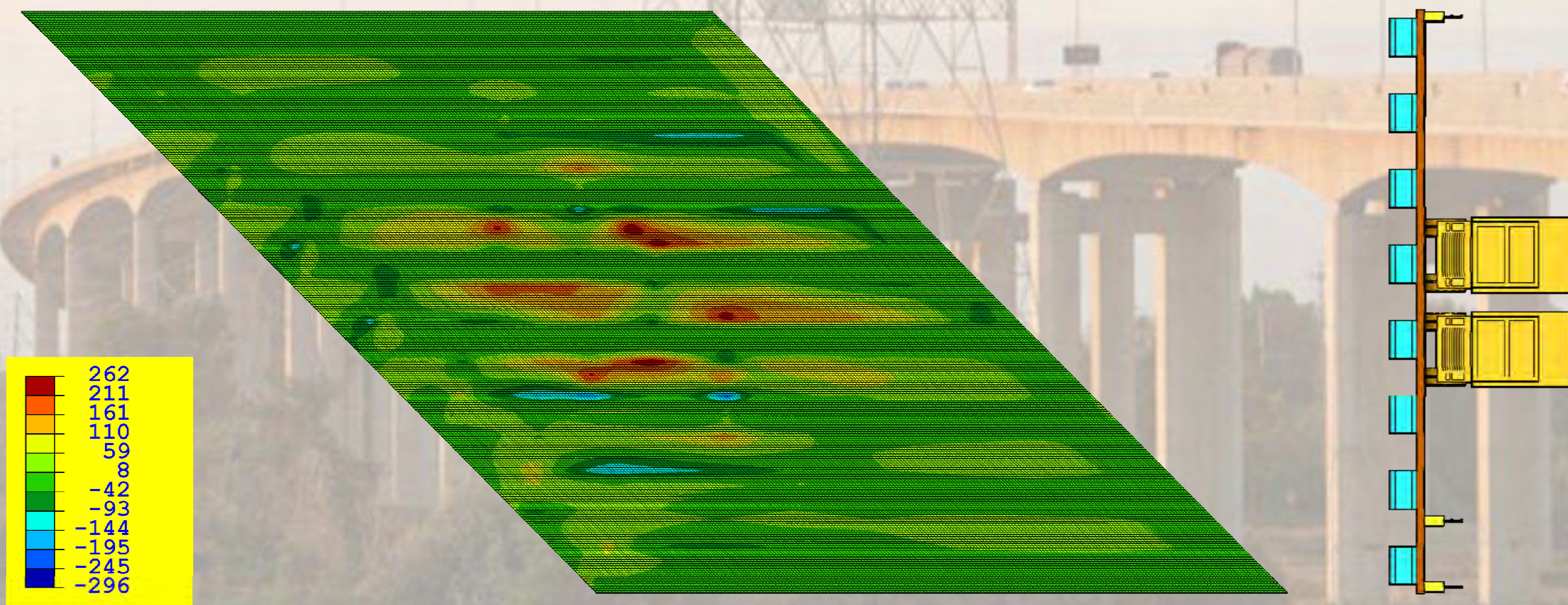
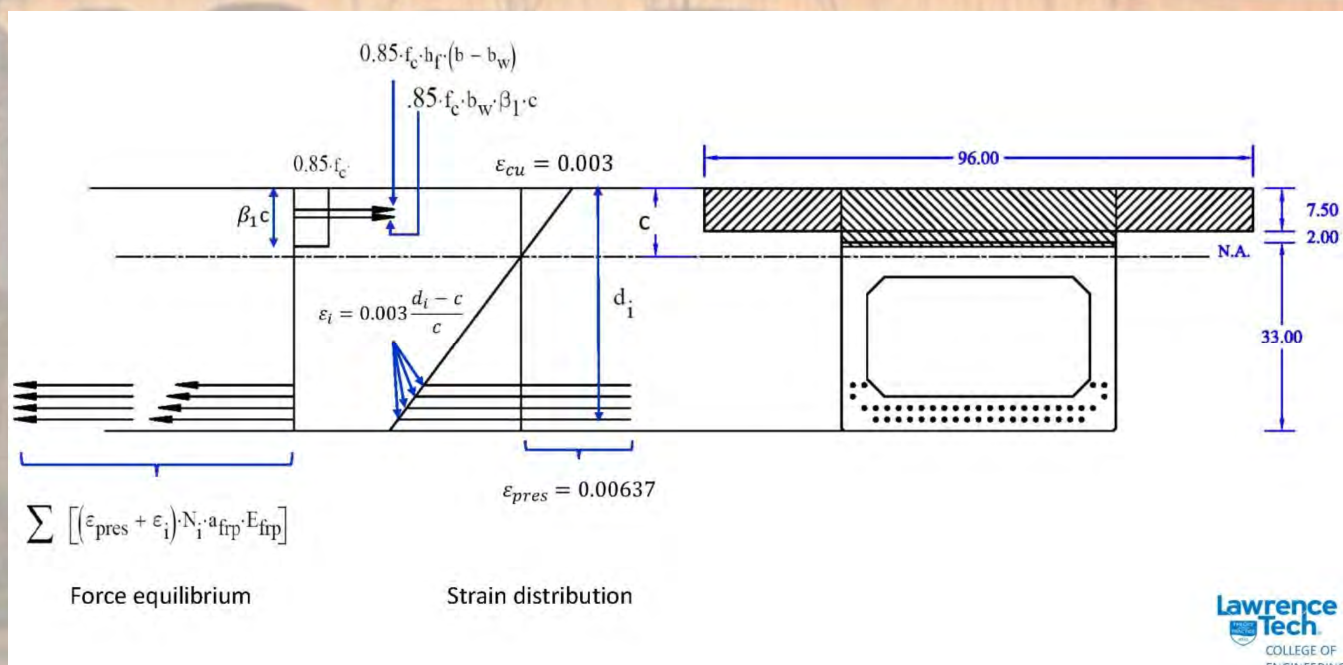


M-102 over Plum Creek: Design

- Since the stress/strain distribution is linear, the nominal moment capacity is based on the area of strands per layer, not the centroid of the strand pattern like with steel

- The moment provided by each layer of prestressing is proportional to the distance of the layer from the neutral axis



M-102 over Plum Creek: Letting

- Material contract was let in January 2013 due to lead times for materials
- Construction contract was let in March 2013
- CFCC materials began arriving at fabrication facility in May 2013
- EB bridge built in 2013, WB bridge built in 2014

M-102 over Plum Creek: Fabrication

- Challenges:
  - Estimating enough contract quantities of CFCC assuming fabricator would cast more than on beam per bed
  - CFCC coefficient of thermal expansion different from that of steel – must take into account losses from prestressing bed contraction, and stress increases from prestressing bed expansion
  - Load cells installed on bed to verify calculated elongations and gage pressures

M-102 over Plum Creek: Fabrication

- Elongation calculations:

Basic Elements	STEEL
Required Load	32,800
Inititial Load	3,000
Length	537
Modulus of Elasticity	28,800,000
Strand Area	0.22025

Basic Elements	CF
Required Load	32,800
Inititial Load	3,000
Length	1,872
Modulus of Elasticity	21,973,217
Strand Area	0.17918

Elongation / Force Adjustments

Dead End Seating	0.1250	
Splice Chuck Seating	0.0000	
Bed Shortening/Abut. Rot.	0.2500	0.1318
Live End Seating	0.3750	

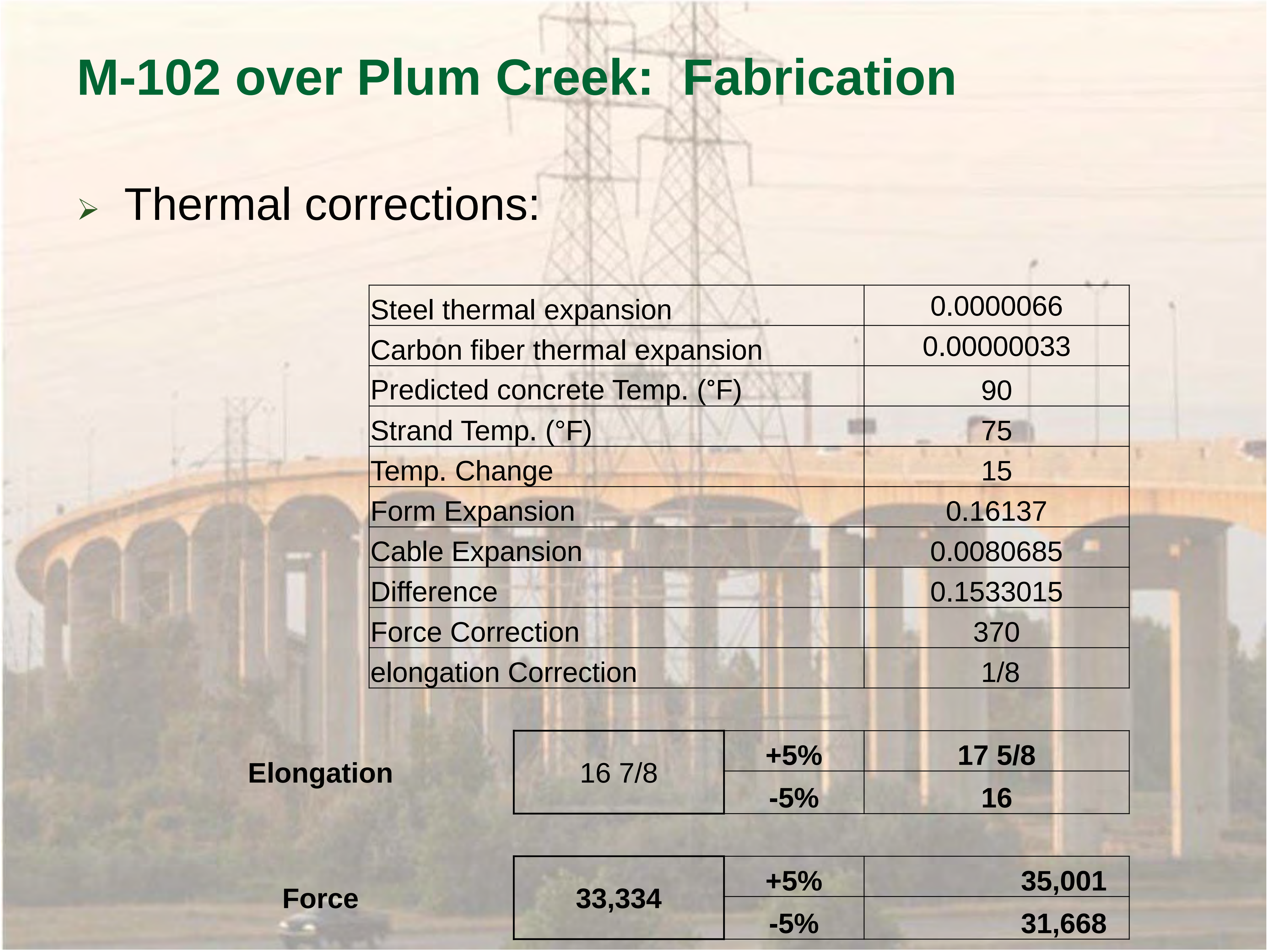
Force Correction

STEEL	CF	Total
1556.349	277.109	235.227
4429.609	788.694	669.491

	STEEL	CF	Total
Basic Elongation	2.523	14.169	16.692

Net

Elongation	17	+5%	17 7/8
		-5%	16 1/8
Force	33705	+5%	35390
		-5%	32019



M-102 over Plum Creek: Fabrication

- Thermal corrections:

Steel thermal expansion	0.0000066
Carbon fiber thermal expansion	0.00000033
Predicted concrete Temp. (°F)	90
Strand Temp. (°F)	75
Temp. Change	15
Form Expansion	0.16137
Cable Expansion	0.0080685
Difference	0.1533015
Force Correction	370
elongation Correction	1/8

Elongation	16 7/8	**+5%**	**17 5/8**
		-5%	**16**
Force	**33,334**	**+5%**	**35,001**
		-5%	**31,668**

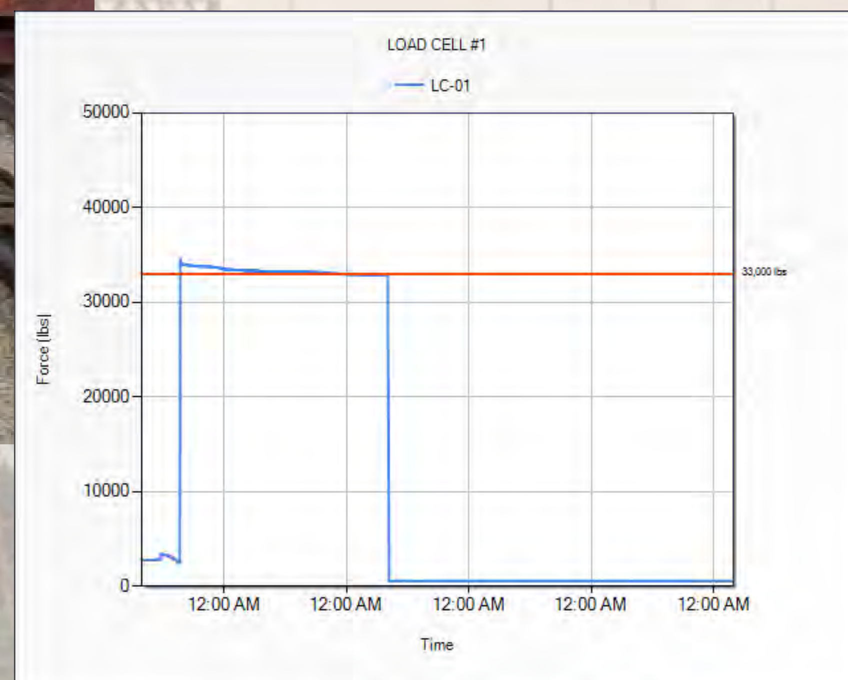
M-102 over Plum Creek: Fabrication

- 15.2 mm strand reels – 1043 m each

M-102 over Plum Creek: Fabrication

- Coupled strands, pull steel strands

M-102 over Plum Creek: Fabrication



- ➢Monitoring force in strands via load cells

M-102 over Plum Creek: Fabrication

- Strand stressing complete, pouring concrete

M-102 over Plum Creek: Fabrication

- Setting void, stirrups, and mild reinforcement

M-102 over Plum Creek: Fabrication

- Reinforcement complete, finishing concrete pout

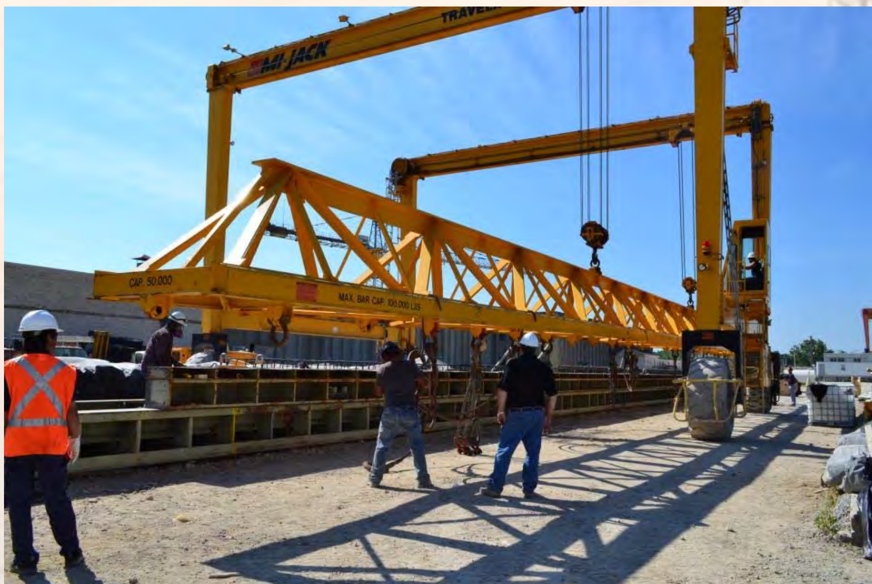
M-102 over Plum Creek: Fabrication

➢Slab tie installation

M-102 over Plum Creek: Fabrication

- Cutting of steel strand, removal of couplers

M-102 over Plum Creek: Fabrication



- Removal of first two beams from forms

M-102 over Plum Creek: Fabrication

- Removal of first two beams from forms

M-102 over Plum Creek: Fabrication

- Completed beam – no release cracking

M-102 over Plum Creek: Construction

- Completed structure

MDOT CFRP Deployment

- Research activities:
  - Deck bulb-T beam pooled fund project with MI, IA, OR, WI & MN
  - Long term durability and Michigan specific Design Guidelines
  - Long term field monitoring
- National research – NCHRP 12-97: *AASHTO LRFD Guide Specification for the Design of Concrete Bridge Beams Prestressed with CFRP Systems*

Components of Decked Bulb T beam Bridge Model

- *Four prestressing strands/beam*
- *Initial prestressing force = 33 kip/strand (132 kip/beam)*

UHPC shear key

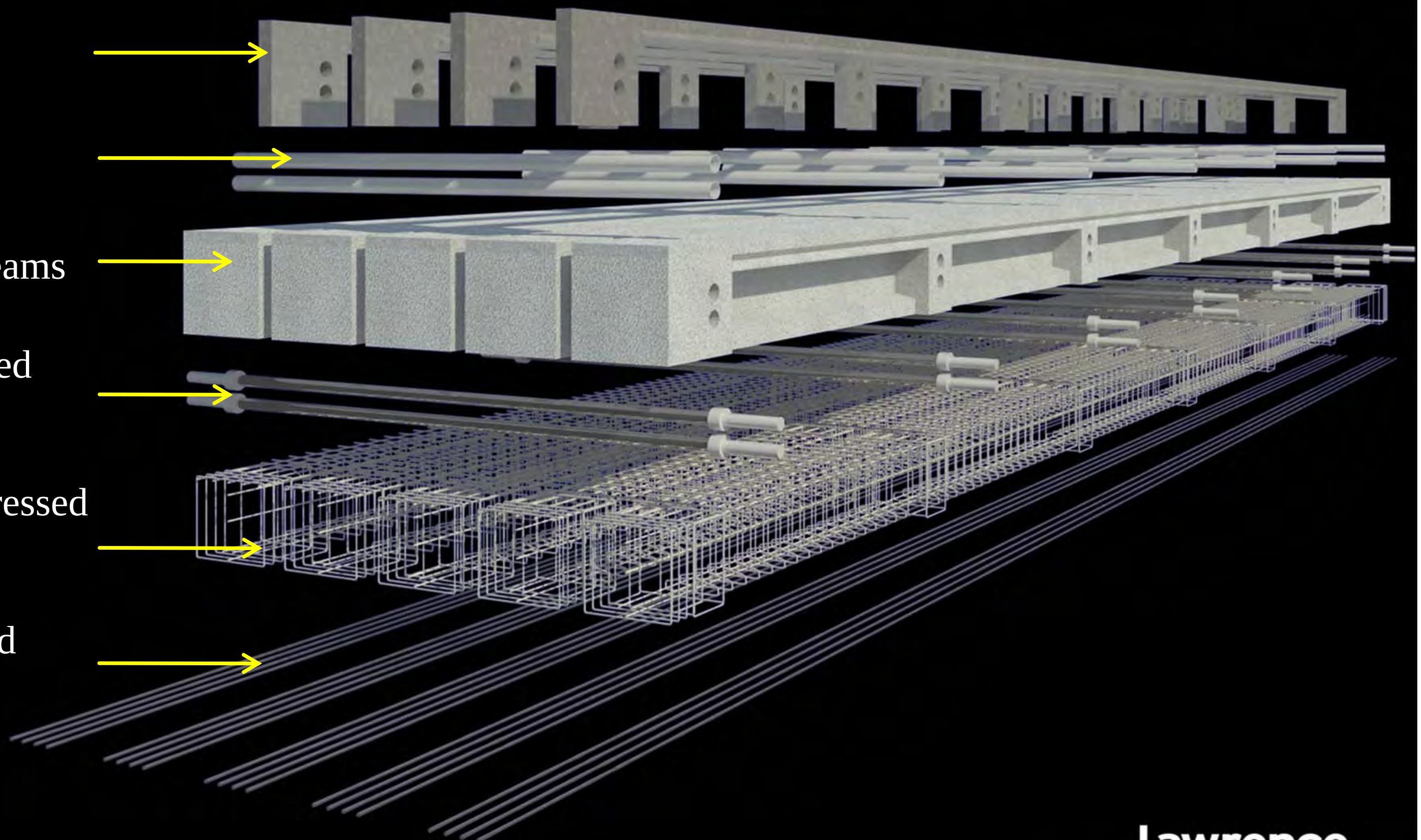
Post-Tension Ducts

7,000 psi Concrete beams

1″ (1x7) post-tensioned CFCC strands

3/8″ (1x7) non-prestressed CFCC strands

0.6″ (1x7) prestressed CFCC strands



Current Worldwide CFRP Guidelines

USA

- ACI 440.1R-06
- ACI 440.2R-08
- ACI 440.3R-12
- ACI 440.4R-04
- ACI 440.5-08
- ACI 440.6-08
- ACI 440R-07
- AASHTO LRFD GFRP-Reinforced Concrete Bridge Decks and Traffic Railings -09

Canada

- CAN/CSA-S807-10
- CAN/CSA-S806-12
- ISIS Design Manual No. 3-01
- CAN/CSA-S6-06

Europe

- CNR-DT 203-06
- Fib bulletin No. 40-07

Japan

- Conc. Eng. Series 23-97

Guidelines for prestressed elements (highlighted: ACI 440.4R-04, CAN/CSA-S806-12, Conc. Eng. Series 23-97)

Drawbacks of Current Worldwide CFRP Guidelines

- **Lack of comparative review**

  Discrepancies and differences have been observed among guidelines (Fib bulletin No. 40-07)

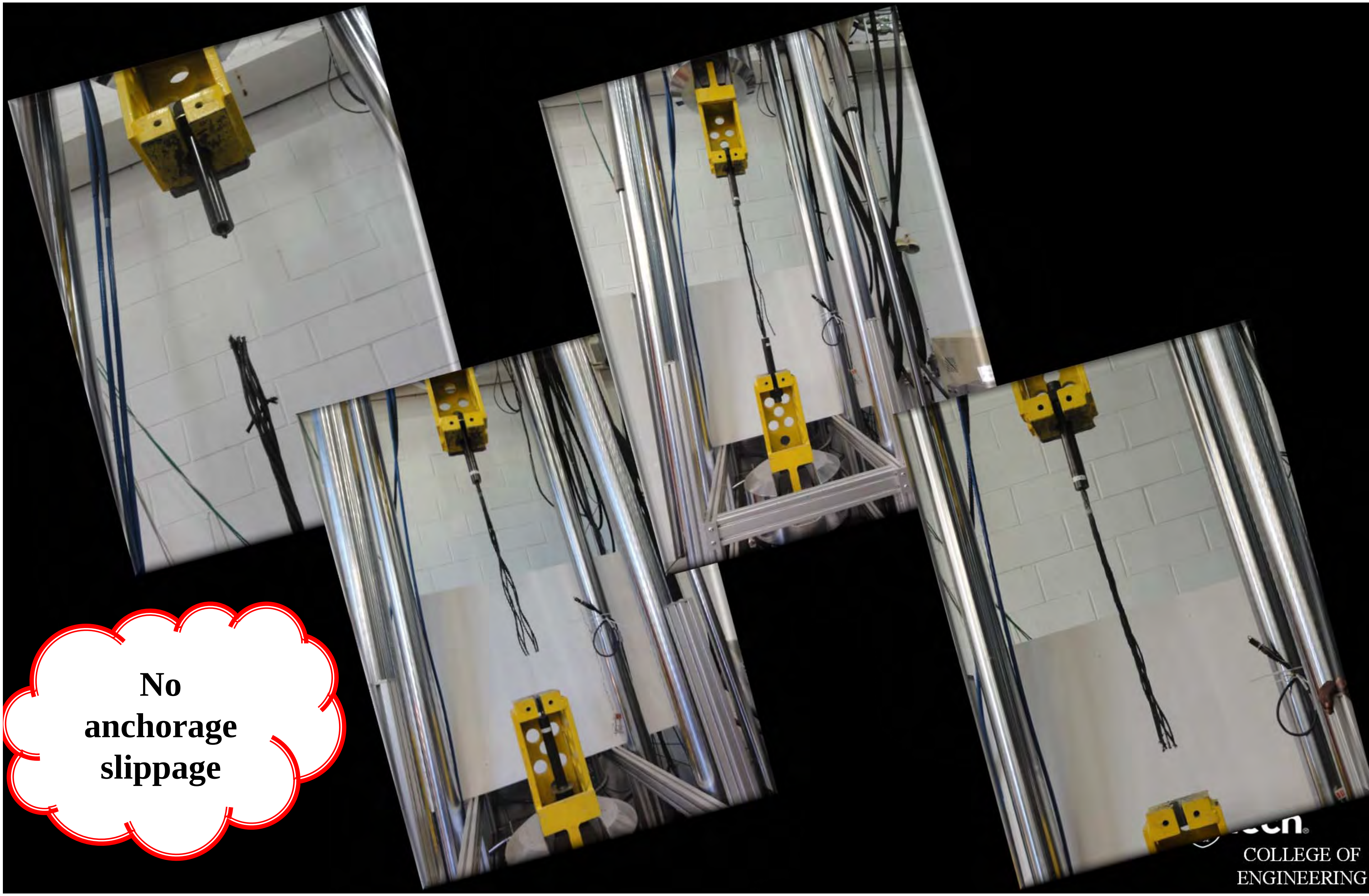
- **Absence of some design matters:**

  Susceptibility to fire damage
  Bond length for splices
  Bond fatigue
  Methodologies to quantify long-term losses in prestressing strands

- **Uncertainty in several design matters:**

  Creep rupture of CFRP strands
  Exposure to severe environmental conditions
  Prestress loss due to creep & shrinkage of concrete
  Strength reduction factor

Anchorage Testing



No anchorage slippage

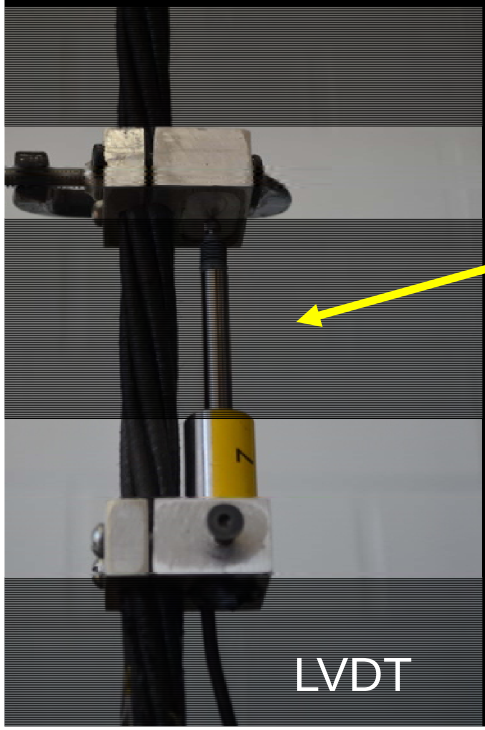
Loading Specimens in Creep Rupture Frame

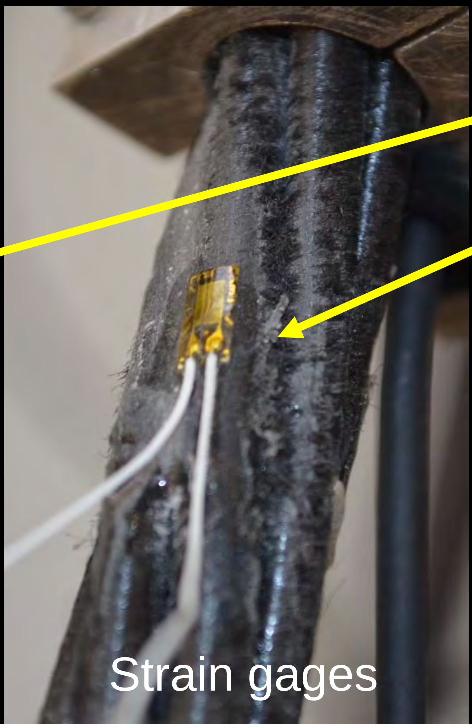
Creep Rupture

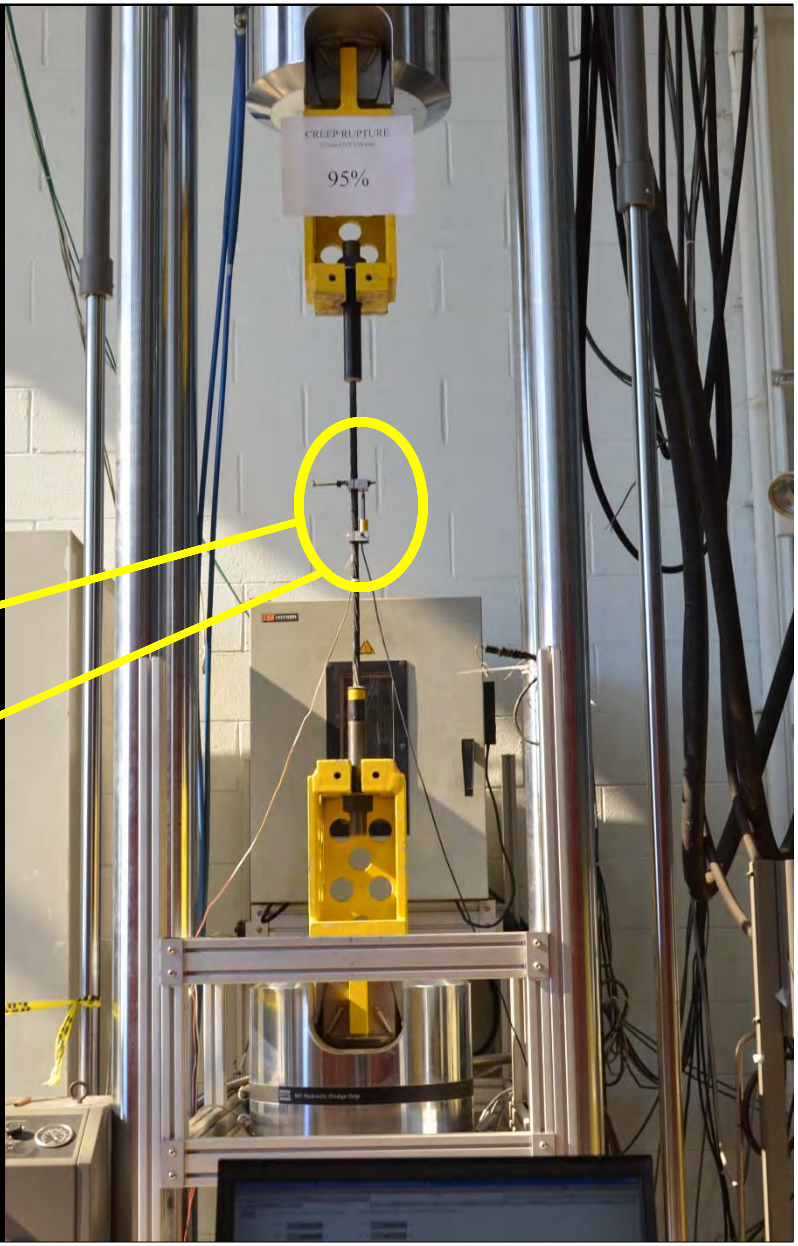
Creep rupture loading for prestressing levels of:
*≥ **90 %** of ultimate strength (68.4 kip)*

Test Duration: 1000 hours for each prestressing level

Test Temperature: 68 °F ± 4 °F





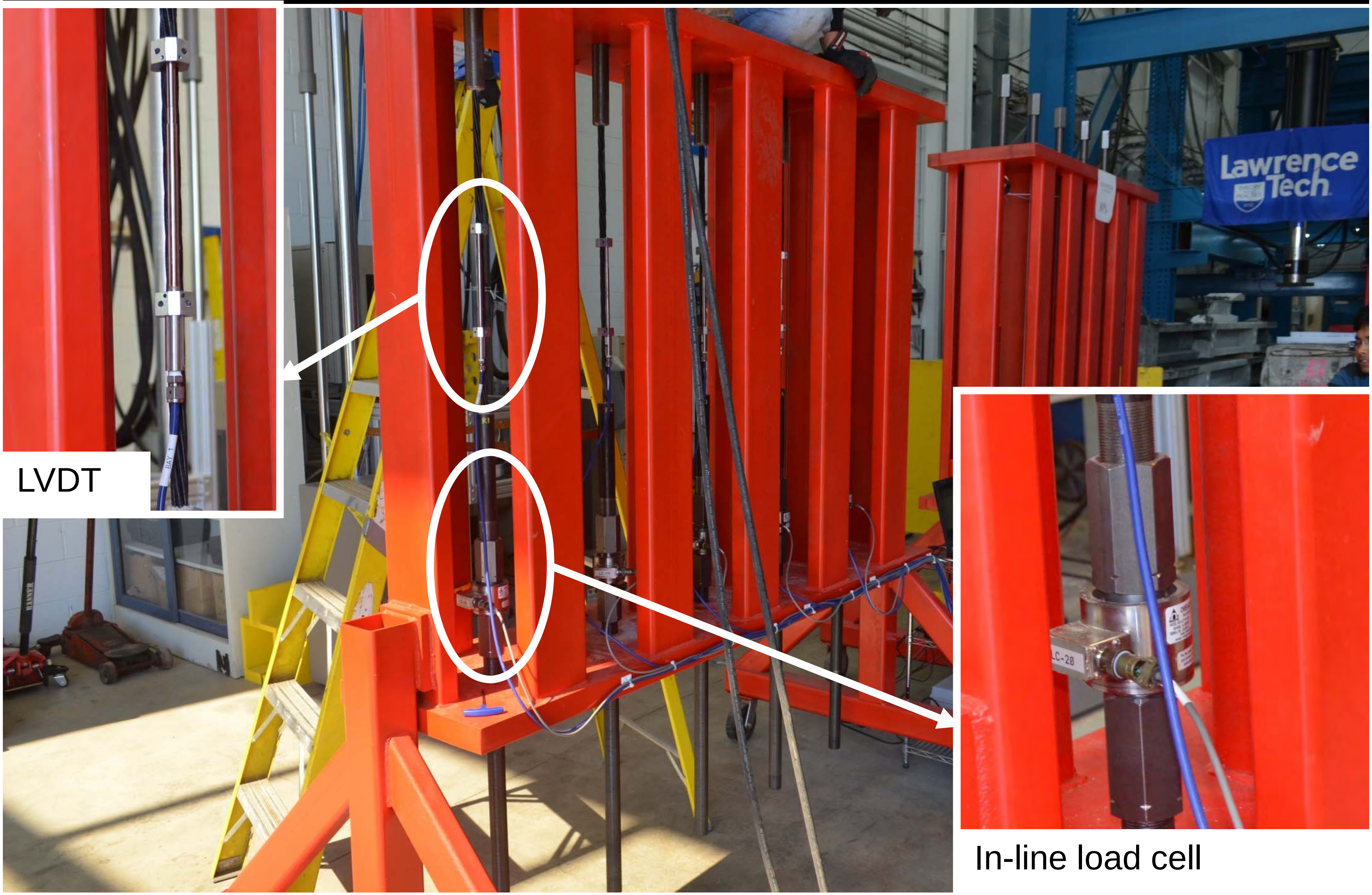


Long Term Relaxation

ACI440.3R-12-B.9 Test method for long term relaxation of FRP bars.

- Test includes five 4-ft-long test specimens
- Applied load is 80% of anticipated 1.0-million-hour creep rupture capacity
- Anticipated 1.0-million-hour creep rupture capacity ≈ 86% of 68.4 kip –based on limited results obtained so far, (it is 85%, reported by JSCE 1997).
- Strain is recorded using LVDT.
- Load reduction is recorded via load cells
- Test lasts for 1000 hrs.

Long Term Relaxation

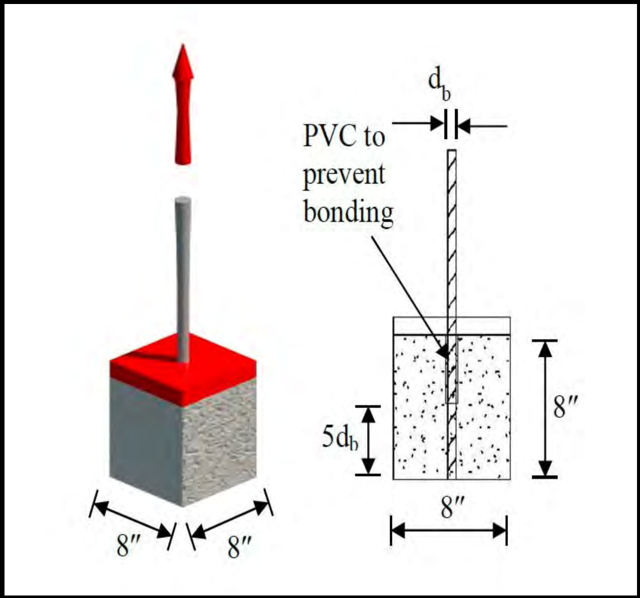


Bond Fatigue Strength

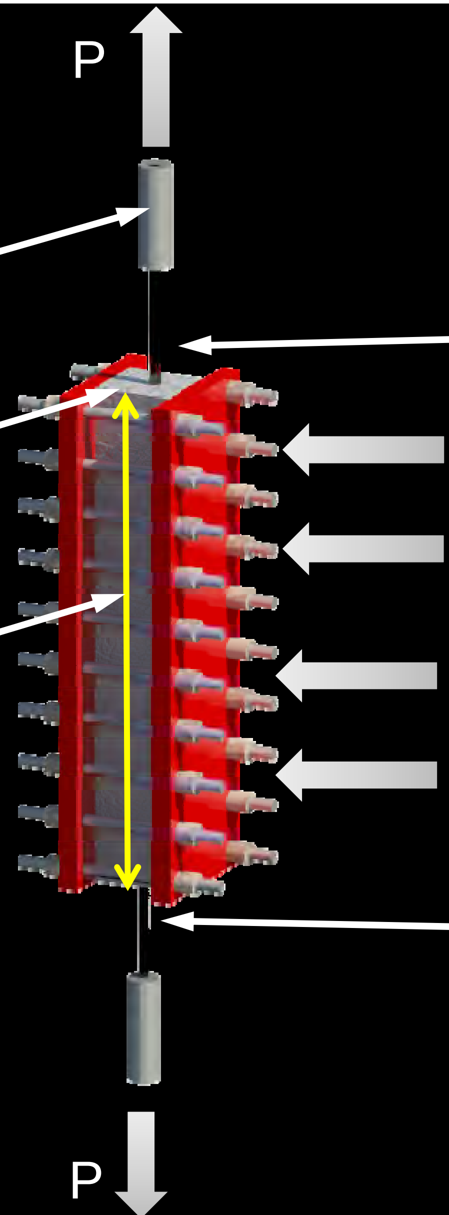
Establish bond strength of CFRP → **Perform fatigue test on bond test specimens**

ACI440.3R-12-B.3 Test method for bond strength of FRP bars by pullout testing

ACI440.3R-12-B.7 Test method for tensile fatigue of FRP bars *(performed on bond strength specimens)*



Bond Splice Length (Test #1*)



* This test depends on loading both CFCC strands & concrete under axial tension

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Bond Splice Length (Test #1, Testing)

Loading and failure of specimens with lateral confinement (4"×8"×15")

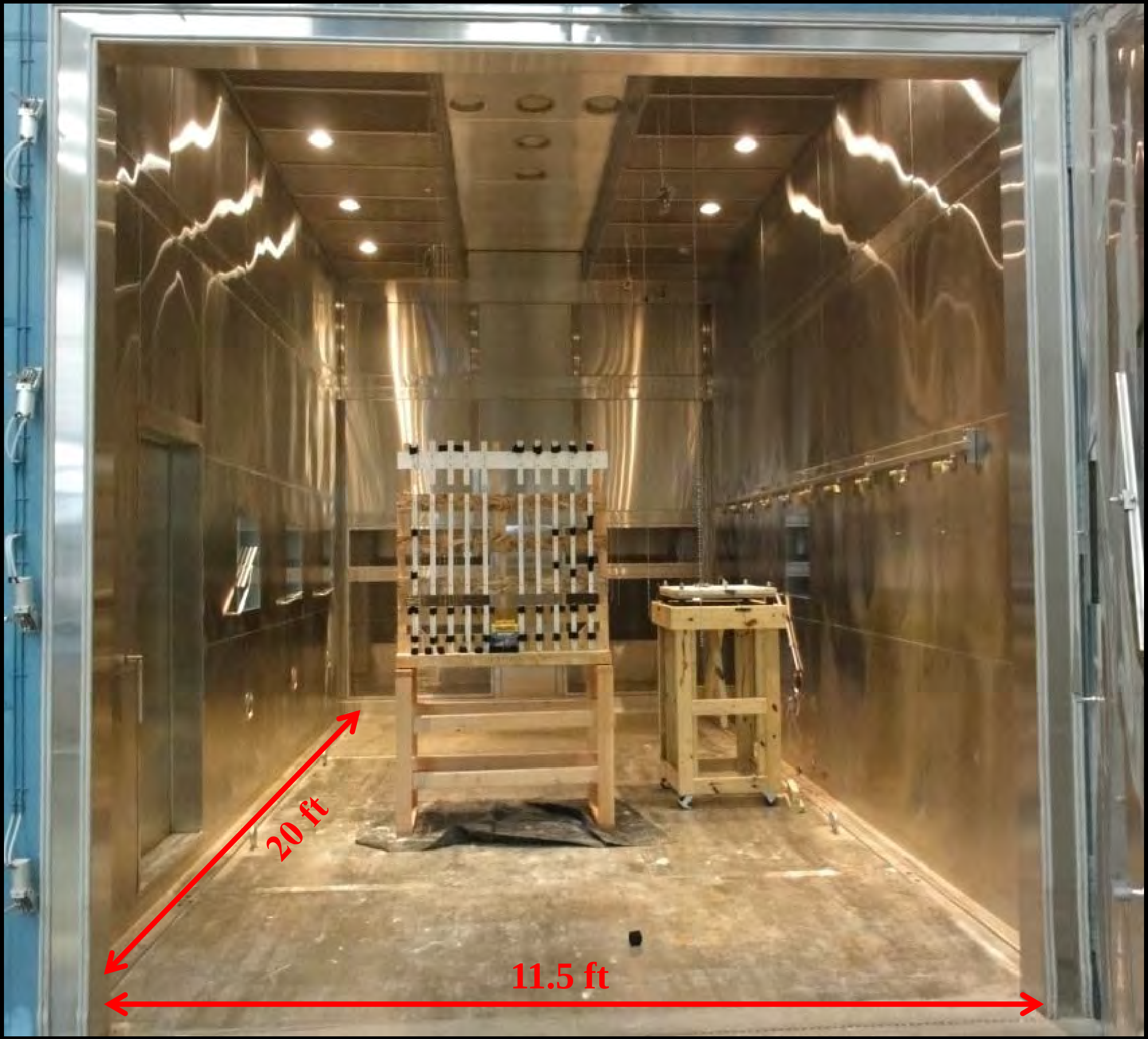
Prestress Loss Due to Creep of Concrete

Indoors & outdoors concrete creep testing

Susceptibility to Fire

Beam testing under three-point load setup in fire chamber

Environmental Chamber for Freeze Thaw



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MDOT CRFP Implementation in Summary

- As part of the MDOT capital program, 2 – 3 bridges per year are selected for CFRP prestressing or post-tensioning

- As part of the AASHTO Innovation Initiative, MDOT will be a Lead State Initiator in assisting other agencies for a potential national deployment

- MDOT has several large future corridor projects where CFRP elements will be proposed for long term service life benefits

MDOT CRFP Implementation in Summary

- The benefits of using these materials for other MAASTO states is the non-corrosive properties, and eliminating the need to grout post-tensioning ducts

- Analysis shows a potential 60% reduction in overall life cycle costs compared to bridges that use traditional steel reinforcement and prestressing/post-tensioning materials

Thank You

Questions?

MDOT
Michigan Department of Transportation
BRIDGE FIELD SERVICES

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