Performance of Carbon Fiber Strand in a Maine Cable Stay Bridge

ASBI Webinar Series

"ASBI has met the standards and requirements of the Registered Continuing Education Program. Credit earned on completion of this program will be reported to RCEP at RCEP.net. A certificate of completion will be issued to each participant. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the RCEP."

ENGINEERING RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose and Learning Objectives

Purpose

The Webinar provides an educational forum to learn new techniques in successful projects, lessons learned from development projects, and showcases a case study allowing discussion of the project

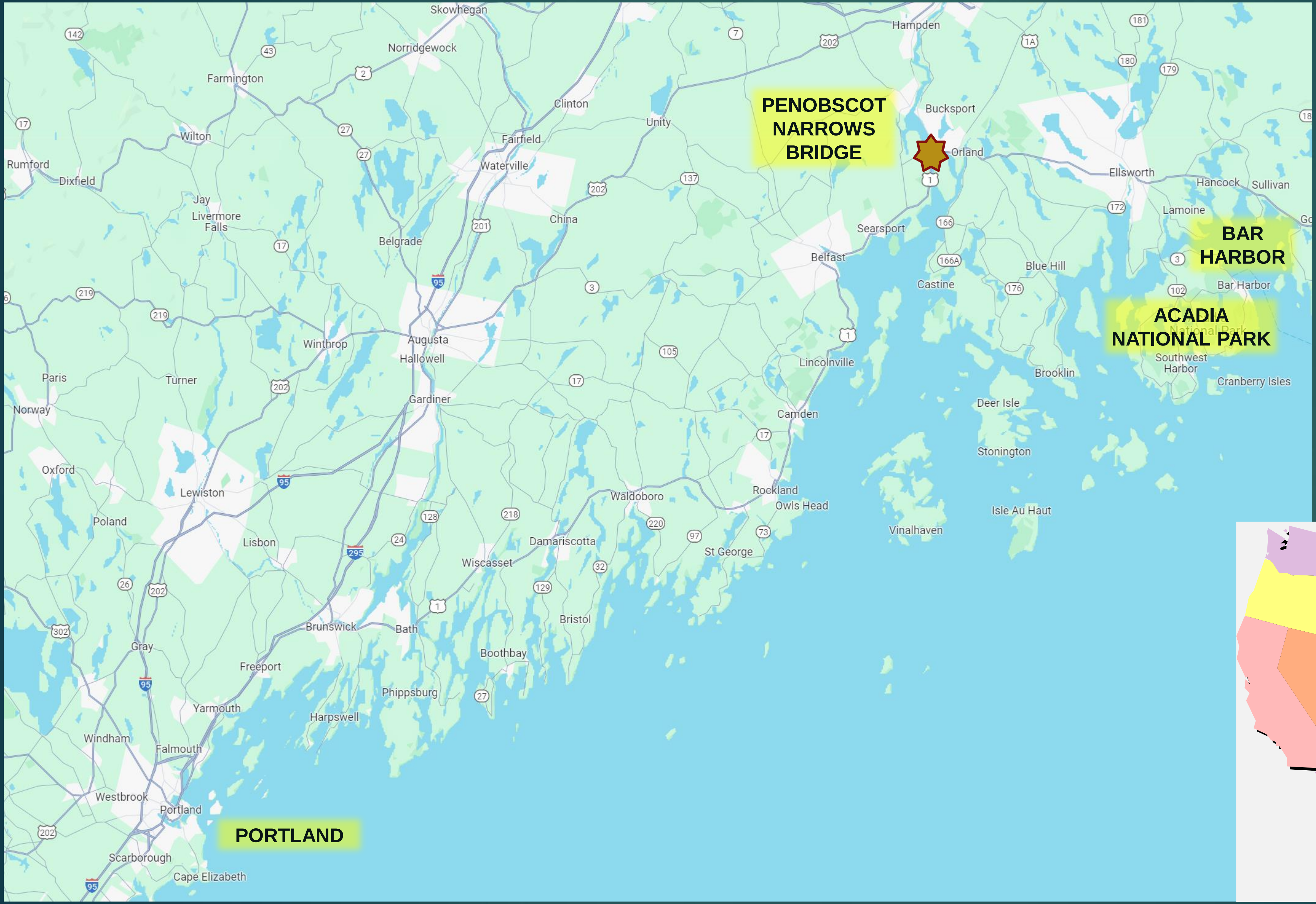
At the end of this presentation you will be able to:

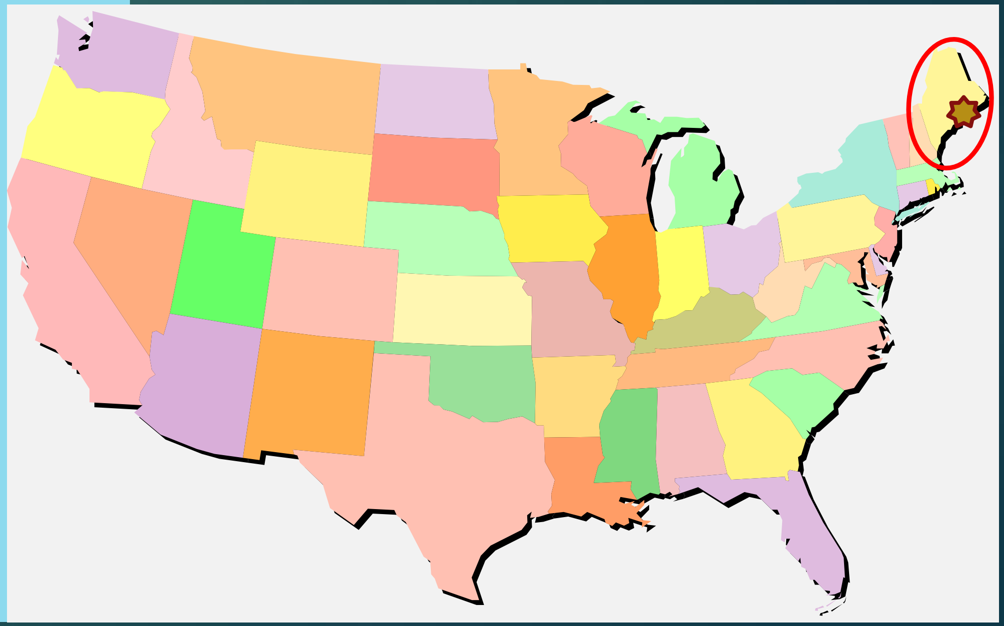
- Learn about the Penobscot Narrows Bridge and how it relates to the carbon fiber research program
- Become familiar with the properties of carbon fiber strand and how the properties compare with steel prestressing strand
- Understand how the strands were installed while the bridge was open to traffic
- Gain knowledge of carbon fiber stay strand behavior in real-world conditions from the obtained long-term monitoring results

Presentation Outline

- Project location
- Project description
- Carbon fiber research program
- Carbon fiber properties
- Carbon fiber installation
- Monitoring results
- Conclusions

Project Location

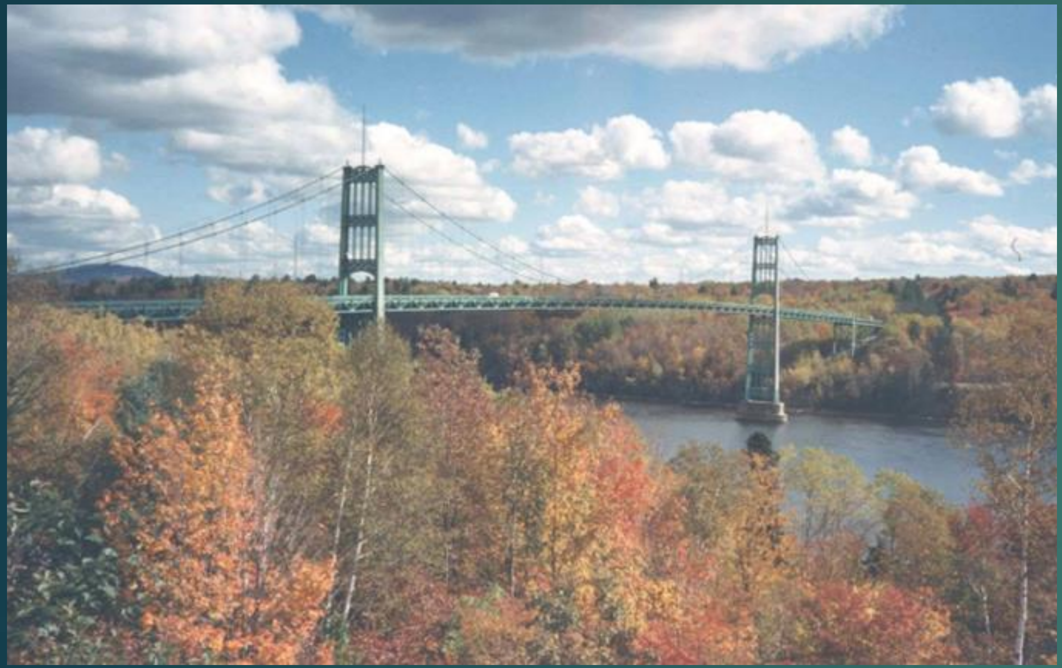




- Project location
- **Project description**
- Carbon fiber research program
- Carbon fiber properties
- Carbon fiber installation
- Monitoring results
- Conclusions

Project Description

Original Waldo-Hancock Bridge



Completed in 1931

May 2003 – Major cable deterioration uncovered
308 wire breaks
(out of 1369 total – 22%)

Posted at 12 tons with 43-mile detour

First in the world cable strengthening
November 2003
(Re-posted at 40 tons)

New bridge needed ASAP

Project Description – Replacement

Penobscot Narrows Bridge

Ground "chipping"
December 2003

Ribbon cutting
December 2006

Early CM/GC bridge project in USA

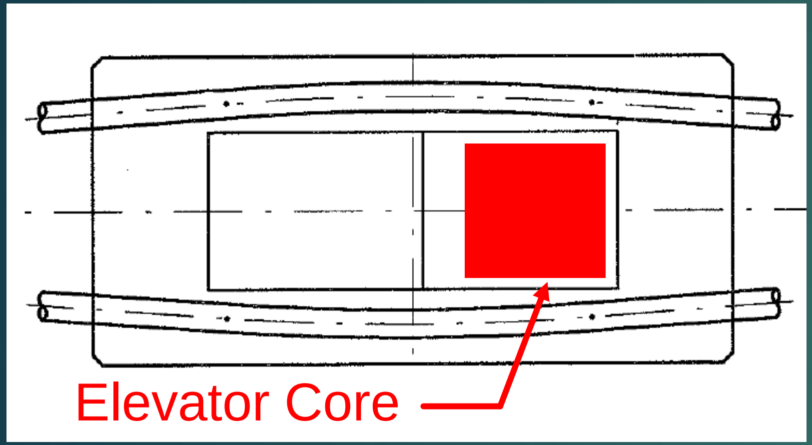
"Owner Facilitated Design Build"

Designed by Figg Engineers, Inc.

Project Description

- 2,120' (646.2 m) long with 1,161' (353.9 m) main span & asymmetric 479.5' (146.2 m) back spans (back to main ratio = 0.413)
- 57.5' (17.5 m) wide that carries 2 traffic lanes and 2 multi-use lanes
- 80' of west end contains a 380' radial curve with corresponding cross-slope change
- 12'-10" (3.91 m) tall box girder that houses stay anchor blocks and struts
- 20 stays per pylon (41 to 72 strands)
- West pylon has a publicly accessible elevator that rises to the 420' (128.0 m) high observatory

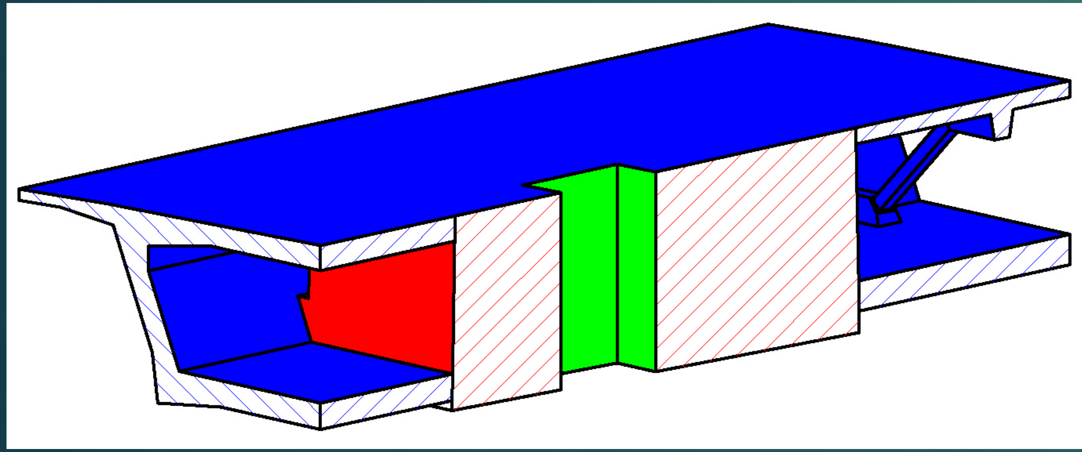
Project Description



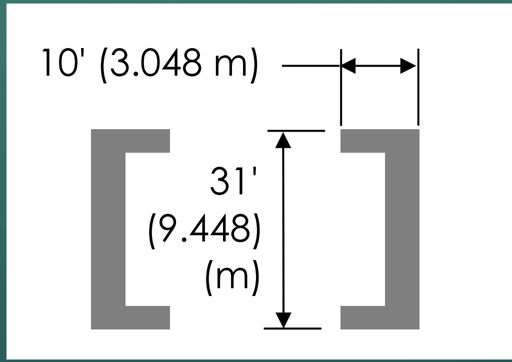
Upper Pylon

Cradles

Stay anchors inside deck (not in pylon)



Tower Table



Lower Pylon

Project Description

Superstructure erected CIP Balanced Cantilever with Form Travelers

Form Traveler (main span)

Form Traveler (back span)

Back segments 20% shorter & 44% heavier

Project Description

Superstructure Stay Anchors located inside the box girder

Project Description

Segmental Bridge construction allowed for building concurrently in 6 directions with friendly competition between 2 pylon crews

Project Description

Bridge was opened to traffic late 2006

Pedestrian Day
October 14th, 2006

Approximately 15,000 people showed up to see their new bridge!

- Project location
- Project description
- **Carbon fiber research program**
- Carbon fiber properties
- Carbon fiber installation
- Monitoring results
- Conclusions

Carbon Fiber Research Program

Demonstration Project History

- Genesis developed from the thought of "what could we use for cables without steel"
- Meetings were arranged with Dr. Nabil Grace from Lawrence Technological University (Southfield Michigan) to develop initial concepts
- A collaborative effort:

MaineDOT
FHWA (Innovative Bridge Research & Deployment Program
Figg Bridge Engineers
Lawrence Technological University
University of Maine

Funding for the structural health monitoring system for carbon fiber composite strands in the Penobscot Narrows Bridge project was provided by the Transportation Infrastructure Durability Center (TIDC) at the University of Maine under grant 69A3551847101 from the U.S. Department of Transportation's University Transportation Centers Program

Carbon Fiber Research Program

2 reference strands in stay 2, 10 and 17 at west pylon were replaced with carbon fiber composite cable

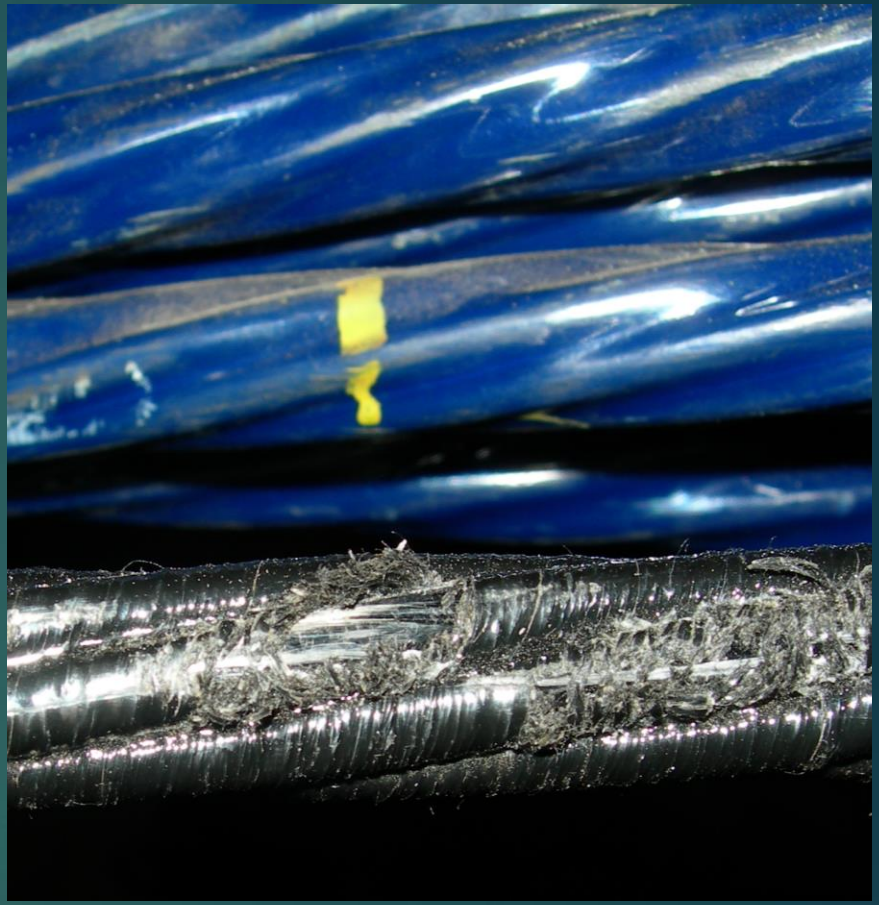
Replacement performed after bridge opening during the spring of 2007 while the bridge was open to traffic

- Project location
- Project description
- Carbon fiber research program
- **Carbon fiber properties**
- Carbon fiber installation
- Monitoring results
- Conclusions

Carbon Fiber Properties

What is it?

- Carbon fiber based non-metallic strand
- Similar composition used in many products, sports equipment (tennis rackets, fishing poles, aircraft parts)
- Now it is possible to economically fabricate strand in long lengths for commercial use
- CFRP = Carbon Fiber Reinforced Polymer
- CFCC = Carbon Fiber Composite Cable



Piece of carbon strand held up against steel strands

Protective coating removed to show detail of fibers that are loaded

Carbon Fiber Properties

Designation (Configuration diameter) 呼称		Diameter 直径 (mm)	Effective cross sectional area 有効断面積 (mm^2)	Guaranteed capacity 保証破断荷重 (kN)	Nominal mass density 単位長さ質量 (g/m)
	U 5.0φ	5.0	15.2	28	30
	1×7 7.5φ	7.5	30.4	57	64
	1×7 10.5φ	10.5	55.7	104	114
	1×7 12.5φ	12.5	76.0	142	151
	1×7 15.2φ	15.2	113.6	199	226
	1×7 17.2φ	17.2	149.8	262	290
	1×19 20.5φ	20.5	206.2	316	410
	1×19 25.5φ	25.5	304.7	467	606
	1×19 28.5φ	28.5	401.0	594	777
	1×37 35.5φ	35.5	591.2	841	1,185
	1×37 40.0φ	40.0	779.4	1,070	1,508

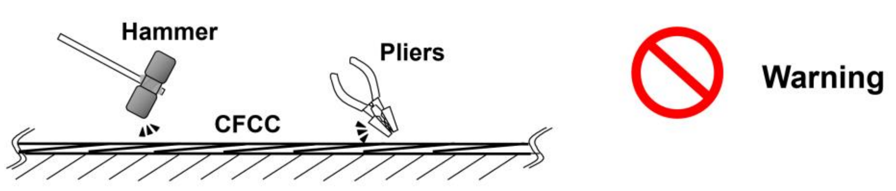
Similar to steel strands standard sizes of carbon fiber strands are available

Property	**Carbon Fiber Strand**		**Epoxy Coated Steel Strand**		**Change from Steel Strand**	
Diameter:	0.6"	(15.2 mm)	0.6"	(15.0 mm)	No change	
Area:	0.176 in^2	(113.6 mm^2)	0.217 in^2	(140.0 mm^2)	1.23 x less	
Capacity:	44.8 kips 255 ksi	(199 kN) (1758 MPa)	58.6 kips 270 ksi	(261 kN) (1862 MPa)	1.31 x less 1.06 x less	(force) (stress)
Unit Weight:	0.15 lb/ft	(226 g/m)	0.82 lb/ft	(1220 g/m)	5.40 x less	(weighs less)
Modulus:	19,877 ksi	(137,047 MPa)	28,500 ksi	(196,501 MPa)	1.43 x less	(more elongation)
Expansion:	1.1×10^{-6}/°F	(2.0×10^{-6}/°C)	6.5×10^{-6}/°F	(11.7×10^{-6}/°C)	5.91 x less	(less thermal effect)
Friction:	0.3	(unitless)	0.5	(unitless)	1.67 x less	(less friction over radii)
Ductility:	Stress/strain relationship linear all the way to failure				(low ductility – no strain hardening)	

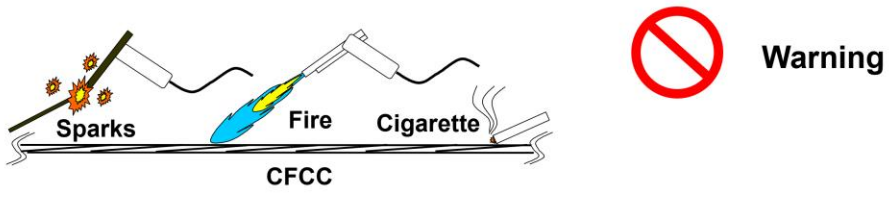
- Project location
- Project description
- Carbon fiber research program
- Carbon fiber properties
- **Carbon fiber installation**
- Monitoring results
- Conclusions

Carbon Fiber Installation - Handling

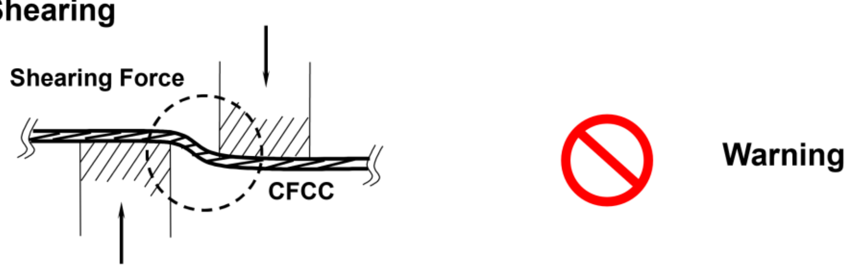
1) Falling object (tools and other hard objects) on CFCC



2) Fire / heat (contact with hot objects)

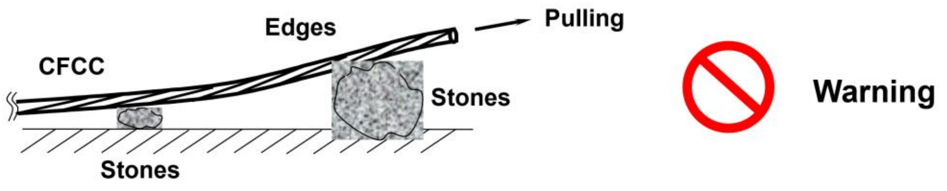


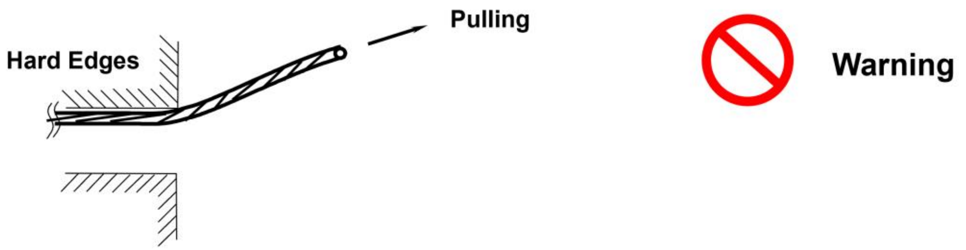
3) Shearing



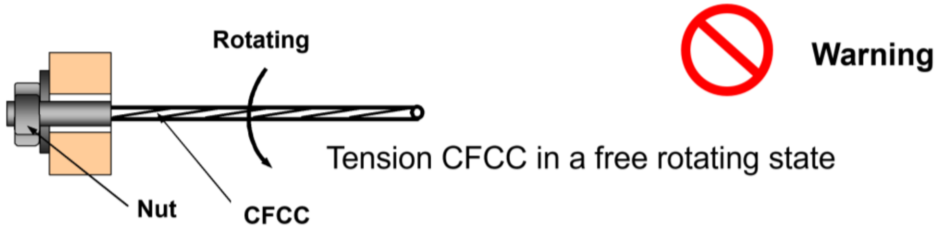
4) Bending on the neck of socket

5) Scraping (friction with hard objects)

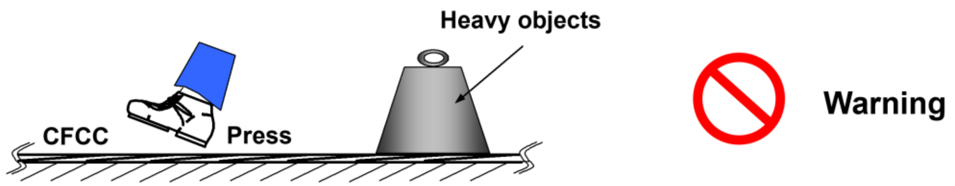




6) Untwisting (tension CFCC in a free rotating state)



7) Stamping and loading heavy objects

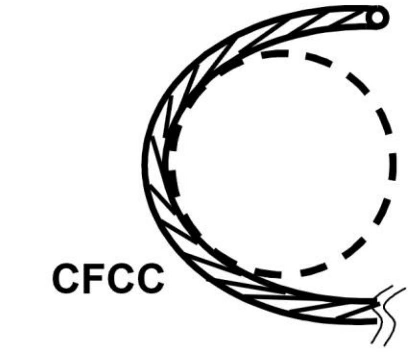


Carbon Fiber Installation

Handling Precautions

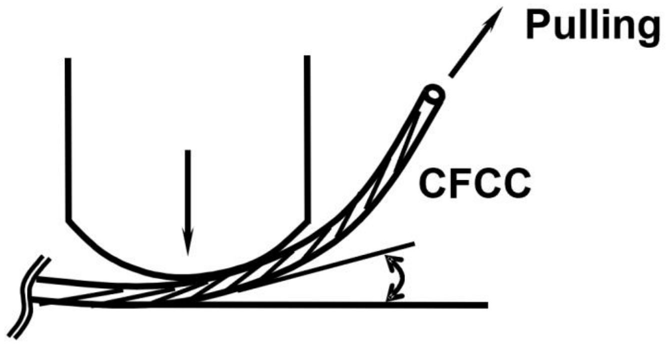
1) Bending without tension

When bending CFCC during work other than tensioning bend it with as large a bending radius as possible



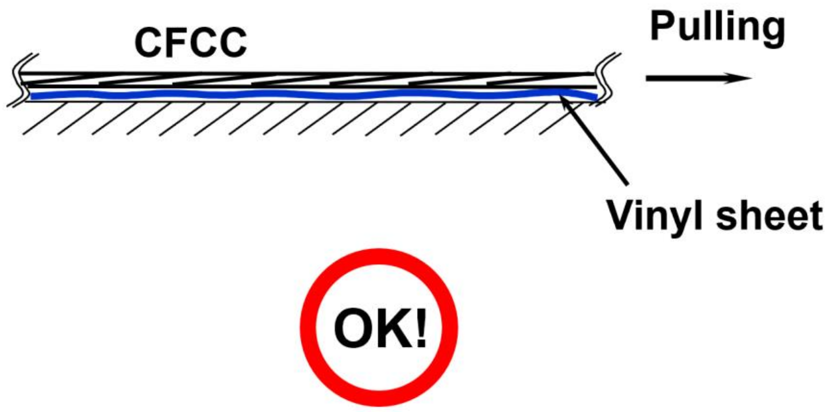
2) Bending with tension

When tensioning CFCC while it is bent, strictly observe the bending radius and bending angle



3) Dragging

Before spreading and dragging CFCC, spread a vinyl sheet to avoid scratches and stains on the CFCC.



Carbon Fiber Installation

Carbon strand reel

Tray to protect carbon strand during installation

Coupler to de-tension original steel strand

- Installed completely from inside the deck box section
- Traffic not affected during installation (no restrictions)
- Previous steel strand de-tentioned and utilized as the pulling wire
- Carbon strand attached to previous strand and pulled through upper tower cradle to other end at deck level (tower access not required)
- Replaced 2 strands per stay

Carbon Fiber Installation

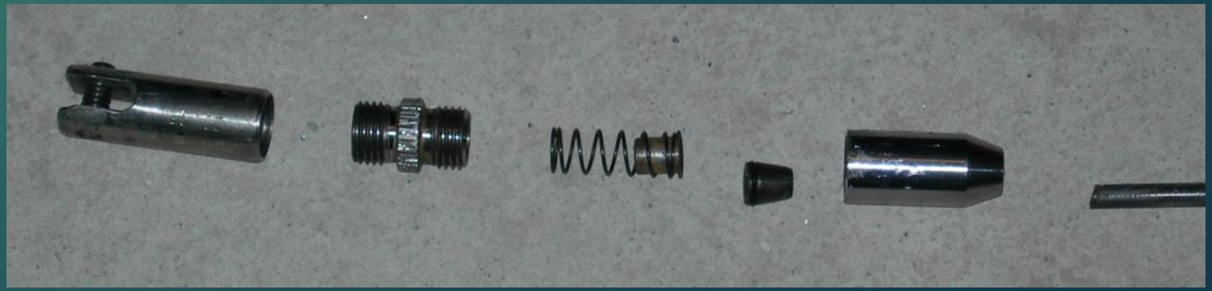
- Attach carbon strand to previous steel strand via king wire
- King wire coupler must be same diameter as strand to facilitate travel through cradle
- Cut to length once pulled through

Example of an exposed king wire for pulling

Cut strand to length after pulling

Pass through cradle

Steel strand King wire coupler Carbon strand

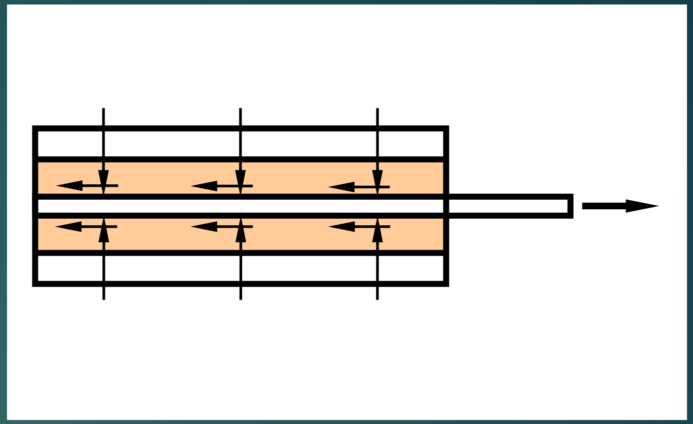


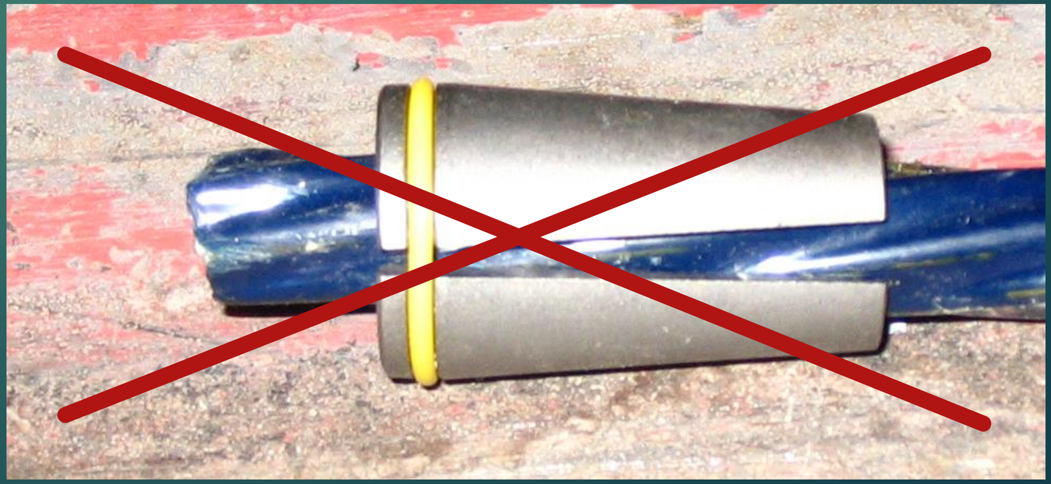
King wire coupler pieces

Carbon Fiber Installation

Anchorages

- Cannot utilize conventional steel wedges (too brittle)
- Anchoring system uses a Highly Expansive Material
- The HEM is confined to create bonding through side friction
- Permanent bonding pressure is 7250 psi to 14,500 psi (50 Mpa – 100 Mpa)





Carbon Fiber Installation

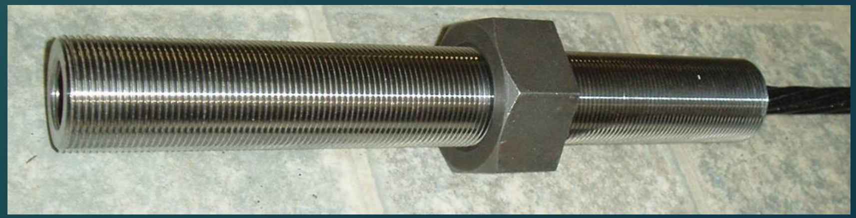
Anchorages

Place carbon stand in HEM and cure

- HEM curing is temperature controlled
- Normal traffic on bridge during cure
- Curing complete after 24 hours

Temperature monitoring of
HEM during curing

Curing complete



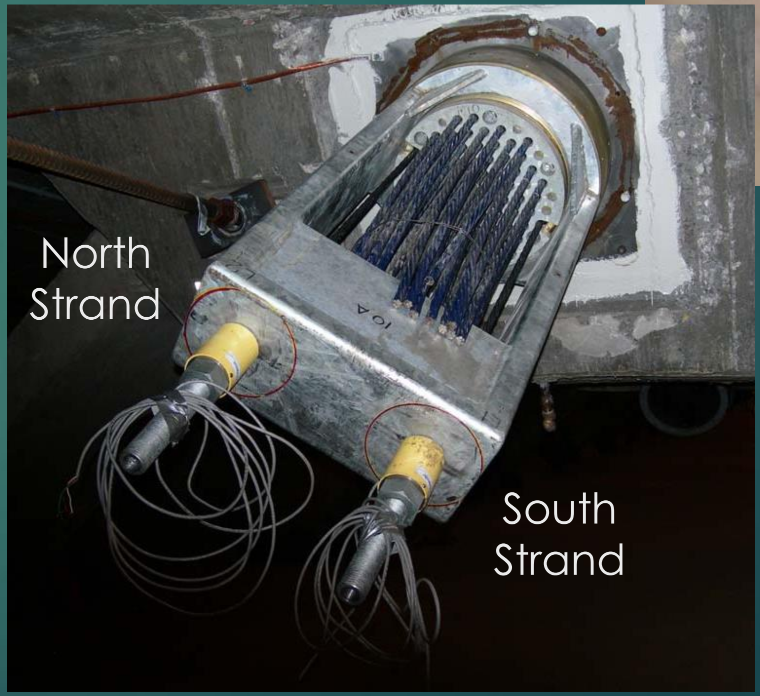
Carbon Fiber Installation

Stressing and Instrumentation

Stressing

Monitoring table inside bridge

Strain sensor on strand



Completed carbon fiber anchor chair without permanent cap

Carbon fiber anchor with permanent cap (note see-through end cap)

Carbon Fiber Installation

Types of Instruments

- Linear variable differential transformers (LVDTs)
  (used to monitor carbon fiber anchor chair displacements)
- Fiber optic strain (FOS) sensors
  (used to monitor carbon fiber strains)
- Center hole load-cells
  (used to monitor force in carbon fiber strands)
- Temperature sensors
  (used to monitor temperatures at measuring locations and the ambient temperature at the bridge site)

- Project location
- Project description
- Carbon fiber research program
- Carbon fiber properties
- Carbon fiber installation
- **Monitoring results**
- Conclusions

Monitoring Results

Initial Installation – June 2007

Anchor Location *	Stressing Length Deck to Pylon	Adjacent Steel Strand Force	Initial Carbon Fiber Strand Force
Stay 02 (A = Back Span)	134' (40.8 m)	25.20 kips (112 kN)	**25.92 kips (115 kN)**
(B = Main Span)	149' (45.4 m)	22.20 kips (99 kN)	**22.98 kips (102 kN)**
Stay 10 (A = Back Span)	303' (92.4 m)	22.20 kips (99 kN)	**20.03 kips (89 kN)**
(B = Main Span)	346' (105.5 m)	21.10 kips (94 kN)	**21.01 kips (93 kN)**
Stay 17 (A = Back Span)	459' (139.9 m)	22.20 kips (99 kN)	**20.86 kips (93 kN)**
(B = Main Span)	526' (160.3 m)	21.30 kips (95 kN)	**20.53 kips (91 kN)**

* Locations A and B on later slides refer to the back and main spans sides respectively

Monitoring Results

Data Obtained *

Date	Single Readings	Continuous Readings
2007 June	Yes	---
2013 March	Yes	---
2018 November	Yes	---
2023 November	Yes	Yes
2024 May	Yes	Yes

Single Readings: Obtained once

Continuous Readings: Obtained every hour over a two-day period

* Additional data exists – Data above represents values utilized for this presentation
The University of Maine monitors and maintains the system and is now fully automated and remotely accessed

Additional Data/Publications

Performance of Carbon Fiber Strand in a Maine Cable Stay Bridge

JEFF FOLSOM, PE, Maine Department of Transportation, Augusta, Maine and CHRIS BURGESS PE, SE, GM2, Denver, Colorado

IBC 24–12

KEYWORDS: Demonstration Project, carbon fiber strands, carbon fiber reinforced polymer strands, CFRP, Maine Department of Transportation, MaineDOT

ABSTRACT: MaineDOT in association with FHWA used federal IBRC funds in 2006 to implement a Demonstration Project for evaluating carbon fiber strands in bridges. This program involved installing representative carbon fiber strands in the cable stays of the Penobscot Narrows Bridge and Observatory in Maine. Background will be shared about carbon fiber stay strand installation along with results from inspection and load monitoring that has been performed from 2007 through May 2024.

A comprehensive reference for additional information is the recently completed 2024 IBC publication:

"Performance of Carbon Fiber Strand in a Maine Cable Stay Bridge"

Jeff Folsom, PE – Maine DOT
Chris Burgess, PE, SE – GM2 Associates, Inc.

REFERENCES

1. ACI Committee 440, "State –of-the-Art Report on Fiber Reinforced Plastic Reinforcement for Concrete Structures," American Concrete Institute, Farmington Hills, MI, 1996, 153 pp.

2. Rizkalla, S. H., "A New Generation of Civil Engineering Structures and Bridges," Proceedings of the Third International Symposium on Non-metallic (FRPRC) Reinforcement for Concrete Structures, Sapporo, Japan, V. 1, October 1997, pp. 113-128.

3. Dolan, C. W., "FRP Prestressing in the USA," ACI Concrete International, V. 21, No. 10, October 1999, pp. 21-24.

4. Tadros, G., "Provisions for Using FRP in the Canadian Highway Bridge Design," ACI Concrete International, V. 22, No. 7, July 2000, pp. 42-47.

5. Japan Society of Civil Engineers (JSCE), "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials," Concrete Engineering Series 23, Japan Society of Civil Engineers, Tokyo, Japan, October 1997, 325 pp.

6. Grace, N. F. and Abdel-Sayed, G., "Ductility of Prestressed Concrete Bridges Using CFRP Strands," ACI Concrete International, V. 20, No. 6, June 1998, pp. 25-30.

7. Grace, N. F. and Abdel-Sayed, G., "Behavior of Externally Draped CFRP Tendons in Prestressed Concrete Bridges," PCI Journal, V. 43, No. 5, September-October 1998, pp. 88-101.

8. Grace, N. F., "Response of Continuous CFRP Prestressed Concrete Bridges Under Static and Repeated Loadings," PCI Journal, V. 45, No. 6, November-December 2000, pp. 84-102.

9. Grace, N. F., "Transfer Length of CFRP/CFCC Strands for Double-T Girders," V. 45, No. 5, September-October 2000, pp. 110-126.

10. Grace, N. F., Enomoto, T., and Yagi, K., "Behavior of CFCC and CFRP Leadline Prestressing System in Bridge Construction," PCI Journal, V. 47, No. 3, May-June 2002, pp. 90-103.

11. Grace, N. F., Navarre, F., Nacey, R. B., Bonus, W., and Collavino, L. "Design Construction of Bridge Street Bridge-First CFRP Bridge in the USA," PCI Journal, September-October 2002.

12. Tokyo Rope Mfg. Co. Ltd., "Technical Data on CFCC," Product Manual, 1993.

13. Grace, N. F., Enomoto, T., Abdel-Sayed, G., Yagi, K., and Collavino, L., "Experimental Study and Analysis of a Full-Scale CFRP/CFCC Double-Tee Bridge Beam," PCI Journal, V. 48, No. 4, July 2003, pp. 120-139.

14. Grace, N. F., "Response of Continuous CFRP Prestressed Concrete Bridges under Static and Repeated Loadings," PCI Journal, V. 45, No. 6, November 2000, pp. 84-102. Tokyo Rope Mfg. Co. Ltd., "Technical Data on CFCC," Product Manual, 1993.

15. Penobscot Narrows Bridge Certification CFCCTM Quality Report, Tokyo Rope Mfg. Co. Ltd., September 29, 2006.

16. Keith A. Berube, University of Maine. Data provided via email on November 15, 2023 and May 3, 2024.

17. Funding for the structural health monitoring system for carbon fiber composite strands in the Penobscot Narrows Bridge project was provided by the Transportation Infrastructure Durability Center (TIDC) at the University of Maine under grant 69A3551847101 from the U.S. Department of Transportation's University Transportation Centers Program.

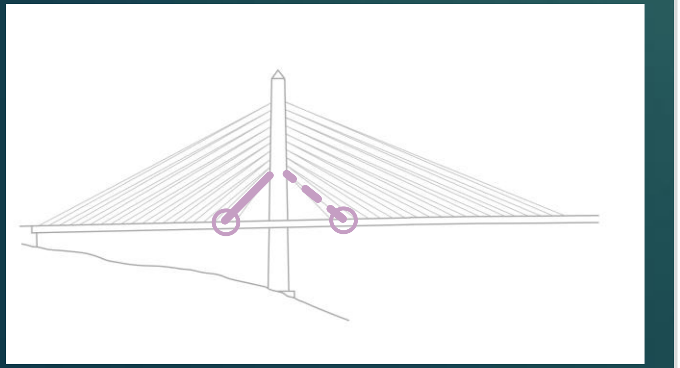
Single Reading Monitoring Results

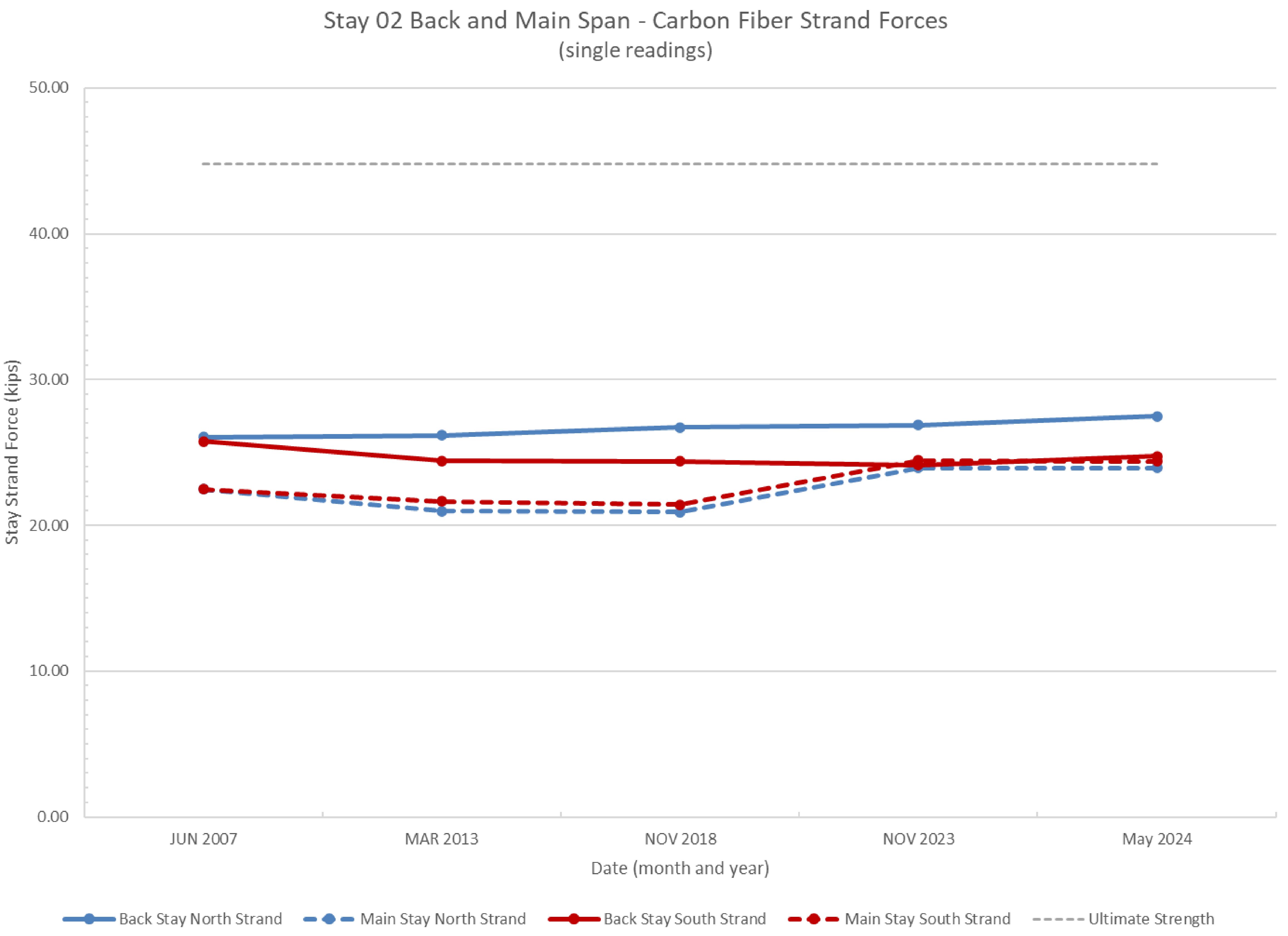
Stay 02

Ultimate Strength
44.8 kips (199 kN)

Minimum Value
20.91 kips
(93.0 kN)

Maximum Value
27.49 kips
(122.3 kN)





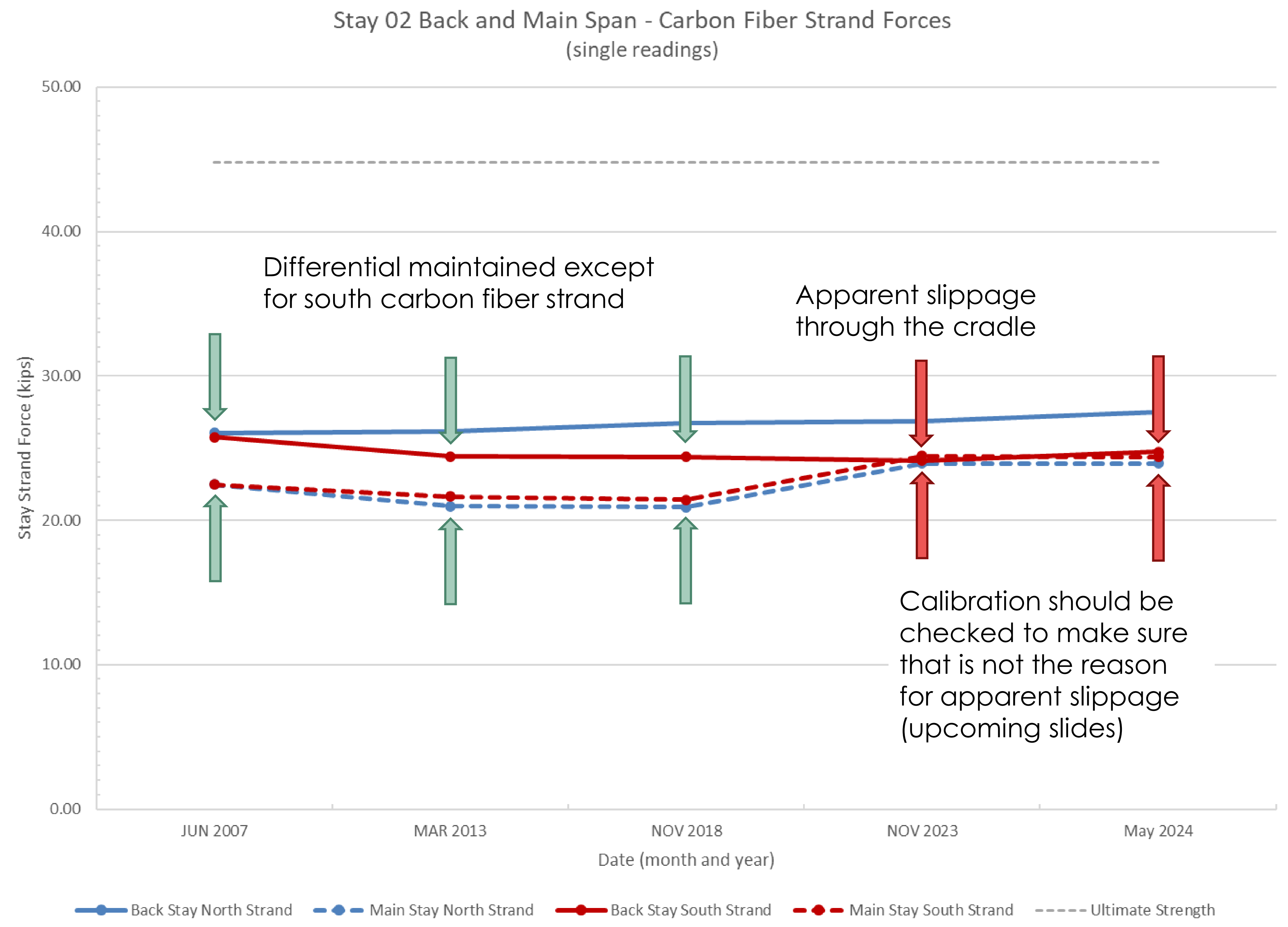
Single Reading Monitoring Results

Stay 02

Restressed at End of Construction

Initial locked in differential over cradle
2.94 kips
(9.6 kN)

Appears that the south carbon fiber strand may have slipped through the cradle sometime between 11/2018 & 11/2023



Stay 02 Additional Comments

- Carbon fiber strand very hard to the touch – when sliding through a steel sleeve sample it seems less restrained by friction compared to the steel strand (μ=0.3 versus 0.5) – Epoxy coating on steel strand seems "grippy" on the cradle sleeve

- Carbon fiber strands are not required by design

- Steel strands also have a monitoring system at each stay (DSI-DYNA Force™)

- Steel strand monitoring (every five years) show that there is no slippage and the expected differential forces through cradle have been maintained

- Will check calibration of equipment at Stay 02B

Close-up of epoxy and carbon fiber strand

Epoxy coated strand through stainless steel cradle sleeve

DSI-DYNA Force™ monitoring system for steel stay strands (at each anchorage)

DSI-DYNA Force™ portable data acquisition box (manual hookup at each stay)

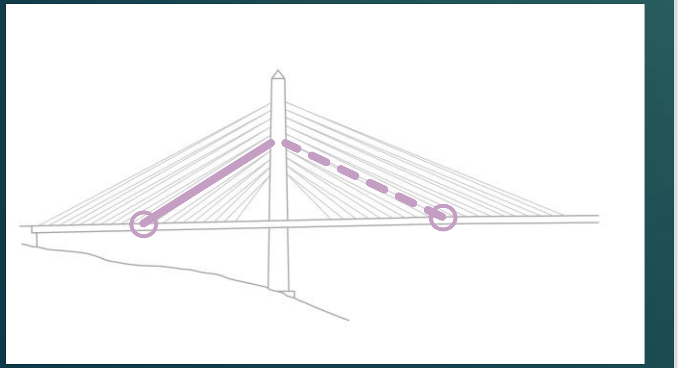
Single Reading Monitoring Results

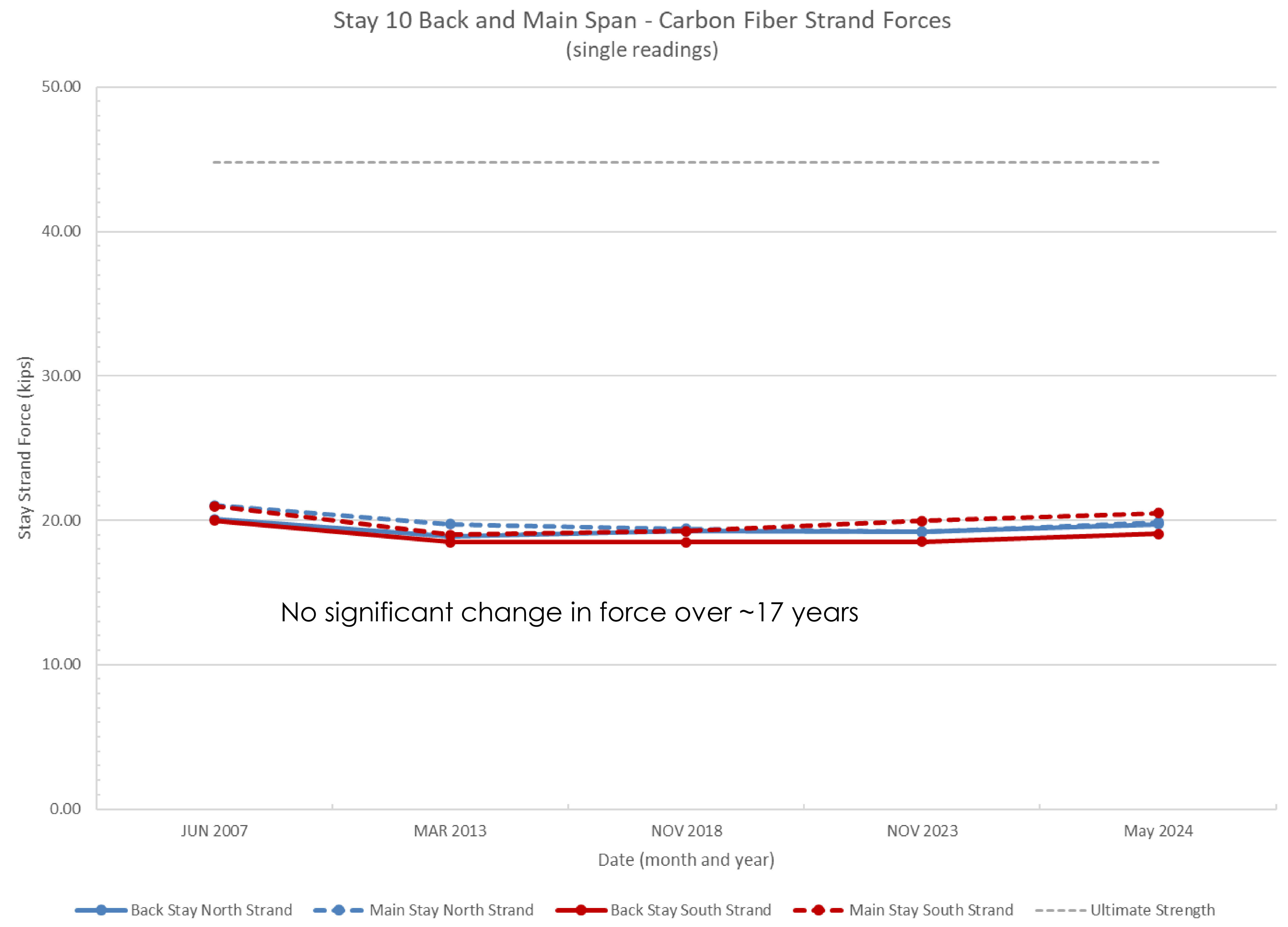
Stay 10

Ultimate Strength
44.8 kips (199 kN)

Minimum Value
18.48 kips
(82.2 kN)

Maximum Value
21.01 kips
(93.5 kN)





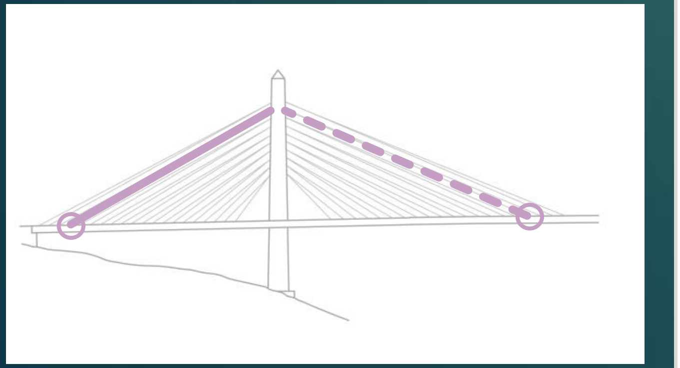
Single Reading Monitoring Results

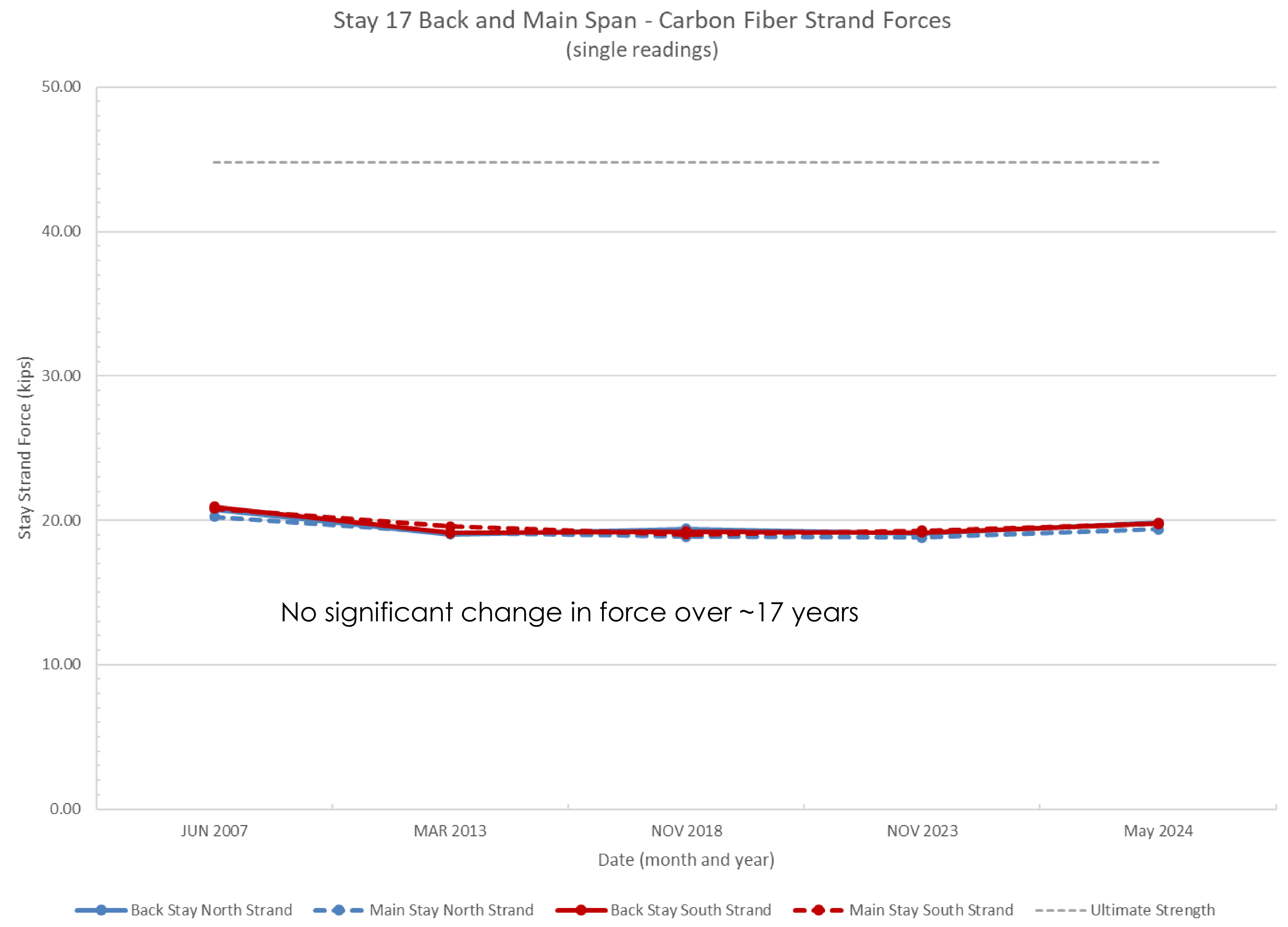
Stay 17

Ultimate Strength
44.8 kips (199 kN)

Minimum Value
18.82 kips
(83.7 kN)

Maximum Value
20.86 kips
(92.8 kN)





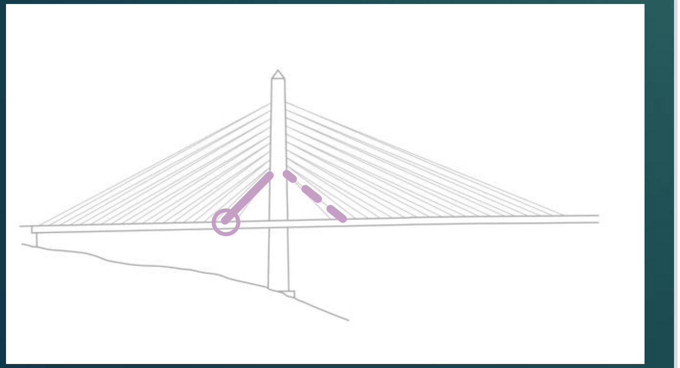
Continuous Reading Monitoring Results

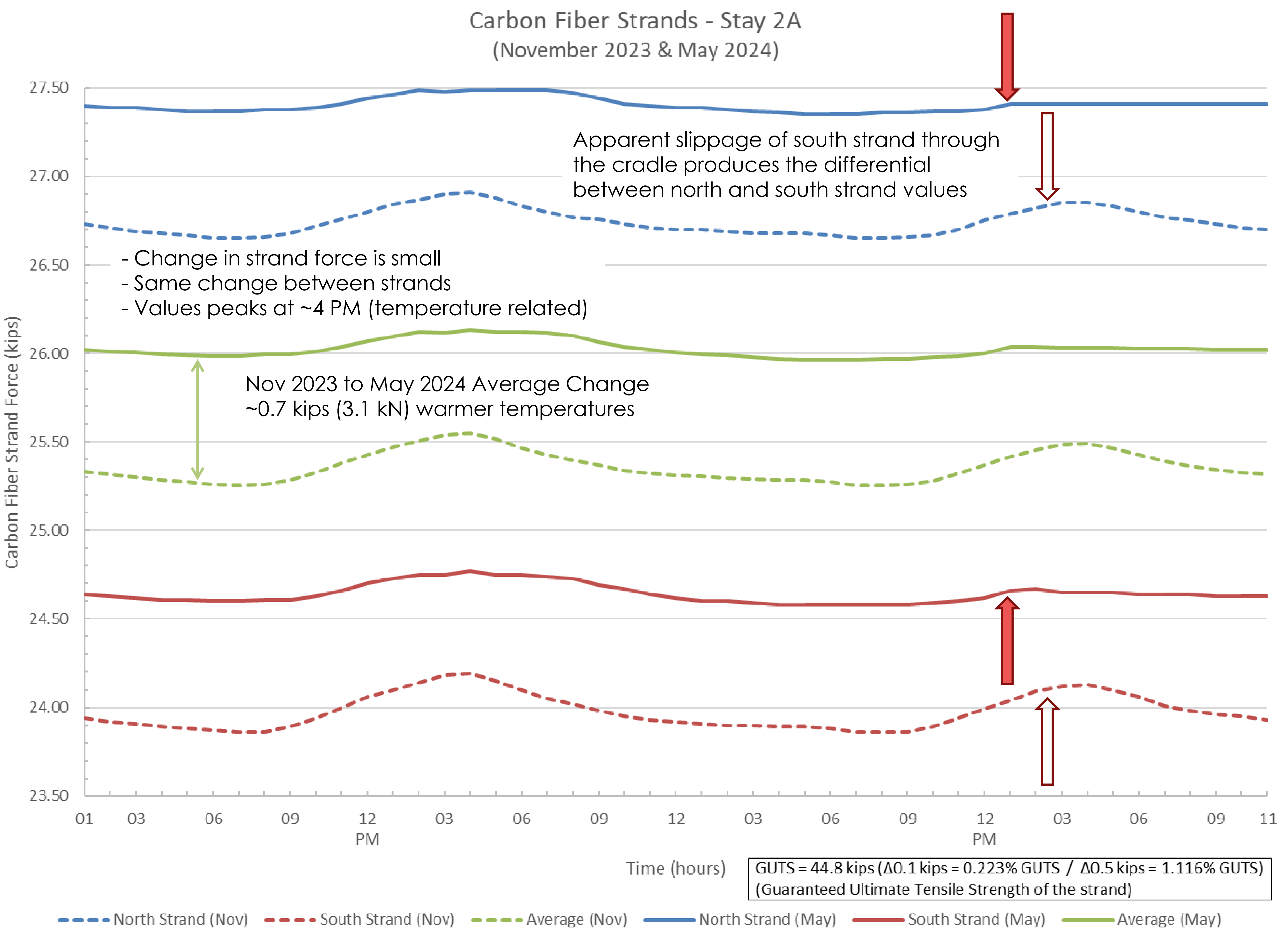
11/13 to 11/14/2023
05/01 to 05/02/2024
(2 days – each hour)

Stay 02A (Backspan)

Average Value
25.36 kips (Nov)
26.03 kips (May)

Maximum Change
Δforce = ~0.3 kips
(Nov or May)





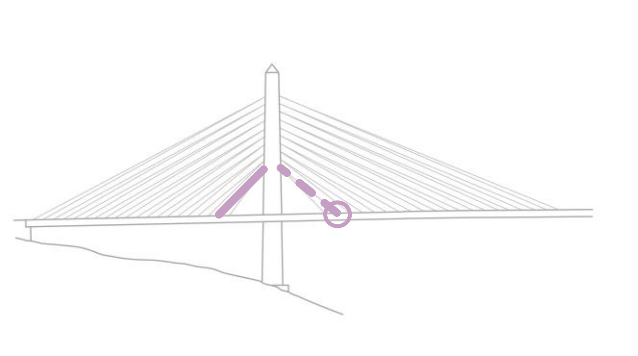
Continuous Reading Monitoring Results

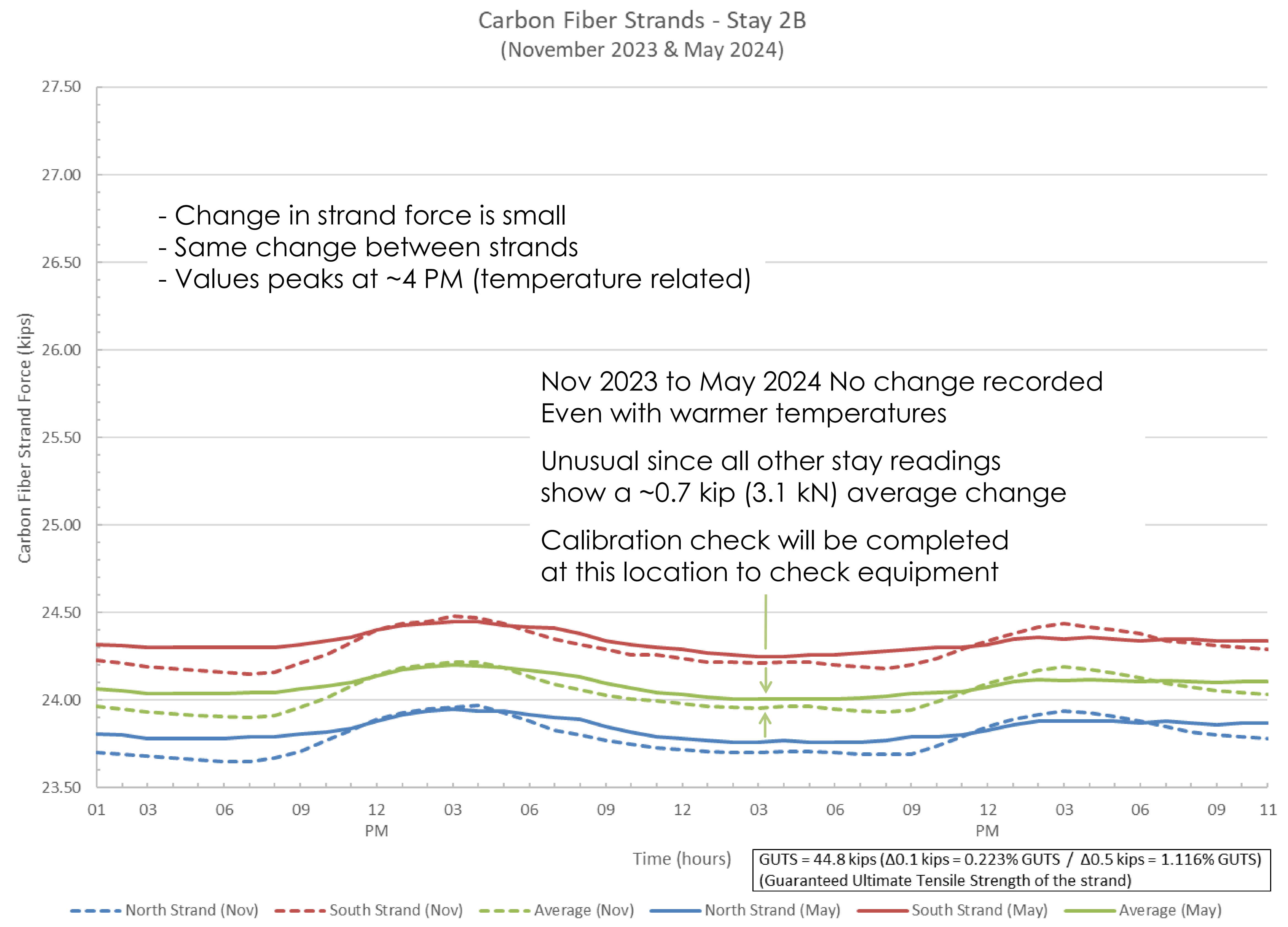
11/13 to 11/14/2023
05/01 to 05/02/2024
(2 days – each hour)

Stay 02B (Mainspan)

Average Value
24.04 kips (Nov)
24.08 kips (May)

Maximum Change
Δforce = ~0.3 kips
(Nov or May)





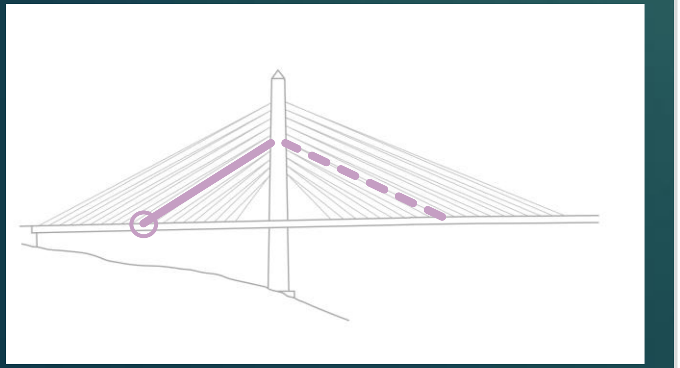
Continuous Reading Monitoring Results

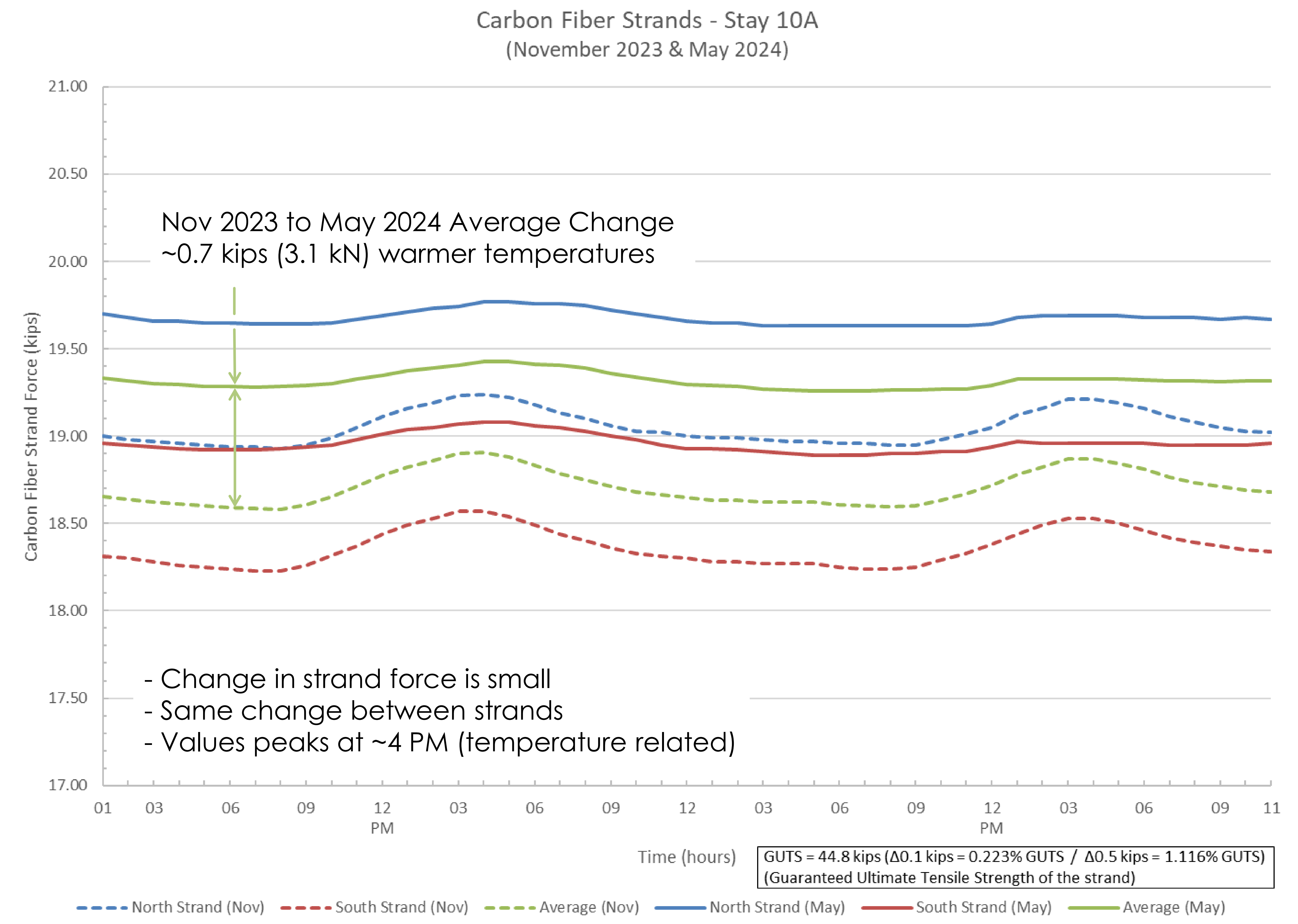
11/13 to 11/14/2023
05/01 to 05/02/2024
(2 days – each hour)

Stay 10A (Backspan)

Average Value
18.71 kips (Nov)
19.32 kips (May)

Maximum Change
Δforce = ~0.3 kips
(Nov or May)





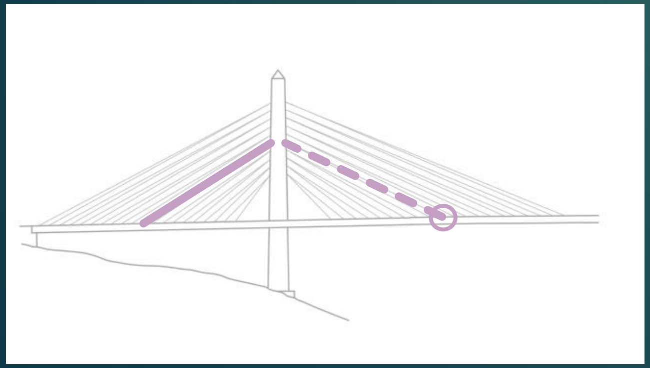
Continuous Reading Monitoring Results

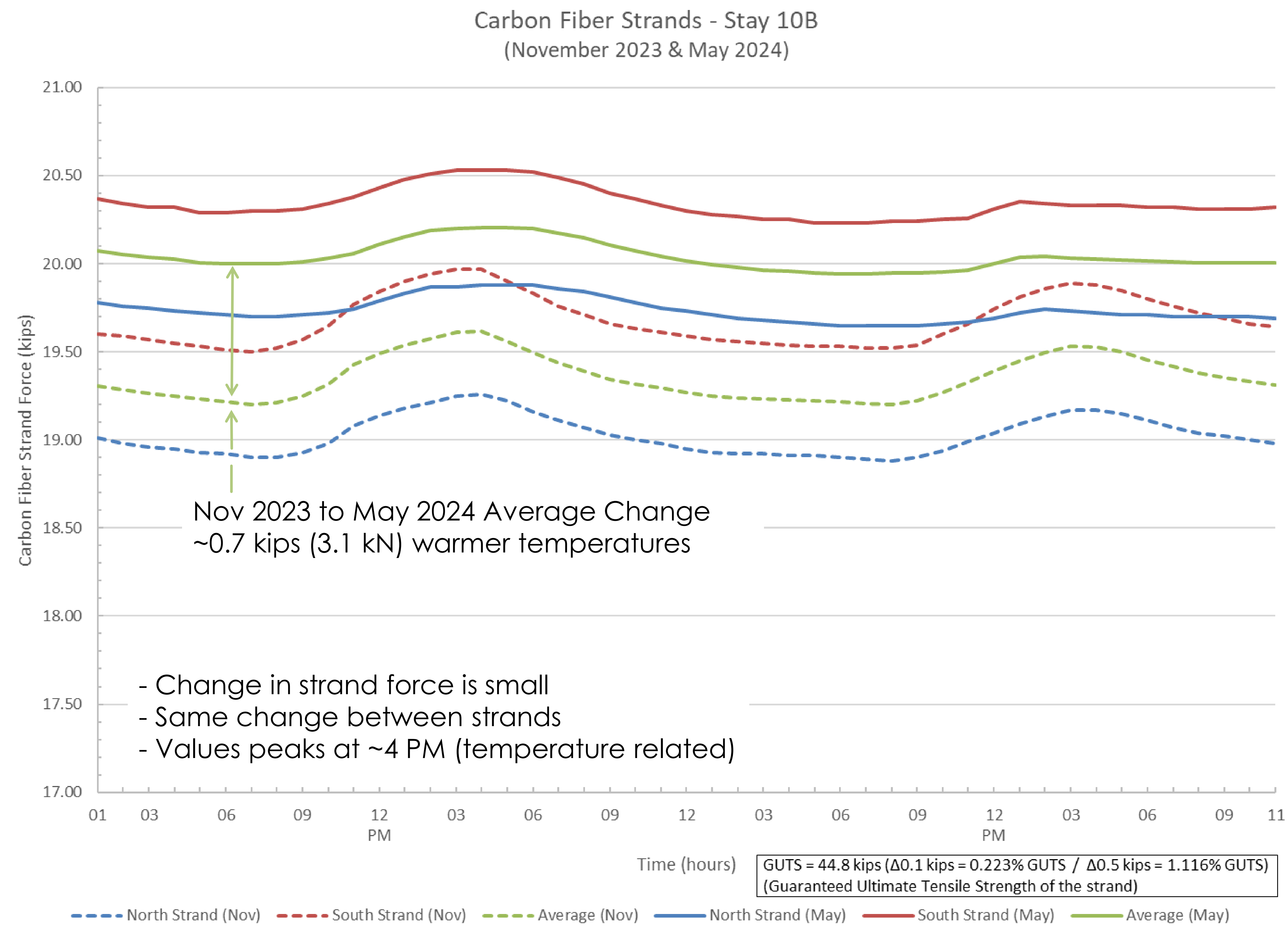
11/13 to 11/14/2023
05/01 to 05/02/2024
(2 days – each hour)

<u>Stay 10B (Mainspan)</u>

Average Value
19.35 kips (Nov)
20.04 kips (May)

Maximum Change
Δforce = ~0.4 kips
(Nov or May)





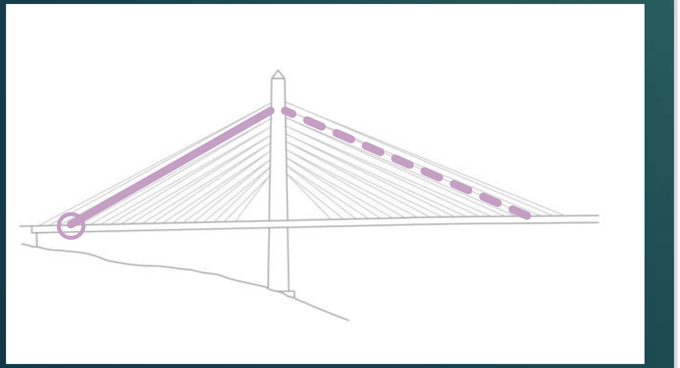
Continuous Reading Monitoring Results

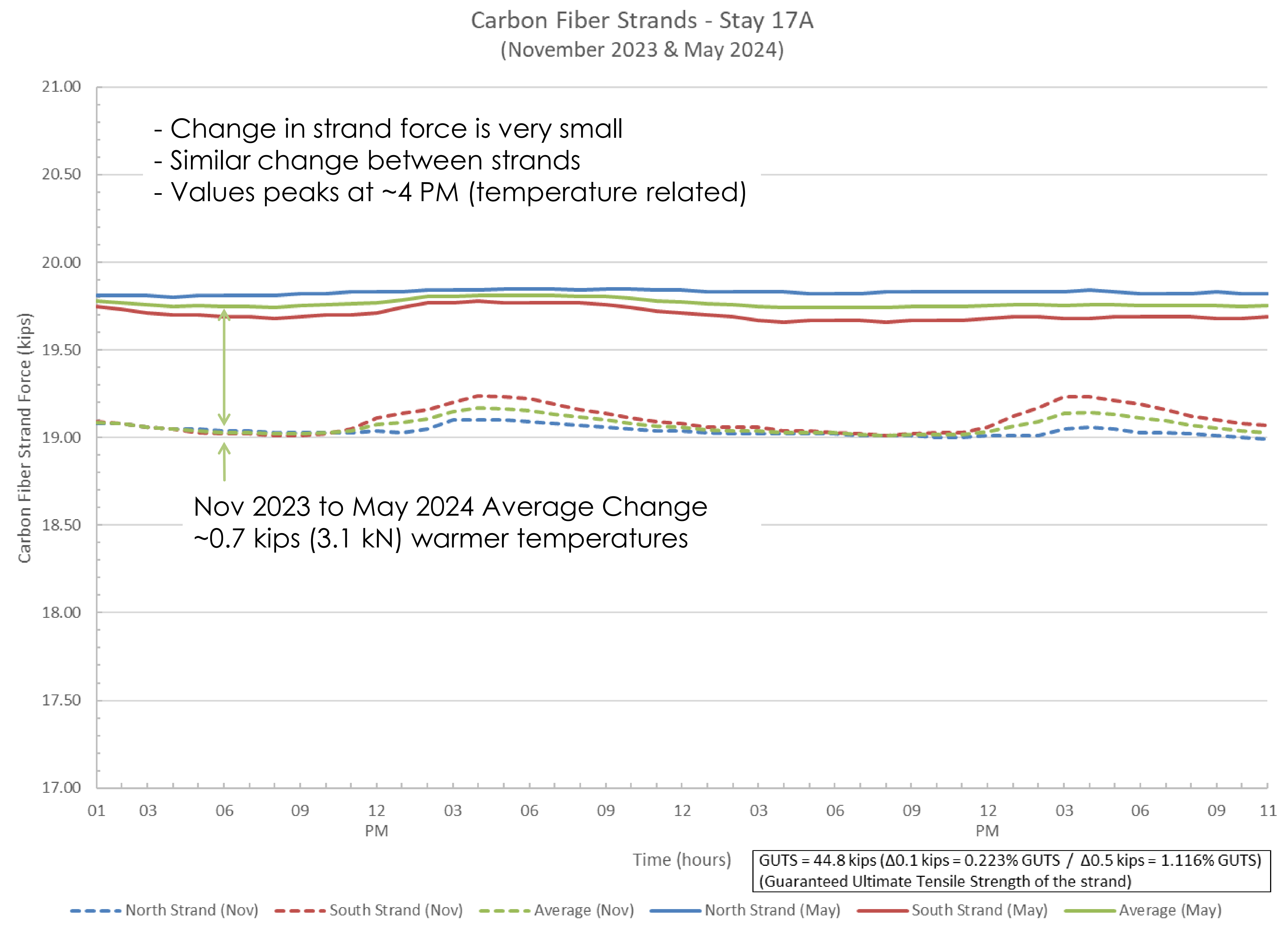
11/13 to 11/14/2023
05/01 to 05/02/2024
(2 days – each hour)

Stay 17A (Backspan)

Average Value
19.07 kips (Nov)
19.77 kips (May)

Maximum Change
Δforce = ~0.2 kips
(Nov or May)





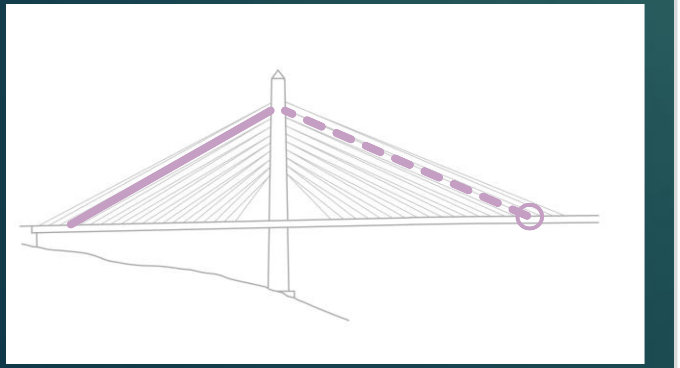
Continuous Reading Monitoring Results

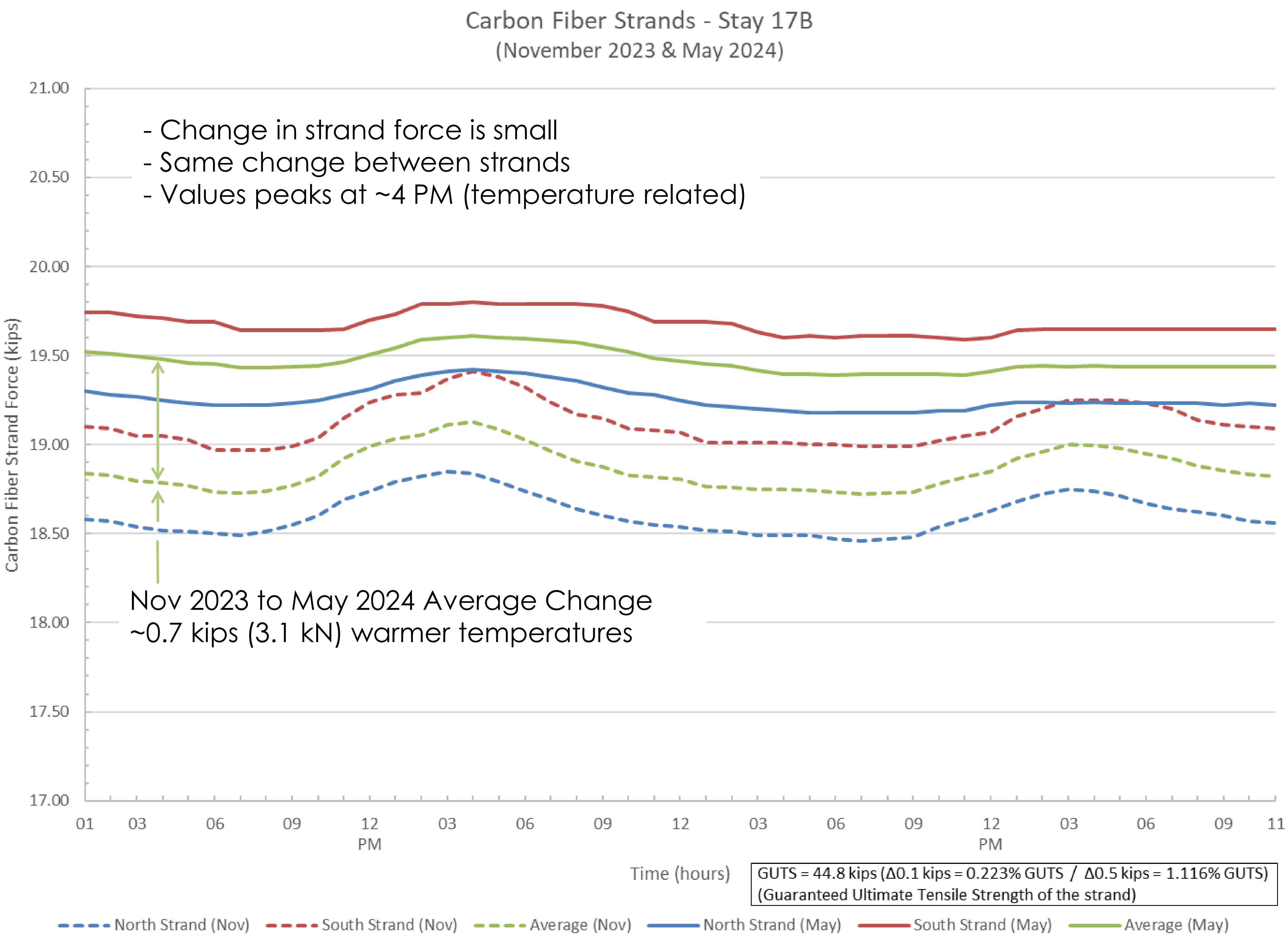
11/13 to 11/14/2023
05/01 to 05/02/2024
(2 days – each hour)

Stay 17B (Mainspan)

Average Value
18.86 kips (Nov)
19.47 kips (May)

Maximum Change
Δforce = ~0.4 kips
(Nov or May)





Monitoring Results

Continuous Reading Additional Comments

- Results show stable strand forces with no concerning or unexpected behavior for the strands themselves

- Stay temperature does influence the forces, producing a slight oscillation of the readings

- Thermal effects are investigated further with the next set of graphs

University of Maine
On-site automated Weather Station

Continuous Reading Monitoring Results

11/13 to 11/14/2023
05/01 to 05/02/2024

(2 days – each hour)

Average of all Stays

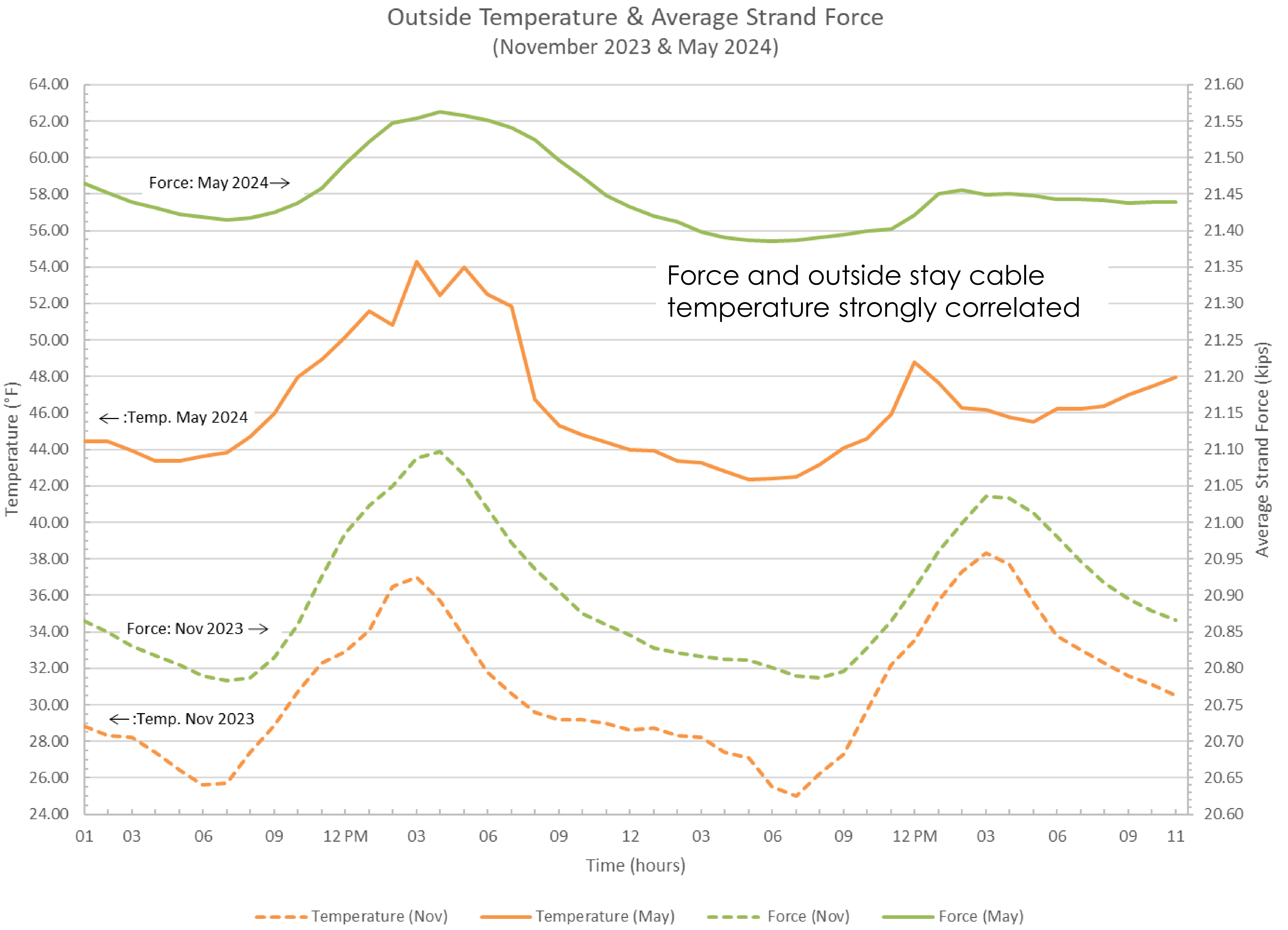
Force and temperature strongly correlated

Peaks at ~4 PM

Overall Variations:

Low: 25.0 °F (-3.89 °C)
High: 54.3 °F (12.39 °C)
ΔT: 29.3 °F (16.28 °C)

Low: 20.8 kips (92.5 kN)
High: 21.6 kips (96.1 kN)
ΔF: 0.8 kips (3.6 kN)



Continuous Reading Monitoring Results

11/13 to 11/14/2023
05/01 to 05/02/2024

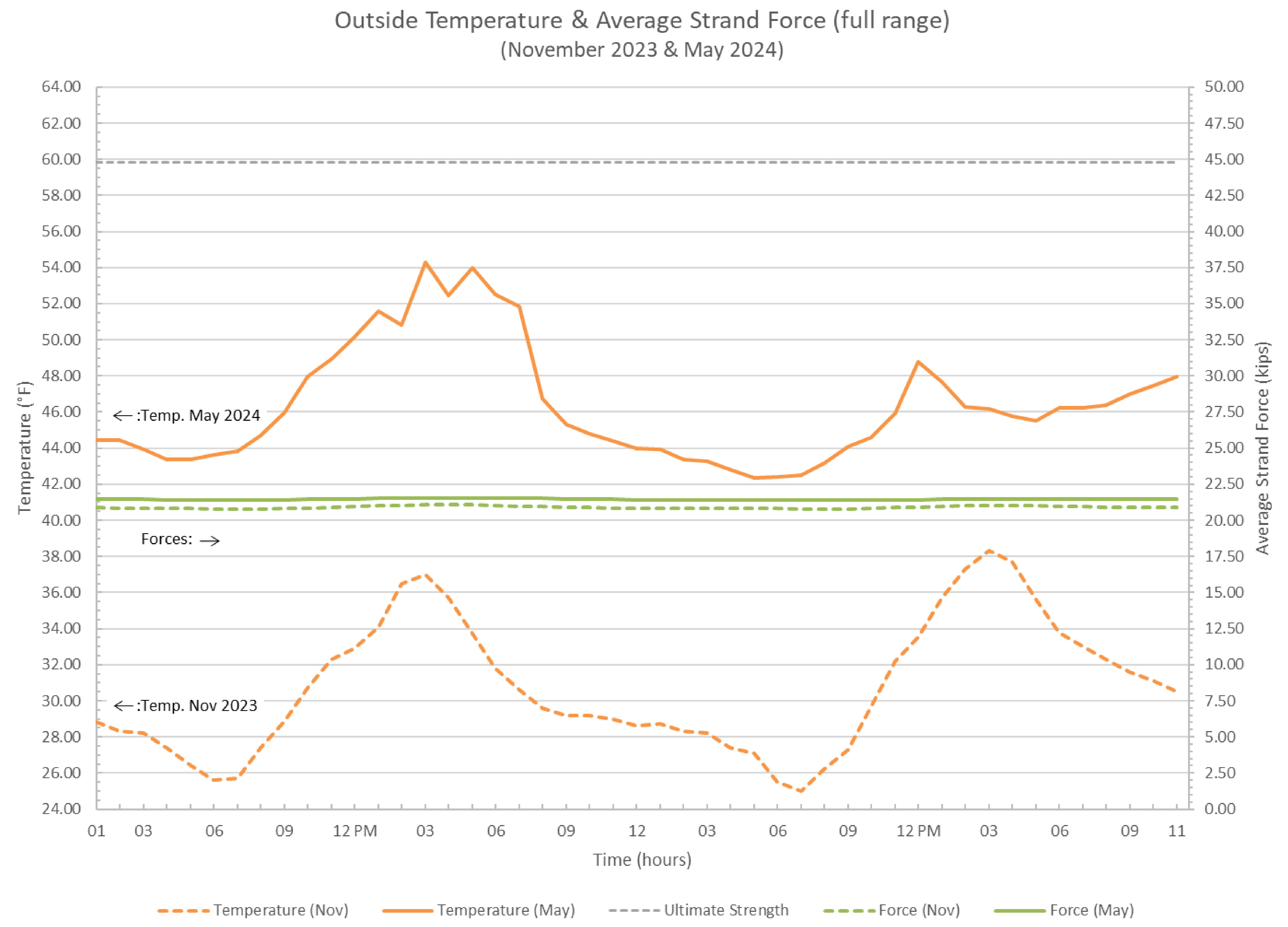
(2 days – each hour)

Average of all Stays

Same as the previous graph

Strand force plotted with respect to ultimate capacity

Shows small change in force (thermal coefficient 5.91 x less than steel strands)



- Project location
- Project description
- Carbon fiber research program
- Carbon fiber properties
- Carbon fiber installation
- Monitoring results
- **Conclusions**

Conclusions

- Monitoring for the past 17 years shows that long-term performance of the carbon fiber strands are behaving as expected (except for the south strand at Stay 2 which appears to have slipped within the cradle sleeve sometime in the last 5 years or calibration check needed at Anchor 02B)

- Regardless, important during design to carefully consider the reduced coefficient of friction on the carbon fiber strand relative to that for typical steel strands when developing carbon fiber strand deviation and anchorage details

- Carbon fiber strand may be successfully handled, installed and stressed on a long span cable stay bridges within an actual construction environment

Conclusions (continued)

- Carbon fiber strands are significantly lighter (~5.5x)

- Non-corrosive, eliminating potential corrosion related challenges

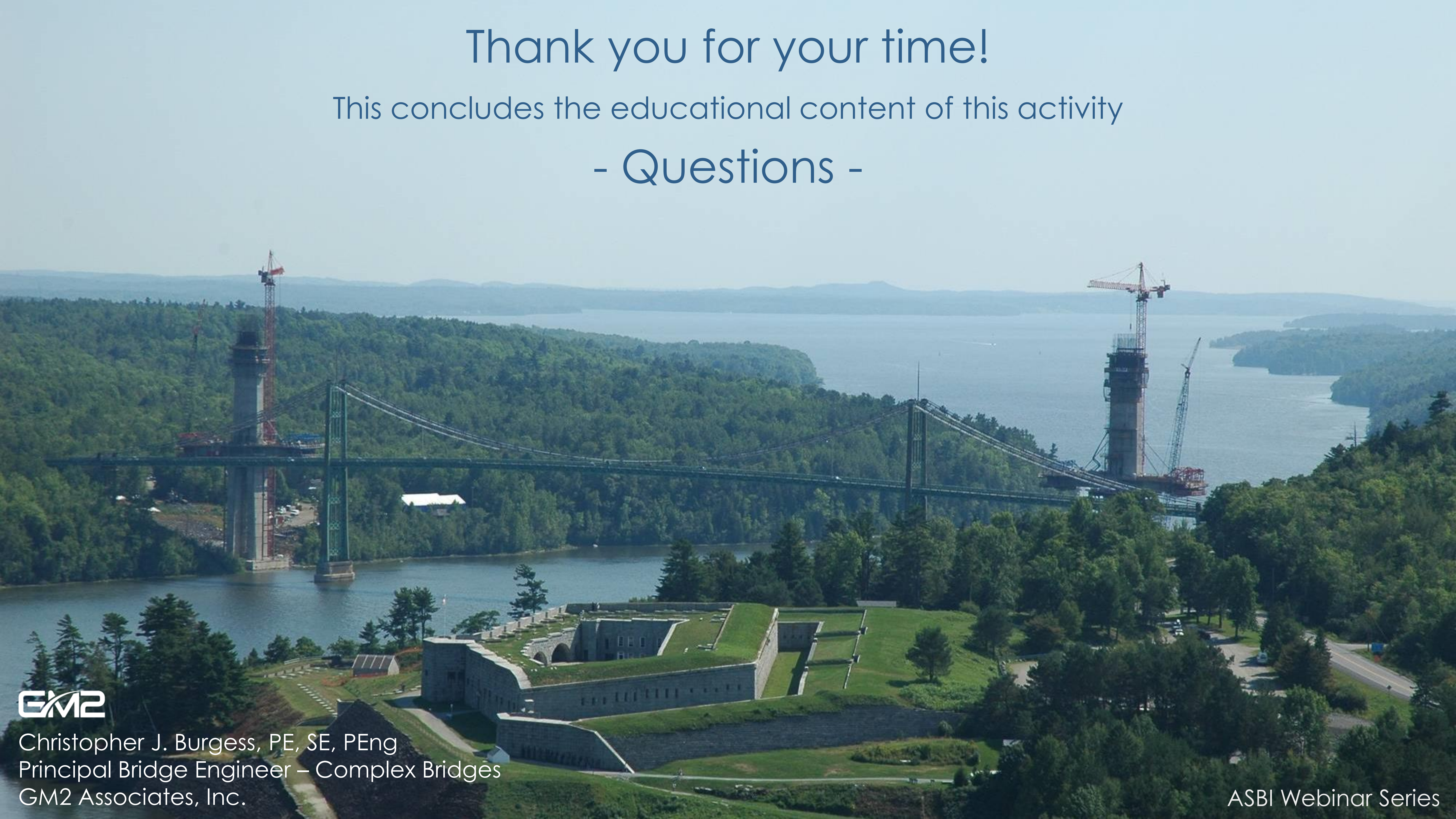
- Coefficient of Thermal Expansion is significantly smaller compared to steel strands (~5.9x), this would significantly reduce thermal effects from the stays, which may provide a direct benefit during design of the structure

- Need to refine and further develop the anchorage methods for the carbon fiber to allow for quick construction and efficient use of anchorage area

Conclusions (continued)

- The successful deployment and current long-term performance (in harsh conditions) provides support for continuing to explore and advance the application of these non-corrosive composite materials

- Data collection and monitoring will continue, which has been significantly streamlined by an automated electronic recording system that is accessed remotely



Thank you for your time!

This concludes the educational content of this activity

- Questions -

Christopher J. Burgess, PE, SE, PEng
Principal Bridge Engineer – Complex Bridges
GM2 Associates, Inc.