Evaluating fatigue, relaxation, and creep rupture of carbon-fiber-reinforced polymer strands for highway bridge construction

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- Fatigue strength, relaxation, and creep rupture strength of carbon-fiber-reinforced polymer (CFRP) strands were evaluated.
- Test results showed that fatigue strength of CFRP strands is superior to that of low-relaxation steel and stainless steel prestressing strands.
- Extended exposure to environmental conditions did not affect the tensile capacity of CFRP strands.

Carbon-fiber-reinforced polymer (CFRP) strands have been successfully deployed in the construction of several highway bridges with a potential for a life span of 100 years or more. Given the durability and noncorrodible nature of CFRP strands, such a long life span may be predicted; however, factors such as future increase in traffic loads, long-term prestress loss, and creep rupture of CFRP under sustained stress could shorten the service lives of bridges. This paper addresses three major design criteria that could affect the target life span of CFRP prestressed concrete highway bridge beams: fatigue strength, relaxation of CFRP strands, and creep rupture strength.

Fatigue is generally not a design issue because CFRP prestressed concrete beams, similar to conventional steel prestressed concrete beams, are designed to satisfy the service and strength limits states set forth in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] Under the service limit state, the precompressed tensile zone in CFRP prestressed concrete beams is designed with enough prestressing to remain uncracked during the service life of the structure. Consequently, it is not necessary to assess the fatigue strength of prestressed strands.[1] Nevertheless, it is unlikely that traffic as well as design loads will remain at their current levels for structures with a target life span of 100 years or more. Consequently, bridge beams designed as uncracked under current levels of traffic loads may experience cracks under future traffic loads. After cracking, fatigue of prestressing strands can represent an issue if the amplitude of repeated traffic load is large enough to trigger fatigue rupture of strands.

Limited literature addresses the fatigue, relaxation, or creep rupture strength of CFRP strands. Saadatmanesh and Tannous[2] investigated the fatigue strength of 0.3 in. (8 mm) diameter CFRP bars and carbon-fiber-composite-cable (CFCC) strands. The test specimens sustained 2 million loading cycles under a maximum stress level of approximately 90% of the ultimate tensile strength, with a stress range of 14.5 to 15.5 ksi (100 to 107 MPa). Alam et al.[3] reviewed a wide range of fatigue tests on CFRP and concluded that the results tend to show considerable scatter. Moreover, the authors of this paper did not find data in the literature regarding the fatigue strength of larger-diameter CFRP strands, such as 0.6 in. (15 mm) diameter CFCC strands, currently used in bridge construction.

The relaxation rate of fiber-reinforced polymer (FRP) composite materials is a controversial issue, although there is general consensus that CFRP has the smallest relaxation rate among different FRP materials. For example, Ali et al.[4] reported negligible relaxation of CFRP, a finding that contradicted the relaxation rate of 1.8% over a 100-year period estimated by ISIS Canada.[5] Zou[6] documented a negligible force loss due to CFRP relaxation when the initial applied stress was equal to or less than 50% of the ultimate tensile strength. This finding was attributed partly to the low creep coefficient under such applied stress. Balázs and Borosnyói[7] estimated a relaxation rate of 1.8% to 2% for CFRP and 5% to 8% for aramid-fiber-reinforced polymer (AFRP) over a 1000-hour period. When extrapolated to 50 years, the authors estimated the relaxation of CFRP and AFRP strands to be 2% to 10.5%, and 11% to 25% respectively, depending on the applied initial stress. An experimental study conducted by Ando et al.[8] on 0.5 in. (13 mm) diameter CFRP and 0.6 in. (15 mm) diameter AFRP at 68ºF, 104ºF, and 140ºF (20ºC, 40ºC, and 60ºC) for 3000 hours indicated that higher temperatures promoted higher relaxation rates and this effect was pronounced in AFRP bars. Tahsiri and Belarbi[9] performed an experimental investigation to evaluate relaxation of CFRP bars and cables and showed that stress relaxation was invariant of CFRP length, and, after accounting for anchorage losses, stress relaxation of CFRP was found to be within the same range as that for low-relaxation steel strands.

Lastly, creep rupture of CFRP has been a design and safety concern since the introduction of CFRP in civil engineering applications. Unlike the prestress level in steel strands, the prestress level in CFRP strands is typically influenced by the strands' susceptibility to rupture due to creep phenomenon. Earlier research showed that CFRP is less susceptible to creep than AFRP and glass fiber-reinforced polymer (GFRP). Nevertheless, no consensus was established regarding the appropriate creep rupture strength levels. For example, Yamaguchi et al.[10] showed that GFRP, AFRP, and CFRP exhibited creep strengths approximately 29%, 47%, and 93% of their ultimate tensile strengths, respectively. In contrast, a similar test conducted by Ando et al.[8] over the same test time frame revealed creep rupture stresses of 66% for AFRP and 79% for CFRP. Saadatmanesh and Tannous[2] showed that CFRP was not susceptible to creep at a stress level equal to 80% of the tensile strength. According to Karbhari et al.,[11] creep rupture stresses at ambient conditions, with a 10% probability of failure, for glass, aramid, and carbon fibers are 50%, 60%, and 75% of their average tensile strengths, respectively. However, Jiang et al.[12] studied the effects of high temperature and sustained load on creep of CFRP cables and concluded that the presence of sustained load before heating accelerated the damage of strength and stiffness for CFRP cable at high temperatures.

Because there is no consensus about creep rupture strength levels, ACI PRC-440.4R-04, *Prestressing Concrete Structures with FRP Tendons*,[13] limits the jacking stress and the allowable stress immediately following transfer in CFRP strands to 65% and 60% of their guaranteed strength, respectively. While the lower jacking stress ensures safety against creep rupture, it typically results in an inefficient beam design and limits the use of CFRP strands to short-span bridge beams.

To overcome the discrepancies found in literature and establish design values that can be implemented in the design and construction of highway bridge beams prestressed with CFRP strands, this paper presents a comprehensive eight-year-long experimental study conducted on CFRP strands to evaluate the fatigue strength and establish the creep rupture strength and relaxation loss.

Experimental program

The CFCC strands are polyacrylonitrile-based carbon-fiber strands in which individual wires are twisted and wrapped with synthetic yarns (polyester resin) to protect the fibers from mechanical abrasion and ultraviolet radiation. The CFCC strands are manufactured with nominal diameters ranging from 0.2 to 1.6 in. (5 to 41 mm) and produced as 7-, 19-, or 37-wire strands. The research presented in this paper was conducted mainly on seven-wire (1 × 7) CFCC strands with a nominal diameter of 0.6 in. (15 mm) because that is the strand size that has been widely used in bridge construction in the last two decades.[14]

A series of test specimens were constructed and split into three groups to evaluate fatigue strength, relaxation, and creep rupture strength of the CFCC strands. All test specimens were provided with sleeve anchorage devices that were developed and tested to eliminate strand slippage and guarantee a failure within the free length of specimens. The anchorage device was constructed from high-strength threaded steel pipe with varying dimensions to satisfy the specific requirements of each test. To conform to ASTM D7205/7205M-06(2016), *Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars*,[15] the minimum free length of the specimen between the anchors was taken as 40 times the strand diameter. Therefore, 0.6 in. (15 mm) diameter CFCC strand specimens were constructed with a free length of 24 in.

(610 mm) between anchorage devices. The space between the strand and the steel pipe anchors was filled with a cementitious-based, highly expansive material, which exhibited a high degree of expansion during curing and generated a confining pressure of approximately 5800 psi (40 MPa). This confining pressure provided the strand–to–highly expansive material interface with sufficient gripping resistance to eliminate anchorage slippage before strand failure.

The first group of CFCC specimens was evaluated for fatigue strength by subjecting the specimens to cyclic loading until failure or reaching 2 million cycles, whichever occurred first. In addition, for comparison purposes and to establish a benchmark for the test results, the fatigue test matrix extended to include test specimens made of conventional 0.6 in. (15 mm) diameter low-relaxation Grade 270 (1860 MPa) steel strands and 0.6 in. diameter Grade 250 (1720 MPa) seven-wire stainless-steel strands (**Fig. 1**). Curves representing the load versus the number of cycles to failure were prepared and plotted for the three materials. The stainless-steel strands were made of duplex alloy 2205. The low-relaxation steel strands were uncoated Grade 270 seven-wire strands that were manufactured and tested mechanically as specified in ASTM A416/A416M-18, *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*.[16]

The second group of specimens was prepared to evaluate relaxation loss. Test specimens of 0.6 in. (15 mm) diameter CFCC strands were loaded and monitored for prestress loss in custom-made steel frames to establish the one-million-hour relaxation rate of CFCC. Some of the specimens were kept in laboratory conditions, whereas other specimens were kept outdoors in Michigan for approximately three years. The outdoor specimens were subjected to environmental conditions such as humidity, ultraviolet light, rain, freezing rain, and snow, as well as changes in daily and seasonal temperatures. After concluding the monitoring stage, the indoor and outdoor CFCC specimens were released from the frames and loaded under a uniaxial test setup to failure to determine their residual tensile strength.

The third group of test specimens was prepared to evaluate the creep rupture strength of CFCC strands. Multiple sets of 0.6 in. (15 mm) diameter CFCC strands were loaded and monitored under different levels of sustained stress. Several techniques were developed to maintain a constant stress during the monitoring period. Specimens with high stress levels were loaded in a four-post load frame with a hydraulic system that maintained a constant stress. In this group of specimens, the monitoring lasted until the failure of the specimen or 1000 hours, whichever occurred first. Specimens with lower stress levels were loaded in special steel frames provided with either a closed-loop hydraulic system or high-strength steel springs. Some specimens in this group have been under continuous monitoring since 2014. The results from creep rupture specimens were compiled in a logarithmic time-stress

Figure 1. Cross-sectional views of 0.6 in. (15 mm) diameter low-relaxation steel, carbon-fiber-composite cable, and stainless steel prestressing strands.

graph to estimate the one-million-hour creep rupture strength. In addition, CFCC strand specimens with a diameter of 0.7 in. (18 mm) were also prepared and evaluated for creep rupture strength to validate the results for both diameters.

The CFCC specimens for different tests were constructed from different CFCC lots over the span of eight years. Therefore, the exact material properties of each CFCC lot are provided in the paper along with the details and results of each test.

Fatigue test

Stainless steel, CFCC, and low-relaxation steel strand test specimens were prepared and provided with anchorage devices made of threaded steel pipes with an outer diameter of 2.0 in. (51 mm), a wall thickness of 0.5 in. (13 mm), and a length of 18 in. (460 mm). With a free strand length of 24 in. (610 mm), the specimens had an overall length of 60 in. (1500 mm) (**Fig. 2**). **Table 1** presents the mechanical properties of the strands, as reported by the manufacturers.

Before the fatigue test, three specimens each of the CFCC, stainless steel, and low-relaxation steel prestressing strands were prepared and loaded to failure under uniaxial tensile load to verify the tensile strength of each material (**Fig. 3**). The testing was conducted in a four-post loading frame with a 270 kip (1200 kN) actuator. Universal joints designed to allow rotation and eliminate load eccentricity were used to attach the specimens to the heads of the loading actuator. The load was applied monotonically in a force-control module at room temperature to failure at a rate of 6 kip/min (27 kN/min). Tensile testing of the stainless steel and low-relaxation steel specimens conformed to ASTM A1061/A1061M-20, *Standard Test Methods for Testing Multi-Wire Steel Prestressing Strand*,[17] and the tensile testing of the CFCC specimens was conducted in accordance with ASTM D7205/7205M-06 (2016).[15] At approximately 10% of the anticipated breaking load, each test was paused and a Class B-1 linear variable displacement transducer (LVDT) extensometer with gauge length of 18.8 in. (478 mm) was attached to the strand to record the strain. In addition, a high-definition advance video extensometer (AVX) camera was used to capture the strain and validate the readings of the LVDT extensometer. The LVDT extensometer was removed from the specimen before failure to avoid possible damage due to strand rupture, while the AVX camera continued to capture the elongation until failure. Load and elongation were recorded using a data acquisition system. Table 1 presents the results of uniaxial tensile tests, and **Fig. 4** shows the failure modes of the test specimens. In addition, **Fig. 5** shows the load-strain curves for the three materials.

CFCC test specimens failed by rupture of CFCC with an average tensile capacity of 82.3 kip (366 kN) and average strain at failure of 1.95%. The CFCC strand completely shattered at failure over its entire length between the anchorage devices (Fig. 4). Stainless steel specimens failed by rupture of all strand wires at an average tensile capacity of 57.8 kip (257 kN) with an average failure strain of 1.98%. Rupture of the wires occurred near the anchorage devices. However, no wires fractured within a distance of 0.25 in. (6.4 mm) from the anchorage device, which was deemed satisfactory according to ASTM A1061.[17] Similar to the anchors of the CFCC specimens, the anchors of the stainless steel specimens did not experience any failure or slippage during the testing. The average yield load of stainless steel specimens was estimated as 48.9 kip (218 kN), which matched the yield load provided by the manufacturer.

The low-relaxation steel strand specimens experienced a failure mode similar to that for the stainless steel strands but with a much higher plastic deformation at failure. The mean tensile capacity of the low-relaxation steel specimens was 61.9 kip (275 kN) with a mean maximum elongation of 5.1%. Bond-type anchorage was not used while testing the low-relaxation steel specimens under the uniaxial tensile test. The high plastic deformation of the low-relaxation steel strands caused the bond anchors to slip without reaching the minimum tensile strength specified by the manufacturer. Therefore, special gripping devices with semicylindrical grooves[17] were used (Fig. 4), and the test specimens achieved failure loads higher than the failure load documented by the manufacturer. Using the offset method, the yield load of the low-relaxation steel specimens averaged 54.1 kip (241 kN).

After the tensile capacity for each strand type was verified, test specimens from the three strand materials were prepared and cyclically loaded under various levels of cyclic/fatigue loading using the 270-kip (1200-kN) loading frame with a setup similar to the tensile test. The load cycle was defined by three parameters: a minimum load, a maximum load, and a load range (the difference between the maximum and minimum loads). Typically, five test specimens were cyclically loaded under any load range (**Table 2**). The specimens were first loaded monotonically to the mean cycle load (the average between the maximum and minimum loads) with a loading rate of 6 kip/min (27 kN/min). The cyclic load was then applied in a sinusoidal waveform with a frequency of 2 Hz.

The minimum load of all load cycles was maintained at 35 kip (156 kN). This load level represented approximately the average effective prestressing force per the strand during the service life of the structure, based on available codes and standards.[1,13] For example, the AASHTO LRFD specifications[1] specify an initial prestress level immediately before transfer for low-relaxation steel strands as 75% of the tensile strength, which is approximately 202.5 ksi (1396 MPa) for Grade 270 (1860 MPa) strands. Therefore, for 0.6 in. (15 mm) diameter steel strands, the initial prestressing force is 44 kip (200 kN), and with an approximate overall prestress loss of 20%, the effective prestressing force is estimated as 35.2 kip (157 kN).

The maximum load of the load cycle was adjusted for each group of test specimens to induce a failure corresponding to number of load cycles between 1000 and 2 million cycles. Specimens that sustained 2 million cycles under a certain load

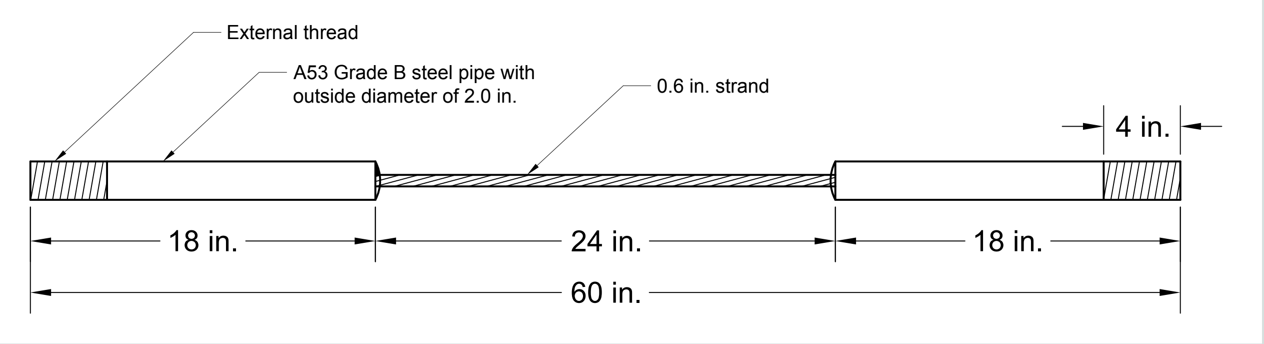


Figure 2. Schematic diagram for 0.6 in. diameter carbon-fiber-composite cable, stainless steel, and low-relaxation steel fatigue test specimens. Note: 1 in. = 25.4 mm.

Table 1. Mechanical properties of stainless steel, low-relaxation steel, and CFCC prestressing strands used in fatigue testing

Properties	Stainless steel	Low-relaxation steel	CFCC
Grade	250	270	n/a
Strand configuration	1 × 7	1 × 7	1 × 7
Diameter, in.	0.6	0.6	0.6
Effective area, in.^{2}	0.23	0.22	0.18
Guaranteed breaking load, kip	55.6	60.6	60.7
Yield load, kip	50.4	55.4	n/a
Tensile strength, ksi	242	279	358
Elastic modulus, ksi	23,700	28,400	20,885
Maximum elongation, %	1.6	5.4	1.7
Experimental yield load, kip	50.4	54.2	n/a
	48.3	53.5	n/a
	48.0	54.6	n/a
Mean experimental yield load, kip	48.9	54.1	n/a
Experimental tensile load, kip	57.7	62.1	81.5
	57.8	61.9	81.7
	57.8	61.8	83.6
Mean experimental tensile load, kip	57.8	61.9	82.3
Mean experimental tensile stress, ksi	251	281	457
Experimental elongation at failure, %	2.0	5.4	1.98
	1.96	5.1	1.97
	n.d.	4.7	1.91
Mean experimental elongation at failure, %	1.98	5.1	1.95

Note: CFCC = carbon-fiber-composite cable; n/a = not applicable; n.d. = no data. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.

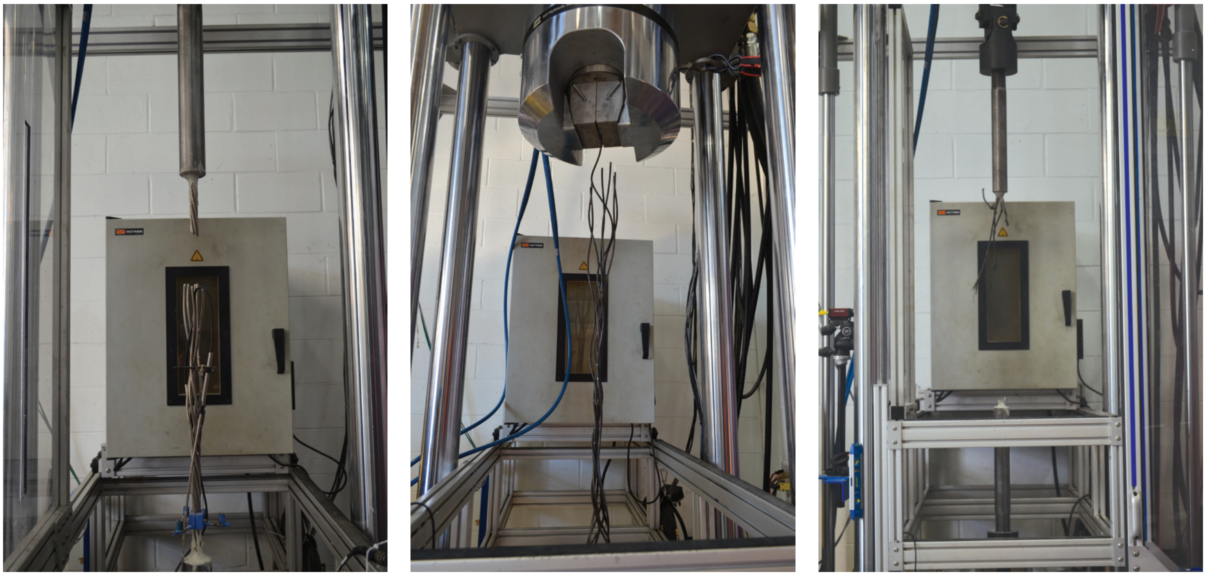
Figure 3. Tensile test setup with an advance video extensometer camera and linear variable displacement transducer extensometer for strain measurement.

range without failure were released. Load, displacement, time, and number of load cycles were recorded.

Fatigue test results

The stainless steel specimens were tested at five different load ranges, A through E (Table 2). With a minimum load of 35 kip (156 kN), the maximum loads of ranges A through E were 37, 39, 41, 43, and 45 kip (165, 173, 182, 191, and 200 kN), which corresponded, respectively, to 64%, 68%, 71%, 75%, and 78% of the average tensile capacity of the stainless steel strands. The number of load cycles to failure was recorded for each load range. The stainless steel specimens sustained 2 million cycles without failure under ranges A and B with maximum loads of 37 and 39 kip. With the increase of the maximum load, the fatigue life of the strands decreased significantly, with an average number of load cycles of 200,905 under range E with a maximum load level of 45 kip.

The low-relaxation steel specimens were tested under ranges D through G (Table 2), with maximum loads that corresponded, respectively, to 69%, 73%, 76%, and 79% of the average tensile capacity of the low-relaxation steel strands. Under range D, with a maximum load of 43 kip (191 kN), the low-relaxation steel strands completed 2 million cycles without failure. Similar to the fatigue life of the stainless steel strands, the fatigue life of low-relaxation steel strands decreased as the load range increased. At range G, with maximum load of 49 kip (218 kN), the low-relaxation steel specimens failed after 104,978 load cycles, on average.



Stainless steel | Low-relaxation steel | Carbon-fiber-composite cable

Figure 4. Failure of tensile test specimens.

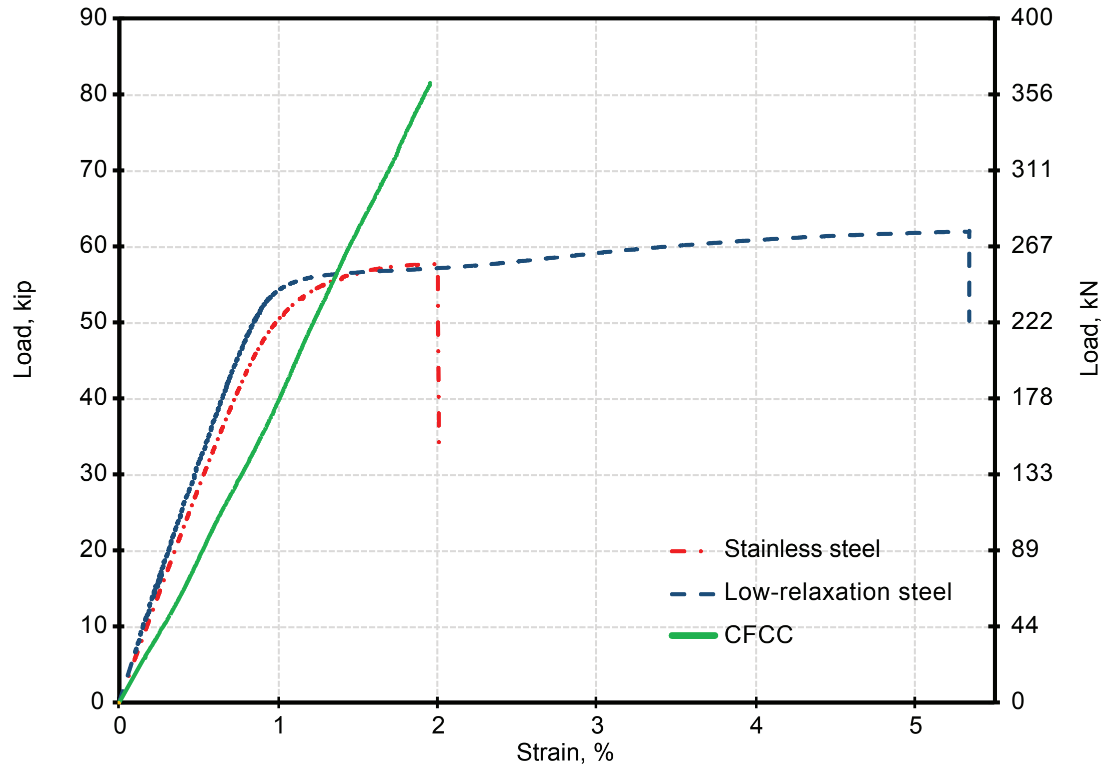


Figure 5. Load versus strain curves for stainless steel, low-relaxation steel, and carbon-fiber-composite cable strands.

The CFCC strand specimens were evaluated under ranges F through K, with maximum loads of 47, 49, 51, 53, 57, and 61 kip (209, 218, 227, 236, 254 and 271 kN). The maximum loads corresponded, respectively, to 57%, 60%, 62%, 65%, 69%, and 74% of the average tensile capacity of the CFCC strands. The CFCC strands completed 2 million cycles without failure under ranges F and G (Table 2), with maximum loads of 47 and 49 kip. Under range K, with a maximum load level of 61 kip, the CFCC strands failed after 4204 cycles, on average.

Figure 6 presents the load level plotted against the number of cycles. It shows that the stainless steel, low-relaxation steel, and CFCC strands achieved 2 million load cycles at load ranges of 4, 8, and 14 kip (18, 36, and 62 kN), respectively. Those load ranges are equivalent to stress ranges of 17, 37, and 78 ksi (117, 255, and 538 MPa), respectively. (The stress range is calculated by dividing the load range by the respective cross-sectional area of the strand.) These load/stress ranges can be regarded as the maximum safe ranges for the three materials before fatigue failure becomes a concern in prestressed concrete beam construction.

Relaxation test

Multiple sets of CFCC strand specimens were constructed, tensioned, and monitored for stress loss in custom-made steel frames. Test setup and testing conditions followed the specifications of the Japan Society of Civil Engineers' *Test Method for Long-Term Relaxation of Continuous Fiber Reinforcing Materials* (JSCE-E534-1995).[18] A sleeve-type anchorage similar to the one used for the fatigue test specimens was prepared from an externally threaded high-strength steel pipe and a high-strength steel nut. However, the anchorage device for the relaxation testing was slightly smaller than that used with the fatigue specimens; it had a pipe outer diameter of 1.5 in. (38 mm), an inner diameter of 0.875 in. (22.2 mm), a wall thickness of 0.3125 in. (7.938 mm), a tensile strength of 110 ksi (758 MPa), and a yield strength of 101 ksi (696 MPa). **Figure 7** provides a schematic diagram for the test specimens. The test specimens were prepared in 2013 from an older batch of CFCC strands with an experimentally verified average tensile strength of approximately 70 kip (310 kN), a maximum breaking load of 80.2 kip (357 kN), a minimum breaking load of 66.6 kip (296 kN), an average elastic modulus of 22,828 ksi (157.40 GPa), and a strain at failure of approximately 1.7%.[19] The specimens had an overall length of 48 in. (1220 mm) with a free length of 40 times the strand diameter (that is, 24 in. [610 mm]) and two anchors with a length of 12 in. (300 mm) each.

Strand relaxation versus anchorage relaxation

The first set of test specimens was prepared and instrumented to precisely evaluate strand relaxation. The set contained

Table 2. Summary of fatigue test results for stainless steel, low-relaxation steel, and CFCC specimens

Range	Load range, kip		Number of load cycles to failure (release after 2 million cycles)		
	Minimum	Maximum	Stainless steel	Low-relaxation steel	CFCC
A	35	37	2,000,000	n/a	n/a
B	35	39	2,000,000 2,000,000 2,000,000 2,000,000 2,000,000	n/a	n/a
C	35	41	2,000,000 657,368 617,258 597,810 566,175	n/a	n/a
D	35	43	390,029 353,745 338,126 332,895 319,539	2,000,000 2,000,000 2,000,000 2,000,000 2,000,000	n/a
E	35	45	237,381 220,876 189,530 188,193 168,542	509,452 406,083 317,392 288,251 273,405	n/a
F	35	47	n/a	190,156 189,364 188,310 154,692 148,873	2,000,000
G	35	49	n/a	123,231 109,352 107,131 98,236 86,936	2,000,000 2,000,000 2,000,000 2,000,000 2,000,000
H	35	51	n/a	n/a	2,000,000 2,000,000 276,181 49,113 44,729
I	35	53	n/a	n/a	388,505 189,765 77,045 23,231 19,925
J	35	57	n/a	n/a	27,765 22,809 14,479 12,695 11,920
K	35	61	n/a	n/a	5914 5170 3545 3450 2942

Note: CFCC= carbon-fiber-composite cable; n/a = not applicable. 1 kip = 4.448 kN

five specimens initially tensioned to a load level of 47.5 kip (211 kN). The CFCC specimens were monitored for load loss for 1351 days before they were destressed and tested under a uniaxial tensile test setup to failure. The set was kept in laboratory-controlled conditions with a temperature of 68°F ± 4°F (20°C ± 2°C). The relaxation of the CFCC strands was calculated by recording the loss in load through inline load cells and the change in the strain through vibrating wire

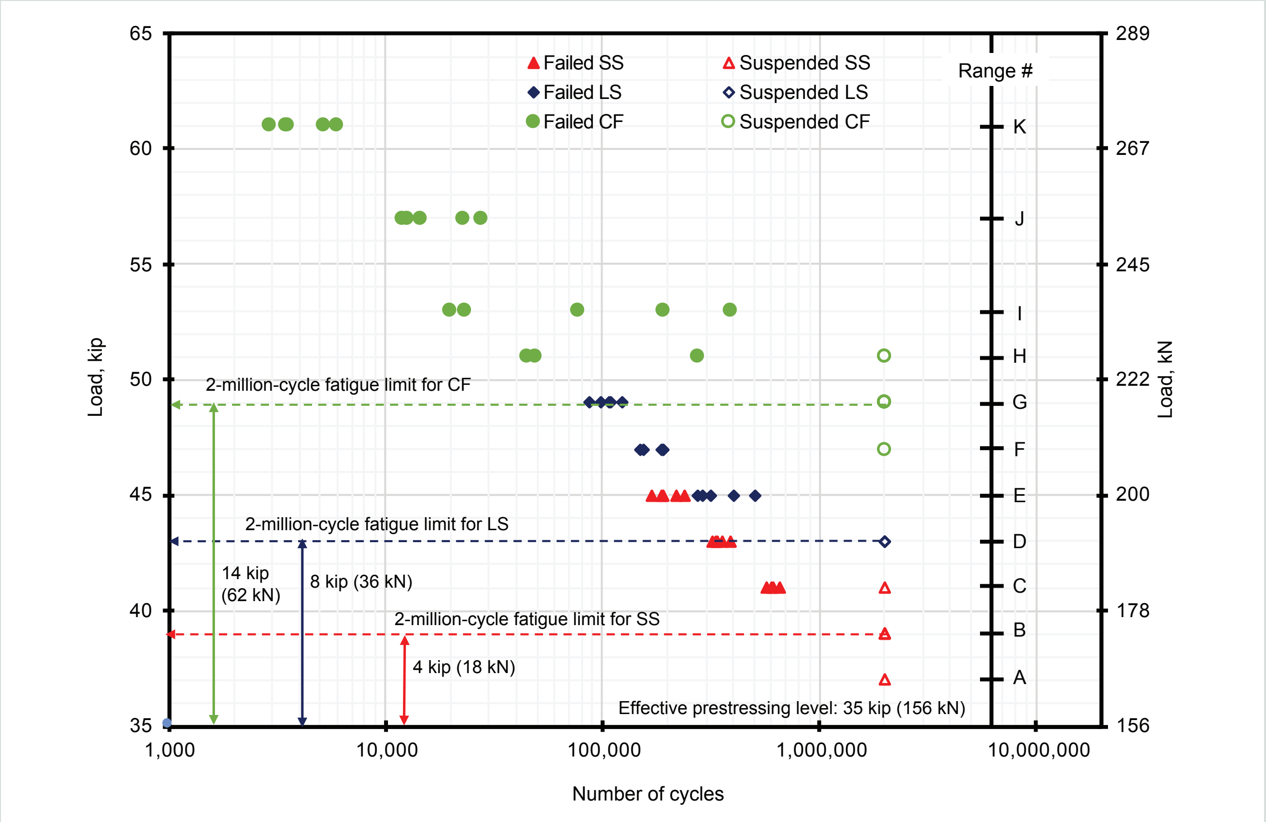


Figure 6. Maximum load of fatigue cycle versus number of cycles to failure. Note: CF = carbon-fiber-composite cable; LS = low-relaxation steel; SS = stainless steel.

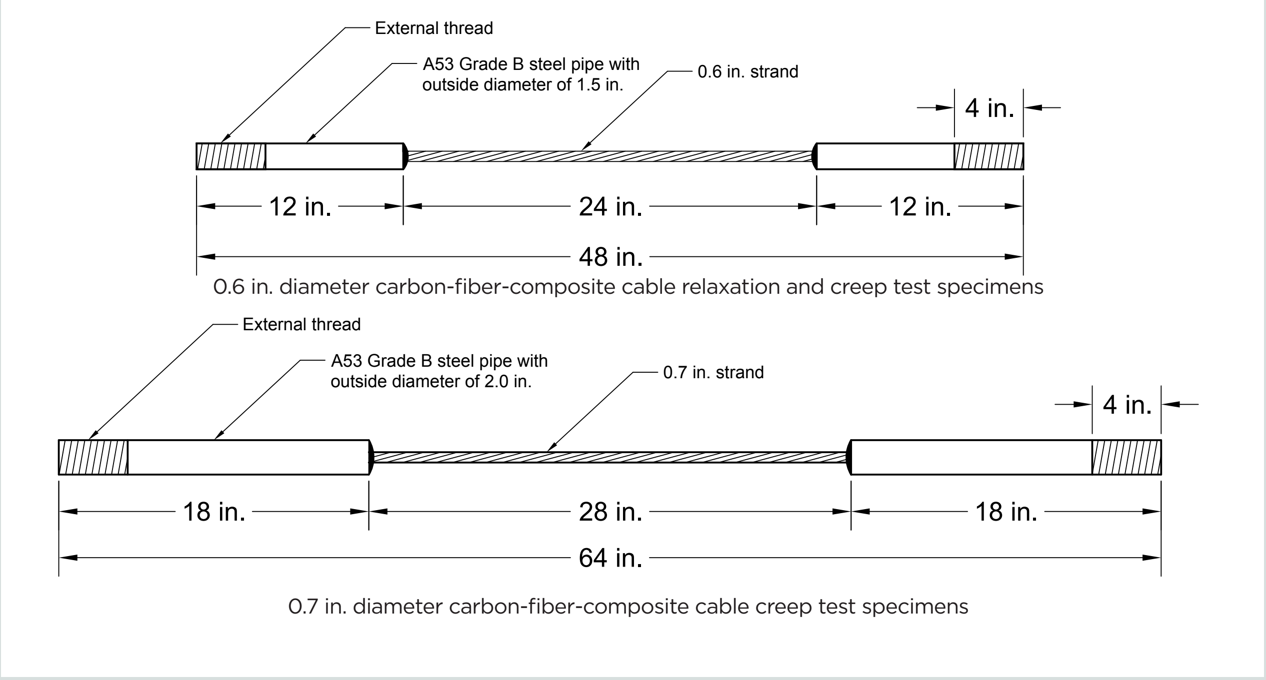


Figure 7. Schematic diagrams. Note: 1 in. = 25.4 mm.

strand meters attached to the strands. All attached sensors were connected to a computerized data acquisition system that captured and stored the data continuously.

Indoor versus outdoor relaxation loss

In addition to the relaxation specimens of the first set, 35 identical test specimens were tensioned and monitored for load loss in indoor and outdoor conditions (**Fig. 8** and **9**) to evaluate the effect of environmental exposure on the long-term relaxation of CFCC. The specimens were divided into seven sets of five and loaded in steel frames. The indoor group included one set tensioned to an initial load of 50.1 kip (223 kN), and two sets tensioned to 56.5 kip (251 kN). The outdoor group included two sets tensioned to 50.1 kip, and two sets to 56.5 kip. The two load levels represented approximately 70% and 80% of the average tensile strength of the CFCC batch. The higher load level of 56.5 kip was the maximum load that could be safely applied considering the test setup and available equipment and space. The lower load level of 50.1 kip was included in the test matrix for comparison purposes to assess the impact of the prestress level on the long-term performance and the residual strength of CFCC. In all test specimens (indoor and outdoor), the load was monitored and recorded for approximately three years through attached inline load cells on selected strands in each set. After completion of the monitoring period, the test specimens were released and loaded under a uniaxial test setup to failure to determine the residual tensile strength.

Relaxation test results

Figure 10 shows the change of the load over time in the first set of test specimens. The loss in the load followed a bilinear pattern, with an approximate load loss of 4.5% in the first 4 months and an additional load loss of 3% between 4 and 36 months. The average total loss was approximately 7.5%. **Figure 11** shows the strain readings over time in the five CFCC specimens. The CFCC strain gradually decreased over time concurrently with the loss of the load.

To correlate the strain readings with the loss in the load, it is imperative to analyze the movement of the strands. Relaxation of the strand causes a loss in the load through inducing additional strand elongation between the anchor points. Consequently, CFCC strain increases with strand relaxation. On the other hand, anchorage relaxation or slippage, or both relaxation and slippage, will cause a loss in the load by allowing the strands to recoil back to their original lengths, which causes a reduction in the recorded strain. Both strand relaxation and anchorage relaxation are expected in the test setup. Consequently, it is reasonable to assume that the recorded change in the strain over time was due to a combination of strand relaxation and anchorage relaxation.

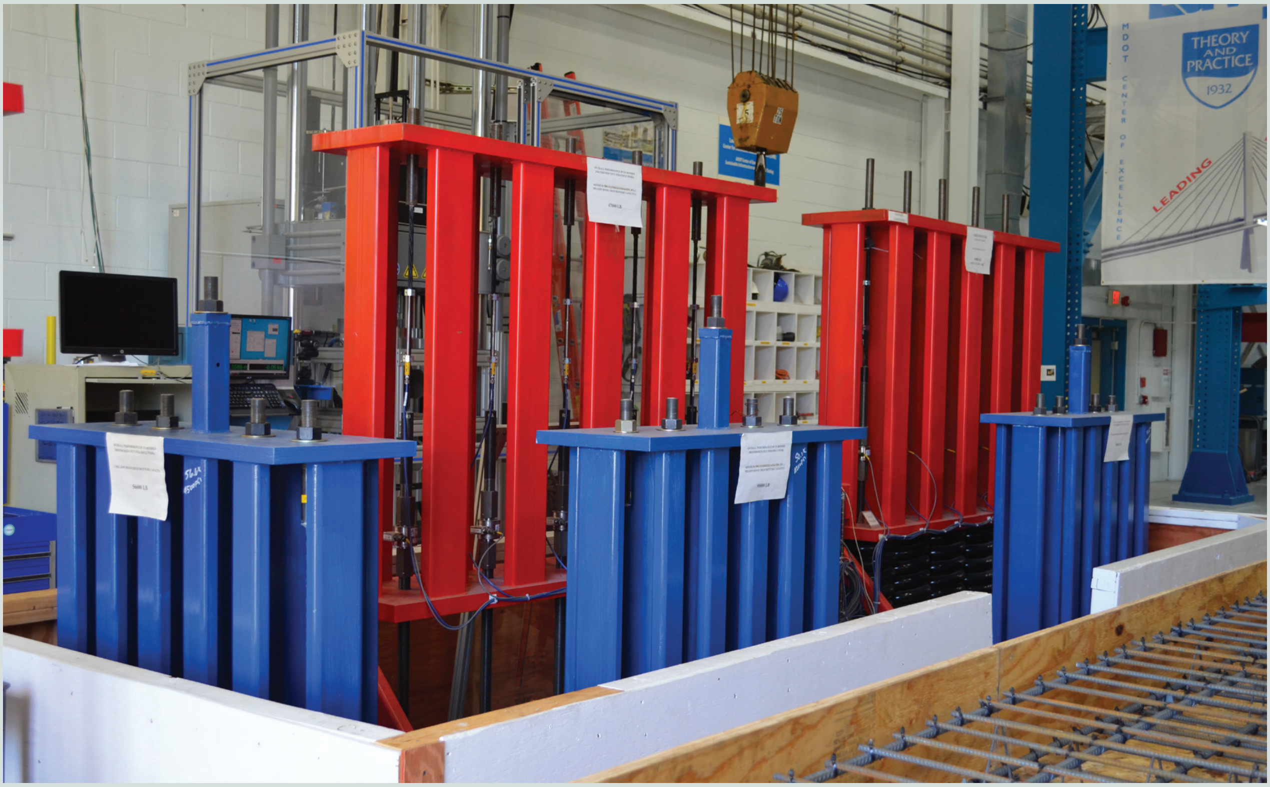


Figure 8. Stressed carbon-fiber-composite-cable specimens stored in a controlled laboratory environment.

Figure 9. Stressed carbon-fiber-composite-cable specimens exposed to weather conditions.

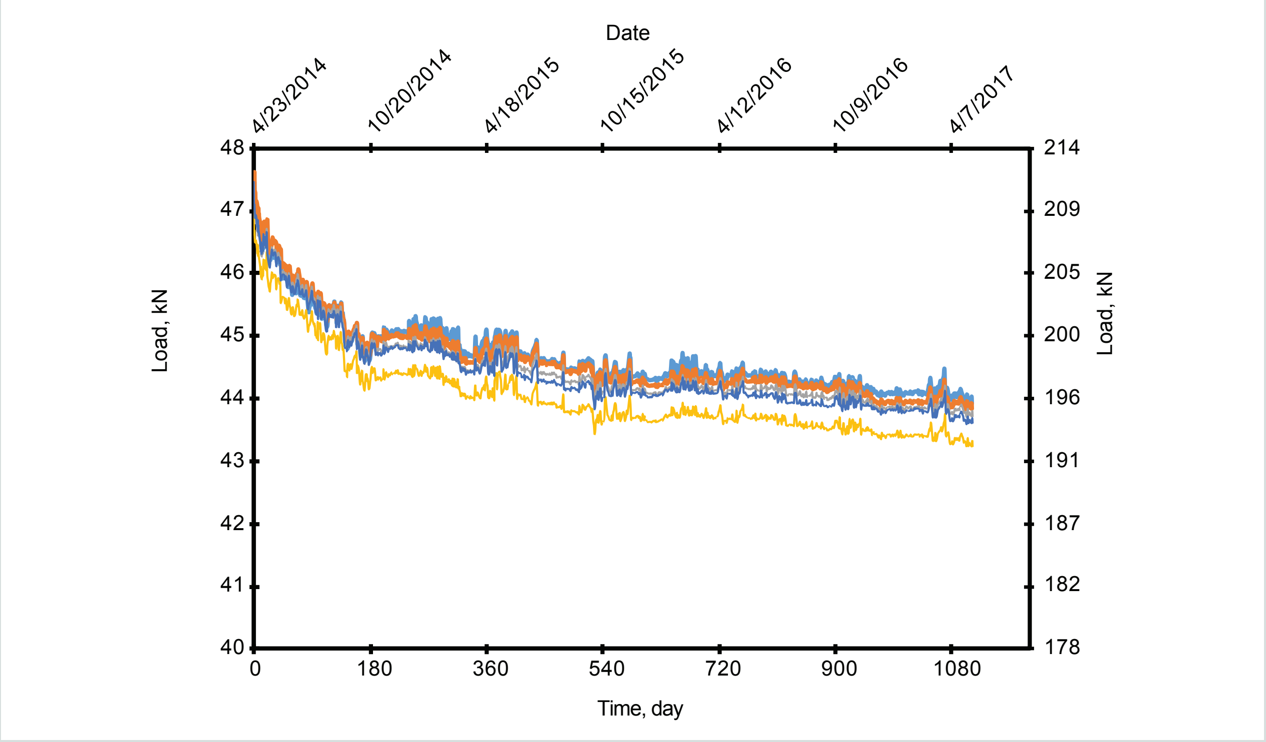


Figure 10. Force monitoring of 0.6 in. (15 mm) diameter carbon-fiber-composite-cable relaxation test specimens.

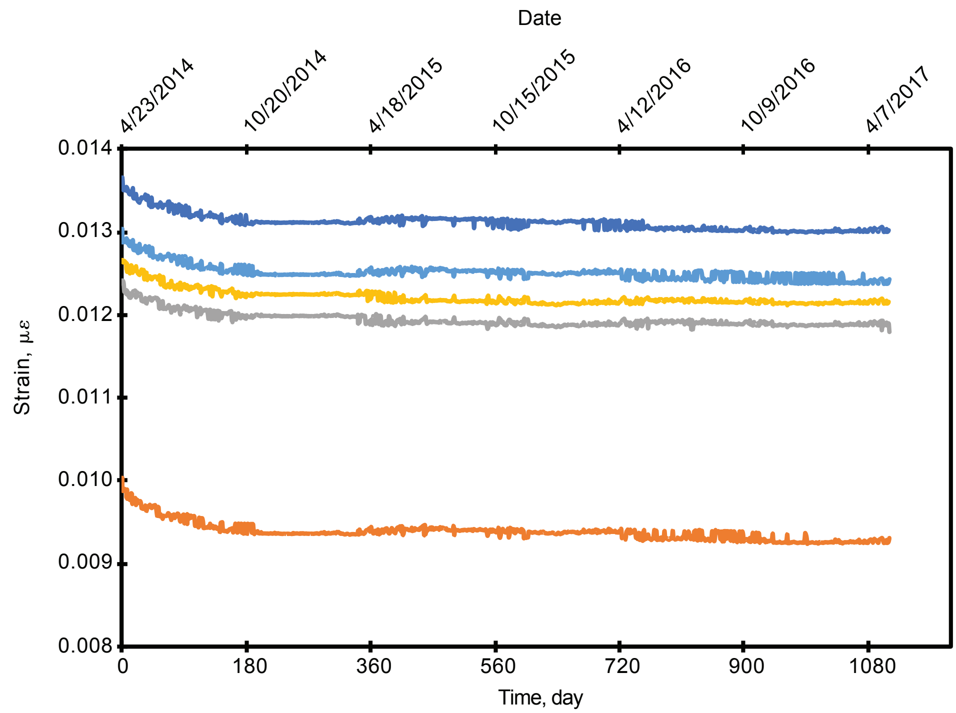


Figure 11. Strain monitoring of 0.6 in. (15 mm) diameter carbon-fiber-composite-cable relaxation test specimens.

The loss in load due to strand relaxation and the loss in load due to anchor relaxation can be mathematically separated by analyzing the strain readings versus the corresponding load cell readings. The attached load cells in the setup measured total loss (strand relaxation loss + anchor relaxation loss) from the strand and the anchor. Meanwhile, the strand meters on the strands measured the net loss due to anchor relaxation and strand relaxation (anchor relaxation loss – strand relaxation loss). By converting the strain reading to an equivalent loss in load and solving the two equations simultaneously, the loss due to strand relaxation and due to anchorage relaxation were separated.

On average, the combined loss of load in the CFCC specimens was approximately 3.6 kip (16 kN). This loss was mathematically split into anchorage relaxation loss of 3.1 kip (14 kN) and strand relaxation loss of approximately 0.5 kip (2 kN), which means the strand relaxation loss corresponded to approximately 1% of the initial prestressing force. When plotted on a logarithmic scale, the estimated one-million–hour relaxation loss (relaxation rate) for 0.6 in. (15 mm) diameter CFCC was approximately 1.91% (**Fig. 12**).

Figures 13 and **14** present the change of load over time in indoor and outdoor CFCC specimens, respectively, and **Fig. 15** shows the temperature change over time in the outdoor CFCC specimens. The average load losses for the indoor specimens with initial loads of 50.1 and 56.5 kip (223 and 251 kN) were approximately 6.7% and 5.9%, respectively, over three years. Because of the difference in thermal expansion between the steel frames and CFCC strands, the outdoor specimens exhibited a fluctuation in the load associated with the seasonal change in temperature. However, when corrected for temperature change, the load losses were similar to those observed in indoors specimens.

None of the indoor or outdoor CFCC specimens experienced any rupture or slippage during the monitoring period. Therefore, it can be concluded that environmental exposure did not cause deterioration in the strength or mechanical properties of the CFCC strands that could have triggered failure.

After concluding the monitoring phase, all 40 specimens, including five relaxation CFCC specimens of the first set, were released and tested to failure to evaluate the residual uniaxial tensile capacity. **Tables 3** and **4** present the uniaxial testing results. For comparison purposes, tensile testing was also conducted on virgin test specimens that were constructed at the same time from the same CFCC batch and kept in controlled laboratory conditions. Test results from unstressed specimens showed an average tensile capacity of 80.6 kip (359 kN) with an average strain at failure of 1.85%.

Tables 3 and 4 show that all test groups achieved an average tensile capacity higher than the original average tensile capacity of the CFCC batch obtained at the time of specimen construction three years earlier (70 kip [310 kN]). The average tensile capacity for all specimens was also higher than that obtained

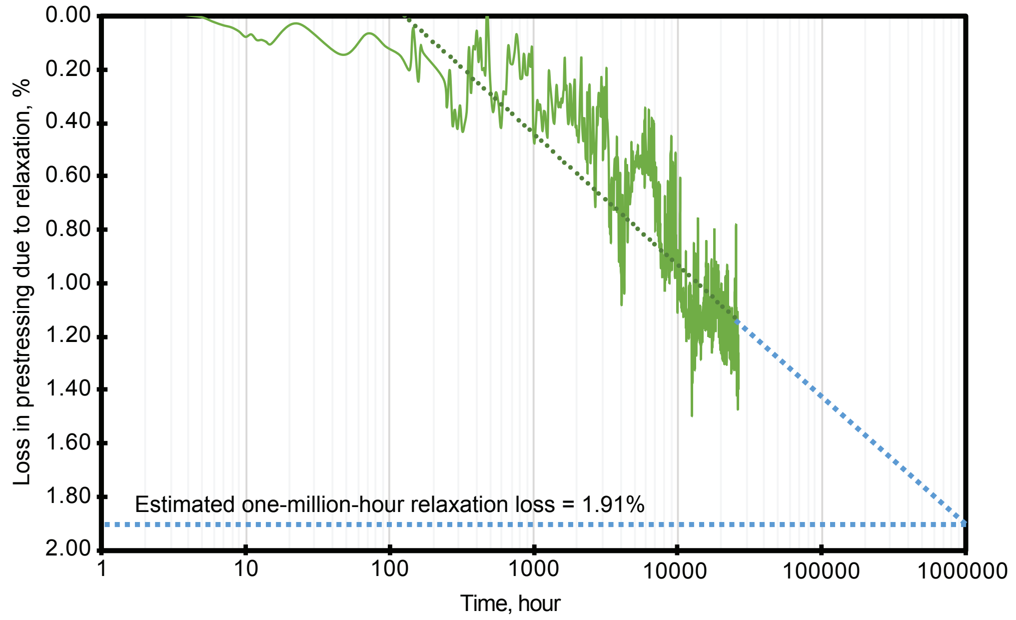


Figure 12. Estimated one-million-hour relaxation rate for 0.6 in. (15 mm) diameter carbon-fiber-composite-cable specimens.

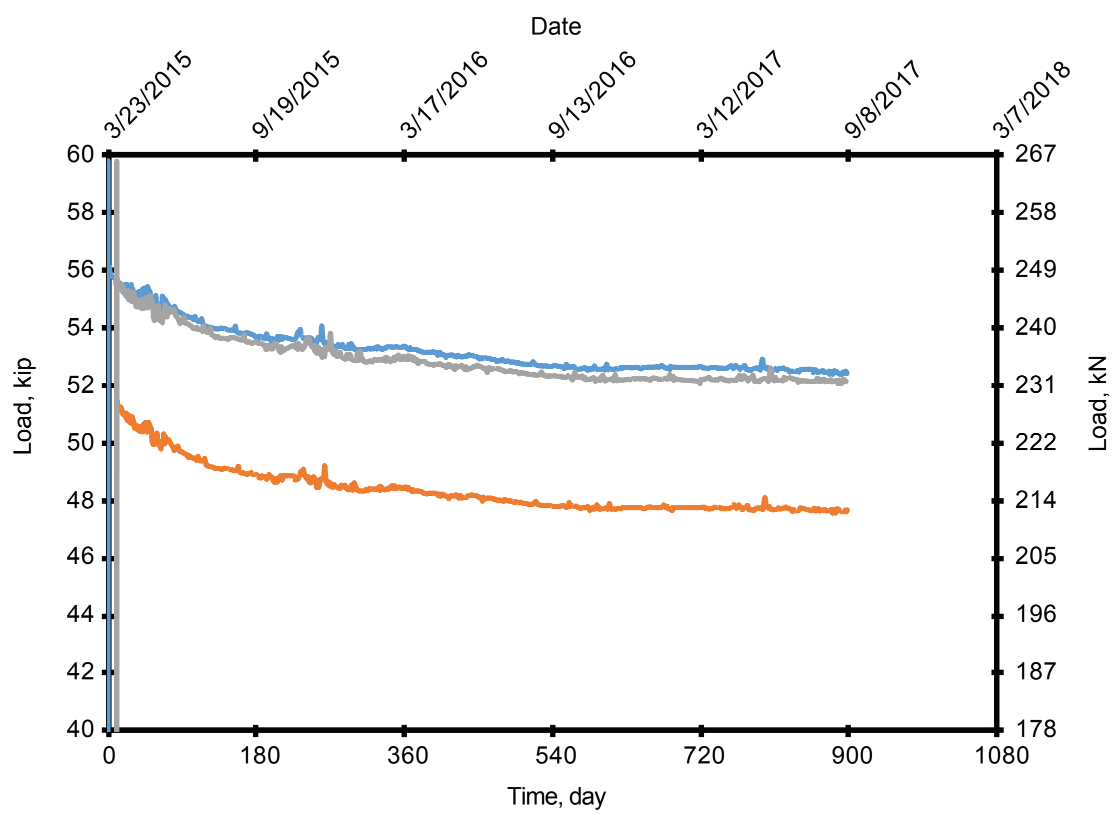


Figure 13. Long-term monitoring of 0.6 in. (15 mm) diameter carbon-fiber-composite-cable specimens in a controlled laboratory environment.

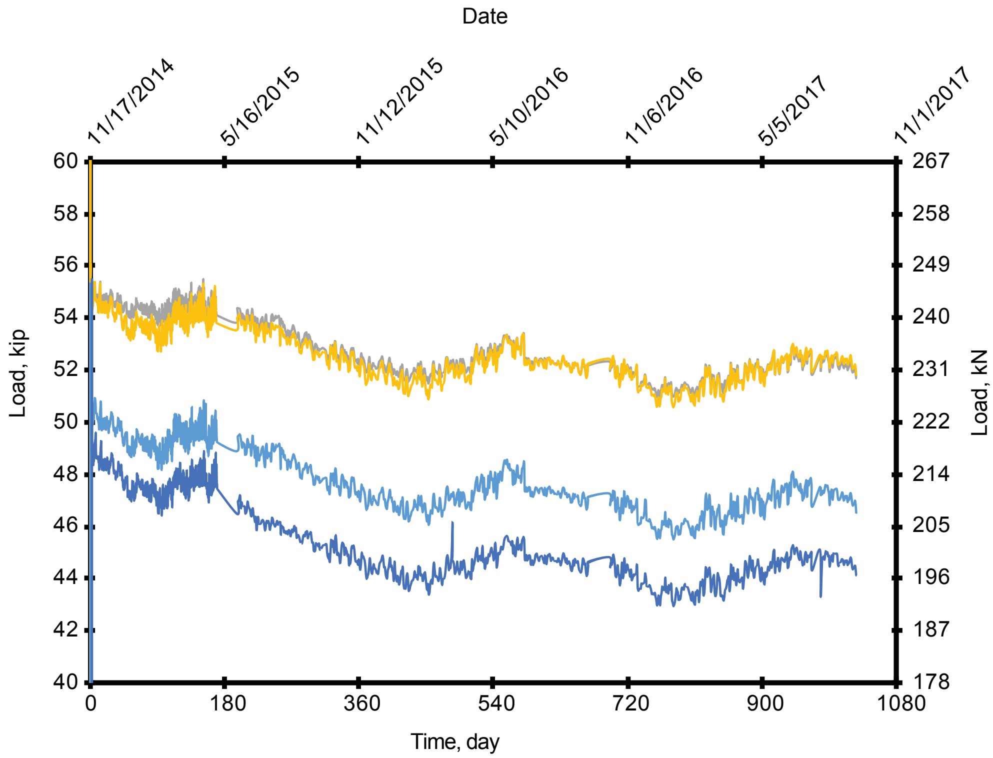


Figure 14. Long-term monitoring of 0.6 in. (15 mm) diameter carbon-fiber-composite-cable specimens exposed to weather conditions.

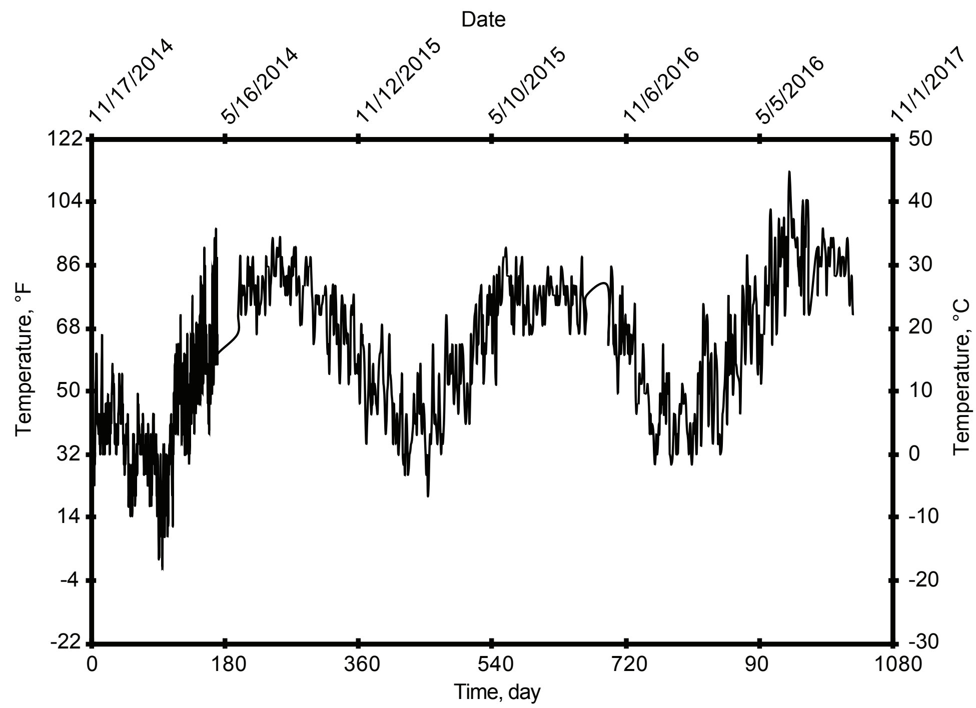


Figure 15. Temperature change in 0.6 in. (15 mm) diameter carbon-fiber-composite-cable specimens exposed to weather conditions.

Table 3. Uniaxial test results of indoor 0.6 in. diameter carbon-fiber-composite-cable specimens after relaxation test

Specimen number	Relaxation test		Tensile test	
	Initial tension load, kip	Duration of monitoring, days	Failure load, kip	Failure strain, %
1	0.0	1500	80.7	1.95
2			80.4	1.92
3			80.9	1.96
4			79.6	1.69
5			81.5	1.73
Average			80.6	1.85
1	47.5	1351	83.8	1.87
2			81.2	1.80
3			74.8	1.83
4			80.8	1.98
5			79.8	1.61
Average			80.1	1.82
6	50.1	994	82.9	1.92
7			84.5	1.88
8			83.9	1.94
9			80.4	2.05
10			83.0	1.93
Average			83.0	1.94
11	56.5	1002	82.5	1.97
12			84.0	1.96
13			83.6	2.2
14			83.1	1.98
15			83.7	1.95
16			85.5	1.88
17			84.0	1.85
18			75.3	1.50
19			84.2	1.90
20			61.9	1.40
Average			80.8	1.86

Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.

from testing the CFCC specimens stored in a laboratory environment for the entire monitoring period. The increase in capacity can be attributed to the extended curing of the CFCC.

The environmental conditions did not seem to have any detrimental effect on the residual tensile capacity of the CFCC strands. Both the indoor and outdoor specimens achieved roughly the same average tensile capacity. Also, the stress level in the CFCC strands during monitoring did not seem to negatively affect the residual tensile capacity. The specimen set with the highest average tensile capacity was the indoor set, with an initial load of 50.1 kip (223 kN), whereas the specimen set with the lowest average tensile capacity was also the indoor set, with an initial load of 47.5 kip (211 kN) per strand.

Table 4. Uniaxial test results of outdoor 0.6 in. diameter carbon-fiber-composite-cable specimens after relaxation test

Specimen number	Relaxation test		Tensile test	
	Initial tension load, kip	Duration of monitoring, days	Failure load, kip	Failure strain, %
1	50.1	1148	84.1	1.93
2			77.0	1.58
3			72.0	1.66
4			83.8	1.83
5			84.1	1.74
6			81.9	1.82
7			82.0	1.97
8			84.3	1.98
9			84.6	1.83
10			82.9	1.87
Average			81.7	1.82
11	56.5	1145	84.5	1.88
12			82.2	2.12
13			85.0	2.25
14			75.3	1.84
15			74.9	1.73
16			84.7	2.03
17			79.9	1.66
18			79.1	1.73
19			84.5	2.11
20			78.5	1.76
Average			80.9	1.91

Note: 1 kip = 4.448 kN.

Creep rupture strength

The creep rupture tests were conducted in accordance with JSCE-E533-1995, *Test Method for Creep Failure of Continuous Fiber Reinforcing Materials*.[20] The construction process of the 0.6 in. (15 mm) diameter CFCC specimens with an overall length of 48 in. (1220 mm) followed the same procedures described previously (Fig. 7).

Three groups of 0.6 in. (15 mm) diameter CFCC strands specimens were prepared (**Fig. 16**). Group 1 (G1-0.6) contained five CFCC specimens subjected to an initial load of 55 kip (245 kN). The specimens were loaded in a custom-made steel frame fabricated from ASTM A500[21] Grade B HSS rectangular sections and ASTM A36[22] plates. To minimize load loss over time, the specimens were provided with in-line high-strength steel springs with an outside diameter of 12.5 in. (318 mm) and a linear stiffness of 10 kip/in. (1.1 kN/m). In-line load cells and vibrating wire strand meters were attached to each CFCC specimen (Fig. 16).

Group 2 (G2-0.6) consisted of five 0.6 in. (15 mm) diameter CFCC specimens that were loaded in a custom-made steel frame provided with a closed-loop constant pressure (Fig. 16) instead of the steel springs used for group 1. Each specimen in G2-0.6 was loaded to 64 kip (285 kN) and monitored through a system of pressure gages and load cells. In addition, vibrating wire strand meters were attached to the specimens to monitor the strain.

With sustained load levels higher than 90% of the tensile strength of CFCC, the third group of specimens (G3-0.6) was composed of twenty 0.6 in. (15 mm) diameter CFCC

0.6 in. diameter CFCC with high-strength steel springs

0.6 in. diameter CFCC with a closed-loop hydraulic system

0.7 in. diameter CFCC with a closed-loop hydraulic system

Figure 16. Creep test setup of CFCC specimens. Note: CFCC = carbon-fiber-composite cable. 1 in. = 25.4 mm.

specimens. Because of the proximity of the load levels to the tensile strength of the CFCC, the specimens were loaded in the four-post loading frame with a setup similar to the uniaxial tensile test setup (Fig. 3). The CFCC specimens in G3-0.6 were loaded to their respective load levels for 1000 hours or until the failure of the specimen, whichever occurred first. The load in the CFCC specimens was monitored using a load cell attached to the loading actuator, while the strain was monitored and recorded using the high-definition AVX camera.

The creep rupture test was extended to include CFCC specimens with a diameter of 0.7 in. (18 mm) and dimensions in Fig. 7. The 0.7 in. diameter CFCC strands were 1 by 7 twisted-wire strands with a cross-sectional area of 0.234 in.^{2} (151 mm^2), an elastic modulus of 22,626 ksi (156.01 GPa), average tensile strength of 113.9 kip (506.6 kN), and elongation at failure of 2.05%. In a setup similar to the one used for G2-0.6, the five 0.7 in. diameter CFCC specimens in group G2-0.7 were loaded to 94 kip (418 kN) in a closed-loop hydraulic system (Fig. 16). Also, in a setup similar to the one used for G3-0.6, the fourteen 0.7 in. diameter CFCC specimens in group G3-0.7 were loaded to different load levels in the four-post loading frame.

Creep test results

Figure 17 shows the load-time history for the G1-0.6 test specimens—that is, the 0.6 in. (15 mm) diameter CFCC specimens loaded to 55 kip (245 kN) per strand with high-strength steel springs. A slight load loss was observed in the first 200 days before the load plateaued over time (Fig. 17). Monitoring of these specimens started in January 2014 and is ongoing. At the time when this paper was written (July 2022), the average sustained load for the G1-0.6 specimens was approximately 52.7 kip (234 kN) with a corresponding average strain of 1.47%. G2-0.6 specimens have been under continuous monitoring since March 2018, with a current average sustained load of 63.8 kip (284 kN) and a corresponding average strain of 1.66%. **Figure 18** shows the load over time for the G2-0.7 specimens. The specimens have been under continuous monitoring since May 2017 with a current average sustained load of 94.8 kip (422 kN) and a corresponding average strain of 1.67%.

In G3-0.6 (the third group of 0.6 in. [15 mm] diameter CFCC specimens), 17 out of 20 specimens failed within 72 hours (3 days) of loading, whereas the remaining three completed the 1000 hours of loading and were released later. The G3-06 test results appeared scattered with less tangible correlation between the load level and the time to failure. For example, one specimen with a load level of 63.7 kip (283 kN) sustained the load for approximately 57 hours before it failed. An identical specimen sustained the same load level for 1000 hours, after which it was released.

Similarly, all but two of the CFCC specimens in G3-0.7 failed within the first 72 hours of loading. One of the remaining specimens failed after 200 hours under a load level of 109.4 kip (486.6 kN), whereas the second specimen completed 1000 hours without failure under a load level of 110.5 kip

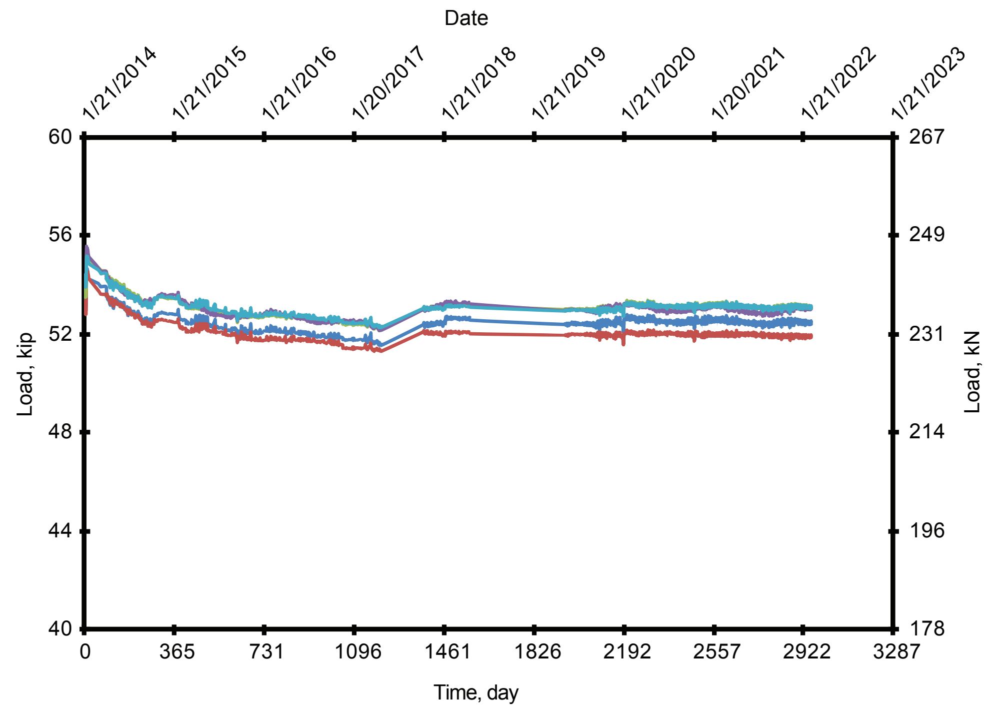


Figure 17. Force monitoring of 0.6 in. (15 mm) diameter carbon-fiber-composite-cable specimens loaded with steel springs to an initial tension load of 55 kip (245 kN).

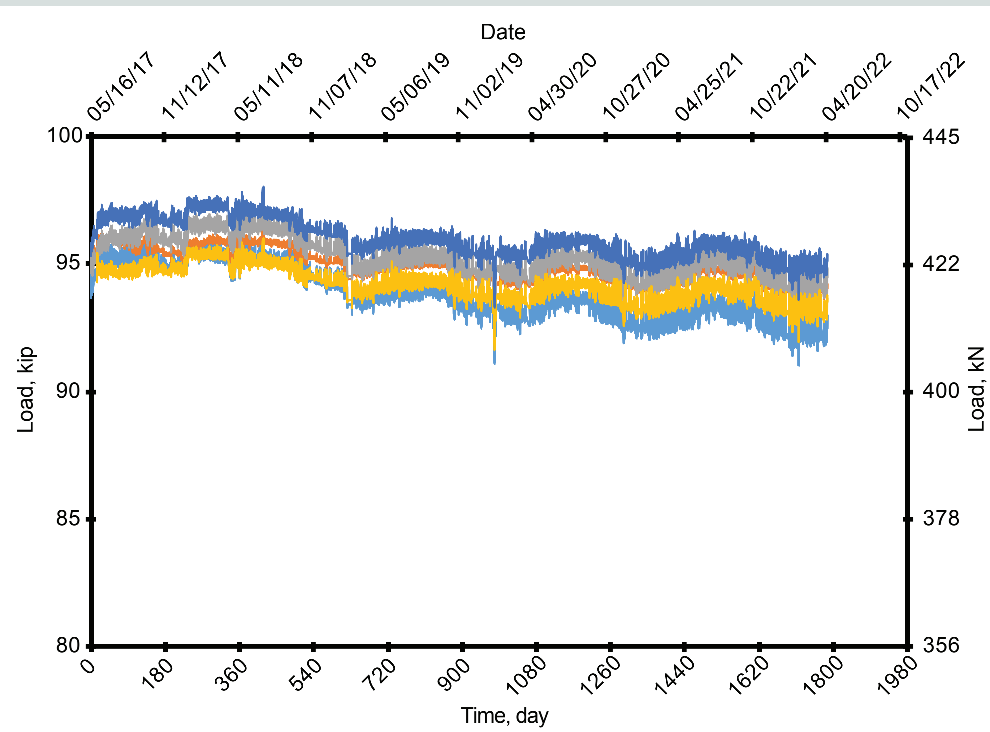


Figure 18. Force monitoring of 0.7 in. (18 mm) diameter carbon-fiber-composite-cable specimens loaded with a closed-loop hydraulic system to an initial tension load of 94 kip (418 kN).

(491.5 kN). An identical specimen with a 110.5 kip sustained the load for only 0.1167 hours before failure. This difference in performance was expected because the applied load was close to the average tensile capacity of the strand.

One-million-hour creep rupture strength

The test results from the 0.6 and 0.7 in. (15 and 18 mm) diameter CFCC specimens were compiled to estimate the one-million-hour creep rupture strength. In addition, test data for the indoor and outdoor relaxation specimens were also included as additional points with corresponding sustained load levels equal to their load levels before release. Test results were plotted on a stress ratio versus log-time chart (**Fig. 19**). The one-million-hour creep rupture strength can be estimated by extending a line separating the failed specimens from those still sustaining the applied load and under continuous monitoring or those that sustained the load for a period of time before they were released without failure. The region above the line represents the unsafe zone, where specimens may or may not fail by creep rupture, whereas the region below the line represents the safe stress zone, where no specimen experienced failure. By extrapolation, the minimum one-million-hour creep rupture strength for CFCC strands is estimated as 88% of the average tensile strength. For example, for 0.6 in. diameter CFCC strands with average tensile capacity of 82.3 kip (366 kN), the lower bound for one-million-hour creep rupture capacity is approximately 72.4 kip (322 kN). For 0.7 in. diameter CFCC strands with a tensile capacity of 113.9 kip (506.6 kN), the estimated one-million-hour creep rupture capacity is 100.2 kip (445.7 kN).

Implications of test results on bridge design

Drawing from findings from studies that addressed durability and life-cycle cost analysis of beams prestressed with CFRP strands,[23–25] CFRP strands were used to prestress several highway bridge superstructures. For example, in 2019, a two-span bridge was constructed to carry Brush Street over Interstate 94 in Detroit, Mich. The superstructure of the bridge is composed of twenty 54 in. (1370 mm) deep precast and prestressed concrete bulb-tee beams (10 beams per span), with a 28-day design concrete strength of 9000 psi (62 MPa) and a beam spacing of 6 ft (1.8 m). The beams support a 9 in. thick (230 mm), reinforced cast-in-place concrete deck with a 28-day design compressive strength of 5000 psi (35 MPa). The length of the first span of the bridge, measured between the centerlines of supports, is 120.75 ft (36.80 m), and the second span has a length of 101.5 ft (30.94 m). Each beam in the first span is prestressed with a total of sixty-nine 0.6 in. (15 mm) diameter CFCC strands, and each beam in the second span is prestressed with forty-nine CFCC strands of the same diameter. The initial prestressing force in both spans was 35.5 kip (158 kN) per

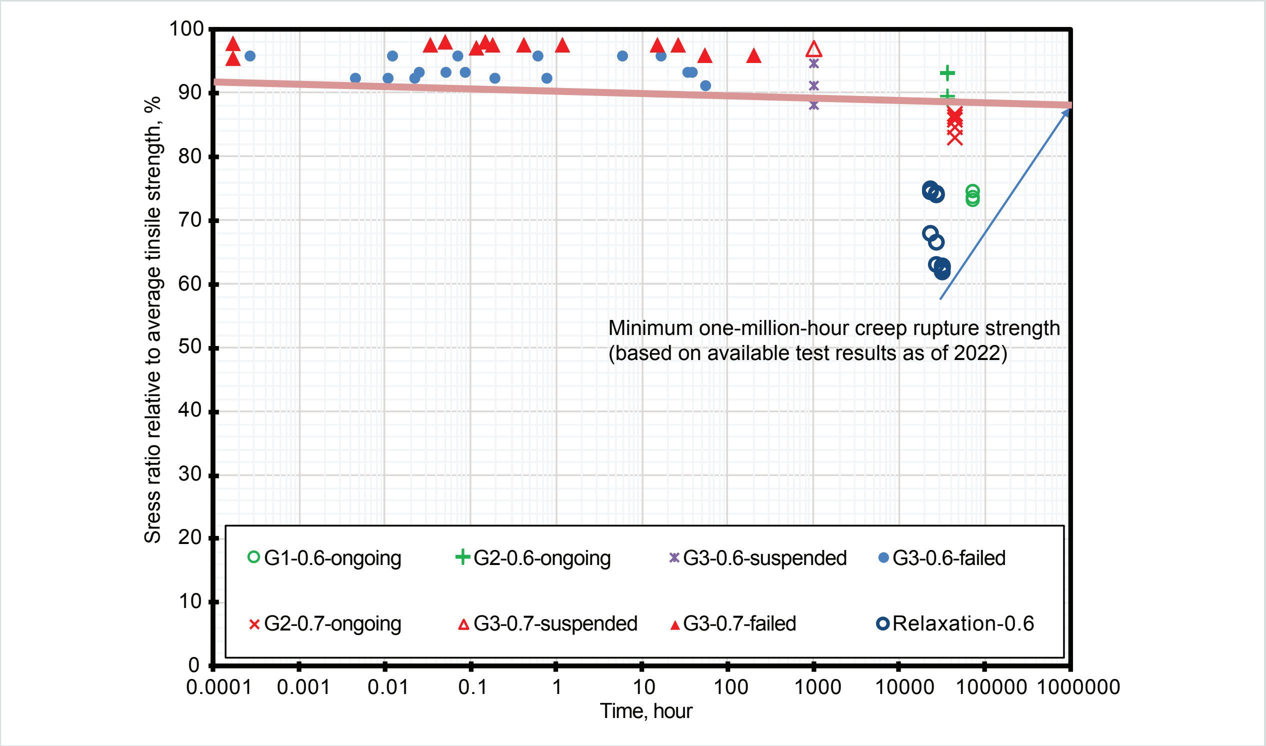


Figure 19. Lowest estimate for one-million-hour creep-rupture strength. Note: CFCC = carbon-fiber-composite cable; G1-0.6 = group 1 0.6 in. (15 mm) diameter CFCC specimens; G2-0.6 = group 2 0.6 in. diameter CFCC specimens; G2-0.7 = group 2 0.7 in. (18 mm) diameter CFCC specimens; G3-0.6 = group 3 0.6 in. diameter CFCC specimens; G3-0.7 = group 3 0.7 in. diameter CFCC specimens.

strand, which conformed to permissible prestress levels in ACI PRC-440.4R.[13] As mentioned earlier, the low prestress level in ACI PRC-440 is directly related to concerns about the creep rupture strength of CFRP strands. The beam top and transverse reinforcement and the deck reinforcement were assembled from epoxy-coated mild steel reinforcement no. 3, 4, 5, 6, and 8 (M10, 13, 16, 19, and 25).

The design process for a CFCC prestressed concrete beam is generally similar to that for a steel prestressed concrete beam, although there are a few differences to account for the differences in strand material. For example, the calculations of long-term prestress loss in a CFCC prestressed concrete beam extend to account for the fluctuation in prestressing force with temperature change due to the difference in thermal coefficient of expansion between CFCC and concrete. In addition, and as an added safety measure, no concrete tensile stress is allowed at the precompressed tensile zone (soffit of the beam at midspan) under Service III.[1] Furthermore, the strength reduction factor at strength limit state is taken equal to 0.85 when the net tensile strain in the extreme CFCC strands is equal to or greater than 0.005, and it drops to 0.65 when the net tensile strain is equal to or less than 0.002. For sections in which the net tensile strain in the CFCC at nominal resistance is between 0.002 and 0.005, the strength reduction factor at strength limit state is linearly increased from 0.65 to 0.85 as the net tensile strain in the extreme tension CFCC increases from 0.002 to 0.005. The net tensile strain of CFCC strands is that caused by external forces. Effects of primary prestressing forces are not included.

Linear stress and strain distribution of the uncracked section are considered when evaluating the stresses at service limit state, whereas strain compatibility and force equilibrium of a cracked section are used to calculate the nominal moment capacity of the section at strength limit state.

The construction process for a CFCC prestressed concrete beam is also similar to that of a steel prestressed concrete beam. However, prestressing is executed by using a special coupler system to couple steel strands to both ends of the CFCC strands (**Fig. 20**). Consequently, the construction crew can use conventional steel anchorage devices at the live and dead ends and use the conventional tensioning equipment for prestressing CFCC strands. **Figure 21** shows a bridge beam during construction at the precasting yard, and **Fig. 22** shows beam placement over the supports on site. For additional information regarding the design and construction procedure for this type of bridge superstructure with prestressing CFCC strands, refer to Grace et al.[14]

Based on findings from the current study and with the estimated one-million-hour creep rupture strength of approximately 88% of the average tensile strength, prestress levels may be safely increased beyond the prestress limits recommended in ACI PRC-440.4R[13] without jeopardizing the safety of the structure or triggering creep rupture failure. **Table 5** presents the effect of

Figure 20. Coupler system to connect carbon-fiber-composite-cable strands to steel strands during prestressing.

Figure 21. Completing the reinforcement cages of a carbon-fiber-composite-cable prestressed concrete beam for the Brush Street Bridge over Interstate 94 in Detroit, Mich.

Figure 22. Placing the beams over the supports in Brush Street Bridge over Interstate 94.

increasing the prestressing force in the strands. Increasing the prestressing force results in a decrease in the number of strands per beam, which also results in a reduction in the reinforcement ratio. For example, with an initial prestress level of 45.3 kip (201 kN) per strand, the beams in the first span of the Brush Street Bridge could be prestressed with 47 strands, instead of 69, while still satisfying the service and strength limits states set forth in the AASHTO LRFD specifications.[1] A further increase in the prestressing force per strand with a further reduction in the reinforcement ratio leads to unsatisfactory nominal moment capacity at strength limit state. For example, the last row of Table 5 shows that increasing the initial prestressing force to 46.4 kip (206 kN) per strand results in a satisfactory service limit state but inadequate nominal moment capacity at strength limit state. This situation can be mitigated by increasing the reinforcement ratio and using additional prestressed or nonprestressed strands. In this particular case, adding one additional prestressed strand or four additional non-prestressed strands increases the nominal moment capacity to an acceptable level.

As the prestressing force per strand is increased, the reserve net tensile strain of CFCC (the difference between guaranteed strain and effective prestressing strain) is reduced. Consequently, with a higher prestressing force per strand such as 45.3 and 46.4 kip (201 and 206 kN), the last two values in Table 5, the strength reduction factor falls below 0.85 because the net tensile strain of extreme CFCC strands falls below 0.005 and enough ductility is not achieved at the strength limit state.

Overall, it seems that the low initial prestressing force recommended by ACI PRC-440.4R[13] results in an excessive number of prestressing strands and that the initial prestressing force can be safely increased to 75% to 80% of the design strength of CFCC strands. The increase in initial prestressing force will result in an adequate section design with a reasonable number of CFCC strands to satisfy both service and strength limit states, while still providing a reasonable level of ductility. **Table 6** shows that when the beam design was repeated using conventional 0.6 in. (15 mm) diameter Grade 270 (1860 MPa) steel strands, 42 steel strands (only 60% of the number of CFCC strands) were needed to satisfy service and strength limit states because each strand had an initial prestressing force of 44 kip (196 kN) according to the AASHTO LRFD specifications.[1]

Finally, it seems that a future increase in traffic loads probably will not pose a fatigue concern in beams prestressed with CFCC strands (Table 6). For example, the current live load would need to increase by more than 3.5 times to increase the force in the CFCC strands beyond the predicted two-million-cycle load range of 14 kip (62 kN) and trigger a fatigue failure. Even if the initial prestressing force is increased to 43.7 kip (194 kN) per strand and only 50 CFCC strands were used, a threefold increase in the live load would need to occur before fatigue failure would become a concern. On the other hand, with conventional 0.6 in. (15 mm) diameter steel strands, with a two-million-cycle load range of 8.0 kip (36 kN) per strand, the steel prestressed concrete beam, after cracking, can only handle a 68% increase in the live load before fatigue of the steel strands becomes a concern.

Conclusion

Based on the test results presented in this paper, the following conclusions are drawn:

- With a minimum load of 35 kip (156 kN), the two-million-cycle load range of the 0.6 in. (15 mm) diameter CFCC strands was 14 kip (62 kN), whereas the two-million-cycle load ranges of stainless steel and low-relaxation steel strands with the same diameter were 4 and 8 kip (18 and 36 kN), respectively. Thus, the CFCC strands exhibited a significantly larger fatigue range when compared with the stainless steel and low-relaxation steel strands. Consequently, fatigue of CFCC does not seem

Table 5. Effect of increasing prestressing force in 0.6 in. diameter CFCC strands on the beam design of Brush Street Bridge over Interstate 94 in Detroit, Mich.

Ratio of initial prestress to CFCC design strength	Initial prestress force per strand, kip	Number of strands	Strength reduction factor	Nominal moment kip-ft	Resistance moment, kip-ft	Concrete compressive strain at failure	Ratio of resistance moment to factored moment
0.65	35.5	69	0.85	15,674	13,323	0.00276	1.29
0.70	38.3	61	0.85	14,369	12,213	0.00203	1.19
0.75	41.0	55	0.85	13,265	11,276	0.00151	1.11
0.80	43.7	50	0.85	12,292	10,448	0.00114	1.03
0.83	45.3	47	0.83	11,662	9692	0.00097	0.99
0.85	46.4	46	0.812	11,453	9304	0.00089	0.99

Note: CFCC design strength = guaranteed CFCC strength × environmental reduction factor of 0.9, and resistance moment = nominal moment × strength reduction factor. CFCC = carbon-fiber-composite cable. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 kip-ft = 1.356 kN-m.

Table 6. Comparison between using 0.6 in. diameter CFCC strands with two different prestress levels per strand and conventional 0.6 in. diameter steel strands in prestressing the beams of the Brush Street Bridge over Interstate 94 in Detroit, Mich.

	CFCC 35.5 kip/strand	CFCC 43.7 kip/strand	Steel 44 kip/strand
Effective area of strand, in.^{2}	0.179	0.179	0.217
Guaranteed strength, ksi	339	339	270
Environmental reduction factor	0.9	0.9	1.0
Design strand strength, ksi	305	305	270
Unfactored moment due to dead load, kip-ft	4150	4150	4150
Unfactored moment due to superimposed dead load, kip-ft	173	173	173
Unfactored moment due to live load with impact, kip-ft	2280	2280	2280
Factored moment (Strength Limit State I), kip-ft	9437	9437	9437
Number of prestressing strands	69	50	42
Initial prestressing force before transfer, kip/strand	35.5	43.7	44
Effective prestressing force, kip/strand	26.7	35.2	36.1
Concrete stress at beam soffit at Service III, psi	-61	-12	+548
Nominal moment capacity, kip-ft	15,674	12,292	10,699
Reduction factor	0.85	0.85	1.0
Resistance moment, kip-ft	13,323	10,448	10,699
Resistance moment/factored moment	1.41	1.11	1.13
Fatigue load range, kip/strand	14.0	14.0	8.0
Strand stress to trigger fatigue, ksi	227	275	203
Moment capacity at specified fatigue stress, kip-ft	12,215	11,185	8162
Live load moment to trigger fatigue, kip-ft	7891	6862	3839
Fatigue live load/current live load	3.46	3.01	1.68

Note: CFCC= carbon-fiber-composite cable; design strand strength = guaranteed strength × environmental reduction factor; resistance moment = nominal moment × strength reduction factor; live load moment to trigger fatigue = moment capacity at specified fatigue stress – (unfactored moment due to dead load + unfactored moment due to superimposed dead load); strand stress to trigger fatigue = (effective prestressing force + fatigue load range)/effective area of strand. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 kip-ft = 1.356 kN-m.

to be a design concern even when considering a possible future increase in traffic load and cracking of the prestressed concrete beams.

- The one-million-hour relaxation rate—defined as the expected percentage loss in the force in a CFCC strand over 1 million hours—of the 0.6 in. (15 mm) diameter CFCC strands was approximately 1.9% based on relaxation test results of strands initially tensioned to a force level of 47.5 kip (211 kN). This value can be used in design to estimate the long-term prestress loss due to strand relaxation.

- Weather conditions did not seem to induce additional relaxation or permanently alter the force loss in the CFCC strands. In addition, after approximately three years of exposure to outdoor weather conditions under high stress levels, the residual tensile capacity of the CFCC strands was marginally higher than the average tensile capacity of virgin specimens of the same age, and approximately 15% higher than the average tensile capacity of CFCC strands within the first month after specimen construction three years earlier.

- The minimum estimate for the one-million-hour creep rupture strength of CFCC based on testing strands with different diameters is 88% of the average CFCC tensile strength. Therefore, initial prestressing force in CFCC strands may be safely increased to approximately 75% to 80% of the design strength of CFCC without a concern of creep rupture failure.

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Abstract

Fatigue strength, relaxation, and creep rupture strength of carbon-fiber-reinforced polymer (CFRP) strands were evaluated experimentally, and their impact on bridge beam design was investigated. The long-term relaxation of CFRP strands was evaluated by loading CFRP test specimens under different environmental conditions and monitoring prestress loss over time. Creep rupture strength of CFRP strands after 1 million hours of sustained stress exposure was predicted by loading and monitoring CFRP test specimens under a range of sustained stress levels for an extended time. The fatigue strength of CFRP strands was established by cyclically loading CFRP test specimens using different stress amplitudes. In addition, and as a benchmark for fatigue evaluation, low-relaxation steel and stainless steel strand test specimens were prepared and cyclically loaded within the fatigue test matrix. Test results showed that fatigue strength of CFRP strands is superior to that of low-relaxation steel and stainless steel prestressing strands. In addition, the one-million-hour relaxation loss of CFRP strands is approximately 2% for a wide range of initial stress levels. Furthermore, the one-million-hour creep rupture strength is at least 88% of the average tensile strength of the strands. Extended exposure to environmental conditions did not seem to affect the tensile capacity of CFRP strands.

Keywords

Carbon-fiber-reinforced polymer, CFRP, creep rupture, environmental exposure, fatigue, prestressing strands, relaxation.

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