# DEVELOPMENT OF A NEW-GENERATION HIGH-STRENGTH POST-TENSIONED ANCHOR BAR

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## KEYWORDS

2507 duplex; Anchor Bar; Post-Tension, corrosion resistant; high-strength; hydrogen embrittlement; post-tensioned (PT); shakedown; stainless steel; stress corrosion .

## INTRODUCTION

The Interstate 74 (I-74) Iowa-Illinois Corridor project encompasses the interstate corridor area bordered by I-280 to the south in Illinois and I-80 to the north in Iowa, through the Quad Cities region (Bettendorf and Davenport, IA; Moline and Rock Island, IL). The project involves several roadway and bridge structure improvements, including the replacement of a pair of two-lane suspension bridges crossing the Mississippi River, presently known as the Iowa-Illinois Memorial Bridges. The replacement bridges are two parallel, signature steel arch bridges where I-74 crosses the Mississippi River. The bridge arches consist of rectangular, steel rib box members with suspender cables supporting the deck structure. The two through-arches of each structure tilt inward to meet at the crown of each bridge, forming a "basket-handle" configuration. Each arch bridge is 72 ft (22 m) wide and spans 795 ft (242 m) over the main navigation channel of the Mississippi River.

The steel arches bear on massive concrete buttress abutments. The abutments are reinforced concrete set on drilled-shaft foundations founded within the Mississippi River. The arch-to-buttress connections are critical to the bridge structures. Each steel-arch end is constructed with steel stiffeners and base plates anchored to concrete. The present design connects each steel-arch end to the reinforced concrete buttress abutment with 48 high-strength, post-tensioned (PT) anchor bars (150 ksi [1030 MPa]) embedded in the concrete. The eight steel arch ends require 384 total anchor bars. The original design required 2-1/2 in. (63.5 mm) diameter anchor bars, approximately 16 ft (4.9 m) long.

Common high-strength, cementitious-grouted, anchor bar systems for PT applications consist of threaded carbon steel bars with a minimum tensile strength of 150 ksi (1030 MPa), per ASTM A722. This standard covers plain carbon steel bar with no requirements or guidance for their corrosion protection.

The anchor bar connection is an important component of this bridge—failure and replacement of an anchor bar will be difficult, if not impossible—and the risk of failure, albeit small, has major consequences to the long-term performance of the structure.

The project team desired an alternate material for the abutment anchor bars. Experimental candidate materials included two high-strength carbon steel control specimens, representing the current state of the art, and three stainless steel alloys. Physical and material property tests conducted include tensile, stress relaxation, hardness, Charpy V-notch toughness, threshold galling stress, critical pitting temperature, stress corrosion cracking, and hydrogen embrittlement testing. End and coupling nuts of different lengths were proof-tested to verify their ability to develop the full strength of the bar. This research recommended Alloy 2507 duplex stainless steel or the conventional plain, ASTM A722 high-strength, carbon-steel bar with a corrosion protection system. The design team selected Alloy 2507, primarily due to the corrosion resistance found through accelerated corrosion testing.

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## RESEARCH SIGNIFICANCE

The subject study evaluated several feasible candidate stainless steel materials for PT applications. The project sought to identify a more robust, high-strength anchor bar that provides better corrosion resistance to achieve the design 100-year service life. Many infrastructure projects are considering high-strength, stainless steel, PT anchor bars in various applications in both precast concrete and steel superstructure bridges.

**Table 1—Comparison of standard requirements**

| Property/ Standard | ASTM A722 | British Standard (BS) 4486 | Japanese Industrial Standard (JIS) G3109 |
|---|---|---|---|
| **Breaking load** | According to ASTM A370 | Characteristic breaking load and characteristic 0.1% proof load | No change from ASTM A722 |
| **Relaxation** | Not included | Relaxation limits at 1000 hours<br>- Initial load levels of 60, 70, 80% of actual breaking load and maximum relaxation values of 1.5, 3.5, and 6.0% respectively | Relaxation limits at 1000 hours. The standard specifies an initial force of 70% of the ultimate tensile strength and a maximum relaxation value of 4% |
| **Elongation** | 4.0% in a gage length equal to 20 bar diameters, or 7.0% in a gage length equal to 10 bar diameters | No change from ASTM A722 | Minimum required elongation of 5% |

## PRESENT STATE OF THE ART

The present state of the art material conforming to ASTM A722 includes both plain bar (Type I) and bar with surface deformations (Type II) and prescribes the chemical composition, mechanical properties, dimensions, deformation requirements, and inspection certification. Notably, ASTM A722 does not include relaxation testing requirements. Table 1 compares the requirements of similar standards from other countries.

For corrosion protection technology, *fib* Bulletin 33, *Durability of Post-Tensioning Tendons* (2005), provides many recommendations and strategies applicable to a PT bar system. In aggressive environments, *fib* advocates the principle of multiple-layer protection, which provides a redundant system for protection and durability. *fib* recognizes it is difficult to achieve perfect corrosion protection with any one individual means, so multiple methods are recommended. Each method or layer of protection is designed to provide total protection in the event one layer breaks down or fails to remain effective. *fib* makes several recommendations on how to construct a durable system, which starts with the design specifications and continues through concrete construction requirements. It appears the most predominant method or best state of the practice for a PT anchor bar system is to encapsulate the anchor bar in corrosion-inhibiting grease/wax, cementitious grout, or a combination of the two.

## CANDIDATE MATERIALS

Stainless steels contain an alloying addition of at least 11% chromium by weight, which passivates the alloy by forming a chromium-rich oxide surface film. This self-healing film is resistant to aqueous corrosion in the presence of pure water; however, further alloying is necessary to provide protection against contaminant chemical species such as chlorides and sulfides.

The proposed candidate materials identified from a literature search included the following:

- Custom 450 precipitation-hardened stainless steel, in the H1050 condition, due to its high strength (160 ksi [1103 MPa]), adequate corrosion resistance, and availability due to extensive use in the oilfield and medical industries.
- Custom 465 precipitation-hardened stainless steel, in the H1050 condition, due to its very high strength (230 ksi [1590 MPa]) and superior resistance to corrosion and stress corrosion cracking.
- Custom 630 (17-4) precipitation-hardened stainless steel, in the H1100 condition, due to its high strength (164 ksi [1131 MPa]) and superior corrosion resistance to Custom 450.
- Duplex Stainless Steel 2507, which is most commonly available as the commercial variant of Zeron® 100FG (strain hardened), due to its excellent resistance to pitting and stress corrosion cracking.
- Ti-6Al-4V Grade 5 titanium alloy, due to its excellent corrosion resistance and good strength (150 ksi [1030 MPa]) and toughness.
- Ti-10-2-3 titanium alloy, due to its high strength (170 ksi [1172 MPa]) excellent corrosion resistance, and resistance to stress corrosion cracking.

Cost and schedule limitations eliminated the Custom 465, Ti-6Al-4V, and Ti-10-2-3 from the test program.

Final candidate materials tested include the following:

- Plain carbon steel bar (control)
- Galvanized carbon steel bar (control)
- Custom 450 H1050 precipitation-hardened stainless steel
- Custom 630 H1100
- Alloy 2507 duplex stainless steel

## BAR FABRICATION

Present carbon steel, PT anchor bars use a mixture of hot- and cold-rolled thread forming processes with deformations along the entire length as required by ASTM A722. The bars for this testing were fabricated from plain bar stock in a nominal 2-3/4 in. (70 mm) diameter and there are presently no suppliers of hot-roll threaded stainless steel bars.

Two thread-forming methods were considered: cold-rolled and machine-cut.

- Cold-rolled threads typically are formed on plain bar stock by hardened steel dies through a cold-forging process (Reed Machinery 2014). As illustrated in Fig. 1, die faces press against the perimeter of the plain cylindrical blank of the material as it rotates, and the threads form, under pressure, in the material. In pressing the bar stock surface, the stamping dies displace the material to form the thread root (low point) and force the displaced material radially outward to form the thread crests. Material cold working can alter the material properties, particularly at the perimeter surface of the bar. Cold working can increase the yield strength but has little effect on the tensile strength.
- Machine-cut threads are formed by physically cutting threads into the material on a cutting lathe. Machine cutting threads is possible for almost all materials; however, thread forming is an art and depends on the lathe speeds, tooling dies, and cutting lubricants used to cut the threads. A limited number of machine shops are capable of handling and machining the size specimens required for the testing.

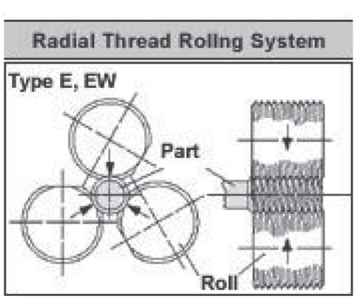


*Fig. 1—Means of achieving threads on bar through cold-rolling (Koepfer 2003).*

Figure 2 conceptually illustrates the difference between a machine-cut thread and a cold-roll thread on a typical metallurgical cross section. Rolled threads tend to have softer edges on the thread and the material is displaced slightly, such that residual compressive stresses form at the thread root or valley.

## MATERIAL AND PHYSICAL PROPERTY TESTING

A test program was developed to demonstrate comparative performance of the commonly used and the alternate candidate materials for the desired 100-year service life. Sample populations were selected to balance cost, statistical significance, and the predictive value of the test.

### Yield strength, tensile strength, and elongation

PT anchor bars are traditionally identified by a specified minimum tensile strength. For the subject anchor bars, the project team desired a minimum tensile strength, $f_{pu}$, of 150 ksi (1030 MPa) to match present PT bar technology. The stress-strain behavior of most high-strength steels gradually transitions from elastic to inelastic behavior without a well-defined yield point, which is referred to as a roundhouse stress-strain curve or a gradual strain-hardening curve.

Table 2 provides the measured yield and tensile strengths, tensile elongation, and calculated modulus of elasticity for full-size specimens tested in accordance with ASTM A370. The 0.2% offset method was used to determine anchor bar yield strength. Figure 3 shows the stress-strain curve for all materials up to approximately 0.9% strain prior to removing the extensometer. Figure 4 shows a general force-displacement relationship for each material from the cross-head displacement of the test machine. Notably in the tensile test results, the Alloy 2507 duplex has a significant amount of tensile elongation. Only one of the four specimens exhibited tensile fracture; two specimens elongated sufficiently to reach the displacement limit (30 in. [600 mm] stroke) of the testing machine and

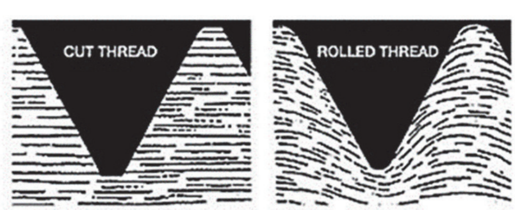


*Fig. 2—Metallurgical differences in cut and rolled threads on bar as shown by modified grain structure (Reed Machinery 2014).*

had to be unloaded prior to failure; one specimen failed by stripping the internal threads in one end nut at a 120.1 ksi (828 MPa) ultimate stress without any softening behavior in the load-displacement curve. The two specimens that did not fracture began necking after achieving peak strength, resulting in a decrease in tensile load due to local reduction of area in the specimen with increasing elongation, often characterized as a negative slope in the load-displacement curve.

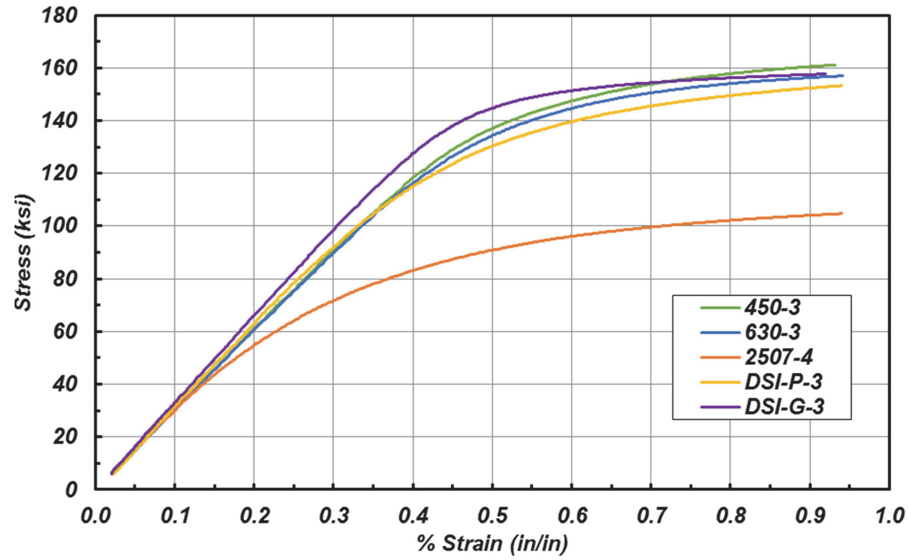


*Fig. 3—Representative stress-strain curves prior to removing extensometer. (Note: 1 ksi = 6.89 MPa.)*

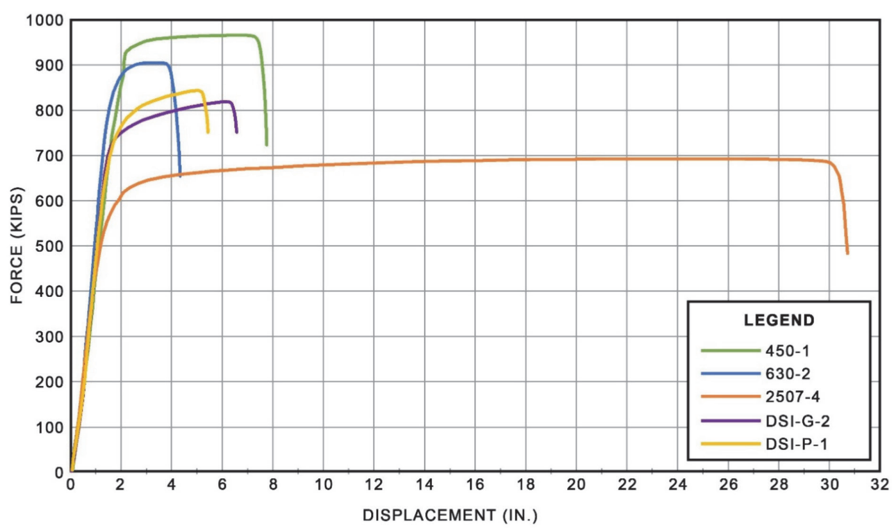


*Fig. 4—Representative force-displacement curves. (Note: DSI-G-2 and DSI-P-1 bars had effective area of 5.16 in.$^2$; other bars had effective area of 5.76 in.$^2$; 1 kip = 4.448 kN; 1 in. = 25.4 mm.)*

## End and coupling nuts

End nuts anchor the PT anchor bar after stressing. The nut must hold the load in the bar without fracturing or stripping out the threads, as this failure mode is insidious. It starts at the lead thread and progresses through the entire thread engagement length, as the remaining threads peel off, and failure occurs without warning. Suitable nut length to hold the load is an important system attribute. A full ultimate tension testing of end nuts was not performed due to laboratory safety concerns. The end nut was tested until the test stress-strain curve exhibited clear nonlinear behavior, demonstrating the end nut would develop at least the yield strength of the bar. The resulting applied stress was also greater than 125% of the specified yield strength of the bar in tension, which is a requirement of AASHTO for full-mechanical connections. All end nuts met the applicable performance criteria.

Many applications require anchor bars longer than the maximum fabrication length of the steel rolling mill or threading supplier. In addition, coupling nuts are typically used during the tensioning operation to stress the bar prior to tightening the end nut. Tension tests were performed on full-size coupled 6 ft (1.8 m) long bars according to ASTM A370. All coupling nut tests failed by anchor bar fracture, indicating the coupling nut developed the full capacity of the anchor bar.

## Relaxation

Under sustained high stress, steel will stress-relax, or under constant strain, stress diminishes. For a given steel, the degree of relaxation depends on the initial stress level and temperature. Little relaxation occurs at relatively low stress levels (less than 50% of the material tensile strength). For ASTM A722-conforming, high-strength bars and the bar being developed herein, post-tensioning will stress the bar above 50%—hence the need to determine relaxation for design loss calculations. For a given steel material, stress relieving by preloading and heat treatment may improve stress relaxation properties of the steel.

ASTM A722 does not contain relaxation requirements for high-strength anchor bars while other standards do; refer to Table 1. The test criteria were similar to the requirements of BS 4486, except that the initial load was determined based on the specified minimum tensile strength instead of the actual breaking load from an adjacent test piece. For the control carbon steel, galvanized steel specimens, Custom 450, and Custom 630 specimens, a specified minimum tensile strength of 150 ksi (1030 MPa). was assumed. For the Alloy 2507, a specified minimum tensile strength of 110 ksi (759 MPa) was selected.

Design standards limit the tensile stresses in prestressed reinforcement and anchorages as follows:

- ACI 318-14, Table 20.3.2.5.1 (2014), limits the permissible tensile stresses in prestressed reinforcement to $0.94f_{py}$ or $0.80f_{pu}$ during stressing operations. The maximum tensile stress is $0.70f_{pu}$ after force transfer (that is, seating).
- AASHTO LRFD Bridge Design Specifications Table 5.9.3-1 (2012) provides stress limits for prestressing tendons. For deformed high-strength bars, the maximum stress prior to seating is $0.90f_{py}$. The maximum tensile stress is $0.70f_{pu}$ at anchorages and couplers immediately after anchor set.

For the target initial load, 80% of the specified minimum tensile strength was selected. ASTM A722 specifies the minimum yield strength as 80% of the minimum tensile strength for Type II (deformed) bars. As a result, the target initial load is close to the specified minimum yield strength. The target initial load is a higher percentage of both yield and tensile strengths than either design standard permits. The highest level was elected to determine the largest relaxation percentage. Relaxation testing was also performed on an additional set of plain carbon steel specimens at an initial load level of approximately 60% to provide a comparison of relaxation at various load levels for this material.

Table 2 provides the jacking stress, initial stress after seating, and relaxation losses for each material tested. Figure 5 shows the relationship between measured relaxation loss and initial stress as a percentage of specified minimum tensile strength and includes the limits from the various reference standards. The first set of Alloy 2507 specimens had initial stresses of 39.0, 58.7, and 66.2%. The initial stress standard deviation was higher than other material tests due to difficulties tightening the nuts on the test specimen. As the test specimens were stressed, the nuts were typically tightened to limit the seating losses that occur. It was not possible to tighten the nut on the Alloy 2507 specimens. This resulted in higher seating losses than other materials and corresponding lower initial loads. Three additional Alloy 2507 specimens were tested at a higher initial

**Table 2—Relaxation test results (average of three tests except Alloy 2507)**

| Material | | Jacking stress, ksi | Jacking stress% of design minimum tensile strength* | Initial load after seating, ksi | Initial load % of design minimum tensile strength* | Final load, ksi | Total relaxation, ksi | % relaxation |
|---|---|---|---|---|---|---|---|---|
| Plain carbon steel—high | | 127.5 | 85.0% | 111.7 | 74.5% | 108.6 | 3.1 | 2.75% |
| Plain carbon steel—low | | 104.3 | 69.5% | 93.6 | 62.4% | 92.0 | 1.6 | 1.74% |
| Galvanized carbon steel | | 125.0 | 83.3% | 106.5 | 71.0% | 103.8 | 2.7 | 2.51% |
| Custom 450 H1050 | | 141.8 | 94.6% | 126.0 | 84.0% | 123.8 | 2.0 | 1.58% |
| Custom 630 H1100 | | 125.3 | 83.6% | 111.0 | 74.0% | 109.5 | 1.5 | 1.32% |
| Alloy 2507 | Test 1 | 83.9 | 76.2% | 72.9 | 66.2% | 71.0 | 1.9 | 2.60% |
| | Test 2 | 87.0 | 79.1% | 64.5 | 58.7% | 63.4 | 1.1 | 1.75% |
| | Test 3 | 87.2 | 79.2% | 42.9 | 39.0% | 42.6 | 0.3 | 0.71% |
| Alloy 2507 Tests 4-6 | | 86.2 | 78.3% | 75.7 | 68.9% | 73.0 | 2.7 | 3.59% |

*Design tensile strength: $f_{pu}$ = 150 ksi (1030 MPa) for carbon steel, Custom 450, and Custom 630; $f_{pu}$ = 110 ksi (759 MPa) for Alloy 2507.

Note: 1 ksi = 6.89 MPa.

stress. Due to availability, the test specimens were two coupled 6 ft (1.9 m) bars to replicate field conditions of coupled bars. This higher initial stress was achieved by reducing the nut length, which allowed tightening of the nuts. These Alloy 2507 specimens were stressed to an average initial stress of 68.9% after seating losses.

## Hardness

The Rockwell hardness of the materials was measured according to ASTM E18. Equivalent depths from the bar surface of 0.1*R* were tested, which is close to the thread root, 0.45*R*, and 0.8*R*, where *R* is the bar radius. The Brinell hardness of the materials was measured according to ASTM E10.

Table 3 shows the measured hardness along with the tensile strengths for each material. For the plain carbon steel, Custom 450, and Custom 630, a significant difference in hardness between the near-surface and center of the bar was not measured. For the galvanized carbon steel bar, the near-surface of the bar measured slightly softer than the center. This indicates a slight softening of the bar during the galvanizing process, as is reflected in the slightly lower strength compared to the plain bar. For the Alloy 2507, the hardness decreased significantly with distance from the surface. This indicates the cold-rolled thread forming process causes surface work hardening of the material and reflects the higher ductility and ability to work-harden the Alloy 2507 compared to the other materials.

## Charpy V-Notch (toughness)

The Charpy V-Notch (impact) toughness of the materials was measured according to ASTM E23, using both full-sized (10 x 10 x 55 mm [0.39 x 0.39 x 2.17 in.]) and sub-sized (7.5 x 10 x 55 mm [0.30 x 0.39 x 2.17 in.]) specimens.

AASHTO LRFD Article 6.6.2 and Table 6.6.2-1 (2012) specify three temperature zone designations for Charpy V-Notch requirements. A minimum service temperature for the anchor bars of –30°F (–34.4°C) was selected, which corresponds to the low temperature for Zone 2. The samples were also tested at an ambient temperature of 68°F (20°C) and a slightly elevated temperature of 90°F (32.2°C) to represent typical working temperatures of the structure.

Figures 6(a) to 6(d) show the relationship between absorbed energy and temperature from the Charpy V-Notch testing. Both the plain and galvanized carbon steel

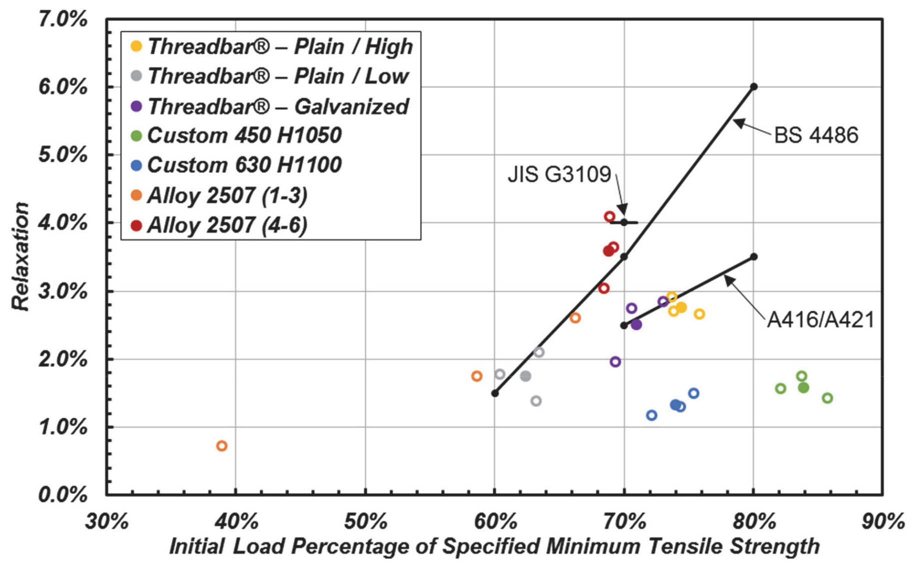


*Fig. 5—Relaxation testing results compared standard limits (solid circles represent average relaxation from three samples; open circles represent individual test data).*

**Table 3 —Hardness test results**

| Material | Rockwell hardness: Depth from surface (*R* is bar radius) 0.1R | 0.45R | 0.8R | Average hardness | Brinell hardness | Measured tensile strength, ksi |
|---|---|---|---|---|---|---|
| Plain carbon steel | 34 | 37 | 34 | 35 | 363 | 166 |
| Galvanized carbon steel | 29 | 36 | 34 | 33 | 341 | 159 |
| Custom 450 H1050 | 39 | 39 | 38 | 39 | 375 | 170 |
| Custom 630 H1100 | 38 | 36 | 36 | 37 | 352 | 160 |
| Alloy 2507 | 32 | 25 | 22 | 26 | 262 | 121 |

specimens had lower impact toughness across all temperatures. Custom 450 and Custom 630 have slightly greater impact toughness than the carbon steel. The Alloy 2507 exhibited significantly higher impact toughness with no significant change in the impact energy with decreasing test temperature

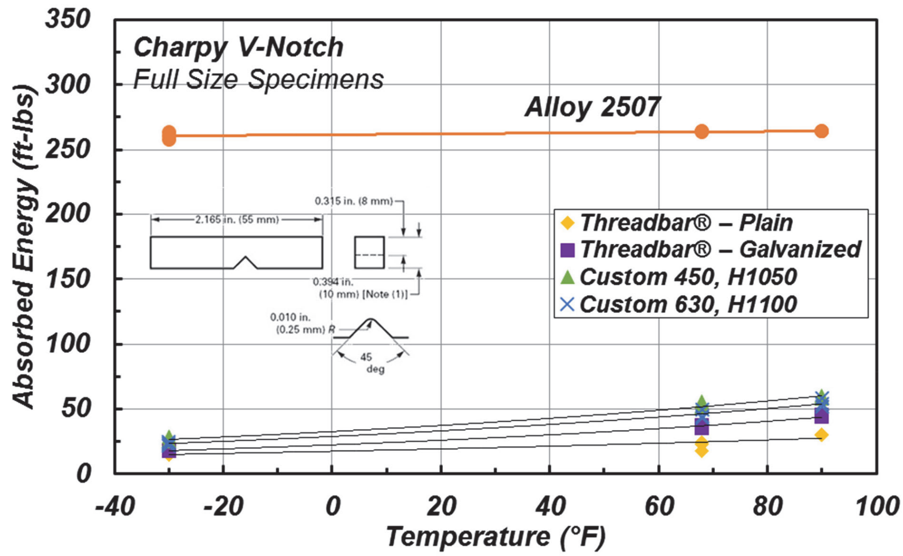


Fig. 6(a)—Charpy V-Notch, full-size specimen test results (entire range). (Note: 1 ft-lb = 1.355 J; °C = [°F – 32]/1.8.)

## Galling

The threshold galling stress of the materials was measured according to ASTM G98. The carbon steel bar shows a slightly higher threshold galling stress than the other bars. Note that galling is a subjective test, and the threshold galling stress measurements were lower than other published data.

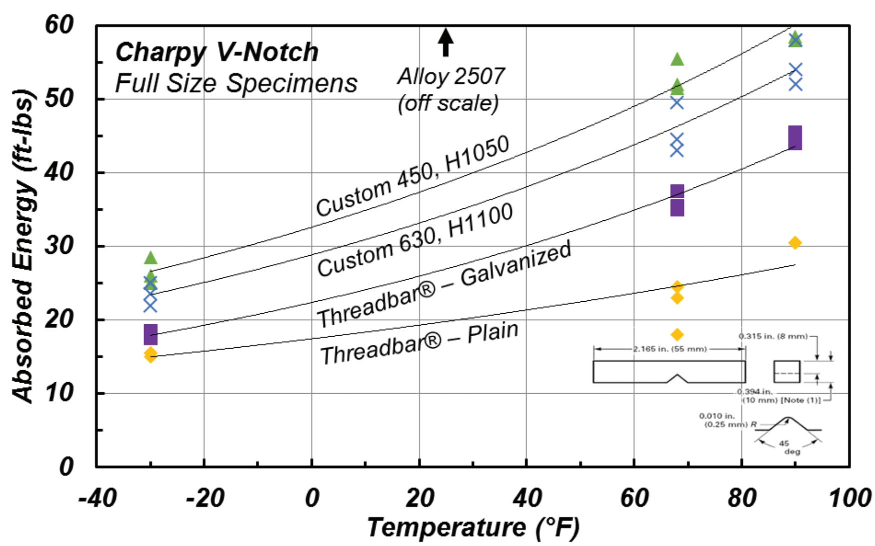


Fig. 6(b)—Charpy V-Notch, full-size specimen test results (low range). (Note: 1 ft-lb = 1.355 J; °C = [°F – 32]/1.8.)

## Pitting corrosion

The pitting corrosion test is designed to test the resistance to corrosion of stainless steels, which have a normal passive surface layer to protect against corrosion. Carbon steel does not have a passive surface layer and corrodes by a general surface corrosion mechanism rather than by pitting.

The resistance to pitting corrosion of the materials was measured according to ASTM G48. Machined samples were suspended in individual beakers and immersed each in 200 mL of acidified 6 wt.% ferric chloride test solution. The pitting corrosion test was not conducted on a galvanized carbon steel bar because this test is performed on machined samples independent of the galvanizing.

The Custom 450 and Custom 630 specimens failed the test at low critical pitting temperatures. Alloy 2507 clearly demonstrated the highest critical pitting temperature and resistance to pitting corrosion. The plain carbon steel did not fail by pitting corrosion; however, it was substantially corroded on the surface.

## Stress corrosion cracking

The materials' resistance to stress corrosion cracking (SCC) was measured according to ASTM G123. C-ring specimens from each material were machined, loaded each sample to a nominal 85% of the yield stress (derived from material product sheets) and immersed them in a test solution of 25% sodium chloride, acidified to a pH of 1.5. SCC testing was not conducted on a galvanized carbon steel because this test is performed on machined samples independent of the galvanizing.

The carbon steel bar and Alloy 2507 did not exhibit susceptibility to SCC, although the carbon steel was heavily corroded by this test. The Custom 450 and Custom 630 perform poorly in SCC testing, exhibiting a suscep-

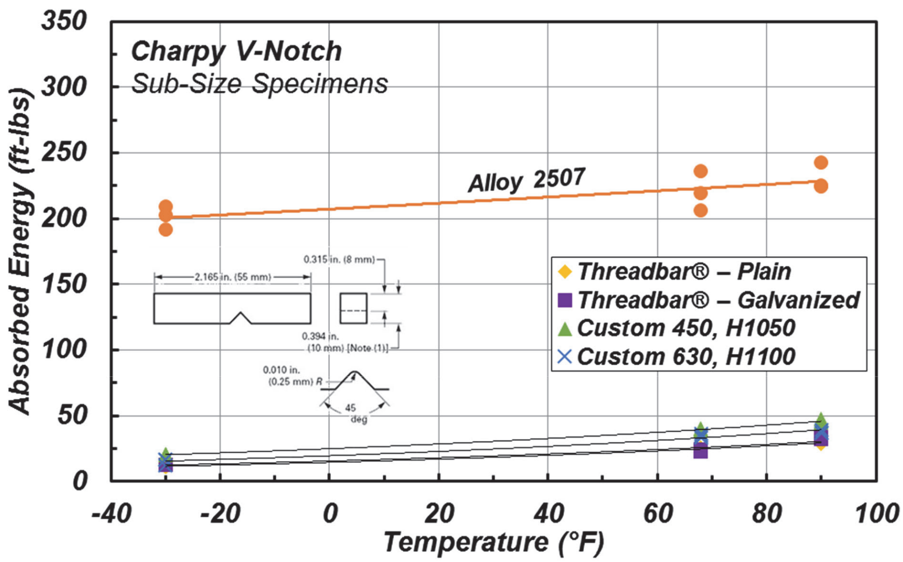


*Fig. 6(c)—Charpy V-Notch, sub-size specimen test results (entire range). (Note: 1 ft-lb = 1.355 J; °C = [°F – 32]/1.8.)*

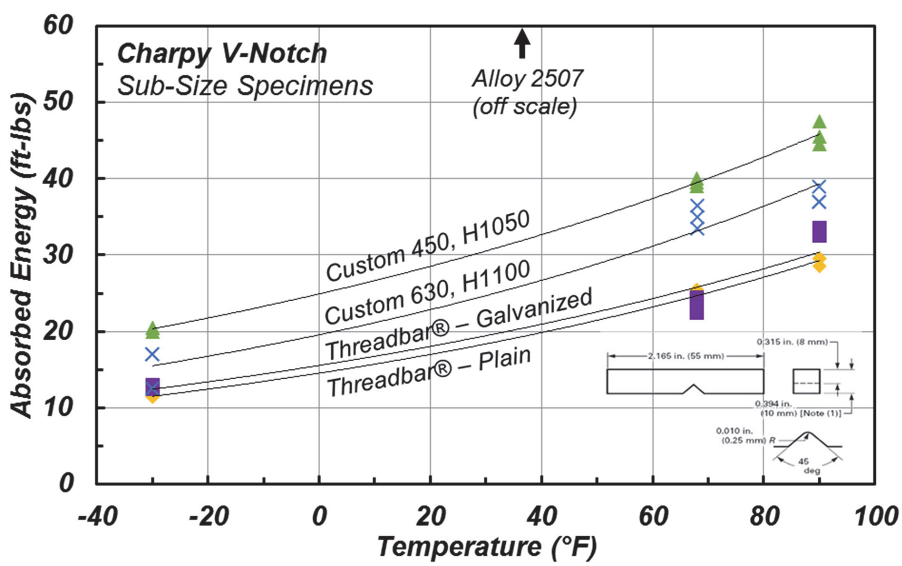


*Fig. 6(d)—Charpy V-Notch, sub-size specimen test results (low range). (Note: 1 ft-lb = 1.355 J; °C = [°F – 32]/1.8.)*

tibility to corrosion and cracking in the test environment after only a short duration.

### Hydrogen embrittlement

The objective of hydrogen embrittlement testing is to determine whether the fracture toughness of a material is reduced by hydrogen contamination and the threshold at which subcritical crack growth can occur. Hydrogen embrittlement testing was conducted according to ASTM F1624. This test method uses a rising step load protocol applied to a pre-cracked specimen to determine the material's susceptibility to hydrogen cracking. The test procedure consisted of the following steps: 1) machining the test specimen from the parent roll-threaded bar; 2) fatigue pre-cracking the specimen; 3) hydrogen charging the specimen (for the hydrogen charged specimens); 4) measurement of hydrogen content; and 5) load testing the specimen. Additional information on the hydrogen charging method is found in Humphreys et al. (2018).

For the carbon steel material, the hydrogen charging produced a severe decrease in the fracture toughness of the sample. No significant difference in the fracture behavior of the carbon steel material between the plain and galvanized forms was detected. For the Custom 450 and Custom 630 materials, there was a moderate decrease in the fracture toughness from hydrogen charging. The fracture toughness of the Alloy 2507 was unaffected by hydrogen charging.

## INELASTIC BEHAVIOR OF ALLOY 2507

Initial results on the Alloy 2507 demonstrated favorable behavior and characteristics. The corrosion testing indicated superior performance of Alloy 2507. However, Alloy 2507 has a monotonic stress-strain behavior that begins to roundhouse at a much lower stress than the other carbon and stainless steels of this study (Fig. 3 and 4). The initial elastic portions of the stress-strain curve only extend to approximately 40 ksi (276 MPa), where the material begins to transition into the nonlinear range. The yield point defined by the 0.2% offset is well within the nonlinear range of the material.

The pretension force applied to the anchor bar during installation and jacking will stress the material into the nonlinear part of the stress-strain curve. The pretension force after losses will be less than this initial jacking force; however, the expected design forces on the anchor bars will exceed the pretension force after losses. The typical forces on the anchor bars are not expected to exceed the pretension force, the design forces result from strength load combinations that should have infrequent occurrence over the life of the structure.

The initial evaluation of the performance of Alloy 2507 was based on the premise that, following the initial jacking force, during loss of pretension and anticipated reloading, the stress-strain relationship will follow a linear unloading path that is parallel to the initial elastic modulus. If this premise is true, then continued loading and unloading should follow the same linear path without further increase in inelastic strain, so long as the subsequent force on the anchor bar does not exceed the maximum previously applied load. This stable condition is known as "linear shakedown." If this assumption is incorrect, then the reloading curve may be nonlinear, resulting in "ratcheting," leading to additional inelastic strain and loss of preload with subsequent cycles.

To evaluate if Alloy 2507 exhibits stable linear shakedown and is a viable material for the anchor bar application, the material's inelastic behavior was evaluated by conducting a series of cyclic tests on several specimens at varying stress and strain levels in the nonlinear range. Similar inelastic behavior tests on the other candidate materials were not conducted because the stress-strain relationship of those materials is similar to materials commonly used in this type of application.

Inelastic behavior testing was conducted on both full-size and reduced-size specimens.

## Full-size specimens

For full-size specimens, two tests were conducted: one on a 12 ft (3.7 m) long bar from prior relaxation testing, and one on a pair of 6 ft (1.9 m) long bars coupled to form a 12 ft (3.7 m) long test specimen. For the 12 ft (3.7 m) specimen from prior relaxation, a specimen previously stressed to 83 ksi (573 MPa) prior to the relaxation duration of 1000 hours was used. The test was conducted using the following protocol:

- Load the specimen to an initial jacking stress of 80 ksi (552 MPa).
- Reduce the stress in the specimen to a seating stress of approximately 68 ksi (469 MPa). This was used as the baseline value for subsequent cyclic testing on this specimen.
- Increase the stress in 5% increments and unload to the seating stress for five total cycles, from 5 to 20% with a final cycle at 30%.

For the two coupled 6 ft (1.9 m) specimens, bars that were not previously stressed were used. The test was conducted using the following protocol:

- Load the specimen to an initial jacking stress of 78 ksi (538 MPa).
- Reduce the stress in the specimen to a seating stress of approximately 69 ksi (476 MPa). This was used as the baseline value for subsequent cyclic testing on this specimen.
- Increase the stress in 5% increments and unload to the seating stress for five total cycles, from 5 to 30%, with a final cycle at 40%.

Both the 12 ft (3.7 m) and coupled 6 ft (1.9 m) test specimens exhibited stable response with consistent stress-strain behavior until the applied stress exceeded the previous jacking stress for the specimen. Above this stress, each group of cycles at a higher level exhibited nonlinear behavior with some stress loss over the five cycles.

## Reduced-size specimens

The following tests were conducted on reduced-size specimens:

- Monotonic tensile testing to verify the stress-strain relationship for the reduced sized specimen
- Cyclic tensile testing with increasing strain increments
- Stress relaxation followed by monotonic tensile testing
- Stress relaxation followed by cyclic tensile testing at constant strain increment

The cyclic test was conducted with increasing strain increments using the following protocol:

- The specimen was loaded to an initial jacking stress of 80.6 ksi (556 MPa).
- The test was decreased to a lock-off stress of 67.9 ksi (468 MPa). This strain was used as the baseline value for subsequent cyclic testing on this specimen.
- The stress was increased in 5% increments, from 5 to 70%, and unloaded to the seating stress for 10 total cycles.

Stress relaxation was conducted followed by cyclic tensile testing at constant strain increment using the following protocol:

- A stress of 90 ksi (621 MPa) was loaded and held at this stress for approximately 66 hours.
- The stress was decreased to a lock-off stress of 49.5 ksi (341 MPa). This was used as the baseline value for subsequent cyclic testing on this specimen.
- The stress was increased to 76.5 ksi (527 MPa). The measured strain value was used as the maximum strain increment for subsequent cyclic testing on this specimen.
- The specimen was cycled at the strain increment for 1000 cycles.

For the cyclic tensile testing with increasing strain increments, the behavior remained stable for the initial two groups of cycles where the stress remained less than the initial jacking stress. When the stress exceeded the initial jacking stress, some loss of initial pretension occurred with each increment.

For the 66-hour relaxation test, the initial jacking stress decreased to approximately 73 ksi (503 MPa). Some of this loss is believed to be due in part to relaxation but also likely due to the loss of hydraulic pressure in the test frame. For the specimen subjected to cyclic tensile testing at a constant strain increment, no appreciable decrease in stress was observed at the tested strain limits after 1000 cycles.

## DISCUSSION

### Mechanical properties

As noted earlier, the carbon steel bar, both plain and galvanized, Custom 450, and Custom 630 tensile strengths exceeded 150 ksi (1030 MPa). Alloy 2507 had a minimum average tensile strength of 121.4 ksi (837 MPa). The carbon steel, Custom 450, and Custom 630 clearly met the specified performance criteria. The project team evaluated the ability of the present design to accommodate a lower design tension strength of the Alloy 2507 as discussed later.

### Relaxation under load

The initial load applied to the relaxation test specimens was highly dependent on the amount of seating following the release of jacking pressure. To achieve an initial load magnitude for the relaxation test approximately equivalent to service conditions, the test specimens had to be jacked to a higher percentage of the minimum tensile strength of the bar than either AASHTO or ACI would permit for design consideration. This was the result of the test setup, specifically the deflections of the relaxation frames and crushing of the plate washers, rather than representative of actual material performance.

The measured relaxation performance of the plain and galvanized carbon steel bar. Custom 630 and Custom 450 met the interpolated limits of BS 4486. The tests also met the relaxation requirements of ASTM A416 and JIS G3109.

The first set of relaxation tests on the Alloy 2507 bars did not achieve initial loads suitable to quantify the relaxation performance and compare to reference standards. The minimum initial load percent according to BS 4486 is 60% of the characteristic breaking load of the material. This initial load is less than the expected preload that will be introduced in application of the subject anchors. The second set of tests on coupled 6 ft (1.9 m) bar specimens achieved suitable preloads to compare the relaxation performance to the reference standards. The coupled specimens resulted in an average relaxation of 3.59%, which slightly exceeds the requirement in BS 4486; however, this relaxation is less than the requirement in JIS G3109.

### Galling

All of the materials tested exhibited a tendency to gall at an applied stress of less than 1 ksi (7 MPa). Galling resistance often increases with increasing tensile strength, a significant increase in galling resistance between the various stainless steels was not measured. During mechanical testing of full-size specimens (tensile, coupling nut, end nut, and relaxation), there was not an appreciable difference in the thread-ability of the materials except the galvanized specimens. For the galvanized specimens, threading the nuts onto the bars was difficult. The bar thread tips had to be grinded or filed to facilitate threading. For all other materials tested, a lubricant was used on the threads to prevent galling and thread binding; however, lubricant was not required in all test setups.

### Toughness (Charpy V-Notch)

The standards for high-strength anchor bars (ASTM A722, BS 4486, and JIS G3109) do not specify minimum toughness requirements. The test results were reviewed and compared to the following standards:

- ASTM A320 specifies an impact energy of 20 ft-lb (27.1 J) for stainless steel bolting materials in fracture-critical applications.
- AASHTO LRFD Bridge Design Specifications (2012), Article 6.2.2, specifies impact (Charpy) toughness requirements for steel structures, including a minimum impact energy of 25 ft-lb (33.9 J) for non-fracture critical and 35 ft-lb (47.4 J) for fracture-critical tension components at the test temperature.

In the tests, all stainless steels demonstrated higher toughness compared to the carbon steel bar. At the design low temperature of –30°F (–34°C), both Custom 450 and Custom 630 stainless steels have an impact (Charpy) toughness greater than 20 ft-lb (27.1 J). Both plain and galvanized carbon steel bar had an impact toughness less than 20 ft-lb (27.1 J) at this test temperature. The Alloy 2507 has a much greater toughness, 261 ft-lb (354 J), than all other tested materials due to its ductile two-phase microstructure. Only the Alloy 2507 met the referenced standards.

## CORROSION RESISTANCE

The three tests conducted to assess pitting corrosion, stress corrosion cracking, and hydrogen embrittlement are summarized in Table 4.

## DESIGN CONSIDERATIONS

### Re-passivation of stainless steel

Following installation and stressing of any stainless steel anchor bar, the exposed surfaces that were in contact with other metallic tools will need to be re-passivated. This removes any residual-free iron from the surface that has been exposed by machining or other contact and reestablishes the protective layer of protective oxides—one or more of chromium, nickel and molybdenum—that provide stainless steel grades with their enhanced corrosion resistance.

### Design stress limits

The test results demonstrate the Custom 450 and Custom 630 meet the minimum requirements of ASTM A722; therefore, a revised design with either of these materials would be the same as the original design with carbon steel bar. Alloy 2507 requires a reduced design stress limits due to its lower tensile strength and yield strength.

Figure 3 showed that Alloy 2507 has a short linear-elastic monotonic stress-strain behavior that gradually "rolls over" into the inelastic range; this pronounced roundhouse behavior becomes nonlinear around 40 ksi (276 MPa). The initial anticipated jacking load will carry the Alloy 2507 well into the nonlinear range. Initial losses (seating and elastic shortening of the concrete) and long-term losses (relaxation, creep, and shrinkage) cause the bars to unload to a lower level of anchor pretension. Inelastic behavior testing indicated that reloading of Alloy 2507 will continue on a linear path that is parallel to the initial stress-strain curve until the force in the bar exceeds the previous maximum force in the anchor bar. This stable condition is known as "linear shakedown." The upper limit of this linear path is established by the maximum prior force applied to the bar, either by pre-straining during fabrication or over-jacking during the anchor stressing operation. The project team specified an initial prestressing level in the bar that is anticipated to be higher than the maximum stress the bars will be required to resist over their service life to establish this linear shakedown behavior.

## SUMMARY OF CANDIDATE MATERIALS

The following was concluded for each of the materials:

***Plain carbon steel bar*** meets the project's strength and ductility requirements as expected. In the accelerated corrosion testing, it exhibited a high degree of surface corrosion in all tests and was susceptible to hydrogen embrittlement. The bar would need extensive corrosion protection when exposed to the environment to meet the design 100-year service life.

***Hot-dipped galvanized carbon steel bar*** is not a viable material for the application. A galvanized coating system was not recommended following the literature review, as galvanized coatings have a limited

**Table 4—Summary of corrosion resistance testing**

| | Alloy 2507 | Custom 450 | Custom 630 | Carbon Steel |
|---|---|---|---|---|
| Pitting corrosion | No corrosion at standard test temperatures. Required temperature of 185°F (85°C) for pitting to occur. | Have a passive surface layer protecting against aqueous corrosion. However, this passive layer becomes unstable in the presence of chloride ions, resulting in pitting corrosion. | | Susceptible to corrosion in the presence of water and oxygen. |
| Stress corrosion cracking | No cracking after 2 weeks of testing. High resistance to stress corrosion cracking. | Cracked within 6 hours of testing. | | No cracking – likely due to rapid corrosion of the entire surface blunting any crack tip allowing SCC to occur. |
| Hydrogen embrittlement | No decrease in toughness or brittle crack behavior after hydrogen charging. Can be expected to resist hydrogen cracking in the long term. | Exhibited brittle cracking in the surface layer after hydrogen charging for 60 hours. Brittle hydrogen cracking will occur. | | Susceptible to hydrogen embrittlement and subcritical crack growth resulting in a significant decrease in the fracture toughness of the material. |

life of protection and poor bond adhesion to cementitious grout. The Phase 2 testing provides further corroboration that galvanized bar is not a viable option. The coating in the region of the fracture de-bonded completely. The adjacent coating displayed significant cracking. These failures indicate that the galvanized coating is likely more brittle than the parent carbon steel bar.

***Custom 450* precipitation-hardened stainless-steel bar** in the H1050 heat treatment condition meets the strength and ductility requirements of the project. It has the best toughness of the non-duplex materials. However, it has limited resistance to pitting corrosion and stress corrosion cracking in high chloride concentrations; it was found to be susceptible to hydrogen embrittlement.

***Custom 630* precipitation-hardened stainless-steel bar** in the H1100 heat treatment condition meets the original strength and ductility requirements of the project. It has slightly decreased toughness and corrosion resistance to the Custom 450 in the testing and exhibited similar susceptibility to hydrogen embrittlement.

***Alloy 2507* duplex stainless-steel bar** exhibited excellent resistance to pitting corrosion, stress corrosion cracking, and hydrogen embrittlement. The material performed exceptionally well in the accelerated corrosion testing environment. The toughness at the design low temperature was an order of magnitude greater than all other materials tested.

The performance of Alloy 2507 necessitated additional testing because of its lower tensile strength and roundhouse mechanical behavior. The material does not exhibit a well-defined yield point, but rather a gradually yielding or roundhouse stress-strain curve, which "rolls over" after departing from linear behavior, resulting in increasing inelasticity with strain. The acceptability of Alloy 2507 under service cyclic load excursions through additional material mechanical testing and review with M&M was reviewed. This led to a refinement of the anchor bar design with the initial prestress level exceeding the maximum service load stress under typical design conditions.

## RECOMMENDATIONS

Alloy 2507 duplex stainless steel or the traditional plain high-strength, carbon-steel bar with a robust corrosion protection system was recommended as the preferred materials (Fig 7). This information was presented to the project team of Alfred Benesch & Company, Modjeski and Masters, Inc., Iowa DOT, Illinois DOT, and Federal Highway Administration (FHWA). The team recommended proceeding with Alloy 2507, which received concurrence from the governmental agencies.

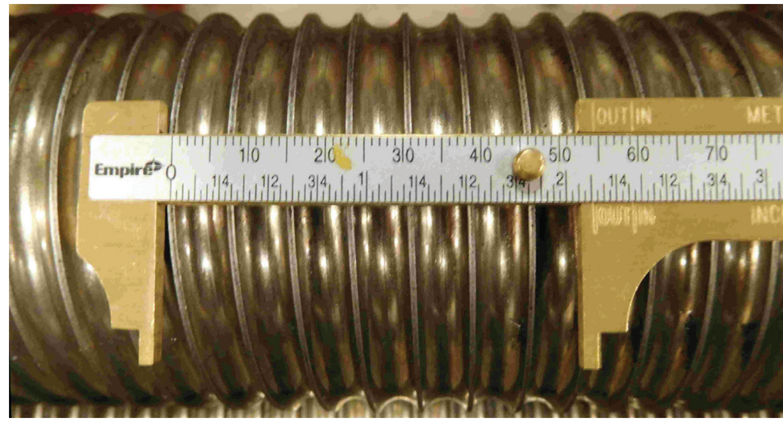

*Fig. 7—Alloy2507 anchor bar.*

## CONCLUSIONS

A Special Provision was created for the material to include in the project specifications for the I-74 Bridge. This special provision could serve as a starting point for an eventual ASTM/AASHTO material standard for the stainless steel anchor bar. A full report of the experimental testing is available on the Iowa DOT website (Anderson et al, 2017).

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