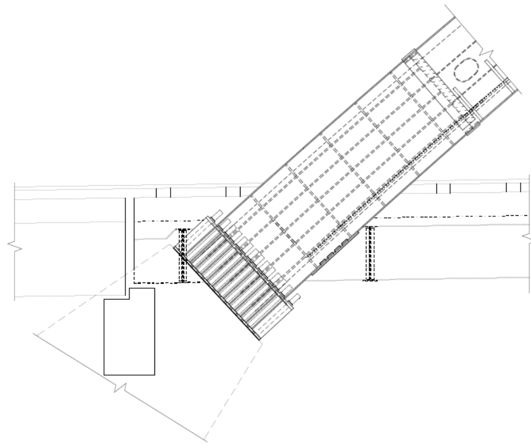


Development of a New Generation High-Strength P/T Anchorage Bar (Experimental Program)

I-74 Bridge over the Mississippi River
between
Bettendorf, Iowa and
Moline, Illinois

3 May 2017
Final Report

SGH Project 141685.10

SIMPSON GUMPERTZ & HEGER

Engineering of Structures
and Building Enclosures

PREPARED FOR:

Alfred Benesch & Company
205 North Michigan Avenue
Suite 2400
Chicago, IL 60601

AND

Modjeski and Masters, Inc.
100 Sterling Parkway
Suite 302
Mechanicsburg, PA 17050

REPRESENTING THE:

Iowa Department of Transportation
(Lead Agency)

Illinois Department of
Transportation

PREPARED BY:

Neal S. Anderson
Jared E. Brewe, PhD
Alan O. Humphreys, PhD
Chase M. Slavin

Simpson Gumpertz & Heger Inc.
135 South LaSalle Street
Suite 3800
Chicago, IL 60603
Tel: 312.754.7500
Fax: 312.754.7501

www.sgh.com/contact/Chicago

Design, Investigate,
and Rehabilitate

Boston
Chicago
Houston
New York
San Francisco
Southern California
Washington, DC

www.sgh.com

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
141685.10-P2AB		

4. Title and Subtitle	5. Report Date
Development of a New Generation, High-Strength P/T Anchorage Bar (Phase 2 Experimental Program)	3 May 2017
	6. Performing Organization Code Simpson Gumpertz & Heger

7. Author(s) (ORCid Numbers)	8. Performing Organization Report No.
Neal S. Anderson (0000-0002-6879-675X); Jared E. Brewe, PhD (0000-0001-9735-2819); Alan O. Humphreys, PhD (0000-0003-1887-3443); and Chase M. Slavin (0000-0003-4416-0228)	141685.10-P2AB

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Simpson Gumpertz & Heger Inc. 135 South LaSalle Street, Suite 3050 Chicago, IL 60603	
	11. Contract or Grant No. Thru Contract #0174A

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Iowa Department of Transportation Office of Bridges & Structures 800 Lincoln Way Ames, IA 50010	March 2016 - May 2017
	14. Sponsoring Agency Code IM-74-1(186)5--13-82

15. Supplementary Notes

Administered through a contract with Alfred Benesch & Company, 205 North Michigan Avenue Suite 2400, Chicago, IL 60601 (Project No. 10061.00)

16. Abstract

The I-74 Iowa-Illinois Corridor project includes two parallel, signature steel arch bridges crossing the Mississippi River. The bridges consist of steel rib box arches in a “basket-handle” configuration with suspender cables supporting the deck structure. The design initially specified each steel arch rib to be connected to the reinforced concrete buttress abutment with (48) 2-1/2 in. diameter (63.5 mm), high-strength, carbon-steel post-tensioned (P/T) anchorage bars. The anchorage bar connection to the abutment is a critical connection in these bridge structures. This experimental study was performed to identify a more robust, high-strength anchorage bar material providing better corrosion resistance to achieve the design 100-year service life.

Final 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.

17. Key Words	18. Distribution Statement
Post-Tension, P/T, Anchor Bar, 150 ksi, 1,030 MPa, Corrosion Resistant, High-Strength, Stainless Steel, Stress Corrosion, Hydrogen Embrittlement, ASTM A722, 2507 Duplex, British Standard 4486, Shakedown	- Public distribution -

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	346	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Disclaimer Notice

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Iowa Department of Transportation.

The sponsors assume no liability for the contents or use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The sponsors do not endorse products or manufacturers. Trademarks or manufacturer's names appear in this report only because they are considered essential to the objectives of the document.

Statement of Non-Discrimination

Federal and state laws prohibit employment and/or public accommodation discrimination on the basis of age, color, creed, disability, gender identity, national origin, pregnancy, race, religion, sex, sexual orientation or veteran's status. If you believe you have been discriminated against, please contact the Iowa Civil Rights Commission at 800-457-4416 or Iowa Department of Transportation's affirmative action officer. If you need accommodations because of a disability to access the Iowa Department of Transportation's services, contact the agency's affirmative action officer at 800-262-0003.

Norm McDonald, P.E., State Bridge Engineer
Iowa Department of Transportation
Office of Bridges & Structures

May 2017

SIMPSON GUMPERTZ & HEGER INC.
Illinois Professional Design Firm No. 184.003981

Illinois SE
Seal on File

/s/ *Neal S. Anderson*

Neal S. Anderson, S.E.
Licensed Structural Engineer
Illinois No. 081.004947
Expires 11-30-2018

/s/ *Jared E. Brewe*

Jared E. Brewe, Ph.D., S.E.
Senior Staff II – Structures
IL License No. 081.007513

/s/ *Alan O. Humphreys*

Alan O. Humphreys, Ph.D.
Senior Staff II – EMI

/s/ *Chase M. Slavin*

Chase M. Slavin
Staff I – Structures

Iowa PE Seal on File	I hereby certify that this engineering document was prepared by me or under my direct personal supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Iowa. /s/ *Neal S. Anderson* — *3 May 2017* (*signature*) (*date*) Printed or typed name: **Neal S. Anderson** License Number: **18566** My license renewal date is December 31, **2018** Pages or sheets covered by this seal: ***Entire report document*.**

Development of a New Generation, High-Strength P/T Anchorage Bar
(Phase 2 - Experimental Program)

Table of Contents

List of Figures and Tables

Figures

Tables

Acknowledgements

Simpson Gumpertz & Heger (SGH) would like, again, to express our sincere gratitude to the Alfred Benesch and Modjeski & Masters design team for selecting us to work on this very interesting project. We commend the design team and Iowa DOT for recognizing the criticality of the arch rib-to-concrete buttress anchorage and the durability and maintenance challenges it entails, and for their prudence to consider alternative materials.

This project required multiple levels of coordination from material procurement, to fabrication, to transportation, to testing at the various laboratory sites from the Midwest to the East Coast. The cooperation and hard work of those involved made this project successful. For bar fabrication, we wish to thank the Dywidag team of David Martin, Shaun Elder, and Mike Meder; and Tom Huiras at Midwest Precision Manufacturing. The team at the Bowen Structural Engineering Laboratory at Purdue University was a lot of fun to work with; thanks to Dr. Robert Frosch, Dr. Chris Williams, and Kevin Brower (Sr. Lab Manager). Special thanks to the hard work of the graduate students - "The Ryans" - (Illinois) Ryan Molley, Master's student, and (K-State) Ryan Whelchel, PhD student - continued success in your studies. We also enjoyed working with the folks at the Fritz Engineering Lab at Lehigh University; thank you to Robin Hendricks, Gene Matlock (Lab Foreman), and their staff.

Successful completion of this large and complex undertaking would not have been possible without the help of several SGH employees. The following engineers assisted with witnessing tests, performing tests, reducing experimental data, or providing their expertise when consulted; thank you to Rebecca S. Reising and Matthew S. Johnson (SE - Chicago); Glenn R. Bell, Dr. Ron Mayville, and Silas J. Wolff-Goodrich (EMI - Boston); Dr. Stan Zagajeski (SE - Boston); and Casey Sturrup and Zachary Svec (Lab - Boston). Dr. Paul Lambert, Technical Director of Corrosion and Materials Engineering, Mott MacDonald, provided invaluable contributions and review for the corrosion testing work.

A comprehensive document requires a wealth of knowledge of the subject matter to review and provide constructive commentary to the content. We thank Glenn R. Bell (EMI - Boston) for his extensive review of the document. Tina Konczal provided the necessary word processing skills and patience to produce this report. And to Bette Johnson, in accounting, for your patience and hard work in keeping track of everything, thanks for all your help

We recognize and thank the following outside team members for their review of the document, which was essential to the project success.

Alfred Benesch & Company

Diane M. Campione, PE, SE
Andrew J. Keaschall, PE, SE
Kevin M. Placzek, PE, SE

Modjeski and Masters, Inc.

Thomas P. Murphy, PhD, PE, SE
Todd B. McMeans, PE
Philip A. Ritchie, PhD, PE
Nohemy Y. Galindez, PhD, PE

Iowa Department of Transportation

Timothy Dunlay, PE
Ahmad Abu-Hawash, PE
Norm McDonald, PE
Ron Meyer, PE

Federal Highway Administration

Dennis D. Bachman, PE
Chris Cromwell
Brian Kozy, PhD, PE
Justin Ocel, PhD, PE
Andrew K. Wilson, PE

Illinois Department of Transportation

Mark P. Thomson, PE, SE

Executive Summary

The I-74 Iowa-Illinois Corridor project is a significant transportation corridor project in the Quad Cities region. The project hallmark is a pair of parallel, signature steel arch bridges crossing the Mississippi River. The arches consist of steel rib box members in a “basket-handle” configuration with suspender cables supporting the deck structure. Each arch rib is founded on a sloping, buttress-type abutment. These abutments are reinforced concrete construction set on drilled shaft foundations founded in the Mississippi River.

Post-Tension Anchor Bars

Initially, the design specified each steel arch rib to be connected to the reinforced concrete buttress abutment with forty-eight 2-1/2 in. diameter (63.5 mm), high-strength, carbon steel post-tensioned (P/T) anchorage bars, with each anchorage bar approximately 16 ft (4.9 m) long. The project includes eight arch bearing locations, resulting in 384 total anchorage bars. The anchorage bar connection to the abutment is a critical connection in these bridge structures.

Common high-strength, cementitious-grouted, anchorage bar systems for post-tensioning applications consist of threaded bars, up to a 3 in. (75.2 mm) diameter, with a minimum tensile strength of 150 ksi. The mechanical and chemical requirements for these high-strength, post-tensioned steel bars for prestressing concrete are contained in ASTM A722, *Standard Specification for High-Strength Steel Bars for Prestressed Concrete*. This standard covers plain, carbon steel bar with no commentary on their corrosion protection.

SHRP2 Research Project R19B, *Bridges for Service Life Beyond 100 Years: Service Limit State Design* [Modjeski and Masters 2015], has set the stage for transportation planning into the future. Federal transportation entities are looking to develop design and detailing guidance, and calibrated service limit states (SLSs) to provide 100-year bridge life and to develop a framework for further development of these calibrated SLSs. Improving the corrosion resistance of steel used in concrete is in the forefront of this effort, with different materials being explored within the context of project budgets and cost/benefit ratios.

This project aligns with the above goal because the anchor bar connection is an important component of this bridge; failure and replacement of an anchor bolt will be difficult, if not impossible; and the risk of failure, albeit small, has major consequences to the long-term performance of the structure. This document reports on an experimental study undertaken to develop a more robust, high-strength anchorage bar that provides corrosion protection to attain the 100-yr service life goal.

This project conducted by Simpson, Gumpertz & Heger (SGH) evaluated several feasible candidate stainless steel materials for post-tensioning applications. This project consisted of a literature review and experimental program to identify a more robust, high-strength anchorage bar that provides better corrosion resistance to achieve a design 100-yr service life. In addition, a standard specification section was developed for this project so the bridge stakeholders (State DOTs, engineers, manufacturers) know the requirements for product production and performance.

Literature Review

Phase 1 of this study was a literature review of the present state-of-the-art for P/T anchor bars installed into a concrete member and prestressed in-service. The report examined present U.S. and foreign standards and reviewed the important mechanical and characteristic properties desired in an alternative anchorage bar material. These properties, and the significance and importance of these properties were addressed in the Phase 1 study report.

Given the need for a more corrosion resistant material, four stainless steel and two titanium alloys were identified as candidate materials for further testing. The candidate materials identified in the Phase 1 study include the following:

- Custom 450 H1050 Precipitation Hardened Stainless Steel
- Custom 465 H1050 Precipitation Hardened Stainless Steel
- Custom 630 H1100 Precipitation Hardened Stainless Steel
- Duplex 2507 Stainless Steel - Strain Hardened
- Ti-6Al-4V Grade 5 Titanium Alloy
- 10-2-3 Titanium Alloy

Experimental Study

This report details the Phase 2 experimental study. Final candidate materials tested include the following:

- Plain Dywidag Threadbar® (control)
- Galvanized Dywidag Threadbar® (control)
- Custom 450 H1050 Precipitation Hardened Stainless Steel
- Custom 630 H1100 Precipitation Hardened Stainless Steel
- Alloy 2507 Duplex Stainless Steel

The following physical and material property tests were conducted to assess the performance of the alternative anchorage bar material:

- Tension testing for yield strength, tensile strength, and elongation
- Coupling nut and end nut proof testing
- Stress relaxation
- Hardness (Brinell and Rockwell C)
- Toughness (Charpy V-Notch)
- Threshold galling stress (self-couple)
- Critical pitting temperature
- Stress corrosion cracking
- Hydrogen embrittlement

Where available for the tests listed above, standard ASTM tests were performed. In the case of relaxation testing, the ASTM standard for high-strength, P/T bar has no test requirements. Thus, recognized foreign standards are used to augment ASTM standards for prestressing strand or other materials.

Summary of Candidate Materials

Based on Phases 1 and 2 in this study, we conclude the following for each of the materials:

Plain Threadbar® meets the project's strength and ductility requirements as expected. In our 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 Threadbar® is not a viable material for the application. We did not recommend a galvanized coating system following our Phase 1 literature review, as galvanized coatings have a limited life of protection and poor bond adhesion to cementitious grout. The Phase 2 testing provides further corroboration that galvanized Threadbar® is not a viable option.

Custom 450 precipitation-hardened stainless steel 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; we found it susceptible to hydrogen embrittlement.

Custom 630 precipitation-hardened stainless steel 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 our testing and exhibited similar susceptibility to hydrogen embrittlement.

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

Recommendations

We recommended Alloy 2507 duplex stainless steel and the traditional plain high-strength, carbon-steel bar (Threadbar®) with a corrosion protection system as the preferred materials. This information was presented to the design team, Iowa DOT, Illinois DOT, and Federal Highway Administration (FHWA). The design team recommended proceeding with Alloy 2507, which received concurrence from the governmental agencies.

The selection 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. We reviewed the acceptability of Alloy 2507 under service cyclic load excursions through additional material mechanical testing and review with Modjeski and Masters (M&M). 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.

Closure

A Special Provision (or specification section) was created for the material and is contained in Appendix P. This special provision could serve as a starting point for an eventual ASTM / AASHTO material standard for the stainless steel anchorage bar.

Simpson, Gumpertz & Heger
Chicago, Illinois
May 2017

1. INTRODUCTION

1.1 Background

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, Iowa; Moline and Rock Island, Illinois). The project involves a number of roadway and bridge structure improvements, including the replacement of a pair of 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 wide and spans 795 ft over the main navigation channel of the Mississippi River, as shown in Figure 1-1.

The steel arches bear on massive concrete buttress abutments. The abutments are reinforced concrete construction set on drilled-shaft foundations founded within the Mississippi River. Common abutments support the adjacent interior arches of the parallel bridges. The abutment structures are shown in Figure 1-2.

The arch-to-buttress connections are critical to the bridge structures. Each steel-arch end is constructed with steel stiffeners and base plates resembling a large machine base anchored to concrete. The present design connects each steel-arch end to the reinforced concrete buttress abutment with forty-eight high-strength, post-tensioned (P/T) anchorage bars embedded in the concrete. The eight steel arch ends require 384 total anchorage bars. The design presently requires 2-1/2 in. diameter (63.5 mm) anchorage bars approximately 16 ft (4.9 m) long. HSS steel pipe encloses the anchorage bars with grout filling the annular space.

The I-74 Iowa-Illinois Corridor project includes the following project team entities:

- Iowa Department of Transportation (Iowa DOT) – lead agency and project sponsor
- Illinois Department of Transportation (Illinois DOT) - co-project funding agency
- Federal Highway Administration (FWHA) - co-project funding agency
- Alfred Benesch & Company (Benesch) – overall project manager for the corridor project
- Modjeski and Masters (M&M) – designer of record for the steel arch bridges

Common high-strength, cementitious-grouted, anchorage bar systems for applications similar to the arch abutment anchorages typically consist of cold-rolled thread, carbon steel bars with a minimum tensile strength of 150 ksi (1040 MPa) conforming to ASTM A722 – *Standard Specification for High-Strength Steel Bars for Prestressing Concrete* [2015]. Common suppliers include Dywidag Systems International and Williams Form Engineering.

In most applications, these anchorage bars are exposed to the environment. This exposure may include deicing salts, which produce a corrosive environment that must be considered in design and construction. Common protection methods include cementitious grout encapsulation; grease wrapping or encapsulation; use of epoxy coatings, waxes, galvanizing, or high-performance coatings; or a combination of these methods/systems. The corrosion protection system must be durable. The loss of bar material through corrosion reduces the section of a highly stressed bar and may lead to stress-corrosion cracking, resulting in bar rupture.

SHRP2 Research Project R19B, *Bridges for Service Life Beyond 100 Years: Service Limit State Design* [Modjeski and Masters 2015], has set the stage for transportation planning into the future. Federal transportation entities are looking to develop design and detailing guidance, and calibrated service limit states (SLSs) to provide 100-year bridge life and to develop a framework for further development of these calibrated SLSs. Improving the corrosion resistance of steel used in concrete is in the forefront of this effort, with different materials being explored within the context of project budgets and cost/benefit ratios.

Several DOTs are apparently looking at high-strength, stainless steel, post-tension anchor bars in various applications in both precast concrete and steel superstructure bridges. The applications of high-strength bars consist of clamping down a precast bridge pier to the foundation, attaching the bridge superstructure to piers and abutments, or otherwise attaching the bridge superstructure to a massive foundation; the I-74 Bridge is an example of the latter.

The challenge to date has been selecting the appropriate candidate material and the standard by which the stainless steel bar should conform. There are a myriad of stainless steel alloys available, and only a few are high-strength, available in bar form, and suitable for post-tensioning. The suitable materials have a number of pros and cons, and weighing of the benefits and risks becomes the design challenge. In general, the typical structural engineer is not aware of the subtleties of the various stainless steels for post-tensioned bar applications, and will likely select based on three criteria: 150 ksi minimum tensile strength, availability (vis-à-vis, schedule implications), and cost.

The anchor bar connection is an important component of this bridge; failure and replacement of an anchorage 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 I-74 Bridge design criteria established by M&M requires a 100-year design life for durability. The use of a more robust base material or protection system for high-strength, P/T bars may be required to achieve the FHWA service life goal of 100 years for long-span or signature structures.

The project team decided to evaluate alternative materials and systems for the high-strength, P/T anchorage bars to seek a solution with better corrosion resistance than the high-strength anchorage bar systems now commonly in use. To that end, Benesch issued a Request for Proposals from consultants, as described below.

1.2 Request for Proposals and Engagement of Simpson Gumpertz & Heger

The Request for Proposals (RFP) that resulted in the research of this report is titled "Corrosion Resistant Anchor Bar System Research" and dated 1 April 2014. The RFP specifies the anchorage bars shall meet the following mechanical property performance criteria:

- Minimum ultimate tensile strength of approximately 150 ksi.
- Minimum yield strength, elongations, and ductility as those required for ASTM A722 bars.
- Stress loss over time due to relaxation equal to or better than ASTM A722 bars.
- Although there is no requirement in ASTM A722 specifically for toughness, it is recommended to define a minimum baseline for impact testing. The corresponding limit values are to be determined in this work.
- The bars will be used in a prestressed state, similar to ASTM A722 bar use.

The RFP specifies that the bars shall exhibit corrosion resistance to the following mechanisms:

- General corrosion
- Pitting corrosion

- Stress Corrosion Cracking (SCC) at prestressing levels typical of ASTM A722 bars
- Hydrogen Embrittlement (a form of SCC)

The RFP suggested high-strength stainless steel and titanium alloys as possible options. The RFP divided the project into two phases: Phase 1, a literature review, and Phase 2, a testing program.

Benesch awarded a contract for the Phase 1 study to Simpson Gumpertz & Heger Inc. (SGH) on 17 November 2014. We issued the Phase 1 report on 28 September 2015. Benesch awarded a contract for Phase 2 to SGH on 9 March 2016. This report, while presenting the findings of Phase 2, also summaries the findings of Phase 1 for completeness and readability.

1.2 Objective

The overall objective of the program (Phases 1 & 2) is to develop a high-strength anchorage bar system with superior corrosion resistance to systems now commonly in use.

We understand that Benesch, M&M, the Iowa DOT, and FHWA will use our findings to select the best system to specify for construction of the I-74 Bridge. The project team will incorporate this information into a special provision for the project.

1.3 Phase 1 Findings and Recommendations

The literature review of Phase 1 report contained a literature review of the current state-of-the-art for P/T anchorage bars installed in concrete. The report examines current U.S. and International standards for high-strength anchorage bar, and reviews the important mechanical and characteristic properties related to strength and durability. The Phase 1 report discusses candidate materials, protective coating systems, and the significance of the mechanical and characteristic properties of possible alternative materials.

Toward the goal of improved corrosion resistance, SGH recommended the following potential candidate materials:

- Custom 450 precipitation hardened stainless steel in the H1050 condition
- Custom 465 precipitation hardened stainless steel in the H1050 condition
- Custom 630 precipitation hardened stainless steel in the H1100 condition

- Alloy 2507 duplex stainless steel
- Ti-6Al-4V Grade 5 titanium alloy
- Ti-10-2-3 titanium alloy

During the peer review of the Phase 1 report, the Illinois DOT suggested two other stainless steel alloys: 2205 Duplex and 2707 Duplex. We found the 2205 Duplex and 2707 Duplex to be comparable to the selected 2507 Duplex. We recommended Alloy 2507 be selected for the test program for material sourcing.

For comparison with present high-strength anchorage bar technology, we also recommended that a control material, high-strength carbon steel, be included in the experimental program.

The report reviewed currently available coating materials, including galvanizing, and did not identify any corrosion-resistant coating to be a viable corrosion protection method for the high-strength carbon steel anchorage. Recent experience on the Hood Canal Bridge in Washington and the San Francisco-Oakland Bay Bridge in California showed the risk of hydrogen embrittlement of galvanizing high-strength steel anchorage bars. Considering the risk of hydrogen embrittlement, SGH did not recommend exploring the use of galvanizing conventional steel bars in this study. However, the FHWA believes the recent problems encountered with hydrogen embrittlement during the San Francisco-Oakland Bay Bridge construction were an anomaly and can be overcome with proper fabrication procedures. Accordingly, the FHWA requested conventional, high-strength, hot-dip galvanized anchorage bars be included in the test program.

The Phase 1 report recommended the following testing program to assess the performance of the new anchorage system:

- Tensile Strength (ksi)
- 0.2% Yield Strength (ksi)
- Ductility (tensile elongation, %)
- Stress Relaxation (% loss in 1,000 hour test at 0.80f_{pu})
- Hardness (Brinell and/or Rockwell C) over the cross-section

- Toughness (CVN, ft-lb, temperature levels to be determined)
- Machinability and Threading (relative measure through hardness or machinability rating)
- Threshold Galling Stress (self-couple, ksi)
- Critical Pitting Temperature ($FeCl_3$ °F)
- Stress Corrosion Cracking (boiling NaCl)
- Hydrogen Embrittlement (HE threshold stress, ksi)

Our intent is for the test results to provide a comparison of the relative performance of the selected candidate materials. The results will inform and enable the project team to select and specify minimum performance requirements for the subject anchorage bars.

1.4 Selection of Phase 2 Candidate Materials

Upon consulting with SGH, the project team initially elected to proceed into Phase 2 with the four stainless steel and two titanium alloys we recommended in the Phase 1 report as potential candidate materials, along with plain and galvanized coated carbon steel control specimens.

The testing program in SGH's Phase 2 proposal, dated 9 October 2015, involves evaluating the six recommended candidate materials and two control specimens. During the proposal and contract negotiation phase of Phase 2, cost and schedule considerations drove the project team to eliminate the Custom 465 H1050 and 10-2-3 Titanium Alloy from the test program.

The supplier of the Ti-6Al-4V Grade 5 Titanium Alloy initially agreed to donate test specimens, but as the supplier subsequently reviewed the material requirement for the project, the amount of material needed to complete the test program was beyond their planned contribution. Due to the increase in material procurement cost along with developing schedule implications for the titanium, the project team eliminated the Ti-6Al-4V from the program.

We initially recommended the Alloy 2507 duplex stainless steel in the strain-hardened condition. Strain hardening is a process in which a metal is deformed in the cold condition to increase its yield strength. Strain hardened materials are common in bolts and other threaded fasteners where large-diameter bar stock is reduced in diameter to create the final product. During material procurement, we were unable to identify a supplier for 2.75 in. (70 mm) diameter round bar in the strain hardened condition; the largest diameter available was 2.5 in. (63.5 mm). The small quantities for experimental testing made it infeasible to acquire strain hardened test samples, so we elected to proceed with the Alloy 2507 in the standard condition to evaluate the mechanical and other physical properties in the unhardened condition.

1.5 Phase 2 Scope of Work

The final materials included in the Phase 2 test program are:

- Custom 450 H1050 Precipitation Hardened Stainless Steel
- Custom 630 H1100 Precipitation Hardened Stainless Steel
- Alloy 2507 Duplex Stainless Steel
- Plain standard carbon steel
- Galvanized standard carbon steel

We procured the following materials and services to fabricate anchorage bars from the candidate materials:

- Solid round bar stock, including smaller diameter stock for the anchorage bars and larger diameter stock for end nuts and coupling nuts
- Fabrication services to thread the full length of the smaller diameter bar stock
- Fabrication services to hollow and internally thread the larger diameter bar stock

We procured standard, off-the-shelf anchorage bars for the plain and galvanized control specimens, including end nuts and coupling nuts.

We procured the following materials, equipment, and services to complete the testing program:

- Laboratory services to conduct testing
- Test equipment to conduct testing in our laboratories
- Test equipment and materials to conduct relaxation testing including a high-capacity hydraulic ram, load-cells, test frames, and other miscellaneous hardware

- Trucking and shipping services to transport materials to the various testing sites

We conducted the following tests on fabricated anchorage bars:

- Tension testing according to ASTM A370 in the Fritz Engineering Laboratory at Lehigh University
- Coupling nut testing according to ASTM A370 in the Fritz Engineering Laboratory at Lehigh University
- End nut testing similar to the requirements in ASTM A963 and ASTM F606 in the Bowen Structural Engineering Laboratory at Purdue University
- Relaxation testing according to several relevant industry standards in the Bowen Structural Engineering Laboratory at Purdue University
- Hardness testing according to ASTM E18 (Rockwell) and ASTM E10 (Brinell) in the SGH Waltham (MA) Laboratory
- Charpy V-Notch testing according to ASTM E23 at Massachusetts Materials Research
- Galling testing according to ASTM G98 in the SGH Waltham (MA) Laboratory
- Pitting Corrosion testing according to ASTM G48 Type F at Corrosion Testing Laboratories
- Stress Corrosion Cracking testing according to ASTM G123 at Corrosion Testing Laboratories
- Hydrogen Embrittlement testing according to ASTM F1624 in the SGH Waltham (MA) Laboratory

Phase 2 includes the following deliverables:

- This report containing descriptions and results of the tests performed on the candidate and control materials. This report supplements and builds on our Phase 1 report and includes our recommended material selection. This report includes an estimated cost of the candidate materials in comparison to those currently in use and that typically meet the ASTM A722 requirements.

- Following material selection by the project team are product specifications for the selected anchorage bar material. In the event product specifications are not readily cited or available for use, SGH will provide guide specifications for the anchorage bar. This will include the bar stock, special coupling nuts, lock-off devices, and other system hardware.

- Following material selection by the project team are standard drawings and special provisions for the selected anchorage bar system, suitable for use in DOT-type construction contracts.

The project goal is to verify the performance of the contemplated system and to provide supplemental specifications or state DOT special provisions so that the actual anchorage bars for the bridge project perform consistently with the tested bar(s). The special provision(s) will leverage existing ASTM or AASHTO standards, in as much as possible, and we will provide other material specific recommendations as appropriate.

Figure 1-1 - Overall elevation view of the new I-74 twin basket-handle, through arch bridges over the Mississippi River.

Figure 1-2 - Approach view of the bridges

2. DOCUMENT REVIEW

The Phase 1 report provided a comprehensive literature review for the project. Below, we briefly review the abutment connection and standards applicable to the project, as they are related to the Phase 2 testing program discussed in this report.

2.1 Arch-to-Buttress Connection

Figures 2-1 to 2-3 show the arch-rib connection to the concrete buttress abutment from the present contract drawings. The design includes forty-eight, 2-1/2 in. (63.5 mm) diameter, carbon steel anchorage bars at the top of the buttress.

Figure 2-1 shows the anchorage bars extending 8 ft (2.4 m) into the concrete abutment with an anchor bearing plate at the end of each bar. For corrosion protection within the concrete, the anchorage bars are encapsulated in a 6 in. diameter by 3/8 in. thick (152 mm x 9.5 mm) HSS round pipe with cement grout placed in the annular space.

Figures 2-2 and 2-3 show a large steel plate assembly at the end of the arch rib. The exposed, mild steel plate assembly includes an upper 3-3/4 in. (95.3 mm) thick anchor bearing plate and a lower 2-1/2 in. (63.5 mm) thick base plate. The lower plate is milled to bear on a 3-1/8 in. (79.4 mm) embedded bearing plate set flush in the concrete abutment. The upper and lower bearing plates are separated by 5 ft (1.52 m) with a series of 1-1/2 to 1-3/4 in. (38.1 to 44.5 mm) thick stiffener plates connecting the upper and lower plates. The 6 ft wide by 12 ft (1.82 m by 3.66 m) deep arch rib box section penetrates and is welded to both the upper and lower anchor-bearing plates.

Figure 2-1 shows that the anchorage bar extension in the 5 ft (1.52 m) space between the upper and lower plates is placed in 6 in. diameter, 3/8 in. thick (152 mm x 9.5 mm) HSS pipes. Once assembled, a cementitious grout fills this steel pipe. The projection of the anchorage bar above the top plate is covered with a pipe cap also filled with the grout. This cap protects the exposed nuts and the bar projection beyond the nuts.

2.2 Industry Standards

2.2.1 ASTM A722

ASTM A722, *Standard Specification for High-Strength Steel Bars for Prestressing Concrete* [2015], addresses carbon steel, post-tensioning bars. The Standard addresses both plain bar (Type I) and bar with surface deformations (Type II). The bars are intended for use in pre-tensioned or post-tensioned prestressed concrete construction or in prestressed ground anchors. Appendix A contains Table 3.1 from our Phase 1 report summarizing the requirements in ASTM A722.

ASTM A722 specifies several attributes of the bars, including chemical composition, mechanical properties, dimensions, deformation requirements, inspection certification, etc. The pertinent attributes from ASTM A722 include the following items:

- Minimum tensile strength of 150 ksi (1035 MPa)

- Minimum yield strength of 85% of the minimum the tensile strength (127.5 ksi (880 MPa)) for Type I bars and 80% (120 ksi (827 MPa)) for Type II bars

- Minimum elongation of 4.0% and 7.0% for gage lengths of 20$\boldsymbol{d_b}$ and 10$\boldsymbol{d_b}$, respectively

The Standard specifies the bars shall be subjected to cold stressing to not less than 80% of the minimum tensile strength and then stress-relieved to achieve the specified mechanical properties. ASTM A722 does not provide relaxation requirements. The Standard specifies supplementary requirements for quality control bending should it be required by the bar purchaser.

2.2.2 British Standard (BS) 4486

British Standard (BS) 4486, *Specification for Hot Rolled, and Hot Rolled and Processed High Tensile Alloy Steel Bars for the Prestressing of Concrete* [1980], is the British Standard equivalent to ASTM A722. The current version of the Standard was reaffirmed in 2012. Appendix A contains Table 3.1 from our Phase 1 report summarizing the requirements in BS 4486. The pertinent attributes from BS 4486 include the following items:

- Specified tensile properties based on a characteristic breaking load and characteristic 0.1% proof load. These characteristic values are the lower limit of the one sided statistical tolerance interval for which there is a 95% probability that at least 95% of the values will be equal to or greater than this lower limit. The nominal tensile strength of 1030 MPa (149 ksi) and 0.1% proof stress of 835 MPa (121 ksi) are similar to ASTM A722.

- The elongation limit of 6% is required over a gage length of 5.65$\sqrt{\boldsymbol{S_o}}$, where $\boldsymbol{S_o}$ is the original cross-sectional area of the gage length.

Relaxation limits are at test duration of 1,000 hrs. The standard defines initial load levels of 60, 70, and 80% of the actual breaking load. Maximum relaxation values for these load levels are specified as 1.5, 3.5, and 6.0%, respectively.

2.2.3 Japanese Industrial Standard (JIS) G3109

The Japanese Industrial Standard (JIS) G3109, *Steel Bars for Prestressed Concrete* [2008], includes a number of options for P/T anchorage bars. The Standard prescribes provisions for round and deformed steel bars in eight steel grades that include bars with tensile strengths of 150, 157, 172, and 178 ksi (1,030, 1,080, 1,180, and 1,230 MPa). JIS G3109 indicates that hot-rolled, killed steel shall be used to manufacture the bars by hot stretching, drawing, heat treatment, or any combinations of these processes. Appendix A contains Table 3.5 from our Phase 1 report summarizing the requirements in JIS G3109. The pertinent attributes from JIS G3109 include the following items:

- JIS G3109 specifies nine round, plain bar diameters and includes specifications for four optional round, plain bar diameters. The Standard does not prefer the optional diameter bars. The largest plain bar diameter permitted is 1.57 in. (40 mm).
- JIS G3109 specifies nine deformed bar diameters. The largest deformed bar diameter is 1.42 in. (36 mm), which corresponds to the conventional US #11 bar.
- The minimum required elongation is 5%.
- JIS G3109 specifies a 1,000-hour relaxation test at an initial force corresponding to 70% of the tensile strength. The maximum relaxation permitted is 4% for all bar grades, types, and diameters. Testing is to be conducted under ambient conditions of 59 to 77°F (15 to 25°C).

Figure 2-1 - Arch Rib to Concrete Connection Details

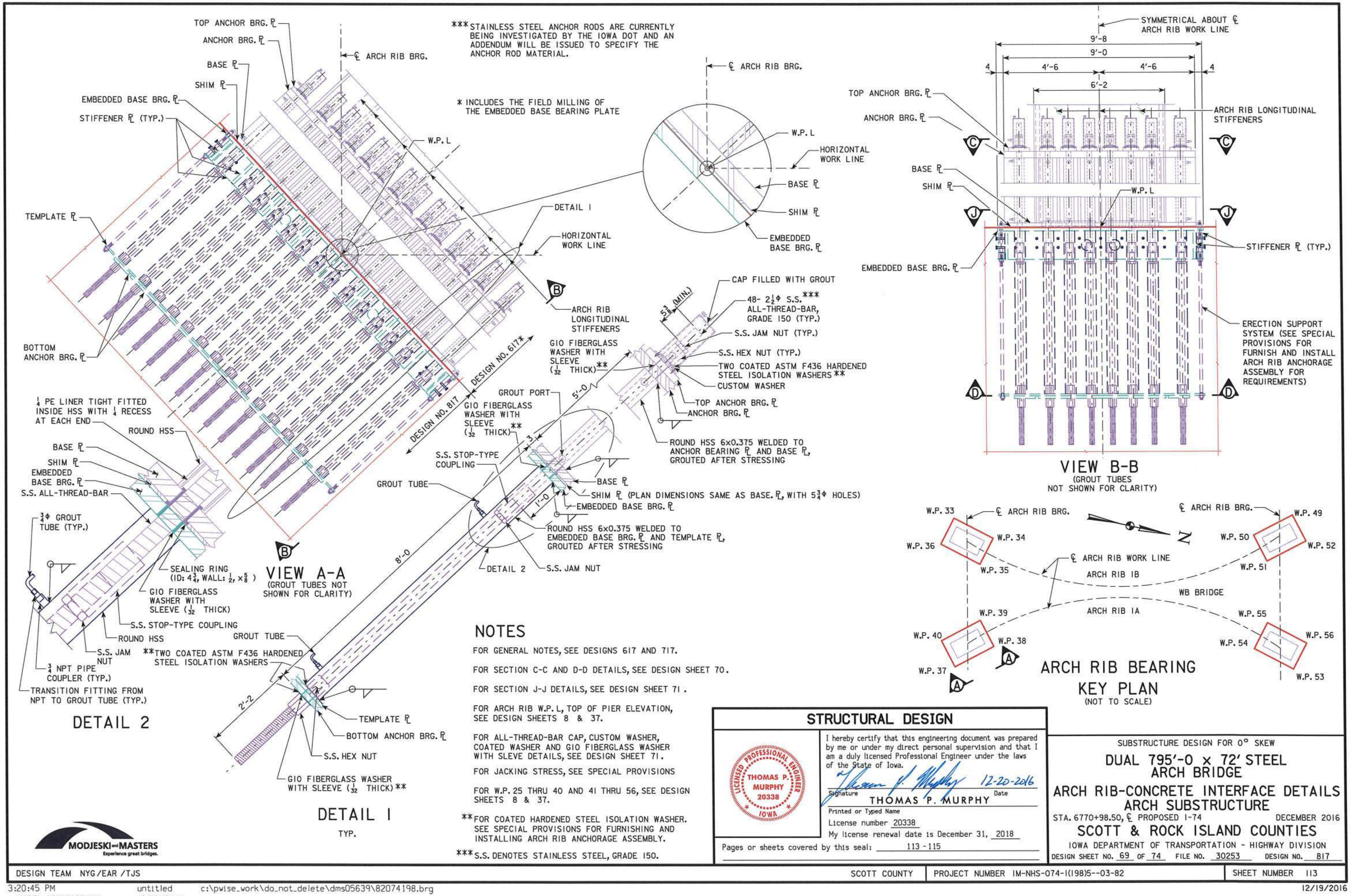


Figure 2-2 - Arch Rib to Concrete Connection Details

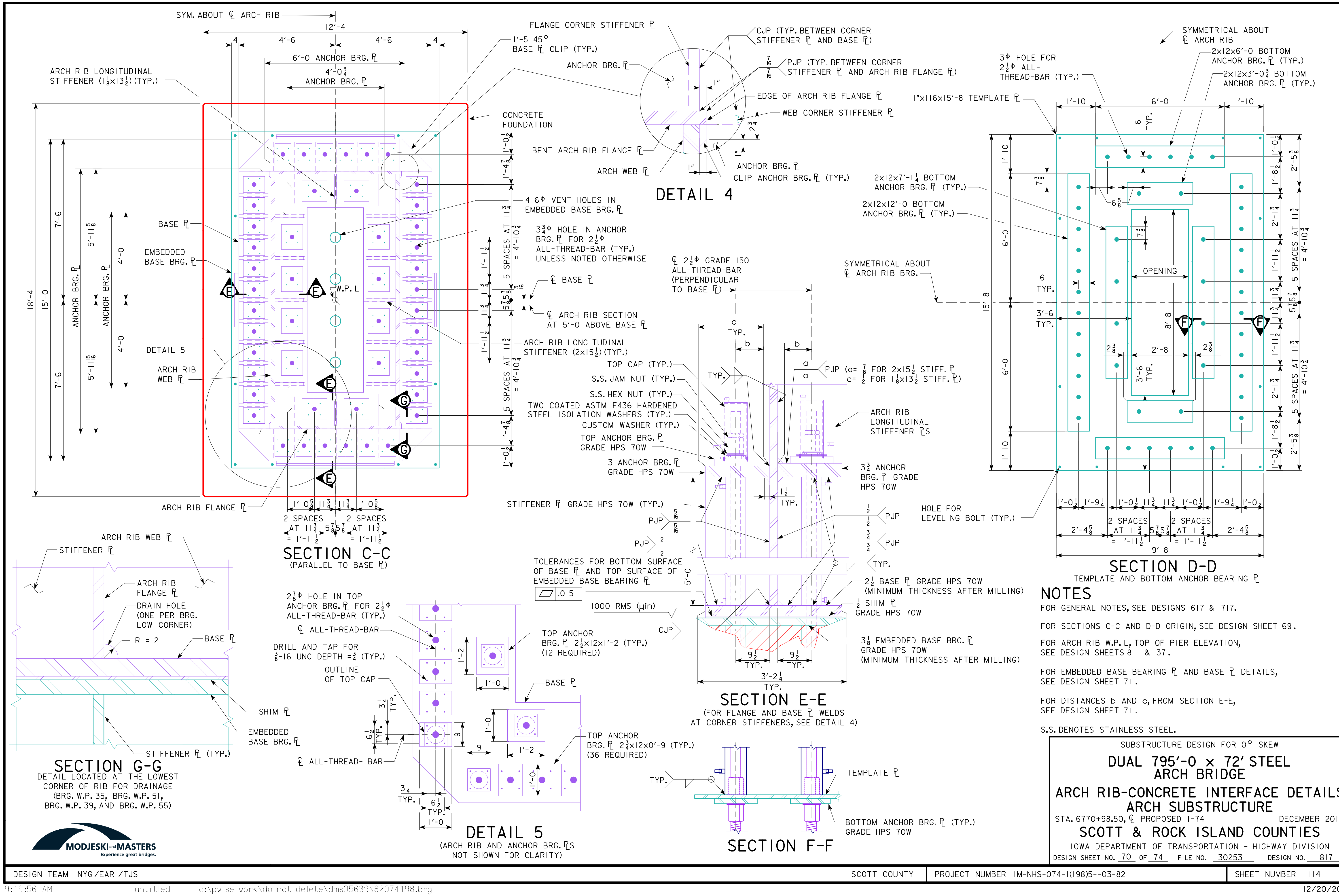
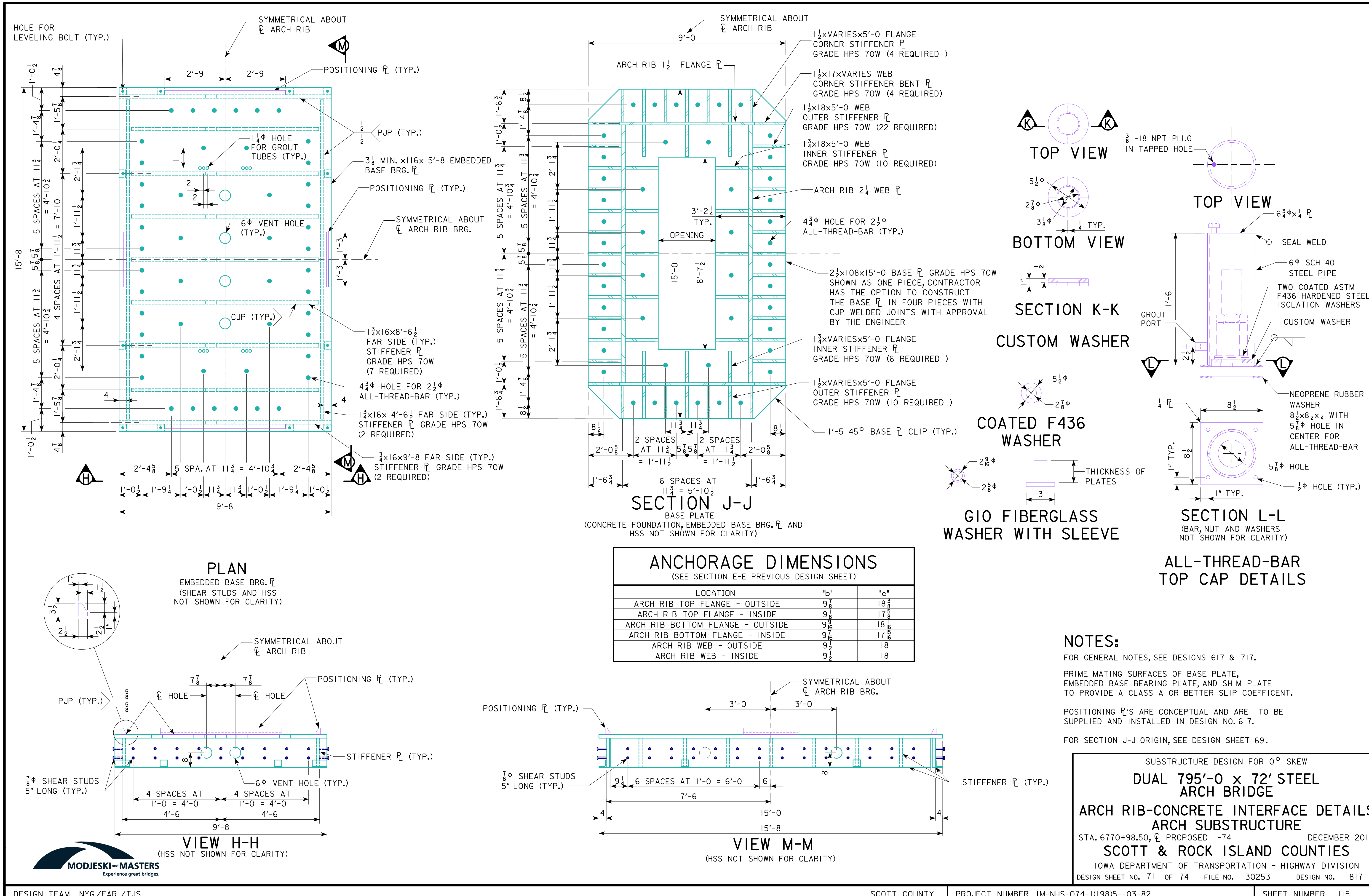


Figure 2-3 - Arch Rib to Concrete Connection Details



ANCHORAGE DIMENSIONS

(SEE SECTION E-E PREVIOUS DESIGN SHEET)

LOCATION	"b"	"c"
ARCH RIB TOP FLANGE - OUTSIDE	$9\frac{7}{8}$	$18\frac{3}{8}$
ARCH RIB TOP FLANGE - INSIDE	$9\frac{1}{8}$	$17\frac{5}{8}$
ARCH RIB BOTTOM FLANGE - OUTSIDE	$9\frac{9}{16}$	$18\frac{1}{16}$
ARCH RIB BOTTOM FLANGE - INSIDE	$9\frac{7}{16}$	$17\frac{15}{16}$
ARCH RIB WEB - OUTSIDE	$9\frac{1}{2}$	18
ARCH RIB WEB - INSIDE	$9\frac{1}{2}$	18

NOTES:

FOR GENERAL NOTES, SEE DESIGNS 617 & 717.

PRIME MATING SURFACES OF BASE PLATE, EMBEDDED BASE BEARING PLATE, AND SHIM PLATE TO PROVIDE A CLASS A OR BETTER SLIP COEFFICENT.

POSITIONING ℞'S ARE CONCEPTUAL AND ARE TO BE SUPPLIED AND INSTALLED IN DESIGN NO. 617.

FOR SECTION J-J ORIGIN, SEE DESIGN SHEET 69.

SUBSTRUCTURE DESIGN FOR 0° SKEW

DUAL 795′-0 x 72′ STEEL ARCH BRIDGE

ARCH RIB-CONCRETE INTERFACE DETAILS
ARCH SUBSTRUCTURE

STA. 6770+98.50, ℄ PROPOSED I-74 — DECEMBER 2016

SCOTT & ROCK ISLAND COUNTIES

IOWA DEPARTMENT OF TRANSPORTATION - HIGHWAY DIVISION

DESIGN SHEET NO. 71 OF 74 — FILE NO. 30253 — DESIGN NO. 817

DESIGN TEAM NYG/EAR/TJS — SCOTT COUNTY — PROJECT NUMBER IM-NHS-074-1(198)5--03-82 — SHEET NUMBER 115

3. MATERIALS AND FABRICATION

3.1 Control Specimens

3.1.1 Plain High-Strength Carbon Steel

We selected Dywidag Systems International (DSI) Threadbar® for the plain carbon steel anchorage bar due to its common use as post-tensioned, high-strength anchorage bars. The Threadbar® is similar to the anchorage bar manufactured by Williams Form Engineering (WFE). We intend no appearance of preference in selecting the DSI product for testing; we selected DSI based on responsiveness to our requests for information and cooperation.

3.1.2 Galvanized High-Strength Carbon Steel

We selected hot-dip galvanized Threadbar® for consistency with the plain control sample.

3.2 Candidate Materials

Presently, no manufacturers produce high-strength anchorage bars using the candidate materials proposed for this test program. Traditionally, anchorage bar manufacturers source materials from preferred suppliers and provide anchorage bars as a finished product. For this project, we procured raw materials and arranged threaded bar fabrication for the test specimens.

3.2.1 Custom 450 H1050 Precipitation Hardened Stainless Steel

We recommended Custom 450 H1050 due to its high tensile strength (160 ksi, 1,103 MPa), adequate corrosion resistance, and availability due to extensive use in the petroleum industry. Custom 450 stainless is a martensitic age-hardenable stainless steel. We elected to heat-treat the alloy at 1,050°F (566°C) to produce an optimal combination of strength, ductility, toughness, and corrosion resistance.

3.2.2 Custom 630 H1100 Precipitation Hardened Stainless Steel

We recommended Custom 630 due to its high tensile strength (164 ksi, 1,131 MPa), and superior corrosion resistance to Custom 450. Custom 630 stainless is a martensitic age-hardenable stainless steel. We elected to heat-treat the alloy at 1,100°F (593°C) to produce an optimal combination of strength, ductility, toughness, and corrosion resistance.

3.2.3 Alloy 2507 Duplex Stainless Steel

We recommended Alloy 2507 due to its excellent resistance to pitting corrosion and SCC. Alloy 2507 is the highest strength, commonly available duplex stainless steel with published tensile strengths of 110-135 ksi (758-931 MPa). This tensile strength range is below the target tensile strength of 150 ksi (1,030 MPa). However, Appendix A to the Phase 1 report (a memo with peer review comments and responses) notes that M&M believes the required tensile strength may be reduced to about 135 ksi with the current design and bar diameter. Duplex stainless steels generally have corrosion and stress corrosion cracking resistance that is superior to the other materials included in this study.

3.3 Material Procurement

We procured the control specimens of plain and galvanized Threadbar® directly from DSI. We understand all base material originated from the same heat of steel with a portion sent for galvanizing and the balance remaining plain.

Typical stainless steel mill production quantities range from 100 to 150 tons (90.7 to 136 Metric tons). Our project required 8,800 lbs (3,992 kg) of raw material total for each candidate material. This total includes about 5,700 lbs (2,585 kg) of smaller diameter material for the bars and about 3,100 lbs (1,406 kg) of larger diameter material for the nuts. Steel mills often specify minimum order quantities and subsequent order increments based on weight for each material. These quantities vary depending on the alloy, material shape (plate, round bar, squares, hexagon), size, and producing mill. Our Phase 2 program required relatively small quantities of material, and our orders were usually dictated by these minimum quantities. For the actual bridge application, we expect the threaded anchorage bar supplier (such as DSI, WFE, or another) to handle material procurement. The number of anchorage bars required for the final bridge also lends to efficiencies of scale on mill ordering, which may not be subject to the mill minimums.

We procured the Custom 450 and Custom 630 materials directly from Carpenter Technologies, a primary domestic manufacturer of specialty stainless steels. Materials originated from their mills located in Pennsylvania. Other domestic manufacturers include Valbruna Stainless (Indiana), Allegheny Technologies Inc. (Pennsylvania), AK Steel (Ohio), and North American Stainless (Kentucky). Each mill has a specific product line and rolling capability and a given mill may only produce plate, bar, sheet, etc.

We selected Carpenter as an experienced manufacturer of the specialty alloys included in the test program, and they produce the candidate materials in the round bar size we required. During the initial mill production of the Custom 450, Carpenter had to scrap a portion of the production during the rolling process due to a mill cobble. (A cobble is an incident when a hot-rolled bar jams in the rolling guides, or comes out of its high speed, horizontal rolling trajectory, frequently landing in the area adjacent to the rolling mill stands.) This resulted in the aggregate of the material included in the test program originating from different lots. We originally intended for all test specimens to derive from the same lot to eliminate any lot-to-lot variability. However, the remake of the material matched the other chemistry and material properties well, so this is not of concern.

The quantity of Alloy 2507 material required for the test program was not sufficient to procure an entire heat of material from a mill as done for the Custom 450 and Custom 630. Carpenter Technologies does produce the material; however, Carpenter requires a minimum order of 20,000 lbs (9,072 kg) for production. Therefore, we procured the necessary test material from a stainless steel service center, Ram Alloys in Texas. Sandvik of Sweden manufactured the material.

Table 3-1 shows the material properties from the mill certificate for each of the candidate materials. We include the manufacturer's data sheet in Appendix B and the full mill certificates in Appendix C for each material.

3.3.1 Plain Bar Stock

DSI fabricates standard, off-the-shelf Threadbar® for P/T applications from plain bar stock. DSI uses 2.64 in. (66 mm) diameter plain bar to produce a nominal 2-1/2 in. (63.5 mm) diameter bar. We understand DSI purchases sufficient material quantity from their source mill to obtain the optimal bar size needed, i.e., the non-standard 2.64 in. diameter. When procuring bar stock, DSI specifies that the bars shall be "Turned and Polished" with a diameter tolerance of ± 0.006 in. (0.15 mm). Turned and polished denotes that the bars shall be free from any mill scale, dirt, or debris. DSI also specifies the plain bar stock to be out-of-round by no more than 0.008 in. (0.20 mm) in any cross section and that deviation from straightness may not exceed 0.125 in. in any 5 ft (2.09 mm/m) length.

We selected the bar diameter from standard, mill available diameters. In the 2 to 3 in. (50.8 to 76.2 mm) diameter range, we could select diameters in 1/4 in. (6.35 mm) increments. We procured the plain bar stock to fabricate the anchorage bar for each candidate material from nominal 2-3/4 in. (70 mm) diameter solid bars. In planning bar fabrication, we selected this larger initial diameter bar stock with the expectation that threads would be machine cut. Cut threads would result in an effective bar (minor) diameter of 2.5 in. (63.5 mm) or less in the root to provide the desired effective area, $\boldsymbol{A_{se}}$. However, as described below, the threads eventually were rolled.

We also procured a larger, 5 in. (127 mm) diameter round bar stock to fabricate end nuts and coupling nuts for the anchorage system. We fabricated nuts from the same stainless steel alloy as the round bar stock, but from a different heat.

3.4 Bar Specimens

3.4.1 Thread Forming

Present carbon steel, P/T anchorage bars use a mix of hot- and cold-rolled thread forming processes with deformations along the entire length as required by ASTM A722. The 1, 1-1/4, and 1-3/8 in. (26.5, 32, and 36 mm) nominal diameter Threadbar® is hot-rolled threaded. The 1-3/4, 2-1/2, and 3 in. (46, 66, and 75 mm) nominal diameter Threadbar® is cold-roll threaded. We understand the Williams All-Thread-Bars all are cold-rolled threaded.

We considered two thread-forming methods for the subject anchorage bars: cold-rolled and machine cut. We deemed hot-roll forming of the candidate material bars infeasible at this time due to the cost of purchasing finish rolls for the producing mill.

- 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 Figure 3-1, 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 upon 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.

Cold-rolled threads are advantageous in that no material is removed and no chips, burrs, or excess material shavings are produced. In addition, rolled threads provide more-rounded profile, which helps to mitigate material galling. Figure 3-2 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.

We initially planned to machine cut threads on the plain bar stock, intending to identify a machine shop capable of forming threads the subject anchorage bars. We were unable to find a shop that would machine cut the quantity of bar needed for the test program, as the shops did not have the capability to accommodate a 12 ft bar length on a cutting lathe.

As traditional P/T bars of this diameter are cold-rolled threaded, we approached both DSI and WFE regarding their willingness to cold-roll thread. DSI was the sole respondent and expressed interest in fabricating anchorage bars from alternative materials. We discussed the “rollability” of the selected candidate materials with DSI and concluded cold-roll thread forming was a viable option. As previously noted, we understand cold rolling can alter the material properties, particularly around the bar perimeter. Accordingly, we scheduled all test specimens to originate from the threaded bar stock to evaluate this effect, if any.

The Unified Thread Standard (UTS) [ASME B1.1 2008] requires for bar sizes larger than a nominal 2.5 in. (63.5 mm) diameter to have a coarse thread pitch of four threads per inch UNC (Unified - Coarse). The DSI cold-rolled thread pattern is slightly coarser than the UNC standard thread. Figure 3-3 is a representative photo of a threaded stainless steel anchorage bar specimen with the thread pattern used. The resultant cold-rolled thread pattern produced a thread pitch of about 3.5 threads per inch for the bars in this test program. This required the end and coupling nut hardware to be longer because of the necessary thread engagement to develop strength.

3.4.2 Effective Area

The effective area of a threaded bar depends on the net root area of the bar inside the threads. ASTM A722 specifies the nominal dimensions and effective area of deformed, Type II, carbon steel anchorage bars, where footnote B of Table 2 notes that “Nominal area is determined from the bar weight [mass] less 3.50% for the weight [mass] of the deformations." We measured the length and weight of several small length specimens used in the testing program to calculate the effective linear densities, included in Table 3-2. Using these effective linear densities with the published density of the stainless steel material, we calculated an effective area of the 2-3/4 in. (69.9 mm) diameter anchorage bars to be an average of approximately 5.76 in^2 (3716 mm^2). This effective area depends on the assumed density of the stainless steel materials. We did not determine the actual density of the materials used in the test program. The material data sheets, in Appendix B, provide densities for each of the materials. The density of the heat-treated, stainless steel alloys depend on the temperature of heat treatment.

We also determined the effective area of the threaded specimens using the measured outside diameter of the threaded bars. We initially measured the outside thread diameter of a standard Threadbar® to determine the overall diameter. We determined the effective root diameter of the standard Threadbar® from the area reported by DSI. We calculated the thread height as the difference between the measured outside diameter and the effective root diameter of the Threadbar®. We subtracted this thread height from the measured outside diameter of the 2-3/4 in. threaded anchorage bars and calculated an effective root area. We also calculated the effective root area based on the inside nut diameter using a similar relationship. Table 3-3 details the calculations of effective root area based on measured dimensions of the bar outside diameter and nut inside diameter.

We used the effective area of 5.76 in^2 based on linear density according to ASTM A722 in our calculations.

3.5 Nut Specimens

DSI traditionally fabricates end nuts from carbon steel tube. This shape aids in minimizing machining the inside material of the nuts. We explored procuring thick wall tubing of the candidate materials to fabricate end nuts; however, the mills were reluctant to produce tube stock with the 1 in. (25.4 mm) wall thickness we requested because of the stainless mill capabilities, though this may be an option in the future. We subsequently elected to machine the nuts from solid round bar stock. The work required to remove the inside 2-1/2 in. from a 5 in. diameter solid bar was costly and time consuming. To expedite hollowing the solid bar stock, we arranged for trepanning the bar initially prior to commencing nut machining. Trepanning or tight tolerance, gun drilling is similar to a deep hole drilling process where longer initial bar lengths are internally cored to remove the unwanted material. The oil and gas industry uses this machine process for specialty piping. Trepanning is feasible for bar lengths up to about 12 ft

(3.7 m) to maintain the tolerance precision needed, so the hole-boring tool does not wander. Midwest Precision Manufacturing in Wisconsin performed the trepanning for this project.

ASME Standard B18.2.2 [2015] specifies standard dimensions for conventional heavy hex nuts, including thickness (height or length), width across flats, and width across points. The basis of the specified heavy hex nut length is a thread pitch conforming to the UNC. For a bar with a nominal diameter of 2.5 in. (63.5 mm), the standard heavy nut length is 2.453 in. (62.3 mm) with a tolerance of ± 0.052 in. (1.3 mm). This is approximately ***1.0d***, based on four threads per inch. For the actual 2.75 in. (69.9 mm) diameter bar, the standard heavy nut length is 2.703 in. (68.7 mm) with a tolerance of ± 0.056 in. (1.4 mm).

DSI Threadbar® uses a standard nut length of 5 in. (127 mm) for the cold-rolled threads. We elected to mimic the DSI nut length, ***2d***, for the starting length and work upward in length in the testing.

DSI cut the stock material to length and internally threaded the prepared hollow stock to create the end nuts. The test program included end nut lengths of ***2d*** (5 in.), ***2.5d*** (6-1/4 in.), and ***3d*** (7-1/2 in.), based on a nominal diameter. We included the different lengths to evaluate the required end nut length to develop the full strength of the anchorage bar, should the stainless steel threads prove softer or less strong than high-strength, carbon steel.

In addition, we used "test nut" lengths of ***4d*** (10 in.) to avoid nut failure or thread stripping during tension or relaxation testing. We requested DSI provide parallel flats along a portion of one end of each nut to facilitate wrench tightening, if necessary. We include a piece drawing for the end nuts in Appendix D.

Coupling nut length is not a standard length. For some materials, the coupling nut length can be determined from standard references. A rule-of-thumb, recognized by ASME, is that coupling nuts should have a minimum length of ***3d*** for standard cut threads. However, the scale and diameter of the bars in this project required testing the coupling nut length to verify full strength development of the bar.

Similar to the end nuts, DSI fabricated coupling nuts from the hollowed-out, round stock material. The test program included coupling nut lengths of ***4.4d*** (11 in.) and ***5.4d*** (13.5 in.). For Threadbar®, DSI has a coupling nut length of 10-3/4 in. Our minimum test coupling nut length approximately matched this, but we rounded the length up to an even 11 in. We included the different lengths similar to the various end nut lengths. We requested the parallel flats on the coupling nuts as well. We include a piece drawing for the coupling nuts in Appendix D.

Table 3-1 - Anchorage Bar Candidate Materials – Mill Certificate Properties

Property	Material or Alloy					
	Custom 450 H1050		Custom 630 H1100	Alloy 2507	Threadbar®	
					Plain	Galvanized
Tensile Strength (ksi)	168.0	169.0	156.0	118.8	167.0	
Yield Strength – 0.2% Offset (ksi)	158.0	160.0	150.0	84.0	154.0	
Elongation in 2 in. (%)	19.0	19.0	16.0	42.0	14.0	
Reduction in Area (%)	61.0	63.0	61.0	77.0		
Hardness – Rockwell (HRC) [A]	38	(39)	36	23	(40)	
Hardness – Brinell (HBW) [A]	(353)	363	336	(243)	369	
Batch Weight (lbs)	1679	3118	5775	8088		
Heat Number	578213	578213	971709	545813	NF15100387	
Report Date	9/30/2016	11/09/2016	10/18/2016	7/12/2016	5/27/2015	
Supplier	Carpenter Technologies		Carpenter Technologies	Sandvik via RAM Alloys	DSI	

[A] Hardness value in parentheses are converted per ASTM E140 [2012].

Table 3-2 - Anchorage Bar Effective Area based on weight per ASTM A722

Material	Length (in)	Weight (lbs)	Linear Density (lbs/in.)	Effective Linear Density (lbs/in.) [A]	Unit Weight (lb/in.^{3}) [B]	Effective Area (in^2)	Average Effective Area (in^2)
Custom 450	24.00	40.11	1.671	1.613	0.280	5.76	5.75
	14.47	24.14	1.668	1.610	0.280	5.75	
	24.03	40.12	1.669	1.611	0.280	5.75	
Custom 630	24.13	40.31	1.671	1.613	0.282	5.72	5.72
	23.06	38.54	1.671	1.613	0.282	5.72	
	24.25	40.55	1.672	1.614	0.282	5.72	
Alloy 2507	23.94	40.23	1.681	1.622	0.282	5.76	5.78
	23.94	40.40	1.688	1.629	0.282	5.78	
	24.13	40.73	1.688	1.629	0.282	5.78	
	24.06	40.64	1.689	1.630	0.282	5.79	
	23.94	40.37	1.687	1.628	0.282	5.78	
	24.13	40.67	1.686	1.627	0.282	5.78	
	24.13	40.79	1.691	1.632	0.282	5.79	

[A] Effective linear density based on weight less 3.5%.
[B] Published unit weight from Carpenter Technologies.

Table 3-3 - Anchorage Bar Effective Area based on measured dimensions

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Material	**Average Outside Diameter of Bar (in.)**	**Effective Outside Diameter of Bar (in.)**	**Effective Area of Bar (in^2)**	**Average Inside Diameter of Nut (in.)**	**Effective Outside Diameter of Bar (in.)**	**Effective Area of Bar (in^2)**
Threadbar®	2.759	2.563	5.16	2.625	2.563	5.16
Custom 450	2.883	2.688	5.67	2.728	2.667	5.59
Custom 630	2.902	2.707	5.76	2.728	2.667	5.59
Alloy 2507	2.881	2.686	5.66	2.717	2.656	5.54

Column (2): Also known as the major diameter for external threads.
Column (3): Also known as the minor diameter for external threads. Values based on effective thread height of 0.061 in.
Column (5): Also known as the minor diameter for internal threads.
Column (6): Also known as the minor diameter for external threads. Values based on effective nut clearance of 0.196 in.

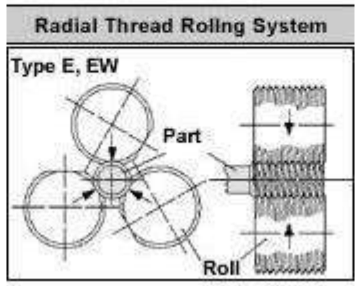


Figure 3-1 – Means of achieving threads on a bar through cold-rolling [Koepfer 2003].

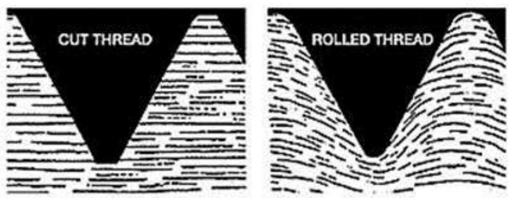


Figure 3-2 – Metallurgical differences in cut and rolled threads on a bar as shown by the modified grain structure [Reed Machinery 2014].

Figure 3-3 – Representative thread size and pitch of the threaded bar.

4. MATERIAL AND PHYSICAL PROPERTY TEST PROGRAM

The test program is intended to demonstrate comparative performance of the commonly used and the alternate candidate materials for the desired 100-yr service life. We selected sample populations to balance cost, statistical significance, and the predictive value of the test. We consulted with the project team to determine sample populations that will aid selection of a suitable candidate material of the bridge application.

4.1 Yield Strength, Tensile Strength, and Elongation

Post-tensioning anchorage bars traditionally are identified by a specified minimum tensile strength. Anchorage bar design usually is based on a percentage of the specified tensile strength, f_{pu}, ranging from 0.7 to 0.8f_{pu}. For the subject anchorage bars, the project team desired a minimum tensile strength f_{pu} of 150 ksi (1,030 MPa) to match present P/T bar technology.

Characteristic of most high-strength steels, the stress-strain behavior is not the classic, sharply yielding shape, as it does not exhibit a well-defined yield point. Rather, the stress-strain behavior gradually transitions from elastic to inelastic behavior, which is referred to as a roundhouse (RH) stress-strain curve or a gradual strain-hardening curve.

4.1.1 Test Standards

We determined the yield and tensile strength of the materials using the test method in ASTM A370 – *Test Methods and Definitions for Mechanical Testing of Steel Products* [2017]. We conducted tension testing at the Fritz Engineering Laboratory at Lehigh University in Bethlehem, Pennsylvania. We selected Lehigh University for their five million pound-capacity, Universal Testing Machine in the Fritz Engineering Laboratory.

4.1.2 Test Methods

We used full-sized specimens to conduct tension tests of the anchorage bars. Figure 4.1-1 shows a representative full-size bar specimen loaded in the testing machine.

We conducted three tests on full-length (12 ft.) specimens for each of the five selected materials. Lehigh University laboratory technicians recorded stress-strain data and elongation measurements at gage lengths of 25 in. and 50 in. (635 and 1,270 mm) for the beginning of each test. These represent gage lengths of 10d_b and 20d_b, respectively, per ASTM A722. Linear position transducers or wire extensometers were used to measure elongation.

Documentation included force-elongation and force-crosshead displacement curves for each test. SGH documented the fracture surfaces of each specimen as well as the condition of the threads on the anchorage bar and nuts after testing.

The maximum loading rate of the Lehigh Universal Testing Machine limited the rate of test loading, which deviated from ASTM A370 limits based on displacement control. ASTM A370 specifies the following maximum load application rates:

- Zero to one-half specified yield strength - any convenient speed of testing.

- One-half to full specified yield strength - the free-running rate of separation of the crossheads shall be adjusted so as not to exceed 1⁄16 in. per min per inch of reduced section, or the distance between the grips. For our tests, this is approximately 8 in. (203 mm) per minute based on a crosshead separation distance of 128 in. (3.25 m).

- Yield strength to tensile strength - the free-running rate of separation of the heads shall not exceed 1⁄2 in. (12.7 mm) per min per inch of reduced section, or the distance between the grips. For our tests, this is approximately 64 in. (1.63 m) per minute based on a crosshead separation distance of 128 in. (3.25 m).

ASTM A370 specifies the minimum testing speed shall not be less than 1⁄10 the specified maximum rates for determining yield point or yield strength and tensile strength. For these tests, this is 0.8 in. to 6.4 in. (20 to 163 mm) per minute.

ASTM has other criteria based on load speed. Section 8.4.3 states: "As an alternative, if the machine is equipped with a device to indicate the rate of loading, the speed of the machine from half the specified yield point or yield strength through the yield point or yield strength may be adjusted so that the rate of stressing does not exceed 100,000 psi (690 MPa)/min. However, the minimum rate of stressing shall not be less than 10,000 psi (70 MPa)/min."

The ASTM standard specifies a not-to-exceed maximum load rate as a very rapidly applied load will result in higher strength results due to dynamic effects and artificially inflate the strength results obtained by testing. This can occur especially in a production-testing environment.

We loaded all specimens except for one (630-1) at a rate of 0.4 inches (10.2 mm) per minute up to yield strength and a rate of 0.9 inches (22.9 mm) per minute from the yield strength to the end of the test. Specimen 630-1 was loaded at a rate of 0.2 inches (5.1 mm) per minute until after the yield strength and a rate of 0.35 inches (8.9 mm) per minute from the yield strength to the end of the test. Although our load application rate was variable, we conformed to the limits of Section 8.4.3 of the ASTM standard.

ASTM A370 permits determining yield strength by one of two methods: the offset method and extension under load method. The offset method yield strength is typically defined as a 0.2% offset from the lower, linear portion of the stress-stain curve. ASTM A722 permits either method for determining yield strength. We used the 0.2% offset method in assessing anchorage bar yield strength. The slope of the initial elastic region of the stress-strain curve determines the modulus of elasticity of the steel, ***E***. We calculated the modulus of elasticity, ***E,*** using a linear regression analysis on the stress-strain data in the elastic region.

The tensile-to-yield ratio (T/Y) is defined as the ratio of tensile strength to yield strength. This ratio indicates the degree of strain hardening beyond yield strength. For carbon steels, T/Y ratio and high tensile strength are typically competing properties. Steels with higher tensile strengths typically harden less beyond their yield strengths than steels with lower tensile strengths.

Elongation is determined during tension testing. According to ASTM A722, the gage length is $20d_b$ or 50 in. for a 2-1/2 in. (65 mm) diameter bar. Much like T/Y ratios, elongation and high tensile strength are typically competing properties in carbon steels. Steels with higher tensile strengths typically elongate less at fracture than steels with lower tensile strengths.

Due to the size and weight of the tested specimens, we could not measure tensile elongation by fitting together the two broken pieces of the specimen and measuring the new tested length over the initial 25 in. or 50 in. gage length. Instead, we estimated the tensile elongation using the crosshead displacement of the Universal Testing Machine. This method differs significantly from the ASTM A370 method typically used to calculate tensile elongation. The results will differ in the following ways:

- The testing machine undergoes a small amount of deformation. This is included in the tensile elongation value.

- After fracture, the anchorage bar elastically rebounds by an amount approximately equal to the load at fracture divided by the elastic modulus. The elongation prior to elastic rebound is included in our method of measuring the tensile elongation, but not in the fit-up method typically employed.

- The typical elongation method computes the average elongation over only the gage length. If the necking and fracture region occurs outside this gage length, the elongation is measured over the entire specimen length and lowers the reported elongation. ASTM A370 notes this elongation may not be representative of the material.

These variations mean that the absolute tensile elongation may not be directly comparable to those values given in mill certificates (small-sized samples) or the minimum values given in ASTM A722. The values reported herein are relative and are provided for comparison.

4.1.3 Test Results

The yield force and tensile force were recorded in kips (1 kip = 1,000 lbs), and we determined the yield strength and tensile strength using an effective cross-sectional area of each anchorage bar. The nominal cross-sectional area used for all three stainless steel materials was 5.76 square inches (as calculated in Section 3.4.2) and the nominal cross-sectional area used for the two control materials was 5.16 square inches (3,329 mm^2), as provided in Table 2 of ASTM A722 and reported by DSI. A summary of the test results for each material is in the following sections and in Table 4.1-1. Figure 4.1-2 shows a representative stress-strain curve for each material up to approximately 0.9% strain prior to removing the extensometer. Figure 4.1-3 shows a general force-displacement relationship for each material from the cross-head displacement of the Universal Testing Machine. Appendix E contains individual test results for each tension test, representative stress-strain curves for each material, photographs of testing, and the test report from Lehigh University.

Control: Threadbar® Carbon Steel

The three specimens failed by anchorage bar fracture. The average yield strength of the specimens was 142.7 ksi (983.9 MPa) with a standard deviation of 1.5 ksi (10.3 MPa). The average tensile strength of the specimens was 166.3 ksi (1,147 MPa) with a standard deviation of 2.9 ksi (20 MPa).

The average, relative tensile elongation was approximately 4.8%, which exceeds the minimum tensile elongation specified in ASTM A722 for a gage length of 20$\boldsymbol{d_b}$ (4%).

Control: Threadbar® Carbon Steel, Hot-Dip Galvanized

One specimen (DSI-G-1) failed at the edge of one of the end nuts at 149.2 ksi (1,029 MPa). This specimen began softening at a strain of less than 0.6%, a consequence of which is that the strain was too small to use either the 0.2% offset method or the offset strain method to determine yield strength. The other two specimens failed at strains large enough to determine yield strength. The average yield strength of the two specimens was 149.9 ksi (1,034 MPa). We did not calculate the yield strength standard deviation because only two data points are available. The average tensile strength of all three specimens was 159.2 ksi (1,098 MPa) with a standard deviation of 9.2 ksi (63.4 MPa).

The average, relative tensile elongation was approximately 4.3%, which exceeds the minimum tensile elongation specified in ASTM A722 for a gage length of 20d_b (4%).

Custom 450 H1050 Precipitation-Hardened Stainless Steel

All three specimens failed by anchorage bar fracture. The average yield strength of the specimens was 153.9 ksi (1,061 MPa) with a standard deviation of 0.9 ksi (6.2 MPa). The average tensile strength of the specimens was 170.1 ksi (1,173 MPa) with a standard deviation less than 0.1 ksi (0.7 MPa).

The average, relative tensile elongation was approximately 6.5%, which exceeds the 4% minimum tensile elongation specified in ASTM A722 for a gage length of 20d_b. However, as noted above, the method of determining elongation in this program likely underestimates the elongation determined by the traditional fit-up method.

Custom 630 H1100 Precipitation-Hardened Stainless Steel

The three specimens failed by anchorage bar fracture. The average yield strength of the specimens was 148.8 ksi (1,026 MPa) with a standard deviation of 2.3 ksi (15.9 MPa). The average specimen tensile strength was 159.8 ksi (1,102 MPa) with a standard deviation of 1.9 ksi (13.1 MPa).

The average, relative tensile elongation was approximately 3.7%, which is less than the minimum tensile elongation specified in ASTM A722 for a gage length of 20d_b (4%). Again, the method of determining elongation in this program likely underestimates the elongation determined by the traditional fit-up method.

Alloy 2507 Duplex Stainless Steel

This material had a significant amount of ductility, as demonstrated by the tensile elongation. Only one of the four specimens exhibited tensile fracture; two specimens elongated sufficiently to reach the displacement limit (30 in. (762 mm) stroke) of the Lehigh Universal Testing Machine and had to be unloaded prior to failure; one specimen (2507-2) failed by stripping the internal threads in one end nut at a 120.1 ksi (828 MPa) ultimate stress. This test did not demonstrate any softening behavior in the load - displacement curve. While we determined a maximum load to thread stripping, we could not determine the tensile strength magnitude for this anchorage bar. We did not use this test in the computation to ascertain the average tensile strength.

The two specimens that did not fracture began necking after achieving peak strength. Necking results in a decrease in tensile load due to local reduction of area in the specimen with increasing elongation; it is characterized as a negative slope in the load-displacement curve.

The average yield strength of the four specimens was 91.1 ksi (628 MPa) with a standard deviation of 1.0 ksi (6.9 MPa). The average tensile strength based on three specimens was 121.4 ksi (837 MPa) with a standard deviation of 0.6 ksi (4.1 MPa).

The average, relative tensile elongation was approximately 20.8%, which greatly exceeds the minimum tensile elongation specified in ASTM A722 for a gage length of 20$\boldsymbol{d_b}$ (4%).

Table 4.1-1 – Tension test results

Material	Average					Standard Deviation				
	0.2% Yield Strength (ksi)	Tensile Strength (ksi)	T/Y Ratio	Tensile Elongation[1]	Modulus of Elasticity (ksi)	0.2% Yield Strength (ksi)	Tensile Strength (ksi)	T/Y Ratio	Tensile Elongation[1]	Modulus of Elasticity (ksi)
Threadbar® – Plain	142.7	166.3	1.166	4.8%	32,100	1.5	2.9	0.031	1.4%	301
Threadbar® – Galvanized	149.9 [2]	159.2	1.096 [2]	4.3%	33,300	N/A	9.2	N/A	1.8%	337
Custom 450 H1050	153.9	170.1	1.106	6.5%	30,700	0.9	< 0.1	0.007	0.6%	164
Custom 630 H1100	148.8	159.8	1.073	3.7%	30,100	2.3	1.9	0.004	0.1%	224
Alloy 2507	91.1	121.4 [2]	1.327 [2]	20.8% [2]	30,000	1.0	0.6 [2]	0.005 [2]	N/A	366

[1] Tensile elongation is estimated based on cross-head displacement of the universal testing machine and measured over the length of the entire specimen. These values may not be comparable to the minimum tensile elongations specified in ASTM A722 or the measured tensile elongations in the mill certificates.
[2] Not all test results were used to compute average and standard deviation

Figure 4.1-1 –Tension test setup in Universal Testing Machine (Note for scale: The test specimen is a 12 ft bar).

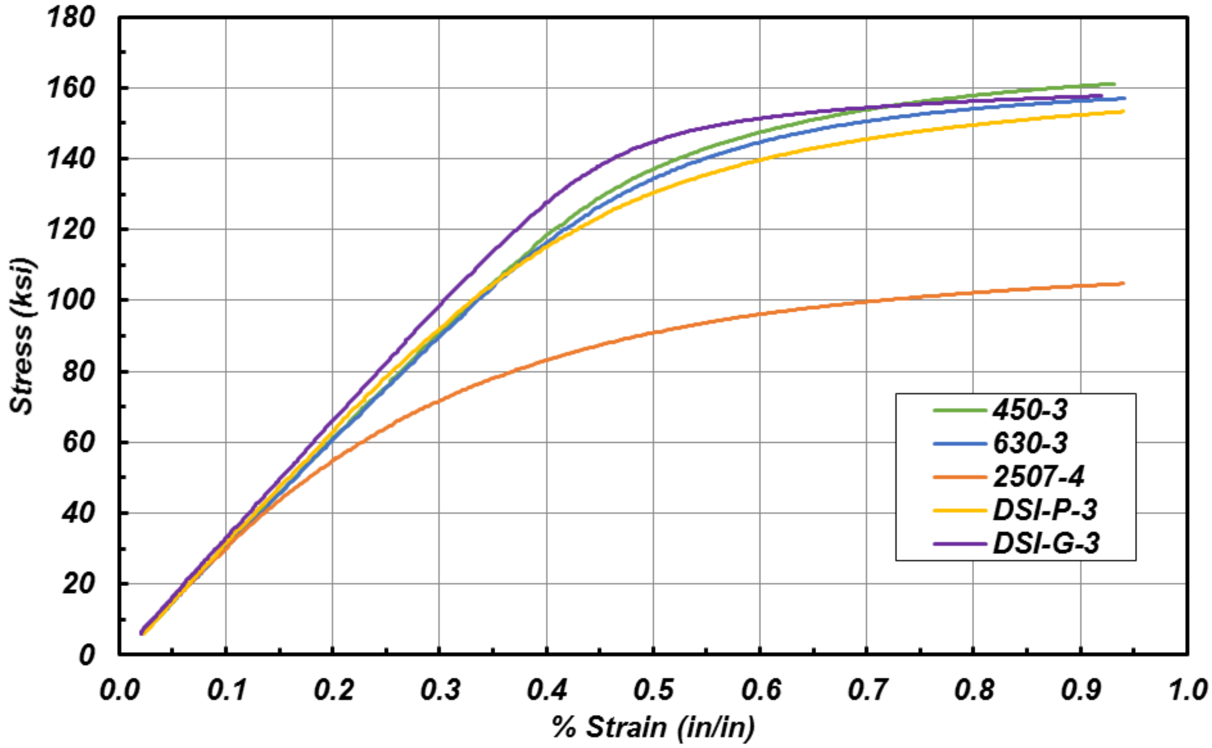


Figure 4.1-2 – Representative stress-strain curves prior to removing extensometer.

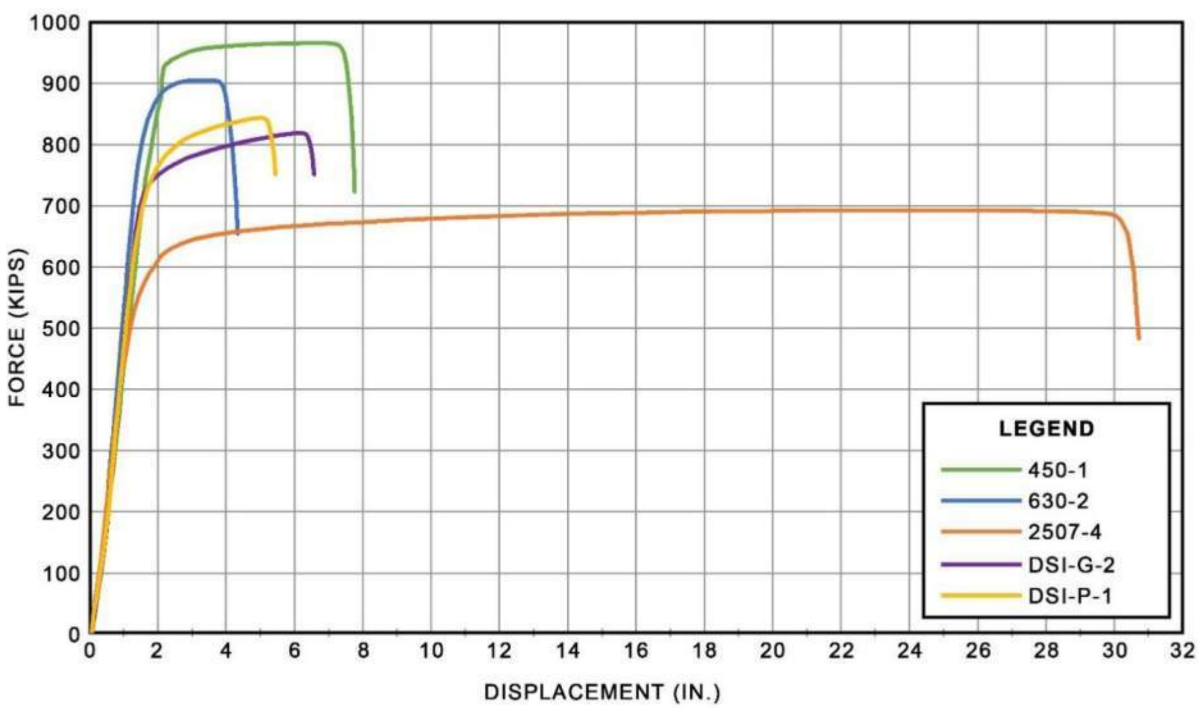


Figure 4.1-3 – Representative force-displacement curves (Note: the DSI-G-2 and DSI-P-1 bars had an effective area of 5.16 in^2; the others bars had an effective area of 5.76 in^2).

4.2 Coupling Nuts

The I-74 Bridge will use anchorage bars in the abutments greater than 12 ft (3.66 m) long. Therefore, the anchorage bars will likely require splicing along their length, using a coupling nut. In addition, a coupling nut is used to engage the bar tail at the exposed end to load the post-tensioning force in the bar, prior to lock-off. The coupling nut must develop the full-strength of the bar.

4.2.1 Test Standards

We performed testing of coupling nuts similar to tensile strength testing, according to ASTM A370. These tests were to verify the coupling/splice capacity as may be limited by the coupling nut. We conducted coupling nut testing at the Fritz Engineering Laboratory at Lehigh University in Bethlehem, Pennsylvania.

4.2.2 Test Methods

We performed three tests each on spliced specimens with a $4.4\boldsymbol{d_b}$ and $5.4\boldsymbol{d_b}$ coupling nuts for the 450 and 630 stainless steel alloys. For the tests using Alloy 2507, we tested only the $4.4\boldsymbol{d_b}$ long coupling nuts. The standard 10.75 in. (273 mm) coupling nut was tested for the plain and galvanized Threadbars®. Spliced bar specimens consisted of two half-length (6 ft) specimens with a center-located coupling nut. We determined capacity as the maximum force before either anchorage bar failure, end nut stripping, or coupling nut stripping. Documentation included stress-strain data for the beginning of each test, and elongation measurements at gage lengths of 25 and 50 in. (635 to 1,270 mm) set symmetrically about the coupling nut.

Similar to the tension tests, the rate of loading in the coupling nut tests deviated from that suggested by the ASTM standard, as addressed in the previous section. Most specimens were loaded at a rate of 0.2 inches (5.1 mm) per minute until after the yield strength and a rate of 0.4 inches (10.2 mm) per minute from the yield strength to the end of the test. The maximum loading rate of the Universal Testing Machine limited the rate of loading. The Alloy 2507 strain hardened stainless steel coupling nuts were loaded at a rate of 0.2 inches (5.1 mm) per minute until after the yield strength and 0.9 inches (22.9 mm) per minute from the yield strength to the end of the test. This material exhibited a much higher fracture elongation than any other and, therefore, these tests were performed at a higher loading rate to decrease the duration of each test.

4.2.3 Test Results

All twenty-one coupling nut tests failed by anchorage bar fracture, indicating every tested coupling nut sufficiently developed the full capacity of the anchorage bar.

A summary of the test results for each material is in the following sections and in Table 4.2-1. In addition, the individual test results for each coupling nut test are included in Appendix E.

Table 4.2-1 – Coupling nut test results

Material	Average		Standard Deviation	
	Tensile Strength (ksi)	Tensile Elongation (%) [1]	Tensile Strength (ksi)	Tensile Elongation (%) [1]
Threadbar® – Plain	168.1	6.1%	1.8	0.6%
Threadbar® – Galvanized	168.5	6.3%	0.4	0.7%
Custom 450 H1050	169.7	6.0%	0.5	1.7%
Custom 630 H1100	157.2	3.4%	1.5	0.2%
Alloy 2507	121.4	21.7%	0.3	0.5%

[1] Tensile elongation is estimated based on cross-head displacement of the universal testing machine and measured over the length of the entire specimen. These values may not be comparable to the minimum tensile elongations specified in ASTM A722 or the measured tensile elongations in the mill certificates.

4.3 End Nuts

End nuts anchor the P/T anchorage bars after stressing. The Industrial Fasteners Institute (IFI) [2014] notes that when selecting fasteners, it is desirable for the failure to occur in the anchor rod or bolt, and not through thread stripping. Rod or bolt fracture is most likely to occur when the bar is being tightened or stressed.

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.

4.3.1 Test Standards

We performed end nut proof testing similar to the requirements in ASTM A962 – *Standard Specification for Common Requirements for Bolting Intended for Use at Any Temperature from Cryogenic to the Creep Range* [2016] and ASTM F606 – *Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets* [2016]. These standards include the procedures for conducting proof testing. We conducted testing similar to the procedures in ASTM F606 Method 2, Yield Strength, where the end nut is loaded to achieve 0.2% offset of the threaded bar.

ASTM A962 and F606 do not specify the minimum proof load; the proof load is specified in the material standard specification, such as ASTM F3125 – *Standard Specification for High Strength Structural Bolts, Steel and Alloy Steel, Heat Treated, 120 ksi (830 MPa) and 150 ksi (1040 MPa) Minimum Tensile Strength, Inch and Metric Dimensions* [2015]. ASTM F3125 includes the minimum proof load for tests according to ASTM F606 Method 2. The proof load value is based on a stress of 130 ksi (896 MPa) for A490 bolts, which have a specified minimum tensile strength of 150 ksi (1,040 MPa), similar to the bar strength in this test program.

4.3.2 Test Methods

We conducted end nut proof testing at the Bowen Structural Engineering Laboratory at Purdue University in West Lafayette, Indiana. The test set-up consisted of a new 6 ft (1.83 m) section of untested bar inserted through a center-hole ram and load cell. Three, 12 in. x 12 in. x 2 in. (305 x 305 x 51 mm) thick plate washers were used in the test set-up - one located at each end of the ram and one between the load cell and ram. On one end of the bar, we installed a coupling nut or longer test nut to prevent failure on that end. We installed the test end nut on the other end of the bar. The gage length of the threaded bar between end nuts was 35 in. (0.9 m). Figures 4.3-1 and 4.3-2 show the test set-up. Appendix F includes details of the test set-up. Additional nuts on the bar served to hold instrumentation stands.

Concrete blocks surrounded the entire test set-up for safety. Instrumentation consisted of a strain-gage based load cell, a pressure gauge on the ram, and cable extension linear potentiometers to measure displacement. Figure 4.3-3 shows the displacement instrumentation. We measured displacement of the test end nut and the bar relative to the stationary ram. Any difference between the two displacement measurements indicates nut slippage.

For each candidate material, we performed three tests on ***2d*** end nuts measuring 5 in. (127 mm) in length. For plain Threadbar®, we performed three tests on standard, 5 in. (127 mm), end nuts. For galvanized Threadbar®, we performed two tests on standard, 5 in. (127 mm), galvanized end nuts. The galvanized nuts were very difficult to thread on the galvanized bar specimens. Significant grinding and filing was required on the galvanized threads to facilitate threading.

From prior tension testing, we knew the actual 0.2% offset yield and tensile strength for the bars. The tensile-to-yield ratio of the bars ranged from 1.073 to 1.327. We selected a target proof load for the end nuts of approximately 5% above the 0.2% offset yield strength. 5% above the actual yield strength also represents a load approximately 25% greater than the design yield strength based on 80% of the specified minimum tensile strength. The value of 25% derives from AASHTO LRFD Bridge Design Specifications, Sixth Edition, Article 5.11.5.2.2 [2012], which specifies full-mechanical connections shall not be less than 125% of the specified yield strength of the bar in tension.

During testing, we switched from a load-based proof load to an elongation-based proof test. We loaded the bar until it elongated sufficiently to clearly exhibit nonlinear stress-strain behavior on the real-time, load-deformation plot.

4.3.3 Test Results

Table 4.3-1 shows the test results for the end nut proof load testing. For the candidate materials, the ***2d*** or 5 in. (127 mm) long end nuts met the performance criteria. For the

Threadbar® specimens, the standard length end nut passed. For all except the galvanized Threadbar® tests, the nuts were easily removed following the proof load test.

There is a small discrepancy in loads measured between the tension testing at Lehigh and the end nut testing at Purdue. The maximum load achieved was often close to or sometimes exceeded the tensile strength of the anchorage bar based on tension testing. For most tests, the difference ranges from 2% to 3.5%. We consider these differences negligible given the error in load cells and pressure transducers at the high load levels of the test program. For the tests on galvanized nuts, the difference was about 10%.

The hot-dip galvanized nuts were very difficult to thread on the bars due to the galvanizing filling the threads and hindering free spinning. The nuts were "frozen" on the bars and could not be removed after the test.

We did not test the remaining, longer length end nuts, as the short ***2d*** length nuts were able to resist the load.

Table 4.3-1 – End nut proof load test results

Material	Test ID	Nut Length (in)	Target Proof Load (kips)	Maximum Recorded Load (kips)	Test Termination Condition	Test Notes
Threadbar® – Plain	DSI-P-2d-1	5	773	882	2 in. elong.	Easily removed after test, no damage noted
	DSI-P-2d-2	5	773	879	2 in. elong.	Nut initially jammed; hand spun after broken free; no damage noted
	DSI-P-2d-3	5	773	895	2 in. elong.	Nut initially jammed; hand spun after broken free; no damage noted
Threadbar® – Galvanized	DSI-G-2d-1	5	812	909	3 in. elong.	Nut extremely difficult to thread onto bar - could not remove after test
	DSI-G-2d-2	5	812	902	3 in. elong.	Nut difficult to thread onto bar - removed after test, no damage noted.
	DSI-G-2d-3	5	Not tested due to difficulty threading nut			
Custom 450 H1050	450-2d-1	5	935	955	+5% yield	Easily removed after test, no damage noted
	450-2d-2	5	935	940	+5% yield	Easily removed after test, no damage noted
	450-2d-3	5	935	1000.5	2.5 in. elong.	Easily removed after test, no damage noted
Custom 630 H1100	630-2d-1	5	905	930	1.5 in. elong	Easily removed after test, no damage noted
	630-2d-2	5	905	958.5	1.5 in. elong	Easily removed after test, no damage noted
	630-2d-3	5	905	947	1.5 in. elong	Easily removed after test, no damage noted
Alloy 2507	2507-2d-1	5	554	702	1.5 in. elong	Easily removed after test, no damage noted
	2507-2d-2	5	554	704	1.5 in. elong	Easily removed after test, no damage noted
	2507-2d-3	5	554	710	3 in. elong.	Easily removed after test, no damage noted

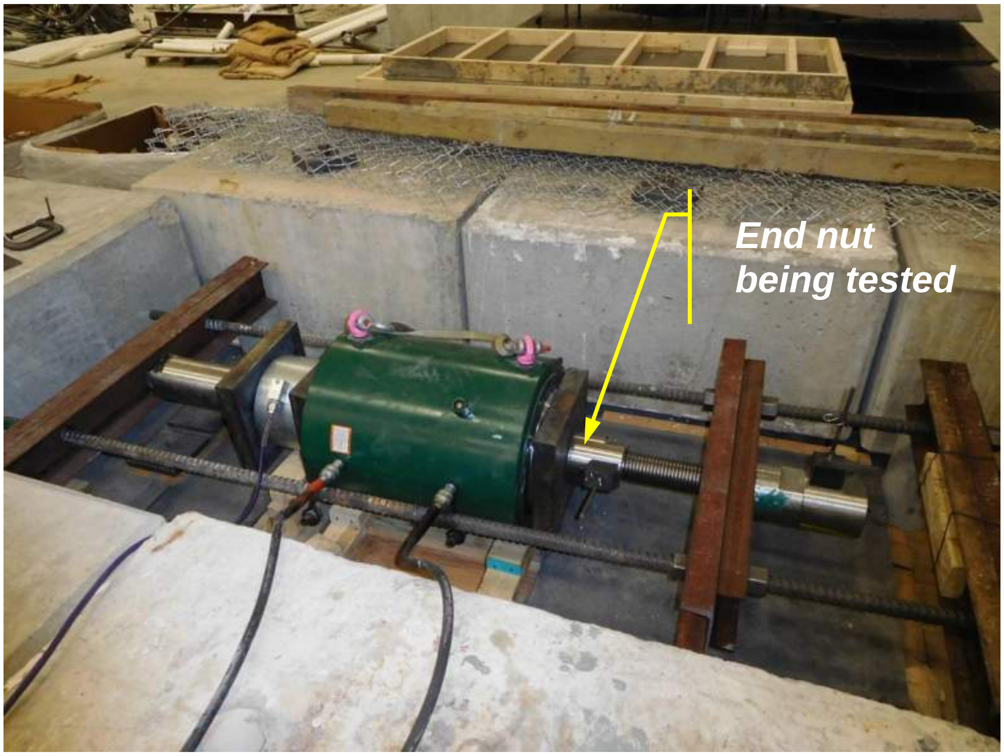


Figure 4.3-1 – Elevation view of the end nut test set-up.

Figure 4.3-2 – The end nut test set-up located in a “concrete block box” for safety.

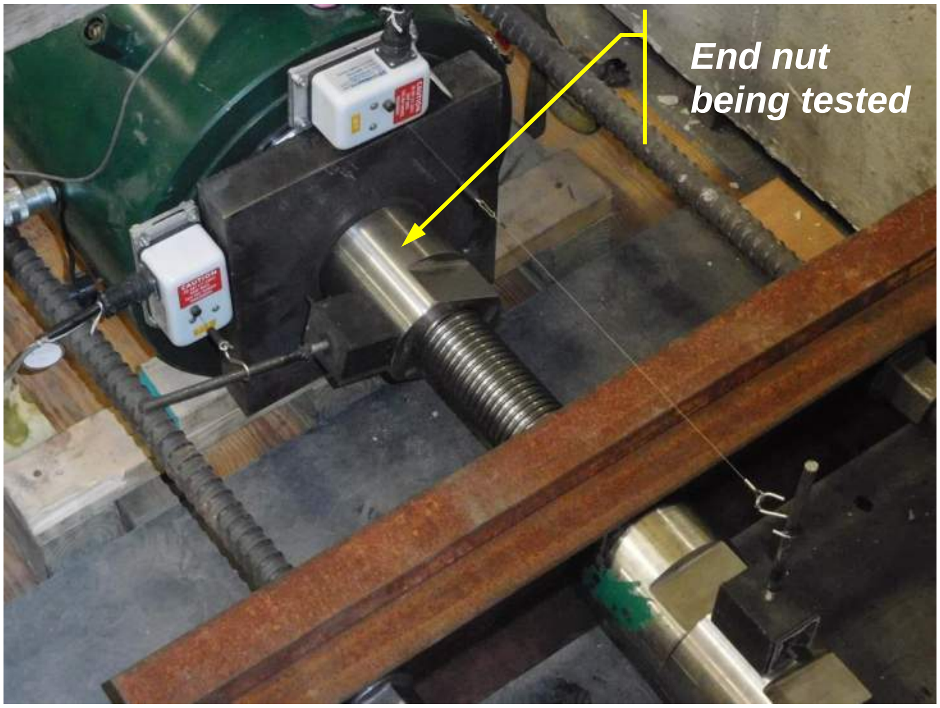


Figure 4.3-3 – Displacement instrumentation on the end nut tests.

4.4 Relaxation under Load

Under sustained high stress steel will stress-relax, meaning, under constant strain stress diminishes. The significance of stress relaxation in the anchorage bar applications in this project is that the post-installation prestress, necessary for proper long-term performance, can reduce.

For a given steel, the degree of relaxation depends on the initial stress level and temperature. For a given temperature, the smaller the initial stress the smaller the relaxation with time. Little relaxation occurs at relatively low stress levels (less than 50% of the material tensile strength) as indicated in the literature. 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.

4.4.1 Test Standards

ASTM A722 does not contain relaxation requirements for high-strength anchorage bars. Other reference standards for relaxation testing of high strength steel bars and prestressed reinforcement include the following:

- ASTM A416 – *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete* [2016] includes required relaxation properties for prestressing strand. It specifies initial test loads at 70% or 80% of the specified minimum breaking strength. For strand, the minimum breaking strength is either 250 or 270 ksi (1,724 or 1,862 MPa). The specified test period is 1,000 hours. The maximum relaxation losses are limited to 2.5% and 3.5% for 70% and 80% of the specified minimum breaking strength, respectively.

- ASTM A421 – *Standard Specification for Uncoated Stress-Relieved Steel Wire for Prestressed Concrete* [2015] includes relaxation test requirements similar to ASTM A416. It is provided as Supplementary Requirement S1.

- British Standard (BS) 4486 includes relaxation testing of post-tensioning, steel bars. It specifies initial test loads at 60%, 70%, and 80% of actual breaking load determined on an adjacent test piece. The specified test period is 1,000 hours. The maximum relaxation values are limited to 1.5%, 3.5%, and 6.0% for 60%, 70%, and 80% of breaking load, respectively. Testing is conducted at room temperature conditions.

- Japanese Industrial Standard (JIS) G3109 includes relaxation test conditions in Annex C. It specifies an initial test load of 70% of the lower limit value (i.e. minimum specified) tensile strength. The specified test period is 1,000 hours. The standard limits the relaxation value to 4.0% maximum.

Because they sell products internationally, domestic manufacturers of conventional high-strength anchorage bar typically use the relaxation requirements of BS 4486. We understand this standard forms the basis of a new European Normative (EN) Standard: *EN 10138-2, Prestressing Steels - Part 4: Bars* [2000]. Our test criteria was similar to the requirements of BS 4486, except we determined the initial load based on the specified minimum tensile strength instead of the actual breaking load from an adjacent test piece. We also referred to ASTM E328 – *Standard Test Methods for Stress Relaxation for Materials and Structures* [2013], and ASTM A1061 – *Standard Test Methods for Testing Multi-Wire Steel Strand* [2016] for relaxation testing methods.

During Phase 1, the Illinois DOT suggested conducting relaxation tests at a second test temperature of 150°F (65.6°C). The Illinois DOT engineer felt this condition would replicate a maximum in-service temperature condition in the I-74 abutment. Although there is merit in testing at a higher temperature, the standards containing relaxation requirements require only testing at room temperature. We did not include elevated temperature relaxation tests.

We conducted relaxation testing at The Bowen Structural Engineering Laboratory at Purdue University in West Lafayette, Indiana. The Bowen Lab offered the best combination of capacity, availability, and proximity to our Chicago office.

Initial Test Loads

The reference standards cited above differ slightly in the initial load requirements. BS 4486 specifies the initial load to be a percentage of the actual breaking load; both ASTM standards and JIS G3109 base the initial load on the specified minimum breaking (tensile) strength. When relaxation testing initially commenced for most specimens, we had not completed the full-scale tension testing to know the actual breaking load/strength of the full-size anchorage bars. Therefore, we followed the ASTM standards by using the specified minimum breaking strength.

For the control Threadbar®, the specified minimum tensile strength by ASTM A722 is 150 ksi (1,034 MPa). For the Custom 450 and Custom 630 specimens, the actual tensile strength from mill certificates was 168 and 156 ksi (1,158 and 1,076 MPa), respectively, and exceeded 150 ksi. Based on this we assumed an appropriate specified minimum tensile strength for these specimens to be 150 ksi, similar to ASTM A722. For the Alloy 2507, the mill certificate tensile strength was 118.8 ksi (819 MPa). We selected an appropriate specified minimum tensile strength of 110 ksi (758 MPa) for the Alloy 2507. This value represents an equivalent actual-to-specified minimum tensile strength ratio for the Alloy 2507 as ASTM A722 does for the other materials.

For reference, American 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 $0.94\boldsymbol{f_{py}}$ or $0.80\boldsymbol{f_{pu}}$ during stressing operations. The maximum tensile stress is $0.70\boldsymbol{f_{pu}}$ after force transfer (i.e. 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 $0.90\boldsymbol{f_{py}}$. The maximum tensile stress is $0.70\boldsymbol{f_{pu}}$ at anchorages and couplers immediately after anchor set.

Based on the above test and design standards, we selected 80% of the specified minimum tensile strength as our target initial load. This value of 80% is one of the three stressing levels of BS 4486 and one of the two stressing levels of ASTM A416. ASTM A722 specifies the minimum yield strength as 80% of the minimum tensile strength for Type II (deformed) bars. As a result, our target initial load is close to the minimum yield strength of the test specimen. Our target initial load is a higher percentage of both yield and tensile strengths than either design standard permits. We elected the highest level in an effort to determine the largest relaxation percentage.

We recognized the initial stress level and resultant relaxation amount we would obtain might not be representative of actual service conditions. As such, we performed relaxation testing on an additional set of plain Threadbar® specimens at an initial load level of approximately 60%. This provides a good comparison of relaxation at various load levels for this material.

The relaxation testing is primarily a comparison study of the various materials and not an evaluation of the absolute relaxation of the material. We could not build an infinitely stiff test frame to determine the absolute material relaxation properties.

4.4.2 Test Methods

We designed structural steel load frames and procured a hydraulic ram and load cells to conduct the relaxation testing. Design drawings for the relaxation frames are included in Appendix G. To control frame deformations we designed them to a stress limit of 50% of yield. The frame initially deforms during the jacking operation, undergoes additional deformation during seating as the post-tension load is transferred to the frame, and recovers deformation as the bars relax and impart less load.

We tensioned three 12 ft long samples of each candidate material to the target initial load. We used a gage length of 112.5 in. (2.9 m). This represents forty-five times the nominal diameter for 2-1/2 in. (63.5 mm) diameter bars or forty-one and a half times an effective diameter of 2.70 in. (68.6 mm) for the specialty-fabricated bars. In accordance with ASTM A1061 [2016], Section 9.4.7: *"The test gage length shall be at least 60 times the nominal diameter. If this gage length exceeds the capacity of the extensometer or testing machine, then it is permitted to substitute a gage length of 40 times the nominal strand diameter."* The gage length met this standard.

We used Geokon vibrating-wire gage load cells to monitor the load. Vibrating wire load cells operate by measuring the change in vibration frequency of a wire gage as its tension changes. Vibrating wire-based load cells are ideal for this long-duration test because of their long-term stability.

Unfortunately, the Bowen Laboratory is not a temperature-controlled space. We conducted the tests in the fall and winter months, with the assistance of the Purdue graduate students and faculty. We recorded temperature fluctuations of up to 20°F (11°C) during the 1,000-hour test duration. This temperature fluctuation affects the thermal expansion and contraction of the steel relaxation frame and the test specimens. The load cells have thermocouples built-in to record temperature data for the duration to compensate for temperature. The graduate research assistants helping with the data collection corrected the measured relaxation losses for the temperature fluctuations based on the technical information and correction procedure provided by the load cell manufacturer. We also compensated for the axial deformation of the test frames due to temperature variation.

We monitored the jacking load during initial stressing via a pressure transducer connected to the hydraulic ram. We compared this load to the load measured via the vibrating wire load cell following its initial reading. The pressure transducers provided direct feedback on the jacking load as it was increased and the load cell provided the actual jacking load. The correlation between the pressure transducer and the load cells was variable throughout the test program.

The initial target load is the anchorage bar post-tension load following jacking and seating of the test frames. This requires stressing the test specimens to a jacking load higher than the target initial load of 80%. The amount of jacking load, seating, and final initial load varied between the various tests, both for the three tests per material and between materials. BS 4486 specifies the initial target load to be recorded one minute after stressing to accommodate seating and any other initial losses in the test set-up.

We monitored the loss of load due to relaxation for the 1,000-hour test duration. We measured the jacking load, initial load, and relaxation loss with load cells connected to an automatic data acquisition system. We converted load values to stress using the effective areas reported in Section 3.4.2.

4.4.3 Test Results

Table 4.4-1 provides the jacking stress, initial stress after seating, and relaxation losses for each material tested. Appendix G contains individual values for each test. Figure 4.4-1 shows the relationship between measured relaxation loss and initial stress as a percentage of specified minimum tensile strength. Figure 4.4-1 also includes the limits from the various reference standards. Figure 4.4-2, 4.4-3, 4.4-4 show the percentage of specified minimum tensile strength over time, the percentage of specified minimum tensile strength over time on a logarithmic scale, and the percent loss over time for the representative Alloy 2507 specimens. Additional figures from relaxation testing are provided in Appendix G.

Control: Threadbar® Carbon Steel

The plain Threadbar® specimens were the first bars stressed for the relaxation testing. The jacking load was 84% before lock-off and seating. After release and the initial seating losses, the first set of control plain Threadbar® specimens had an average initial resultant stress of 74.5%. We attributed the seating losses to the following:

- Nut engagement and internal thread seating.
- Shear and bending deflection of the two, 18 in. (457 mm) deep, double channel spreader beams.
- Axial shortening of the tube columns in the frame.

- Local crushing of the 2 in.-thick (51 mm) plate washer due to nut bearing.

After tensioning, we observed the unhardened, steel plate washer had an imprint of the nut due to local bearing indenting the A36 plate. This stressing revealed the initial losses were about 9 to 10% for the load magnitude of 700 to 800 kips (3,114 to 3,559 kN).

We stressed all three Threadbars® equally, and achieved repeatable results. The standard deviation of initial design stress was 1.0%. We calculated an average relaxation for the control plain Threadbar® specimens at this stress level as 2.75%. This average relaxation is below the limits specified in BS 4486, JIS G3109, and ASTM A416.

To study the effect of a lower initial stress on relaxation properties, we stressed the second set of control plain Threadbar® specimens to an average initial stress of 62.4%, after seating losses. The standard deviation of initial design stress was 1.4%. We calculated an average relaxation for the control plain Threadbar® specimens at this stress level as 1.74%. This measured relaxation is within the limits of BS 4486. The ASTM and JIS G3109 limits do not apply, as they do not include initial stress limits as low as this set of tests.

Control: Threadbar® Carbon Steel, Hot-Dip Galvanized

We stressed the control galvanized Threadbar® specimens to an average initial stress of 71.0%, after seating losses. The standard deviation of initial design stress was 1.5%. We calculated an average relaxation for the control plain Threadbar® specimens as 2.51%. This average relaxation is below the limits specified in BS 4486, JIS G3109, and ASTM A416.

Custom 450 H1050 Precipitation Hardened Stainless Steel

We stressed the Custom 450 specimens to an average initial stress of 84.0%, after seating losses. The standard deviation of initial design stress was 1.5%. We calculated an average relaxation for the Custom 450 specimens as 1.58%. This average relaxation is below the limits specified in BS 4486, JIS G3109, and ASTM A416.

Custom 630 H1100 Precipitation Hardened Stainless Steel

We stressed the Custom 630 specimens to an average initial stress of 74.0%, after seating losses. The standard deviation of initial design stress was 1.3%. We calculated an average relaxation for the Custom 630 specimens as 1.32%. This average relaxation is below the limits specified in BS 4486, JIS G3109, and ASTM A416.

Alloy 2507 Duplex Stainless Steel

We stressed the first set of Alloy 2507 specimens to initial stresses of 39.0%, 58.7%, and 66.2%. The standard deviation of initial design stress was 11.5%. We did not average the test results for the Alloy 2507 specimens due to the wide variation of initial load. We calculated relaxation values for the Alloy 2507 specimens of 0.71%, 1.75%, and 2.60% for the initial stress of 39.0%, 58.7%, and 66.2%, respectively. Our initial design stress was outside the values specified in the reference standards. If we extrapolate the specified limits to our initial design stress, the measured relaxation will exceed the limits specified in ASTM A416, ASTM A421, and BS 4486.

The initial stress standard deviation was higher than other material tests due to difficulties tightening the nuts on the test specimen. As we stressed the test specimens, we typically tightened the nuts to limit the seating losses that occur. We were unable to fully tighten the nut on the Alloy 2507 specimens; our test nuts were too long and the bar stretch in the nut length bound-up the bar in the nut. This resulted in higher seating losses than other materials and corresponding lower initial loads.

In order to represent the initial design stresses more accurately, we tested three additional Alloy 2507 specimens at a higher initial stress. Due to availability, the test specimens were two coupled 6 ft. bars to replicate field conditions of coupled bars. We achieved a higher initial stress by reducing the nut length and double-nutting, which enabled us to tighten the nuts. We stressed these Alloy 2507 specimens to an average initial stress of 68.9%, after seating losses. The standard deviation of initial design stress was 0.3%. We calculated an average relaxation for these Alloy 2507 specimens as 3.59%. This average relaxation is above the limits specified in BS 4486 and ASTM A416, but below the limit specified in JIS G3109 for an initial load of 70% of specified minimum tensile strength.

Table 4.4-1 – Relaxation test results (average of three tests except Alloy 2507)

Material		Jacking Stress (ksi)	Jacking Stress % of Design Minimum Tensile Strength [A]	Initial Load After Seating (ksi)	Initial Load % of Design Minimum Tensile Strength [A]	Final Load (ksi)	Total Relaxation (ksi)	% Relaxation
Threadbar® – Plain / High		127.5	85.0%	111.7	74.5%	108.6	3.1	2.75%
Threadbar® – Plain / Low		104.3	69.5%	93.6	62.4%	92.0	1.6	1.74%
Threadbar® – Galvanized		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%

[A] Design tensile strength:
f_{pu} = 150 ksi for Threadbar®, Custom 450, and Custom 630
f_{pu} = 110 ksi for Alloy 2507

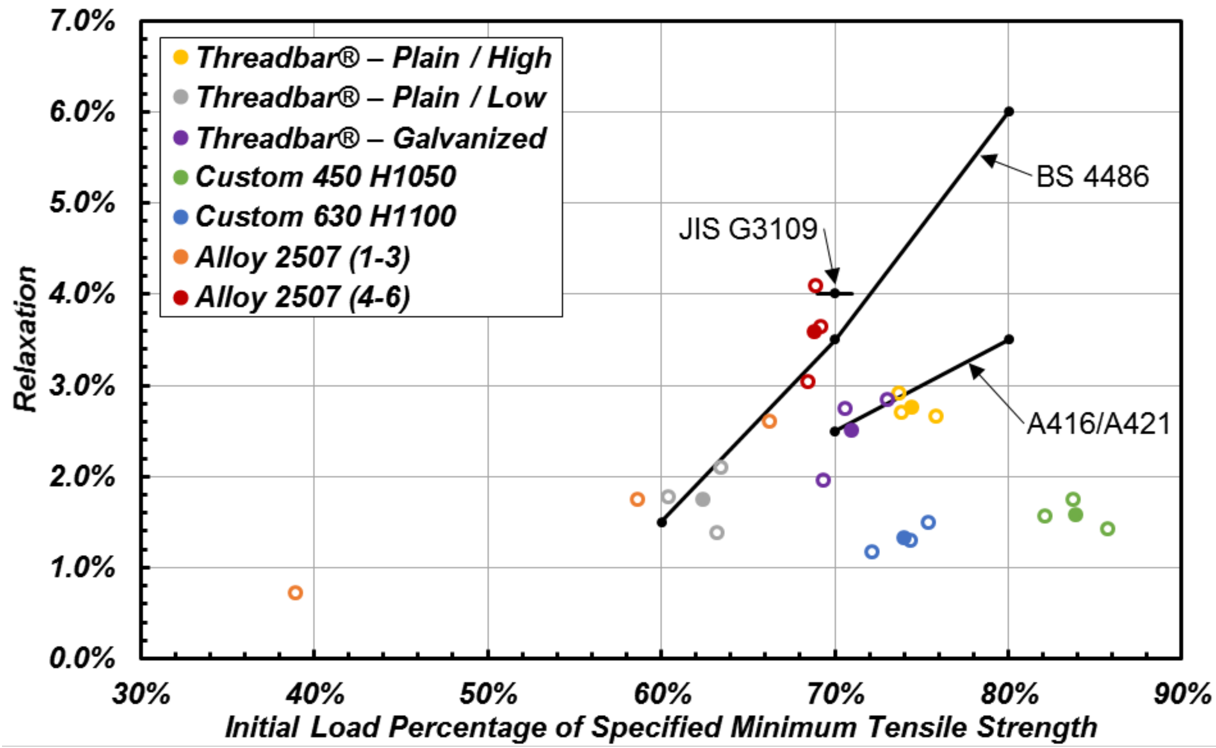


Figure 4.4-1 – Relaxation testing results compared to BS 4486 (solid circles represent average relaxation from three samples; open circles represent individual test data).

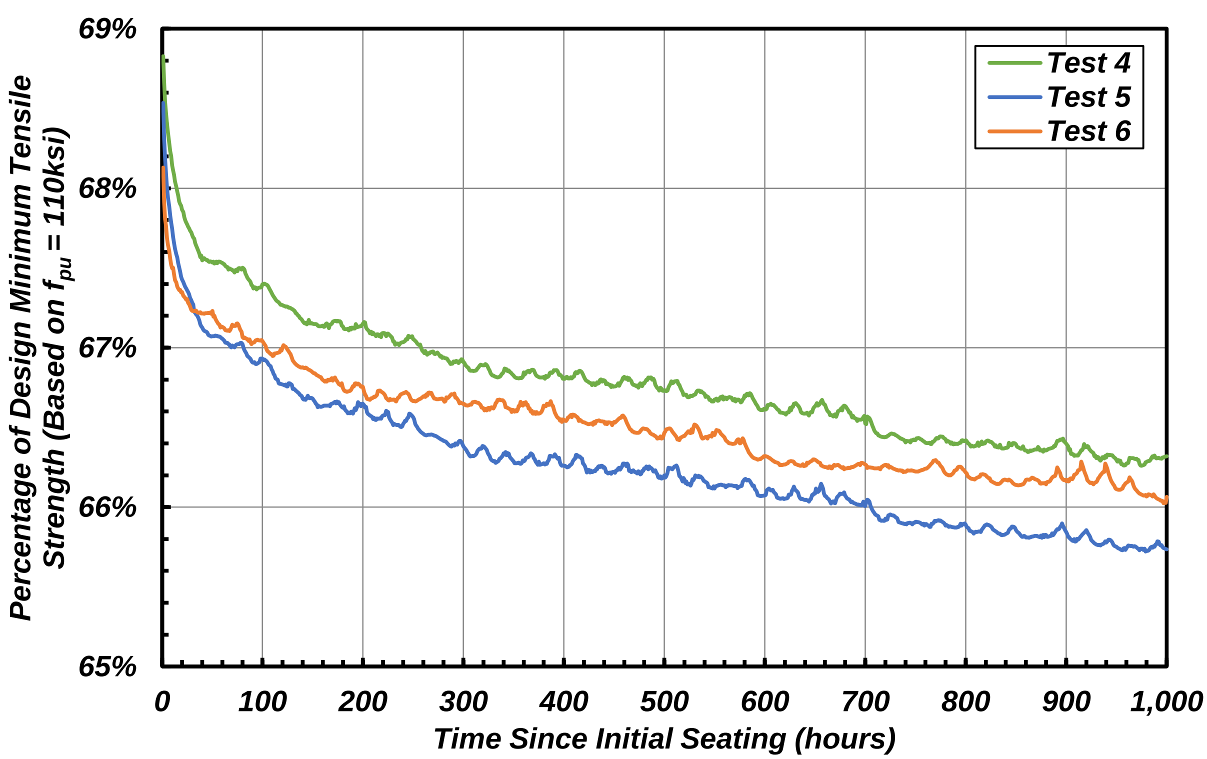


Figure 4.4-2 – Relaxation over time (sample shown for Alloy 2507).

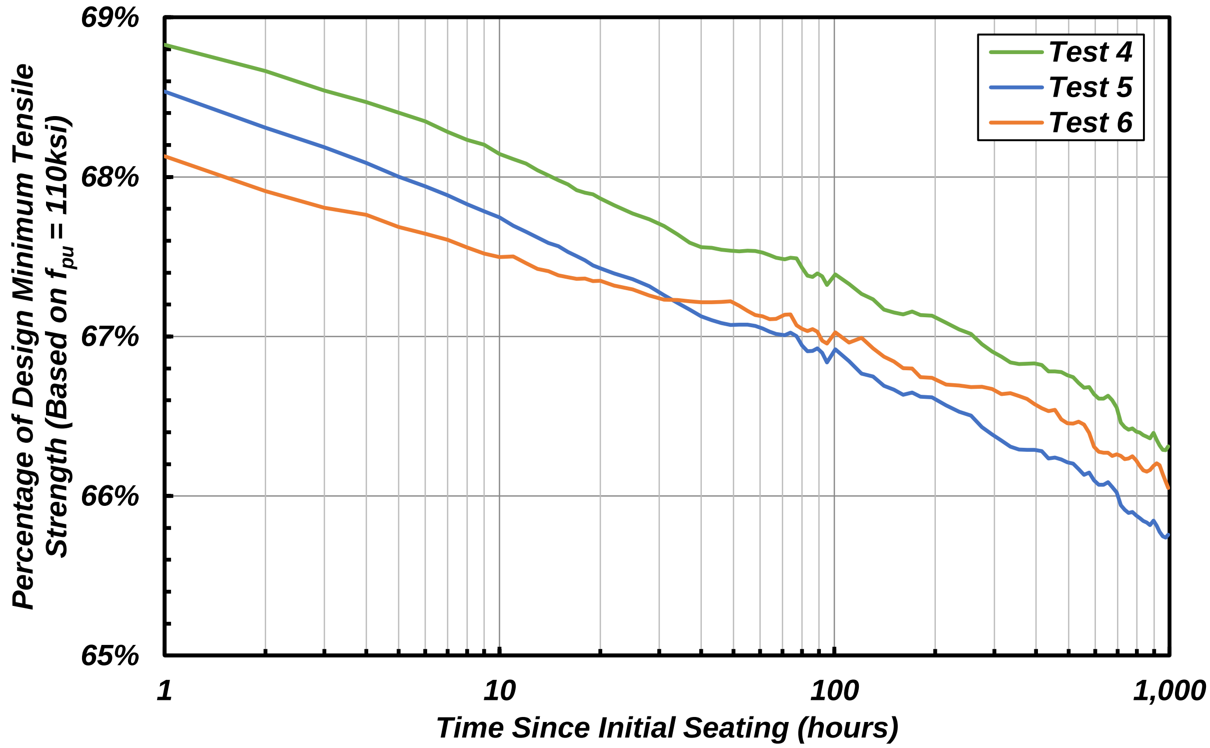


Figure 4.4-3 – Relaxation over time on a logarithmic scale (sample shown for Alloy 2507).

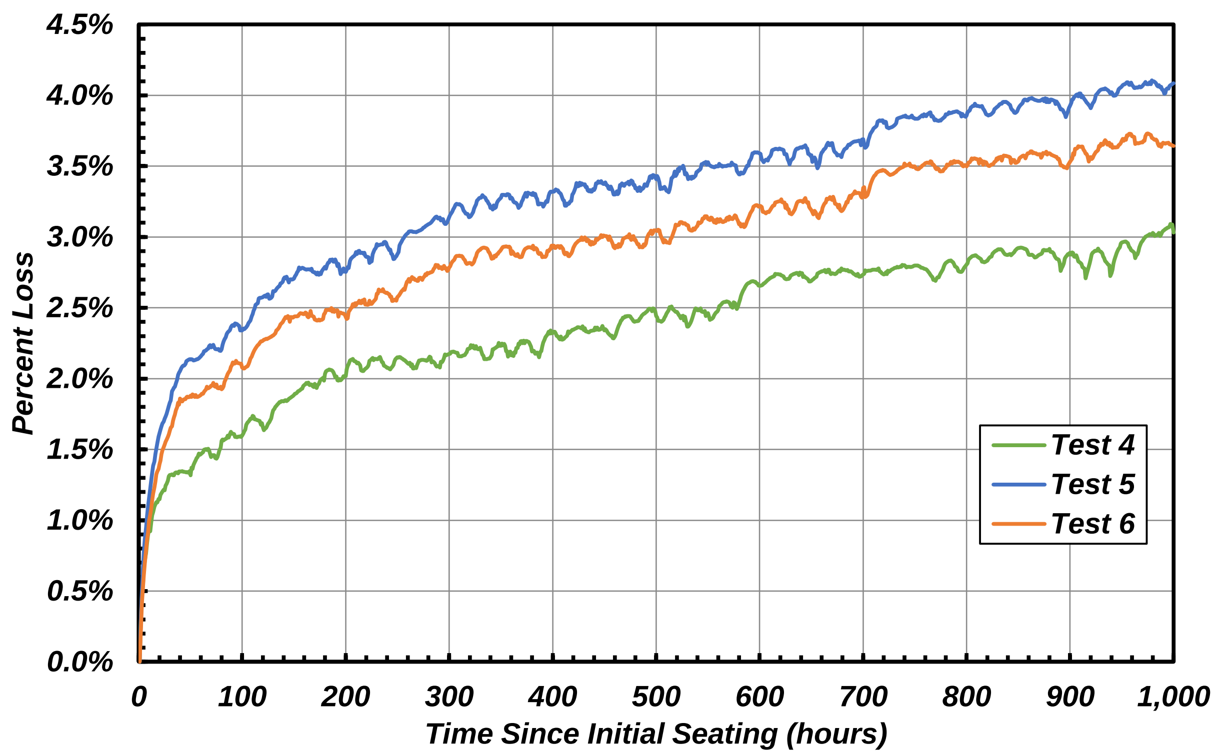


Figure 4.4-4 – Percent loss over time (sample shown for Alloy 2507).

4.5 Hardness

4.5.1 Test Standards

We measured the Rockwell hardness of the materials according to ASTM E18 – *Standard Test Methods for Rockwell Hardness of Metallic Materials* [2016]. We measured the Brinell hardness of the materials according to ASTM E10 – *Standard Test Method for Brinell Hardness of Metallic Materials* [2015]. We conducted this testing at our laboratory in Waltham, Massachusetts.

4.5.2 Test Methods

For Rockwell hardness, we sectioned each bar material and ground the surface using silicon carbide paper to a finish of 600 grit. We tested according to the Rockwell C scale, with a diamond indenter and a nominal force of 150 kg (331 lb). We tested at equivalent depths from the bar surface of 0.1R, which is close to the thread root, 0.45R and 0.8R, where R is the bar radius (Figure 4.5-1).

For Brinell hardness, we sectioned each bar material and ground the surface using silicon carbide paper to a finish of 120 grit. We tested at the center of each bar according to the Brinell hardness scale of HBW 10/3000, with a ball diameter of 10 mm (0.39 in.) and a nominal force of 3000 kg (6,614 lb).

For both hardness methods, each test consists of an average of three measurements per location. We tested each material at an ambient temperature of 67°F (19.4°C).

4.5.3 Test Results

The test results are listed in Table 4.5-1; individual test results are included in Appendix H. Table 4.5-1 also shows the tensile strengths we measured for each material. The relative ranking of material hardness is similar to the ranking of measured tensile strengths.

For the plain Threadbar®, Custom 450, and Custom 630, we did not measure a significant difference in hardness between the near-surface and center of the bar.

For the galvanized Threadbar®, we measured the near-surface of the bar to be 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 Threadbar®.

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.

Table 4.5-1 – Hardness test results

Material	Rockwell Hardness				Brinell Hardness	Measured Tensile Strength (ksi)
	Depth From Surface (R – bar radius)			Average Hardness		
	0.1R	0.45R	0.8R			
Threadbar® – Plain	34	37	34	35	363	166
Threadbar® – Galvanized	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

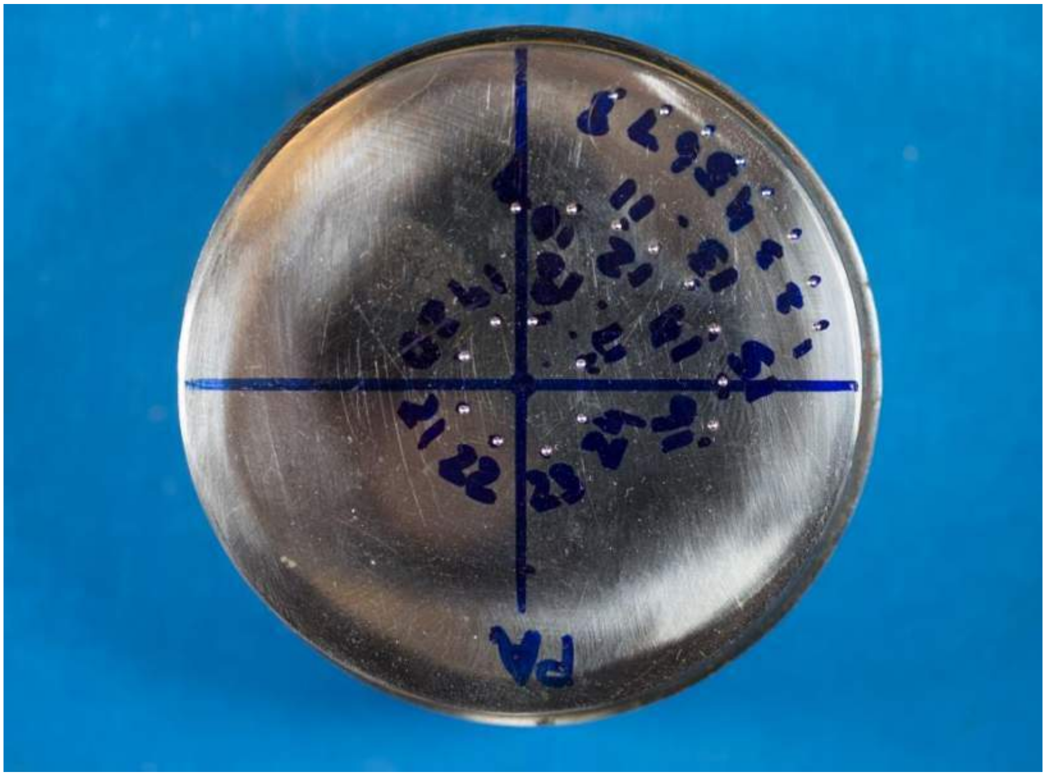


Figure 4.5-1 – Sectioned bar showing tested hardness locations (plain Threadbar® shown).

4.6 Charpy V-Notch (Toughness)

4.6.1 Test Standards

We measured the Charpy V-Notch (impact) toughness of the materials according to ASTM E23 – *Standard Test Methods for Notched Bar Impact Testing of Metallic Materials* [2016]. We conducted this testing at Massachusetts Materials Research, West Boylston, Massachusetts.

4.6.2 Test Methods

We cut samples from the roll-threaded bars oriented along the axis of the bar, at an approximate mid-sample depth of 0.5 in. (12.7 mm). We machined samples to 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 with a standard 45° V-notch, with a depth of 2 mm (0.079 in.) and a notch tip radius of 0.025 mm (1 mil.), in each specimen. Note that we tested both full-sized and sub-sized specimens to compare these values to historical DOT data.

AASHTO LRFD Article 6.6.2 and Table 6.6.2-1 [2012] specifies three temperature zone designations for Charpy V-Notch requirements. We selected a minimum service temperature for the anchorage bars of -30°F (-34.4°C), which corresponds to the low temperature for Zone 2 according to the requirements of AASHTO LRFD Table 6.6.2-1 [2012] and ASTM A709 – *Standard Specification for Structural Steel for Bridges* [2016]. We also tested the samples 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. Each result consists of an average of three specimens per temperature condition.

4.6.3 Test Results

The test results are listed in Table 4.6-1. Figures 4.6-1 to 4.6-4 show the relationship between absorbed energy and temperature from the Charpy V-Notch testing. Typical fracture specimens are shown in Figures 4.6-5 and 4.6-6 for plain Threadbar® and Alloy 2507, respectively. Appendix J contains photographs of the fractured cross sections and the test reports from Massachusetts Materials Research.

Both the plain and galvanized Threadbar® had the lower impact toughness across all temperatures. Galvanizing appears to slightly increase the impact toughness of this material. The Threadbar® specimens had approximately half the impact energy at the lowest test temperature.

Custom 450 and Custom 630 have slightly greater impact toughness than the Threadbar®, and showed similarly that the impact energy is halved by decreasing the test temperature.

The Alloy 2507 exhibited significantly higher impact toughness with no significant change in the impact energy with decreasing test temperature.

Table 4.6-1 – Charpy V-Notch test results

Material	Absorbed Energy (ft-lbs)					
	Full-sized specimens			Sub-sized Specimens		
	Test Temperature					
	90°F	68°F	-30°F	90°F	68°F	-30°F
Threadbar® – Plain	31	22	16	29	25	12
Threadbar® – Galvanized	45	36	18	33	23	13
Custom 450 H1050	59	53	27	46	40	21
Custom 630 H1100	55	46	24	38	34	16
Alloy 2507	264	264	261	231	221	201

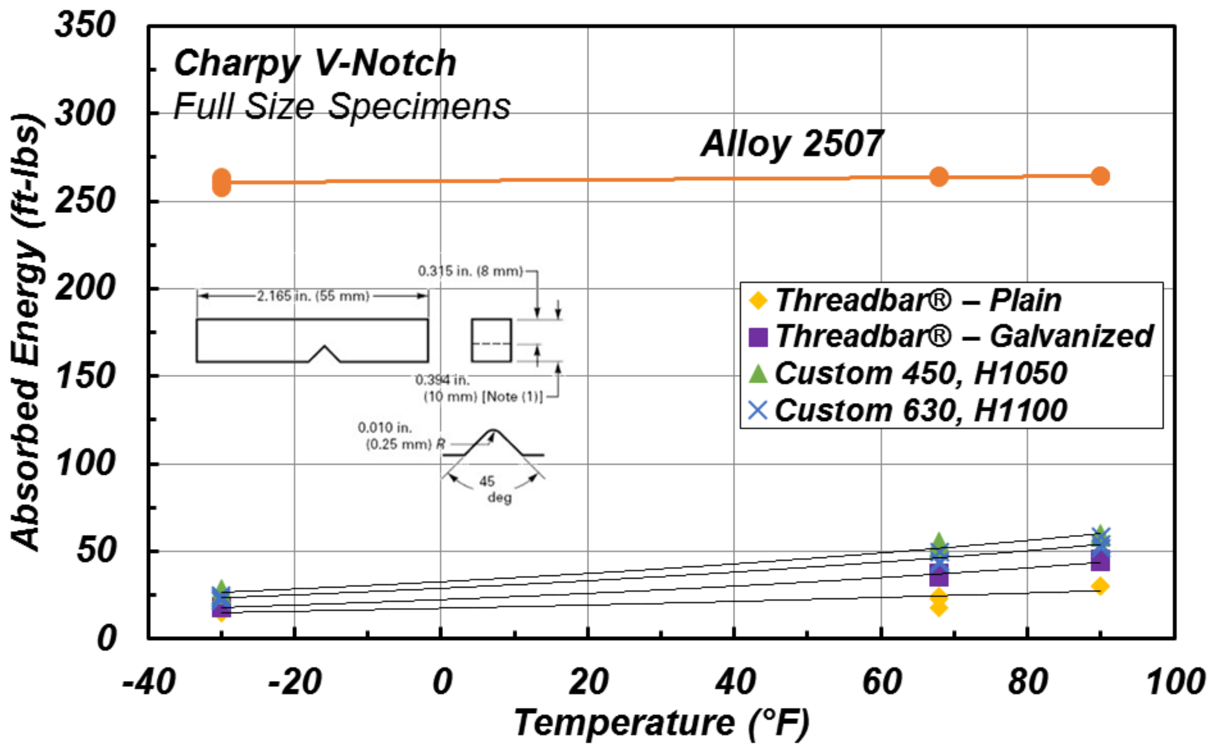


Figure 4.6-1 – Charpy V-Notch, full-size specimen test results (entire range).

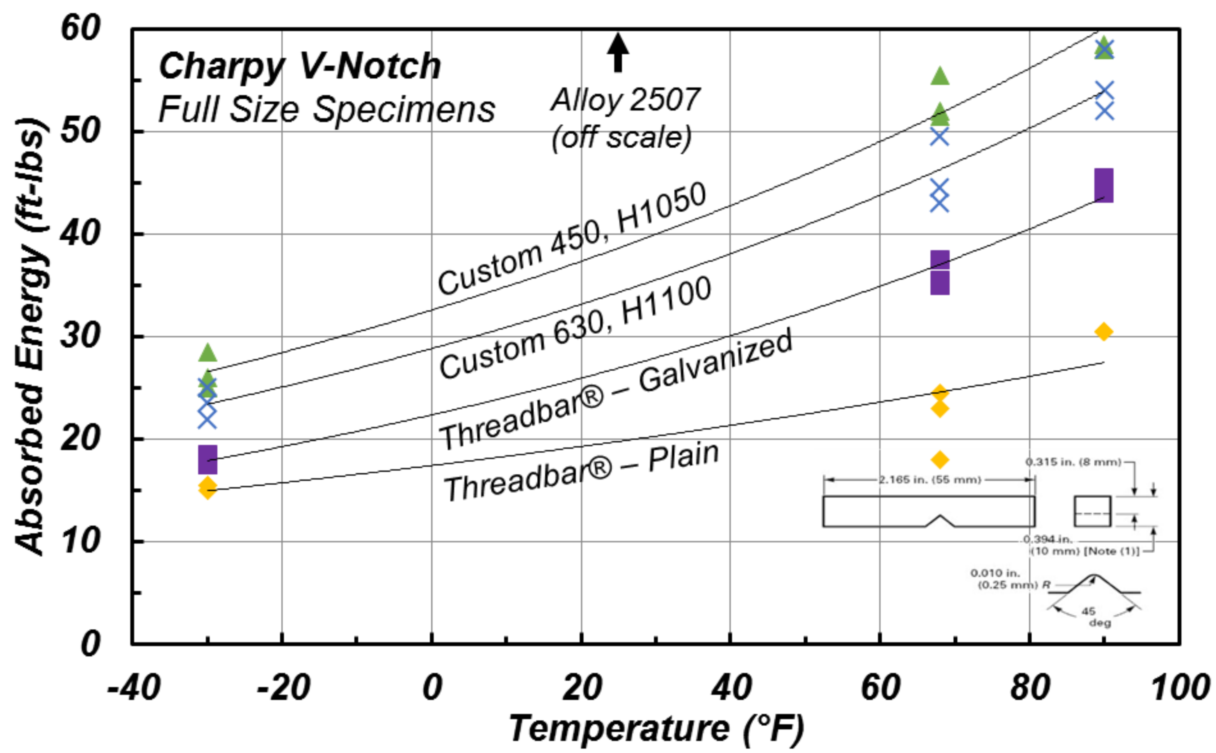


Figure 4.6-2 – Charpy V-Notch, full-size specimen test results (low range).

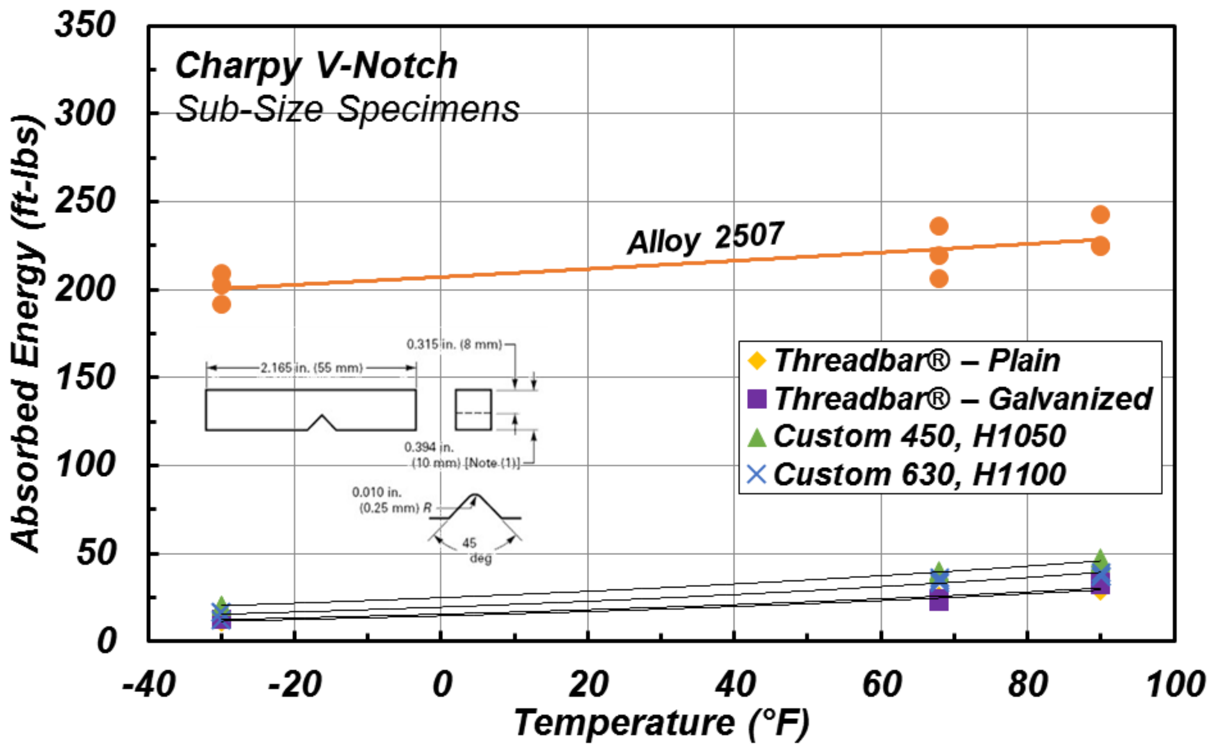


Figure 4.6-3 – Charpy V-Notch, sub-size specimen test results (entire range).

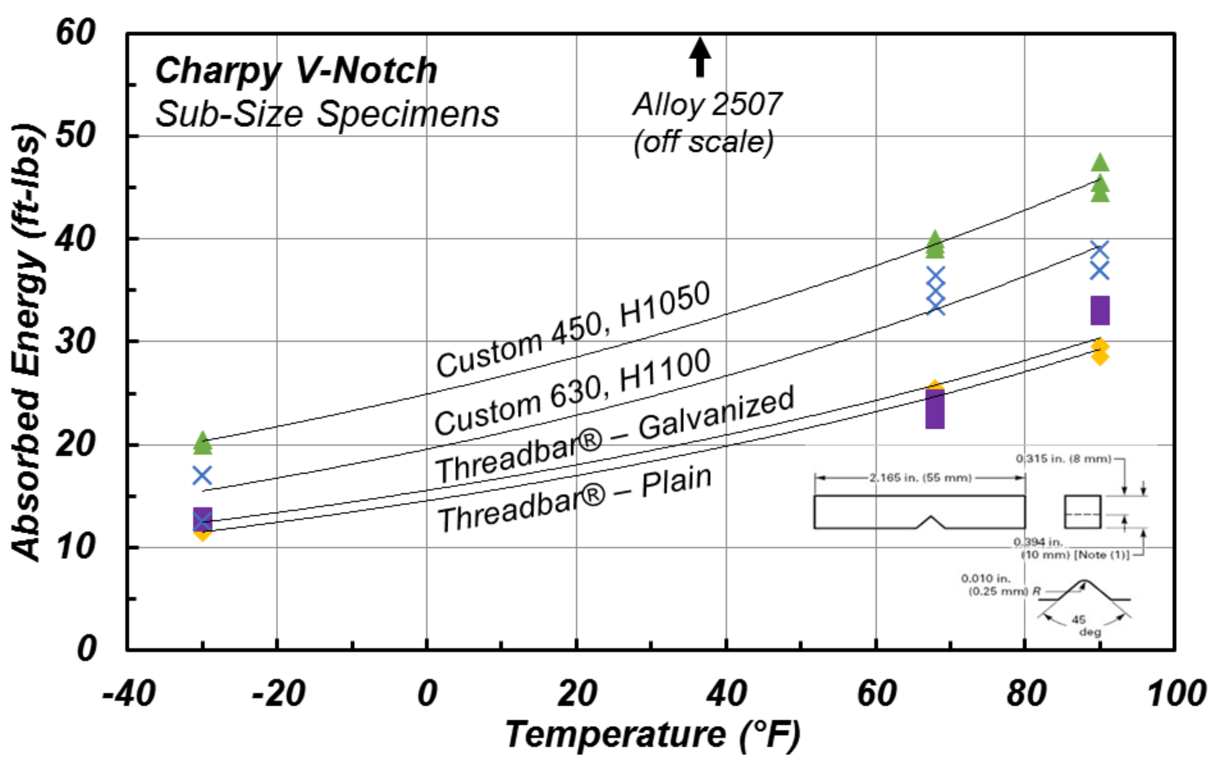


Figure 4.6-4 – Charpy V-Notch, sub-size specimen test results (low range).

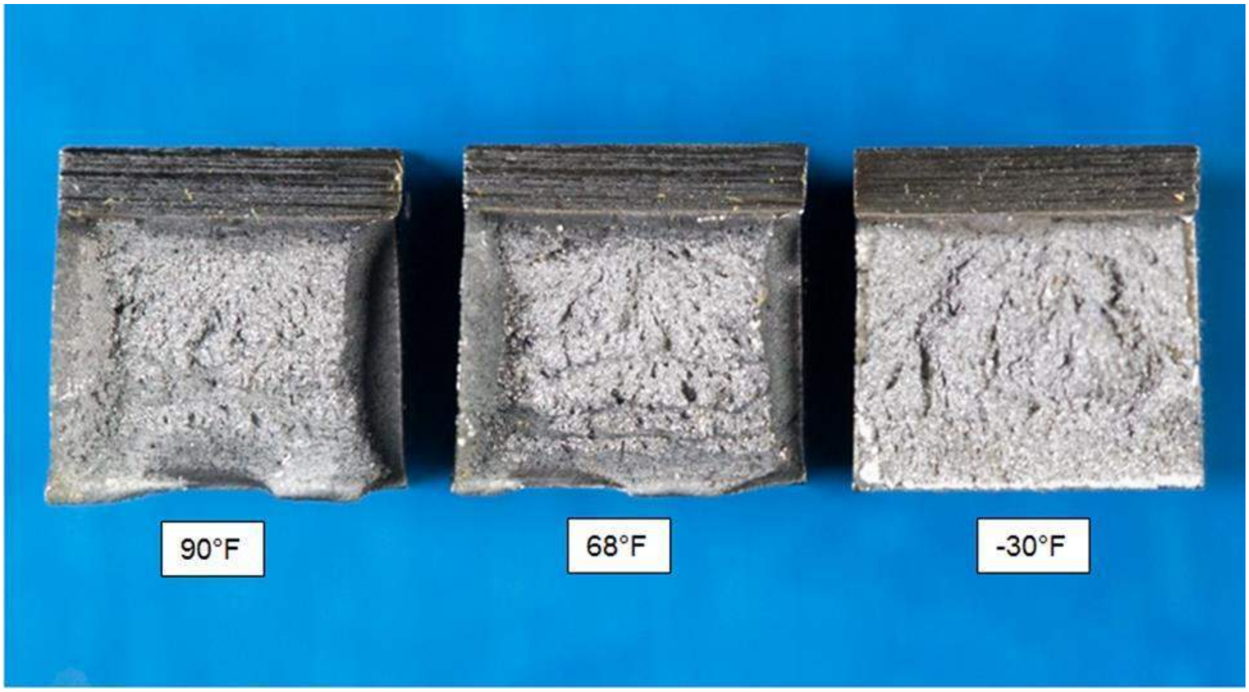


Figure 4.6-5 – Charpy specimen fractures surfaces for plain Threadbar®.

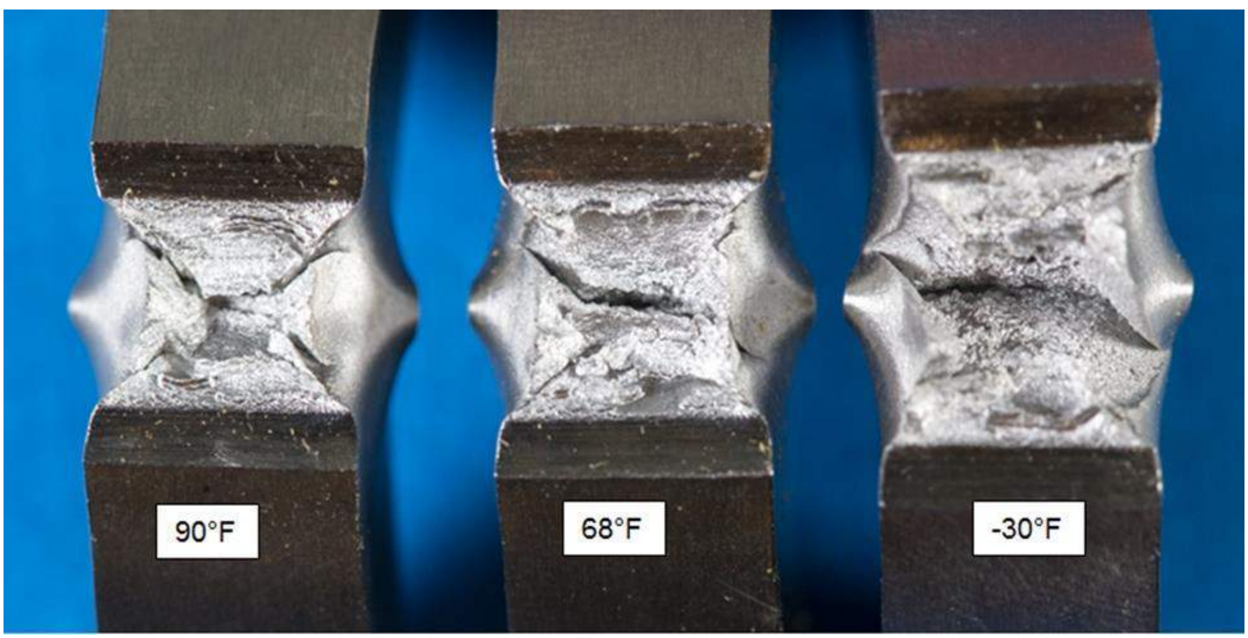


Figure 4.6-6 – Charpy specimen fractures surfaces for Alloy 2507. (Note: the samples did not break at any of the test temperatures)

4.7 Galling

4.7.1 Test Standards

We measured the threshold galling stress of the materials according to ASTM G98 – *Standard Test Method for Galling Resistance of Materials* [2009]. We conducted this testing at our laboratory in Waltham, Massachusetts.

4.7.2 Test Methods

We cut samples from roll-threaded bars close to the center of the bar. We machined cylindrical buttons with a test surface diameter of 0.5 in. (12.7 mm). We machined a matching flat test bar with a diameter of 1.5 in. (38.1 mm) and ground using silicon carbide paper to a surface finish of 1200 grit. We cleaned the test surfaces using acetone immediately prior to testing.

We conducted the galling test at ambient temperature of 68°F (20°C) using a screw-driven MTS® 30-G test machine and a manual turning system. Figure 4.7-1 shows a schematic of the test setup. At the start of each test, we loaded the test button against the test bar to the target load. We then manually rotated the test button by one revolution using a steady rotation rate and a time of approximately ten seconds. After each test, we inspected the test surfaces using a stereomicroscope to determine whether galling had occurred. We repeated the test on new specimens with increasing load increments until we observed galling. We then calculated the threshold galling stress.

We did not conduct the galling test on a galvanized Threadbar®, because this test is performed on machined samples independent of the galvanizing process.

4.7.3 Test Results

The test results are listed in Table 4.7-1; individual test results for each test are listed in Appendix K. Typical tested specimens are shown in Figure 4.7-2. The carbon steel Threadbar® has a slightly higher threshold galling stress. Note that galling is a subjective test, and our threshold galling stress measurements were lower than other published data. However, we did not measure a significant variation in resistance to galling for any of the materials. For one material to have a significant difference in galling compared to another, it would be expected to have an order of magnitude increase in the threshold galling stress.

Table 4.7-1 – Threshold galling stress results

Material	Galling Stress (ksi)
Threadbar® – Plain	0.9
Custom 450 H1050	0.6
Custom 630 H1100	0.5
Alloy 2507	0.7

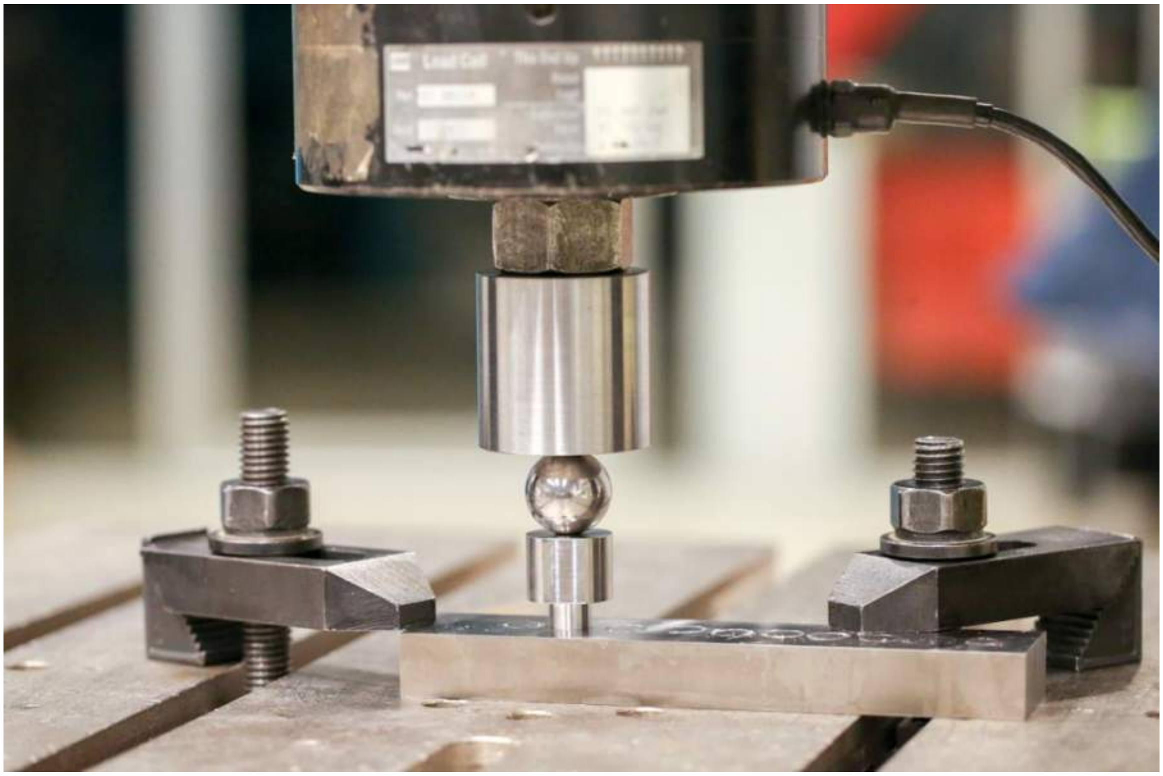


Figure 4.7-1 – Galling test setup.

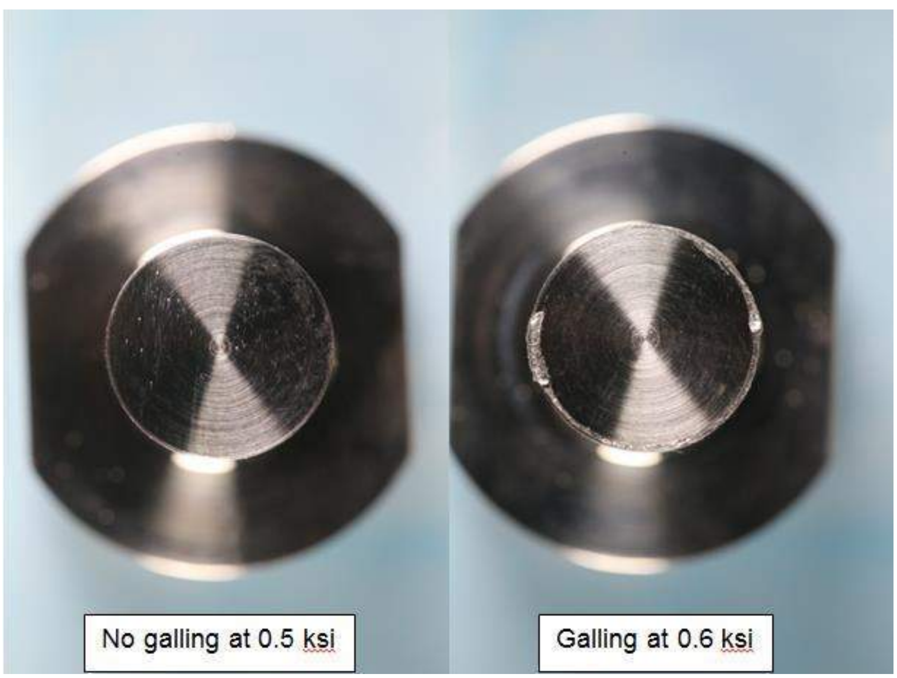


Figure 4.7-2 – Typical galling test specimens (Custom 450 H1050 shown).

4.8 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 Threadbar® does not have a passive surface layer like the stainless steels and corrodes by a general, surface corrosion mechanism rather than by pitting.

4.8.1 Test Standards

We measured the resistance to pitting corrosion of the materials according to ASTM G48 – *Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution* [2011]. We used Method E - Critical Pitting Temperature Test for Stainless Steels. We conducted this testing at our laboratory in Waltham, Massachusetts.

The critical pitting temperature is used to rank the resistance of materials to pitting corrosion in chloride environments. It can be supplemented by long-term exposure tests in the intended (chemical and temperature) environment of the application.

4.8.2 Test Methods

We cut 3/4 in. x 1-1/2 in. x 1/4 in. (19.1 x 38.1 x 6.4 mm) samples from close to the center of the roll-threaded bar. The sample surface was oriented normal to the bar axis. We ground the surface of each sample using silicon carbide paper to a finish of 240-grit using silicon carbide paper. Prior to testing, we passivated the stainless steel samples in a nitric acid solution for twenty minutes, according to ASTM A967 - *Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts* [2013].

We suspended samples in individual beakers using a glass cradle and immersed each in 200 ml (6.8 oz.) of acidified 6 wt.% ferric chloride test solution (Figure 4.8-1). We used an incubator to keep these samples at the desired test temperature for a period of 24 hrs. After the test period, we removed each sample and inspected the surface using a stereomicroscope, and measured the pit depth using needle-pointed calipers to determine whether pitting corrosion had occurred. According to the ASTM G48, pitting occurs if the pit depth is greater than 1 mil.

We tested the samples at increasing temperature intervals of 10°C (18°F) from 0°C (32°F) up to a maximum of 85°C (185°F). If pitting occurred, we repeated the test at a lowered test temperature of5°C (9°F) to more precisely determine the critical pitting temperature.

We did not conduct the pitting corrosion test on a galvanized Threadbar®, because this test is performed on machined samples independent of the galvanizing.

4.8.3 Test Results

The test results are listed in Table 4.8-1 and typical specimen results are shown in Figure 4.8-2. The plain Threadbar® did not fail by pitting corrosion; however, it was substantially corroded on the surface.

The Custom 450 and Custom 630 failed the test at low critical pitting temperatures.

Alloy 2507 clearly demonstrated the highest critical pitting temperature and resistance to pitting corrosion.

Table 4.8-1 – Critical Pitting Temperature results

Material	Critical Pitting Temperature (°F)
Threadbar® – Plain	No pitting, but heavily corroded at ≥32°F
Custom 450 H1050	50
Custom 630 H1100	32
Alloy 2507	185

Figure 4.8-1 – Pitting corrosion test setup.

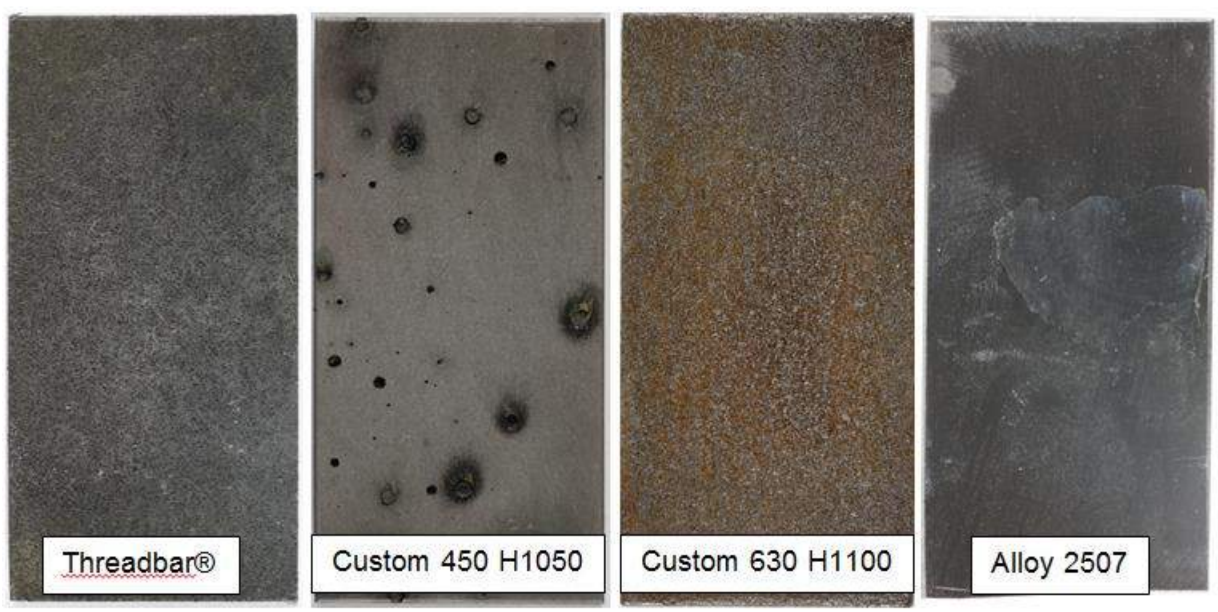


Figure 4.8-2 – Typical pitting corrosion test specimens (test at 68°F (20°C)).

4.9 Stress Corrosion Cracking (SCC)

4.9.1 Test Standards and Methods

We measured the materials' resistance to SCC according to ASTM G123 - *Standard Test Method for Evaluating Stress-Corrosion Cracking of Stainless Alloys with Different Nickel Content in Boiling Acidified Sodium Chloride Solution* [2000]. We conducted this testing at Corrosion Testing Laboratories in Newark, Delaware.

We originally proposed SCC testing according to ASTM G49 – *Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens* [2011]. ASTM G49 covers the preparation of the test specimens and references ASTM G36 – *Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution* [2013] for the corrosive environment exposure. After additional literature review, we believe ASTM G123 is more relevant for stainless steels than the ASTM G36 boiling manganese chloride test, as the sodium chloride solution is less aggressive, allowing a longer time to failure and hence improved differentiation between different materials.

4.9.2 Test Methods

We machined C-ring specimens from each material with a diameter of 62 mm (2.44 in.), width of 21 mm (0.83 in.), and wall thickness of 1.5 mm (0.06 in.). Figure 4.9-1 shows a typical test setup. We loaded each sample using corrosion-resistant bolts and ceramic insulators to a nominal 85% of the yield stress (derived from material product sheets). The applied stresses are listed in Table 4.9-1.

We calculated the necessary ring deformation to produce the required load according to ASTM G38 - *Standard Practice for Making and Using C-ring Stress-Corrosion Test Specimens*, Annex A1 [2013].

We tested four specimens per material, using a different test vessel for each material. We prepared a test solution of 25% sodium chloride, acidified to a pH of 1.5. We heated two liters of test solution in each vessel to boiling point (approximately 230°F (110°C)) and immersed the test samples for a period of up to 2 wks. We inspected the samples every 6 hrs during the first 24 hrs of exposure, then daily afterwards. We removed any observed cracked specimens from exposure.

We did not conduct SCC testing on a galvanized Threadbar® because this test is performed on machined samples independent of the galvanizing. The galvanizing would not be expected to impact the stress corrosion cracking resistance of the Threadbar® material.

4.9.3 Test Results

The test results are listed in Table 4.9-2. The test report from Corrosion Testing Laboratories in included in Appendix M. Example tested specimens are shown in Figure 4.9-2.

The carbon steel Threadbar® and Alloy 2507 did not exhibit susceptibility to SCC, although the Threadbar® was heavily corroded by this test.

The Custom 450 and Custom 630 perform poorly in SCC testing, exhibiting a susceptibility to corrosion and cracking in the test environment after only a short duration.

Table 4.9-1 – Stress Corrosion Cracking Test Specimen Applied Stress

Material	Yield Stress from Material Data Sheet (ksi)	Appled Stress (ksi)
Threadbar® – Plain	154	131
Custom 450 H1050	158	134
Custom 630 H1100	150	128
Alloy 2507	95	81

Table 4.9-2 – Stress Corrosion Cracking results

Material	Time to Cracking	Appearance after Test
Threadbar® – Plain	Did not fail after 336 hrs (14 days)	Heavily Corroded, but uncracked
Custom 450 H1050	<6 hrs	Slightly corroded, and covered with cracks
Custom 630 H1100	<6 hrs	Slightly corroded, and covered with cracks
Alloy 2507	Did not fail after 336 hrs (14 days)	Uncorroded and uncracked

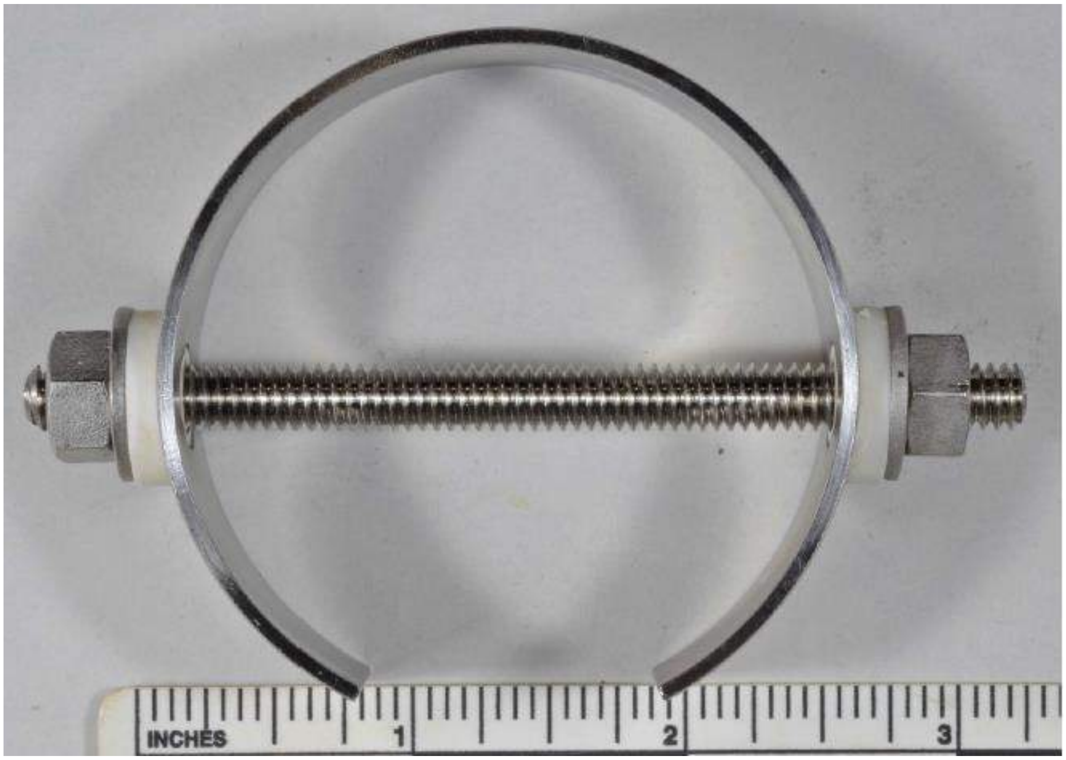


Figure 4.9-1 – Typical stressed SCC test specimen.

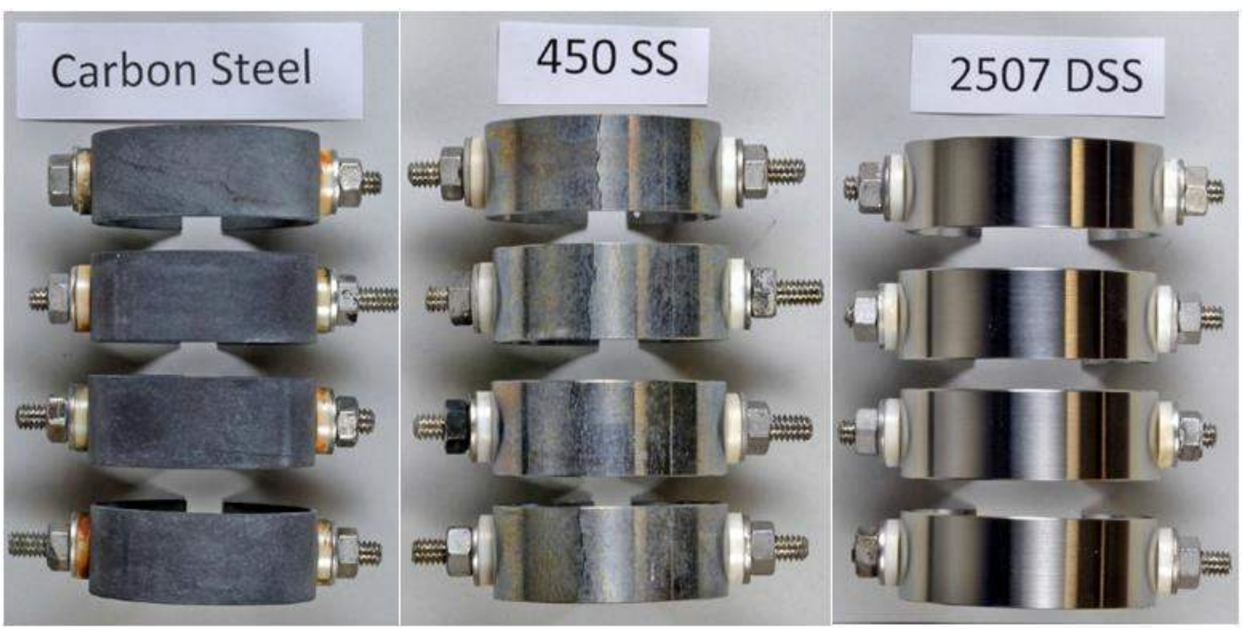


Figure 4.9-2 – Stress corrosion cracking specimens after testing.

4.10 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. We designed our testing to evaluate the susceptibility to hydrogen embrittlement and not to produce results for fracture mechanics calculations.

4.10.1 Test Standards

We conducted hydrogen embrittlement testing according to ASTM F1624 - *Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique* [2012]. This test method uses a rising step load protocol applied to a precracked specimen to determine the material's susceptibility to hydrogen cracking. We tested the susceptibility of each material to hydrogen cracking in both the as-received and hydrogen-charged conditions. We conducted hydrogen embrittlement testing at our laboratory in Waltham, Massachusetts.

4.10.2 Test Methods

Our test procedure consisted of the following steps: (1) machining the test specimen from the parent roll-threaded bar; (2) fatigue precracking the specimen; (3) hydrogen charging the specimen (for the hydrogen charged specimens); (4) measurement of hydrogen content; and (5) load testing the specimen.

We used fracture toughness test specimens with dimensions per ASTM E399 *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness* K_{IC} *of Metallic Materials* [2012]. We machined single-edge notch bend (SEB) specimens with a size of 0.75 x 1.5 x 6.5 in. (19.1 x 38.1 x 165 mm). We cut test samples from the center of the roll-threaded bar using Electrical Discharge Machining (EDM) and ground the surface of each test specimen to remove the oxide layer following EDM.

Our selected specimen size is too small to measure a valid K_{IC} fracture toughness value according to ASTM E1620. The size of the anchorage bars limited our sample size due to the high fracture toughness of the candidate materials. Since we designed our testing to evaluate the susceptibility to hydrogen embrittlement, we did not consider it necessary to obtain valid K_{IC} values.

Fatigue Precracking of Samples

We grew a sharp fatigue precrack at the notch root of each specimen according to ASTM E399 prior to hydrogen charging. We used a servo-hydraulic mechanical testing machine, with an R-ratio of 0.1 and load cycle of 200 to 2,000 lb (0.9 to 8.9 kN) at a frequency of 20 Hz in three point bending. The precracking test setup is shown in Figure 4.10-1. We observed the crack growth using a loupe, and grew each crack to the nominal length required. Typically, cracks took 50,000 to 100,000 cycles to reach the required length.

Charging Specimens with Hydrogen

In order to compare the fracture behavior of the materials with and without residual hydrogen, we charged select precracked SEB test specimens with hydrogen using an electrochemical technique at ambient temperature. No ASTM or other industry standards specify methods or durations for charging steel test specimens with hydrogen. We conducted a literature review of academic work to determine the appropriate charging conditions.

We ground the surface of each test specimen using silicon carbide paper to a finish of 600 grit prior to charging. We cleaned each specimen in an ultrasonic bath of methanol for five minutes, then pickled it in a 10% hydrochloric acid solution for five minutes, before washing in distilled water.

We applied a potential of 2 to 3 V between a mixed metal oxide (MMO) anode and the specimen (cathode) using a current density of approximately 55 mA/cm^2. The electrochemical charging setup is shown in Figure 4.10-2.

For the charging electrolyte, we initially used a 3.5% sodium chloride solution saturated with calcium carbonate. Although this charging method was satisfactory for the Threadbar® material, we found that it did not significantly charge the stainless steels with hydrogen, presumably due to the surface passive layer. Therefore, we switched to a 0.1 molar sulfuric acid solution, with an addition of 0.25 g/L of arsenic trioxide, a hydrogen recombination poison, that facilitates adsorption of hydrogen during electrochemical charging.

We electrochemically charged each applicable specimen for approximately 60 hrs. Once charging was completed, we washed the specimen in distilled water and tested it within 30 min. to avoid loss of hydrogen from the specimen by diffusion.

Measurement of Hydrogen Content

We verified the hydrogen content of the electrochemically charged specimens using a vacuum hot extraction method according to ASTM E146 - *Methods of Chemical Analysis of Zirconium and Zirconium Alloys (Silicon, Hydrogen, and Copper)* [1983].

We hydrogen charged similarly sized dummy samples of each material using identical methods and conditions as those used for the test specimens. Immediately after hydrogen charging was completed, we cut 1/4 x 1/4 x 1/4 in. (6.4 x 6.4 x 6.4 mm) samples for hydrogen measurement using a water-cooled abrasive wheel. We packed these test specimens in dry ice to minimize degassing by diffusion, and dispatched to a chemical testing laboratory (Luvak Inc., Boylston MA) to be tested within 12 hrs.

We tested samples from both the surface and center of the specimens, to verify that we had achieved uniform charging through the specimen.

Fracture Toughness Testing

For each material and condition, we conducted an initial fracture test by monotonically loading a specimen to fracture to establish the fast fracture load. We then conducted the rising step load test for the same material and condition using twenty equal steps to load the specimen to its nominal fracture load over a period of 60 hrs. This slow loading is designed to encourage hydrogen cracking in susceptible materials.

We conducted the fast fracture and rising step load testing according to ASTM F1624, using a 30 kip (133.4 kN) MTS® screw-driven test machine and a four-point bend fixture with a clip gauge to measure the crack opening displacement. The test setup is shown in Figure 4.10-3. For all tests, we used a crosshead displacement rate of 0.25 mm/min. (0.01 in/min).

For specimens tested using fast fracture loading conditions, we calculated the fracture toughness using the maximum load sustained. For specimens tested under rising step loading, we calculated the fracture toughness at the nominal load of the step prior to that at which the specimen failed, as prescribed by ASTM F1624.

4.10.3 Test Results

Table 4.10-1 shows the measured hydrogen content of the candidate materials. The results demonstrate that our hydrogen charging technique results in a uniform increase through the specimens for the Threadbar® material only. However, for the Custom 450, Custom 630, and Alloy 2507 materials, only the surface of the material (to a depth of up to 0.25 in.) has any significant increase in hydrogen.

Figure 4.10-4 shows a typical load-displacement curve for both fast fracture and rising step load testing. Appendix N contains load-displacement curves for each test, together with images of each fracture surface.

We measured the fatigue precrack length from the fracture surface faces and calculated the Threshold K_{IC} values according to ASTM E399. The results are listed in Table 4.10-2.

For the Threadbar® material, the hydrogen charging produced a severe decrease in the fracture toughness of the sample, from 136 to 17 ksi√in. We did not detect any significant difference in the fracture behavior of the Threadbar® material between the plain and galvanized forms.

For the Custom 450 and Custom 630 materials, there was a moderate decrease in the fracture toughness from 136 to 117 ksi√in. from hydrogen charging.

We found the fracture toughness of the Alloy 2507 unaffected by hydrogen charging.

Table 4.10-1 – Measured Hydrogen Content of Test Specimens (ppm)

Material	Uncharged Specimen	60 hr charging, Measurement at Center	60 hr charging, Measurement at Surface
Threadbar® – Plain	0.3	3.5	4.1
Threadbar® – Galvanized	0.5	N/A	N/A
Custom 450 H1050	1.0	1.4	31.3
Custom 630 H1100	1.1	1.8	18.8
Alloy 2507	1.4	1.4	5.2

Table 4.10-2 – Threshold K_I Fracture Toughness Values for ASTM F1624 Testing (ksi√in.)

Material	Uncharged Specimen		Hydrogen Charged Specimens	
	Fast Fracture	Rising Step Load	Fast Fracture	Rising Step Load
Threadbar® – Plain	136	N/A	43	15
Threadbar® – Galvanized	143	94	N/A	N/A
Custom 450 H1050	154	N/A	137	119
Custom 630 H1100	135	N/A	133	114
Alloy 2507	148	N/A	154	145

Figure 4.10-1 – Pre-cracking Test Setup.

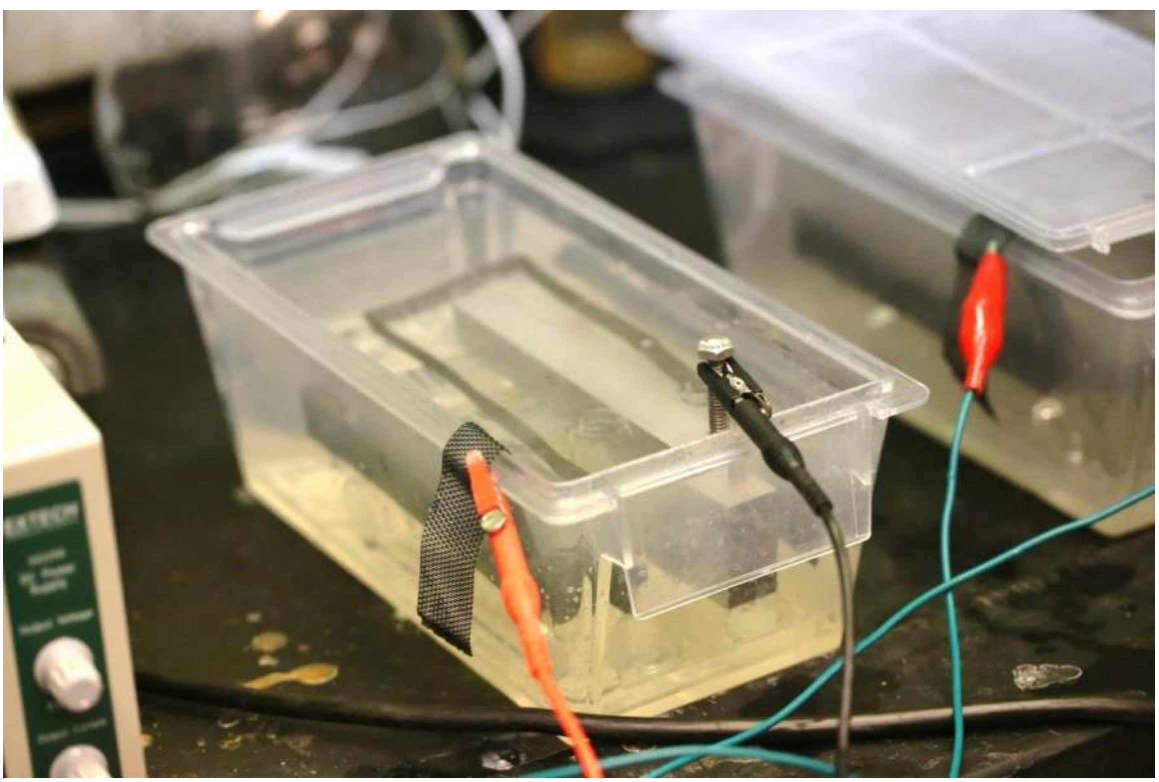


Figure 4.10-2 – Electrochemical Charging Setup.

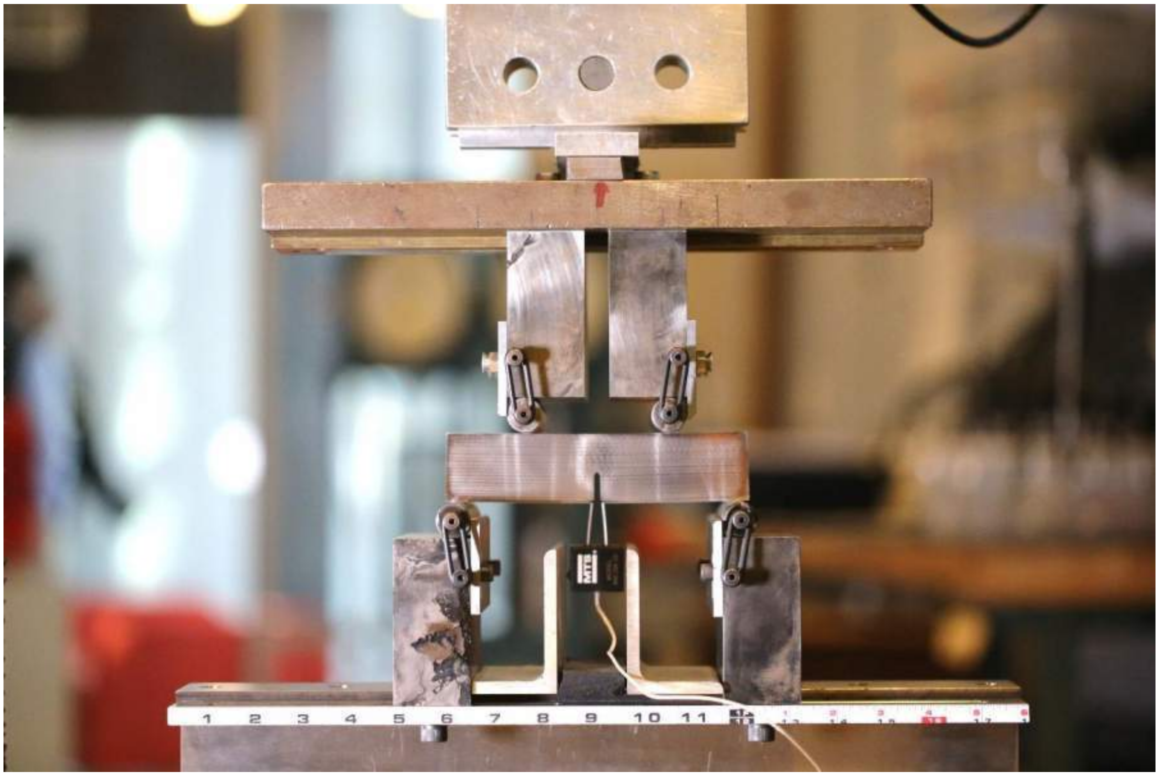


Figure 4.10-3 – Rising Step Load Fracture Toughness Test Setup.

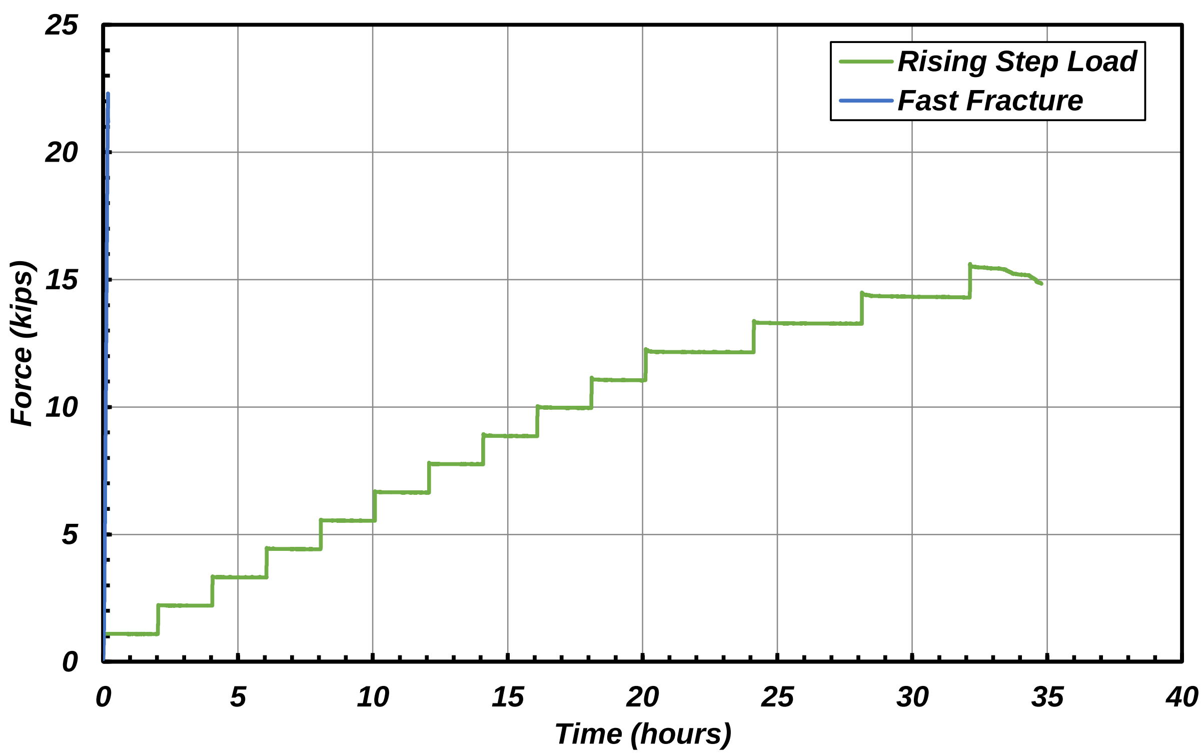


Figure 4.10-4 – Typical Load-Displacement Plots for Rising Step Load Testing (shown for Custom 450, hydrogen charged).

4.11 Inelastic Behavior of Alloy 2507

Initial results on the Alloy 2507 demonstrated favorable behavior and characteristics; in particular, the corrosion testing indicated superior performance of Alloy 2507. However, its lower strength and roundhouse stress-strain behavior at a low stress level necessitated additional study.

Alloy 2507 has a monotonic stress-strain behavior that is different from the other carbon and stainless steels of this study (see Figures 4.1-2 and 4.1-3). The initial elastic portions of the stress-strain curve only extend to about 40 ksi (276 MPa) where the material begins to rollover into the nonlinear range. The yield point defined by the 0.2% offset is well within the nonlinear range of the material. The implications of this differing behavior required further experimental testing to validate the behavior of Alloy 2507 under simulated loading from the actual bridge application.

We worked with the M&M bridge designers to better understand the initial prestress load and design forces on the actual bars in service. The pretension force applied to the anchorage bar during installation and jacking will stress the material into the non-linear part of the stress-strain curve. The pretension force after losses will be less than this initial jacking force; however, we understand from M&M the expected design forces on the anchorage bars will exceed the pretension force after losses. The typical forces on the anchorage 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.

We based our initial evaluation of the performance of Alloy 2507 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 anchorage 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 confirm Alloy 2507 exhibits stable linear shakedown and is a viable material for the anchorage bar application, we evaluated the material’s inelastic behavior by conducting a series of cyclic tests on several specimens at varying stress and strain levels in the nonlinear range. We did not conduct similar inelastic behavior tests on the other candidate materials because the stress-strain relationship of those materials is similar to materials commonly used in this type of application.

4.11.1 Test Standards

We conducted inelastic behavior testing on both full-size and reduced-size specimens. Full-size specimens were used to evaluate the performance on a scale similar to the actual anchorage bar size, whereas reduced-size specimens were used to evaluate the performance under a larger number of load cycles.

We performed inelastic behavior testing similar to the requirements in ASTM E606 – *Standard Test Method for Strain-Controlled Fatigue Testing* [2012] and ASTM E466 – *Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials* [2015]. We did not follow either test method in every detail, as we did not perform high frequency fatigue testing; rather we used these standards to formulate the test protocol. We conducted the testing according to the protocols in ASTM A370 [2017].

Full-size specimen testing was conducted at the Bowen Structural Engineering Laboratory at Purdue University in West Lafayette, Indiana. We conducted testing on reduced size specimens at our structural laboratory in Waltham, Massachusetts.

4.11.2 Test Methods

Full Size Specimens

For full size specimens, we conducted two tests: one on a 12 ft long bar from prior relaxation testing, and one on a pair of 6 ft long bars coupled to form a 12 ft long test specimen. The test setup used the frames fabricated for relaxation testing for this program. Each test consisted of a 12 ft long test specimen (both solid and coupled) inserted through the relaxation frame. The gage length of the threaded bar between end nuts was 112.5 in. (2.9 m), similar to relaxation testing. The test specimen was coupled to a 6 ft long tail bar that passed through the center-hole ram and load cell for stressing. The hydraulic controls for the ram prevented steady loading and unloading of the test specimen; however, we worked to load and unload the specimen in a controlled manner with as consistent a load rate as possible.

We used vibrating-wire gage load cells to monitor load at the dead end of the test specimen. The vibrating-wire load cells require a discreet input signal for each measurement, and, therefore, do not provide continuous load readings. For real-time load readings, we installed a strain gage-based load cell to monitor load at the outside end of the tail bar near the ram. We installed a pressure transducer within the ram hydraulic system to measure pressure to calculate an approximate real-time force from the ram. Each test frame column was also instrumented with a strain gage, applied at approximately the neutral axis of the HSS cross section, to measure an average strain. We used the average strain on the HSS section to calculate an approximate force in the test frame, and accordingly an approximate force resisted by the test specimen.

Each indicator of force (load cells, pressure transducer, and strain gage) has a limitation that prevented using one throughout the test. The vibrating wire load cell does not provide real-time continuous recording of load. The strain gage load cell did not provide continuous readings, as it was installed along the tail bar, which is completely unloaded during unload cycles. The pressure transducer is less accurate than load cells. The HSS strain gages are dependent on the strain profile throughout the cross section and susceptible to strain gradients. We used the various force indicators at different stages to determine the effective force in the anchorage bars during the testing. We relied on the HSS strain gages for data reporting as the only source providing continuous measurement. The calculated force from strain data is inherently inaccurate compared to a calibrated load cell.

For the 12 ft specimen from prior relaxation, we used a specimen previously loaded to 483 kips (2,148 kN), or approximately 83.9 ksi (578 MPa). We conducted the test using the following protocol (Figure 4.11-1 shows the force versus time plot during the load cycles):

- Load the specimen to an initial jacking load of 464 kips (2,064 kN), which equals an approximate jacking stress of 80 ksi (552 MPa).

- Reduce the force in the specimen to a seating load of 391 kips (1,740 kN), or approximately 68 ksi (469 MPa). We used this force as the baseline value for subsequent cyclic testing on this specimen.

- Increase the force to approximately 410 kips (391 kips + 5%) (1,824 kN), capture a load reading, and unload to the seating load. Repeat this protocol for five (5) total cycles. Load cycling then proceeded as follows:

- Maximum force applied to approximately 430 kips (391 kips + 10%) (1,913 kN) – load-unload cycling five times.
- Maximum force applied to approximately 450 kips (391 kips + 15%) (2,002 kN) – load-unload cycling five times.
- Maximum force applied to approximately 469 kips (391 kips + 20%) (2,086 kN) – load-unload cycling five times.
- Maximum force applied to approximately 508 kips (391 kips + 30%) (2,260 kN) – load-unload cycling five times.

For the two coupled 6 ft specimens, we conducted the test using the following protocol (Figure 4.11-2 shows the force versus time plot during the load cycles):

- Load the specimen to an initial jacking load of 449 kips (1,997 kN), which equals an approximate jacking stress of 78 ksi (538 MPa).

- Reduce the force in the specimen to a seating load of 399 kips (1,775 kN), or approximately 69 ksi (476 MPa). At this force, we tightened the end nut at the jacking end of the test specimen to fix the length of the test section. We used this length as the baseline value for subsequent cyclic testing on this specimen.

- Increase the force to approximately 419 kips (399 kips + 5%) (1,864 kN), capture a load reading, and unload to the seating load. Repeat this protocol for five total cycles. Load cycling then proceeded as follows for seven total increments:

  - Maximum force applied to approximately 439 kips (399 kips + 10%) (1,953 kN) – load-unload cycling five times.
  - Maximum force applied to approximately 459 kips (399 kips + 15%) (2,042 kN) – load-unload cycling five times.
  - Maximum force applied to approximately 479 kips (399 kips + 20%) (2,131 kN) – load-unload cycling five times.
  - Maximum force applied to approximately 499 kips (399 kips + 25%) (2,220 kN) – load-unload cycling five times.
  - Maximum force applied to approximately 519 kips (399 kips + 30%) (2,309 kN) – load-unload cycling five times.
  - Maximum force applied to approximately 559 kips (399 kips + 40%) (2,487 kN) – load-unload cycling five times.

Reduced-Size Specimens

We conducted the following tests 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.

Standard round tension test specimens were machined according to ASTM E8 [2016] from a roll-threaded bar oriented along the longitudinal axis of the bar. The specimens had a test section diameter of 0.5 in. (12.7 mm) and gage length of 2 in. (50.8 mm). For these specimens, we used an Instron® servo-hydraulic universal testing machine and an MTS® electromechanical (screw-driven) Universal Testing Machine. Strain measurements were made with an external extensometer clipped to the specimen. We conducted monotonic tensile testing according to ASTM A370 [2017] using the Instron® under strain control at a strain rate of 0.0005 in./in./min., which corresponds to a displacement rate of 0.001 in./min. (0.025 mm/min.)

We conducted stress relaxation followed by monotonic tensile testing using the MTS® under crosshead displacement control. We initially loaded the specimen for stress relaxation testing at a cross-head displacement rate of 0.05 in./min. (1.27 mm/min.) We conducted the monotonic tensile test at a cross-head displacement rate of 0.01 in./min. (0.25 mm/min.) To conduct this test, we initially loaded the specimen to a stress of 75 ksi (517 MPa) and held the initial crosshead displacement (0.16071 in. (4.1 mm)) at this stress for approximately 66 hours. We then loaded the specimens to failure according to ASTM A370.

We conducted cyclic tensile testing with increasing strain increments using the Instron® under strain control at a strain rate of 0.025 in./in./min, which corresponds to an extension rate of 0.05 in./min. We conducted this test using the following protocol (Figure 4.11-3 shows the stress versus time plot during the load cycles):

- We loaded the specimen to a jacking stress of 80.6 ksi (556 MPa) and held the strain (0.00297 in./in.) at this initial stress for 15 sec. The jacking stress represents the anticipated jacking load on the full size bar.

- We decreased the test to a lock-off stress value of 67.9 ksi (468 MPa) and held the strain (0.00269 in./in.) at this stress for 15 sec. We used this strain as the baseline value for subsequent cyclic testing on this specimen. The lock-off stress represents the approximate pretension after losses of the full size bar.

- We increased the stress to 71.3 ksi (67.9 ksi + 5%) (492 MPa) and held the initial strain (0.00281 in./in.) at this stress for 15 sec. Using the strain values at 67.9 ksi and 71.3 ksi, we determined the strain increase corresponding to a 5% stress increase to be 0.00013 in./in. We used this strain value as our step-increment for subsequent cyclic testing on this specimen.

- We cycled the specimen in 5% strain increments for 14 total increments (+5% to +70%). We cycled each increment ten times using a holding time of 2.5 sec at each strain limit.

We conducted stress relaxation followed by cyclic tensile testing at constant strain increment using the Instron® under strain control at a strain rate of 0.025 in./in./min, which corresponds to an extension rate of 0.05 in./min. We conducted this test using the following protocol:

- We loaded to a stress of 90 ksi (621 MPa) and held the initial strain (0.00328 in./in.) at this stress for approximately 66 hours. This initial stress represents an overjacking stress for the bars for the design application with a jacking force higher than the maximum anticipated design force.

- We decreased the stress to a lock-off stress value of 49.5 ksi (341 MPa) and held the strain corresponding to this stress (0.00245 in./in.) for 15 sec. We used this strain as the baseline value for subsequent cyclic testing on this specimen. This stress represents a worst-case effective pretension after losses.

- We increased the stress to 76.5 ksi (527 MPa) and held the strain corresponding to this stress (0.00340 in./in.) for 15 sec. We used this strain value as our increment for subsequent cyclic testing on this specimen.

- We cycled the specimen at the strain increment (0.00245 in./in. to 0.00340 in./in.) for 1,000 cycles using a holding time of 2.5 sec at each strain limit.

4.11.3 Test Results

Full Size Specimens

Figure 4.11-4 shows the stress versus strain for the 12 ft. specimen subjected to cyclic tensile testing with increasing strain increments. The specimen remained stable with consistent stress-strain behavior until the test exceeded the previous jacking stress of 83.9 ksi from the prior relaxation testing.

Figure 4.11-5 shows the stress versus strain for the two, coupled 6 ft. specimens subjected to cyclic tensile testing with increasing strain increments. The specimen remained stable with consistent stress-strain behavior until the test exceeded the previous jacking stress of 78 ksi (538 MPa). Above this stress, each group of cycles at a higher load level exhibited repetitive behavior with some loss of pretension over the five cycles.

Reduced Size Specimens

Figure 4.11-6 shows the stress versus strain curve from monotonic tensile testing. The extensometer reached its maximum opening displacement before the specimen reached ultimate tensile loading.

In the 66-hr relaxation test in the MTS® machine, the initial jacking stress decreased to approximately 71.2 ksi (491 MPa). Figure 4.11-6 also shows the tensile behavior of the relaxed specimen overlain with the tensile behavior of an unrelaxed specimen. We believe the slight increase in tensile strength for the bar subjected to relaxation is due to the rate of loading of the MTS® machine compared to the Instron®. The test data does not indicate if relaxation causes a shift in the stress-strain behavior.

Figure 4.11-7 shows the stress versus strain for the specimen subjected to cyclic tensile testing with increasing strain increments along with the monotonic tensile stress-strain curve. For the initial two groups of cycles where the stress remained less than the initial jacking stress, the behavior remained stable. When the stress exceeded the initial jacking stress, some loss of initial pretension occurred with each increment.

For the 66-hr relaxation test in the Instron® machine, the initial jacking stress decreased to approximately 73 ksi (503 MPa). We believe some of this loss is likely due to the loss of hydraulic pressure in the test frame. Figure 4.11-13 shows stress versus strain for the specimen subjected to cyclic tensile testing at a constant strain increment. We observed no appreciable decrease in stress (less than 1%) at the tested strain limits after 1,000 cycles.

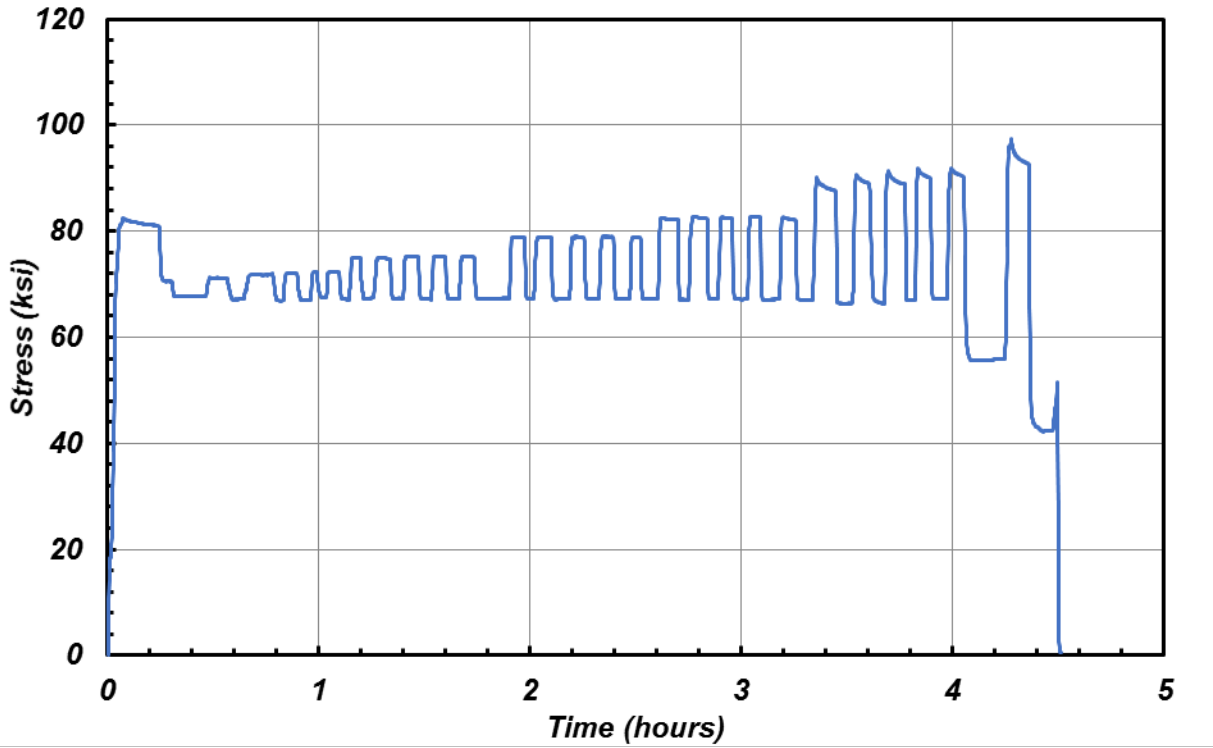


Figure 4.11-1 – Force versus time for full-size test of 12 ft specimen.

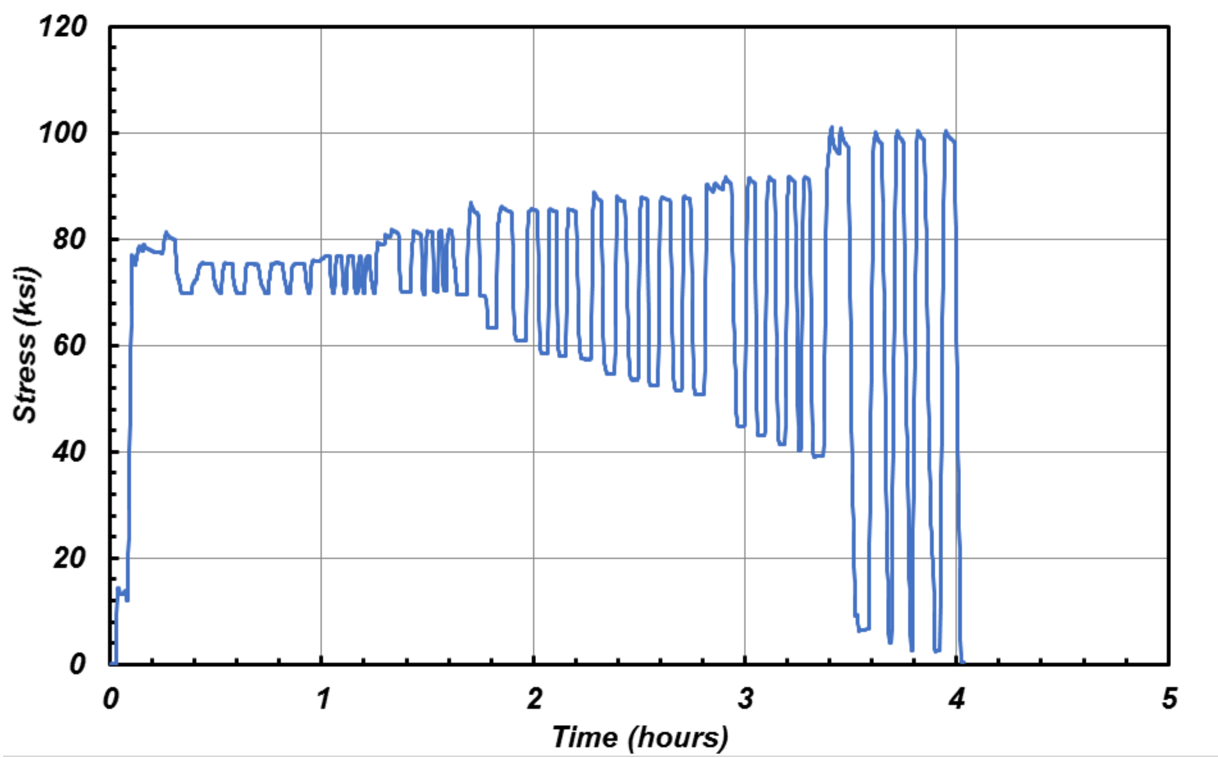


Figure 4.11-2 – Force versus time for full-size test of coupled 6 ft specimen.

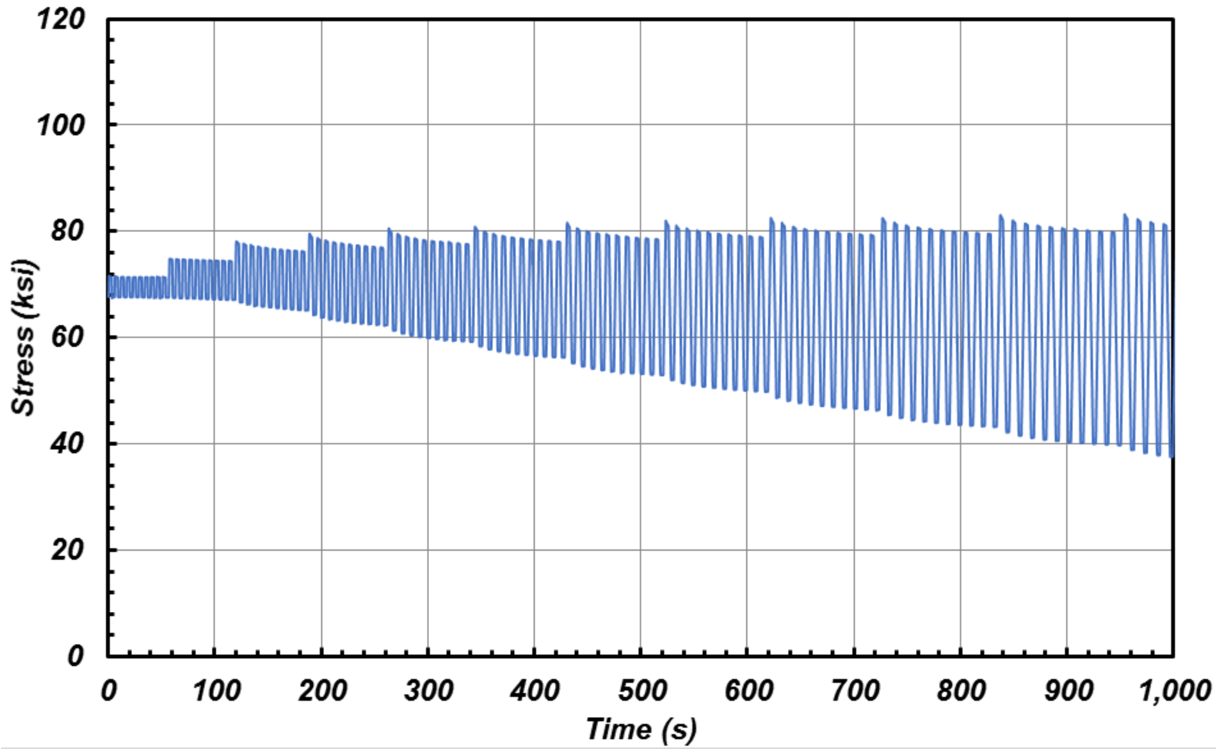


Figure 4.11-3 – Stress versus time for the cyclic test with increasing strain increments.

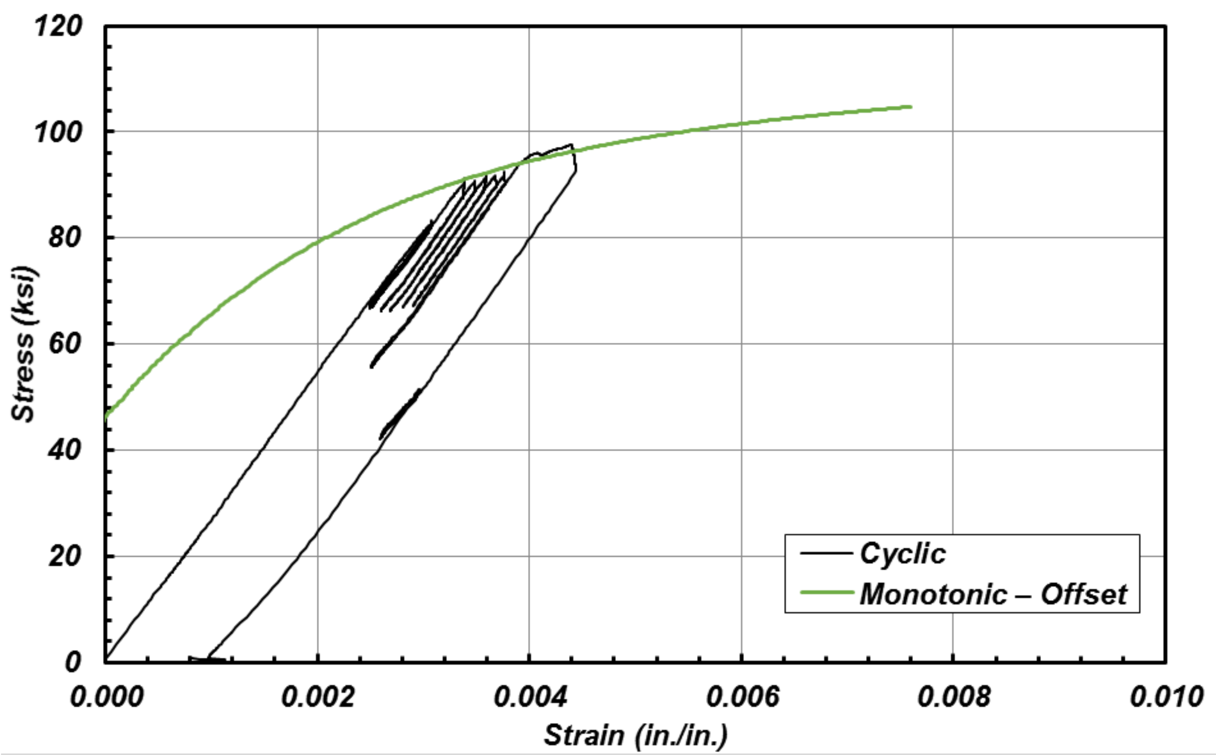


Figure 4.11-4 – Stress-strain curve for the full-size test of 12 ft specimen.

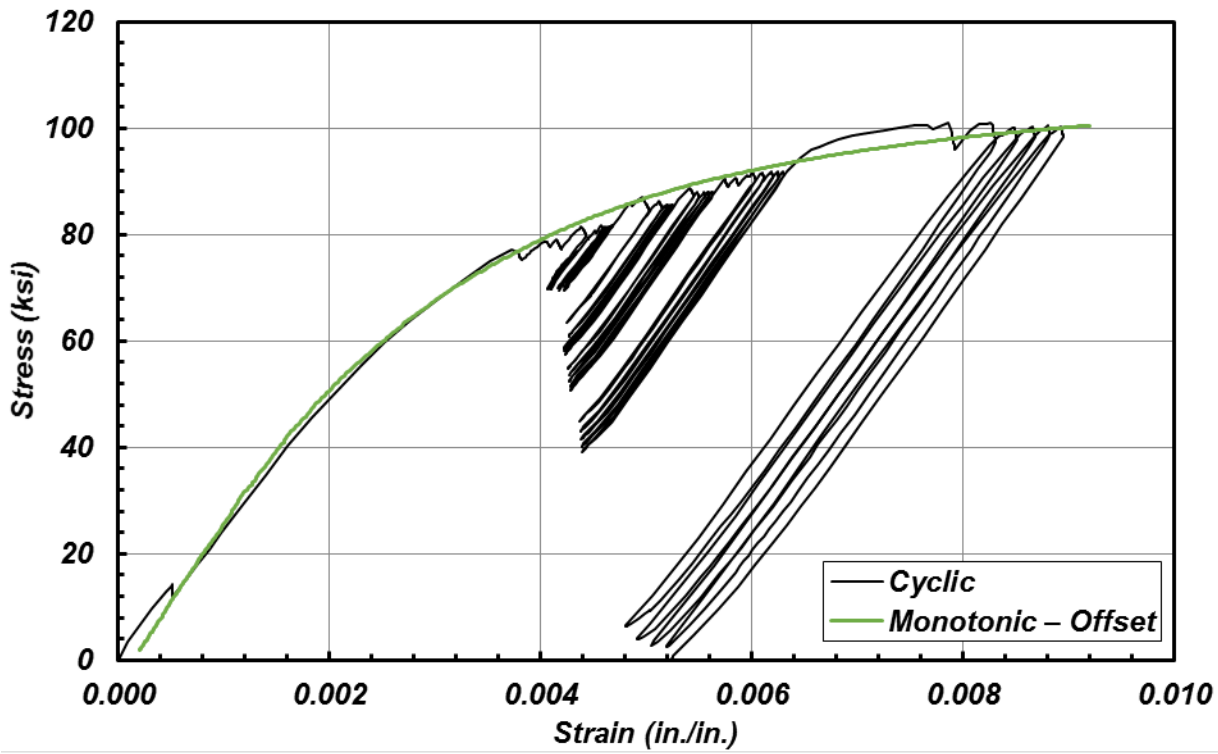


Figure 4.11-5 – Stress-strain curve for full-size test of coupled 6 ft specimen.

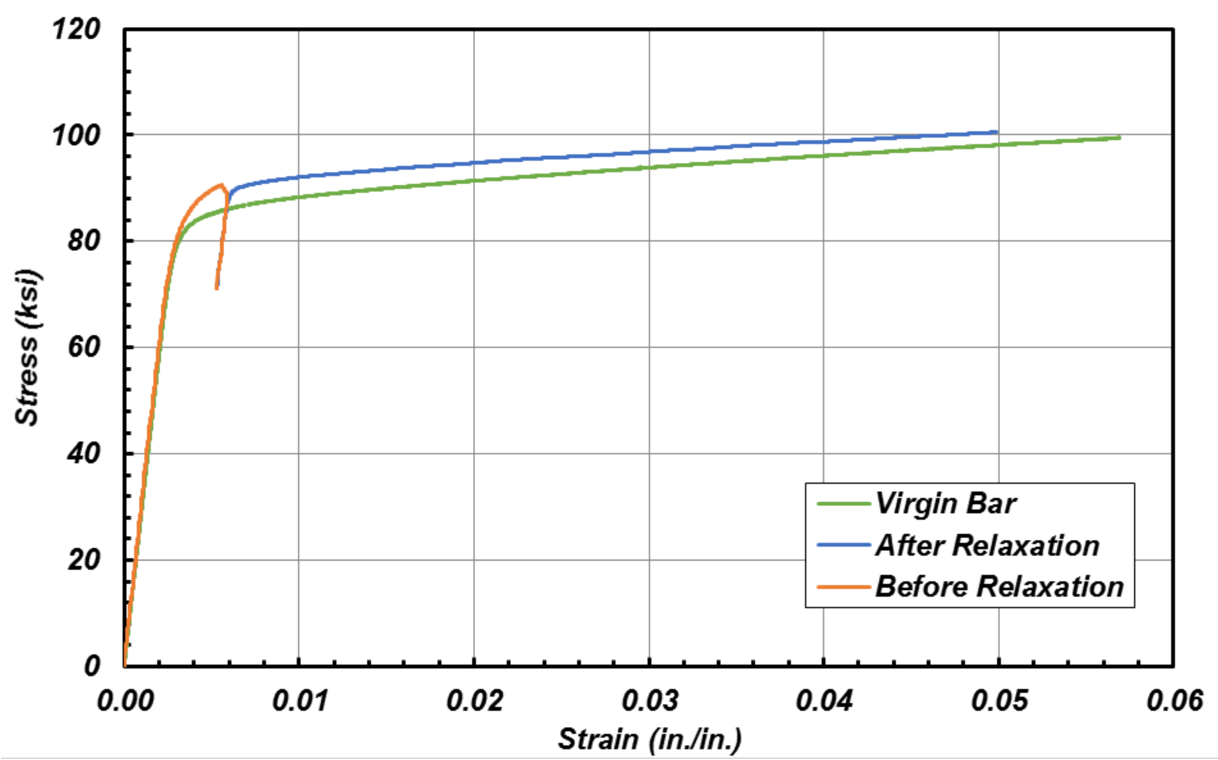


Figure 4.11-6 – Comparison of stress-strain curves for two monotonic tensile specimens.

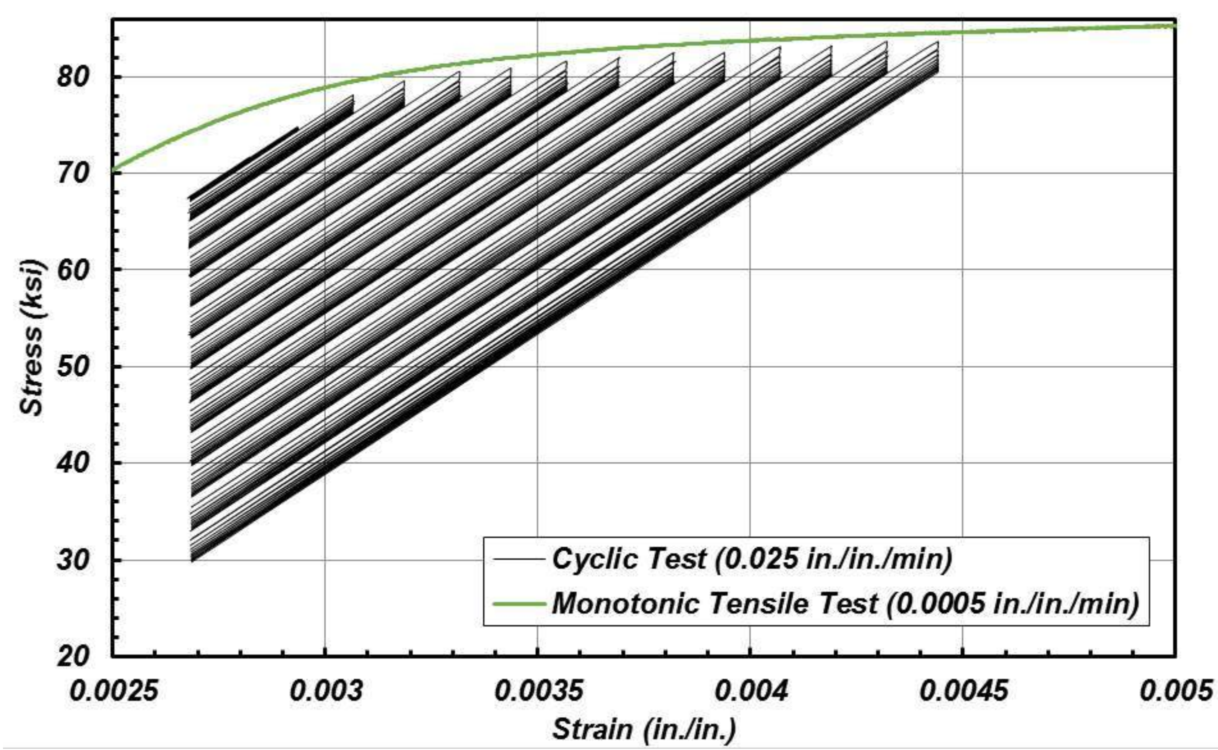


Figure 4.11-7 – Stress-strain curve for cyclic tensile test with overlay monotonic tensile curve.

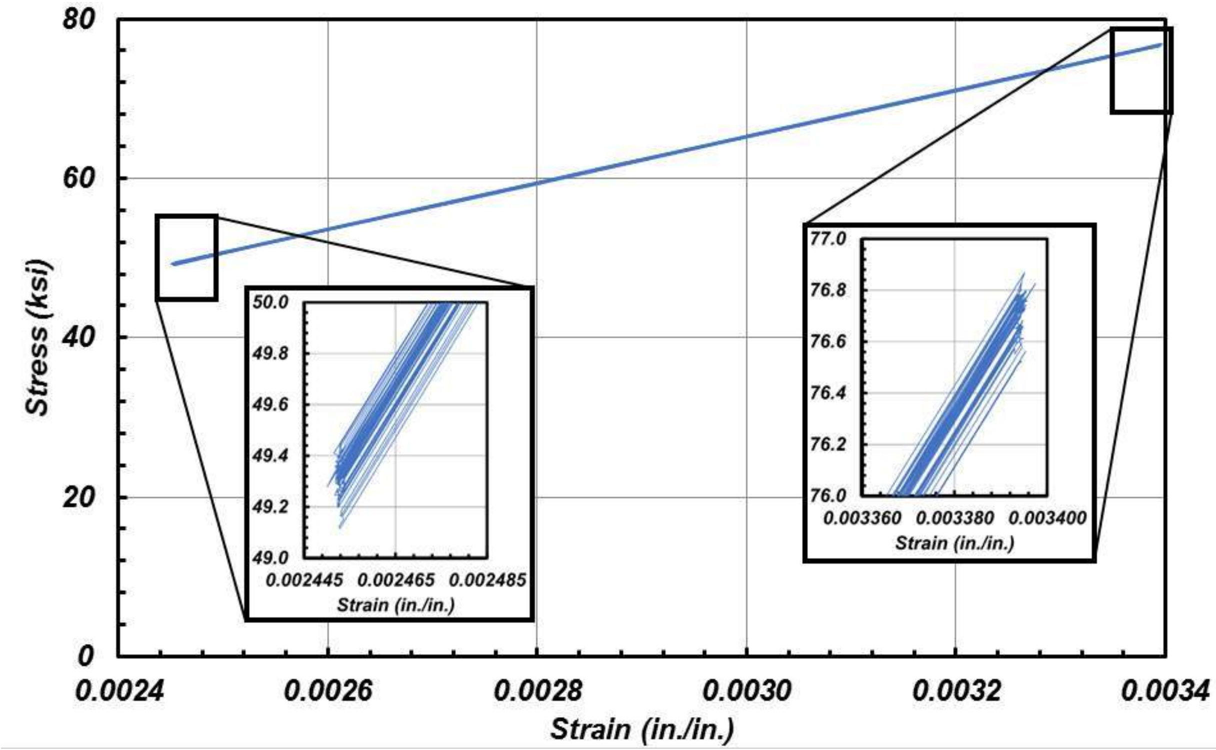


Figure 4.11-8 – Stress-strain plot for specimen that we cycled between nominally 49.5 and 76.5 ksi after relaxation testing. Stress values at strain limits are shown for 1,000 cycles in the inset plots.

5. DISCUSSION

Common high-strength, cementitious-grouted, post-tensioned, steel anchorage bar systems typically consist of threaded bars, up to a 3 in. (75.2 mm) diameter, with a minimum tensile strength of 150 ksi (1,040 MPa). Corrosion protection of high-strength bars may be provided by application of a protective coating, such as galvanizing, durable material selection such as stainless steel, or by precluding the potential sources of corrosion from attacking the bars by other means.

We understand the design for the new Herbert C. Bonner Bridge in North Carolina specified high-strength, stainless steel, cold-rolled 2-1/2 in. to 3 in. (63.5 to 76.2 mm) diameter anchors. We found only limited information regarding the material selection for the Bonner Bridge. Atlanta Rod and Manufacturing published the information shown in Appendix O, which refers to 2.5 in. and 3 in. Type 17-4 swedge bolts. Type 17-4 is a Precipitation Hardened Stainless Steel and an alternative designation for the Custom 630 included in our Phase 2 test program; however, we do not know the selected heat treatment for the Bonner Bridge anchors.

Material Specifications

ASTM A722 contains mechanical requirements for high-strength, post-tensioned plain, carbon steel bars for prestressing concrete, however, does not address corrosion protection. The original RFP for this study referenced ASTM A354 - *Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners* [2011] for hardness requirements. ASTM A354 Grade BD fasteners have a minimum tensile strength of 150 ksi (1034 MPa), similar to the target tensile strength for this project.

We identified two additional ASTM standards for stainless steel that include specifications for materials similar to the candidate materials: ASTM A564 – *Standard Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes* [2013] and ASTM A276 – *Standard Specification for Stainless Steel Bars and Shapes* [2017].

ASTM A564 includes material specifications for Custom 450 and Custom 630 stainless steels. Custom 450 is a refined version of the Unified Numbering System (UNS) designation S45000 or Type XM-25. Custom 630 is a refined version of the UNS designation S17400 or Type 630, also commonly known as 17-4 PH (Precipitation Hardened) stainless. ASTM A564 includes mechanical properties at various hardening or aging treatment conditions, including Type 450 in the H1050 condition and Type 630 in the H1100 condition. Carpenter also referenced ASTM A564 in the mill certificate.

ASTM A276 includes material specification for Alloy 2507, which is identified by the UNS designation S32750. ASTM A276 specifies different mechanical properties for Alloy 2507 products with a diameter or thickness up to and including 2 in. (50.8 mm) and over 2 in. (50.8 mm). Sandvik also referenced ASTM A276 in the mill certificate.

Table 5-1 shows the specified mechanical properties from the ASTM standards for each material.

5.1 Mechanical Property Discussion

Table 5-2 provides a summary of the test results reported in Chapter 4. Tables 5-3 through 5-6 show the full-size specimen test results, the mill certificate values, and the relevant ASTM standards for Threadbar®, Custom 450, Custom 630, and Alloy 2507, respectively..

Comparison of Full-Size Bar Results to Mill Certificates

For the plain Threadbar®, the tensile strength of the full-size bar specimens was 1% lower than that of the smaller coupon samples reported in the mill certificate. The yield strength of the full-size specimens was 7% lower than that of the smaller coupon samples.

For the galvanized Threadbar®, the tensile strength of specimen DSI-G-1 was 11% lower than the smaller coupon samples; while the tensile strength of the other two full-size specimens was 2% lower than the smaller coupon samples reported in the mill certificate. The yield strength of the full-size specimens was 3% lower than the smaller coupon samples.

For the Custom 450 H1050 specimens, the tensile strength of the full-size specimens was 1% higher than the smaller coupon samples reported in the mill certificate. The yield strength of the full-size specimens was 3% lower than the smaller coupon samples.

For the Custom 630 H1100 specimens, the tensile strength of the full-size specimens was 2% higher than the smaller coupon samples reported in the mill certificate. The yield strength of the full-size specimens was 1% lower than the smaller coupon samples.

For the Alloy 2507, the tensile strength of the full-size specimens was 2% higher than the smaller coupon samples reported in the mill certificate. The yield strength of the full-size specimens was 8% higher than the smaller coupon samples.

The comparison between full-size bar results and mill certificate results indicates the following:

- The small coupon sample test results reported in the mill certificate are representative of full-size bar properties and are acceptable for quality control testing of materials.
- The cold-rolled thread forming did not adversely affect the mechanical properties of full-size bars.

Comparison of Results to Material Specifications

For plain Threadbar®, the results of our material testing for tensile strength and yield strength exceeded the minimum values specified in ASTM A722. The values reported in the mill certificate for tensile strength, yield strength, and tensile elongation exceeded the minimum values specified in ASTM A722. The average relaxation values for plain Threadbar® tested at 0.75$\boldsymbol{f_{pu}}$ and 0.62$\boldsymbol{f_{pu}}$ met the requirements of BS 4486. The Rockwell C and Brinell hardness values from both material testing and mill certificates exceeded the maximum limits specified in ASTM A354.

For galvanized Threadbar®, the results of our material testing for tensile strength and yield strength exceeded the minimum values specified in ASTM A722. The values reported in the mill certificate for tensile strength, yield strength, and tensile elongation exceeded the minimum values specified in ASTM A722. The average relaxation values for galvanized Threadbar® tested at 0.71$\boldsymbol{f_{pu}}$ met the requirements of BS 4486.The Rockwell C and Brinell hardness values from material testing were within the minimum and maximum limits specified in ASTM A354; however, the mill certificate values exceeded the maximum limits specified in ASTM A354.

For Custom 450 H1050, the results of our material testing for tensile strength, yield strength, Rockwell C hardness, and Brinell hardness exceeded the minimum values specified in ASTM A564. The values reported in the mill certificate for tensile strength, yield strength, tensile elongation, reduction in area, and Brinell hardness exceeded the minimum values specified in ASTM A564. The results of both material testing and mill certificates exceeded the minimum values specified in ASTM A722 for Type 2 carbon steel anchorage bars. The average relaxation values for Custom 450 tested at 0.84$\boldsymbol{f_{pu}}$ met the requirements of BS 4486. The

Rockwell C and Brinell hardness values from material testing exceeded the maximum limits specified in ASTM A354; however, the mill certificate value for Brinell hardness is within the limits specified in ASTM A354.

For Custom 630 H1100, the results of our material testing for tensile strength, yield strength, Rockwell C hardness, and Brinell hardness exceeded the minimum values specified in ASTM A564. The values reported in the mill certificate for tensile strength, yield strength, tensile elongation, Rockwell C hardness, and Brinell hardness exceeded the minimum values specified in ASTM A564. The results of both material testing and mill certificates exceeded the minimum values specified in ASTM A722 for Type 2 carbon steel anchorage bars. The average relaxation values for Custom 630 tested at $0.74\boldsymbol{f_{pu}}$ met the requirements of BS 4486. The Rockwell C hardness values from both material testing and mill certificates exceeded the maximum limits specified in ASTM A354; however, the Brinell hardness values from both material testing and mill certificates were within the minimum and maximum limits specified in ASTM A354.

For Alloy 2507, the results of our material testing for tensile strength and yield strength exceeded the minimum values specified in ASTM A276. Our testing for Rockwell C hardness and Brinell hardness were less than the maximum values specified in ASTM A276. The values reported in the mill certificate for tensile strength, yield strength, and tensile elongation exceeded the minimum values specified in ASTM A276. The values reported for Rockwell C hardness were less than the maximum values specified in ASTM A276. The relaxation values for the Alloy 2507 test at $0.69\boldsymbol{f_{pu}}$ slightly exceeded the requirements of BS 4486; however, the relaxation value of 3.59% at $0.69\boldsymbol{f_{pu}}$ is less than the requirement of 4% at $0.7\boldsymbol{f_{pu}}$ in JIS G3109. The results of both material testing and mill certificates did not meet the minimum values specified in ASTM A722 for Type 2 carbon steel anchorage bars. The Rockwell C and Brinell hardness values from both material testing and mill certificates were less than the minimum limits specified in ASTM A354.

Yield Strength, Tensile Strength, and Elongation

As noted above, the Threadbar®, both plain and galvanized, Custom 450, and Custom 630 tensile strengths exceeded 150 ksi (1,040 MPa), which represents the minimum tensile strength required by ASTM A722. Alloy 2507 had a minimum average tensile strength of 121.4 ksi (837 MPa).

Where bar fractures occurred, fracture typically occurred at random points along the bar length, with a slight tendency to fracture within 1 or 2 ft. of the end nut. One galvanized Threadbar® fractured immediately adjacent to the end nut. One Alloy 2507 bar failed by thread stripping. Two of the Alloy 2507 bars remained plastic and stretched until the stroke limit of the Baldwin Universal Testing Machine was reached, which ranged from 30 to 36 in. (762 to 914 mm).

Figures 5.1 to 5.4 show a fracture surfaces for each of the tensile test specimens from the plain and galvanized Threadbar®, Custom 450 and Custom 630, respectively. Figure 5.5 shows Test No. 4 of the Alloy 2507; this is the only Alloy 2507 test specimen that fractured. The Alloy 2507 failure region is illustrated in the photographs, showing the high degree of stretch and eventual tearing in the thread roots. We also observed this tearing near the fracture surface of the other bars to a lesser extent. The ductility and energy absorption of the 2507 bars was quite large, as exhibited by the load-deflection curves shown in Figure 4.1-3.

Figure 5.6 shows the typical condition of the galvanized coating after failure. The coating in the region of the fracture debonded completely. The adjacent coating displayed significant cracking. These failures indicate that the galvanized coating is likely more brittle than the parent carbon steel bar.

The photographs of Figure 5.6 also illustrate another characteristic of the carbon steel bars. At failure, the carbon steel bars demonstrated very little necking in the failure zone. (Necking is a reduction in the bar diameter under tensile elongation; necking is typically visible where the bar stretches immediately before failure and is concentrated in a finite length near the failure location.) Fracture was sudden with little visual necking as a precursor to failure. The stainless steel bars all exhibited localized necking down of the bar prior to fracture. Figure 5.7 shows representative necking regions of the stainless steel bars. In the case of the Alloy 2507, Figure 5.7(c) shows necking initiating just beyond the end nut, with the necking region actually constituting the entire 12 ft. bar length for the bars that did not fracture.

Coupling Nuts

Standard coupling nuts for Threadbar® are 10.75 in. (273 mm), approximately $4.3\boldsymbol{d_b}$. The standard coupling nuts for the plain and galvanized Threadbars® developed the tensile strength of the bar. We did not observe slippage or thread stripping in the coupling nut.

For Custom 450 and Custom 630, we tested coupling nut lengths of $4.4\boldsymbol{d_b}$ and $5.4\boldsymbol{d_b}$ to evaluate a suitable coupling nut length to develop the full-strength of the bar. In all tests, the $4.4\boldsymbol{d_b}$

coupling nuts developed the full tensile strength of the bar. We did not observe slippage or thread stripping in the coupling nut.

Figure 5.8 shows a representative load-deflection curve of a Custom 630 tensile test compared to its companion coupler test. In the plot, the two lines represent an unspliced 12 ft. bar and a coupled bar consisting of two, 6 ft. bar lengths connected by a coupling nut. The plot shows the lines track similarly, indicating almost equivalent stress-strain behavior. In the case of the coupling nut test, we used the parent bar area to determine stress. The coupled bar line is smooth and shows no jagged line displacements, which would indicate slippage or thread tearing.

The plot illustrates the coupled bar was slightly stiffer than the un-coupled or non-spliced bar. The coupled bar performed equivalently to its non-spliced companion. This behavior was typical for all of the bars tested.

End Nuts

For the safety of lab personnel, and to prevent equipment damage due to the rapid release of energy typically accompanying a failure, end nut tests were not loaded to failure. The standard, 5 in. (127 mm), end nuts for the plain and galvanized Threadbars® developed the target proof load and the minimum specified tensile strength of the bar.

For each stainless steel, we performed three tests on $2d_b$ long end nuts measuring 5 in. (127 mm) in length. These were the shortest nuts fabricated. For all stainless steel nut tests, the $2d_b$ end nuts developed their full tensile strength of the bar.

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, we had to jack the test specimens 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 Threadbar®. 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.

Our 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. Our second set of test on coupled 6 ft. 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. Galling resistance often increases with increasing tensile strength, but we did not measure a significant increase in galling resistance between the various stainless steels. During mechanical testing of full-size specimens (tensile, coupling nut, end nut, and relaxation), we did not find an appreciable difference in the thread-ability of the materials except the galvanized specimens. For the galvanized specimens, we had difficulty threading the nuts onto the bars. We typically had to grind or file the bar thread tips to facilitate threading. For all other materials tested, we typically used lubricant on the threads to prevent galling and thread binding; however, lubricant was not required in all test setups.

Galling is very sensitive to surface finish and contamination. For construction applications, the anchorage bars will need to be lubricated for installation. The chosen lubricant should not degrade over time or form a contaminant that can be deleterious to other materials in contact. Anti-galling lubricants are traditionally based on dry surface lubricants such as molybdenum disulfide, graphite, mica or talc. While capable of providing high pressure and high temperature protection, these are not appropriate for use with anchorages due to their lack of long-term stability.

Fluorine containing compounds have proved effective in preventing galling, and the use of coatings, sprays and compounds incorporating PTFE (Teflon) have been widely employed for ambient and low temperature applications.

Pre-coating of the threads with such a material should provide the necessary anti-galling characteristics without risk of future breakdown or attack by the dry lubricant or its carrier.

Toughness (Charpy V-Notch)

In the tests, all stainless steels demonstrated higher toughness compared to the carbon steel Threadbar® material. 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 Threadbar® had an impact toughness less than 20 ft-lb 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. Alloy 2507 is often used in artic and cryogenic applications and is very resistant to low temperature crack growth.

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

- ASTM A320 – *Standard Specification for Alloy-Steel and Stainless Steel Bolting in Low-temperature Service* [2017] specifies an impact energy of 20 ft-lb (27.1 J) for stainless steel bolting materials in fracture critical applications; however, this standard is only applicable to other stainless steel material grades. The stainless materials included in the test program met this minimum impact energy for full-size test specimens. The Threadbar® materials exhibited toughness marginally less than this criterion.

- ASTM A564 - *Standard Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes* [2013] specifies a minimum impact toughness of 25 ft-lb (33.9 J) for the equivalent to Custom 630, at a test temperature of 70 to 80°F (21.1 to 26.7°C). We measured an impact toughness for the Custom 630 of 46 ft-lb (62.4 J) at that temperature.

- 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 component at the test temperature. Only the Alloy 2507 met the requirement for fracture critical components.

The original RFP suggested stringent requirements for toughness, including those specified in ASTM A320 and ASTM A709 – *Standard Specification for Structural Steel for Bridges* [2016], which is similar to the requirements in AASHTO Article 6.2.2. Only the Alloy 2507 met both of those standards.

5.2 Corrosion Resistance Discussion

Pitting Corrosion

Carbon steels, such as the Threadbar® material, are susceptible to aqueous corrosion in the presence of water and oxygen. Grouting of this material, which provides a highly alkaline environment at the grout to metal interface, passivates steel from corrosion. However, over time this passivation can diminish due to grout deterioration (such as carbonation), grout cracking, delamination, or ingress of chlorides. Galvanizing can provide additional sacrificial corrosion resistance, but galvanized materials have poor bond strength to mortar and a galvanized coating cannot be expected to provide corrosion resistance for 100 years.

Stainless steels 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. Our pitting corrosion resistance testing is designed to rank the susceptibility of stainless steels to chloride pitting. This test is purposely aggressive and allows discrimination between materials that are susceptible to pitting and those that can resist it. The test uses an acidified 6 wt.% chloride solution to promote pitting corrosion.

Both of the precipitation-hardened stainless steels suffered pitting corrosion at ambient temperature in this test solution, whereas the Alloy 2507 required a temperature of 185°F (85°C) for pitting to occur. In practice, an acidified 6 wt.% chloride solution is an extreme environment that is unlikely to be encountered in the design exposure environment, even with extensive road salt ingress. However, over time chloride concentrations can build up unless the anchorage locations are protected from chloride ingress. Low alloy austenitic stainless steels, such as type 304, are known to have similar corrosion resistance to the precipitation-hardened stainless steels and can pit at chloride concentrations as low as 200ppm. Therefore, over the 100-year lifetime of the structure, the precipitation-hardened stainless steels can be expected to suffer pitting corrosion in a bridge exposed to deicing salts.

In summary, we expect the only material in this study that will not suffer from pitting corrosion is the Alloy 2507. Should a more susceptible material be considered appropriate for use because of its other performance criteria, additional precautions must be adopted to protect against conditions where pitting corrosion can develop.

Stress Corrosion Cracking (SCC)

High-strength carbon steels and precipitation-hardened stainless steels are known to be susceptible to SCC in the presence of chlorides. The stress cracking resistance test that we conducted, which uses an applied stress of 85% of yield and a boiling sodium chloride environment, is an extreme environment designed to rank the susceptibility of stainless steels to this failure mechanism.

In our testing, both the Custom 450 and Custom 630 stainless steels cracked within 6 hrs of testing, whereas the Alloy 2507 did not crack after two weeks of testing in this environment. The Threadbar® material did not crack, but this is probably due to the rapid corrosion of the entire surface blunting any crack tip that would allow SCC to occur.

At ambient temperature, the kinetics of stress corrosion cracking would be much slower than our testing. Tests by the stainless steel manufacturers in an ambient temperature salt spray solution environment have shown that these precipitation-hardened stainless steels have not cracked after a year of testing. However, if chloride accumulation is occurring from deicing salt application, the failure of precipitation-hardened stainless anchorage bars by chloride-induced SCC cannot be discounted in a 100-year lifetime.

The only material in this study that has high resistance to stress corrosion cracking is the Alloy 2507. If other grades from this study are chosen due to strength considerations, then additional precautions are required to avoid the likelihood of significant chloride ingress and cracking.

Hydrogen Embrittlement

It is known that high-strength steels with a tensile strength in excess of 150 ksi are susceptible to hydrogen cracking, as evidenced by the Bay Bridge anchorage failures. Residual hydrogen can be present in a material from processing, such as pickling or galvanizing, or can be generated in-situ due to anaerobic corrosion mechanisms. Our testing showed that hydrogen-charged Threadbar® material is susceptible to hydrogen embrittlement and sub-critical crack growth, resulting in a significant decrease in the fracture toughness of the material. The slow strain rate testing of the galvanized material in the uncharged condition also demonstrated sub-critical crack growth and reduced toughness compared to the plain Threadbar® material.

The Custom 450 and Custom 630 stainless steels exhibited brittle cracking in the surface layer after hydrogen charging for 60 hrs. The diffusion kinetics of hydrogen in this precipitation-hardened stainless steel microstructure is much slower than that of a carbon steel. It would take many months to uniformly charge a hydrogen specimen of this size at ambient temperature. However, our testing has demonstrated that brittle hydrogen cracking will occur in these materials. This supports published literature that shows precipitation-hardened stainless steels can be susceptible to hydrogen cracking, albeit at much slower rates than high strength carbon steels. If hydrogen is accumulating in these materials over many years from corrosion in the structure, then the possibility of brittle hydrogen cracking cannot be ruled out.

The Alloy 2507 stainless steel exhibited no decrease in toughness or brittle crack behavior after hydrogen charging. This material has a more ductile microstructure than the other materials, and is known from published literature to resist hydrogen cracking. In addition, the material is highly corrosion resistant, decreasing the possibility of hydrogen accumulation from corrosion in the lifetime of the structure.

The Alloy 2507 is the only material in this study that can be expected to resist hydrogen cracking in the long term. For alternative materials, corrosion protection will be required. To use the alternatives puts greater emphasis on the design, implementation, and maintenance of an effective system of protection from the ingress of aggressive species such as chlorides.

Galvanized bars conforming to this standard have been used to mitigate corrosion, but their usage is diminishing. Experience with the San Francisco-Oakland Bay Bridge have re-emphasized the problems with galvanizing high-strength steel, and the risks involved if problems occur. The risks of hydrogen embrittlement and future problems in service outweigh the benefits purported to exist with present galvanizing technology. We understand the galvanizing community is becoming more selective and aware of galvanizing high-strength steels, with some going so far as to refuse the business because of liability concerns.

5.3 Design Considerations

Repassivation of Stainless Steel

Following installation and stressing of any stainless steel anchorage bar, the exposed surfaces which were in contact with other metallic tools, will need to be repassivated per ASTM A967 [2013]. This removes any residual free iron from the surface that has been exposed by machining or other contact and re-establishes the protective layer of protective oxides, one or more of chromium, nickel and molybdenum, which provide stainless steel grades with their enhanced corrosion resistance.

Design Stress Limits

M&M provided the jacking force and maximum tension demand values in Table 5-7. We compared these demands to the yield and tension strength of the anchorage bar for three design alternatives: the original design with Threadbar®; a design with Alloy 2507 based on the test values measured in this program; and a design with Alloy 2507 using ASTM A276 specified values. We used the larger tested 2.75 in. diameter bars for both comparisons with Alloy 2507. Our 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 Threadbar®. Table 5-2 shows the ratio of the applied force to the strength of the anchorage bars.

AASHTO LRFD Bridge Design Specifications Table 5.9.3-1 [2012] provides stress limits for deformed high-strength bars, with a maximum stress prior to seating of $0.90\boldsymbol{f_{py}}$ and a maximum stress of $0.70\boldsymbol{f_{pu}}$ immediately after anchor set. Table 5-7 indicates the revised design is acceptable with the Alloy 2507 based on measured test values; however, the revised design using the ASTM A276 specified values for Alloy 2507 exceeds the yield stress limit during jacking.

Inelastic Behavior of Alloy 2507

Figure 4.1-2 shows 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 materials other than Alloy 2507 have a substantial initial linear-elastic region, to about 120 ksi (827 MPa), with a well-defined transition to post-yield behavior (while not a sharp yield point as is typical of mild carbon steels). To study the implications of this differing behavior of Alloy 2507 in the non-linear range, we conducted additional inelastic behavior testing. This non-linear behavior becomes increasingly important under cyclic loading where additional stress and strain can result in unstable inelastic strain and loss of preload following unloading.

The initial design jacking load of 464 kips (2,064 kN) will carry the Alloy 2507 well into the nonlinear range (see Figure 4.1-2 and Table 5-7). 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. For effective pretension in the present design, we understand M&M estimated the upper and lower bound loss of pretension to calculate the effective force after all losses. M&M provided a memo, *I74 MRB Arch Rib Interface Post Tension Bars – Material Recommendation* [2017] included in Appendix P, discussing the selection of Alloy 2507 and determined the effective pretension force after losses to be 391 kips (1,739 kN) maximum and 311 kips (1,383 kN) minimum.

Under design loading, the tensile force in the anchor bars will increase if the load demands exceed the clamping effect of pretension. In fact, the maximum anchor demand reported by M&M exceeded even the jacking load of 464 kips (2,064 kN) in the original design. The likelihood and frequency of load cycles exceeding the clamping effect are greater considering the effective pretension after losses between 311 kips and 391 kips.

Inelastic behavior testing indicated that reloading of Alloy 2507 would 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 anchorage bar. This stable condition is known as “linear shakedown” and is illustrated in Figure 5-9. The upper limit of this linear path is established by the maximum prior force applied to the bar, by either pre-straining during fabrication or over-jacking during the anchor stressing operation. We understand M&M has evaluated this inelastic behavior with respect to the actual anchorage bar application and finds the performance acceptable as long as the anchor is pre-strained during initial stressing.

5.4 Cost and Fabrication Considerations

Buy America Provision

“Buy America” provisions of the FHWA procurement provisions are an important issue when considering stainless steels for this project. The large diameter plain bar stock stainless steel is a very specialized product with limited producing mills; not all of which are domestic. Some domestic steel mills roll the finished product from billets of stainless steel produced internationally. This is usually economical from a world commerce standpoint, as stainless steel mill production and facilities are limited and significantly outnumbered by carbon steel mills. We know of one domestic mill that can produce the stainless steels in round bar form as tested in this study; however, we did not perform an exhaustive search to find others.

Fabrication

Dywidag Systems International (DSI) and Williams Form Engineering (WFE) are the predominant domestic suppliers for continuously threaded high-strength anchorage bars. Other manufacturers, such as Atlanta Rod and Manufacturing, have demonstrated capability to produce large diameter anchorage bolts and bars.

Estimated Cost of Anchorage Bars

Table 5-8 shows our opinion of upper bound probable costs for the anchorage bars from the different candidate materials. We estimated these costs based on material and fabrication cost from specimens used in the Phase 2 test program; however, the project may realize economies of scale for the large quantity of bars required for the project. Both the steel mills producing the raw bar stock and the fabricator cold-rolled thread forming the bars would likely develop efficiencies in production. The raw material costs for stainless steel is also widely variable. We believe the installation labor costs should be consistent for each of the different materials and would not affect the total cost to the project. Table 5-4 demonstrates the significant initial cost to modify the design from carbon steel Threadbar® to a stainless steel anchorage bar; these costs do not include life cycle costs over the 100-year service life.

Table 5-1 – ASTM Specified Mechanical Properties

Property	ASTM A564 Custom 450 H1050	ASTM A564 Custom 630 H1100	ASTM A276 Alloy 2507	ASTM A722 ASTM A354
Tensile Strength (ksi)	145	140	110	150
Yield Strength – 0.2% Offset (ksi)	135	115	75	120
Elongation (%)	12%	14%	15%	4%
Reduction in Area (%)	45%	45%	-	-
Hardness – Rockwell (HRC) [A]	34 min.	31 min.	-	33 min. 34 max.
Hardness – Brinell (HBW) [A]	321 min.	302 min.	310 max.	311 min. 363 max.
Impact Charpy-V (ft-lbf)	-	25	-	

Table 5-2 – Summary of Test Results for Anchorage Bar Candidate Materials

	Material or Alloy				
Property	**Custom 450 H1050**	**Custom 630 H1100**	**Alloy 2507**	**Threadbar® Plain**	**Threadbar® Galvanized**
Tensile Strength (ksi)	170.1	159.8	121.4	166.3	159.2
Yield Strength (ksi)	153.9	148.8	91.1	142.7	149.9
Tensile Elongation [A]	6.5%	3.7%	20.8%	4.8%	4.3%
Stress Relaxation	1.58% at 0.84$\boldsymbol{f}_{pu}$	1.32% at 0.74$\boldsymbol{f}_{pu}$	3.59% at 0.69$\boldsymbol{f}_{pu}$	2.75% at 0.75$\boldsymbol{f}_{pu}$	2.51% at 0.71$\boldsymbol{f}_{pu}$
Hardness - Rockwell C	39	37	26	35	33
Hardness - Brinell	375	352	262	363	341
Toughness - CVN, -30°F (ft-lb)	27	24	261	16	18
Threshold Galling Stress (ksi)	0.6	0.5	0.7	0.9	
Critical Pitting Temperature (°F)	50	32	185	No pitting, but heavily corroded	
Stress Corrosion Cracking (time to failure)	<6 hrs	<6 hrs	Did not fail after 336 hrs	Did not fail after 336 hrs, but heavily corroded	
Hydrogen Embrittlement (threshold K_{ICHE} ksi√in.)	119[B]	114[B]	145	15	94[C]
Notes / Comments	Coupling and End Nut testing passed	Coupling and End Nut testing passed	Coupling and End Nut testing passed	Coupling and End Nut testing passed	Coupling and End Nuts difficult to thread

[A] Tensile elongation measured over the 12 ft. length of the specimen. These values are not comparable to the minimum tensile elongations specified in material specifications or the measured tensile elongations in the mill certificates.
[B] Only partially charged with hydrogen, to a depth of approximately 0.1in.
[C] Test performed on uncharged specimen, containing residual hydrogen from galvanizing

Table 5-3 – Threadbar® Comparison to Specifications

Property	Test Results - Plain	Test Results - Galvanized	Mill Certificate	ASTM A722 [A]
Tensile Strength (ksi)	166.3	159.2	167	150
Yield Strength – 0.2% Offset (ksi)	142.7	149.9	154	120
Elongation (%)	4.8%	4.3%	14%	4%
Reduction in Area (%)	-		-	-
Stress Relaxation (%)	2.75% at $0.75\boldsymbol{f}_{pu}$	2.51% at $0.71\boldsymbol{f}_{pu}$		4.6% at $0.75\boldsymbol{f}_{pu}$
Hardness – Rockwell (HRC)	35	33	40	33 min. 34 max.
Hardness – Brinell (HBW)	363	341	369	311 min. 363 max.
Impact Charpy-V (ft-lbf)	-		-	-
[A] Relaxation requirements per BS4486 [1980]. Hardness requirements per ASTM A354 [2011].				

Table 5-4 – Custom 450 Comparison to Specifications

Property	Test Results	Mill Certificate	ASTM A564	ASTM A722 [A]
Tensile Strength (ksi)	170.1	168.5	145	150
Yield Strength – 0.2% Offset (ksi)	153.9	159	135	120
Elongation (%)	6.5%	19%	12%	4%
Reduction in Area (%)	-	61%	45%	-
Stress Relaxation (%)	1.58% at $0.84\boldsymbol{f}_{pu}$	-	-	6.0% at $0.80\boldsymbol{f}_{pu}$
Hardness – Rockwell (HRC)	39	-	34 min.	33 min. 34 max.
Hardness – Brinell (HBW)	375	358	321 min.	311 min. 363 max.
Impact Charpy-V (ft-lbf [J])	-		-	-
[A] Relaxation requirements per BS4486 [1980]. Hardness requirements per ASTM A354 [2011].				

Table 5-5 – Custom 630 Comparison to Specifications

Property	Test Results	Mill Certificate	ASTM A564	ASTM A722 [A]
Tensile Strength (ksi)	159.8	156	140	150
Yield Strength – 0.2% Offset (ksi)	148.8	150	115	120
Elongation (%)	3.7%	16%	14%	4%
Reduction in Area (%)	-	61%	45%	-
Stress Relaxation (%)	1.32% at $0.74\boldsymbol{f}_{pu}$	-	-	4.5% at $0.74\boldsymbol{f}_{pu}$
Hardness – Rockwell (HRC)	37	36	31 min.	33 min. 34 max.
Hardness – Brinell (HBW)	352	336	302 min.	311 min. 363 max.
Impact Charpy-V (ft-lbf [J])	46	-	25	-
[A] Relaxation requirements per BS4486 [1980]. Hardness requirements per ASTM A354 [2011].				

Table 5-6 – Alloy 2507 Comparison to Specifications

Property	Test Results	Mill Certificate	ASTM A276	ASTM A722 [A]
Tensile Strength (ksi)	121.4	118.8	110	150
Yield Strength – 0.2% Offset (ksi)	91.1	84	75	120
Elongation (%)	20.8%	42%	15%	4%
Reduction in Area (%)	-	77%	-	-
Stress Relaxation (%)	3.59% at $0.69\boldsymbol{f}_{pu}$	-	-	3.3% at $0.69\boldsymbol{f}_{pu}$ -
Hardness – Rockwell (HRC)	26	23	-	33 min. 34 max.
Hardness – Brinell (HBW)	262	-	310 max.	311 min. 363 max.
Impact Charpy-V (ft-lbf [J])	-		-	-
[A] Relaxation requirements per BS4486 [1980]. Hardness requirements per ASTM A354 [2011].				

Table 5-7 – Comparison design demand to strength of anchorage bar

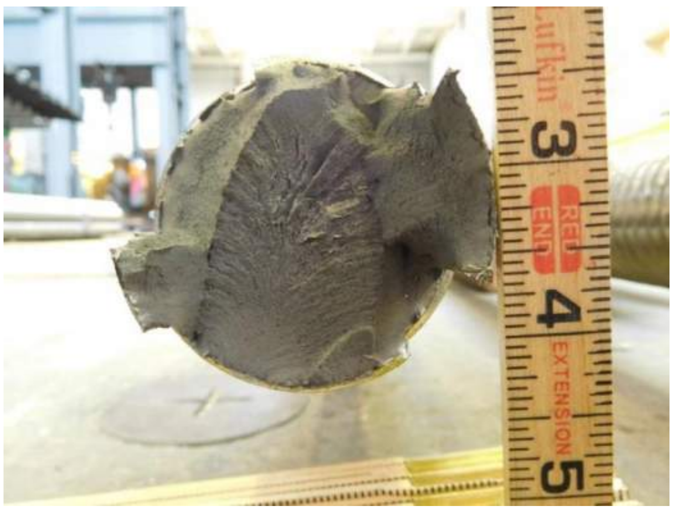
	Original Design with Threadbar®	Revised Design with Alloy 2507 [1]	Revised Design with Alloy 2507 [2]
Yield Strength (ksi)	120	91.1	75
Yield Force (kips)	617	525	432
Tensile Strength (ksi)	150	121.4	110
Force at Tensile Strength (kips)	771	699	634
Jacking Force (kips)	463	464	464
Jacking Force-to-Yield Force Ratio	0.75	0.88	1.07
Jacking Force-to-Tension Force Ratio	0.60	0.66	0.73
Maximum Tension Demand (kips)	482	475	475
Tension Demand-to-Tension Force Ratio	0.63	0.68	0.75

[1] – Yield strength based on 0.2% offset and tensile strength based on average breaking load of test specimens.
[2] – Yield and tensile strength based on specified minimum values from ASTM A276 [2017].

Table 5-8 –Opinion of Upper Bound Cost for the Anchorage Bars

Material	Anchorage Bar Cost for Phase 2 Test Program			Total Estimated Cost for Project (excluding install)
	Material Cost	Fabrication Cost	Total Cost	
Threadbar® – Plain	$ 9,500	(incl.)	$ 9,500	$ 608,000
Threadbar® – Galvanized	$ 10,100	(incl.)	$ 10,100	$ 646,000
Custom 450 H1050	$ 35,500	$ 31,000	$ 66,500	$ 4,256,000
Custom 630 H1100	$ 22,000	$ 31,000	$ 53,000	$ 3,392,000
Alloy 2507	$ 50,000	$ 31,000	$ 81,000	$ 5,184,000

(a) Test No. 1



(b) Test No. 2

(c) Test No. 3

Figure 5-1 - Plain Threadbar® fracture surfaces.

(a) Test No. 1

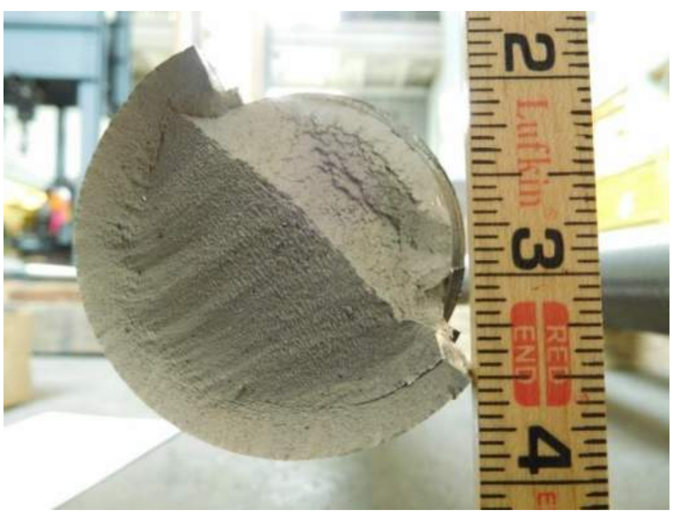
(b) Test No. 2

(c) Test No. 3

Figure 5-2 - Galvanized Threadbar® fracture surfaces.

(a) Test No. 1

(b) Test No. 2



(c) Test No. 3

Figure 5-3 - Custom 450 stainless steel fracture surfaces.

(a) Test No. 1

(b) Test No. 2

(c) Test No. 3

Figure 5-4 - Custom 630 stainless steel fracture surfaces.

(a) End showing metal tearing in the thread roots.

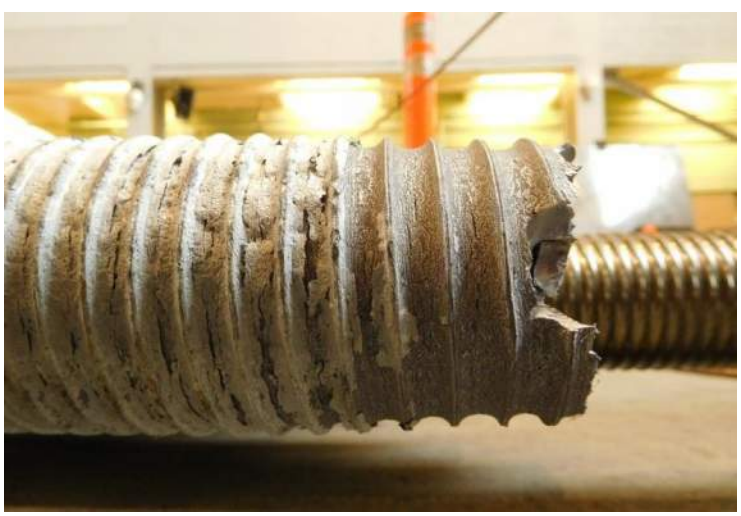
(b) End view of the fracture surface.

(c) Side view showing the irregular fracture surface.

Figure 5-5 – Alloy 2507 failure region for Test No. 4.

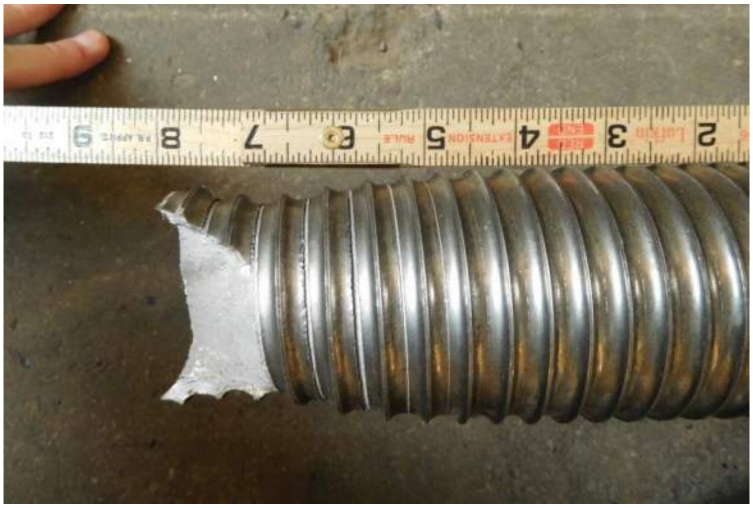
(a) End view showing loss of the galvanized coating.

(b) Side view showing loss of the galvanized coating.

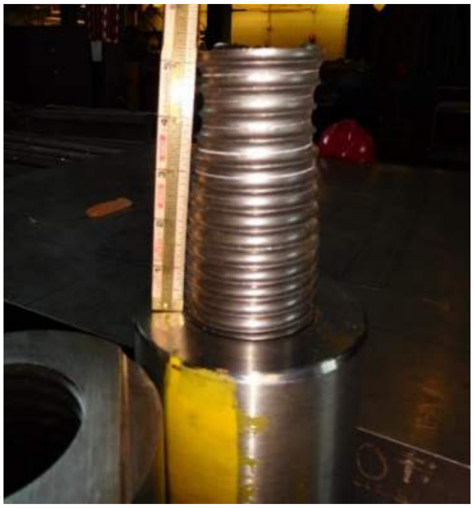


(c) Cracking and flaking of the galvanized coating in the failure region.

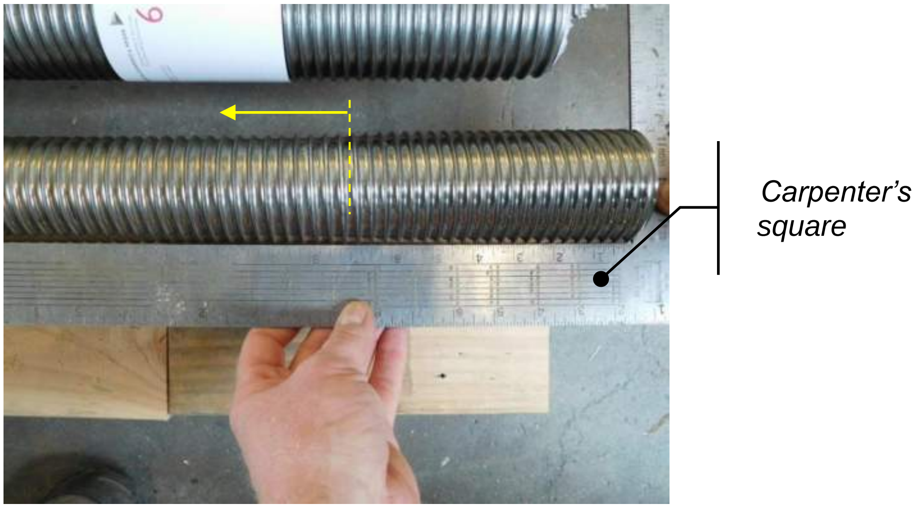
Figure 5-6 - Surface appearance of the galvanized Threadbar® at failure.



(a) Custom 450, Test No. 2



(b) Custom 630, Test No. 3



(c) Alloy 2507, Test No. 1 (dashed yellow line denotes start of necking region outside nut).

Figure 5-7 - Photographs of the necking regions of the three stainless steels.

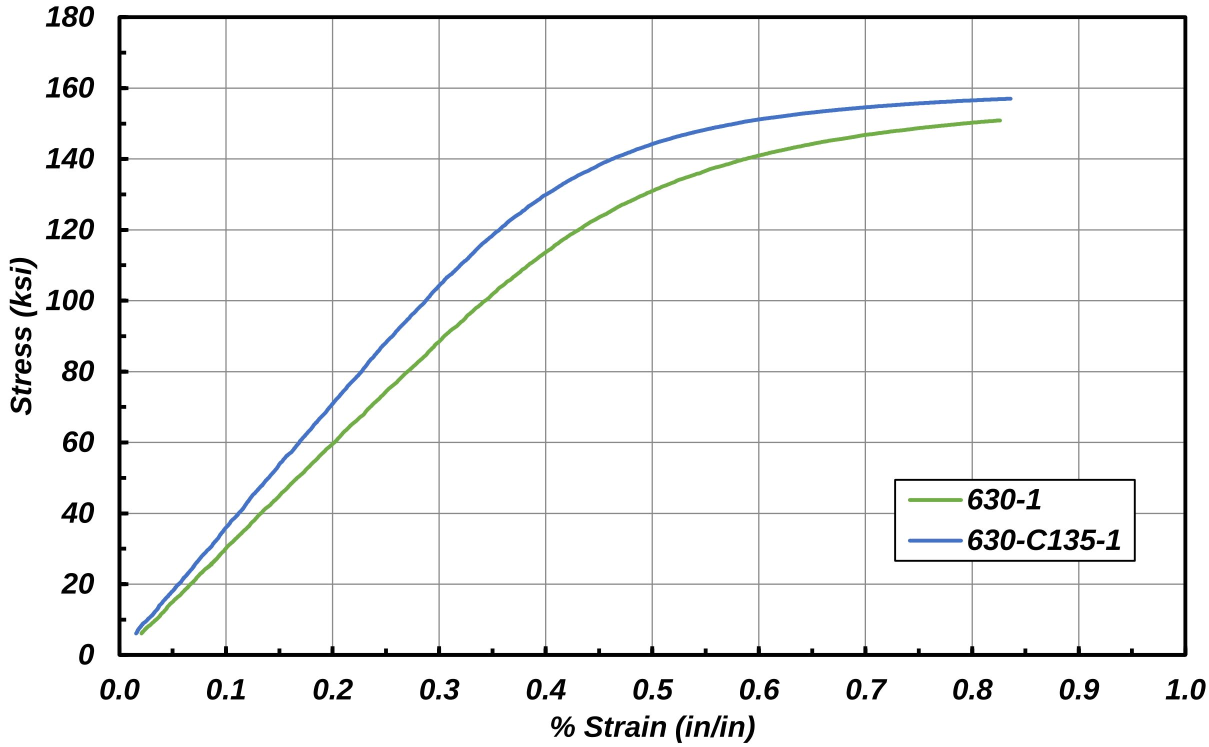


Figure 5-8 – Comparison of stress-strain relations between tensile test and coupling nut test

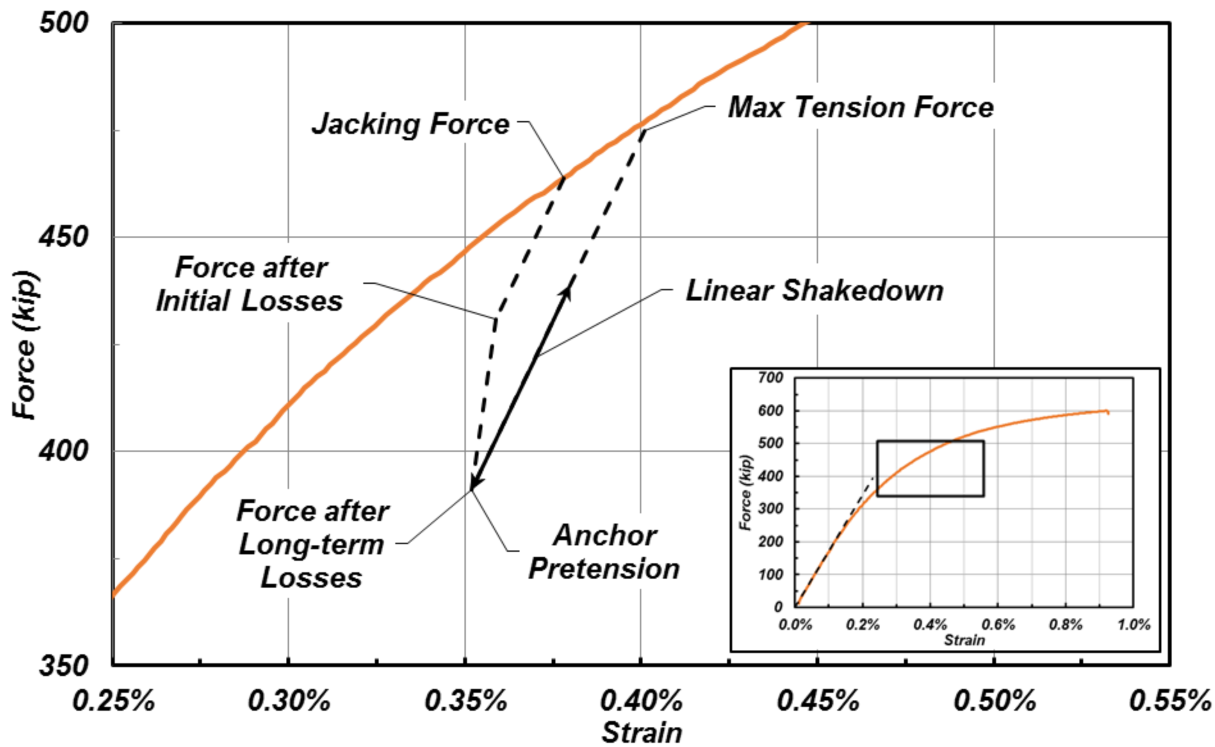


Figure 5-9 – Stress-strain behavior and linear shakedown of Alloy 2507

6. CONCLUSIONS

We summarize the performance of the candidate materials in the Phase 2 testing program in Table 6-1. Based on the entirety of Phases 1 and 2 in this study, we conclude the following for each of the materials:

- **Plain Threadbar®** meets the strength and ductility requirements of the project as expected. In our accelerated corrosion testing, it exhibited a high degree of surface corrosion in all tests and was susceptible to hydrogen embrittlement. The high-strength carbon steel Threadbar® is one of the standard products and materials for this application, conforming to ASTM A722. The successful use of Threadbar® in numerous structures around the world without substantial evidence of reported failure demonstrates its viability. However, the bar needs extensive corrosion protection when exposed to the environment. Cementitious grout encapsulation in a duct is the most common means of protecting the bar. For bar tails exposed to the environment, painting or use of grease caps is common practice. For additional corrosion protection, a dual system that adds additional seals or sacrificial cathodic protection (sacrificial anodes) to grout encapsulation may also be considered. Annex F of British Standard 8081 [2015] provides additional guidance for reference. (We do not recommend an impressed current, cathodic protection system, as this will be detrimental to corrosion protection). Although we did not test them in this study, we expect the A722 equivalent bars produced by other manufacturers to perform similarly.

- **Hot-dipped Galvanized Threadbar®** is not a viable material for the application. We had difficulty during the tests threading galvanized nuts onto the galvanized bars, even removing galvanizing to facilitate threading. Our laboratory testing indicated that this material has some susceptibility to hydrogen cracking with the residual hydrogen in the as-received galvanized form. We did not recommend a galvanized coating system following our Phase 1 literature review, as galvanized coatings have a limited life of protection and poor bond adhesion to cementitious grout. The Phase 2 testing provides further corroboration that galvanized Threadbar® is not a viable option.

- **Custom 450** precipitation-hardened stainless steel in the H1050 heat treatment condition meets the strength and ductility requirements of the project. It has the best toughness, though less than the target toughness, of the non-duplex materials. However, it has limited resistance to pitting corrosion and stress corrosion cracking in high chloride concentrations and we found it susceptible to hydrogen embrittlement. Stainless steel materials are less susceptible to general surface corrosion than carbon steel in atmospheric conditions; however, the precipitation-hardened stainless steels did not perform well in our chloride-rich accelerated corrosion testing environment.

- **Custom 630** precipitation-hardened stainless steel 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 our testing and exhibited similar susceptibility to hydrogen embrittlement.

- **Alloy 2507** duplex stainless steel exhibited excellent resistance to pitting corrosion, stress corrosion cracking, and hydrogen embrittlement. The material performed exceptionally well in our accelerated corrosion testing environment, which is expected for a duplex stainless steel commonly used in the petrochemical industry. The toughness, as measured by the Charpy V-notch test, at the design low temperature was an order of magnitude greater than all other materials tested. In assessing the Alloy 2507 as a candidate material, its lack of a track record in this innovative application should be considered.

  In addition, the following three aspects of the Alloy 2507's mechanical behavior are relevant and required further study to understand the mechanical behavior for its use:

  - The tensile and yield strengths are less than the properties assumed in the original design based on typical high-strength carbon steel anchorage bars. M&M has reviewed this and modified the arch anchorage to accommodate the lower strengths.

  - Our first set of relaxation tests did not achieve initial loads suitable to quantify the relaxation performance and compare to reference standards. Additional relaxation testing at a higher initial load demonstrated relaxation values slightly higher than the reference British Standard but less than the Japanese Standard. Estimates of long-term prestress losses, including relaxation, result in effective pretension values within the anticipated range and these values were considered in the final design by M&M.

  - 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. Inelastic behavior testing of Alloy 2507 under cyclic tensile loading beyond the effective pretension demonstrated stable linear behavior at design tensile forces less than the prior maximum applied load.

Table 6-1 –Performance of Anchorage Bar Candidate Materials

Property	Custom 450 H1050	Custom 630 H1100	Alloy 2507	Threadbar® - Plain	Threadbar® - Galvanized
Tensile Strength	OK	OK	Below Target	OK	OK
Yield Strength	OK	OK	Below Target	OK	OK
Tensile Elongation (Ductility)	OK based on mill certificate	OK based on mill certificate	Excellent	OK	OK
Coupling Nut	Passed	Passed	Passed	Passed	Difficult to thread
End Nut	Passed	Passed	Passed	Passed	Difficult to thread
Stress Relaxation	Passed	Passed	Greater than BS 4486; Less than JIS G3109	Passed	Passed
Hardness	OK	OK	OK	OK	OK
Toughness	Below AASHTO Target	Below AASHTO Target	Excellent	Below Target; lowest of the tests	Below Target; similar to Plain
Galling	Susceptible	Susceptible	Susceptible	Susceptible, but highest resistance	Did not test galvanized surfaces
Pitting Corrosion	Susceptible at ambient temperature	Susceptible at ambient temperature	Requires high temperature to pit (185°F)	Prone to general surface corrosion	
Stress Corrosion Cracking	Susceptible	Susceptible	Passed	Did not crack, but heavily corroded	
Hydrogen Embrittlement	Susceptible when H-charged	Susceptible when H-charged	Performed well in tests	Susceptible when H-charged	Susceptible in as-received condition
Additional Considerations			Stable inelastic behavior		

7. RECOMMENDATIONS

7.1 Material

We considered the relative performance of each candidate material throughout the testing program, and conducted the benefit and risk assessment shown in Table 7-1.

The first-tier anchorage bar material candidates for the I-74 Bridge are the Alloy 2507 duplex and the traditional plain high-strength, carbon-steel bar (Threadbar®) with a corrosion protection system.

In our tests, the Alloy 2507 duplex showed excellent toughness and resistance to pitting corrosion, stress corrosion cracking, and hydrogen embrittlement. The material strength is below target, however further testing of its relaxation behavior and performance in the inelastic range demonstrated mechanical properties acceptable to M&M. Based on the cost of procurement for this test program, the Alloy 2507 represents an increase in initial cost over traditional plain high-strength, carbon-steel bar, but the relative costs should be determined through pricing that considers actual project procurement. If the materials' lack of track record in this application is acceptable, the owner may find that the corrosion resistance and reduction in maintenance afforded by Alloy 2507 over the 100 years may offset the additional initial cost.

The plain high-strength, carbon steel bar (Threadbar®) is the traditional system with mechanical and corrosion performance well understood in this application. It is susceptible to corrosion and hydrogen embrittlement, but these shortcomings can be addressed with a robust corrosion protection system. Traditional corrosion protection systems employ grouted sleeves. For additional corrosion protection, a dual system of grout sleeves and sacrificial cathodic protection can be considered. The most important aspect of corrosion protection of this system is the detailing of the anchorage ends at the arch-to-buttress connections. These end anchorages will require periodic inspection and maintenance throughout the bridge life.

The Custom 450 and Custom 630 materials demonstrated good strength and ductility and better resistance to surface corrosion than the plain high-strength, carbon steel bar material. However, they have marginal toughness and are susceptible to pitting corrosion and stress corrosion cracking in the presence of chlorides. They, also, have no track record in this particular application. The chloride susceptibility would require a corrosion protection system similar to that required for the conventional, high-strength, carbon steel bar. Given the need for a corrosion protection system, the relative lack of track record, and the cost of these materials, there is no apparent advantage to them over a Threadbar® system with corrosion protection. The Custom 450 performed slightly better than the Custom 630 in our test program.

We do not recommend galvanized carbon steel anchorage bars for this application. As stated in our Phase 1 report, the risk of hydrogen embrittlement is high in this high stress service environment and the potential benefits from improved corrosion resistance are offset by the limited life extension due to consumption of the zinc and the possible impairment of the bond to cementitious grout.

7.2 Material Selection and Design Revisions

M&M recommended the selection of Alloy 2507 for the anchorage bars as detailed in the memo included in Appendix P. M&M initially determined the effective pretension force after losses to be between 391 kips maximum and 311 kips minimum; however, we understand the design team has further refined these calculations. For the bridge, M&M specified the Alloy 2507 anchorage bars with a 3 in. (76.2 mm) outside diameter of thread crests, an effective area of 6.14 sq in. (3,960 mm^2), a minimum tensile strength of 116 ksi (800 MPa), and an initial pre-stretch load of 553 kips or 90 ksi (2,460 kN or 621 MPa). M&M also revised the contract drawings for the arch rib to concrete as shown in Appendix P.

SGH prepared a Special Provision (or specification section) for the corrosion resistant material selected for the project in coordination with Benesch and M&M. The final Special Provision issued by the Iowa DOT is contained in Appendix P. This special provision could serve as a starting point for an eventual ASTM/AASHTO material standard for the stainless steel anchorage bar.

The revised Contract Drawings and Special Provision were included in a project addendum in late March 2017.

Table 7-1 – Benefits and Risks of Anchorage Bar Candidate Materials

Material	Benefits	Risks
Threadbar® – Plain	• Meets strength and ductility requirements • Track record of proven performance in post-tensioned anchorage bar applications	• Marginal toughness at design low temperature • Unprotected carbon steels are prone to general surface corrosion, especially in the presence of chlorides • Protection system required and needs to be maintained and inspected.
Threadbar® – Galvanized	• None over other materials	• Susceptible to hydrogen embrittlement in the as-received condition without the addition of hydrogen from service conditions • Difficulty threading coupling and end nuts • Manufacturers either do not recommend galvanizing or provide caution and strict execution requirements
Custom 450 H1050	• Meets strength and ductility requirements • Better resistance to general surface corrosion than carbon steels	• Marginal toughness at design low temperature • Susceptible to pitting and stress corrosion cracking in the presence of chlorides • Protection system required and needs to be maintained and inspected • No track record in structural applications

Custom 630 H1100	• Meets strength and ductility requirements • Better resistance to general surface corrosion than carbon steels	• Marginal toughness at design low temperature • Susceptible to pitting and stress corrosion cracking in the presence of chlorides • Protection system required and needs to be maintained and inspected • No track record in structural applications
Alloy 2507	• Superior corrosion resistance to other materials • Superior toughness to other materials at all temperatures • Does not require corrosion protection system • High ductility and elongation capability	• Available strengths less than target design strengths • Performance of gradual yielding materials unknown in post-tensioned applications • No track record in structural applications • Stress relaxation slightly higher than allowable values in reference standards

8. REFERENCE MATERIAL

8.1 References and Bibliography

American Association of State Highway and Transportation Officials – AASHTO [2012], *AASHTO LRFD Bridge Design Specifications*, U.S. Customary Units, 6th Edition, American Association of State Highway Officials, Washington, D.C., 1672 pp.

ACI Committee 318 [2014], *Building Code Requirements for Structural Concrete* (ACI 318-14), and *Commentary on Building Code Requirements for Structural Concrete* (ACI 318R-14) American Concrete Institute, Farmington Hills, MI, 524 pp.

ASME B1.1 [2004], *Unified Inch Screw Threads (UN and UNR Thread Form)*, B1.1 - 2003 (Re-Affirmed 2008), American Society of Mechanical Engineers, New York, NY, 178 pp.

ASME B18.2.2 [2015], *Nuts for General Applications: Machine Screw Nuts, Hex, Square, Hex Flange, and Coupling Nuts (Inch Series)*, American Society of Mechanical Engineers, New York, NY, 22 pp.

ASTM A276 [2017], *Standard Specification for Stainless Steel Bars and Shapes*, ASTM A276/A276M-17, ASTM International, West Conshohocken, PA, 8 pp.

ASTM A320 [2017], *Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service*, ASTM A320/A320M-17, ASTM International, West Conshohocken, PA, 8 pp.

ASTM A354 [2011], *Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners,* ASTM A354-11, ASTM International, West Conshohocken, PA, 7 pp.

ASTM A370 [2017], *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A370-17*,* ASTM International, West Conshohocken, PA, 49 pp.

ASTM A416 [2016], *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete,* ASTM A416/A416M-16*,* ASTM International, West Conshohocken, PA, 5 pp.

ASTM A421 [2015], *Standard Specification for Stress-Relieved Steel Wire for Prestressed Concrete,* ASTM A421/A421M-15*,* ASTM International, West Conshohocken, PA, 4 pp.

ASTM A564 [2013], *Standard Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes*, ASTM A564/A564M-13, ASTM International, West Conshohocken, PA, 8 pp.

ASTM A709 [2016], *Standard Specification for Structural Steel for Bridges,* ASTM A709/A709M-16a, ASTM International, West Conshohocken, PA, 8 pp.

ASTM A722 [2015], *Standard Specification for High-Strength Steel Bars for Prestressed Concrete,* ASTM A722/A722M-15, ASTM International, West Conshohocken, PA, 5 pp.

ASTM A962 [2016], *Standard Specification for Common Requirements for Bolting Intended for Use at Any Temperature from Cryogenic to the Creep Range,* ASTM A962/A962M-16b*,* ASTM International, West Conshohocken, PA, 12 pp.

ASTM A967 [2013], *Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts,* ASTM A967/A967M-13, ASTM International, West Conshohocken, PA, 8 pp.

ASTM A1061 [2016], *Standard Test Methods for Testing Multi-Wire Steel Prestressing Strand,* ASTM A1061/A1061M-16, ASTM International, West Conshohocken, PA, 4 pp.

ASTM E8 [2016], *Standard Test Methods for Tension Testing of Metallic Materials*, ASTM E8/E8M–16, ASTM International, West Conshohocken, PA, 30 pp.

ASTM E10 [2015], *Standard Test Method for Brinell Hardness of Metallic Materials*, ASTM E10/E10M–15, ASTM International, West Conshohocken, PA, 32 pp.

ASTM E18 [2016], *Standard Test Methods for Rockwell Hardness of Metallic Materials*, ASTM E14/E14M–16, ASTM International, West Conshohocken, PA, 38 pp.

ASTM E23 [2016], *Standard Test Methods for Notched Bar Impact Testing of Metallic Materials*, ASTM E23-16, ASTM International, West Conshohocken, PA, 25 pp.

ASTM E140 [2012], *Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness* ASTM E140 - 12be1, ASTM International, West Conshohocken, PA, 25 pp.

ASTM E146 [1983], *Methods of Chemical Analysis of Zirconium and Zirconium Alloys (Silicon, Hydrogen, and Copper)* (Withdrawn 1989), ASTM E146-83, ASTM International, West Conshohocken, PA, 34 pp.

ASTM E328 [2013]*, Standard Test Methods for Stress Relaxation for Materials and Structures*, ASTM E328-13, ASTM International, West Conshohocken, PA, 15 pp.

ASTM A399 [2012], *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials*, ASTM E399-12e3, ASTM International, West Conshohocken, PA, 33 pp.

ASTM E466 [2015]*, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials,* ASTM E466-15, ASTM International, West Conshohocken, PA, 6 pp.

ASTM E606 [2012]*, Standard Test Method for Strain-Controlled Fatigue Testing*, ASTM E606/E606M-12, ASTM International, West Conshohocken, PA, 16 pp.

ASTM F606 [2016], *Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets*, ASTM F606/F606M-16, ASTM International, West Conshohocken, PA, 19 pp.

ASTM F1624 [2012], *Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique,* ASTM F1624 - 12, ASTM International, West Conshohocken, PA, 12 pp.

ASTM F2329 [2013], *Standard Specification for Zinc Coating, Hot-Dip, Requirements for Application to Carbon and Alloy Steel Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners*, ASTM F2329 – 13, ASTM International, West Conshohocken, PA, 5 pp.

ASTM F3125 [2015], *Standard Specification for High Strength Structural Bolts, Steel and Alloy Steel, Heat Treated, 120 ksi (830 MPa) and 150 ksi (1040 MPa) Minimum Tensile Strength, Inch and Metric Dimensions*, ASTM F3125/F3125M-15a, ASTM International, West Conshohocken, PA, 13 pp.

ASTM G36 [2013], *Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution*, ASTM G36-94(2013), ASTM International, West Conshohocken, PA, 7 pp.

ASTM G38 [2013], *Standard Practice for Making and Using C-Ring Stress-Corrosion Test Specimens*, ASTM G38-01(2013), ASTM International, West Conshohocken, PA, 8 pp.

ASTM G48 [2011], *Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution*, ASTM G48-11, ASTM International, West Conshohocken, PA, 11 pp.

ASTM G49 [2011], *Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens*, ASTM G49-85(2011), ASTM International, West Conshohocken, PA, 6 pp.

ASTM G98 [2009], *Standard Test Method for Galling Resistance of Materials*, ASTM G98-02(2009), ASTM International, West Conshohocken, PA, 4 pp.

ASTM G123 [2015], *Standard Test Method for Evaluating Stress-Corrosion Cracking of Stainless Alloys with Different Nickel Content in Boiling Acidified Sodium Chloride Solution*, ASTM G123-00(2015), ASTM International, West Conshohocken, PA, 10 pp.

British Standards Institute – BS 4486 [1980], *Specification for hot rolled and hot rolled and processed high tensile alloy steel bars for the prestressing of concrete*, BS 4486 - Reaffirmed November 2012, British Standards Institute, London, United Kingdom, 8 pp.

British Standards Institute – BS 8081 [2015], *Code of Practice for Grouted Anchors*, BS 8081:2015, BSI Standards Limited, London, United Kingdom, 146 pp.

European Committee for Standardization – EN 10138-4 [2000], *Prestressing steels - Part 4: Bars*, Draft, Comite Europeen de Normalisation (CEN), Brussels, Belgium, September, 11 pp.

European Organization for Technical Approvals – EOTA [2002], *Guideline for European Technical Approval of Post-Tensioning Kits for Prestressing of Structures*, ETAG 013, European Organisation for Technical Approvals, Brussels, Belgium, 136 pp.

Industrial Fasteners Institute [2014], *Inch Fastener Standards*, 9th Edition, Industrial Fasteners Institute (IFI), Cleveland, OH, 1146 pp.

Japanese Industrial Standard – JIS G3109 [2008], *Steel Bars for Prestressed Concrete*, Japanese Standards Association, Tokyo, Japan, 10 pp.

Koepfer, C. [2003], "Rolling Threads Has Advantages," *Modern Machine Shop*, <http://www.mmsonline.com/articles/rolling-threads-has-advantages>, Web Article (March 2015).

Modjeski and Masters, Inc. [2015], "Bridges for Service Life Beyond 100 Years: Service Limit State Design," *SHRP2 Report S2-R19B-RW-1,* Second Strategic Highway Research Program (SHRP2), Transportation Research Board, Washington, D.C., 509 pp.

Modjeski and Masters, Inc. [2017], "I74 MRB Arch Rib Interface Post Tension Bars - Material Recommendation," *Project Memorandum to Alfred Benesch & Company*, 27 February, 4 pp.

Reed Machinery [2014], *Thread Forming and Rolling*, Technical Data, < http://www.reed-machinery.com/pdf/thread-and-form-rolling-tech-data-master.pdf>, Reed Machinery Inc., Worcester, MA, 35 pp., Web Article (December 2014).

8.2 Technical and Equipment Information Summary

Tensile and Coupling Nut Tests

Test Fixture: 5-million pound capacity, 6-story, Baldwin Universal Testing Machine, Fritz Engineering Laboratory, Lehigh University, Bethlehem, PA. Last calibration date was 12 October 2016 according to ASTM E4. Instron® Calibration Laboratory performed the calibration

Displacement Monitoring: Extensometers consist of two (2), 4 in. long linear potentiometer displacement transducers mounted to brackets. BEI Duncan makes the displacement transducers and the brackets were made in the lab. Gage lengths were set by lab staff.

Data Acquisition: CR5000 data logger data acquisition system and software from Campbell Scientific (Logan, UT)

End Nut Tests

Load Monitoring: Geokon electrical resistance strain gage load cell, 1,000 kip capacity, 6" ID paired with a Geokon Model GK-502 Load Cell Readout monitor (Lebanon, NH).

Load Application: Simplex RCD5006C Center-Hole Ram, 646-ton capacity (1,292 kips). Center hole inside diameter = 5.25 in., Stroke = 6 in., Maximum pressure = 10,000 psi (Menomonee Falls, WI)

Displacement Monitoring: UniMeasure PA-10-DS series precision potentiometer, position transducers (Corvallis, OR).

Relaxation Tests

Load Monitoring: Geokon, 6 vibrating wire strain gage, center-hole load cells, 850 kip capacity, 3 in. inside diameter hole (Lebanon, NH).

Load Application: Simplex RCD5006C Center-Hole Ram (see above)

Displacement Monitoring: UniMeasure PA-10-DS series precision potentiometer, position transducers (Corvallis, OR).

Data Acquisition: Strainsmart 7000 data acquisition system and software from Micro-Measurements (Wendell, NC)

Load Frames: Fabricated by: Benchmark Fabricated Steel, Terre Haute, IN. Special thanks to Ted Hazledine, Dale Arnett, and Clint Davis.

Hardness (Rockwell) Tests

Tests conducted by: SGH Laboratory, Waltham, MA

Charpy V-Notch (Toughness) Tests

Tests conducted by: Massachusetts Materials Research, West Boylston, MA

Galling Tests

Tests conducted by: SGH Laboratory, Waltham, MA

Pitting Corrosion Tests

Tests conducted by: SGH Laboratory, Waltham, MA

Stress Corrosion Cracking Tests

Tests conducted by: Corrosion Testing Laboratories, Newark, DE

Hydrogen Embrittlement Tests

Tests conducted by: SGH Laboratory, Waltham, MA

Trepanning

Midwest Precision Manufacturing, Fredonia, WI

Bar Fabrication

Dywidag-Systems International (DSI), Bolingbrook, IL

Plate Washer Fabrication

Waukegan Steel Corporation, Waukegan, IL. Special thanks to Ernie Burchall for promptly fitting us into their cutting schedule.

Transportation Services

Wal-Zon Transfer Inc., St. Paul, MN, Special thanks to the coordination efforts of Branden Petroff.

I:\CHI\projects\2014\141685.10-P2AB\WP\016NSAnderson-R-141685.10.tmk.docx

Appendix A - Post-tensioned (P/T) bar standard requirements

Appendix A contains tables from our Phase 1 report listing the post-tension bar requirements in the various relevant standards. The tables are as follows:

Appendix Table	Description	Phase 1 Report Table
A.1	Post-tensioned (P/T) bar requirements in ASTM A722 [2012] and BS 4486 [1980].	3.1
A.2	Post-tensioned (P/T) bar requirements in the Japanese Industrial Standard [JIS G 3109:2008]	3.5

Table A.1 - Post-tensioned (P/T) bar requirements in ASTM A722 [2012] and BS 4486 [1980].

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Type of Bar	Nominal Diameter d_b	Nominal Tensile Strength	Surface Type	Nominal Yield Stress	Nominal Cross-Sectional Area	Nominal Mass (or Weight)	Specified Properties			Max. Relaxation at 1000 hours		Chemical Composition	
							Characteristic Breaking Load	Characteristic 0.1% Proof Load	Min. Elongation at Fracture	Initial Load as a % of the actual breaking load	Value	Maximum Phosphorus (P)	Maximum Sulfur (S)
	in. (mm)	psi (MPa)		psi (MPa)	in.^{2} (mm^2)	lbs/ft (kg/m)	lbs (kN)	lbs (kN)		%	%	%	%
ASTM A722 Type I													
	3/4 (19)	150,000 (1035)	Plain	127,500 (880) At nominal 0.2% offset	0.44 (284)	1.50 (2.23)	Not Specified	Not Specified	4.0% for a 20d_b gage length or 7.0% for a 10d_b gage length	No requirement		0.040	0.050
	7/8 (22)				0.60 (387)	2.04 (3.04)							
	1 (25)				0.78 (503)	2.67 (3.97)							
	1 1/8 (29)				0.99 (639)	3.38 (5.03)							
	1 1/4 (32)				1.23 (794)	4.17 (6.21)							
	1 3/8 (35)				1.48 (955)	5.05 (7.52)							
ASTM A722 Type II													
	5/8 (15)	150,000 (1035)	Deformed	120,000 (828) At nominal 0.2% offset	0.28 (181)	0.98 (1.46)	Not Specified	Not Specified	4.0% for a 20d_b gage length or 7.0% for a 10d_b gage length	No requirement		0.040	0.050
	3/4 (20)				0.42 (271)	1.49 (2.22)							
	1 (26)				0.85 (548)	3.01 (4.48)							
	1 1/4 (32)				1.25 (806)	4.39 (6.54)							
	1 3/8 (36)				1.58 (1019)	5.56 (8.28)							
	1 3/4 (46)				2.58 (1664)	9.10 (13.54)							
	2 1/2 (65)				5.16 (3331)	18.20 (27.10)							
	3 (75)				6.85 (4419)	24.09 (35.85)							
BS 4486													
Hot Rolled or Hot Rolled and Processed	1 (26.5)	149,275 (1030)	Smooth (RE) or deformed (RR)	121,100 (835) At nominal 0.1% proof stress	0.81 (522)	2.91 (4.33)	127,700 (568)	103,400 (460)	6.0% for a gage length of $5.65\sqrt{S_o}$ (where S_o is the cross-sectional area)	For all bars		0.040	0.040
	1.25 (32)				1.25 (804)	4.24 (6.31)	186,600 (830)	150,600 (670)		60	1.5		
	1.42 (36)				1.58 (1018)	5.37 (7.99)	235,600 (1048)	191,100 (850)					
	1.57 (40)				1.95 (1257)	6.63 (9.86)	292,300 (1300)	236,100 (1050)		70	3.5		
	1.97 (50)				3.04 (1963)	Size not in specification, although made							
	2.95 (75)				6.49 (4185)	Size not in specification, although made				80	6.0		

Table A.2 - Post-tensioned (P/T) bar requirements in the Japanese Industrial Standard [JIS G 3109:2008]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Type of Bar	**Nominal Diameter d_b in. (mm)**	**Nominal Tensile Strength psi (MPa)**	**Surface Type**	**Nominal Yield Stress psi (MPa)**	**Nominal Cross-Sectional Area in.^{2} (mm^2)**	**Nominal Mass (or Weight) lbs/ft (kg/m)**	**Specified Properties: Characteristic Breaking Load lbs (kN)**	**Characteristic 0.1% Proof Load lbs (kN)**	**Min. Elongation at Fracture**	**Max. Relaxation at 1000 hours: Initial Load as a % of the actual breaking load %**	**Value %**	**Chemical Composition (maximums) %**
Plain Bars												
	0.36 (9.2)				0.103 (66.48)	NA						
	0.43 (11)				0.147 (95.03)	NA						
SBPR	0.51 (13)				0.206 (132.7)	NA						
785/1030	*0.59 (15)*	150 (1030)		114 (785)	0.274 (176.7)	NA						
	0.67 (17)				0.352 (227.0)	NA						
930/1080	*0.75 (19)*	157 (1080)		135 (930)	0.439 (283.5)	NA						
	0.83 (21)		Plain		0.537 (346.4)	NA	Not Specified	Not Specified	5% min.	70%	4%	P 0.030 S 0.035 Cu 0.300
930/1180	0.91 (23)	171 (1180)		135 (930)	0.644 (415.5)	NA						
1080/1230	1.02 (26)	178 (1230)		157 (1080)	0.823 (530.9)	NA						
	1.14 (29)				1.024 (660.5)	NA						
	1.26 (32)				1.246 (804.2)	NA						
	1.42 (36)				1.578 (1018)	NA						
	1.57 (40)				1.948 (1257)	NA						
Deformed Bars												
SBPD	0.67 (17)				0.352 (227.0)	1.20 (1.78)						
785/1030	0.75 (19)	150 (1030)		114 (785)	0.439 (283.5)	1.50 (2.23)						
	0.79 (20)				0.487 (314.2)	1.66 (2.47)						
930/1080	0.87 (22)	157 (1080)		135 (930)	0.589 (380.1)	2.00 (2.98)						
	0.91 (23)		Deformed		0.644 (415.5)	2.19 (3.26)	Not Specified	Not Specified	5% min.	70%	4%	P 0.030 S 0.035 Cu 0.300
930/1180	0.98 (25)	171 (1180)		135 (930)	0.761 (490.9)	2.59 (3.85)						
1080/1230	1.02 (26)	178 (1230)		157 (1080)	0.823 (530.9)	2.80 (4.17)						
	1.26 (32)				1.246 (804.2)	4.24 (6.31)						
	1.42 (36)				1.578 (1018)	5.37 (7.99)						

Column (2) - Plain bar diameters shown in italic font and shaded are not encouraged for use per JIS.

Appendix B - Mill Datasheets

Appendix B contains the basic material datasheets from the stainless steel manufacturers (mills) that produced the stainless steels included in this project. The material datasheets include:

Material	Source
Alloy 2507 Duplex Stainless Steel	Sandvik
Custom 450 H1050 Precipitation Hardened Stainless Steel	Carpenter Technologies
Custom 630 H1100 Precipitation Hardened Stainless Steel	Carpenter Technologies

SANDVIK

SANDVIK SAF 2507
BAR

DATASHEET

Sandvik SAF 2507 is a high alloy duplex (austenitic-ferritic) stainless steel for service in highly corrosive conditions. The grade is characterized by:

- Excellent resistance to stress corrosion cracking in chloride-bearing environments
- Excellent resistance to pitting and crevice corrosion
- High resistance to general corrosion
- Very high mechanical strength
- Physical properties that offer design advantages
- High resistance to erosion corrosion and corrosion fatigue good weldability
- Excellent mechanical properties that allow for lighter constructions, more compact design and less welding

STANDARDS

- Uns: S32750
- EnNumber: 1.4410
- EnName: X2CrNiMoN25-7-4

Product standards

- EN 10088-3, (dimensions up to 160 mm)
- EN 10272, EN 10222-5
- ASTM A479, ASTM A276
- NORSOK MDS D57 Rev 4, Rev 5
- Suitable for manufacturing of components in accordance with ASTM A182

Approvals

Pressure Equipment Directive (97/23/EC)
NORSOK M650 Ed. 4, NORSOK M630 Ed. 6, dimensions up to 260 mm.
Pre-approval for PMA

Certificate

Status according to EN 10 204/3.1

CHEMICAL COMPOSITION (NOMINAL) %

Chemical composition (nominal) %

C	Si	Mn	P	S	Cr	Ni	Mo	N	Cu
≤0.030	≤0.8	≤1.2	≤0.035	≤0.015	25	7	4	0.3	≤0.5

2016/03/31 16:54:03

APPLICATIONS

Sandvik SAF 2507 is a duplex stainless steel especially designed for service in aggressive chloride-containing environments. Typical applications are:

- Oil and gas industry
- Seawater cooling
- Salt evaporation industry
- Desalination plants
- Geothermal wells
- Refineries and petrochemical plants
- Mechanical components requiring high strength
- Pulp and paper industry

FORMS OF SUPPLY

Finishes and dimensions

Sandvik SAF 2507 bar steel is stocked in a large number of sizes. The standard size range for stock comprises 20-250 mm, see pocket card S-02909. Round bar is supplied in solution annealed and water quenched condition. The surface is peeled turned and polished.

Lengths

Bars are delivered in random lengths of 3-7 m, depending on diameter.

Straightness

Diameter mm	Height of arch, mm/m Typical value
20 - 70	1
> 70	2

Tolerances, mm-sizes

Diameter, mm	Tolerances, mm
20-35	-0/+0.15
40-45	-0/+0.16
50-70	-0/+0.19
75-95	-0/+1.00
100-250	-0/+1.50

Surface conditions

Surface conditions	Ra, µm Typical value	Size, mm dia
Peeled and burnished	1	20-250

MECHANICAL PROPERTIES

Bar steel is tested in delivery condition.

The following figures apply to material in the solution annealed and quenched condition.

For small sections the proof strength values are higher than those listed below at 20 °C (68 °F).

2016/03/31 16:54:03

More detailed information can be supplied on request.

At 20°C (68°F)

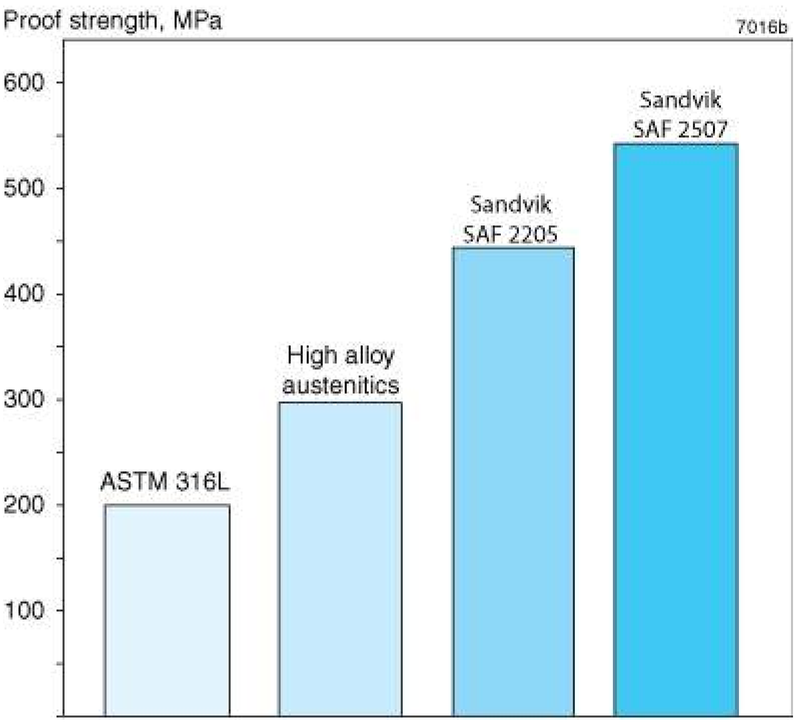
Metric units, bar

Proof strength	Tensile strength	Elong.	HB
$R_{p0.2}$[a)]	R_m	A[b)]	
MPa	MPa	%	
			approx.
≥550	760-930 [c)]	≥25	260

Imperial units, bar

Proof strength	Tensile strength	Elong.	Hardness
$R_{p0.2}$[a)]	R_m	A[b)]	Rockwell C
ksi	ksi	%	
≥80	110-135	≥25	≤28

1 MPa = 1 N/mm^2
a) $R_{p0.2}$ corresponds to 0.2% offset yield strength.
b) Based on $L_0 = 5.65\sqrt{S_0}$, where L_0 is the original gauge length and S_0 the original cross-section area.
c) For sizes below 50 mm/2" R_m min. 800 MPa.



At higher temperatures

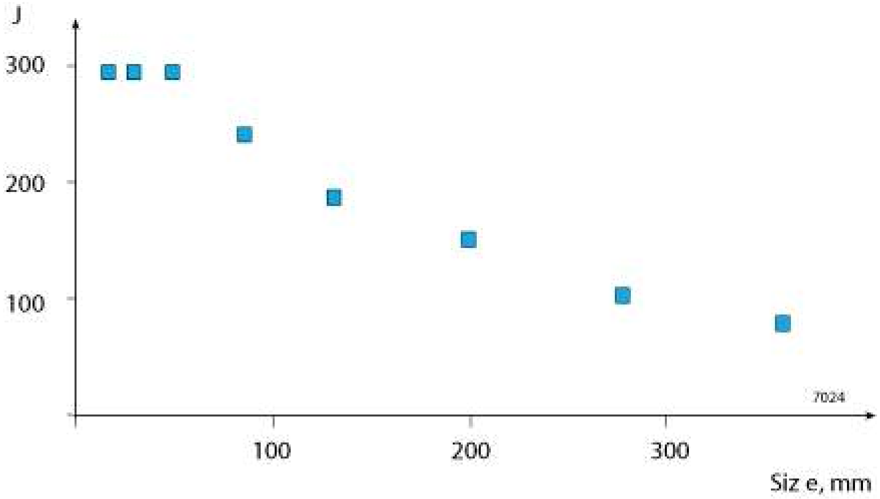
If Sandvik SAF 2507 is exposed for prolonged periods to temperatures exceeding 250°C (480°F), the microstructure changes which results in a reduction in impact strength. This effect does not necessarily affect the behaviour of the material at the operating temperature.

More detailed information can be supplied on request.

2016/03/31 16:54:03

Impact strength

Sandvik SAF 2507 possesses good impact strength. Figure 2 shows typical impact energy values for Sandvik SAF 2507 in different sizes at -20°C (-4°F), using standard Charpy V specimens. Samples taken in the longitudinal direction.



The impact energy (Charpy V) at 20°C (68°F) is min 100 J (74 ft-lb).

CORROSION RESISTANCE

General corrosion

Sandvik SAF 2507 is highly resistant to corrosion by organic acids, e.g. formic and acetic acid. It is suitable for use at high concentrations and temperatures, where austenitic stainless steels corrode at a high rate.

Resistance to inorganic acids is comparable to that of high alloy austenitic stainless steels in certain concentration ranges.

Pitting and crevice corrosion

The pitting and crevice corrosion resistance of a stainless steel is primarily determined by the content of chromium, molybdenum and nitrogen. An index for comparing the resistance to pitting and crevice corrosion is the PRE number (Pitting Resistance Equivalent).

The PRE is defined as, in weight-% PRE = %Cr + 3.3 x %Mo + 16 x %N

For duplex stainless steels the pitting corrosion resistance is dependent on the PRE-value in both the ferrite phase and the austenite phase, so that the phase with the lowest PRE-value will be limiting for the actual pitting corrosion resistance. In Sandvik SAF 2507 the PRE-value is equal in both phases, which has been achieved by a careful balancing of the elements.

The minimum PRE-value for Sandvik SAF 2507 is 41. This is significantly higher than e.g. the PRE-values for other duplex stainless steels of the 25Cr type which are not "super-duplex". As an example UNS S31260 (25Cr3Mo0.2N) has a PRE-value of typically 38.

One of the most severe pitting and crevice corrosion tests applied to stainless steel is ASTM G48, i.e., exposure to 6% $FeCl_3$ with and without crevices (method A and B respectively). When pits are detected following a 24 hours exposure, together with a substantial weight loss (>5 mg), the test is interrupted. Otherwise the temperature is increased 5°C (9°F) and the test is continued with the same sample. Figure 4 shows critical pitting and crevice temperatures (CPT and CCT) from this test.

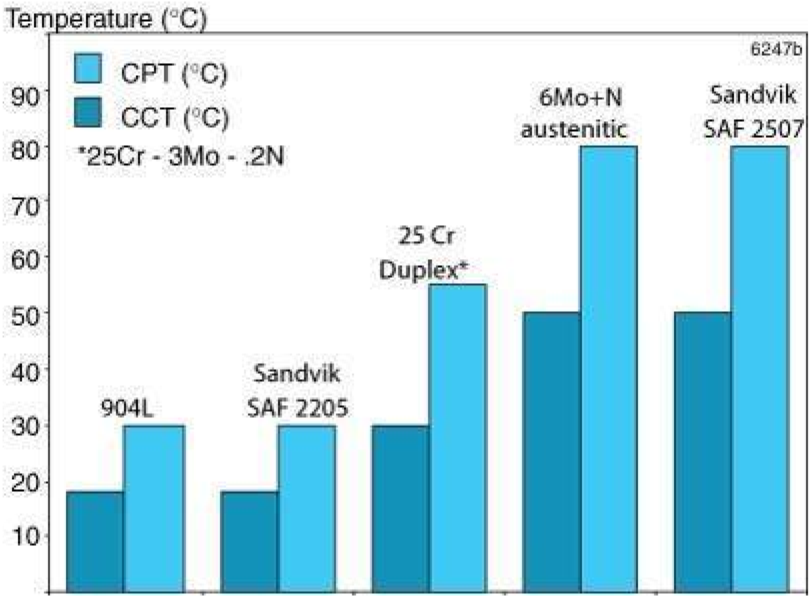


Figure 4. Critical pitting and crevice temperatures in 6% $FeCl_3$. 24h (similar to ASTM G48).

Stress corrosion cracking

Sandvik SAF 2507 has excellent resistance to chloride induced stress corrosion cracking.

Erosion corrosion and corrosion fatigue

The superior mechanical properties combined with the improved corrosion resistance of Sandvik SAF 2507 result in excellent resistance to both erosion corrosion and corrosion fatigue compared to standard austenitic stainless steels.

MACHINING

Being a two-phase material (austenitic-feritic) Sandvik SAF 2507 will present a different wear picture from that of single-phase steels of type ASTM 304L. The cutting speed must therefore be lower than that recommended for ASTM 304L. It is recommended that a tougher insert grade is used than when machining austenitic stainless steels, e.g. ASTM 304L. Also in comparison with SANMAC SAF 2205 lower speed and tougher insert grade is recommended. Machining recommendations available on request. More cutting data information for Sandvik SAF 2507 is available in the product handbook S-02909-ENG, these recommendations could act as guidelines in choice of appropriate cutting data.

PHYSICAL PROPERTIES

Density: 7.8 g/cm^3, 0.28 lb/in^3

Specific heat capacity

Metric units, Imperial units

Temperature, °C	J/(kg °C)	Temperature, °F	Btu/(lb °F)
20	490	68	0.12
100	505	200	0.12
200	520	400	0.12
300	550	600	0.13
400	585	800	0.14

Thermal conductivity

Metric units, W/(m °C)

2016/03/31 16:54:03

Temperature, °C	20	100	200	300	400
SAF 2507	14	15	17	18	20
AISI 316L	14	15	17	18	20

Imperial units, Btu/(ft h °F)

Temperature, °F	68	200	400	600	800
SAF 2507	8	9	10	11	12
AISI 316L	8	9	10	10	12

Thermal expansion

Sandvik SAF 2507 has a coefficient of thermal expansion close to that of carbon steel. This gives Sandvik SAF 2507 definite design advantages over austenitic stainless steels in equipment comprising of both carbon steel and stainless steel. The values given below are average values in the temperature ranges.

Metric units, x10^{-6}/°C

Temperature, °C	30-100	30-200	30-300	30-400
SAF 2507	13.5	14.0	14.0	14.5
Carbon Steel	12.5	13.0	13.5	14.0
AISI 316L	16.5	17.0	17.5	18

Imperial units, x10^{-6}/°F

Temperature, °F	86-200	86-400	86-600	86-800
SAF 2507	7.5	7.5	8.0	8.0
Carbon Steel	6.8	7.0	7.5	7.8
AISI 316L	9.0	9.5	10.0	10.0

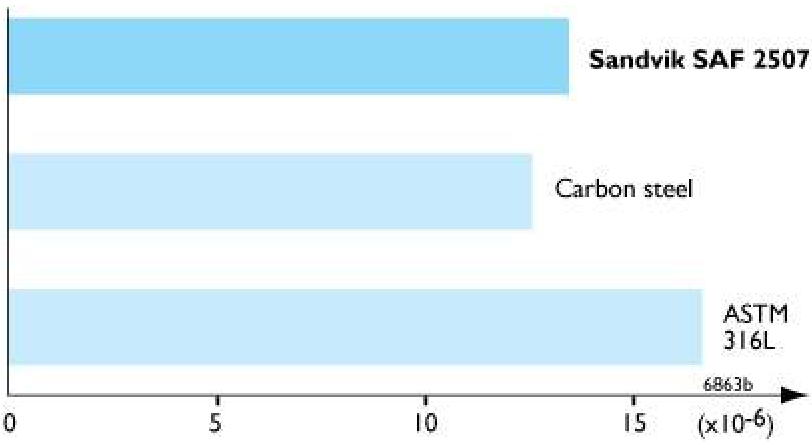


Figure 3. Thermal expansion, per °C (30-100°C, 86-210°F).

Resistivity

Temperature, °C	μΩm	Temperature, °F	μΩin.
20	0.83	68	32.7

Temperature, °C	μΩm	Temperature, °F	μΩin.
100	0.89	200	34.9
200	0.96	400	37.9
300	1.03	600	40.7
400	1.08	800	43.2

Modulus of elasticity, (x10^3)

Metric units Imperial units

Temperature, °C	MPa	Temperature, °F	ksi
20	200	68	29.0
100	194	200	28.2
200	186	400	27.0
300	180	600	26.2

HEAT TREATMENT

Bars are normally delivered in solution annealed and quenched condition. Additional heat treatment, as recommended below is only needed if further hot working has been made.

Solution annealing

Slow heating up to 1000°C (1830°F). Annealing at 1050-1125°C (1920-2060°F), followed by quenching.

Stress relief heat treatment at 350°C (660 °F) for 5h followed by air cooling

WELDING

The weldability of Sandvik SAF 2507 is good. Suitable welding methods are manual metal-arc welding with covered electrodes or gas-shielded arc welding. Welding should be undertaken within the heat input range of 0.2-1.5 kJ/mm and with an interpass temperature of maximum 150°C (300°F). Preheating or post-weld heat treatment is not necessary.

Matching filler metals are recommended in order to obtain a weld metal with optimum corrosion resistance and mechanical properties. For gas-shielded arc welding use Sandvik 25.10.4.L, and for manual metal-arc welding the covered electrode Sandvik 25.10.4.LR.

Technical Datasheet CARPENTER

CarTech® Custom 450® Stainless

Identification

UNS Number
- S45000

Type Analysis

Single figures are nominal except where noted.

Carbon (Maximum)	0.05 %	**Manganese (Maximum)**	1.00 %
Phosphorus (Maximum)	0.030 %	**Sulfur (Maximum)**	0.030 %
Silicon (Maximum)	1.00 %	**Chromium**	14.00 to 16.00 %
Nickel	5.00 to 7.00 %	**Molybdenum**	0.50 to 1.00 %
Copper	1.25 to 1.75 %	**Columbium/Niobium**	8 X C Minimum
Iron	Balance		

General Information

Description

CarTech Custom 450 stainless is a martensitic age-hardenable stainless steel which exhibits very good corrosion resistance (similar to that of CarTech 304 stainless) with moderate strength (similar to that of Stainless Type 410). The alloy has a yield strength somewhat greater than 100 ksi (689 MPa) in the annealed condition, but is easily fabricated. A single-step aging treatment develops higher strength with good ductility and toughness.

This stainless can be machined, hot-worked, and cold-formed in the same manner as other martensitic age-hardenable stainless steels. A particular advantage is ease of welding and brazing.

CarTech Custom 450 stainless is generally supplied in the annealed condition, requiring no heat treatment by the user for many applications. Because it has corrosion resistance like CarTech 304 stainless but three times the yield strength, it has been used in applications where CarTech 304 was not strong enough. On the other hand, it has also replaced Type 410 stainless directly on a strength basis where CarTech 410 had insufficient corrosion resistance. Mechanical properties will depend on the aging temperature selected.

Selection

There are a number of other alloys that are available for specific applications.

Grade: Custom 630 stainless
Characteristic: Similar to Custom 450 stainless, but must be aged prior to use. It cannot be used in the solution-annealed condition.

Grade: 15Cr-5Ni stainless
Characteristic: Similar to Custom 630 stainless, but has better transverse ductility and toughness.

Grade: Pyromet® Alloy 350
Characteristic: Depending on heat treatment, can have an austenitic structure for best formability, or a martensitic structure, for higher strength up to intermediate elevated temperatures.

Grade: Pyromet Alloy 355
Characteristic: Similar to Pyromet Alloy 350 but with a lower ferrite content.

Elevated Temperature Use

Custom 450 stainless shows excellent resistance to oxidation up to approximately 1200°F (649°C). Significant aging occurs when annealed material is heated to 700°F (371°C) and higher.

Long-term exposure to elevated temperatures can result in reduced toughness in precipitation hardenable stainless steels. The reduction in toughness can be minimized in some cases by using higher aging temperatures. Short exposures to elevated temperatures can be considered, provided the maximum temperature is at least 50°F (28°C) less than the aging temperature.

Corrosion Resistance

Custom 450 stainless has resisted atmospheric corrosion including salt water atmospheres. It shows excellent resistance to rusting and pitting in 5% and 20% salt spray at 95°F (35°C). Tests in hot concentrated nitric acid show corrosion resistance approaching that of Type 304.

Optimum corrosion resistance for this alloy is obtained in the annealed condition. However, age hardening results in only a slight change.

For optimum corrosion resistance, surfaces must be free of scale, lubricants, foreign particles, and coatings applied for drawing and heading. After fabrication of parts, cleaning and/or passivation should be considered.

Sour Service:
Custom 450 stainless has acceptable resistance to sulfide stress cracking at Rockwell C 31 maximum hardness per NACE MR-01-75, "Sulfide Stress Cracking Resistant Metallic Materials for Oil field Equipment." Refer to the current document for details on acceptable conditions. A comparison is made for alloys heat treated in accordance with MR-01-75 requirements. Threshold stresses are intended for comparative purposes only and should not be used as design stress level.

Important Note: *The following 4-level rating scale is intended for comparative purposes only. Corrosion testing is recommended; factors which affect corrosion resistance include temperature, concentration, pH, impurities, aeration, velocity, crevices, deposits, metallurgical condition, stress, surface finish and dissimilar metal contact.*

Nitric Acid	Good	Sulfuric Acid	Restricted
Phosphoric Acid	Restricted	Acetic Acid	Moderate
Sodium Hydroxide	Moderate	Salt Spray (NaCl)	Good
Sea Water	Restricted	Sour Oil/Gas	Moderate
Humidity	Excellent		

Effect of Aging on Typical Corrosion Resistance in Acid Solutions

Condition	Rockwell C Hardness	48-Hour Corrosion Rate in mpy		
		20% nitric acid at 200°F (93°C)	5% sulfuric acid at 75°F (24°C)	50% acetic acid boiling
A	30	2	1	1
H 900	41	2	1	1
H 1000	37	2	3	1
H 1150	30	2	9	1

Typical Corrosion Resistance of Various Stainless Steels in Acid Solutions

Alloy	Rockwell Hardness	48-Hour Corrosion Rate in mpy		
		20% nitric acid at 200°F (93°C)	5% sulfuric acid at 75°F (24°C)	50% acetic acid boiling
Type 410	C 45	8	1732*	266*
Type 431	C 45	3	1402*	43*
17Cr-4Ni	C 42	2	2	3
Custom 450	C 41	2	1	1
Type 304	B 80	1	11	1

*Several or all of subsequent 48-hour test periods showed nil rate.

Typical Results for Precracked Cantilever Beam Stress-Corrosion-Cracking Tests
Condition H 900

Test Media	Stress Intensity		Time to Fail
	ksi $\sqrt{in}$	MPa $\sqrt{m}$	
Air	22.5	24.7	—
Air	23.7	26.0	—
3.5% NaCl (pH 3.6) at 75°F (24°C)	18.7	20.6	No failure in 1800-hr. test
3.5% NaCl (pH 3.6) at 75°F (24°C)	20.6	22.6	No failure in 1200-hr. test

Typical Results for U-Bend Stress-Corrosion Tests

Form	Condition	Rockwell C Hardness	Specimen Orientation	No. of Specimens Tested	Environment	Results
0.105" (2.67mm) strip	H 900	43	Longitudinal to rolling direction	5	5% Salt Spray 95°F (35°C)	No cracking in 290-day test
0.105" (2.67mm) strip	H 900	43	Transverse	4	5% Salt Spray 95°F (35°C)	No cracking in 290-day test
0.105" (2.67mm) strip	H 1000	39	Longitudinal	5	5% Salt Spray 95°F (35°C)	No cracking in 290 day test
0.105" (2.67mm) strip	H 1000	39	Transverse	4	5% Salt Spray 95°F (35°C)	No cracking in 290-day test
1$^1/_{32}$" (26.2mm) round bar	H 900	40	Longitudinal	5	5% Salt Spray 95°F (35°C)	No cracking in 220 day test
1$^1/_{32}$" (26.2mm) round bar	H 1000	37	Longitudinal	5	5% Salt Spray 95°F (35°C)	No cracking in 220 day test
0.125" (3.18mm) strip	H 900	41	Transverse	5	Kure Beach 80 Lot	No cracking in 15 years

Typical Stress-Corrosion-Cracking Resistance per NACE TM-01-77 (a)

Alloy	Condition	0.2% Yield Strength		Ultimate Tensile Strength		Rockwell C Hardness	Threshold Stress Level (b) as Percent of Yield Strength
		ksi	MPa	ksi	MPa		
Custom 450	H 1150	82	565	132	910	28	52
17Cr-4Ni	H 1150M	107	738	132	910	29	30
Type 410	Hardened and Tempered 1200°F (649°C) + 1150°F (621°C)	94	648	115	793	20½	15

[a]5 w/o sodium chloride + 0.5 w/o acetic acid solution continuously purged with hydrogen sulfide at 75°F (24°C)

[b]The maximum tensile strength at which no failures occurred in 720 hours.

References:

[1]Burns, D.S., "Laboratory Test for Evaluating Alloys for H_2S Service," *H_2S Corrosion in Oil and Gas Production—A Compilation of Classic Papers*, eds. R.N. Tuttle and R.D. Kane, NACE, Houston, Texas, 1981.

[2]Pressouyre, G.M., Bretin, L., and Zmudzinski, C., "New Steels for Use in H_2S Environments," Corrosion 81, Paper No. 181, April 1981.

Typical Stress-Corrosion-Cracking Resistance in 3.5% NaCl (pH5.2), at 75°F (24°C)
Condition H 900

Applied Stress		Results
ksi	MPa	
169	1165	No failure in 1100-hour test
140	676	No failure in 1100-hour test

Properties

Physical Properties

Specific Gravity		
Condition A	7.75	
Condition H 900	7.76	
Density		
Condition A	0.2800	lb/in³
Condition H 900	0.2800	lb/in³
Mean Specific Heat (73 to 216°F, Condition H 900)	0.1140	Btu/lb/°F
Mean CTE		
75 to 200°F, Condition A	5.88	x 10⁻⁶ in/in/°F
75 to 300°F, Condition A	5.62	x 10⁻⁶ in/in/°F
75 to 400°F, Condition A	5.68	x 10⁻⁶ in/in/°F
75 to 500°F, Condition A	5.80	x 10⁻⁶ in/in/°F
75 to 600°F, Condition A	5.91	x 10⁻⁶ in/in/°F
75 to 700°F, Condition A	5.98	x 10⁻⁶ in/in/°F
75 to 800°F, Condition A	6.09	x 10⁻⁶ in/in/°F
75 to 900°F, Condition A	6.13	x 10⁻⁶ in/in/°F
75 to 1000°F, Condition A	6.08	x 10⁻⁶ in/in/°F
75 to 1100°F, Condition A	6.17	x 10⁻⁶ in/in/°F
75 to 200°F, Condition H 900	6.00	x 10⁻⁶ in/in/°F
75 to 300°F, Condition H 900	5.80	x 10⁻⁶ in/in/°F
75 to 400°F, Condition H 900	5.91	x 10⁻⁶ in/in/°F
75 to 500°F, Condition H 900	6.04	x 10⁻⁶ in/in/°F
75 to 600°F, Condition H 900	6.22	x 10⁻⁶ in/in/°F
75 to 700°F, Condition H 900	6.25	x 10⁻⁶ in/in/°F
75 to 800°F, Condition H 900	6.37	x 10⁻⁶ in/in/°F
75 to 900°F, Condition H 900	6.48	x 10⁻⁶ in/in/°F
75 to 1000°F, Condition H 900	6.53	x 10⁻⁶ in/in/°F
75 to 1100°F, Condition H 900	6.53	x 10⁻⁶ in/in/°F

Mean Coefficient of Thermal Expansion

Temperature		Condition A		Condition H 900	
75°F to	24°C to	10^{-6}/°F	10^{-6}/K	10^{-6}/°F	10^{-6}/K
200	93	5.88	10.58	6.00	10.80
300	149	5.62	10.12	5.80	10.44
400	204	5.68	10.22	5.91	10.64
500	260	5.80	10.44	6.04	10.87
600	316	5.91	10.64	6.22	11.20
700	371	5.98	10.76	6.25	11.25
800	427	6.09	10.96	6.37	11.47
900	482	6.13	11.03	6.48	11.66
1000	538	6.08	10.94	6.53	11.75
1100	593	6.17	11.11	6.53	11.75

Thermal Conductivity	
73°F, Condition H 900	104.0 BTU-in/hr/ft²/°F
212°F, Condition H 900	110.0 BTU-in/hr/ft²/°F
392°F, Condition H 900	126.0 BTU-in/hr/ft²/°F
572°F, Condition H 900	138.0 BTU-in/hr/ft²/°F
752°F, Condition H 900	147.0 BTU-in/hr/ft²/°F
932°F, Condition H 900	169.0 BTU-in/hr/ft²/°F

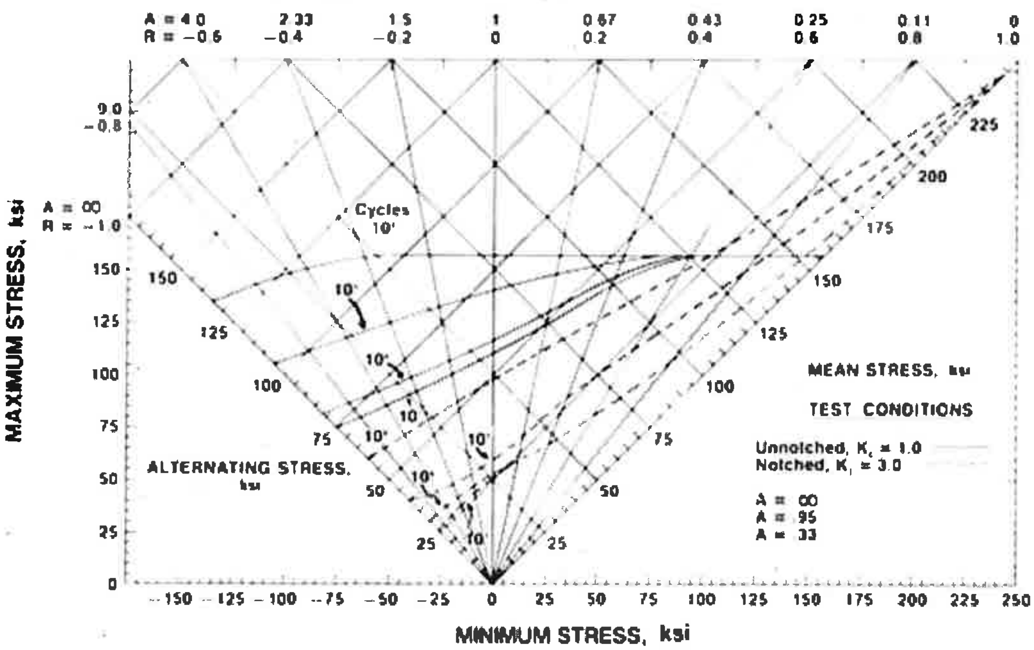
Thermal Conductivity - Condition H 900

Test Temperature		Btu-in/ft²-h-°F	W/m-K
°F	°C		
73	23	104	15.0
212	100	110	16.4
392	200	126	18.2
572	300	138	19.9
752	400	147	21.3
932	500	169	24.4

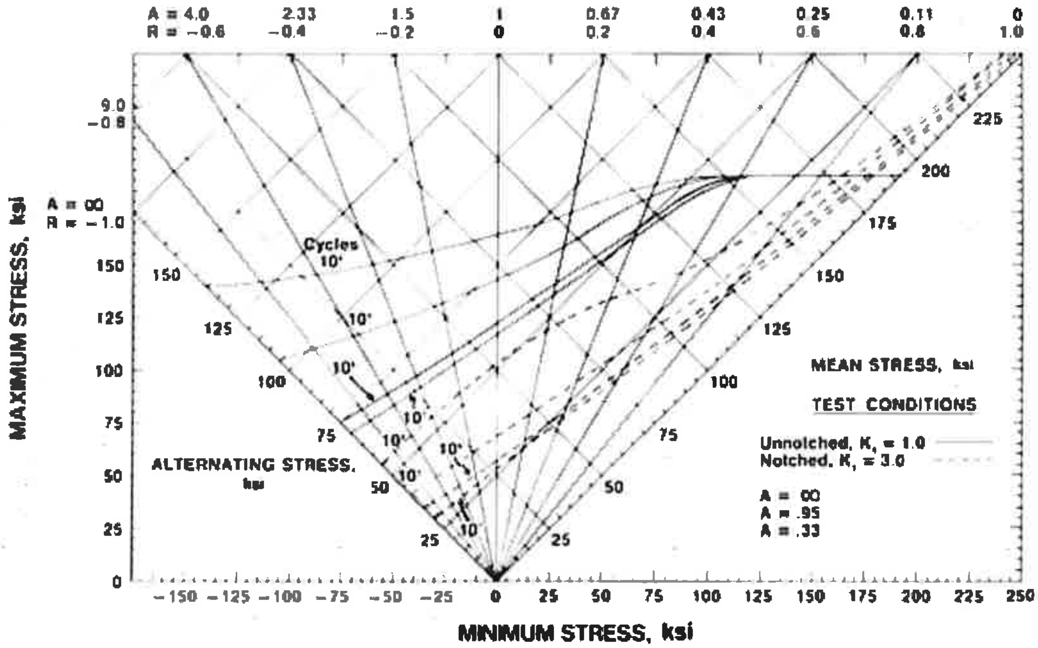
Poisson's Ratio (Condition H 900)	0.290
Modulus of Elasticity (E)	
Condition A	28.0 x 10³ ksi
Condition H 900	29.0 x 10³ ksi
Modulus of Rigidity (G) (Condition H 900)	11.2 x 10³ ksi
Electrical Resistivity	
70°F, Condition A	597.0 ohm-cir-mil/ft
70°F, Condition H 900	509.0 ohm-cir-mil/ft

Typical Mechanical Properties

Typical Constant Life Fatigue Diagram for Custom 450 Stainless Bar in the H 1050 Condition at Room Temperature (Axial tests using longitudinal specimens)



Typical Constant Life Fatigue Diagram for Custom 450 Stainless Bar in the H 900 Condition at Room Temperature (Axial tests using longitudinal specimens)



Typical Cryogenic and Elevated Temperature Mechanical Properties
1" (25.4 mm) round bar

Condition	Test Temperature		0.2% Yield Strength		Ultimate Tensile Strength		Notch Tensile Strength $K_t = 10$		% Elongation in 4D	% Reduction of Area	Charpy V-Notch Impact Strength	
	°F	°C	ksi	MPa	ksi	MPa	ksi	MPa			ft-lb	J
A	-320	-196	179	1234	207	1427	310	2137	17	47	30	41
H 900			249	1717	260	1793	85	586	5	8	1	1
H 1050			205	1413	223	1538	226	1558	22	58	5	7
H 1150			136	938	219	1510	249	1717	30	55	36	49
A	-100	-73	128	883	158	1089	251	1731	15	50	68	92
H 900			207	1427	216	1489	257	1772	16	56	4	5
H 1050			167	1151	180	1241	283	1951	21	65	41	56
H 1150			96	662	166	1145	240	1655	25	67	66	89
A	0	-18	120	827	148	1020	235	1620	15	53	90	122
H 900			194	1338	205	1413	306	2110	15	57	16	22
H 1050			160	1103	170	1172	267	1841	21	66	64	87
H 1150			93	641	154	1062	220	1517	24	69	85	115
H 900	600	316	138	951	160	1103	—	—	12	48	40	54
H 950			140	965	152	1048	—	—	12	49	50	68
H 1050			125	862	133	917	—	—	14	54	82	111
H 1150			97	669	112	772	—	—	17	62	103	140
H 900	800	427	131	903	150	1034	—	—	12	45	42	57
H 950			130	896	143	986	—	—	12	45	54	73
H 1050			115	793	121	834	—	—	13	49	82	111
H 1150			92	634	106	731	—	—	16	57	98	133
H 900	1050	566	76	524	84	579	—	—	24	75	66	89
H 950			78	538	85	586	—	—	27	74	67	91
H 1050			70	483	78	538	—	—	30	77	83	113
H 1150			67	462	81	559	—	—	26	68	97	132

Typical Double Restrained Shear Strength
1-1/16" (27 mm) Rd. to 12" (305 mm) Sq. sections, Longitudinal

Test Temperature		Condition			
		H 900		H 1050	
°F	°C	ksi	MPa	ksi	MPa
-100	-73	138	952	117	807
RT		122	841	100	690
400	204	103	710	87	600
600	316	95	655	80	552
800	427	85	586	71	490

Typical Double Restrained Shear Strength in Condition A at RT in 87 ksi (600 MPa)

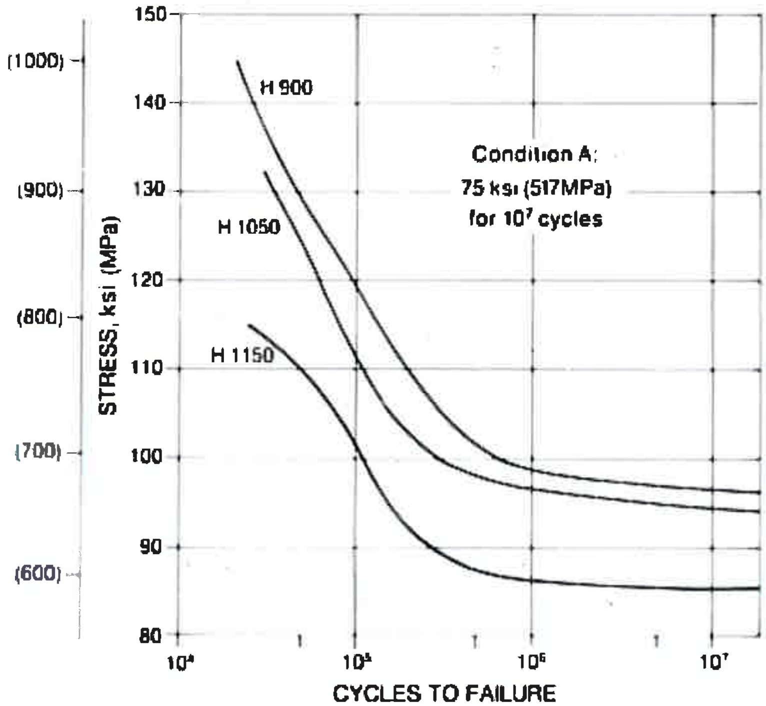
Typical Room Temperature Mechanical Properties
1" (25.4 mm) round bar

Condition	0.2% Yield Strength		Ultimate Tensile Strength		Notch Tensile Strength $K_t = 10$		% Elongation in 4D	% Reduction of Area	Rockwell C Hardness	Charpy V-Notch Impact Strength	
	ksi	MPa	ksi	MPa	ksi	MPa				ft-lb	J
A	118	814	142	979	221	1524	13	50	28	98	133
H 900	188	1296	196	1351	298	2055	14	56	42½	40	54
H 950	184	1269	187	1289	288	1986	16	58	41½	47	64
H 1000	169	1165	173	1193	273	1882	17	63	39	51	69
H 1050	152	1048	160	1103	255	1758	20	66	37	69	94
H 1150	92	634	142	979	209	1441	23	69	28	97	132

Room-Temperature Mechanical Properties – Custom 450® Stainless
0.58" thick strip

Condition	Orientation	0.2% Yield Strength		Ultimate Tensile Strength		% Elongation in 2" (50.8 mm)	Rockwell Hardness (HRC)
		ksi	MPa	ksi	MPa		
Strand	L	109	751	140	965	7	28.5
Annealed	T	111	765	142	979	7	-
	L	185	1275	190	1310	8	41.5
H 900	T	187	1289	192	1323	7	-
	L	177	1220	179	1234	9	40.5
H 950	T	179	1234	181	1248	8	-
	L	164	1130	167	1151	11	38
H 1000	T	164	1130	167	1151	10	-
	L	148	1020	156	1075	12	36
H 1050	T	148	1020	156	1075	11	-
	L	117	806	141	972	14	33
H 1100	T	120	827	144	993	13	-
	L	87	600	140	965	14	30
H 1150	T	90	620	140	965	13	-

Typical Rotating Beam Fatigue Strength
R.R. Moore specimens from 1.125" (28.6 mm) rod bar



Heat Treatment

Solution Treatment

Condition A (Solution Treated or Annealed)

Heat to 1875/1925°F (1024/1052°C), hold one hour at heat and cool rapidly. Water quenching or oil quenching is preferred for optimum response to aging, but air quenching is suitable for thin sections.

Custom 450 stainless will normally be supplied from the mill in Condition A, ready for service or for subsequent age-hardening.

Average Size Change (Contraction)
Solution annealed to aged condition

Condition	Contraction in./in. (m/m)	
	Longitudinal	Transverse
H 900	0.0003	0.0007
H 1000	0.0006	0.0008
H 1150	0.0038	0.0040

Age

Condition H 900, H 950, H 1000, H 1050, H 1150 (Precipitation or Age Hardenend)

Tensile strength and yield strength are increased by aging at 900/1050°F (482/566°C) for 4 hours, followed by air cooling. The 900°F (482°C) age produces the optimum combination of strength, ductility, and toughness. Overaging at temperatures up to 1150°F (621°C) increases the ductility and decreases strength.

Workability

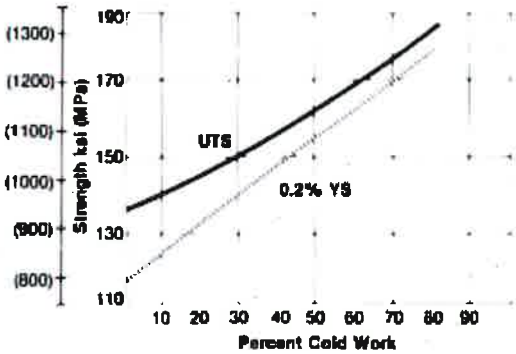
Hot Working

This alloy is easily hot worked in the temperature range of 1650/2300°F (900/1260°C). The optimum hot-working range is 2100/2150°F (1150/1177°C) for the best combination of ease of working and fine grain size. Cool forgings in air to room temperature and anneal.

Cold Working

The work-hardening rate of Custom 450 alloy is relative low, permitting a good deal of cold reduction without intermediate annealing. Deep-drawing or stretching operations with sharp bends which produce localized elongation are to be avoided.

Effect of Cold Work on Typical Tensile Strengths



Machinability

Custom 450 stainless has been machined successfully using the same practices employed with other martensitic stainless steels at comparable hardness levels.

Following are typical feeds and speeds for Custom 450 stainless.

Typical Machining Speeds and Feeds – Custom 450® Stainless

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Turning—Single-point and Box Tools

Depth of Cut (Inches)	High Speed Tools: Tool Material	High Speed Tools: Speed (fpm)	High Speed Tools: Feed (ipr)	Carbide Tools: Tool Material	Carbide Tools: Speed (fpm) Brazed	Carbide Tools: Speed (fpm) Throw Away	Carbide Tools: Speed (fpm) Coated	Carbide Tools: Feed (ipr)
Solution Treated								
.150 .025	M2, T5, T15	70 90	.015 .007	C6 C7	250 300	310 350	400 475	.015 .007
Aged H1150 H1100								
.150 .025	M2, T5, T15	65 75	.015 .007	C6 C7	235 250	290 310	350 425	.015 .007
Aged H1000 H1050								
.150 .025	T15, M41, M42, M43, M44	55 65	.015 .007	C6 C7	220 270	250 300	325 375	.010 .005
Aged H900 H950								
.150 .025	T15, M41, M42, M43, M44	35 40	.010 .005	C6 C7	135 170	170 200	225 260	.010 .005

Turning—Cut-Off and Form Tools

Tool Material: High Speed Tools	Tool Material: Car-bide Tools	Speed (fpm)	Feed (ipr) Cut-Off Tool Width (Inches): 1/16	1/8	1/4	1/2	Form Tool Width (Inches): 1	1 ½	2
Solution Treated									
M2, T15	C6	70 200	.001 .003	.0015 .0045	.002 .006	.0015 .003	.001 .0025	.001 .0025	.0005 .0015
Aged H1100 H1150									
M2, T15	C6	75 200	.001 .003	.0015 .003	.002 .0045	.0015 .003	.001 .002	.001 .002	.0005 .002
Aged H1000 H1050									
T15, M42	C6	60 155	.001 .003	.001 .003	.0015 .0045	.0015 .003	.001 .002	.001 .002	.0005 .002
Aged H900 H950									
T15, M42	C6	30 110	.001 .0025	.001 .0025	.0015 .004	.0015 .0025	.001 .0015	.001 .0015	.0005 .0015

Rough Reaming

High Speed: Tool Material	High Speed: Speed (fpm)	Carbide Tools: Tool Material	Carbide Tools: Speed (fpm)	Feed (ipr) Reamer Diameter (inches): 1/8	1/4	1/2	1	1 ½	2
Solution Treated									
M7	60	C2	190	.003	.005	.008	.011	.015	.018
Aged H1100 H1150									
M7	65	C2	200	.003	.005	.008	.011	.015	.018
Aged H1000 H1050									
T15	45	C2	150	.003	.004	.006	.010	.013	.016
Aged H900 H950									
T15	35	C2	125	.001	.001	.001	.001	.001	.001

Drilling

High Speed Tools									
Tool Material	Speed (fpm)	Feed (inches per revolution) Nominal Hole Diameter (inches)							
		1/16	1/8	1/4	1/2	3/4	1	1 ½	2
Solution Treated									
M1, M10	50	.001	.002	.004	.007	.008	.010	.012	.015
Aged H1100 H1150									
T15, M42	45	.001	.002	.004	.007	.008	.010	.012	.015
Aged H1000 H1050									
T15, M42	35	-	.002	.004	.007	.008	.010	.012	.015
Aged H900 H950									
T15, M42	25	-	.001	.002	.003	.004	.004	.004	.004

Die Threading

FPM for High Speed Tools				
Tool Material	7 or less, tpi	8 to 15, tpi	16 to 24, tpi	25 and up, tpi
Solution Treated				
M1, M2, M7, M10	5 – 12	8 – 15	10 – 20	15 – 25
Aged				
T15, M42	4 – 8	6 – 10	8 – 12	10 – 15

Milling, End-Peripheral

Depth of Cut (inches)	High Speed Tools						Carbide Tools					
	Tool Material	Speed (fpm)	Feed (ipt) Cutter Diameter (in)				Tool Material	Speed (fpm)	Feed (ipt) Cutter Diameter (in)			
			1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
Solution Treated												
.050	M2, M7	85	.001	.002	.003	.004	C2	275	.001	.002	.004	.006
Aged H1100 H1150												
.050	M2, M7	80	.001	.002	.003	.004	C2	225	.001	.002	.004	.006
Aged H1000 H1050												
.050	M2, M7	70	.0005	.001	.002	.003	C2	195	.001	.002	.003	.004
Aged H900 H950												
.050	M2, M7	60	.0005	.001	.002	.003	C2	90	.001	.002	.003	.004

Tapping

High Speed Tools	
Tool Material	Speed (fpm)
Solution Treated	
M1, M7, M10	12 – 25
Aged H1100 H1150	
M1, M7, M10	15 – 20
Aged H1000 H1050	
M1, M7, M10	10 - 20
Aged H900 H950	
M1, M7, M10 Nitrided	5 – 15

Broaching

High Speed Tools		
Tool Material	Speed (fpm)	Chip Load (ipt)
Solution Treated		
T15, M42	15	.002
Aged H1100 H1150		
T15, M42	10	.002
Aged H1000 H1050		
T15, M42	8	.002
Aged H900 H950		
T15, M42	8	.002

Additional Machinability Notes

When using carbide tools, surface speed feet/minute (sfpm) can be increased between 2 and 3 times over the high speed suggestions. Feeds can be increased between 50 and 100%.

Figures used for all metal removal operations covered are average. On certain work, the nature of the part may require adjustment of speeds and feeds. Each job has to be developed for best production results with optimum tool life. Speeds or feeds should be increased or decreased in small steps.

Weldability

Carpenter Custom 450 stainless can be satisfactorily welded by the shielded fusion and resistance welding processes. Oxyacetylene welding is not recommended, since carbon pickup in the weld may occur. Unlike other martensitic stainless steels, no preheating is required to prevent cracking during the welding of this alloy. Normally, the alloy is welded in the solution-annealed condition; however, where high welding stresses are anticipated, it may be advantageous to weld in the overaged (H 1150) condition. If welded in the solution-annealed condition, the alloy can be used as welded or can be aged directly to the desired strength level after welding. However, the optimum combination of strength, ductility and corrosion resistance is obtained by solution annealing the welded part prior to use of aging. If welded in the overaged condition, the part must be solution annealed before aging.

Brazing

The brazing temperature should coincide with the annealing temperature range so that reannealing is not necessary. Brazing materials suitable for Type 304 should be used. See ASTM B 260.

Other Information

Descaling (Cleaning)

Descaling following forging and annealing can be accomplished by acid cleaning or grit blasting. The acid treatment consists of 2 minutes in 50% by volume muriatic acid at 180°F (82°C), followed by 4 minutes in a mixture of 15% by volume nitric acid, plus 3% by volume hydrofluoric acid at room temperature. Water rinse and desmut in 20% by volume nitric acid at room temperature. Repeat cleaning procedure as necessary but decrease the times by 50% (i.e., 1 and 2 minutes, respectively).

The heat tint from aging can be removed by polishing, vapor blasting or pickling 4 or 6 minutes in a mixture of 15% by volume nitric acid, plus 3% by volume hydrofluoric acid, followed by a water rinse. Repeat the acid cleaning procedure if necessary, but decrease the time by 2 to 3 minutes. Desmut in 20% by volume nitric acid at room temperature.

After acid cleaning, bake 1 to 3 hours at 300/350°F (149/177°C) to remove hydrogen.

Applicable Specifications

- AMS 5763
- AMS 5773
- AMS 5863 (Strip)
- ASTM A564 (XM-25)
- ASTM A693 (Strip)
- ASTM A959
- MR0175

Forms Manufactured

- Bar-Flats
- Bar-Rounds
- Bar-Squares
- Billet
- Plate
- Sheet
- Strip
- Weld Wire
- Wire-Shapes

Technical Articles

- A Designer's Manual On Specialty Alloys For Critical Automotive Components
- A Guide to Etching Specialty Alloys for Microstructural Evaluation
- Advanced Stainless Offers High Strength, Toughness and Corrosion Resistance Wherever Needed
- Alloy Selection for Cold Forming (Part I)
- Alloy Selection for Cold Forming (Part II)
- How to Passivate Stainless Steel Parts
- How to Select the Right Stainless Steel or High Temperature Alloy for Heading
- Improved Stainless Steels for Medical Instrument Tubing
- New Ideas for Machining Austenitic Stainless Steels
- New Ph Stainless Combines High Strength, Fracture Toughness and Corrosion Resistance
- New Stainless Steel for Instruments Combines High Strength and Toughness
- Passivating and Electropolishing Stainless Steel Parts
- Selecting Stainless Steels for Valves
- Selection of High Strength Stainless Steels for Aerospace, Military and Other Critical Applications
- Unique Properties Required of Alloys for the Medical and Dental Products Industry

Disclaimer:
The information and data presented herein are typical or average values and are not a guarantee of maximum or minimum values. Applications specifically suggested for material described herein are made solely for the purpose of illustration to enable the reader to make his/her own evaluation and are not intended as warranties, either express or implied, of fitness for these or other purposes. There is no representation that the recipient of this literature will receive updated editions as they become available.

Edition Date: 8/1/1994

Visit us on the web at www.cartech.com

Technical Datasheet

CARPENTER

CarTech® Custom 630 Stainless

Identification

UNS Number
- S17400

AISI Number
- 630

Type Analysis

Single figures are nominal except where noted.

Carbon (Maximum)	0.07 %	**Manganese (Maximum)**	1.00 %
Phosphorus (Maximum)	0.040 %	**Sulfur (Maximum)**	0.030 %
Silicon (Maximum)	1.00 %	**Chromium**	15.00 to 17.50 %
Nickel	3.00 to 5.00 %	**Copper**	3.00 to 5.00 %
Columbium + Tantalum	0.15 to 0.45 %	**Iron**	Balance

General Information

Description

CarTech Custom 630 Stainless is a martensitic precipitation/age-hardening stainless steel offering high strength and hardness along with excellent corrosion resistance. It has good fabricating characteristics and can be age hardened by a single-step, low temperature treatment. It has been used for a variety of applications including oil field valve parts, chemical process equipment, aircraft fittings, fasteners, pump shafts, nuclear reactor components, gears, paper mill equipment, missile fittings, and jet engine parts.

When your application calls for extensive machining of this alloy, you should consider specifying a modified version, Custom 630 Project 70®+ stainless, for improved machinability.

Elevated Temperature Use

Carpenter Stainless Custom 630 shows excellent resistance to oxidation up to approximately 1100°F (539°C).

Long-term exposure to elevated temperatures can result in reduced toughness in precipitation hardenable stainless steels. The reduction in toughness can be minimized in some cases by using higher aging temperatures. Short exposures to elevated temperatures can be considered, provided the maximum temperature is at least 50°F (28°C) less than the aging temperature.

Corrosion Resistance

Carpenter Stainless Custom 630 has withstood corrosive attack better than any of the 400 series hardenable stainless steels, and, in most corrodents, its corrosion resistance closely approaches that of Stainless Types 302 and 304.

Good resistance to stress-corrosion cracking is gained by hardening at temperatures of 1025°F (552°C) and higher. Carpenter Stainless Custom 630 also withstands erosion-corrosion well due to the combination of good corrosion resistance and high hardness.

The alloy has acceptable resistance to sulfide stress cracking at Rockwell C 33 maximum hardness per NACE MR-01-75, "Sulfide Stress Cracking Resistant Metallic Materials for Oil Field Equipment." Refer to the current document for details on acceptable conditions.

For optimum corrosion resistance, surfaces must be free of scale, lubricants, foreign particles, and coatings applied for drawing and heading. After fabrication of parts, cleaning and/or passivation should be considered.

Important Note: *The following 4-level rating scale is intended for comparative purposes only. Corrosion testing is recommended; factors which affect corrosion resistance include temperature, concentration, pH, impurities, aeration, velocity, crevices, deposits, metallurgical condition, stress, surface finish and dissimilar metal contact.*

Nitric Acid	Good	Sulfuric Acid	Restricted

Phosphoric Acid	Restricted	Acetic Acid	Moderate
Sodium Hydroxide	Moderate	Salt Spray (NaCl)	Good
Sea Water	Restricted	Sour Oil/Gas	Restricted
Humidity	Excellent		

Comparative Corrosion Rates - Carpenter Custom 630 (17Cr-4Ni) and Other Alloys Mils per Year

Corrodents	TYPE 410		TYPE 431		CUSTOM 630		
	Hardened and Tempered 300°F (150°C)	Hardened and Tempered 1100°F (590°C)	Hardened and Tempered 500°F (260°C)	Hardened and Tempered 1200°F (650°C)	H900	H1025	H1150
5 w/o H_2SO_4 at 75°F (24°C)	1732[1]	1218	1402[1]	2325[1]	2	3	14[2]
20 w/o HNO_3 at 200°F (93°C)	8	59[2]	3	3	2	2	2
50 w/o Acetic Acid Boiling	266[1]	1627	43[1]	54	3	3	4

Notes: Corrosion rates for one 48 hour period
[1] Several or all of subsequent 48 hour test periods showed nil rates.
[2] Rates increased to 200 mpy by 3rd 48 hour test period.

Properties

Physical Properties

Specific Gravity		
Condition A	7.75	
Condition H 1075	7.81	
Condition H 1150	7.82	
Condition H 900	7.80	
Density		
Condition A	0.2800	lb/in³
Condition H 900	0.2820	lb/in³
Condition H 1075	0.2820	lb/in³
Condition H 1150	0.2830	lb/in³
Mean Specific Heat		
32 to 212°F, Condition A	0.1100	Btu/lb/°F
32 to 212°F, Condition H 900	0.1000	Btu/lb/°F

Mean CTE	
70 to 200°F, Condition A	6.00 x 10^{-6} in/in/°F
70 to 400°F, Condition A	6.00 x 10^{-6} in/in/°F
70 to 600°F, Condition A	6.20 x 10^{-6} in/in/°F
70 to 800°F, Condition A	6.30 x 10^{-6} in/in/°F
-100 to 70°F, Condition H 900	5.80 x 10^{-6} in/in/°F
70 to 200°F, Condition H 900	6.00 x 10^{-6} in/in/°F
70 to 400°F, Condition H 900	6.10 x 10^{-6} in/in/°F
70 to 600°F, Condition H 900	6.30 x 10^{-6} in/in/°F
70 to 800°F, Condition H 900	6.50 x 10^{-6} in/in/°F
70 to 200°F, Condition H 1075	6.30 x 10^{-6} in/in/°F
70 to 400°F, Condition H 1075	6.50 x 10^{-6} in/in/°F
70 to 600°F, Condition H 1075	6.60 x 10^{-6} in/in/°F
70 to 800°F, Condition H 1075	6.80 x 10^{-6} in/in/°F
-100 to 70°F, Condition H 1150	6.10 x 10^{-6} in/in/°F
70 to 200°F, Condition H 1150	6.60 x 10^{-6} in/in/°F
70 to 400°F, Condition H 1150	6.90 x 10^{-6} in/in/°F
70 to 600°F, Condition H 1150	7.10 x 10^{-6} in/in/°F
70 to 800°F, Condition H 1150	7.20 x 10^{-6} in/in/°F
Thermal Conductivity	
300°F, Condition H 900	127.0 BTU-in/hr/ft²/°F
500°F, Condition H 900	135.0 BTU-in/hr/ft²/°F
860°F, Condition H 900	156.0 BTU-in/hr/ft²/°F
900°F, Condition H 900	157.0 BTU-in/hr/ft²/°F
Poisson's Ratio	
Condition H 900	0.272
Condition H 1075	0.272
Condition H 1150	0.272
Modulus of Elasticity (E) (Condition H 900)	28.5 x 10^{3} ksi
Modulus of Rigidity (G)	
Condition H 900	11.2 x 10^{3} ksi
Condition H 1075	10.0 x 10^{3} ksi
Condition H 1150	10.0 x 10^{3} ksi
Electrical Resistivity	
70°F, Condition A	589.0 ohm-cir-mil/ft
70°F, Condition H 900	463.0 ohm-cir-mil/ft

Condition	A		H 900		H 1075		H 1150	
Specific gravity	7.75		7.80		7.81		7.82	
Density—lb/in³	0.280		0.282		0.282		0.283	
kg/m³	7750		7800		7810		7820	
Mean Specific Heat	Btu/lb•°F	J/kg•K	Btu/lb•°F	J/kg•K				
32 to 212°F (0 to 100°C)	0.11	460	0.10	419	—		—	
Electrical resistivity (RT)								
ohm-cir mil/ft	589		463		—		—	
microhm-mm	980		770		—		—	
Mean Coefficient of Thermal Expansion	10^{-6}/°F	10^{-6}/K	10^{-6}/°F	10^{-6}/K	10^{-6}/°F	10^{-6}/K	10^{-6}/°F	10^{-6}/K
-100 to 70°F (-73 to 21°C)	—	—	5.8	10.4	—	—	6.1	11.0
70 to 200°F (21 to 93°C)	6.0	10.8	6.0	10.8	6.3	11.3	6.6	11.9
70 to 400°F (21 to 204°C)	6.0	10.8	6.1	11.0	6.5	11.7	6.9	12.4
70 to 600°F (21 to 316°C)	6.2	11.2	6.3	11.3	6.6	11.9	7.1	12.8
70 to 800°F (21 to 427°C)	6.3	11.3	6.5	11.7	6.8	12.2	7.2	13.0
Thermal Conductivity °F / °C			Btu-in/ft²•h•°F	W/m•K				
300 / 149	—		124	17.9	—		—	
500 / 260	—		135	19.5	—		—	
860 / 460	—		156	22.5	—		—	
900 / 482	—		157	22.6	—		—	
Poisson's Ratio	—		0.272		0.272		0.272	

Modulus of Elasticity and Rigidity—See Mechanical Properties.

Typical Mechanical Properties

Typical Creep Strength - Carpenter Custom 630 (17Cr-4Ni)
Condition H 900

Test Temperature		Stress for creep of			
		0.1% in 1000 hrs.		0.01% in 1000 hrs.	
°F	°C	ksi	MPa	ksi	MPa
600	316	135	931	125	862
700	371	105	724	100	689
800	427	60	414	43	296
900	482	23	159	—	—

Typical Cryogenic Charpy V-Notch Impact Strength - Carpenter Custom 630 (17Cr-4Ni)

Test Temperature		Impact Strength									
		H 925		H 1025		H 1150		H 1150M			
°F	°C	ft-lb*	J	ft-lb*	J	ft-lb*	J	ft-lb*	J	ft-lb**	J
75	24	30	41	75	102	95	129	105	142	95	129
10	-12	16	22	58	79	93	126	—	—	85	115
-40	-40	9	12	40	54	76	103	—	—	75	102
-110	-79	5	7	15	20	48	65	—	—	65	88
-175	-115	—	—	—	—	—	—	—	—	35	47
-250	-157	—	—	—	—	—	—	—	—	18	24
-320	-196	3	4	4	6	6	8	28	38	5	7

*Test samples from 1" (25.4 mm) Rd. Bar—Longitudinal Direction
**Test samples from 4" (102 mm) Rd. Bar—Longitudinal Direction

Typical Cryogenic Tensile Properties - Carpenter Custom 630 (17Cr-4Ni)
Condition H 1100

Test Temperature		0.2% Yield Strength		Ultimate Tensile Strength		% Elongation in 2" (50.8 mm)
°F	°C	ksi	MPa	ksi	MPa	
75	24	135	931	150	1034	17
32	0	183	1262	193	1331	16
-40	-40	189	1303	203	1440	16
-80	-62	196	1351	209	1441	15
-320	-196	243	1675	248	1710	8

Typical Elevated Temperature Tensile Properties - Carpenter Custom 630 (17Cr-4Ni)
Condition H 900

Test Temperature		0.2% Yield Strength		Ultimate Tensile Strength		% Elongation in 2" (50.8 mm)	% Reduction of Area
°F	°C	ksi	MPa	ksi	MPa		
RT	RT	183	1262	198	1365	15	52
600	316	145	1000	172	1186	13	46
800	427	132	910	160	1103	13	51
900	482	118	814	138	952	13	55
1000	538	94	643	115	793	17	64

Typical Room Temperature Mechanical Properties - Carpenter Custom 630 (17Cr-4Ni)

Condition	0.2% Yield Strength		Ultimate Tensile Strength		Elongation in 2" (50.8 mm)	% Reduction of Area	Hardness		Charpy V-Notch Impact Strength		Modulus of Elasticity (E)		Modulus of Rigidity (G)	
	ksi	MPa	ksi	MPa			Rockwell C	Brinell	ft-lb	J	ksi	MPa	ksi	MPa
A	—	—	—	—	—	—	36	352	—	—	—	—	—	—
H 900	183	1262	198	1365	15	52	44	420	16	21	28.5×10^3	197×10^3	11.2×10^3	77×10^3
H 1025	162	1117	168	1158	16	58	38	352	40	54	—	—	—	—
H 1075	148	1020	164	1131	17	59	36	341	45	61	—	—	10×10^3	69×10^3
H 1150	126	869	144	993	20	60	33	311	55	75	—	—	10×10^3	69×10^3
H 1150M	87	600	123	848	22	66	29	293	100	136	—	—	—	—

Typical Stress Rupture Strength - Carpenter Custom 630 (17Cr-4Ni)

Condition	Test Temperature		Stress for rupture in			
			100 Hours		1000 Hours	
	°F	°C	ksi	MPa	ksi	MPa
H 900	625	329	162	1117	157	1082
H 1075	625	329	137	945	134	924
H 900	700	371	156	1076	150	1034
H 1075	700	371	126	869	123	848
H 900	800	427	140	965	128	883
H 1075	800	427	108	745	103	710

Heat Treatment

Carpenter Stainless Custom 630 is hardened by heating solution-treated material, Condition A, to a temperature of 900°F (482°C) to 1150°F (621°C) for one to four hours, depending on the temperature, then air cooling.

Solution Treatment

Heat at 1900°F (1038°C) ±25°F (±14°C) for ½ hour, cool to below 90°F (32°C) so that the material is completely transformed to martensite. Sections under 3" (76.2 mm) can be quenched in a suitable liquid quenchant and sections over 3" (76.2 mm) should be rapidly air cooled.

Do not use this condition without age hardening due to susceptibility to stress-corrosion cracking.

Deformation (Size Change) in Hardening

The precipitation hardening of Carpenter Stainless Custom 630 is accomplished with a slight dimensional change. The amount of contraction in hardening solution-treated (Condition A) material to Condition H 900 is about 0.0004 to 0.0006 in./in. (m/m). Condition A material when hardened to Condition H 1150 will contract approximately 0.0009 to 0.0012 in./in. (m/m).

Age

Condition H 900
Heat solution-treated material at 900°F (482°C) for 1 hour and air cool.

Condition H 925, H 1025, H 1075, H 1100, H 1150
Heat solution-treated material at specified temperature ±15°F (±8°C) for 4 hours and air cool.

Condition H 1150M
Heat solution treated material at 1400°F(760°C) ±15°F (±8°C) for 2 hours, air cool; then treat at 1150°F (621°C) ±15°F (±8°C) for 4 hours and air cool.

Workability

Hot Working

Carpenter Stainless Custom 630 can be readily forged, hot headed and upset. Material which is hot worked must be solution treated prior to hardening if the material is to respond properly to hardening.

Forging

Heat uniformly to 2150/2200°F (1177/1204°C) and hold one hour at temperature before forging. Do not forge below 1850°F (1010°C). To obtain optimum grain size and mechanical properties, forgings should be cooled in air to below 90°F (32°C) before further processing. Forgings must be solution treated prior to hardening.

Cold Working

Carpenter Stainless Custom 630 can be fabricated by cold working to an extent which is limited to the high initial yield strength.

Machinability

Carpenter Stainless Custom 630 is readily machined in both the solution-treated and various age-hardened conditions. In the solution-treated condition, it machines similarly to Stainless Types 302 and 304. The machinability will improve as the hardening temperature is increased. Condition H 1150M provides optimum machinability.

Having procured Condition H 1150M for best machinability, higher mechanical properties can only be developed by solution treating and heat treating at standard hardening temperatures.

Following are typical feeds and speeds for Carpenter Stainless Custom 630.

Typical Machining Speeds and Feeds—Carpenter Custom 630 (17Cr-4Ni)
The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Turning—Single-Point and Box Tools

Depth of Cut (inches)	High Speed Tools: Tool Material	High Speed Tools: Speed (fpm)	High Speed Tools: Feed (ipr)	Carbide Tools: Tool Material	Carbide Tools: Speed (fpm) Brazed	Speed (fpm) Throw Away	Speed (fpm) Coated	Carbide Tools: Feed (ipr)
				Solution Treated				
.150	M2, T5,	80	.015	C6	300	350	450	.015
.025	T15	95	.007	C7	350	400	525	.007
				Double-Aged H1150-M				
.150	M2, T5,	80	.015	C6	300	350	450	.015
.025	T15	95	.007	C7	350	400	525	.007
				Aged H1150 H1100 H1075				
.150	T15, M41,	60	.015	C6	250	300	400	.015
.025	M42, M43,	75	.007	C7	300	350	450	.007
	M44							
				Aged H1025				
.150	T15, M41,	55	.015	C6	245	275	350	.010
.025	M42, M43,	70	.007	C7	290	325	400	.005
	M44							
				Aged H900 H925				
.150	T15, M41,	30	.010	C6	160	190	250	.010
.025	M42, M43,	45	.005	C7	190	225	285	.005
	M44							

Turning—Cut-Off and Form Tools

Tool Material: High Speed Tools	Tool Material: Carbide Tools	Speed (fpm)	Feed (ipr) Cut-Off Tool Width (inches) 1/16	1/8	1/4	1/2	Form Tool Width (inches) 1	1 1/2	2
				Solution Treated					
M2 T15		70	.001	.0015	.002	.0015	.001	.001	.0005
	C6	210	.003	.003	.004	.003	.002	.002	.002
				Double-Aged H1150-M					
M2 T15		100	.0015	.002	.0025	.002	.0015	.001	.001
	C6	250	.003	.003	.0045	.003	.002	.002	.002
				Aged H1050 H1100 H1175					
M2 T15		80	.001	.0015	.002	.0015	.001	.001	.0005
	C6	210	.003	.003	.0045	.003	.002	.002	.002
				Aged H1025					
T15 M42		65	.001	.001	.0015	.0015	.001	.001	.0005
	C6	160	.003	.003	.0045	.003	.002	.002	.002
				Aged H900 H925					
T15 M42		35	.001	.001	.0015	.0015	.001	.001	.0005
	C6	115	.0025	.0025	.004	.0025	.0015	.0015	.0015

Rough Reaming

High Speed Tools		Carbide Tools		Feed (ipr) Reamer Diameter (inches)					
Tool Material	Speed (fpm)	Tool Material	Speed (fpm)	1/8	1/4	1/2	1	1 1/2	2
Solution Treated									
M7	60	C7	190	.003	.005	.008	.011	.015	.018
Double-Aged H1150M									
M7	65	C2	200	.003	.005	.008	.011	.015	.018
Aged H1075-1150									
T15	45	C2	150	.003	.005	.008	.011	.015	.018
Aged H1025									
T15	35	C2	125	.003	.004	.006	.010	.013	.016
Aged H900-925									
T15	30	C2	100	.001	.001	.001	.001	.001	.001

Drilling

High Speed Tools									
Tool Material	Speed (fpm)	Feed (inches per revolution) Nominal Hole Diameter (inches)							
		1/16	1/8	1/4	1/2	3/4	1	1 1/2	2
Solution Treated									
M1, M10	50	.001	.002	.004	.007	.008	.010	.012	.015
Double-Aged H1150M									
M1, M10	60	.001	.002	.004	.007	.009	.011	.013	.016
Aged H1075-1100-1150									
T15, M42	45	—	.002	.004	.007	.008	.010	.012	.015
Aged H1025									
T15, M42	35	—	.002	.004	.006	.008	.009	.011	.012
Aged H900-925									
T15, M42	25	—	.001	.002	.003	.004	.004	.004	.004

Die Threading

FPM for High Speed Tools				
Tool Material	7 or less, tpi	8 to 15, tpi	16 to 24, tpi	25 and up, tpi
Solution Treated				
M1, M2, M7, M10	5-12	8-15	10-20	15-25
Aged				
T15, M42	4-8	6-10	8-12	10-15

Milling, End—Peripheral

Depth of Cut (inches)	High Speed Tools						Carbide Tools					
	Tool Material	Speed (fpm)	Feed (ipt) Cutter Diameter (inches)				Tool Material	Speed (fpm)	Feed (ipt) Cutter Diameter (inches)			
			1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
Solution Treated												
.050	M2, M7	85	.001	.002	.003	.004	C2	270	.001	.002	.004	.006
Double-Aged H1150M												
.050	M2, M7	90	.001	.002	.003	.004	C2	275	.001	.002	.004	.006
Aged H1075-1150												
.050	M2, M7	80	.001	.002	.003	.004	C2	265	.001	.002	.004	.006
Aged H1025												
.050	M2, M7	65	.0005	.001	.002	.003	C2	190	.001	.002	.003	.004
Aged H900-925												
.050	T15	60	.0005	.001	.002	.003	C2	90	.001	.002	.003	.004

Tapping

High Speed Tools	
Tool Material	Speed (fpm)
Solution Treated	
M1, M7, M10	12-25
Double-Aged H1150M	
M1, M7, M10	17-28
Aged H1075-1100-1150	
M1, M7, M10	15-25
Aged H1025	
M1, M7, M10	10-20
Aged H900-925	
M1, M7, M10 Nitrided	5-15

Broaching

High Speed Tools		
Tool Material	Speed (fpm)	Chip Load (ipt)
Solution Treated		
T15, M42	10	.002
Double-Aged H1150M		
T15, M42	15	.002
Aged H1075-1100-1150		
T15, M42	8	.002
Aged H1025		
T15, M42	8	.002
Aged H900-925		
T15, M42	8	.002

When using carbide tools, surface speed feet/minute (SFPM) can be increased between 2 and 3 times over the high-speed suggestions. Feeds can be increased between 50 and 100%.

Figures used for all metal removal operations covered are average. On certain work, the nature of the part may require adjustment of speeds and feeds. Each job has to be developed for best production results with optimum tool life. Speeds or feeds should be increased or decreased in small steps.

Additional Machinability Notes

When using carbide tools, surface speed feet/minute (sfpm) can be increased between 2 and 3 times over the high speed suggestions. Feeds can be increased between 50 and 100%.

Figures used for all metal removal operations covered are average. On certain work, the nature of the part may require adjustment of speeds and feeds. Each job has to be developed for best production results with optimum tool life. Speeds or feeds should be increased or decreased in small steps.

Weldability

Carpenter Stainless Custom 630 can be satisfactorily welded by the shielded fusion and resistance welding processes. Oxyacetylene welding is not recommended, since carbon pickup in the weld may occur. When a filler metal is required, AWS E/ER630 welding consumables should be considered to provide welds with properties matching those of the base metal. When designing the weld joint, care should be exercised to avoid stress concentrators, such as sharp corners, threads, and partial-penetration welds. When high weld strength is not needed, a standard austenitic stainless filler, such as E/ER308L, should be considered.

Normally, welding in the solution-treated condition has been satisfactory; however, where high welding stresses are anticipated, it may be advantageous to weld in the overaged (H 1150) condition. Usually, preheating is not required to prevent cracking.

If welded in the solution-treated condition, the alloy can be directly aged to the desired strength level after welding. However, the optimum combination of strength, ductility and corrosion resistance is obtained by solution treating the welded part before aging. If welded in the overaged condition, the part must be solution treated and then aged.

Other Information

Descaling (Cleaning)

Descaling following forging and annealing can be accomplished by acid cleaning or grit blasting. The acid treatment consists of 2 minutes in 50% by volume muriatic acid at 180°F (82°C), followed by 4 minutes in a mixture 15% by volume nitric acid, plus 3% by volume hydrofluoric acid at room temperature. Water rinse and desmut in 20% by volume nitric acid at room temperature. Repeat cleaning procedure as necessary but decrease the times by 50% (i.e., 1 and 2 minutes, respectively).

The heat tint from aging can be removed by polishing, vapor blasting or pickling 4 to 6 minutes in a mixture of 15% by volume nitric acid, plus 3% by volume hydrofluoric acid, followed by a water rinse. Repeat the acid cleaning procedure if necessary but decrease the time by 2 to 3 minutes. Desmut in 20% by volume nitric acid at room temperature.

After acid cleaning, back 1 to 3 hours at 300/350°F (149/177°C) to remove hydrogen.

Applicable Specifications

- AMS 5643
- ASTM A564
- ASTM A705
- ASME SA564
- ASTM A693 (Strip)

Forms Manufactured

- Bar-Flats
- Bar-Rounds
- Billet
- Wire
- Bar-Hexagons
- Bar-Squares
- Strip

Technical Articles

- A Guide to Etching Specialty Alloys for Microstructural Evaluation
- Advanced Stainless Offers High Strength, Toughness and Corrosion Resistance Wherever Needed
- Alloy Selection for Cold Forming (Part I)
- Alloy Selection for Cold Forming (Part II)
- New Ph Stainless Combines High Strength, Fracture Toughness and Corrosion Resistance
- New Stainless for Fasteners Combines Corrosion Resistance, High Hardness and Cold Formability
- Steels for Strength and Machinability
- Unique Properties Required of Alloys for the Medical and Dental Products Industry

Edition Date: 9/1/2000

Appendix C - Mill Certificates

Appendix C contains the mill certificates from the materials used in this project. The mill certificates include:

Material	**Size**	**Heat Number**	**Source**
DSI Threadbar	2.64 in. diameter	NF15100387	Kreher Steel Company
	Hex Tube for Nuts	A153185	Kreher Steel Company
	Round Tube for Couplers	A153185	Kreher Steel Company
Custom 450 (H1050)	2.75 in. diameter	578213	Carpenter - Reading Mill
	2.75 in. diameter	578213	Carpenter - Reading Mill
	5 in. diameter	H1974	Carpenter - Latrobe Mill
Custom 630 (H1100)	2.75 in. diameter	971709	Carpenter - Reading Mill
	5 in. diameter	H5289	Carpenter - Latrobe Mill
2507 Duplex	2.75 in. diameter	545813	Sandvik - Sandviken Mill
	5 in. diameter	539234	Sandvik - Sandviken Mill

27May15 13:16 TEST CERTIFICATE No: 1 113916

KREHER STEEL COMPANY, LLC.
1550 NORTH 25TH AVENUE
MELROSE PARK, IL 60160
Tel: 708-345-8180 Fax: 708-345-8293

P/O No 409192
Rel
S/O No 1 274677-001
B/L No Shp
Inv No Inv

Sold To: (4470)
DYWIDAG SYSTEMS INTERNATIONAL
320 MARMON DRIVE
BOLINGBROOK, IL 60440

Ship To: (1)
DYWIDAG-HEADQUARTERS
CARL NASH-REC.MGR
320 MARMON DR.
BOLINGBROOK, IL 60440

Tel: 630-739-1100 Fax: 630-972-9604

CERTIFICATE of ANALYSIS and TESTS Cert. No: 1 113916
27May15

Part No B66E04590
TURN & POLISH ROUNDS 4142QT
2.6400 X 45'R/L 0

100% MELTED AND MANUFACTURED IN THE UNITED STATES
HEAT ANALYSES ARE REPORTED IN WEIGHT PERCENT
QUENCH & TEMPERED & MACHINE STRAIGHTENED
TO MEET THE FOLLOWING PARAMETERS:
LOT NO. 8324
TENSILE: (155 KSI MIN) 167,000
YIELD: (128 KSI MIN) 154,000
ELONGATION: (13% MIN) 14 % IN 2"
HARDNESS @ SURFACE: (302-352 HB) 369-370
COLD FINISHED IN ACCORDANCE WITH ASTM A108

Heat Number *** Chemical Analysis ***
NF15100387 C=0.4200 Mn=0.8500 P=0.0100 S=0.0200 Si=0.2100 Cr=0.9000
Mo=0.2200 V=<.032> Cu=<.16> Ni=<.07> Al=<.001> Cb=<.006> Pb=<.0>
Sn=<.009> Ca=<.0003> B=<.0004> Ti=<.001> N=<80PPM> H=<.06PPM>

I hereby certify that this data is correct as
contained in the records of this company.
I hereby certify that no mercury came in contact
with or no weld repair was done to this product
while in our possession.

Page: 1 .... Last

bko

CERTIFICATE OF TESTS ABNAHMEPRUEFZEUGNIS CERTIFICAT DE CONTROLE

CERT SERIAL# 001037919

CARPENTER
Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

- THE RECORDING OF FALSE, FICTICIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PUNISHED AS A FELONY UNDER FEDERAL STATUTES INCLUDING FEDERAL LAW, TITLE 18, CHAPTER 47.
- THE VALUES AND OTHER TECHNICAL DATA REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARPENTER ORDER NUMBER.
- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
- THIS DOCUMENT SHALL NOT BE REPRODUCED, EXCEPT IN FULL, WITHOUT THE WRITTEN CONSENT OF CARPENTER TECHNOLOGY CORPORATION.

09/30/16

CUSTOMER / BESTELLER / CLIENT

SIMPSON GUMPERTZ & HEGER
BUILDING 1, SUITE 500

41 SEYON ST
WALTHAM MA 02453

SELLER / VERKÄUFER / VENDEUR

RAN

CUSTOMER ORDER NO./BESTELL-NR./N° DE COMMANDE	CARPENTER NO./WERKS-NR./N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
14698	W92419	09/30/16	1679.00

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE : 578213

PRODUCT DESCRIPTION: CUSTOM 450 STAINLESS SOLUTION ANNEALED AGED GROUND
CONDITION H1050

SPECIFICATION: ASTM-A564-13 COND H1050 (XM-25)

SIZE 2.750000 IN.(69.85 MM) RD BAR

HEAT CHEMISTRY(WT%): (TEST METHOD IS SHOWN IN PARENTHESIS)

C (COM)	MN(XRF)	SI(XRF)	P (XRF)	S (COM)	CR(XRF)
0.03	0.42	0.53	0.016	0.001	14.80

NI(XRF)	MO(XRF)	CU(XRF)	CB(XRF)	CB+TA
6.47	0.74	1.45	0.66	0.67

THIS HEAT MELTED BY THE ELECTRIC ARC/AOD PROCESSES

HARDNESS AS SHIPPED, HRC - 38 (MIDRADIUS)

(T)RANSVERSE (L)ONGITUDINAL	L
YIELD STRENGTH, (0.20 %) KSI(MPA)	158.0(1089)
TENSILE STRENGTH, KSI(MPA)	168.0(1158)
ELONGATION IN 2.00", %	19.0
REDUCTION OF AREA, %	61.0

MATERIAL HAS BEEN MELTED AND MANUFACTURED IN THE USA WHICH IS A QUALIFYING COUNTRY TO DFARS REQUIREMENTS 252.225-7014 WITH ALTERNATE 1 FOR QUALIFYING COUNTRY 225.872.1, SUPERSEDED BY DFARS REQUIREMENTS DFARS 252.225-7008 AND 252.225-7009.
THIS ORDER WAS MANUFACTURED IN ACCORDANCE WITH CARPENTER SPECIALTY ALLOYS OPERATIONS QUALITY PROGRAM MANUAL, REVISION 34 DATED 11/18/15.

CARPENTER'S QUALITY MANAGEMENT SYSTEM WAS REGISTERED AS OF NOVEMBER 24, 2013 TO THE REQUIREMENTS OF ISO 9001:2008 APPROVAL CERTIFICATE 13-1996R BY PERFORMANCE REVIEW INSTITUTE. THIS CERTIFICATE OF TEST IS TYPE 3.1 PREPARED IN ACCORDANCE WITH EN 10204 (DIN 50049). WE HEREBY CERTIFY THAT THE ABOVE TEST DATA ARE IN ACCORDANCE WITH THE PURCHASE ORDER AND SPECIFICATION REQUIREMENTS, AS DOCUMENTED IN THIS CERTIFICATE OF TESTS.

TEST METHODS ARE PER THE ASTM STANDARDS ON FILE AND IN EFFECT AT TIME OF ORDER ACCEPTANCE, STANDARD PRACTICES, OR AS AGREED UPON BETWEEN CARPENTER & CUSTOMER.

CONTINUED ON NEXT PAGE

FORM F2-366

CERTIFICATE OF TESTS **ABNAHMEPRUEFZEUGNIS** **CERTIFICAT DE CONTROLE**

CERT SERIAL# 001037919

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

- THE RECORDING OF FALSE, FICTICIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PUNISHED AS A FELONY UNDER FEDERAL STATUTES INCLUDING FEDERAL LAW, TITLE 18, CHAPTER 47.
- THE VALUES AND OTHER TECHNICAL DATA REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARPENTER ORDER NUMBER.
- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
- THIS DOCUMENT SHALL NOT BE REPRODUCED, EXCEPT IN FULL, WITHOUT THE WRITTEN CONSENT OF CARPENTER TECHNOLOGY CORPORATION.

09/30/16

CUSTOMER / BESTELLER / CLIENT

SIMPSON GUMPERTZ & HEGER
BUILDING 1, SUITE 500

41 SEYON ST
WALTHAM MA 02453

SELLER / VERKÄUFER / VENDEUR

RAN

CUSTOMER ORDER NO./BESTELL-NR./N° DE COMMANDE	CARPENTER NO./WERKS-NR./N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
14698	W92419	09/30/16	1679.00

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE : 578213

GARY BROWN
MANAGER - SPECIFICATIONS/CERTIFICATIONS
CARPENTER TECHNOLOGY CORPORATION

Gary Brown

FORM F2-366

CERTIFICATE OF TESTS — ABNAHMEPRUEFZEUGNIS — CERTIFICAT DE CONTROLE

CERT SERIAL# 001042178

CARPENTER
Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

11/09/16

CUSTOMER / BESTELLER / CLIENT

SIMPSON GUMPERTZ & HEGER
BUILDING 1, SUITE 500

41 SEYON ST
WALTHAM MA 02453

SELLER / VERKÄUFER / VENDEUR

RAN

CUSTOMER ORDER NO./BESTELL-NR./N° DE COMMANDE	CARPENTER NO./WERKS-NR./N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
14698	W92419 - 1	11/09/16	3118.00

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE : 578213

PRODUCT DESCRIPTION: CUSTOM 450 STAINLESS SOLUTION ANNEALED AGED GROUND CONDITION H1050

SPECIFICATION: ASTM-A564-13 COND H1050 (XM-25)

SIZE 2.750000 IN.(69.85 MM) RD BAR

HEAT CHEMISTRY(WT%): (TEST METHOD IS SHOWN IN PARENTHESIS)

C (COM)	MN(XRF)	SI(XRF)	P (XRF)	S (COM)	CR(XRF)
0.03	0.42	0.53	0.016	0.001	14.80

NI(XRF)	MO(XRF)	CU(XRF)	CB(XRF)	CB+TA
6.47	0.74	1.45	0.66	0.67

THIS HEAT MELTED BY THE ELECTRIC ARC/AOD PROCESSES

HARDNESS AS SHIPPED, HBW - 363 (MIDRADIUS)
THE INDENTATION MEASURING DEVICE WAS A TYPE A.

(T)RANSVERSE (L)ONGITUDINAL	L
YIELD STRENGTH, (0.20 %) KSI(MPA)	160.0(1103)
TENSILE STRENGTH, KSI(MPA)	169.0(1165)
ELONGATION IN 2.00", %	19.0
REDUCTION OF AREA, %	63.0

MATERIAL HAS BEEN MELTED AND MANUFACTURED IN THE USA WHICH IS A QUALIFYING COUNTRY TO DFARS REQUIREMENTS 252.225-7014 WITH ALTERNATE 1 FOR QUALIFYING COUNTRY 225.872.1, SUPERSEDED BY DFARS REQUIREMENTS DFARS 252.225-7008 AND 252.225-7009.
THIS ORDER WAS MANUFACTURED IN ACCORDANCE WITH CARPENTER SPECIALTY ALLOYS OPERATIONS QUALITY PROGRAM MANUAL, REVISION 34 DATED 11/18/15.

CARPENTER'S QUALITY MANAGEMENT SYSTEM WAS REGISTERED AS OF NOVEMBER 24, 2013 TO THE REQUIREMENTS OF ISO 9001:2008 APPROVAL CERTIFICATE 13-1996R BY PERFORMANCE REVIEW INSTITUTE. THIS CERTIFICATE OF TEST IS TYPE 3.1 PREPARED IN ACCORDANCE WITH EN 10204 (DIN 50049). WE HEREBY CERTIFY THAT THE ABOVE TEST DATA ARE IN ACCORDANCE WITH THE PURCHASE ORDER AND SPECIFICATION REQUIREMENTS, AS DOCUMENTED IN THIS CERTIFICATE OF TESTS.

TEST METHODS ARE PER THE ASTM STANDARDS ON FILE AND IN EFFECT AT TIME OF ORDER ACCEPTANCE, STANDARD PRACTICES, OR AS AGREED UPON BETWEEN CARPENTER & CUSTOMER.

CONTINUED ON NEXT PAGE

CERTIFICATE OF TESTS **ABNAHMEPRUEFZEUGNIS** **CERTIFICAT DE CONTROLE**

CERT SERIAL# 001042178

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

- THE RECORDING OF FALSE, FICTICIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PUNISHED AS A FELONY UNDER FEDERAL STATUTES INCLUDING FEDERAL LAW, TITLE 18, CHAPTER 47.
- THE VALUES AND OTHER TECHNICAL DATA REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARPENTER ORDER NUMBER.
- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
- THIS DOCUMENT SHALL NOT BE REPRODUCED, EXCEPT IN FULL, WITHOUT THE WRITTEN CONSENT OF CARPENTER TECHNOLOGY CORPORATION.

11/09/16

CUSTOMER / BESTELLER / CLIENT

SIMPSON GUMPERTZ & HEGER
BUILDING 1, SUITE 500

41 SEYON ST
WALTHAM MA 02453

SELLER / VERKÄUFER / VENDEUR

RAN

CUSTOMER ORDER NO./BESTELL-NR./N° DE COMMANDE	CARPENTER NO./WERKS-NR./N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
14698	W92419 - 1	11/09/16	3118.00

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE : 578213

GARY BROWN
MANAGER - SPECIFICATIONS/CERTIFICATIONS
CARPENTER TECHNOLOGY CORPORATION

Gary Brown

FORM F2-366

CARPENTER®
Latrobe Specialty Metals

CERTIFICATE OF TEST

2626 S. Ligonier St.
Latrobe, PA 15650

Production Order Number	Wgt. Shipped	Sales Order No.	Heat No.
10556208	3904	20239790-1	H1974
Customer Order No./Req. No.			Delivery #
14698			30576326

Bill To: 506708	Ship To: 408815
SIMPSON GUMPERTZ & HEGER 41 SEYON ST WALTHAM MA 02453	MIDWEST PRECISION MFG 627 TOWER DR FREDONIA WI 53021

MATERIAL DESCRIPTION:
(TO SIZE) 5.000 RND BAR 450 PH ESR 10FT - 15FT STAG PP ASTM A564-13 TYPE S45000 (XM-25) CONDITION H1050
INGOT# 1

Chemical Analysis Wt%:

Locn	C	Si	Mn	S	P	Cb	Cr	Ni	Mo	Cu
1T	.028	.26	.72	.001	.021	.59	14.49	6.28	.81	1.62
1B	.031	.24	.71	<.001	.021	.60	14.40	6.27	.81	1.62

Room Temperature Tensile Tests:
Transverse Mid Radius at at 5.5" Rnd.

Locn:	UTS(ksi)	.2TSY(ksi)	El(%in4d)	R.A.(%)
E9	158	148	19	50

Hardness per ASTM E10-15a & ASTM A370-16: 341 HBW

Macroetch per ASTM A-604-07 (Reapproved 2012) & ASTM E-340-15: 1A, 2A, 3A, 4A

Country of origin (Manufacturing & Melting): USA

Testing methods for chemical analysis tested at Latrobe Specialty Metals are as follows: C,S,N,O & H = Combustion Si, Mn, W, Cr V, Ni, Mo, Co, Cu, Al>1%, Ti>.1%, Cb, Ta, Fe & Sn = X-Ray. Balance of elements analyzed on OE. Other testing methods not listed above have been conducted per certified material specification(s).
Latrobe Specialty Metals is registered to Quality Management System Standards: ISO 9001 and AS9100. Tests are accredited under the laboratory`s ISO/IEC 17025 accreditation issued by ANSI-ASQ National Accreditation Board/ANAB. Refer to certificate and scope of accreditation AT-1657, NDT not applicable.

Need certs? Our certs are available online at http://customer.cartech.com/private
We certify this material to have been manufactured, inspected, and tested; and found the results to conform to all drawing and/or specification requirements and order requirements as applicable. The recording of false, fictitious or fraudulent statements or entries on the documents may be punishable as a felony under Federal Statute. This certificate or report shall not be reproduced except in full, without the written approval of Latrobe Specialty Metals.

Rebecca A. Penn 10/19/2016
C - Inspection Department Date
Rebecca A Penn - Group Leader - Met Certification

CERTIFICATE OF TESTS | ABNAHMEPRUEFZEUGNIS | CERTIFICAT DE CONTROLE

CERT SERIAL# 001037495

CARPENTER
Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

10/18/16

CUSTOMER / BESTELLER / CLIENT

SIMPSON GUMPERTZ & HEGER
BUILDING 1, SUITE 500

41 SEYON ST
WALTHAM MA 02453

SELLER / VERKÄUFER / VENDEUR

RAN

CUSTOMER ORDER NO./BESTELL-NR./N° DE COMMANDE	CARPENTER NO./WERKS-NR./N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
14698	W92604	10/18/16	5775.00

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE : 971709 UNS NUMBER S17400

PRODUCT DESCRIPTION: TYPE 17-4 SOLUTION ANNEALED AGED GROUND CONDITION H1100

SPECIFICATION: ASTM-A564-13 COND H1100

SIZE 2.750000 IN.(69.85 MM) RD BAR

HEAT CHEMISTRY(WT%):

C	MN	SI	P	S	CR
0.03	0.72	0.27	0.018	0.027	15.29
NI	MO	CU	N	CB	TA
4.24	0.13	4.01	0.026	0.24	LT .02
CB+TA					
0.24					

THIS HEAT MELTED BY THE ELECTRIC ARC/AOD PROCESSES

HARDNESS AS SHIPPED 336HBW (36HRC)

(T)RANSVERSE (L)ONGITUDINAL	L
YIELD STRENGTH, (0.20 %) KSI(MPA)	150.0(1034)
TENSILE STRENGTH, KSI(MPA)	156.0(1076)
ELONGATION IN 2.00", %	16.0
REDUCTION OF AREA, %	61.0

MATERIAL HAS BEEN MELTED IN USA OR QUALIFYING COUNTRY TO DFARS REQUIREMENTS 252.225-7014 WITH ALTERNATE 1 FOR QUALIFYING COUNTRY 225.872.1, SUPERSEDED BY DFARS REQUIREMENTS DFARS 252.225-7008 AND 252.225-7009. THIS ORDER WAS MANUFACTURED IN ACCORDANCE WITH CARPENTER SPECIALTY ALLOYS OPERATIONS QUALITY PROGRAM MANUAL, REVISION 34 DATED 11/18/15.

CARPENTER'S QUALITY MANAGEMENT SYSTEM WAS REGISTERED AS OF NOVEMBER 24, 2013 TO THE REQUIREMENTS OF ISO 9001:2008 APPROVAL CERTIFICATE 13-1996R BY PERFORMANCE REVIEW INSTITUTE. THIS CERTIFICATE OF TEST IS TYPE 3.1 PREPARED IN ACCORDANCE WITH EN 10204 (DIN 50049). WE HEREBY CERTIFY THAT THE ABOVE TEST DATA ARE IN ACCORDANCE WITH THE PURCHASE ORDER AND SPECIFICATION REQUIREMENTS, AS DOCUMENTED IN THIS CERTIFICATE OF TESTS.

TEST METHODS ARE PER THE ASTM STANDARDS ON FILE AND IN EFFECT AT TIME OF ORDER ACCEPTANCE, STANDARD PRACTICES, OR AS AGREED UPON BETWEEN CARPENTER & CUSTOMER.

CONTINUED ON NEXT PAGE

CERTIFICATE OF TESTS | ABNAHMEPRUEFZEUGNIS | CERTIFICAT DE CONTROLE

CERT SERIAL# 001037495

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

- THE RECORDING OF FALSE, FICTICIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PUNISHED AS A FELONY UNDER FEDERAL STATUTES INCLUDING FEDERAL LAW, TITLE 18, CHAPTER 47.
- THE VALUES AND OTHER TECHNICAL DATA REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARPENTER ORDER NUMBER.
- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
- THIS DOCUMENT SHALL NOT BE REPRODUCED, EXCEPT IN FULL, WITHOUT THE WRITTEN CONSENT OF CARPENTER TECHNOLOGY CORPORATION.

10/18/16

CUSTOMER / BESTELLER / CLIENT

SIMPSON GUMPERTZ & HEGER
BUILDING 1, SUITE 500

41 SEYON ST
WALTHAM MA 02453

SELLER / VERKÄUFER / VENDEUR

RAN

CUSTOMER ORDER NO./BESTELL-NR./N° DE COMMANDE	CARPENTER NO./WERKS-NR./N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
14698	W92604	10/18/16	5775.00

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE : 971709 UNS NUMBER S17400

STEPHANIE E. MCCULLUM
QUALITY ASSURANCE ENGINEER
CARPENTER TECHNOLOGY CORPORATION

Stephanie McCullum

FORM F2-366

CERTIFICATE OF TEST

CARPENTER
Latrobe Specialty Metals

2626 S. Ligonier St.
Latrobe, PA 15650

Production Order Number	Wgt. Shipped	Sales Order No.	Heat No.
10551739	4193	20238803-1	H5289
Customer Order No./Req. No.			Delivery #
14698			30572457

Bill To: 506708	Ship To: 408815
SIMPSON GUMPERTZ & HEGER 41 SEYON ST WALTHAM MA 02453	MIDWEST PRECISION MFG 627 TOWER DR FREDONIA WI 53021

MATERIAL DESCRIPTION:

(TO SIZE) 5.000 RND BAR 17-4 AIRMLT 10FT - 15FT MILL STAG PP ASTM A564-13 TYPE 630 AGED TO CONDITION H1100
INGOT # 4

Chemical Analysis Wt%:

Locn	C	Si	Mn	S	P	Cr	Ni	Cu	Cb+Ta
LADLE	.030	.30	.70	<.001	.012	15.41	4.02	3.49	.25

Room Temperature Tensile Tests per ASTM E8-15a & ASTM A370-16:

Longitudinal Mid-Radius @ 5.3" Rnd

Locn.	UTS(ksi)	.2TYS(ksi)	El(%in4d)	R.A.(%)
P6-1	147	139	22	63

Hardness per ASTM E10-15 & ASTM A370-16: 321 HBW

Macroetch per ASTM A-604-07 (Reapproved 2012) & ASTM E-340-15: 1A, 2A, 3A, 4A
per ASTM E-381-01 & ASTM E-340-15: S1, R1, C1

Country of origin (Manufacturing & Melting): USA

Testing methods for chemical analysis tested at Latrobe Specialty Metals are as follows: C,S,N,O & H = Combustion Si, Mn, W, Cr V, Ni, Mo, Co, Cu, Al> 1%, Ti> .1%, Cb, Ta, Fe & Sn = X-Ray. Balance of elements analyzed on OE. Other testing methods not listed above have been conducted per certified material specification(s).

Latrobe Specialty Metals is registered to Quality Management System Standards: ISO 9001 and AS9100. Tests are accredited under the laboratory`s ISO/IEC 17025 accreditation issued by ANSI-ASQ National Accreditation Board/ANAB. Refer to certificate and scope of accreditation AT-1657, NDT not applicable.

Need certs? Our certs are available online at http://customer.cartech.com/private

We certify this material to have been manufactured, inspected, and tested; and found the results to conform to all drawing and/or specification requirements and order requirements as applicable. The recording of false, fictitious or fraudulent statements or entries on the documents may be punishable as a felony under Federal Statute. This certificate or report shall not be reproduced except in full, without the written approval of Latrobe Specialty Metals.

Paula S. Miller

08/25/2016

C – 10 Inspection Department — Date

Paula S Miller - Administrator II - Quality

SANDVIK

CERTIFICATE No. A/16-591811 Rev 00
Date 2016-07-12 Page 1/3

INSPECTION CERTIFICATE acc to
EN 10204 3.1

SANDVIK MATERIALS TECHNOLOGY
P O BOX 1220
SCRANTON, PA 18501
USA

Customer References

6346 Customer order 2016-07-05

450-00991 RAM ALLOYS, L

Sandvik References

Order No.	Subs No.	ABSMT Dispatch note
	62484	30218/53
ABSMT No.	C.Code	
284-17200	03	

Material description
HOT WORKED STAINLESS BAR STEEL
ROLLED
ANNEALED & STRAIGHTENED
PEEL TURNED AND POLISHED

Melt Source
SMT SANDVIKEN SWEDEN
Steel making process **Origin**
E+AOD+LRF Sweden

Steel/material Designations

Sandvik	UNS
SAF 2507	S32750
EN no	
1.4410	

Technical requirements
EN 10088-3:-2005, ASTM A-479-16, ASME SA-479-ED-15,
ASTM A-276-16, NACE MR0175/ISO 15156-3:2009, NACE MR0103:2012
Norsok Standard M-630-ED.6 for MDS D57-REV.5, Suitable for
manufacturing of components in acc. with ASTM A-182-15, F53

EXTENT OF DELIVERY

It	Product designation	Heat	Lot	Pieces	Kg	Lbs
01	MBR-SAF2507-70	545813	03071	5	856.0	1887.13
		545813	03072	16	2813.0	6201.53
			Total	21	3669.0	8088.66

TEST RESULTS
Chemical composition (weight%)

Heat	PRE
545813	42.2

Heat	C	Si	Mn	P	S	Cr	Ni	Mo
545813	0.014	0.31	0.78	0.024	0.0005	24.90	6.90	3.79

Heat	Cu	N
545813	0.13	0.297

Tensile test at room temperature
Longitudinal

	Yield strength		Tensile strength	Elongation		Red.of Area
	MPa	MPa	MPa	%	%	%
Lot	Rp0.2	Rp1.0	Rm	A	2"	Z
03071	563	658	818	42	42	77
03072	595	659	820	42	42	77

Customer Name	Customer PO#	Shipper No	Heat Number
Simpson Gumpertz & Heger	14697	8089	545813

Quality assurance - Viktor Hellberg/QA-manager Primary Products
MTC Service / Certificates

AB SANDVIK MATERIALS TECHNOLOGY Reg No. 556234-6832 VAT No. SE663000-060901
SE-81181 SANDVIKEN SWEDEN www.smt.sandvik.com mtc_service.smt@sandvik.com

Customer Name	Customer PO#	Shipper No	Heat Number
Simpson Gumpertz & Heger	14697	8089	545813

SANDVIK

CERTIFICATE No. A/16-591811 Rev 00
Date 2016-07-12 Page 2/3

Hardness test

Lot	**Min HRC**	**Max HRC**
03071	22	24
03072	23	24

Impact test, J, -50°C. Longitudinal.

Lot	Single values **Joule**			Average **Joule**
03071	333	351	333	339
03072	318	329	338	328

Lateral expansion

Lot	**mm**		
03071	1.91	2.43	1.91
03072	2.50	1.92	1.93

Corrosion test
According to ASTM G-48A, 50°C for 24 hours.
No pitting corrosion found at 20x enlargement.

Lot	**Specimen weight loss g/m2**
03071	0.00
03072	0.00

Ferrite acc to ASTM E-562

Lot	**%**
03071	46.8
03072	41.4

Following controls/tests have been satisfactorily performed:
- Material Identification.
- Visual inspection and dimensional control.

Heat Treatment:
1100°C/30 min. Quenched in water.

Melt Source
Heat 545813 SMT SANDVIKEN SWEDEN

The raw material is free from radioactive contamination.

Microscopic Examination X 500: Free from grain boundary carbides and intermetallic phases

Material free from mercury contamination.

No welding or weld repair.

NORSOK M-650 ED-4 QTR NO: 25 Cr Duplex SS

The delivered products comply with the specifications and requirements of the order.

The material is manufactured according to a Quality system, approved and registered to ISO 9001:2008.

Customer Name	Customer PO#	Shipper No	Heat Number
Simpson Gumpertz & Heger	14697	8089	545813

Customer Name	Customer PO#	Shipper No	Heat Number
Simpson Gumpertz & Heger	14697	8089	545813

SANDVIK

CERTIFICATE No. A/16-591811 Rev 00
Date 2016-07-12 Page 3/3

No unauthorized alterations. The contents of this Inspection Certificate may not be modified or revised in any way without the prior written approval of AB Sandvik Materials Technology. Unauthorized alterations to the Inspection Certificate, including introduction of false, fictitious or fraudulent statements or entries, may be punishable by fines, imprisonment, or both. This Inspection Certificate may be copied only in the manner and for the purposes specified in Section 6 of EN 10204:2004. Contravention of this notice will be prosecuted to the fullest extent of applicable law.

The certificate is produced with EDP and valid without signature.

Customer Name	Customer PO#	Invoice No	Shipper No	Heat Number
Simpson Gumpertz & Heger	14697	7269	7248	539234

SANDVIK

CERTIFICATE No. A/15-483224 Rev 01
Date 2015-03-02 **Page 1/3**

Rev.date 2016-07-04

INSPECTION CERTIFICATE acc to
EN 10 204 3.1

SANDVIK MATERIALS TECHNOLOGY
P O BOX 1220
SCRANTON, PA 18501
USA

Customer References

HOUSTON STOCK

Customer order 2015-01-12

450-00991 NAFTA

Sandvik References

Order No.	Subs No.	ABSMT Dispatch note
	43086	27771/53

ABSMT No.	C.Code
284-75955	25

Material description
HOT WORKED STAINLESS BAR STEEL
ROLLED
ANNEALED & STRAIGHTENED
PEEL TURNED AND POLISHED

Melt Source
AB SANDVIK MT SWEDEN
Steel making process **Origin**
E+AOD+LRF Sweden

Steel/material Designations
Sandvik UNS
SAF2507 S32750
EN no
1.4410

Technical requirements
EN 10088-3:-2005, ASTM A-479-14, ASME SA-479-ED-13,
ASTM A-276-15, NACE MR0175/ISO 15156-3:2009, NACE MR0103:2012
Norsok Standard M-630-ED.6 for MDS D57-REV.5, Suitable for
manufacturing of components in acc. with ASTM A-182-14, F53

EXTENT OF DELIVERY

It	Product designation	Heat	Lot	Pieces	Kg	Lbs
04	MBR-SAF2507-5"	539234	65761	10	6410.0	14132.00
			Total	10	6410.0	14132.00

TEST RESULTS
Chemical composition (weight%)

Heat	PRE
539234	43.5

Heat	C	Si	Mn	P	S	Cr	Ni	Mo
539234	0.018	0.28	0.89	0.020	0.0007	25.77	6.41	3.90
	Cu	**N**						
539234	0.14	0.304						

Tensile test at room temperature
Longitudinal

	Yield strength		Tensile strength	Elongation		Red.of Area
	MPa	MPa	MPa	%	%	%
Lot	Rp0.2	Rp1.0	Rm	A	2"	Z
65761	623	714	828	39	39	73

Quality assurance - Viktor Hellberg/QA-manager Primary Products
MTC Service / Certificates

AB SANDVIK MATERIALS TECHNOLOGY Reg No. 556234-6832 VAT No. SE663000-060901
SE-81181 SANDVIKEN SWEDEN www.smt.sandvik.com mtc_service.smt sandvik.com

Customer Name	Customer PO#	Invoice No	Shipper No	Heat Number
Simpson Gumpertz & Heger	14697	7269	7248	539234

SANDVIK

CERTIFICATE **No. A/15-483224** **Rev 01**
Date 2015-03-02 **Page 2/3**
Rev.date 2016-07-04

Transversal

	Yield strength		Tensile strength	Elongation		Red.of Area
	MPa	**MPa**	**MPa**	**%**	**%**	**%**
Lot	**Rp0.2**	**Rp1.0**	**Rm**	**A**	**2"**	**Z**
65761	589	705	840	37	37	56

Hardness test

	Min	Max
Lot	**HRC**	**HRC**
65761	24	25

Impact test, J, -50 C. Longitudinal.

	Single values			Average
Lot	**Joule**			**Joule**
65761	97	92	95	95

Corrosion test
According to ASTM G-48A, 50 C for 24 hours.
No pitting corrosion found at 20x enlargement.

	Specimen weight loss
Lot	**g/m2**
65761	0.10

Ferrite acc to ASTM E-562

Lot	**%**
65761	50.1

Following controls/tests have been satisfactorily performed:
- Material Identification.
- Ultrasonic test acc to EN 10228-4, Scan coverage 1, Quality Class 3, Tab 4. API 6A PSL3, ASTM A-388
- Visual inspection and dimensional control.

Heat Treatment:
1100 C/30 min. Quenched in water.

Melt Source
Heat 539234 AB SANDVIK MT SWEDEN

The raw material is free from radioactive contamination.

Microscopic Examination X 500: Free from grain boundary carbides and intermetallic phases

Material free from mercury contamination.

No welding or weld repair.

NORSOK M-650 QTR NO: 25 Cr Duplex SS

The delivered products comply with the specifications and requirements of the order.

The material is manufactured according to a Quality system, approved and registered to ISO 9001:2008.

CERTIFICATE **No. A/15-483224** **Rev 01**
Date 2015-03-02 **Page 3/3**

Rev.date 2016-07-04

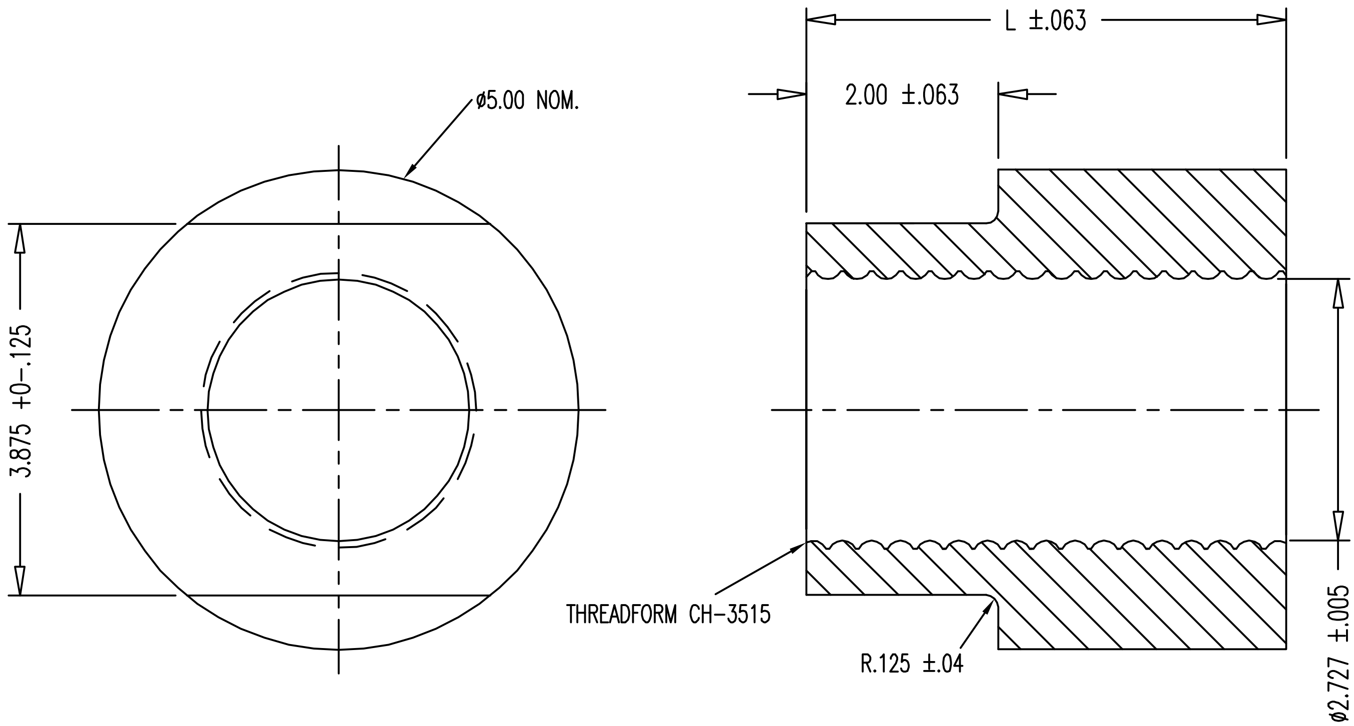
No unauthorized alterations. The contents of this Inspection Certificate may not be modified or revised in any way without the prior written approval of AB Sandvik Materials Technology. Unauthorized alterations to the Inspection Certificate, including introduction of false, fictitious or fraudulent statements or entries, may be punishable by fines, imprisonment, or both. This Inspection Certificate may be copied only in the manner and for the purposes specified in Section 6 of EN 10204:2004. Contravention of this notice will be prosecuted to the fullest extent of applicable law.

The certificate is produced with EDP and valid without signature.

Appendix D – Fabrication

Appendix D contains the following material related to fabrication:

- Fabrication drawings, CH-3494 and CH-3496, for end nuts and coupling nuts, respectively.
- Photographs, D-1 to D-8, showing the fabrication process for threaded bars and nuts.



PART NAME	L
4D TEST NUT	10.00
2D END NUT	5.00
2.5 END NUT	6.25
3D END NUT	7.50

DIMENSIONS: INCH [mm]
mm FOR REFERENCE ONLY

QUALITY PLAN NUMBER: QB00020700S

66mm NUTS FOR SGH

DATE: 05-24-16 | DWG: E. SKOFF | CHK: S.Y. | APP: S.E.

TOLERANCES: ±.020 UNLESS NOTED

WEIGHT

MATERIAL: PROVIDED BY SGH

SCALE 1:2

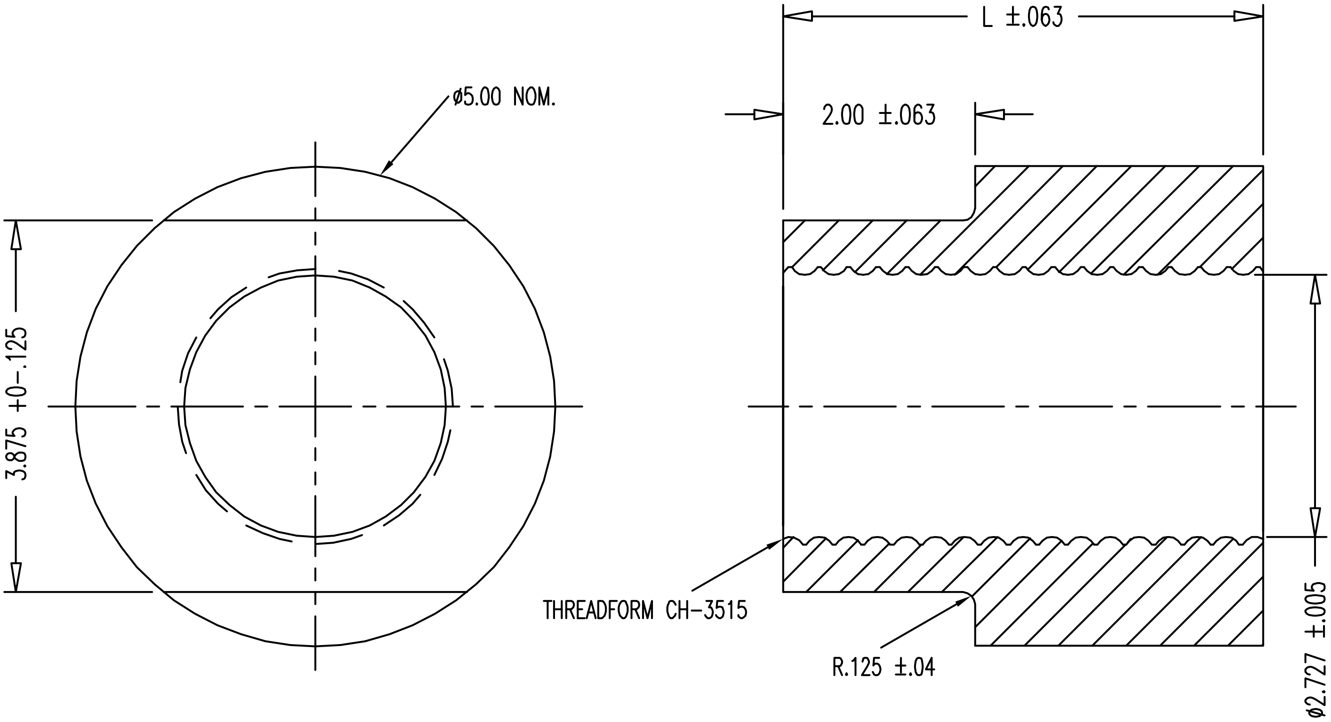
REV.	DATE	NAME	
1	05/26/16	S.Y.	
2	09/21/16	S.Y.	

PART NUMBERS:

DRAWING NUMBER: **CH-3494**

DYWIDAG-SYSTEMS INTERNATIONAL, USA, INC.
320 MARMON DRIVE - BOLINGBROOK, IL 60440
PHONE: 630-739-1100 FAX: 630-739-1405

DSI



PART NAME	L
4.4D COUPLER	11.00
5.4D COUPLER	13.50

DIMENSIONS: INCH [mm] mm FOR REFERENCE ONLY	QUALITY PLAN NUMBER: QB00030800S	TOLERANCES: ±.020 UNLESS NOTED	WEIGHT	REV.	DATE	NAME	PART NUMBERS:
				1	05/26/16	S.Y.	
				2	09/21/16	S.Y.	
		MATERIAL: PROVIDED BY SGH	SCALE 1:2				DRAWING NUMBER: CH-3496

66mm COUPLERS FOR SGH

DATE: 05-24-16 | DWG: E. SKOFF | CHK: S.Y. | APP: S.E.

DYWIDAG-SYSTEMS INTERNATIONAL, USA, INC.
320 MARMON DRIVE - BOLINGBROOK, IL 60440
PHONE: 630-739-1100 FAX: 630-739-1405

DSI

Figure D-1 – Stainless steel bar stock prior to threading.

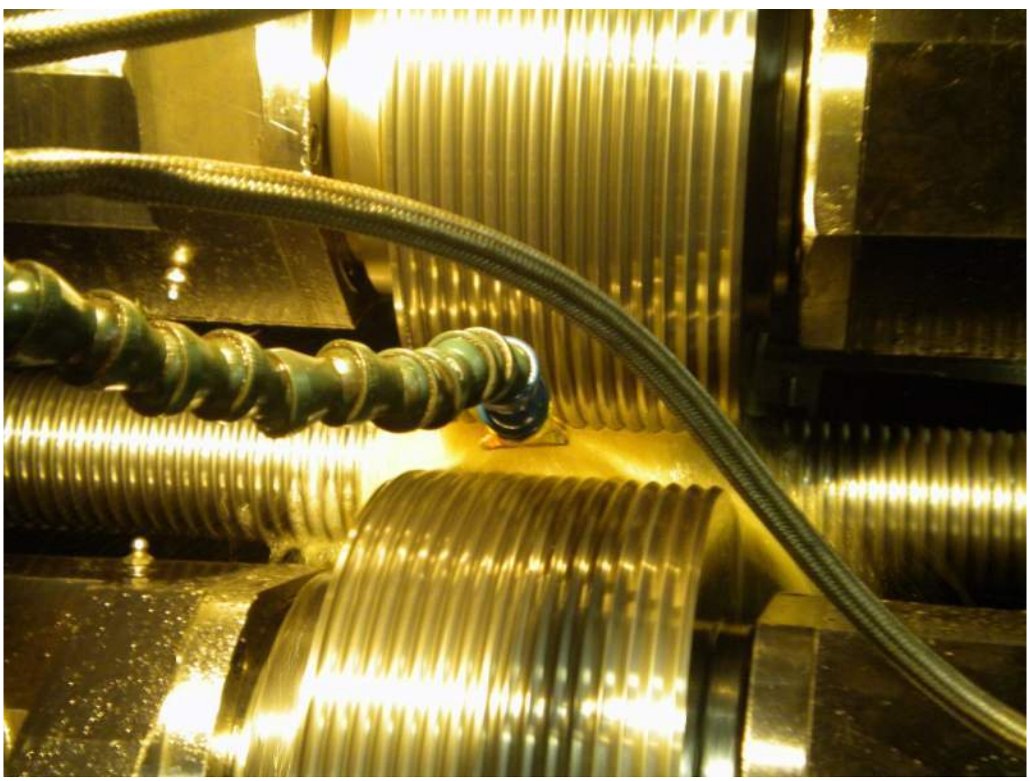


Figure D-2 – Cold-roll thread forming (bars completed multiple passes through rolls).

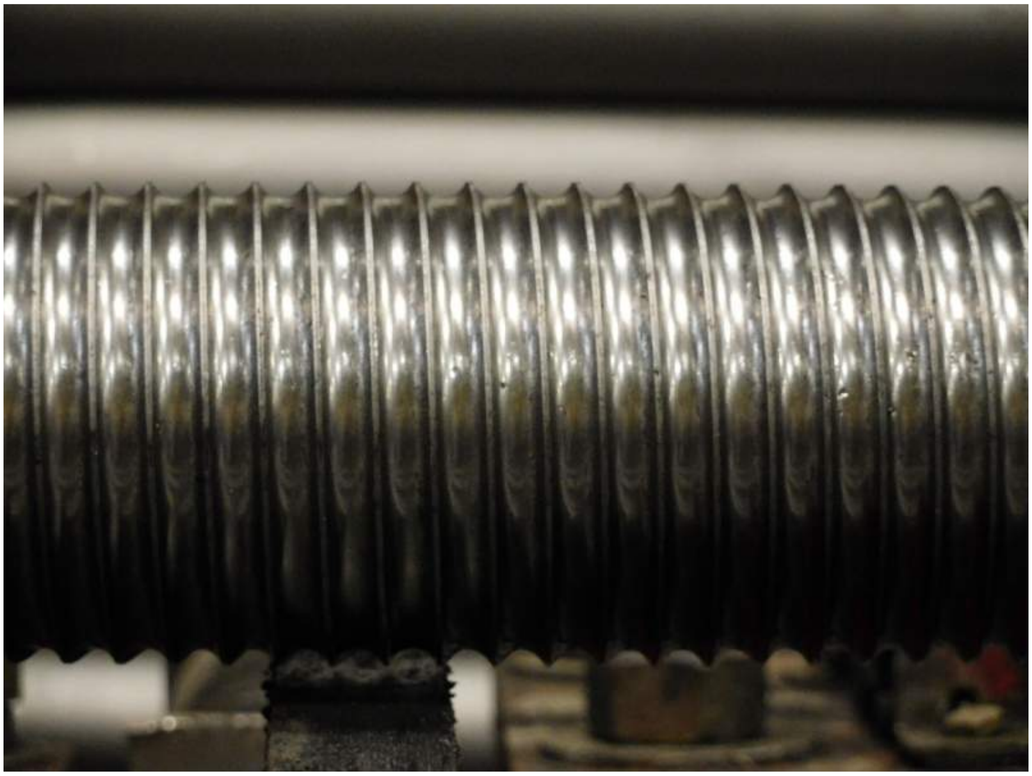


Figure D-3 – Finished threaded stainless steel anchorage bar.

Figure D-4 – Trepanning (bar stock at near end, drill bit, and extension at far end of machine).

Figure D-5 – Bar stock following trepanning.

Figure D-6 – Nuts prior to internal threading.

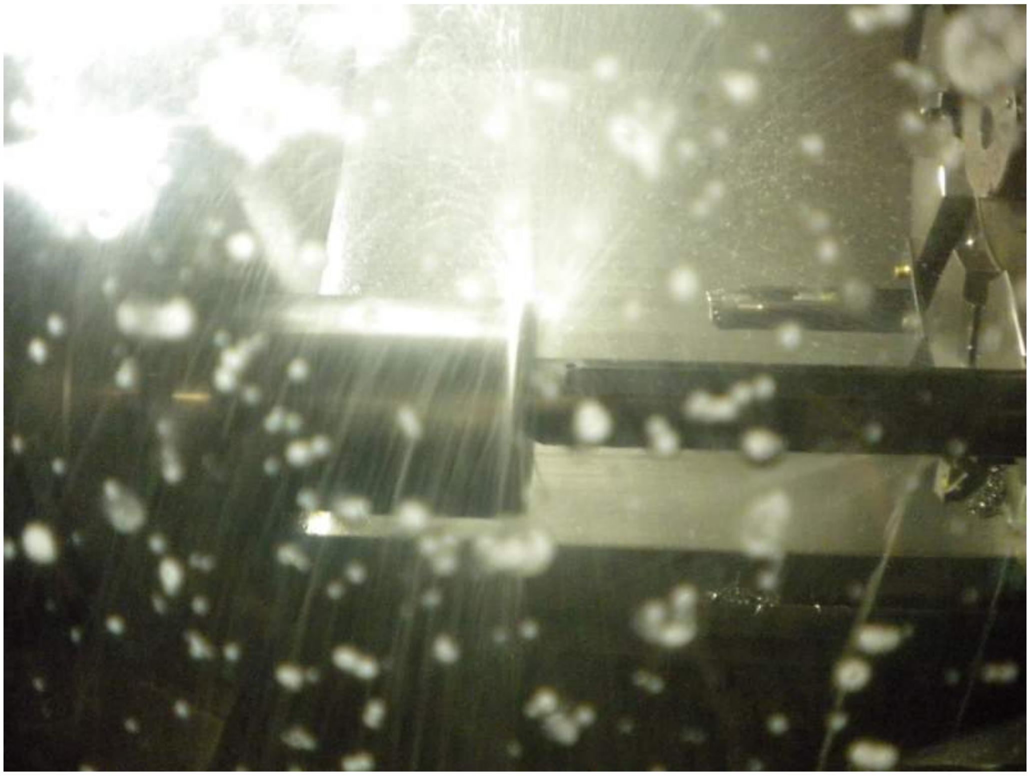


Figure D-7 – Internal threading with CNC machine.

Figure D-8 – Internally threaded stainless steel nut.

Appendix E – Tension and Coupling Nut Testing

Appendix E contains the following material related to tension and coupling nut testing:

- Tabulated individual test results for each specimen.
- Representative stress-strain relationships for each material.
- Schematic stress-strain relationship showing determination of 0.2% offset yield stress.
- Photographs of the test set-up conditions at Lehigh University.
- Test report from Lehigh University.

Table E-1 – Tension Test Results

Material	Test ID	0.2% Yield Strength (ksi)	Tensile Strength (ksi)	T/Y Ratio	Tensile Elongation[1]	Modulus of Elasticity (ksi)
Custom 450 H1050	450-1	154.7	170.1	1.100	6.1%	30,700
	450-2	152.8	170.1	1.113	7.1%	30,800
	450-3	154.1	170.1	1.104	6.1%	30,500
Custom 630 H1100	630-1	146.3	157.6	1.078	3.8%	29,900
	630-2	149.9	160.6	1.071	3.7%	30,100
	630-3	150.4	161.1	1.071	3.5%	30,300
Alloy 2507	2507-1	91.4	121.2	1.326	> 18.6%	30,100
	2507-2	89.9	N/A	N/A	17.4%	29,500
	2507-3	92.3	122.0	1.323	> 26.4%	30,000
	2507-4	90.9	121.0	1.332	24.1%	30,300
Threadbar® – Plain	DSI-P-1	143.9	166.3	1.155	4.3%	32,200
	DSI-P-2	141.0	169.2	1.200	6.4%	32,300
	DSI-P-3	143.1	163.4	1.142	3.7%	31,700
Threadbar® – Galvanized	DSI-G-1	N/A	149.2	N/A	2.3%	33,700
	DSI-G-2	146.3	161.2	1.102	5.1%	33,200
	DSI-G-3	153.5	167.2	1.090	5.5%	33,000

[1] Tensile elongation is estimated based on cross-head displacement of the universal testing machine and measured over the length of the entire specimen. These values may not be comparable to the minimum tensile elongations specified in ASTM A722 or the measured tensile elongations in the mill certificates.

Table E-2 – Coupling Nut Test Results

Material	Coupling Nut Length	Test ID	Tensile Strength (ksi)	Tensile Elongation[1]	Coupler Failure?
Custom 450 H1050	$5d_b$	450-C135-1	169.3	6.0%	No
		450-C135-2	169.3	6.1%	No
		450-C135-3	170.7	7.9%	No
	$4d_b$	450-C11-1	169.8	6.2%	No
		450-C11-2	169.8	6.9%	No
		450-C11-3	169.4	2.8%	No
Custom 630 H1100	$5d_b$	630-C135-1	159.2	3.6%	No
		630-C135-2	157.6	3.7%	No
		630-C135-3	158.5	3.3%	No
	$4d_b$	630-C11-1	156.4	3.2%	No
		630-C11-2	155.2	3.5%	No
		630-C11-3	156.1	3.2%	No
Alloy 2507	$5d_b$	Not Tested			
	$4d_b$	2507-C11-1	121.7	22.2%	No
		2507-C11-2	121.2	21.2%	No
		2507-C11-3	121.2	21.6%	No
Threadbar® – Plain	$4d_b$	DSI-P-C-1	166.7	5.5%	No
		DSI-P-C-2	170.2	6.6%	No
		DSI-P-C-3	167.4	6.3%	No
Threadbar® – Galvanized	$4d_b$	DSI-G-C-1	169.0	6.2%	No
		DSI-G-C-2	168.4	7.1%	No
		DSI-G-C-3	168.2	5.7%	No

[1] Tensile elongation is estimated based on cross-head displacement of the universal testing machine and measured over the length of the entire specimen. These values may not be comparable to the minimum tensile elongations specified in ASTM A722 or the measured tensile elongations in the mill certificates.

Table E-3 – Summary of Coupling Nut Test Results by Coupling Nut Length

Material	Coupling Nut Length	Average		Standard Deviation	
		Tensile Strength (ksi)	Tensile Elongation[1]	Tensile Strength (ksi)	Tensile Elongation[1]
Custom 450 H1050	$5d_b$	169.7	6.7%	0.8	1.0%
	$4d_b$	169.7	5.3%	0.2	2.2%
Custom 630 H1100	$5d_b$	158.4	3.5%	0.8	0.2%
	$4d_b$	155.9	3.3%	0.6	0.1%
Alloy 2507	$5d_b$	Not Tested		Not Tested	
	$4d_b$	121.4	21.7%	0.3	0.5%
Threadbar® – Plain	$4d_b$	168.1	6.1%	1.8	0.6%
Threadbar® – Galvanized	$4d_b$	168.5	6.3%	0.4	0.7%

[1] Tensile elongation is estimated based on cross-head displacement of the universal testing machine and measured over the length of the entire specimen. These values may not be comparable to the minimum tensile elongations specified in ASTM A722 or the measured tensile elongations in the mill certificates.

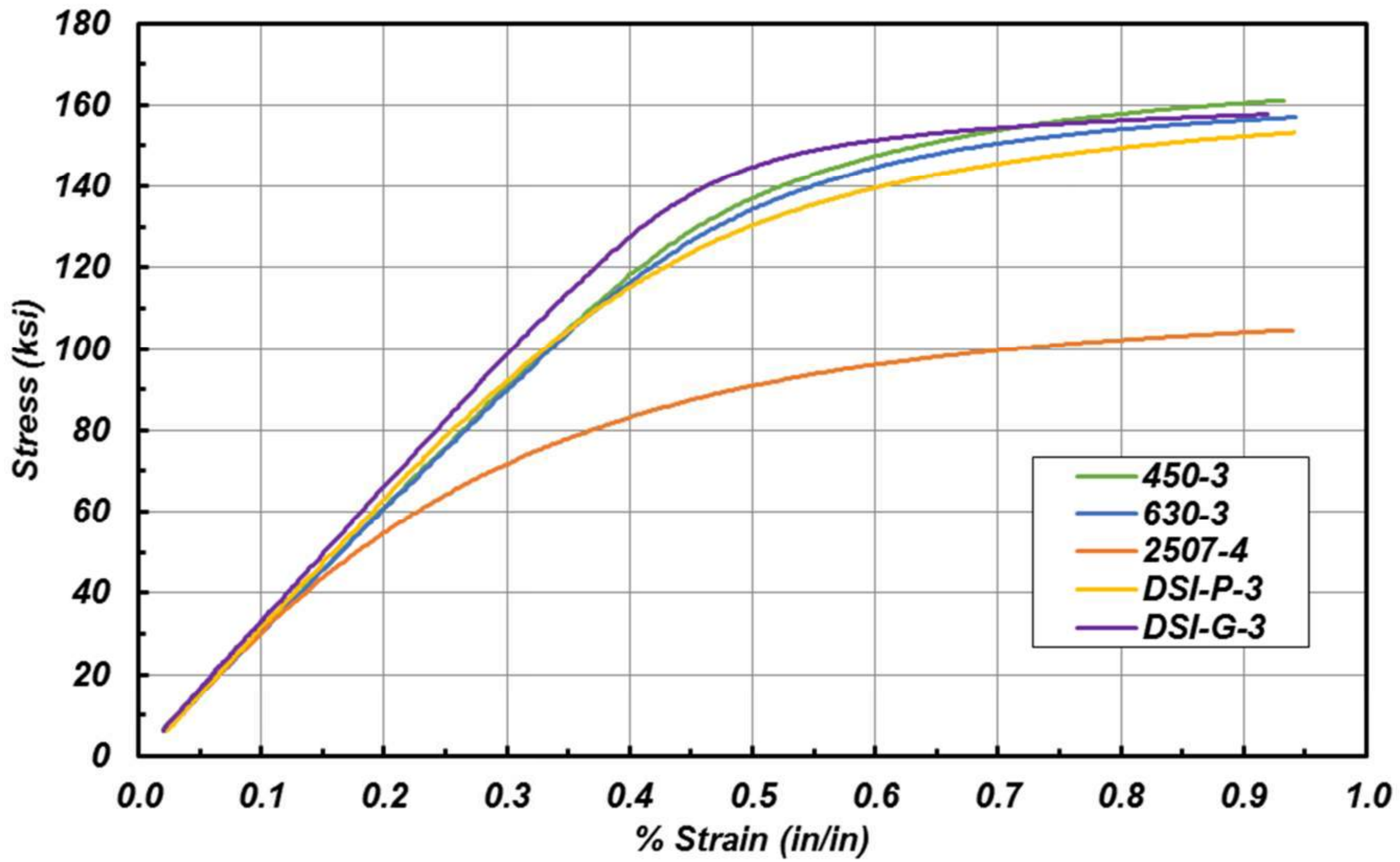


Figure E-1 – Representative stress-strain curves for each material (shown up to approximately 0.9% strain)

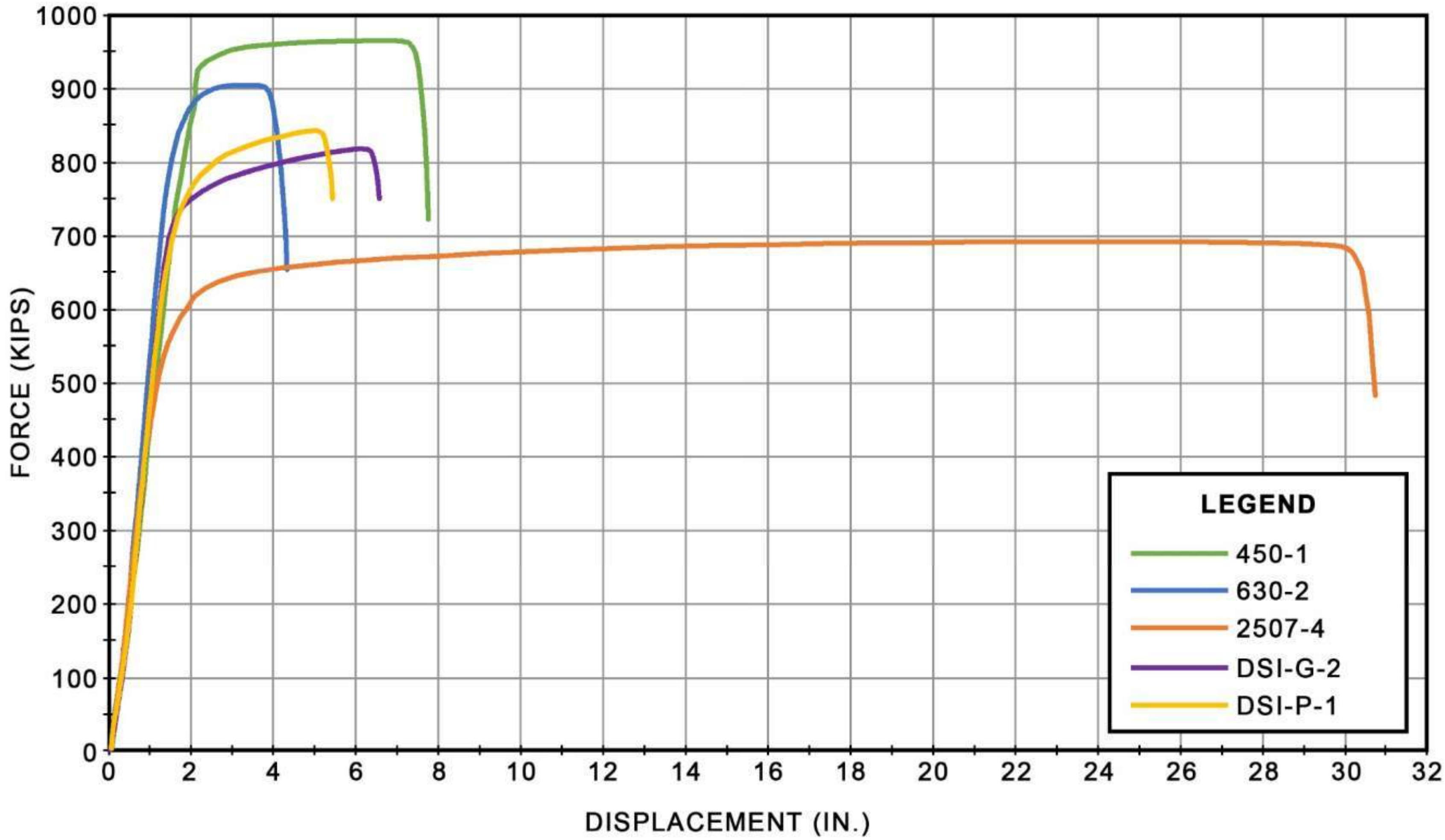


Figure E-2 – Representative force-displacement curves from tension tests

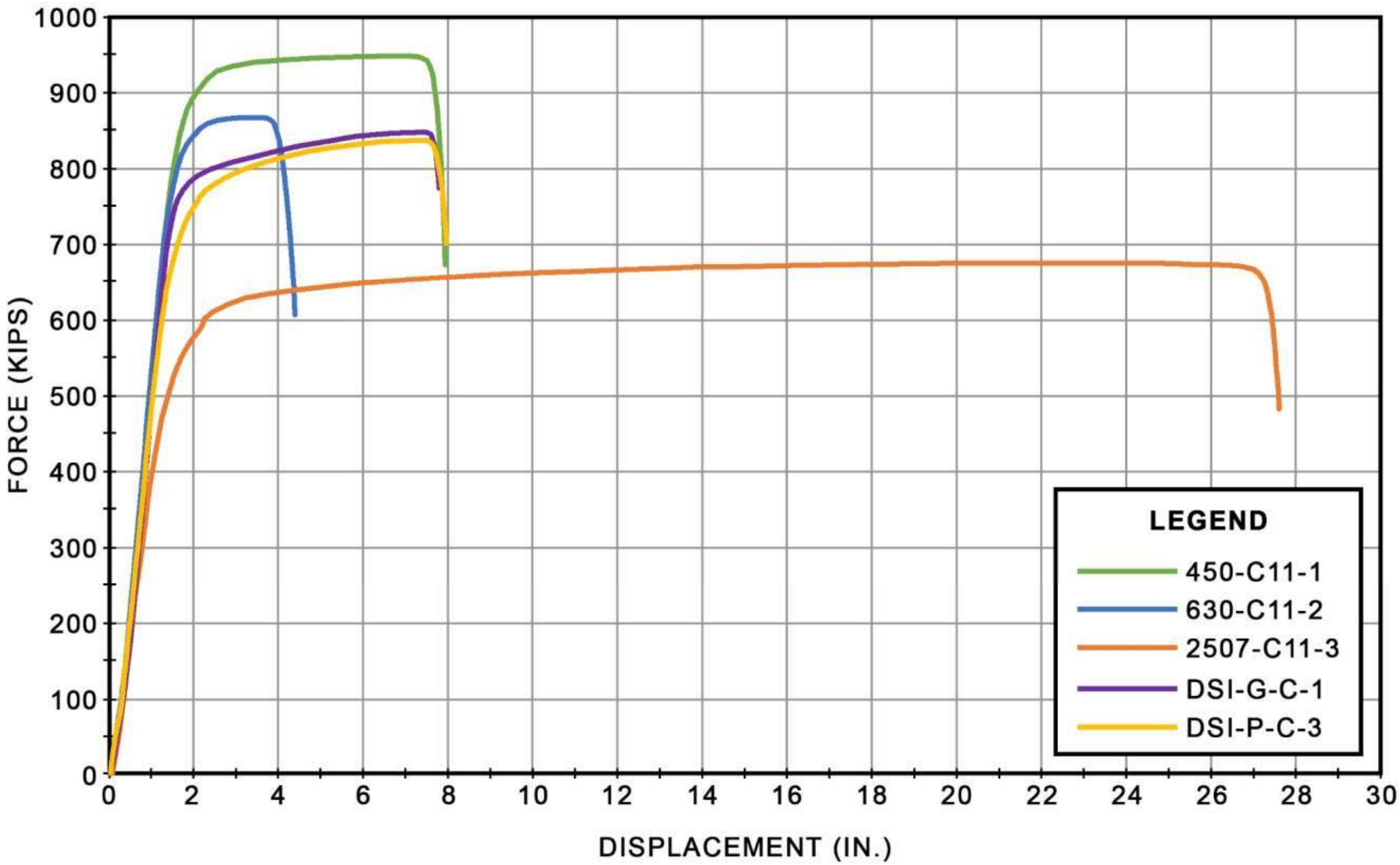


Figure E-3 – Representative force-displacement curves from coupling nut tests

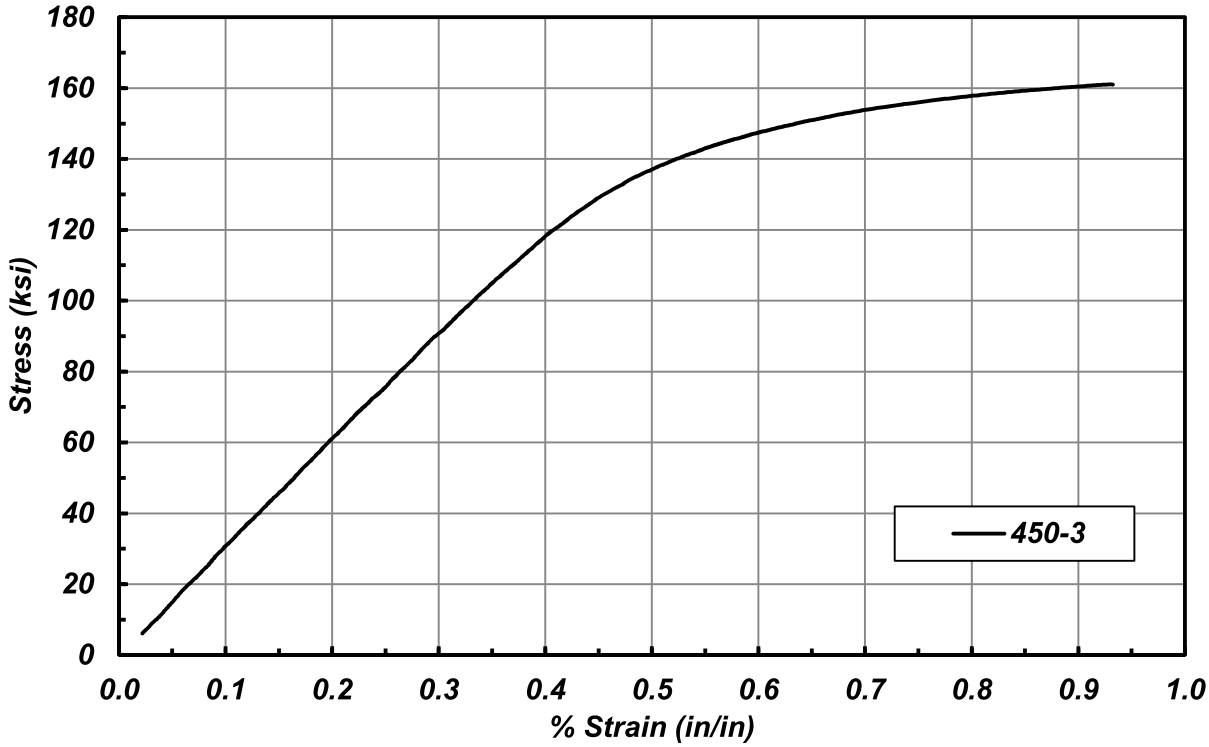


Figure E-4 – Representative stress-strain curve for Custom 450 H1050 (Test 450-3)

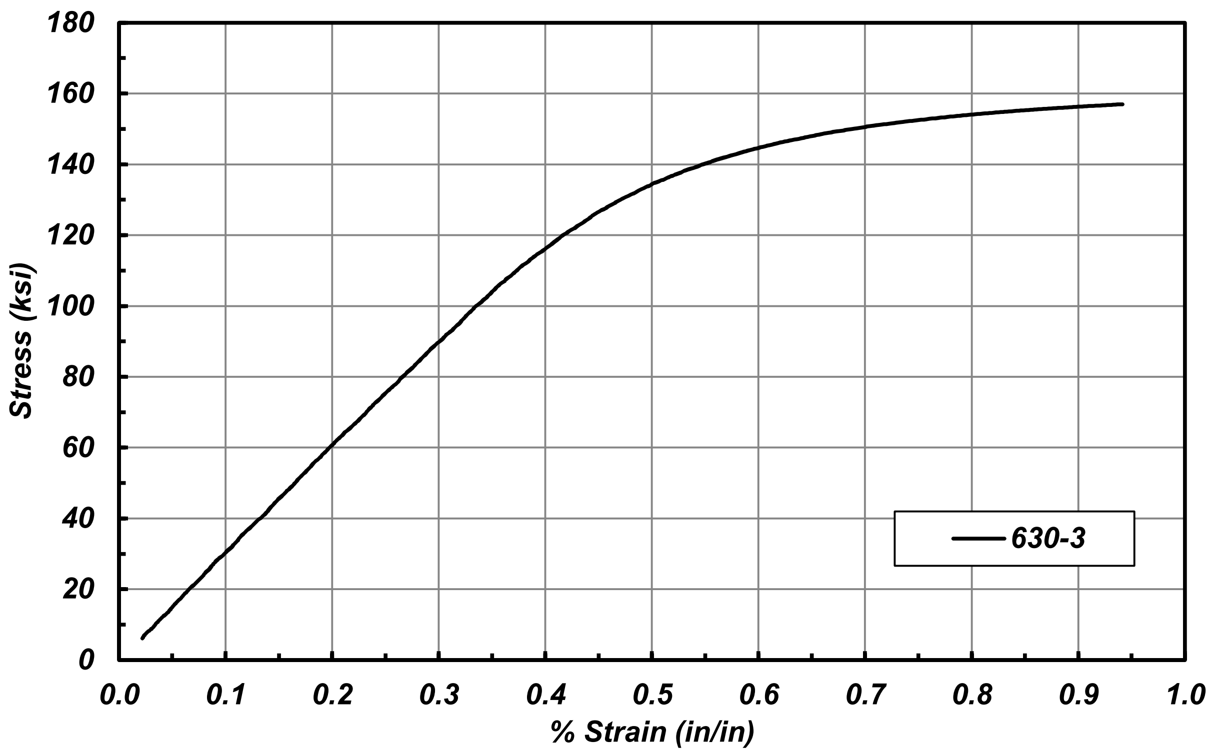


Figure E-5 – Representative stress-strain curve for Custom 630 H1100 (Test 630-3)

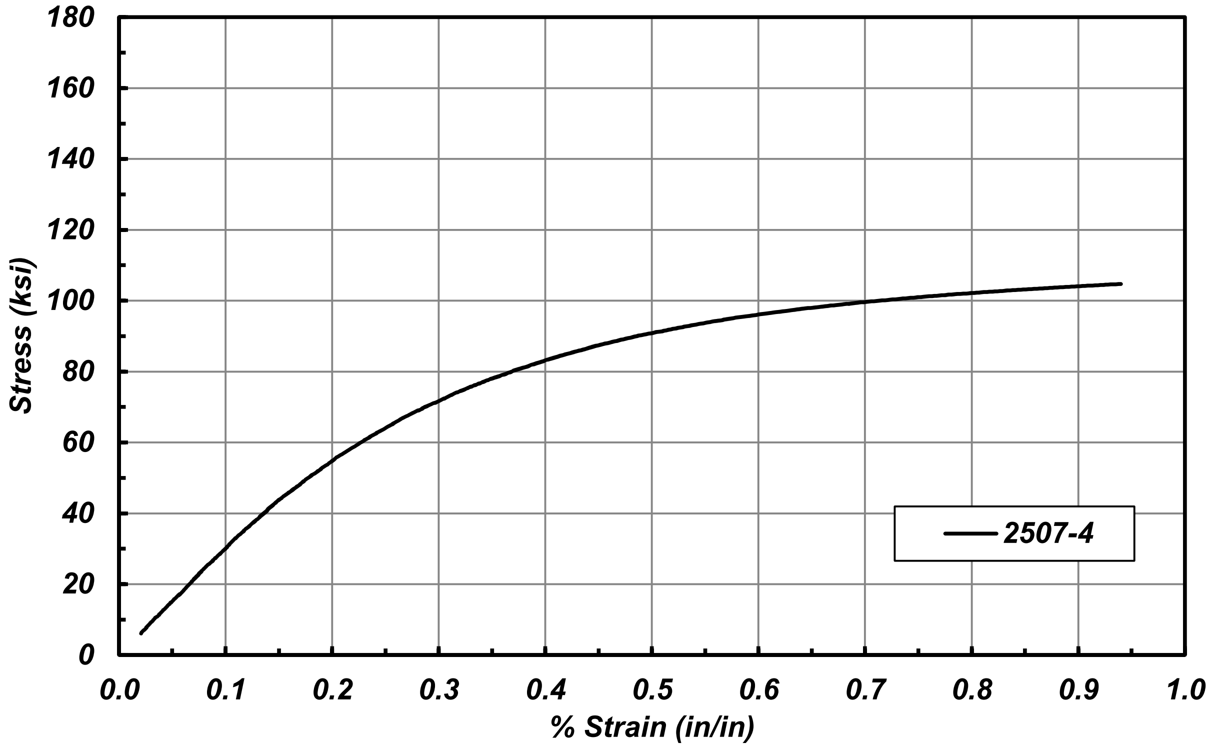


Figure E-6 – Representative stress-strain curve for Alloy 2507 (Test 2507-4)

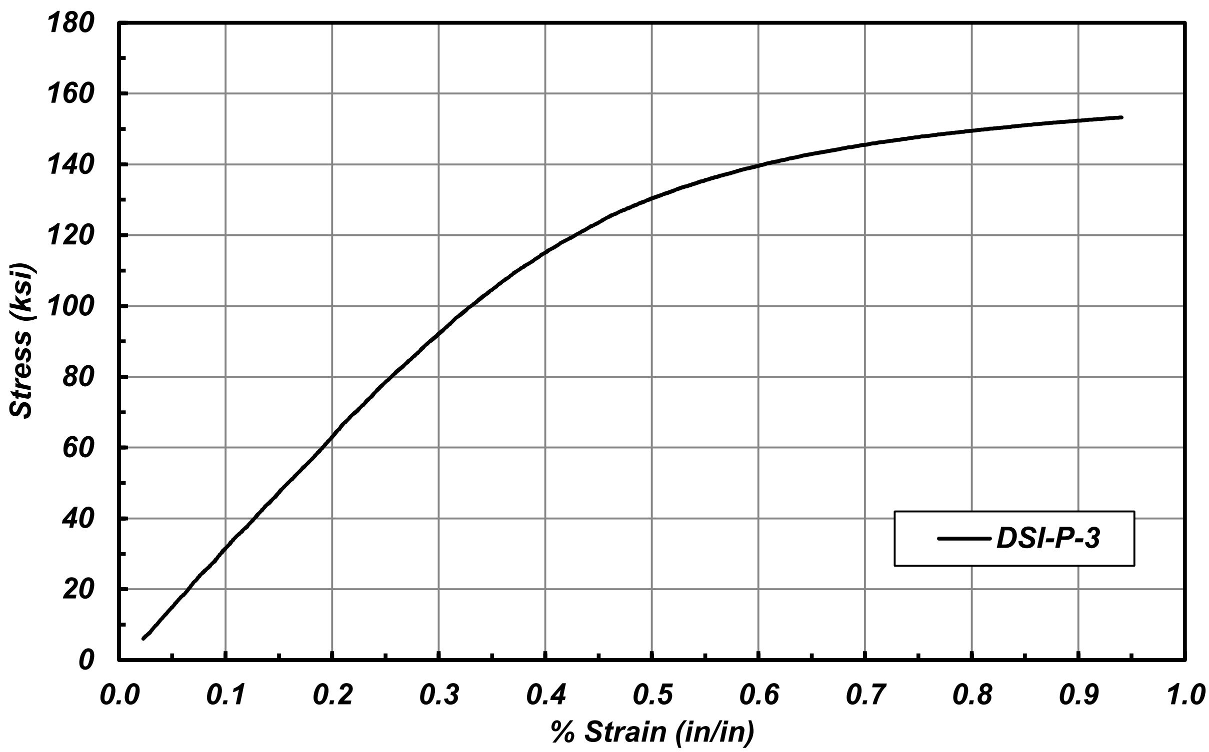


Figure E-7 – Representative stress-strain curve for plain Threadbar® (Test DSI-P-3)

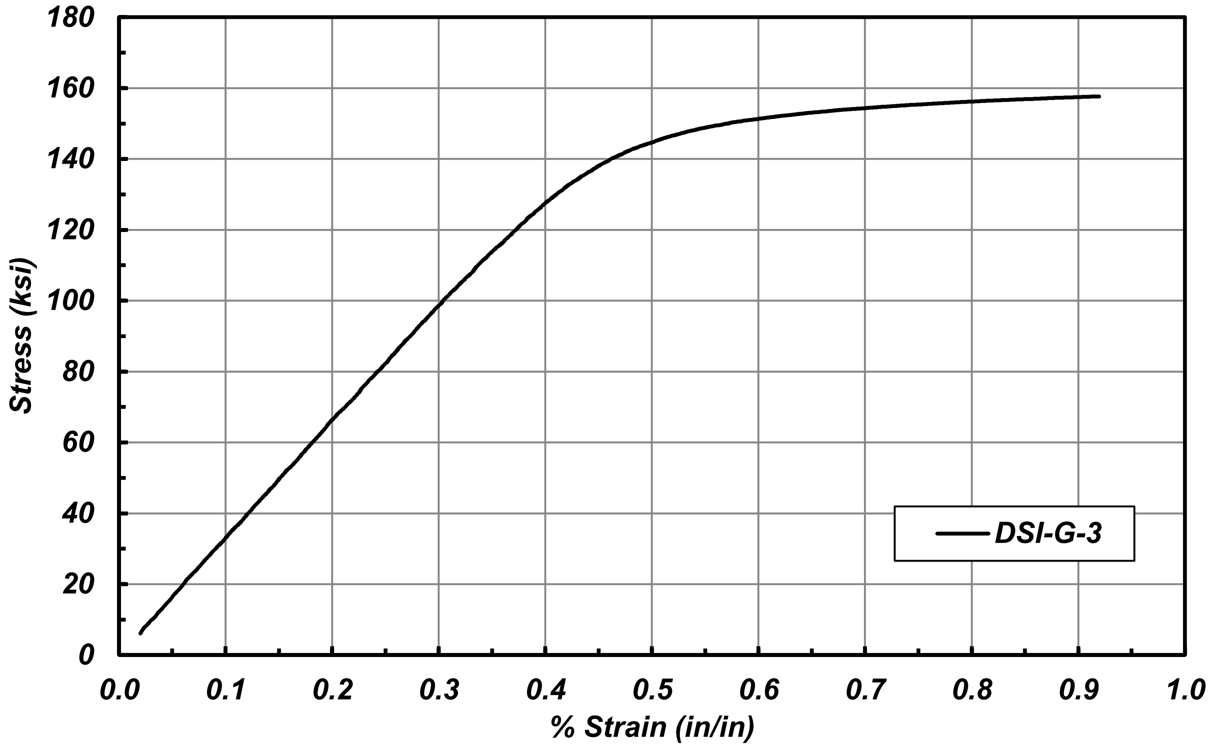


Figure E-8 – Representative stress-strain curve for galvanized Threadbar® (Test DSI-G-3)

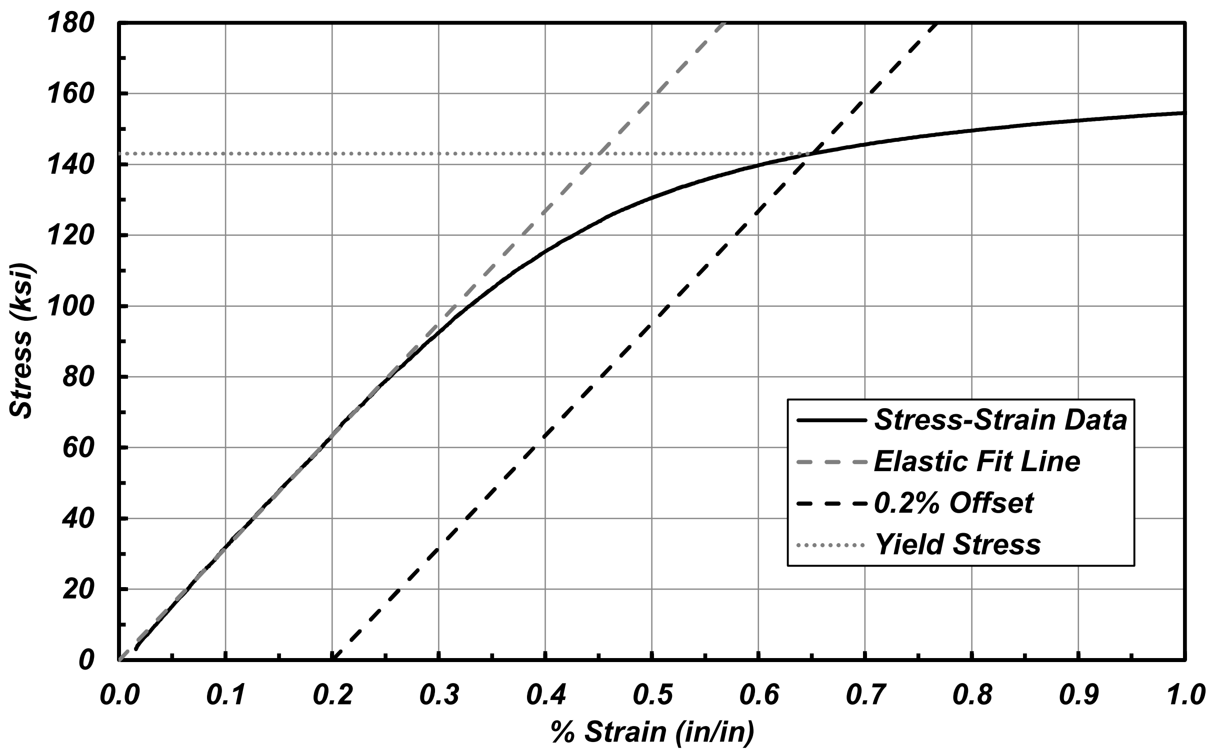


Figure E-9 – Schematic of yield stress determination using the 0.2% offset method.

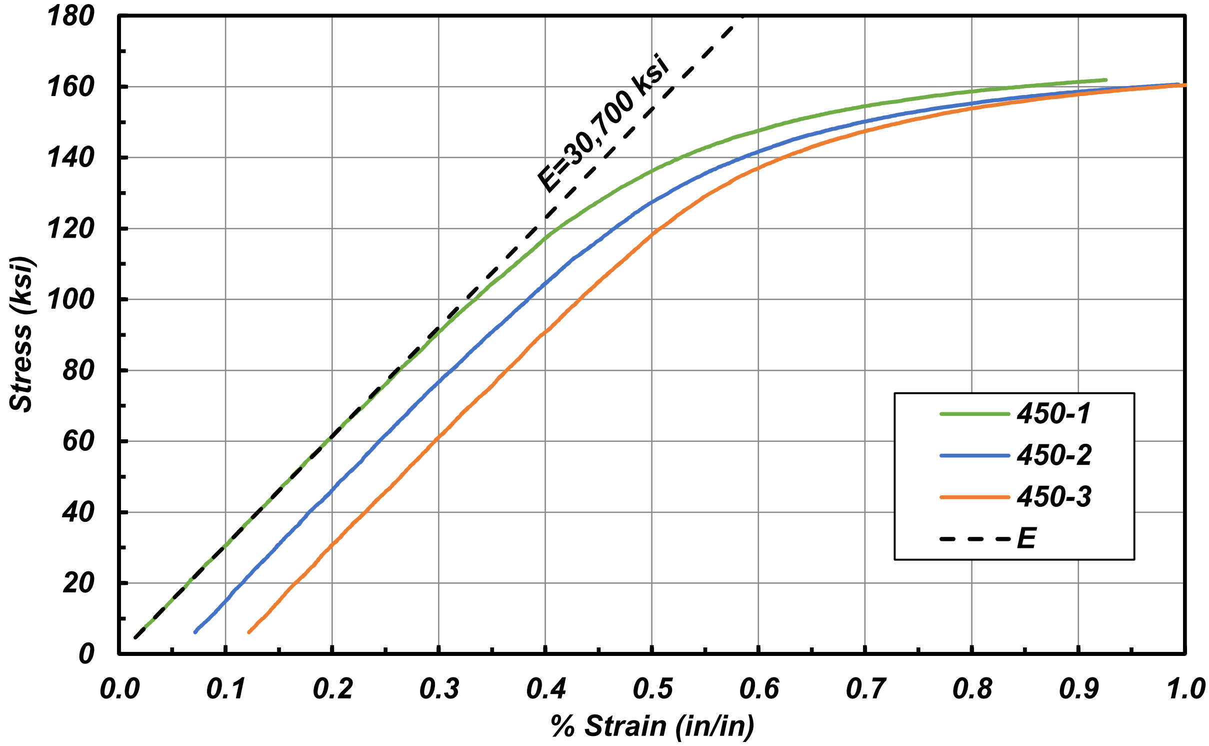


Figure E-10 – All stress-strain curves for Custom 450 H1050 tension tests. Each test is offset from the previous test by 0.5% strain for clarity.

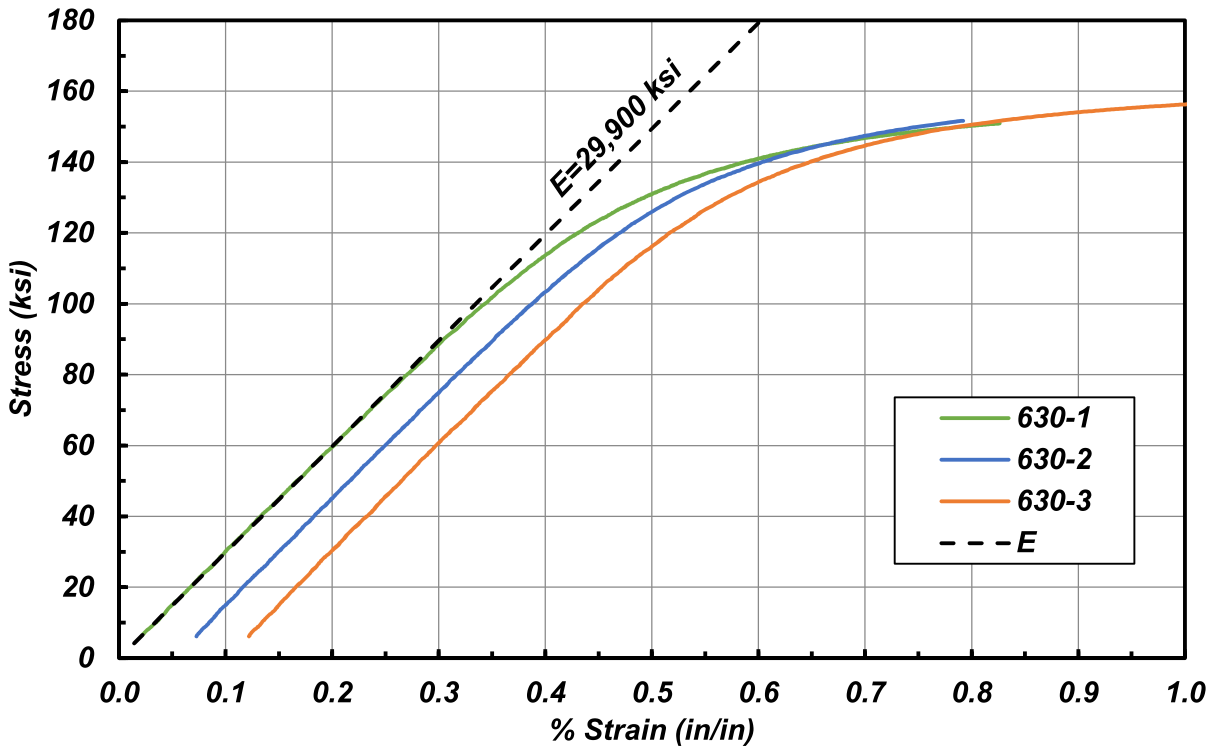


Figure E-11 – All stress-strain curves for Custom 630 H1100 tension tests. Each test is offset from the previous test by 0.5% strain for clarity.

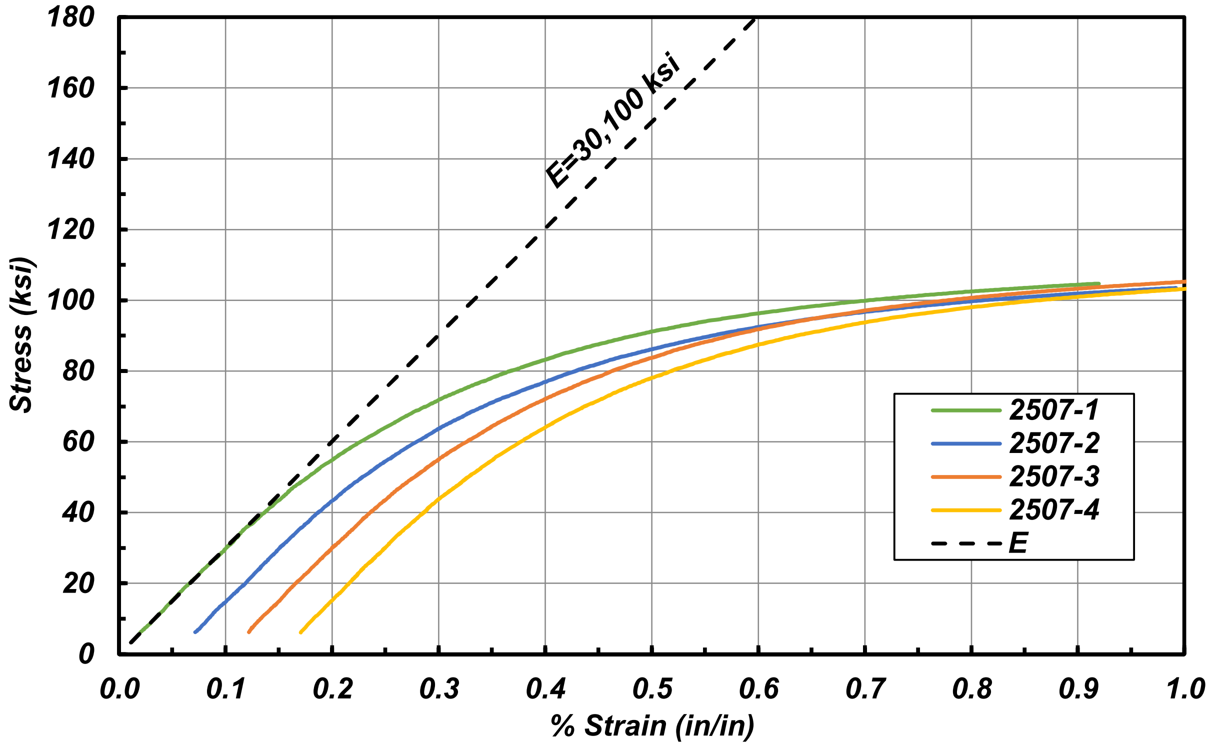


Figure E-12 – All stress-strain curves for Alloy 2507 tension tests. Each test is offset from the previous test by 0.5% strain for clarity.

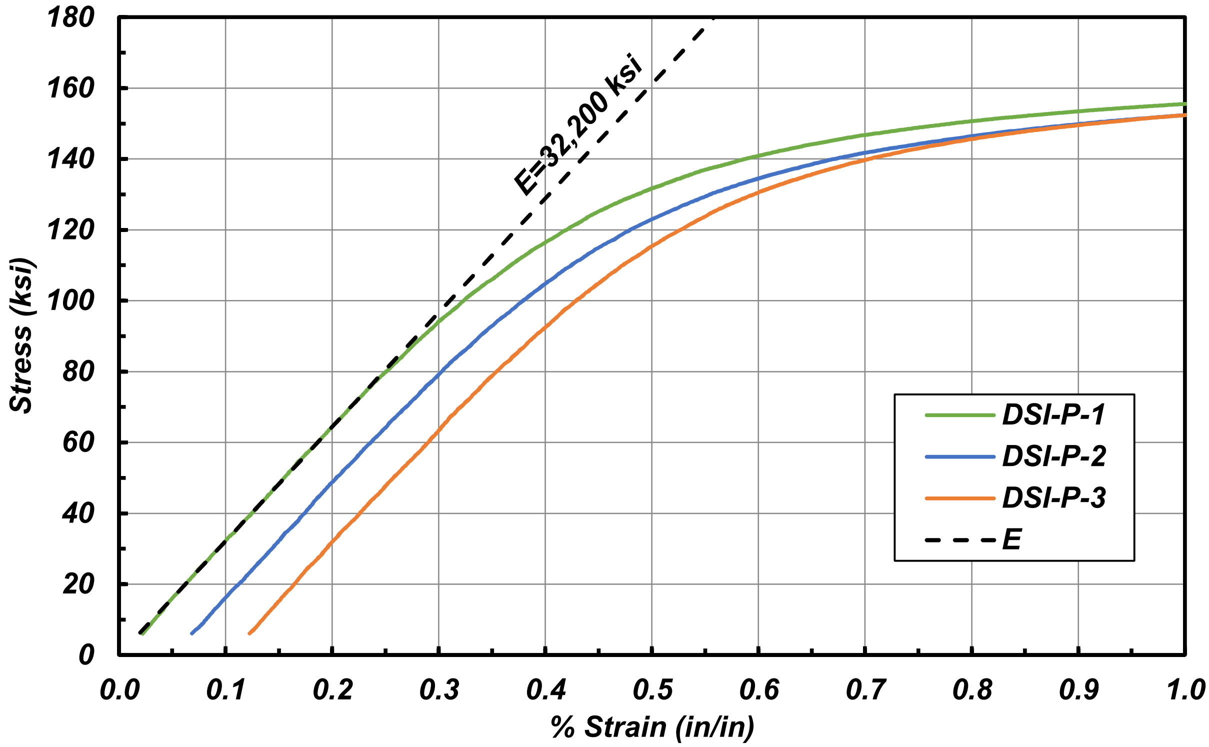


Figure E-13 – All stress-strain curves for plain Threadbar® tension tests. Each test is offset from the previous test by 0.5% strain for clarity.

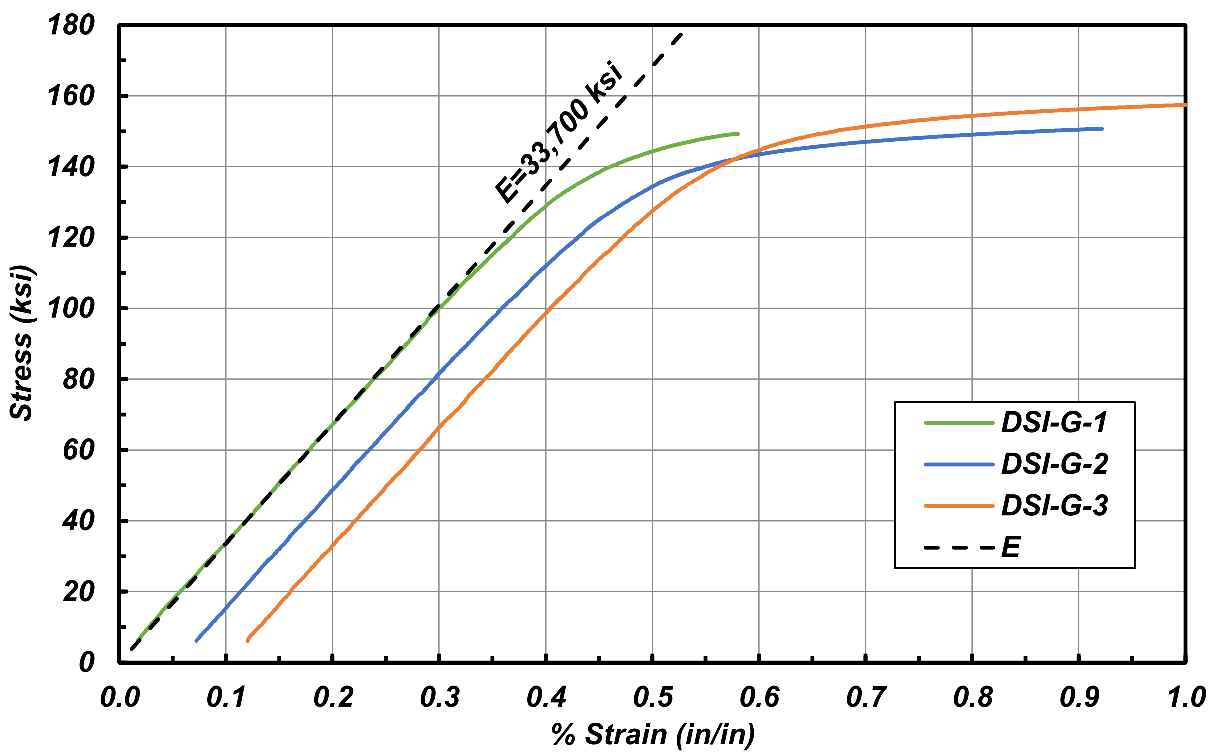


Figure E-14 – All stress-strain curves for galvanized Threadbar® tension tests. Each test is offset from the previous test by 0.5% strain for clarity.

Figure E-15 – Overall view of the tension test set-up in the Baldwin Universal Testing Machine at Lehigh University.

Figure E-16 – End support condition showing the end nut reacting against a clevis pin in the testing machine. (Note wood board below nut intended to absorb energy at failure and prevent damage.)

Figure E-17 – Initial tension loading up to approximately 0.9% strain showing the instrumentation set-up with extensometers at the two gage lengths measured.

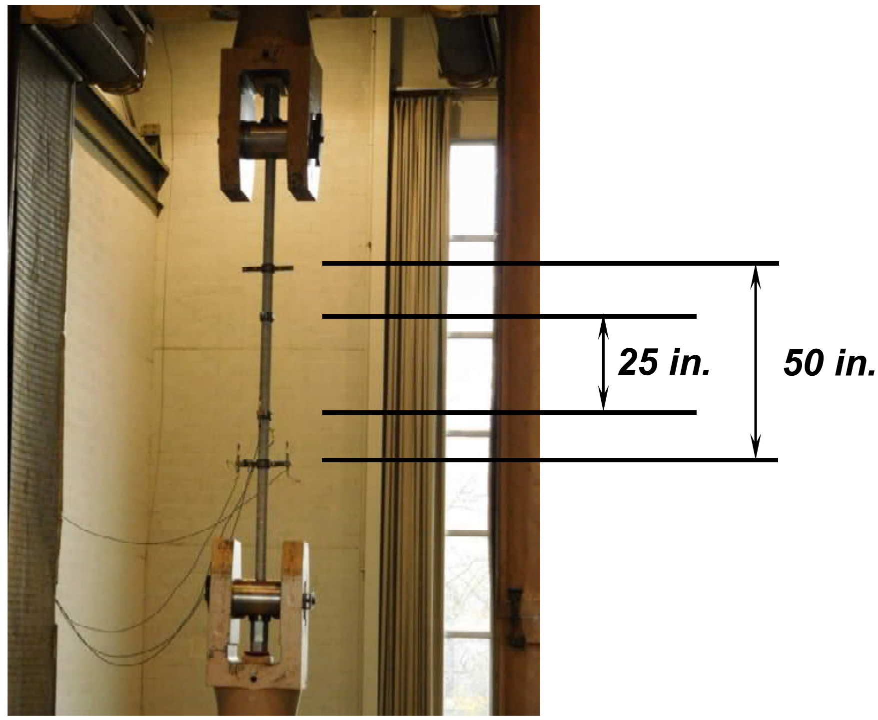


Figure E-18 – Extensometer gage lengths.

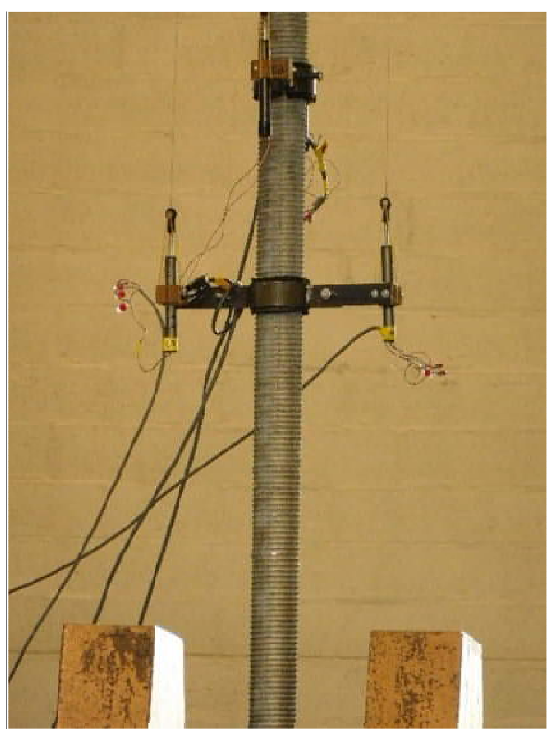


Figure E-19 – Close-up view of the lower extensometers mounted to the bar.

Structural Testing Laboratories
Fritz Engineering Laboratory
13 East Packer Avenue
Bethlehem, PA 18015-4729
(610) 758-3497 Fax (610) 758-5902

March 13, 2017
FL2016.1204.1

Jared Brewe
Simpson Gumpertz & Heger
135 South LaSalle St. Suite 3050
Chicago, IL 60603

Subject: *Tension Testing of 2.5 inch and 2.75 inch Diameter High Strength Threaded Bars*

Dear Mr. Brewe,

In December, 2016 and January, 2017, tension tests were performed on high strength threaded bars in the 5,000K Baldwin test machine in Fritz Lab. Tested assemblies consisted of continuous 12 ft. bars and coupled 6 ft. bars in five material types. Three of the material types were custom grades of stainless steel with a 2.75 inch nominal diameter and two material types were standard 2.5 inch nominal diameter DSI post tensioning bars. The bars were tested with end nuts in bearing and the bar, end nut, and coupler material were matched in all test assemblies.

The assemblies were tested with end nuts in bearing. The assemblies were connected to the test machine clevises via pins with a 3.2 inch diameter transverse through hole and a machined bearing surface. A 1.5 inch thick bushing with a 3.05 inch inside diameter was placed between the bearing surfaces of the pin and end nuts.

Each assembly was instrumented with two sets of BEI Duncan 4 inch linear potentiometer type displacement transducers to determine the bar strain through yield. The displacement transducers were mounted to brackets fabricated by Fritz Lab staff. The brackets were mounted to the bar at 25 and 50 inch gage lengths. The bars were loaded through the 0.2% offset yield point and the displacement transducers were removed from the bar before loading to failure. In general, the load rate was 0.4 inches per minute through yield and 0.9 inches per minute through failure for continuous bar specimens and 0.2 inches per minute through yield and 0.4 inches per minute through failure for coupled assemblies. The exceptions were continuous bar Test 1 where the load rates were 0.2 inches per minute through yield and 0.4 inches per minute to failure and coupled bars Test 10 through Test 12 where the load rates were 0.2 inches per minute through yield and 0.9 inches per minute to failure. The test results are summarized in Table 1. A Typical bar assembly installed in the test machine is shown in Figure 1.

Electronic files containing tabulated load and deflection data from the four displacement transducers for each test were provided electronically. X-Y Plots of applied load versus deflection of the loading head were generated on graph paper on the test machine control console and were provided as scans in PDF format. The load scale for all tests was 2,000 kips. The deflection scale was noted for each test and varied from 10 to 36 inches. The scales noted on the X-Y plots refers to the values at the tenth major gridline for both axes. A modified X-Y plot is shown in Figure 2.

Table 1: Summary of Test Results

Test #	Material	Test Configuration	Ultimate Load	Failure Mode
1	Custom 630 SS H1100	Continuous 12' Bar	908 kips	Bar fracture
2	Custom 630 SS H1100	Continuous 12' Bar	925 kips	Bar fracture
3	Custom 630 SS H1100	Continuous 12' Bar	928 kips	Bar fracture
4	Custom 630 SS H1100	6' Coupled Bars (13.5" Coupler)	917 kips	Bar fracture
5	Custom 630 SS H1100	6' Coupled Bars (13.5" Coupler)	908 kips	Bar fracture
6	Custom 630 SS H1100	6' Coupled Bars (13.5" Coupler)	913 kips	Bar fracture
7	2507 Duplex SS	Continuous 12' Bar	698 kips	N/A deflection exceeded machine capacity
8	2507 Duplex SS	Continuous 12' Bar	692 kips	Thread strip bottom end nut
9	2507 Duplex SS	Continuous 12' Bar	703 kips	N/A deflection exceeded machine capacity
10	2507 Duplex SS	6' Coupled Bars (11" Coupler)	701 kips	Bar fracture
11	2507 Duplex SS	6' Coupled Bars (11" Coupler)	698 kips	Bar fracture
12	2507 Duplex SS	6' Coupled Bars (11" Coupler)	698 kips	Bar fracture
13	Custom 450 SS H1050	Continuous 12' Bar	980 kips	Bar fracture
14	Custom 450 SS H1050	Continuous 12' Bar	980 kips	Bar fracture
15	Custom 450 SS H1050	Continuous 12' Bar	980 kips	Bar fracture
16	Custom 450 SS H1050	6' Coupled Bars (11" Coupler)	978 kips	Bar fracture
17	Custom 450 SS H1050	6' Coupled Bars (11" Coupler)	978 kips	Bar fracture
18	Custom 450 SS H1050	6' Coupled Bars (11" Coupler)	976 kips	Bar fracture
19	DSI Grade 150 Plain	Continuous 12' Bar	858 kips	Bar fracture
20	DSI Grade 150 Plain	Continuous 12' Bar	873 kips	Bar fracture
21	DSI Grade 150 Plain	Continuous 12' Bar	843 kips	Bar fracture
22	DSI Grade 150 Plain	6' Coupled Bars (10.75" Coupler)	860 kips	Bar fracture
23	DSI Grade 150 Plain	6' Coupled Bars (10.75" Coupler)	878 kips	Bar fracture
24	DSI Grade 150 Plain	6' Coupled Bars (10.75" Coupler)	864 kips	Bar fracture
25	Custom 630 SS H1100	6' Coupled Bars (11" Coupler)	901 kips	Bar fracture
26	Custom 630 SS H1100	6' Coupled Bars (11" Coupler)	894 kips	Bar fracture
27	Custom 630 SS H1100	6' Coupled Bars (11" Coupler)	899 kips	Bar fracture
28	DSI Grade 150 Galvanized	Continuous 12' Bar	770 kips	Bar fracture
29	DSI Grade 150 Galvanized	Continuous 12' Bar	832 kips	Bar fracture
30	DSI Grade 150 Galvanized	Continuous 12' Bar	863 kips	Bar fracture
31	Custom 450 SS H1050	6' Coupled Bars (13.5" Coupler)	975 kips	Bar fracture
32	Custom 450 SS H1050	6' Coupled Bars (13.5" Coupler)	975 kips	Bar fracture
33	Custom 450 SS H1050	6' Coupled Bars (13.5" Coupler)	983 kips	Bar fracture
34	DSI Grade 150 Galvanized	6' Coupled Bars (10.75" Coupler)	872 kips	Bar fracture
35	DSI Grade 150 Galvanized	6' Coupled Bars (10.75" Coupler)	869 kips	Bar fracture
36	DSI Grade 150 Galvanized	6' Coupled Bars (10.75" Coupler)	868 kips	Bar fracture
37	2507 Duplex SS	Continuous 12' Bar	697 kips	Bar fracture

Figure 1: Typical Coupled Bar Assembly Installed in Test Machine

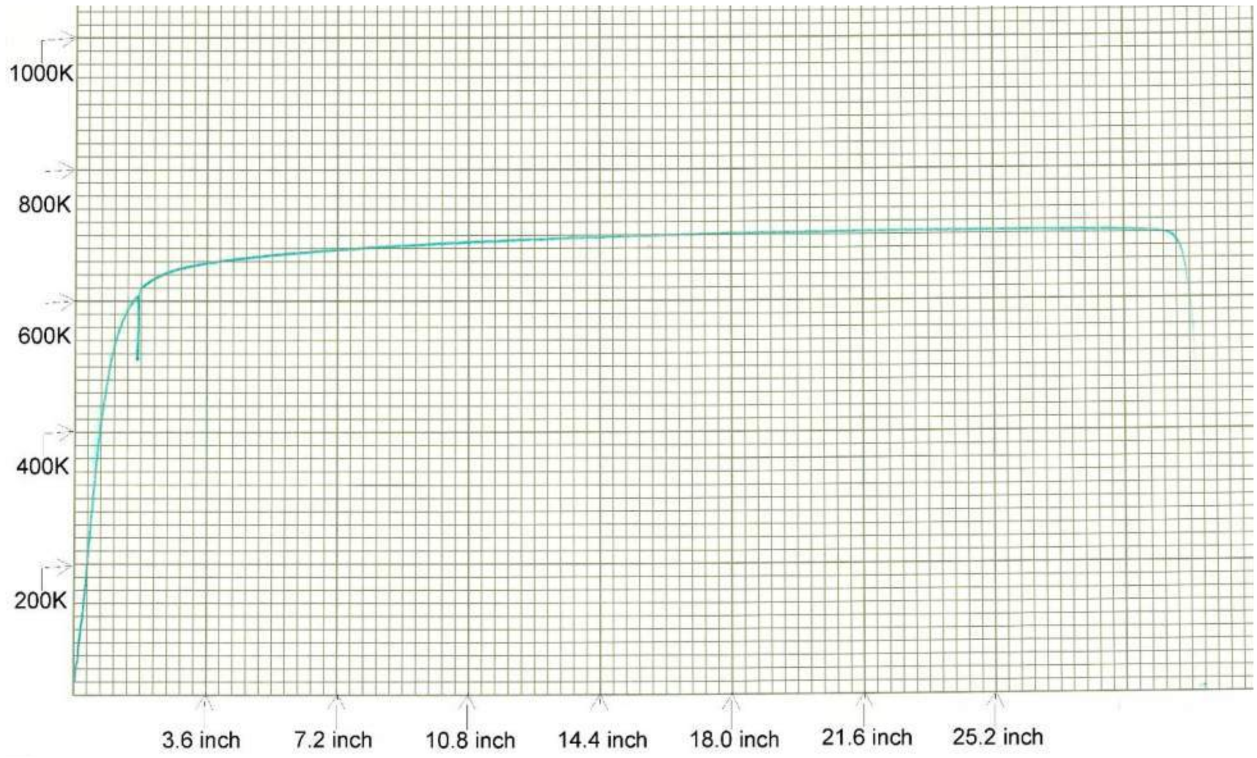


Figure 2: Typical X-Y Load vs. Deflection Plot with Vertical Scale at 2000 kips and Horizontal Scale at 36 inches (plot has been cropped)

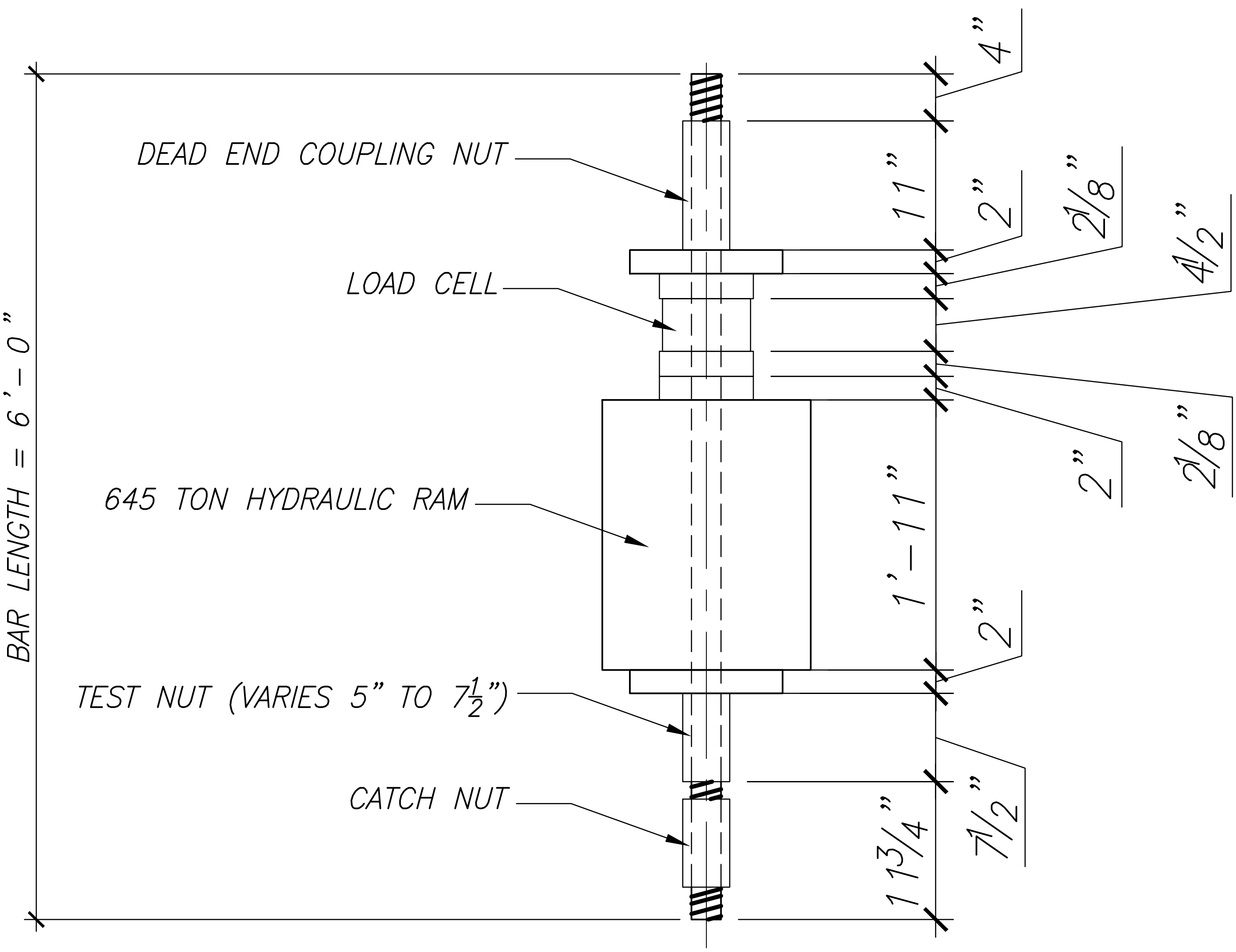
Sincerely,

Robin J. Hendricks
Research Scientist

The results of the project presented in this report are provided on an “AS IS” basis. University makes no warranties of any kind, express or implied, as to any matter whatsoever, including, without limitation, warranties with respect to the merchantability or fitness for a particular purpose of the project or any deliverables. University makes no warranty of any kind with respect to freedom from patent, trademark, copyright or trade secret infringement arising from the use of the results of the project, deliverables, services, intellectual property or other materials provided hereunder. University shall not be liable for any direct, indirect, consequential, punitive, or other damages suffered by Sponsor or any other person resulting from the project or use of any deliverables. Sponsor agrees that it shall not make any warranty on behalf of University, express or implied, to any person containing the application of the results or any deliverables of this project.

Appendix F – End Nut Proof Testing

Appendix F contains the test set-up details utilized for end nut proof testing.


DEAD END COUPLING NUT
LOAD CELL
645 TON HYDRAULIC RAM
TEST NUT (VARIES 5" TO 7½")
CATCH NUT
BAR LENGTH = 6'-0"
4"
11"
2"
2⅛"
4½"
2"
2⅛"
1'-11"
2"
7½"
1 1¾"

Appendix G – Relaxation Testing

Appendix G contains the following material related to relaxation testing:

- Tabulated individual test results for each specimen.
- Relaxation and Percent Loss versus Time plots, G-1 to G-10, for all test specimens tested to date.
- Photographs of the test set-up conditions at Purdue University.
- Design drawings, S-1 and S-2, for the relaxation frame.

Table G-1 – Relaxation test results for individual tests

Material	Test Number	Jacking Stress (ksi)	Jacking Stress % of Design Minimum Tensile Strength [A]	Initial Load After Seating (ksi)	Initial Load % of Design Minimum Tensile Strength [A]	Final Load (ksi)	Total Relaxation (ksi)	% Relaxation
Threadbar® – Plain / High	1	125.8	83.9%	110.8	73.9%	107.8	3.0	2.69%
	2	125.4	83.6%	110.6	73.7%	107.4	3.2	2.91%
	3	131.4	87.6%	113.8	75.9%	110.8	3.0	2.66%
Threadbar® – Plain / Low	1	98.8	65.9%	90.6	60.4%	89.0	1.6	1.77%
	2	105.8	70.5%	95.3	63.5%	93.3	2.0	2.09%
	3	108.1	72.1%	94.9	63.3%	93.6	1.3	1.37%
Threadbar® – Galvanized	1	124.6	83.1%	105.9	70.6%	103.0	2.9	2.74%
	2	124.4	82.9%	109.6	73.1%	106.5	3.1	2.83%
	3	126.0	84.0%	104.1	69.4%	102.0	2.0	1.95%
Custom 450 H1050	1	141.0	94.0%	125.7	83.8%	123.5	2.2	1.75%
	2	138.0	92.0%	123.2	82.1%	121.3	1.9	1.56%
	3	146.5	97.7%	128.6	85.8%	126.8	1.8	1.42%
Custom 630 H1100	1	128.5	85.6%	113.1	75.4%	111.4	1.7	1.50%
	2	126.0	84.0%	111.5	74.4%	110.1	1.4	1.29%
	3	121.5	81.0%	108.3	72.2%	107.0	1.3	1.16%
Alloy 2507	1	83.9	76.2%	72.9	66.2%	71.0	1.9	2.60%
	2	87.0	79.1%	64.5	58.7%	63.4	1.1	1.75%
	3	87.2	79.2%	42.9	39.0%	42.6	0.3	0.71%
	4	86.5	78.6%	76.1	69.2%	73.3	2.8	3.64%
	5	85.8	78.0%	75.8	68.9%	72.7	3.1	4.09%
	6	86.3	78.4%	75.3	68.5%	73.0	2.3	3.03%

[A] Design tensile strength:

f_{pu} = 150 ksi for Threadbar®, Custom 450, and Custom 630

f_{pu} = 110 ksi for Alloy 2507

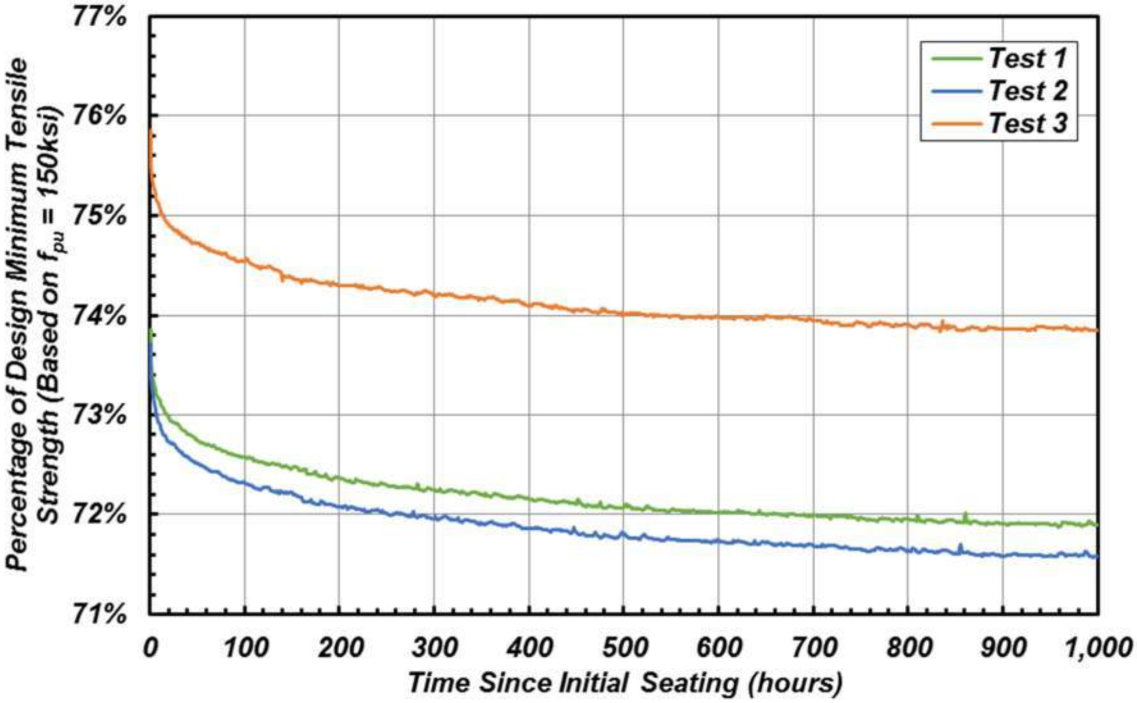


Figure G-1 – Relaxation measurements for plain Threadbar® with target initial percentage of 80%

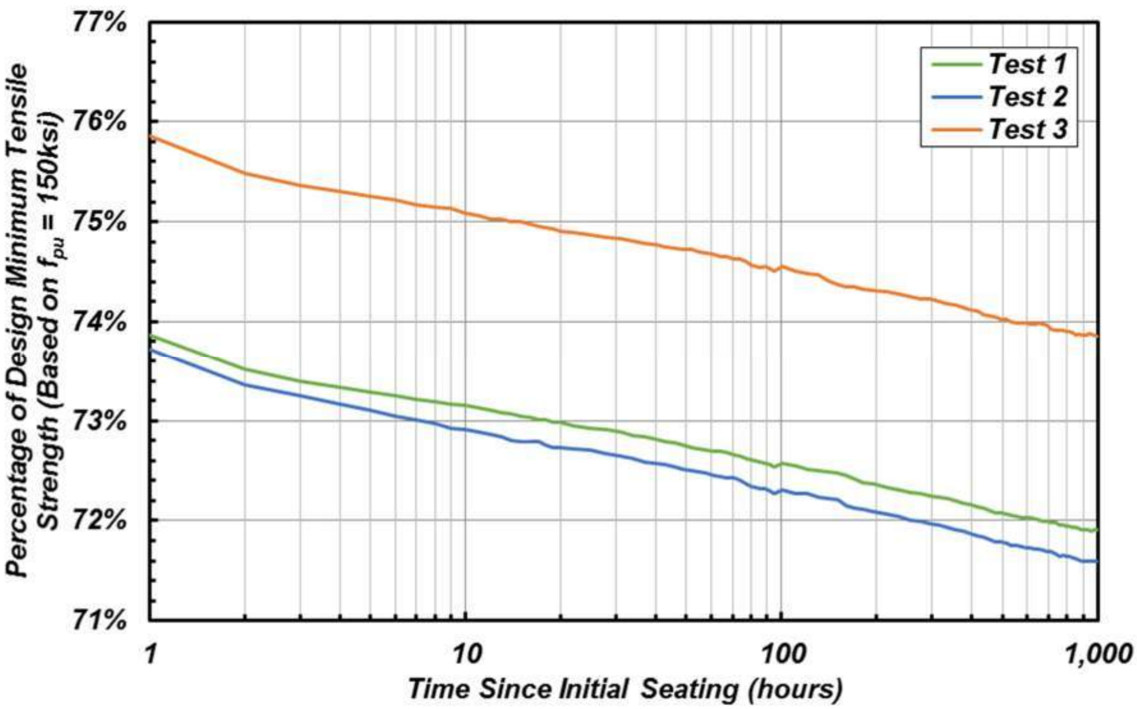


Figure G-2 – Relaxation measurements for plain Threadbar® with target initial percentage of 80% with time on a logarithmic scale

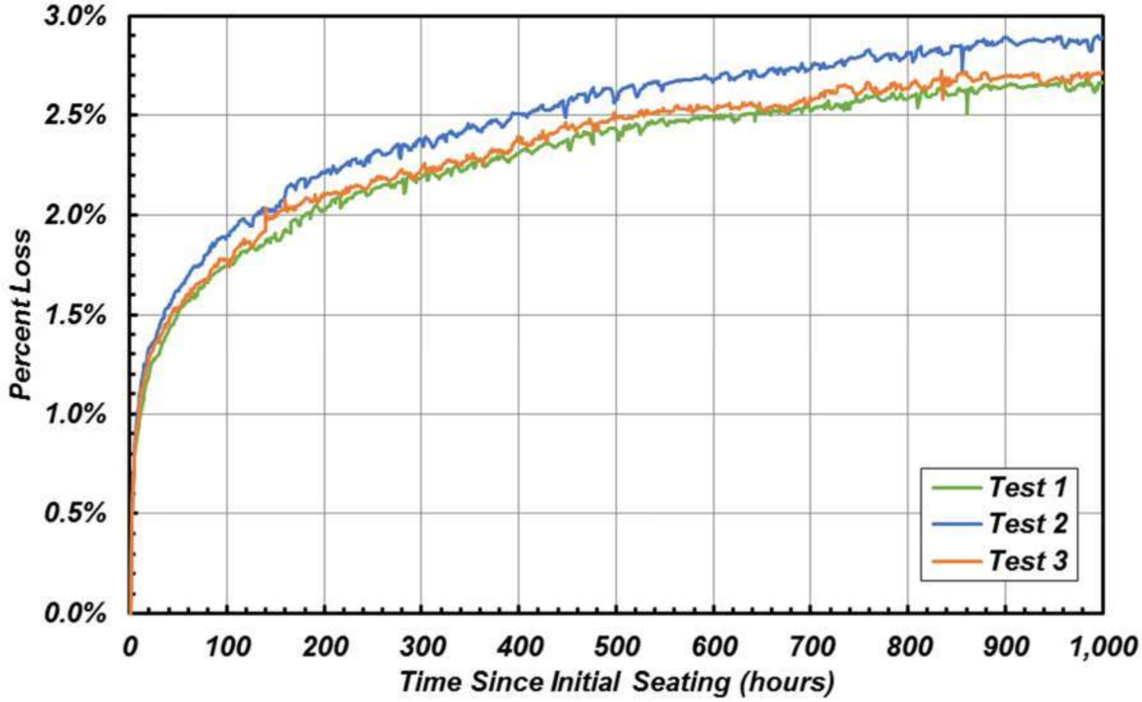


Figure G-3 – Percent loss for plain Threadbar® with target initial percentage of 80%

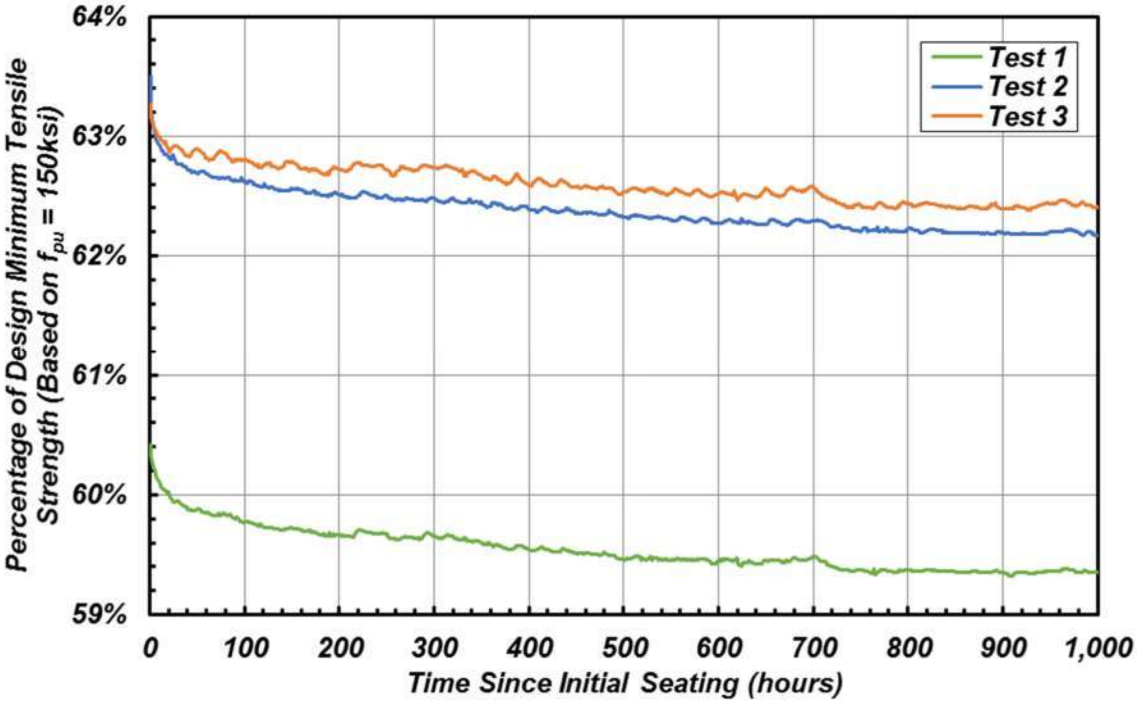


Figure G-4 – Relaxation measurements for plain Threadbar® with target initial percentage of 60%

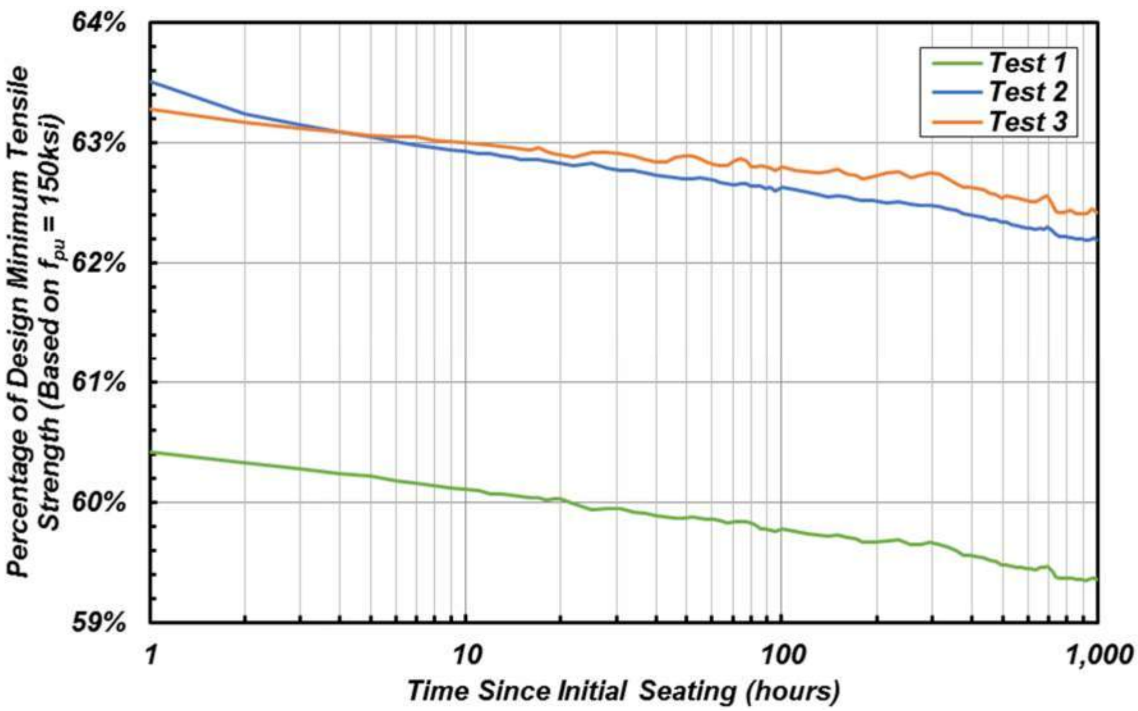


Figure G-5 – Relaxation measurements for plain Threadbar® with target initial percentage of 60% with time on a logarithmic scale

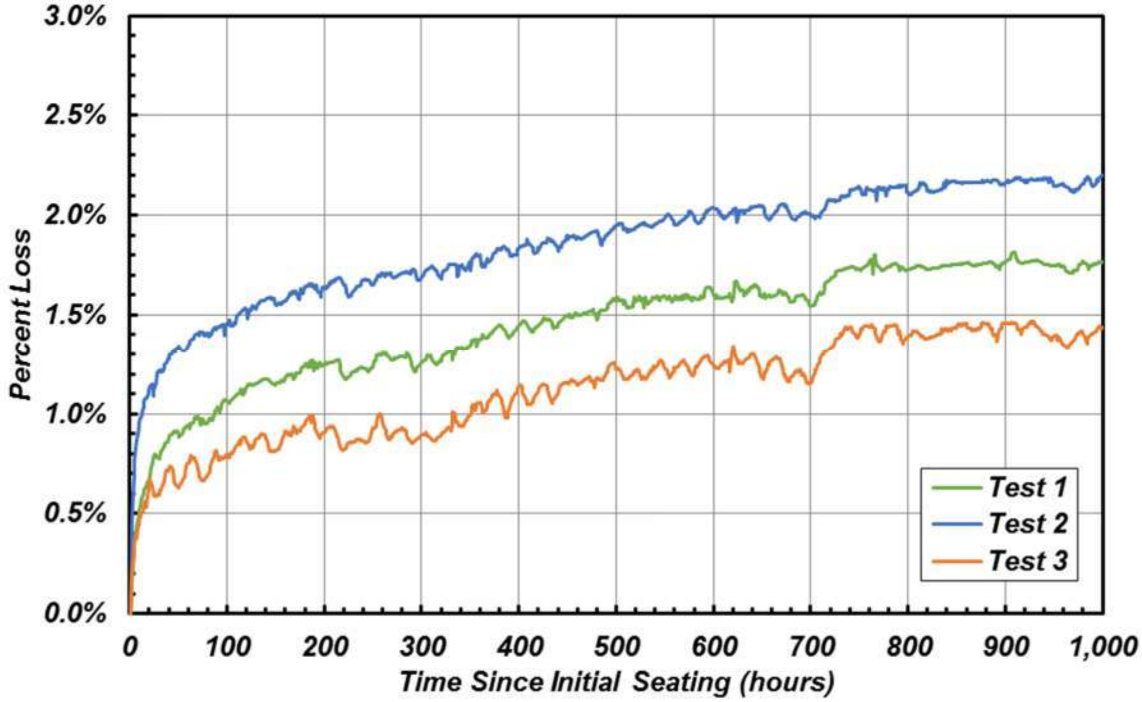


Figure G-6 – Percent loss for plain Threadbar® with target initial percentage of 60%

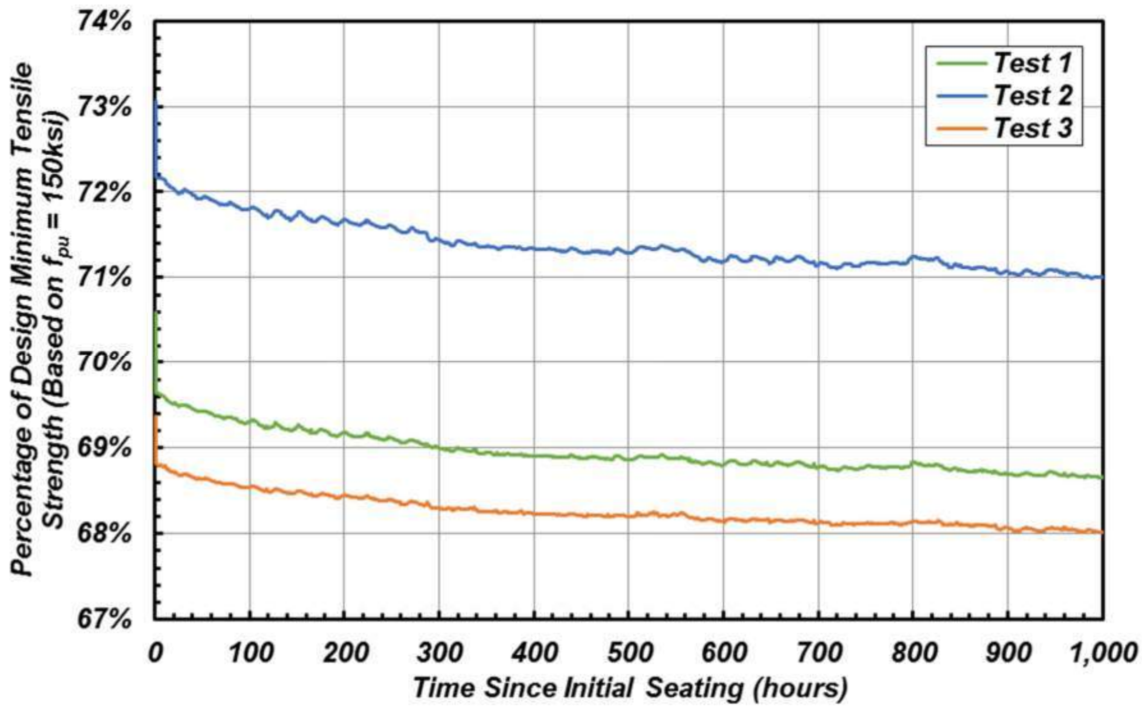


Figure G-7 – Relaxation measurements for galvanized Threadbar®

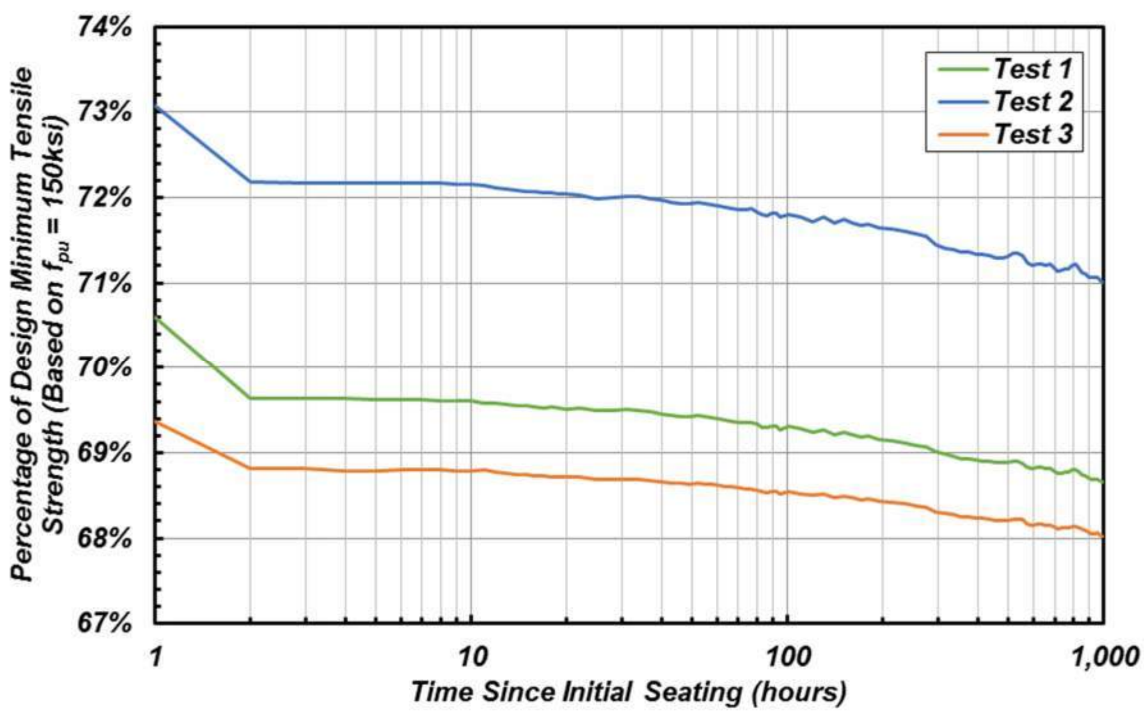


Figure G-8 – Relaxation measurements for galvanized Threadbar® with time on a logarithmic scale

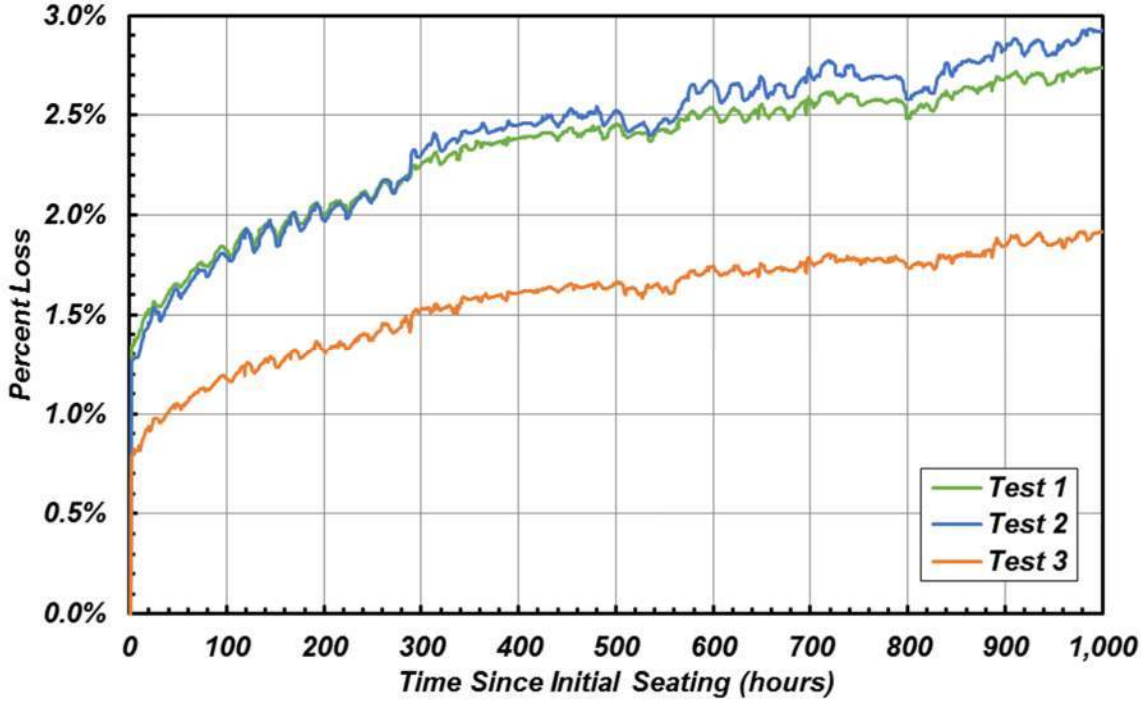


Figure G-9 – Percent loss for galvanized Threadbar®

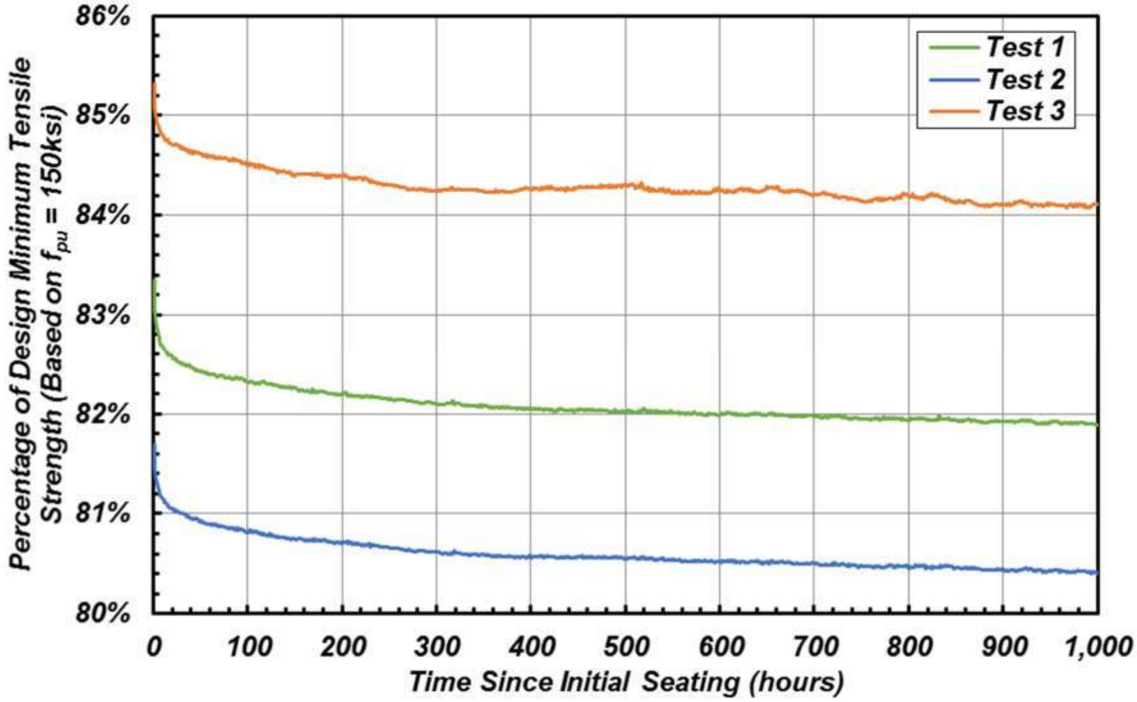


Figure G-10 – Relaxation measurements for Custom 450 H1050

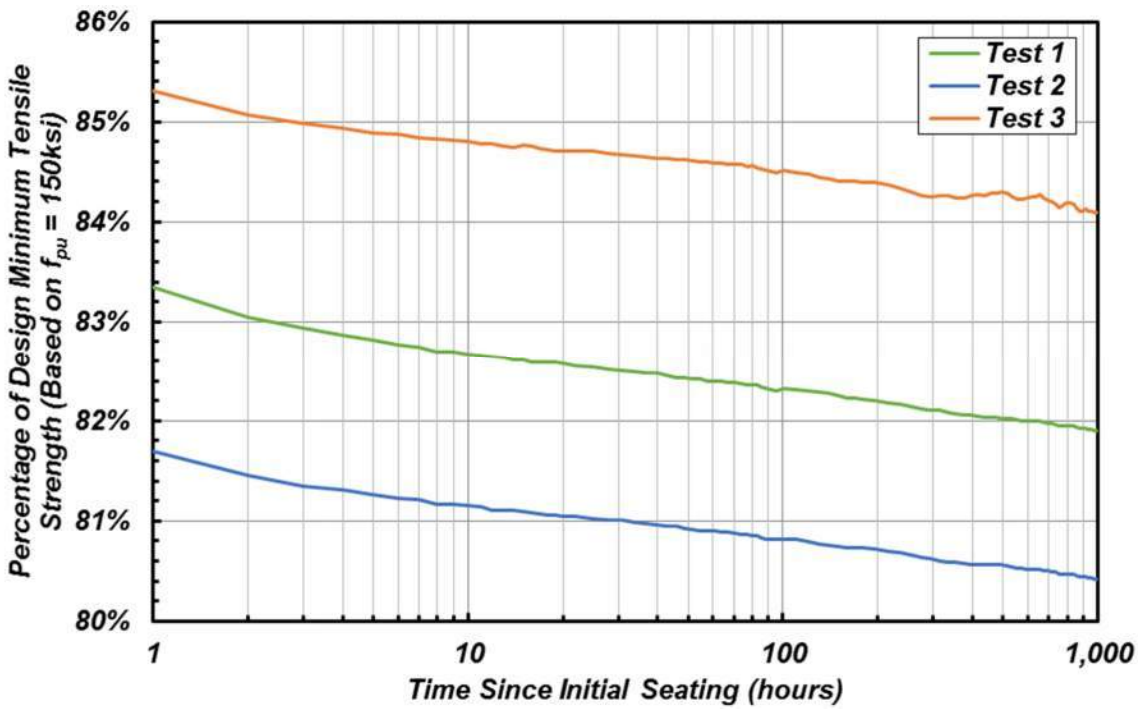


Figure G-11 – Relaxation measurements for Custom 450 H1050 with time on a logarithmic scale

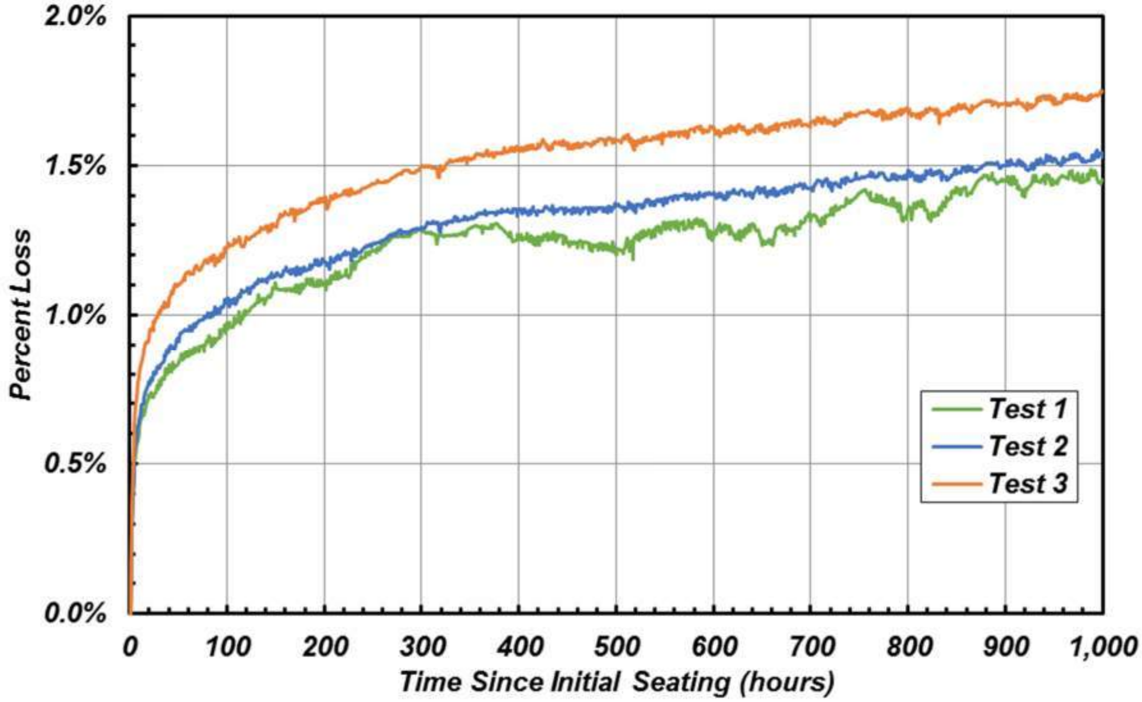


Figure G-12 – Percent loss for Custom 450 H1050

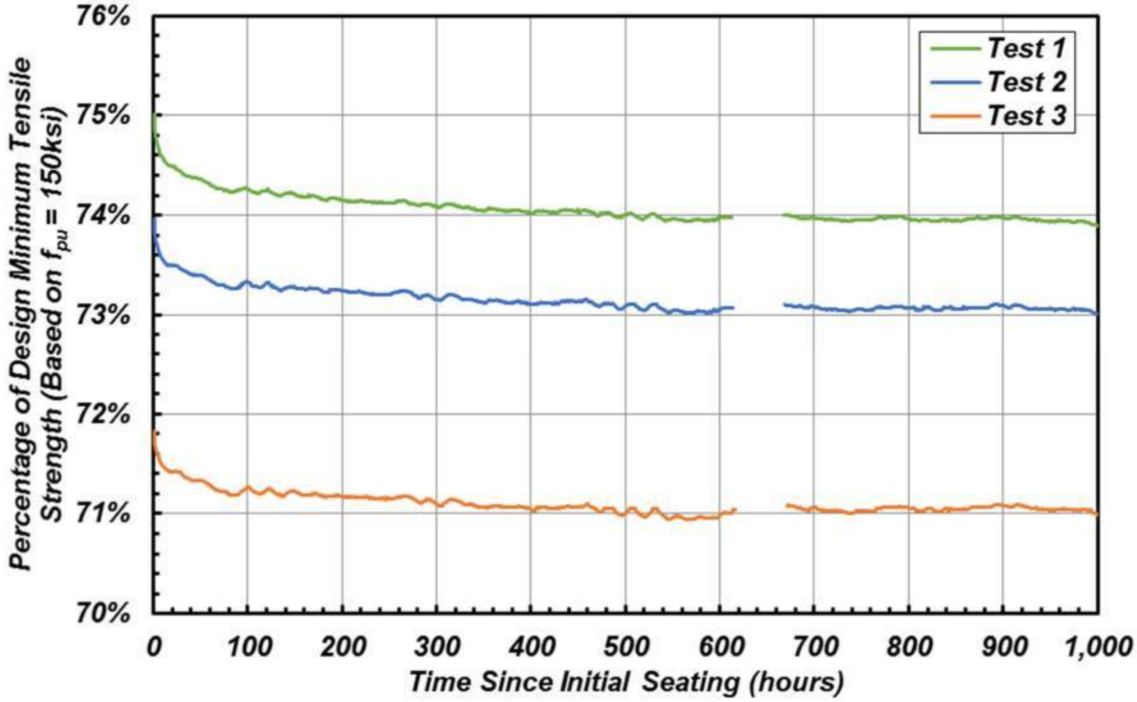


Figure G-13 – Relaxation measurements for Custom 630 H1100

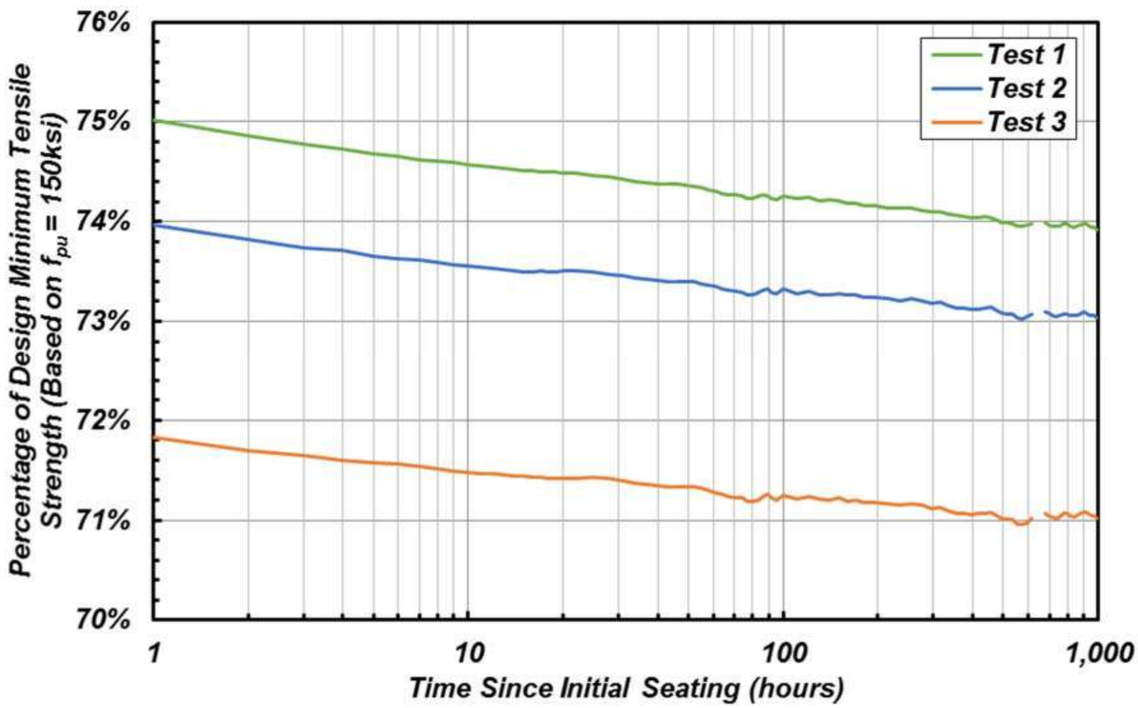


Figure G-14 – Relaxation measurements for Custom 630 H1100 with time on a logarithmic scale

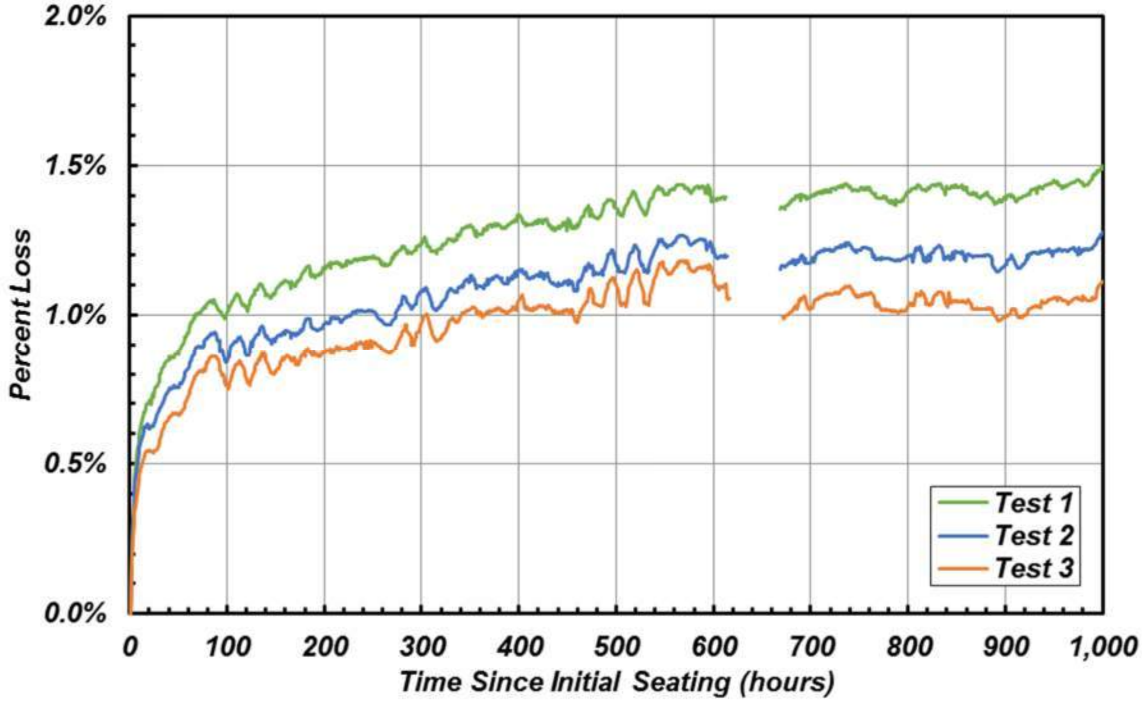


Figure G-15 – Percent loss for Custom 630 H1100

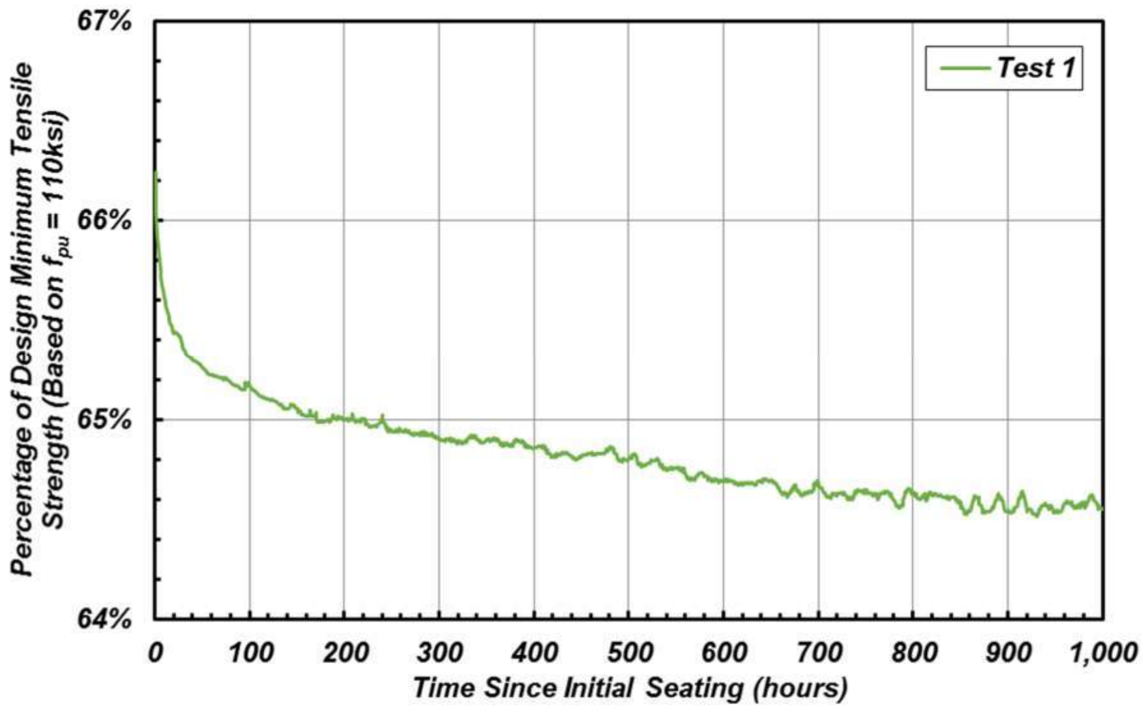


Figure G-16 – Relaxation measurements for Alloy 2507

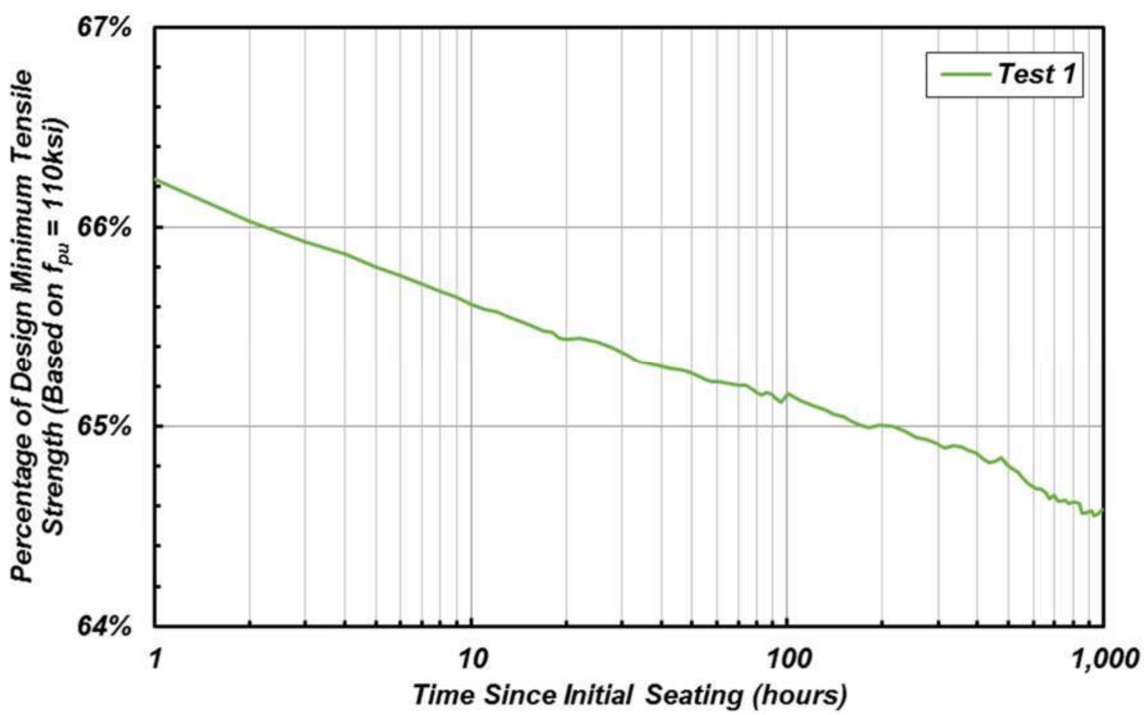


Figure G-17 – Relaxation measurements for Alloy 2507 with time on a logarithmic scale

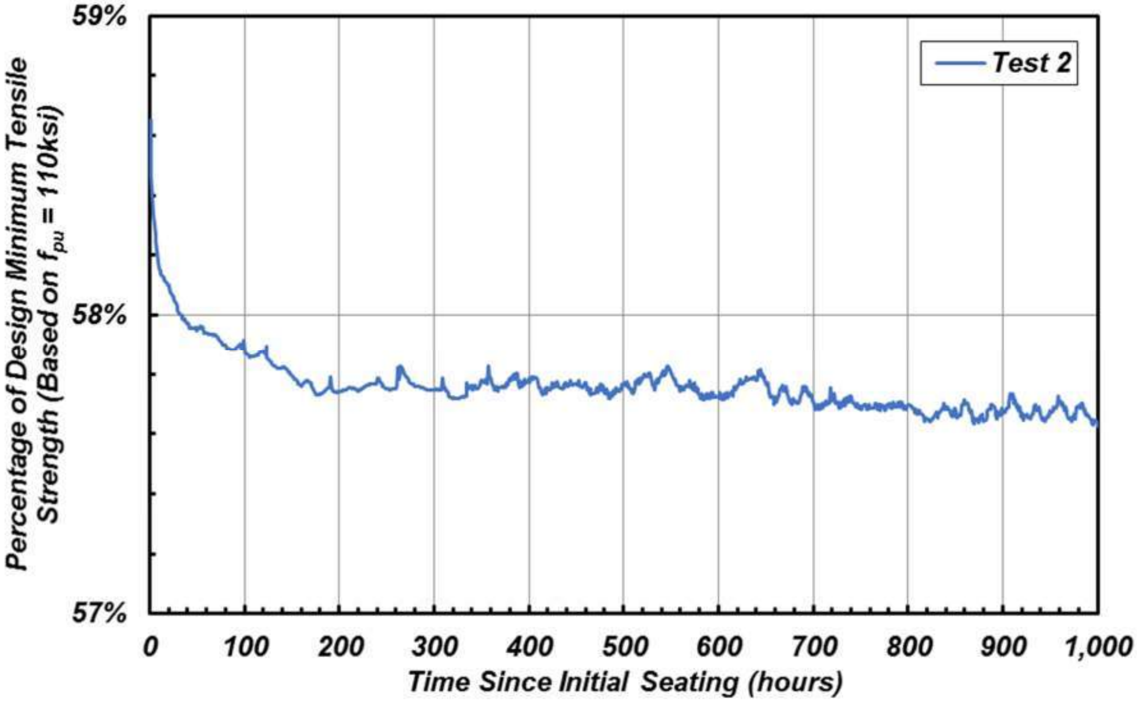


Figure G-18 – Relaxation measurements for Alloy 2507

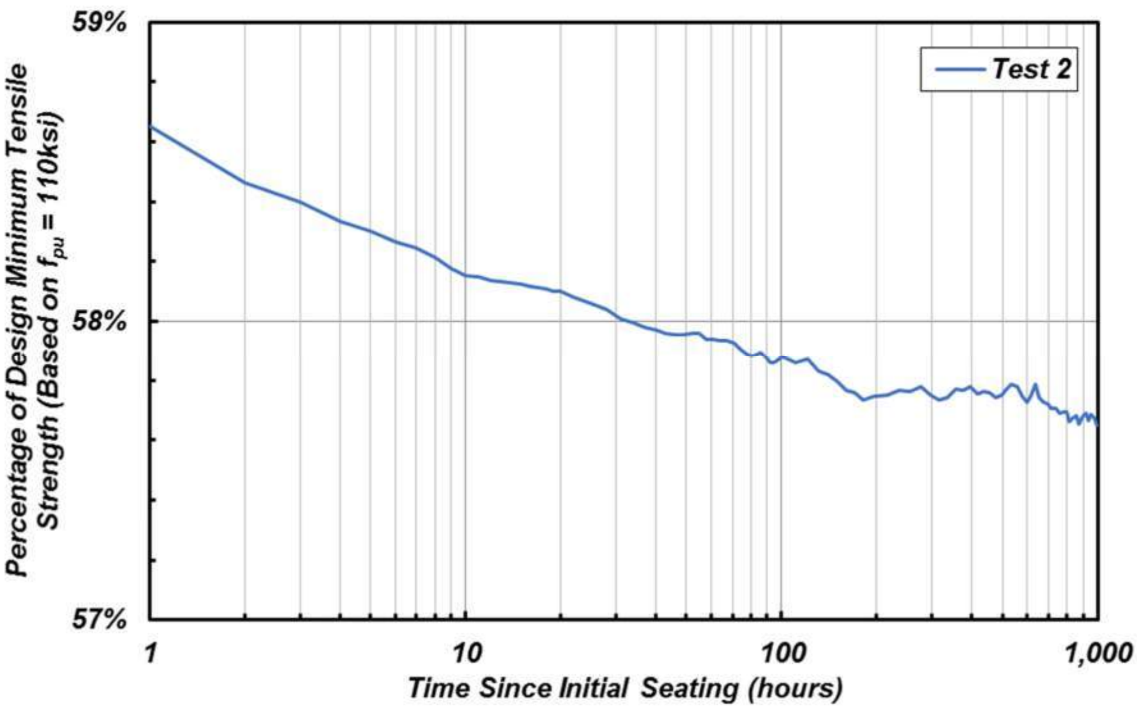


Figure G-19 – Relaxation measurements for Alloy 2507 with time on a logarithmic scale

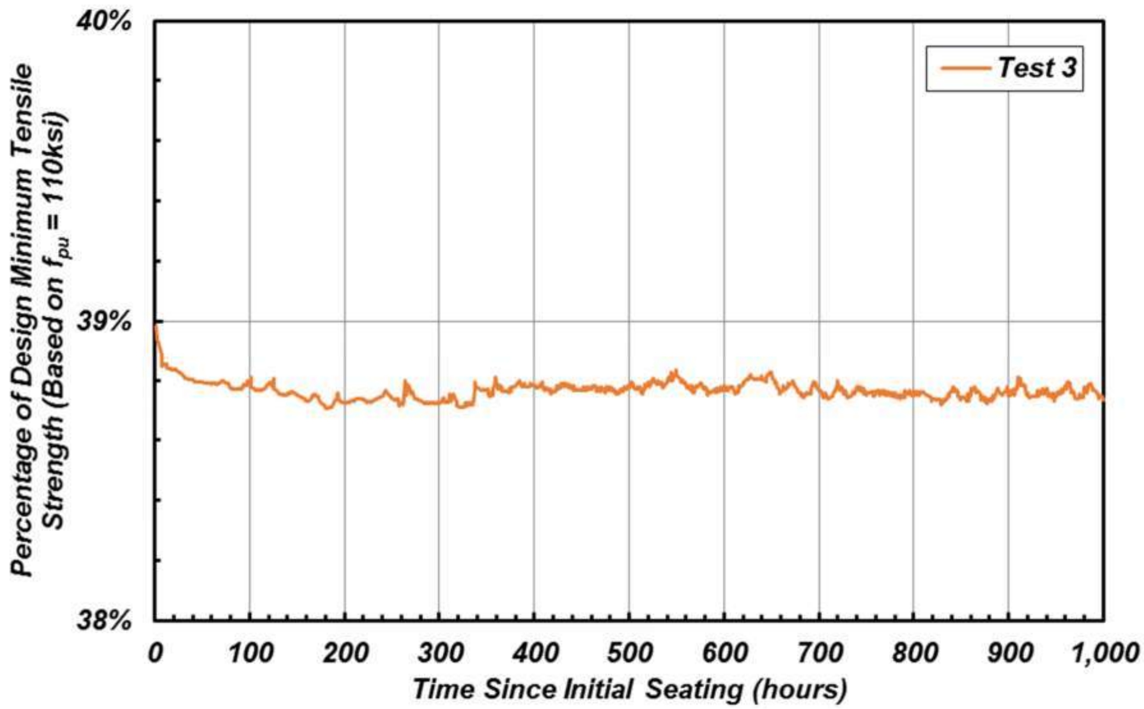


Figure G-20 – Relaxation measurements for Alloy 2507

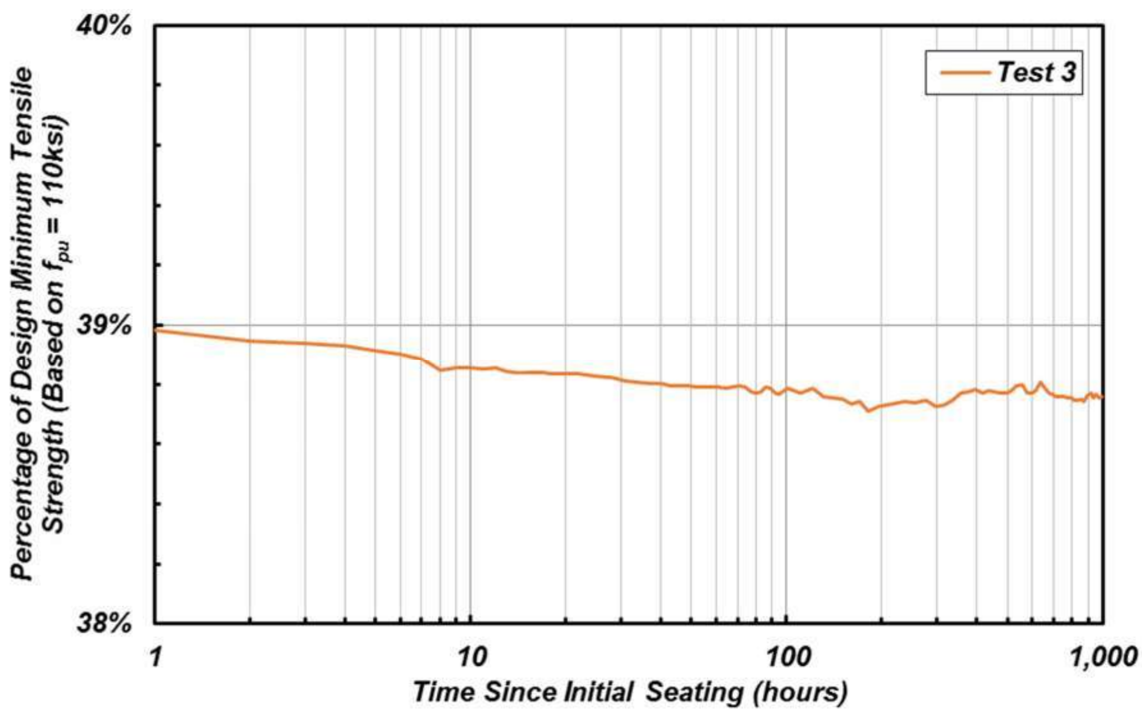


Figure G-21 – Relaxation measurements for Alloy 2507 with time on a logarithmic scale

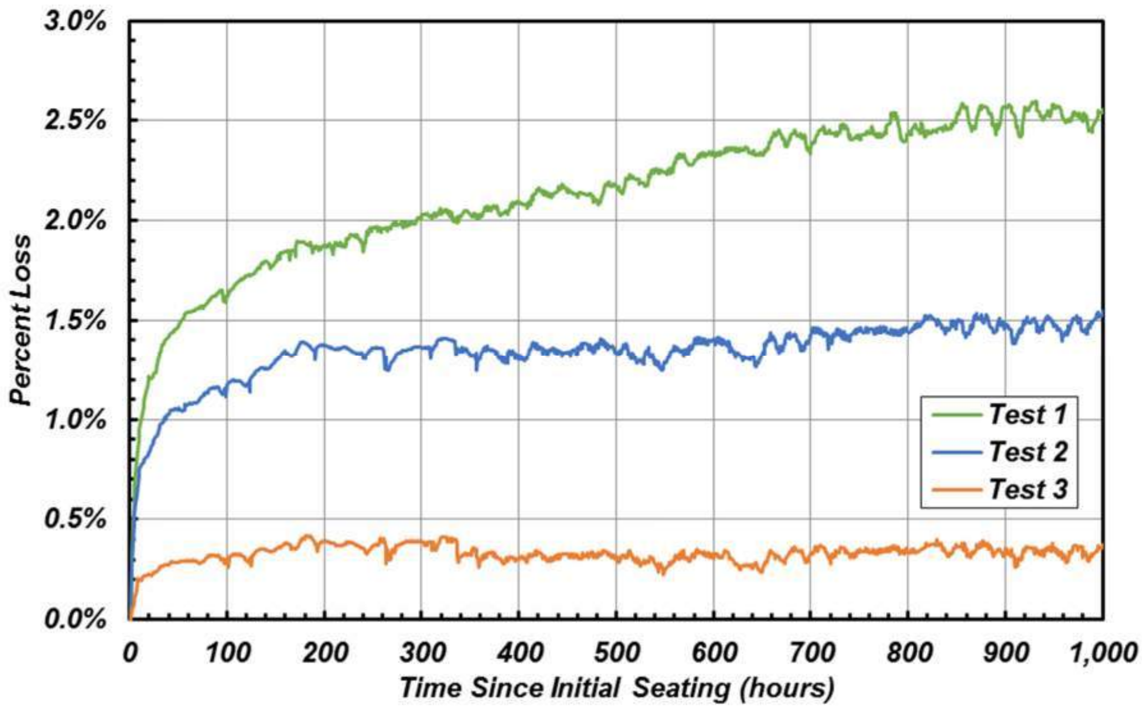


Figure G-22 – Percent loss for Alloy 2507

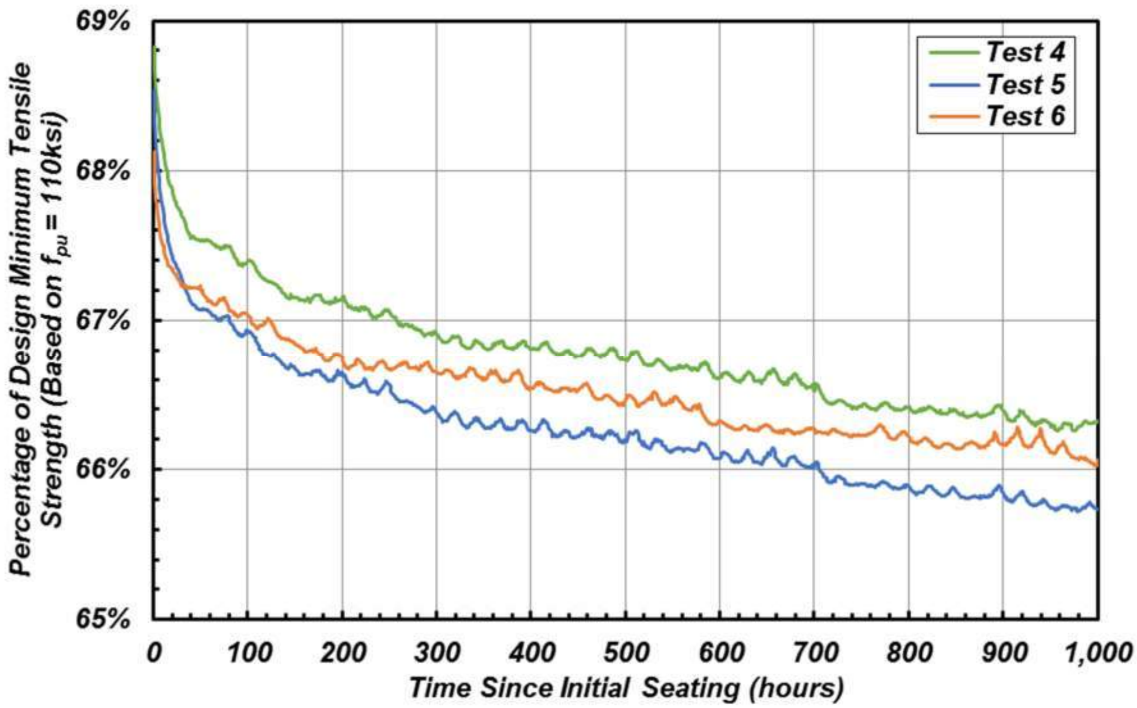


Figure G-23 – Relaxation measurements for Alloy 2507

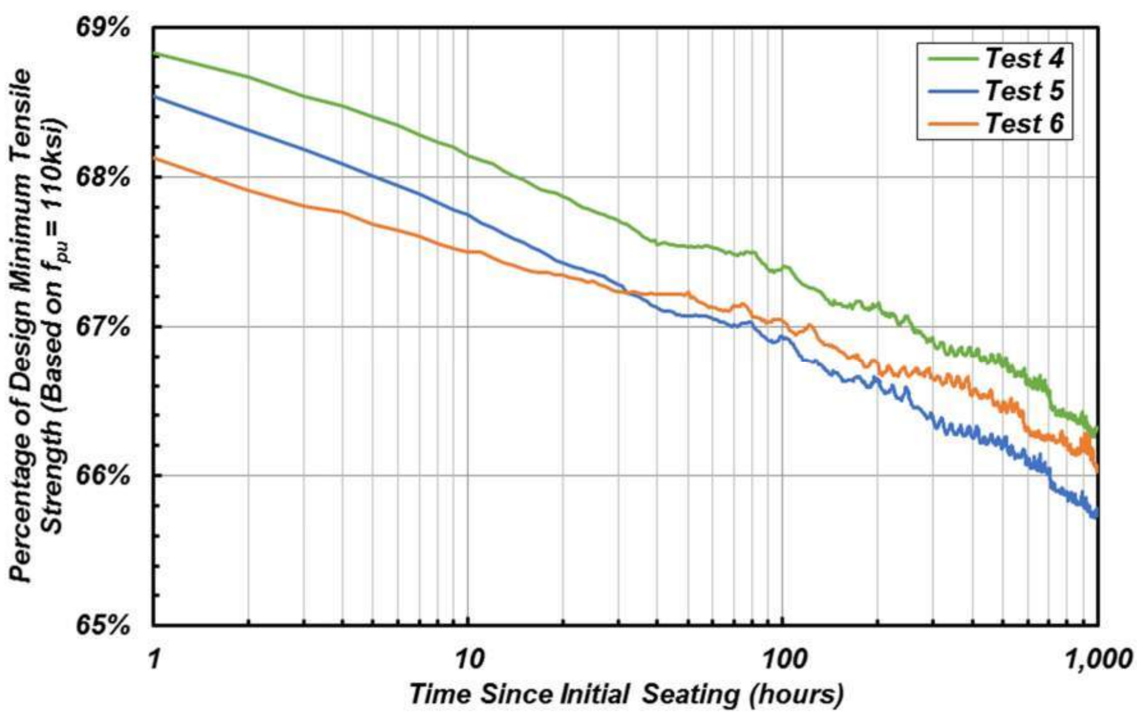


Figure G-24 – Relaxation measurements for Alloy 2507 with time on a logarithmic scale

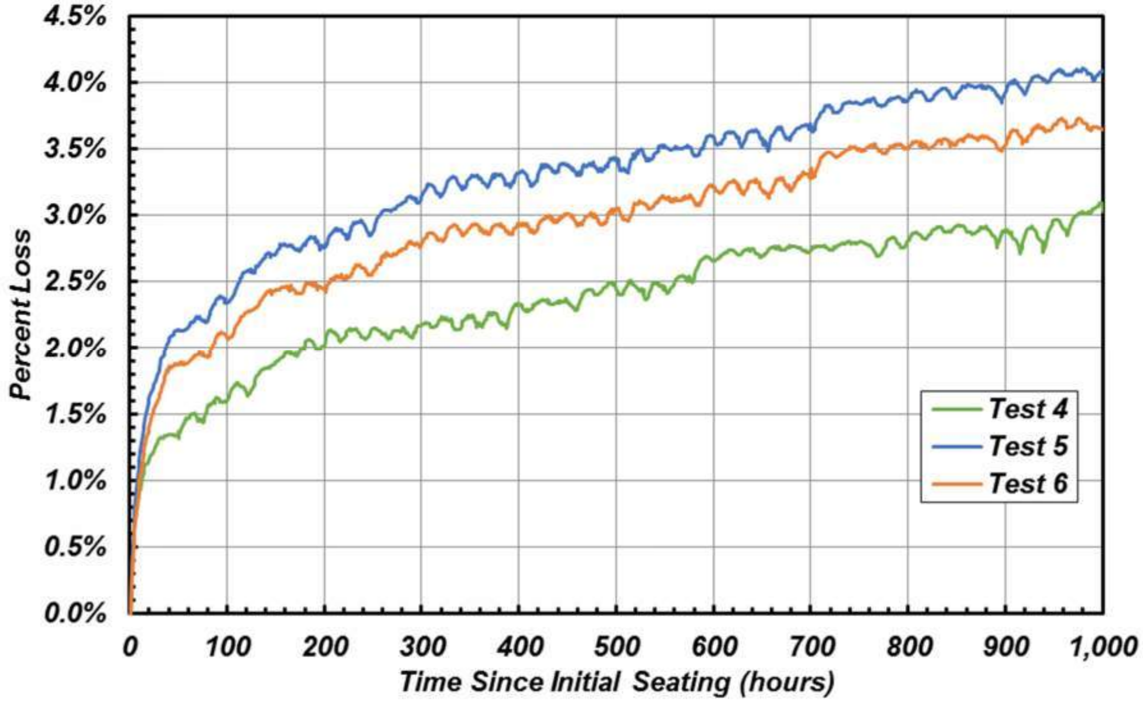


Figure G-25 – Percent loss for Alloy 2507

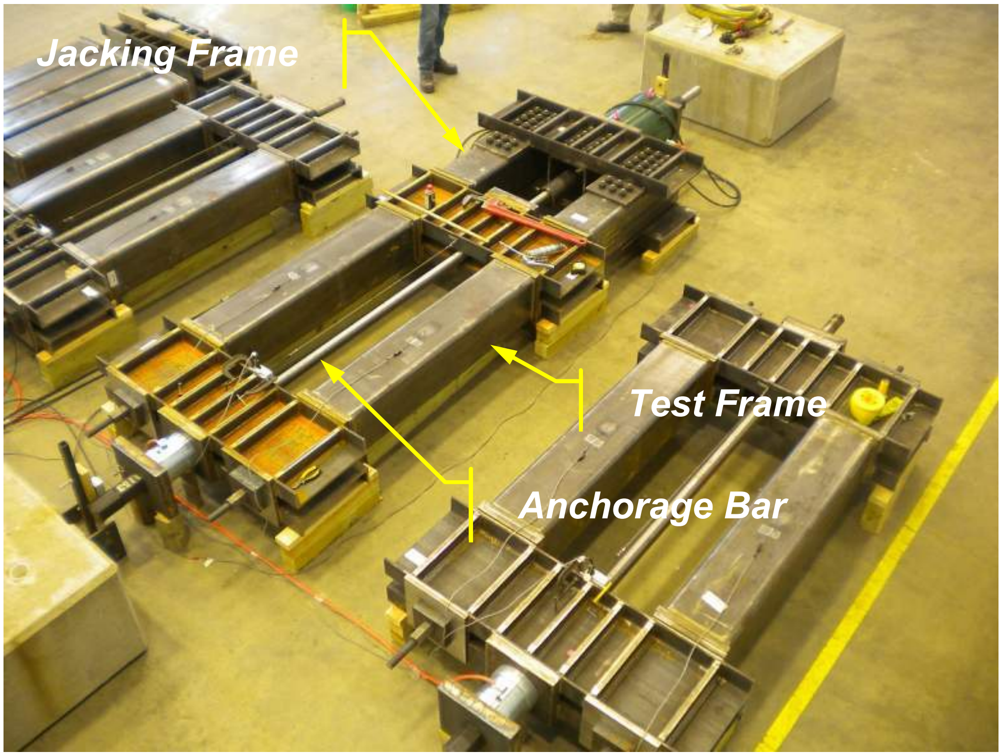


Figure G-26 – Relaxation test set-up

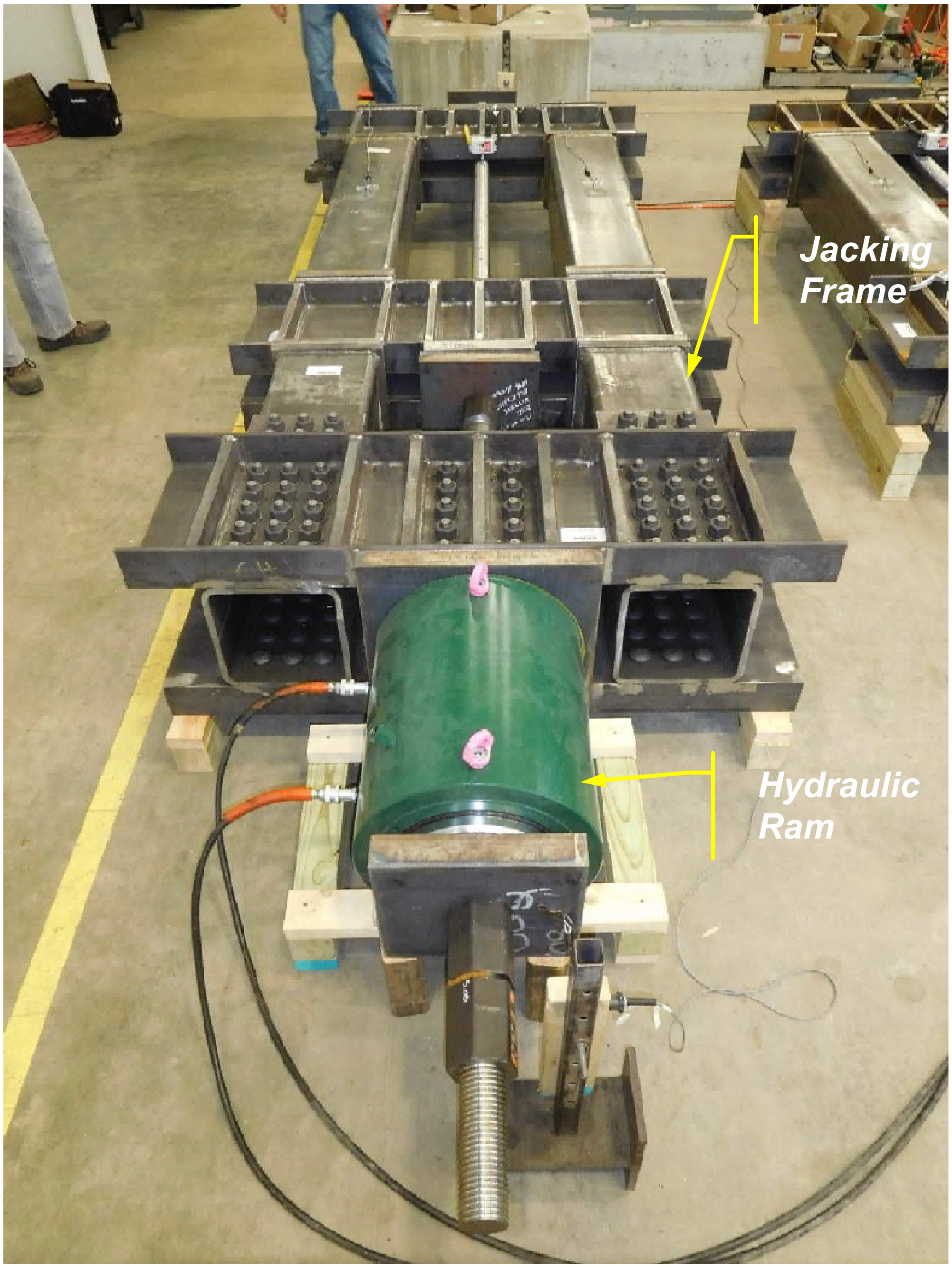


Figure G-27 – Relaxation test set-up and jacking frame

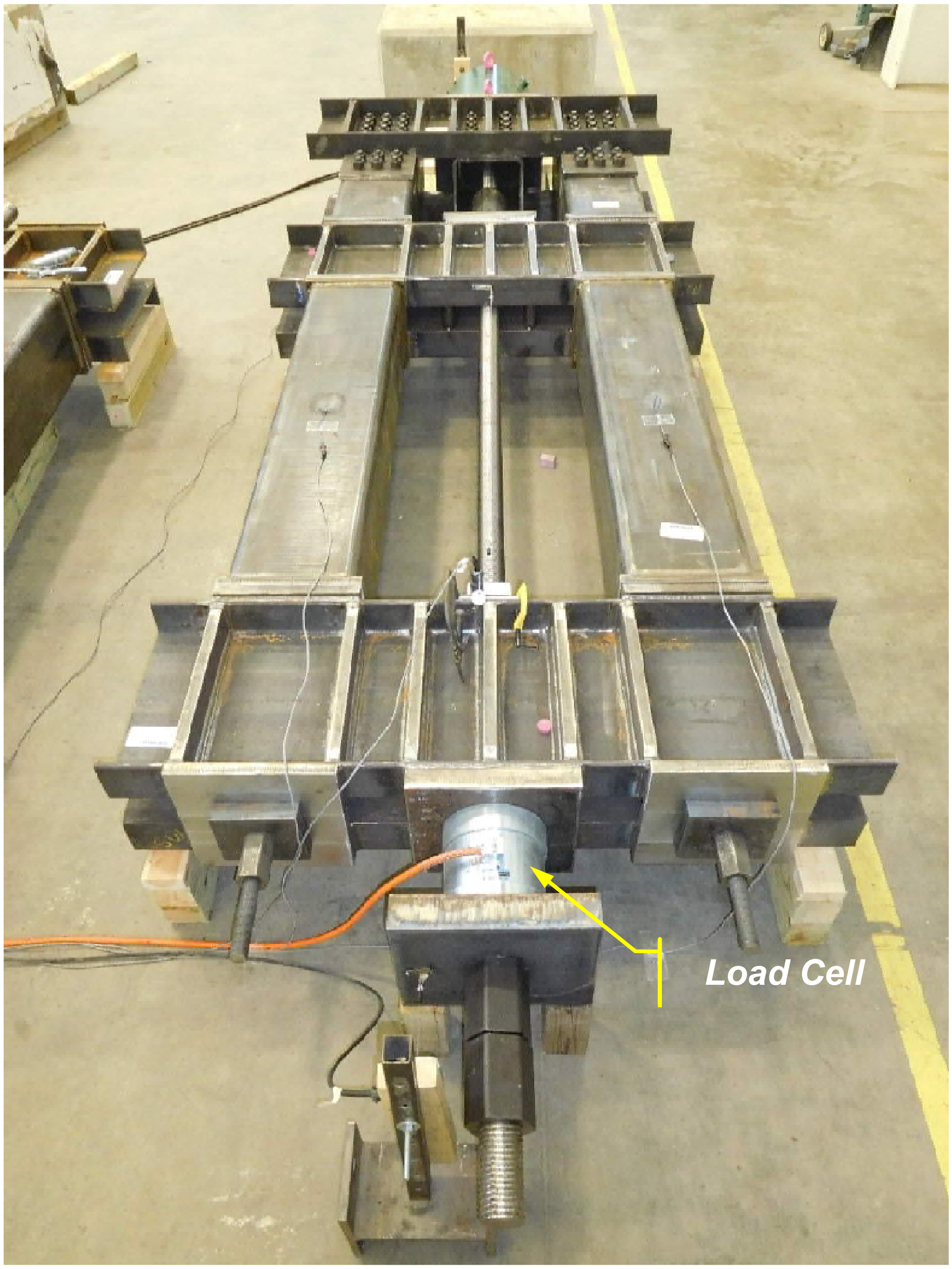
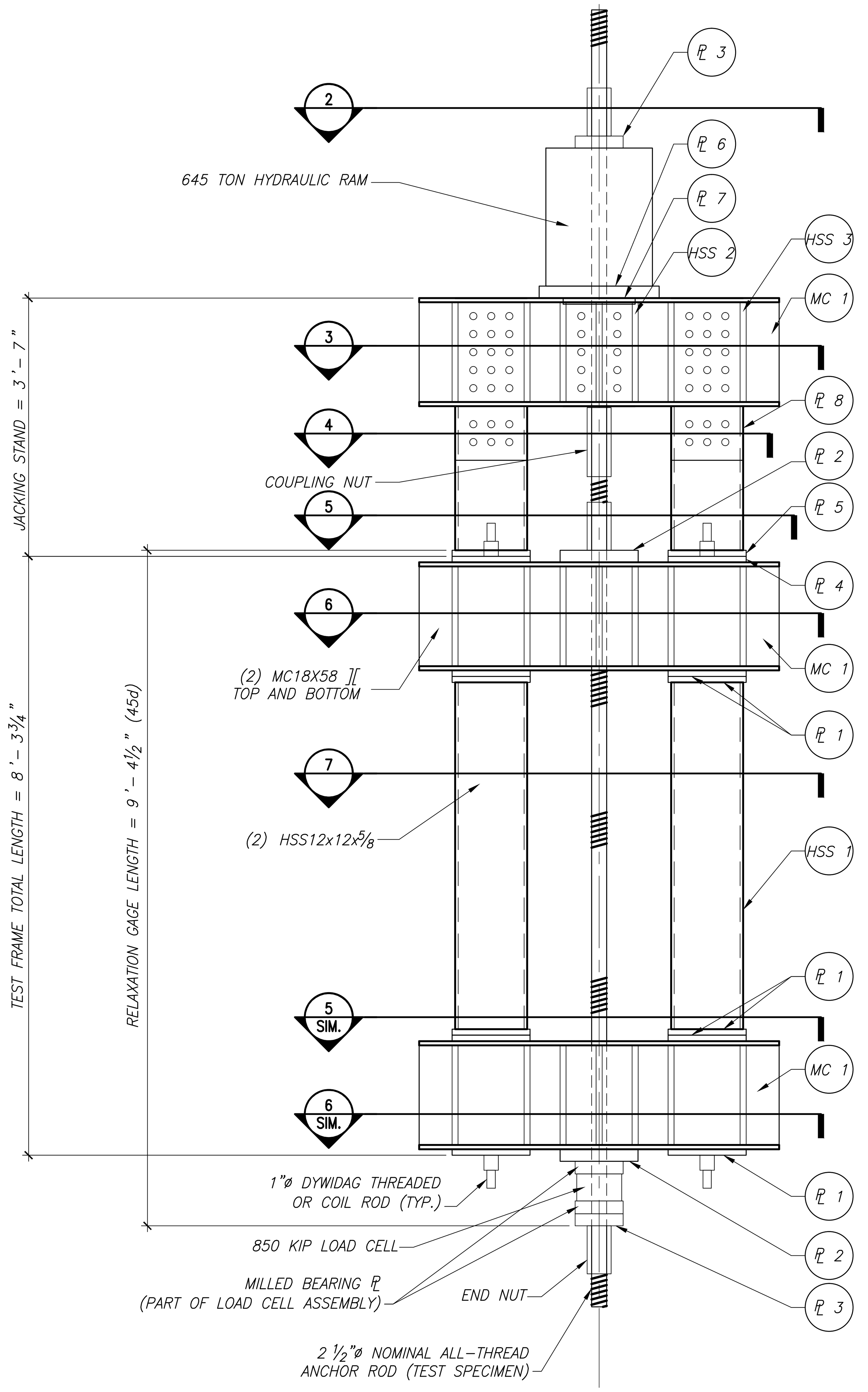
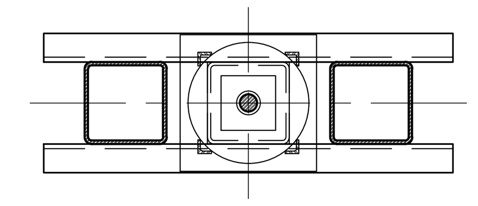


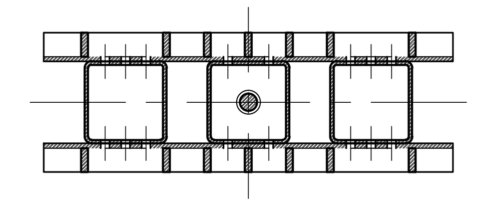
Figure G-28 – Relaxation test set-up and jacking frame



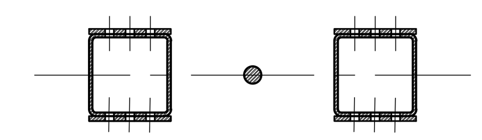
1 RELAXATION FRAME AND JACKING STAND
3/4" = 1'-0"



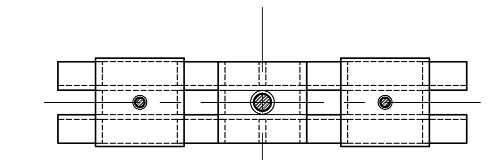
2 SECTION – JACKING STAND
1/2" = 1'-0"



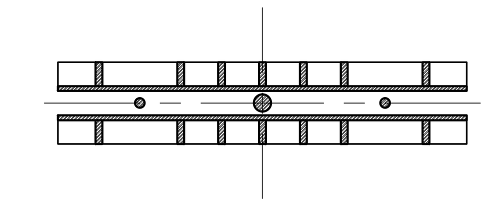
3 SECTION – JACKING STAND
1/2" = 1'-0"



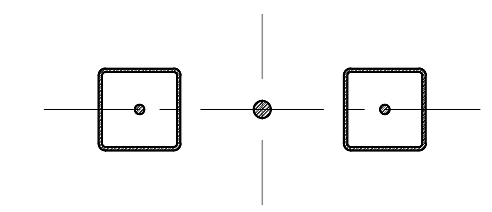
4 SECTION – JACKING STAND
1/2" = 1'-0"



5 SECTION – RELAXATION FRAME
1/2" = 1'-0"



6 SECTION – RELAXATION FRAME
1/2" = 1'-0"



7 SECTION – RELAXATION FRAME
1/2" = 1'-0"

BILL OF MATERIAL – JACKING STAND (1 THUS)

MARK	QTY.	SHAPE	LENGTH	MATERIAL	REMARKS
PL 3	1	PL 8"x8"x2"		ASTM A36	3½"ø CENTER HOLE; LOOSE
PL 5	2	PL 1'-1"x1'-1"x1"		ASTM A36	MILL TO BEAR WITH PL 4; 3½"ø CENTER HOLE
PL 6	1	PL 1'-8"x1'-8"x2"		ASTM A36	3½" ø CENTER HOLE
PL 7	1	PL 1'-0"x1'-0"x1"		ASTM A36	3½"ø CENTER HOLE; ATOP HSS STUB
PL 8	4	PL 1'-0"x9"x¾"		ASTM A36	SEE DETAIL
PL 9	14	PL 1'-4 15/16"x3 1/8"x1"		ASTM A36	STIFFENER PLATE
MC 1	2	MC 18x58	5'-0"	ASTM A572 Gr. 50	BACK-TO-BACK CHANNELS
HSS 2	1	HSS 12x12x5/8	1'-5"	ASTM A500 Gr. B	SEE DETAILS
HSS 3	2	HSS 12x12x5/8	3'-6"	ASTM A500 Gr. B	SEE DETAILS
BOLTS	104	1 1/8" ø	3"	LEJEUNE A490 TC BOLTS	EACH WITH ONE ASTM A436 TYPE 1 HARDENED WASHER AND ONE A563 Gr. DH HEAVY HEX NUT

BILL OF MATERIAL – TEST FRAME (6 THUS)

MARK	QTY.	SHAPE	LENGTH	MATERIAL	REMARKS
PL 1	10	PL 1'-1"x1'-1"x1"		ASTM A36	1½"ø CENTER HOLE
PL 2	2	PL 1'-1"x1'-0"x2"		ASTM A36	3½"ø CENTER HOLE
PL 3	1	PL 8"x8"x2"		ASTM A36	3½"ø CENTER HOLE; LOOSE
PL 4	2	PL 1'-1"x1'-1"x1"		ASTM A36	MILL TO BEAR WITH PL 5; 1½"ø CENTER HOLE
PL 9	28	PL 1'-4 15/16"x3 1/8"x1"		ASTM A36	STIFFENER PLATE
MC 1	4	MC 18x58	5'-0"	ASTM A572 Gr. 50	BACK-TO-BACK CHANNELS
HSS 1	2	HSS 12x12x5/8	4'-9 ¾"	ASTM A500 Gr. B	SEE DETAILS

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

Simpson Gumpertz & Heger Inc.
135 South LaSalle Street, Suite 3050
Chicago, Illinois 60603
main: 312.754.7500 fax: 312.754.7501
www.sgh.com

Boston
Chicago
Houston
Los Angeles
New York
San Francisco
Washington, DC

Consultant

DRAWING STATUS

No.	Date	Description	By

I-74 HIGH STRENGTH P/T ANCHORAGE BAR
PHASE 2 TESTING PROGRAM

Project

RELAXATION FRAME

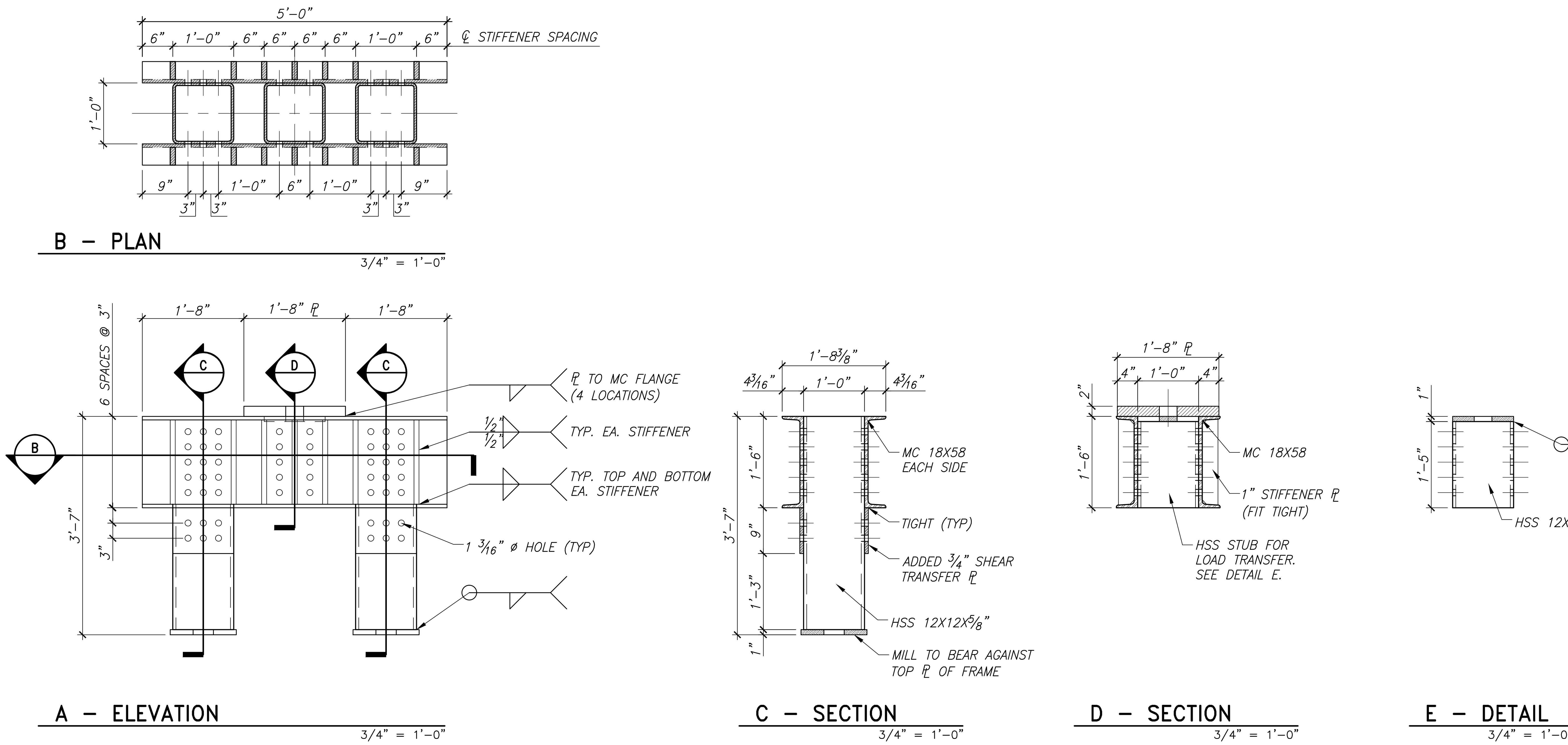
Drawing Title

Project No.	Checked	Date
141685.10	JEB	05/26/2016
Drawn	Approved	Scale
MDS/JEB	NSA	AS SHOWN

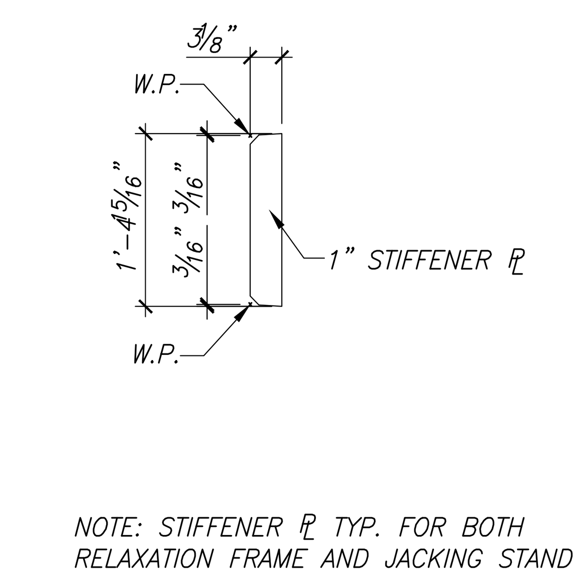
Drawing No.

S-1

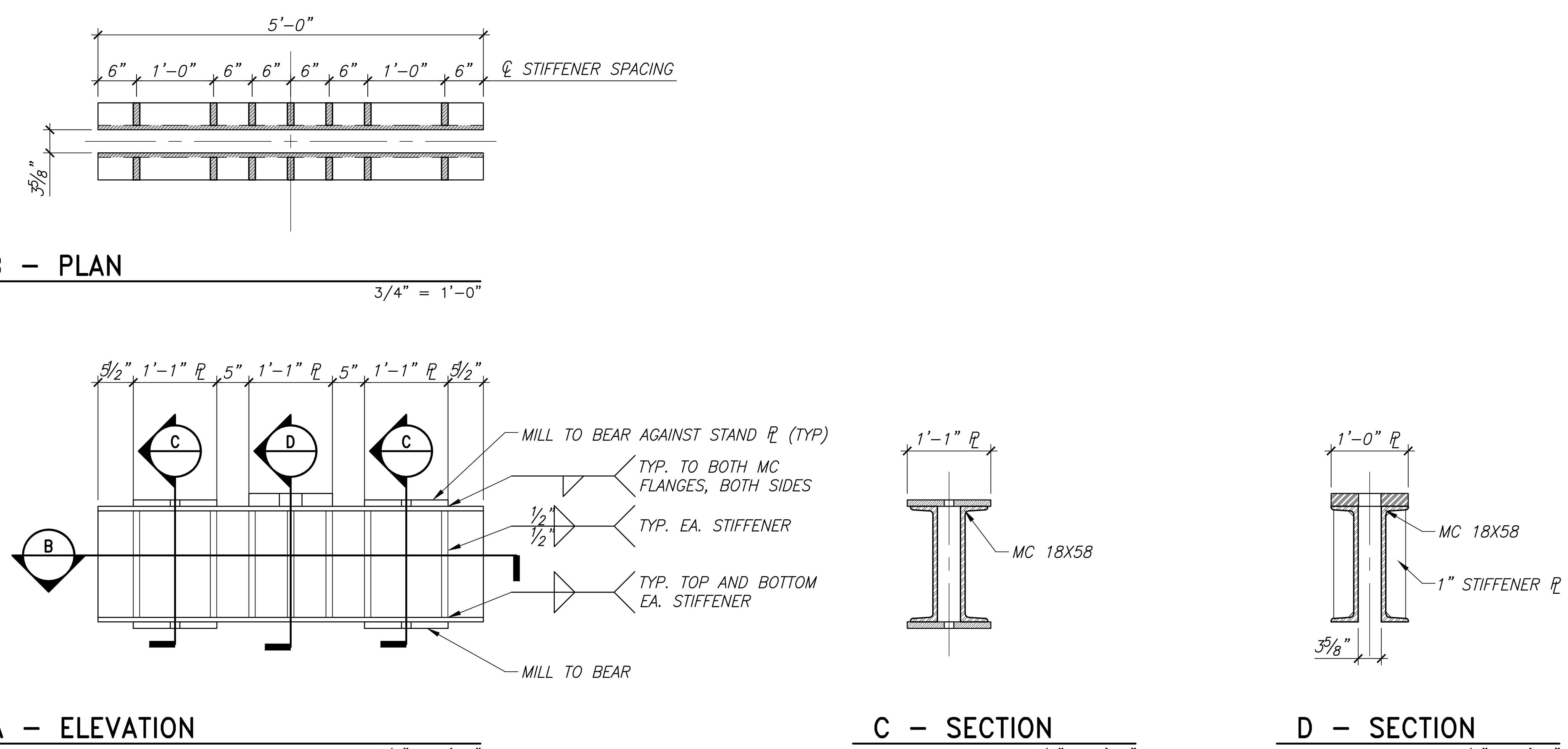
Seal



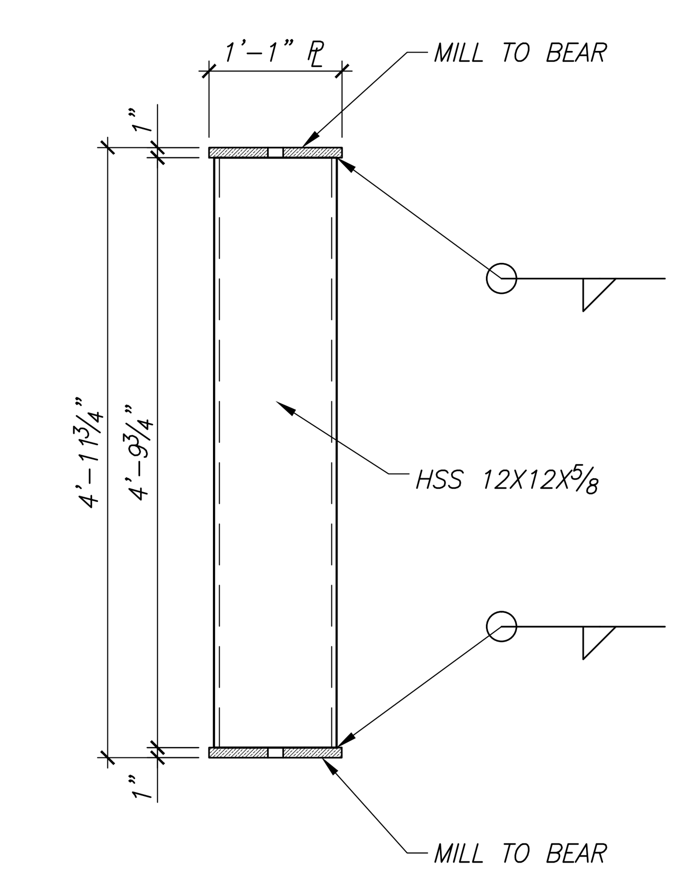
1 JACKING STAND DETAIL
(1 THUS)
3/4" = 1'-0"



3 MC STIFFENER DETAIL
3/4" = 1'-0"



2 SPREADER BEAM DETAIL
(12 THUS)
3/4" = 1'-0"



4 FRAME LEG DETAIL
(12 THUS)
3/4" = 1'-0"

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

Simpson Gumpertz & Heger Inc.
135 South LaSalle Street, Suite 3050
Chicago, Illinois 60603
main: 312.754.7500 fax: 312.754.7501
www.sgh.com

Boston
Chicago
Houston
Los Angeles
New York
San Francisco
Washington, DC

Consultant

DRAWING STATUS

No.	Date	Description	By

I-74 HIGH STRENGTH P/T ANCHORAGE BAR
PHASE 2 TESTING PROGRAM

Project

DETAILS

Drawing Title

Project No.	Checked	Date
141685.10	JEB	05/26/2016
Drawn	**Approved**	**Scale**
MDS/JEB	NSA	AS SHOWN

Drawing No.
S-2

Seal

Appendix H – Rockwell Hardness Testing

Appendix H contains the following material related to hardness testing:

- Photographs of the cross-sections used for hardness testing.
- Tabulated individual test measurements for each specimen.

Figure H-1 - Plain Threadbar®, Rockwell C hardness measurements.

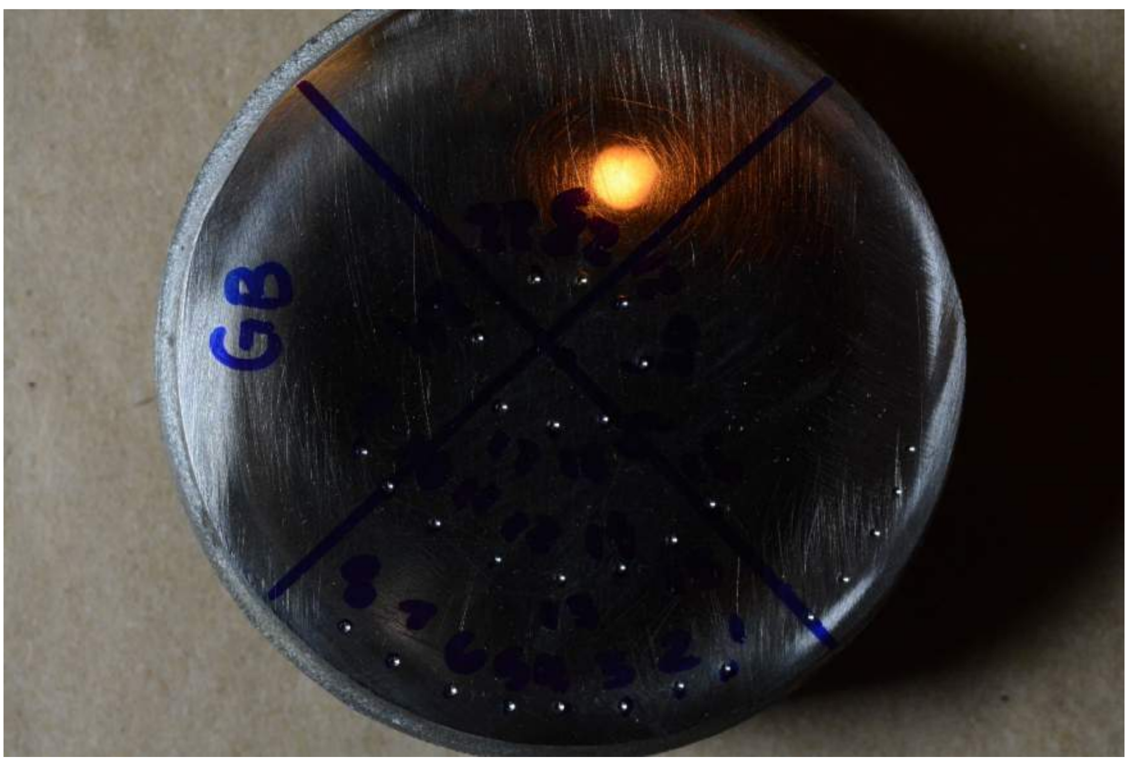


Figure H-2 - Galvanized Threadbar®, Rockwell C hardness measurements.

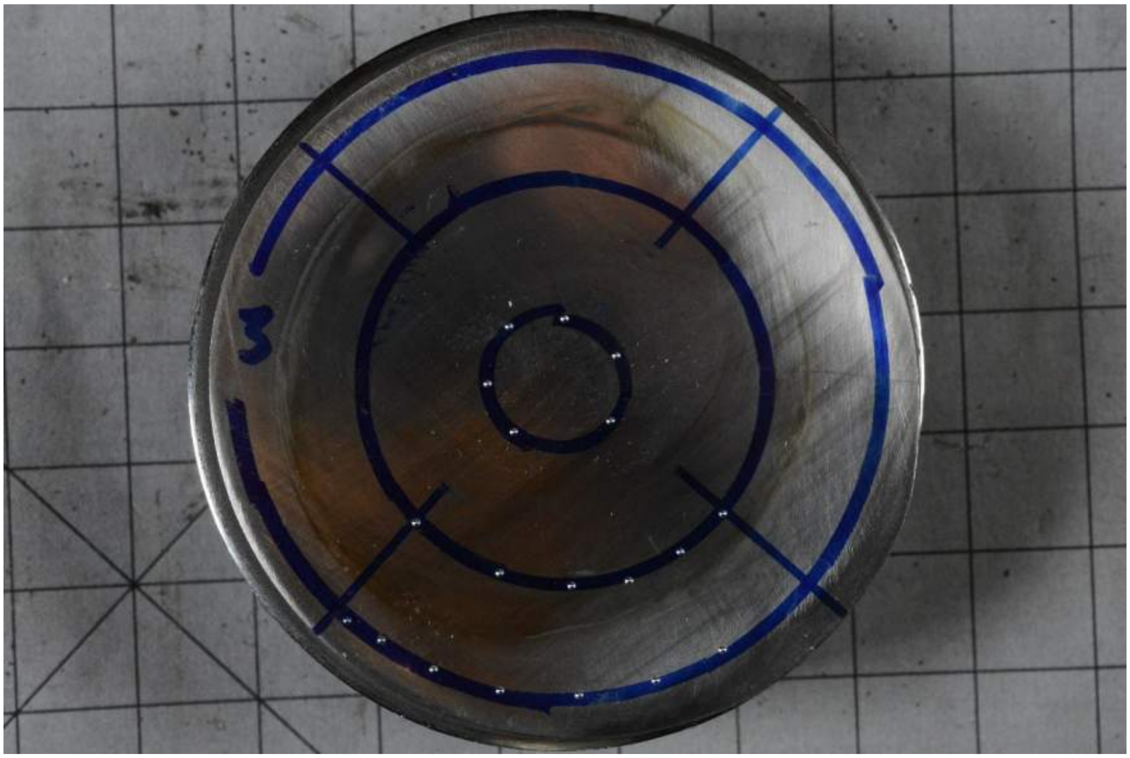


Figure H-3 - Custom 450 H1050, Rockwell C hardness measurements.

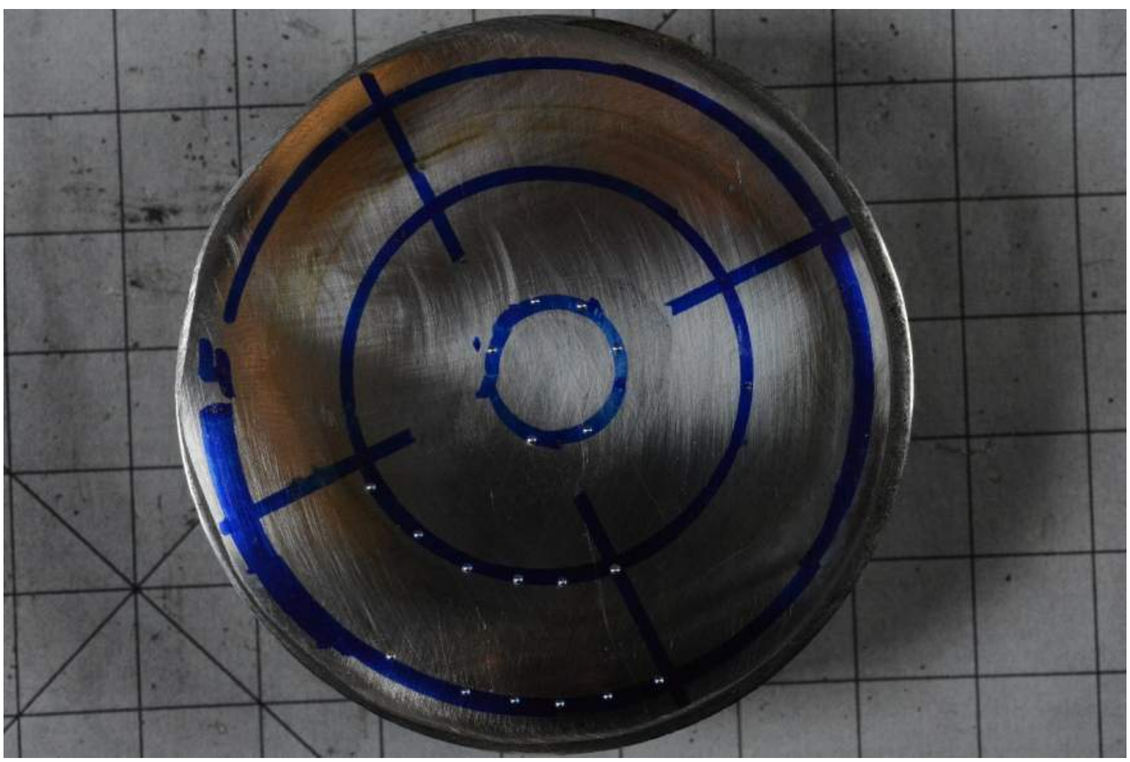


Figure H-4 - Custom 630 H1100, Rockwell C hardness measurements.

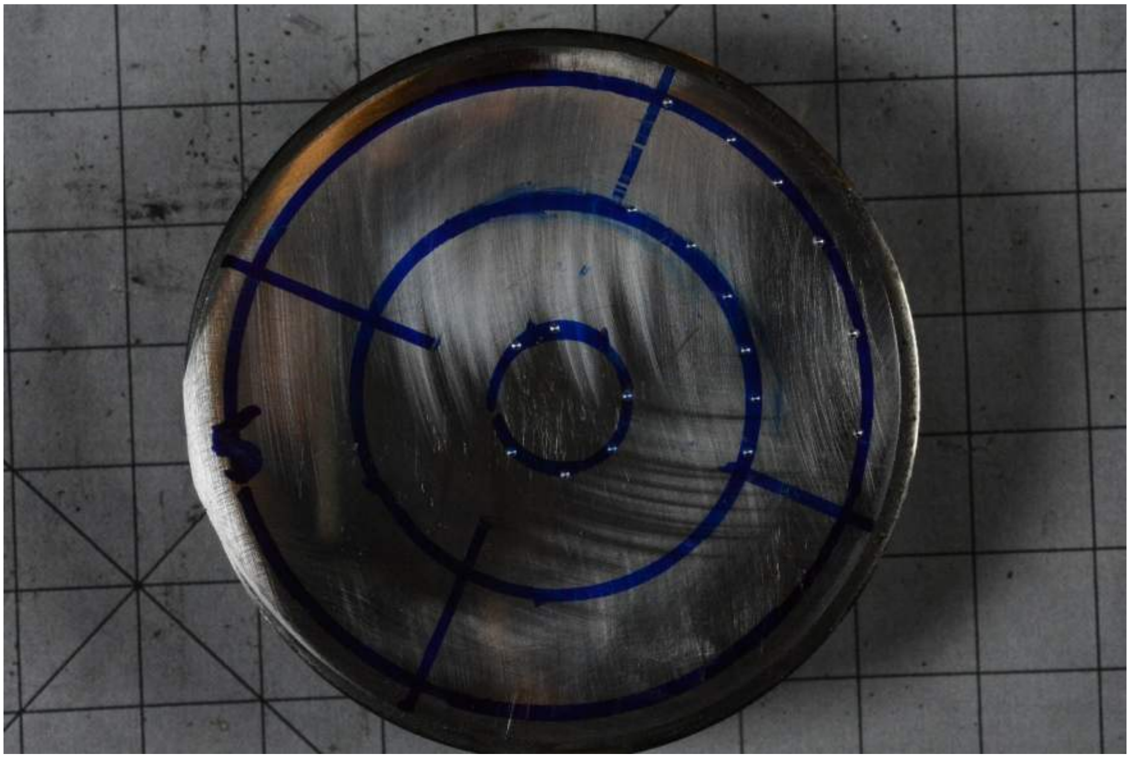


Figure H-5 - Alloy 2507, Rockwell C hardness measurements.

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

SHEET NO.	
PROJECT NO.	141685.12
DATE	2 November 2016
BY	SJWolffGoodrich
CHECKED BY	

CLIENT Alfred Benesch & Company

SUBJECT Hardness of DYWIDAG Plain Bar

Sample ID:	Plain
Operator:	SJWolffGoodrich
ASTM Standard:	E18-15
Apparatus:	Wilson Rockwell 574
Indentor Type:	Diamond
Load:	150 kg

Calibration

Reading	Hardness
1	29.7
2	29.2
3	29.9
4	30.0
5	29.8
Avg	**29.7**

Block ID: 02R10641
Indentor Type: Diamond
Load: 150 kg
Expected Range: [28.3,30.3]

Results

Reading	Hardness	Depth (R/R_0)	Avg	Note
1	34.9	0.10	34.4	
2	34.4	0.10		
3	37.7	0.10		
4	33.7	0.10		
5	30.4	0.10		
6	37.8	0.10		
7	32.5	0.10		
8	33.7	0.10		
9	37	0.45	37.1	
10	36.6	0.45		
11	37	0.45		
12	37.1	0.45		
13	36.9	0.45		
14	36.7	0.45		
15	37.7	0.45		
16	37.7	0.45		
17	33.4	0.80	34.2	
18	35.2	0.80		
19	33.9	0.80		
20	33.5	0.80		
21	35.2	0.80		
22	34.8	0.80		
23	34.5	0.80		
24	32.9	0.80		
Avg	**35.2**			
St. Dev.	**2.0**			

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

SHEET NO.	
PROJECT NO.	141685.12
DATE	2 November 2016
BY	SJWolffGoodrich
CHECKED BY	

CLIENT Alfred Benesch & Company

SUBJECT Hardness of DYWIDAG Galvanized Bar

Sample ID:	Galvanized
Operator:	SJWolffGoodrich
ASTM Standard:	E18-15
Apparatus:	Wilson Rockwell 574
Indentor Type:	Diamond
Load:	150 kg

Calibration

Reading	Hardness
1	29.7
2	29.2
3	29.9
4	30.0
5	29.8
Avg	29.7

Block ID: 02R10641
Indentor Type: Diamond
Load: 150 kg
Expected Range: [28.3,30.3]

Results

Reading	Hardness	Depth (R/R_0)	Avg	Note
1	32.7	0.10	29.1	
2	31.5	0.10		
3	29.7	0.10		
4	27.1	0.10		
5	25.0	0.10		
6	25.8	0.10		
7	29.0	0.10		
8	31.6	0.10		
9	36.9	0.45	35.9	
10	36.9	0.45		
11	36.0	0.45		
12	35.4	0.45		
13	35.3	0.45		
14	35.9	0.45		
15	35.0	0.45		
16	35.9	0.45		
17	33.2	0.80	33.5	
18	34.1	0.80		
19	33.5	0.80		
20	34.2	0.80		
21	32.4	0.80		
22	32.1	0.80		
23	34.3	0.80		
24	34.2	0.80		
Avg	32.8			
St. Dev.	3.3			

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

CLIENT	Alfred Benesch & Company	SHEET NO.	
SUBJECT	Hardness of Custom 450 Bar	PROJECT NO.	141685.12
		DATE	15 December 2016
		BY	SJWolffGoodrich
		CHECKED BY	

Sample ID:	Custom 450
Operator:	SJWolffGoodrich
ASTM Standard:	E18-15
Apparatus:	Wilson Rockwell 574
Indentor Type:	Diamond
Load:	150 kg

Calibration

Reading	Hardness
1	29.7
2	29.2
3	29.9
4	30.0
5	29.8
Avg	**29.7**

Block ID: 02R10641
Indentor Type: Diamond
Load: 150 kg
Expected Range: [28.3,30.3]

Results

Reading	Hardness	Depth (R/R_0)	Avg	Note
1	39.8	0.10	39.4	
2	39.9	0.10		
3	39.7	0.10		
4	39.3	0.10		
5	39.2	0.10		
6	38.3	0.10		
7	38.7	0.45	38.9	
8	38.8	0.45		
9	39.1	0.45		
10	39.3	0.45		
11	38.8	0.45		
12	38.9	0.45		
13	38.0	0.80	38.1	
14	37.7	0.80		
15	38.1	0.80		
16	37.9	0.80		
17	38.2	0.80		
18	38.7	0.80		
Avg	**38.8**			
St. Dev.	**0.6**			

SHEET NO.
PROJECT NO. 141685.12
DATE 15 December 2016
BY SJWolffGoodrich
CHECKED BY

CLIENT Alfred Benesch & Company
SUBJECT Hardness of Custom 630 Bar

Sample ID:	Custom 630
Operator:	SJWolffGoodrich
ASTM Standard:	E18-15
Apparatus:	Wilson Rockwell 574
Indentor Type:	Diamond
Load:	150 kg

Calibration

Reading	Hardness
1	29.7
2	29.2
3	29.9
4	30.0
5	29.8
Avg	29.7

Block ID: 02R10641
Indentor Type: Diamond
Load: 150 kg
Expected Range: [28.3,30.3]

Results

Reading	Hardness	Depth (R/R_0)	Avg	Note
1	37.8	0.10	37.6	
2	37.5	0.10		
3	38.4	0.10		
4	36.5	0.10		
5	37.9	0.10		
6	37.5	0.10		
7	36.3	0.45	36.4	
8	33.5	0.45		
9	36.9	0.45		
10	37.1	0.45		
11	37.2	0.45		
12	37.1	0.45		
13	36.6	0.80	36.2	
14	36.5	0.80		
15	36.6	0.80		
16	35.0	0.80		
17	36.4	0.80		
18	36.3	0.80		
Avg	36.7			
St. Dev.	1.1			

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

CLIENT Alfred Benesch & Company
SUBJECT Hardness of Alloy 2507 Bar

SHEET NO.
PROJECT NO. 141685.12
DATE 15 December 2016
BY SJWolffGoodrich
CHECKED BY

Sample ID:	Alloy 2507
Operator:	SJWolffGoodrich
ASTM Standard:	E18-15
Apparatus:	Wilson Rockwell 574
Indentor Type:	Diamond
Load:	150 kg

Calibration

Reading	Hardness
1	29.7
2	29.2
3	29.9
4	30.0
5	29.8
Avg	29.7

Block ID: 02R10641
Indentor Type: Diamond
Load: 150 kg
Expected Range: [28.3,30.3]

Results

Reading	Hardness	Depth (R/R_0)	Avg	Note
1	32.4	0.10	32.3	
2	32.0	0.10		
3	32.1	0.10		
4	32.0	0.10		
5	32.4	0.10		
6	32.7	0.10		
7	25.1	0.45	25.1	
8	25.2	0.45		
9	25.1	0.45		
10	25.0	0.45		
11	25.2	0.45		
12	25.1	0.45		
13	23.8	0.80	22.0	
14	22.9	0.80		
15	21.4	0.80		
16	21.2	0.80		
17	21.4	0.80		
18	21.3	0.80		

Avg	26.5
St. Dev.	4.3

Appendix J – Charpy V-Notch Toughness Testing

Appendix J contains the following material related to Charpy V-notch testing:

- Photographs of the fractured cross-sections.
- Test reports from Massachusetts Material Testing.

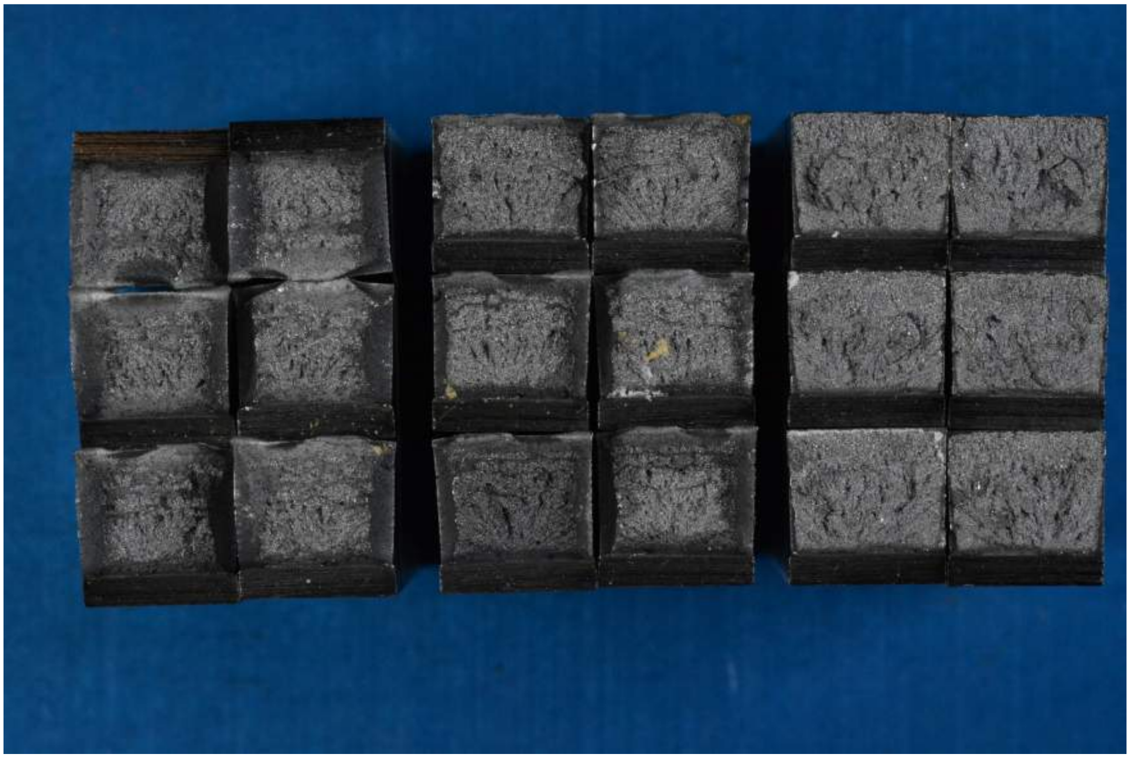


Figure J-1 - Full-Sized Charpy fracture surfaces for Plain Threadbar®. From left to right, test temperature was 90°F, room temperature, and -30°F.

Figure J-2 - ¾-size Charpy fracture surfaces for Plain Threadbar®. From left to right, test temperature was 90°F, room temperature, and -30°F..

Figure J-3 - Full-Sized Charpy fracture surfaces for Galvanized Threadbar®. From left to right, test temperature was 90°F, room temperature, and -30°F.

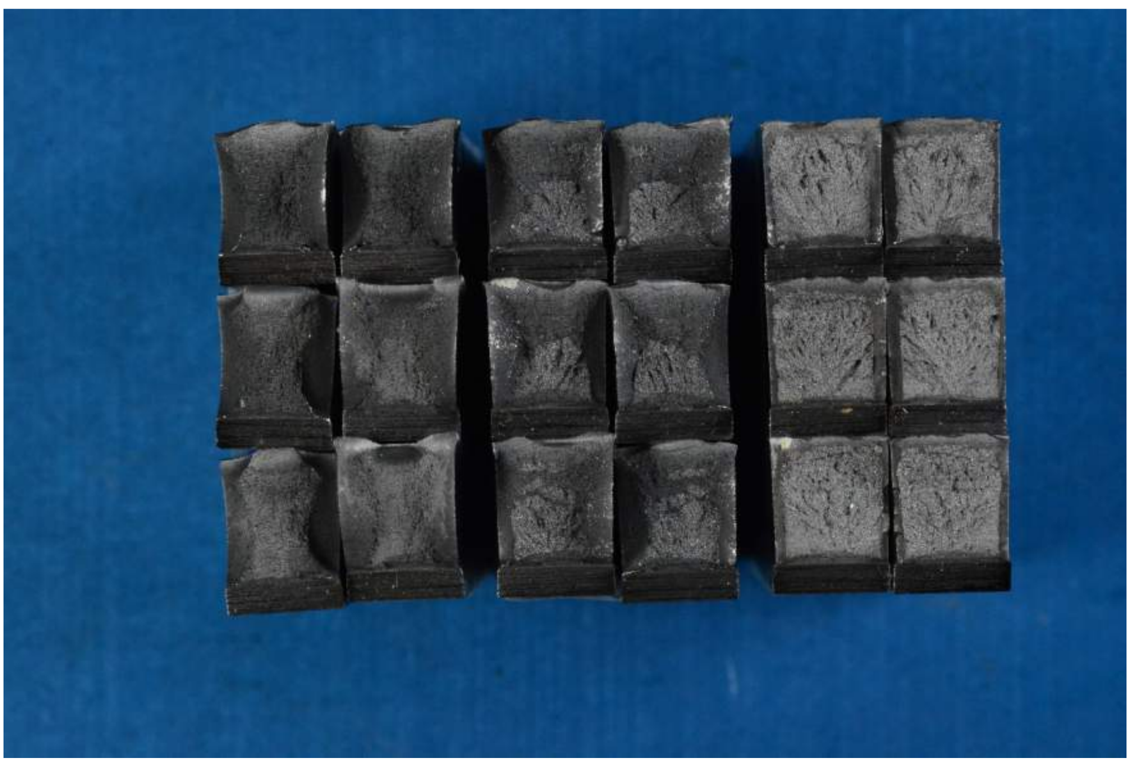


Figure J-4 - ¾-size Charpy fracture surfaces for Galvanized Threadbar®. From left to right, test temperature was 90°F, room temperature, and -30°F.

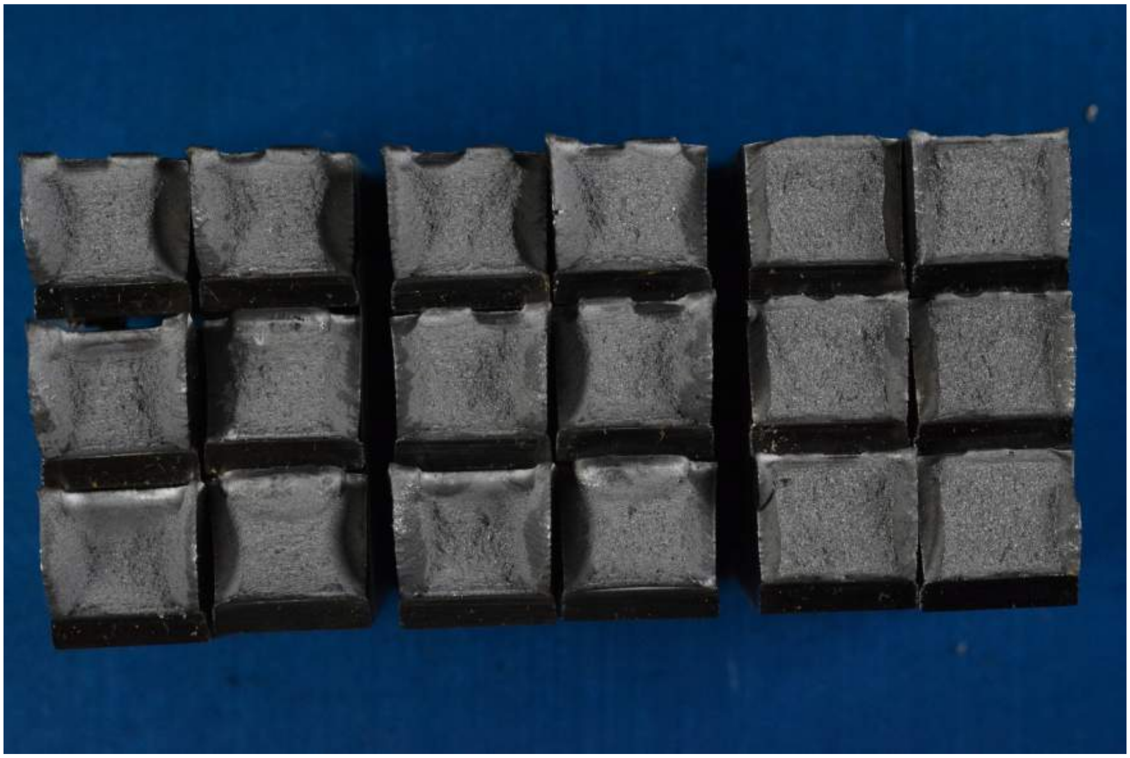


Figure J-5 - Full-Sized Charpy fracture surfaces for Custom 450 H1050. From left to right, test temperature was 90°F, room temperature, and -30°F.

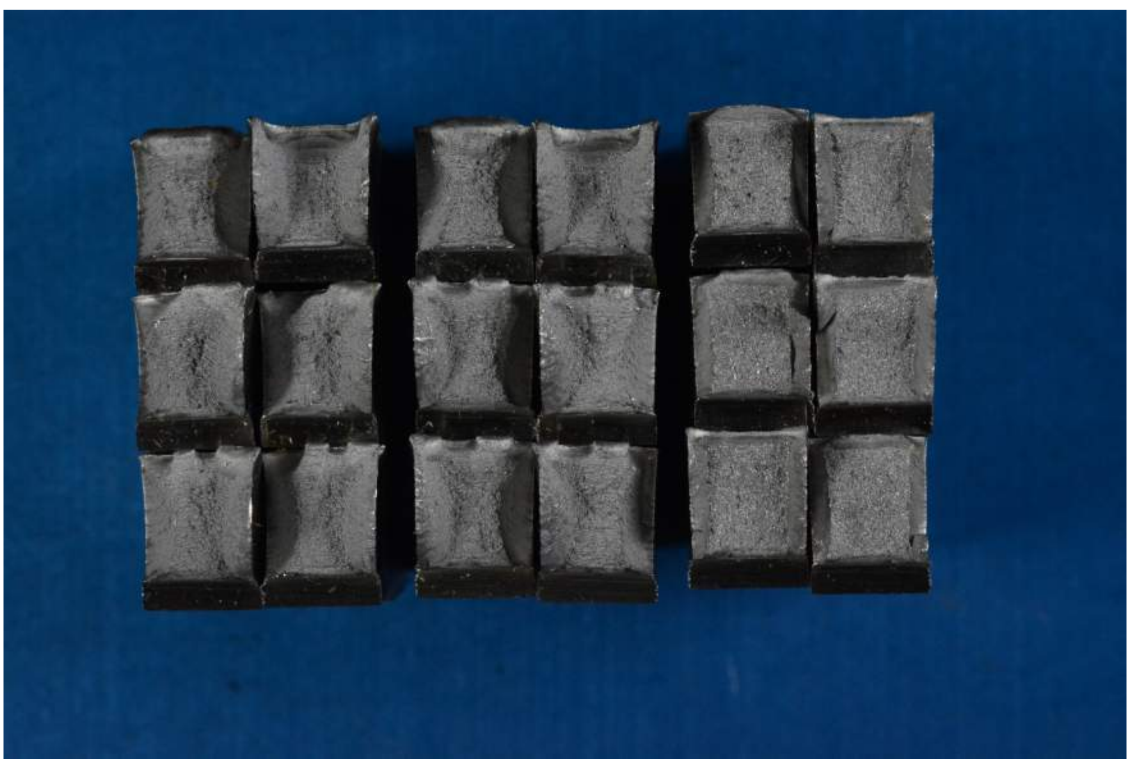


Figure J-6 - ¾-size Charpy fracture surfaces for Custom 450 H1050. From left to right, test temperature was 90°F, room temperature, and -30°F.

Figure J-7 - Full-Sized Charpy fracture surfaces for Custom 630 H1100. From left to right, test temperature was 90°F, room temperature, and -30°F.

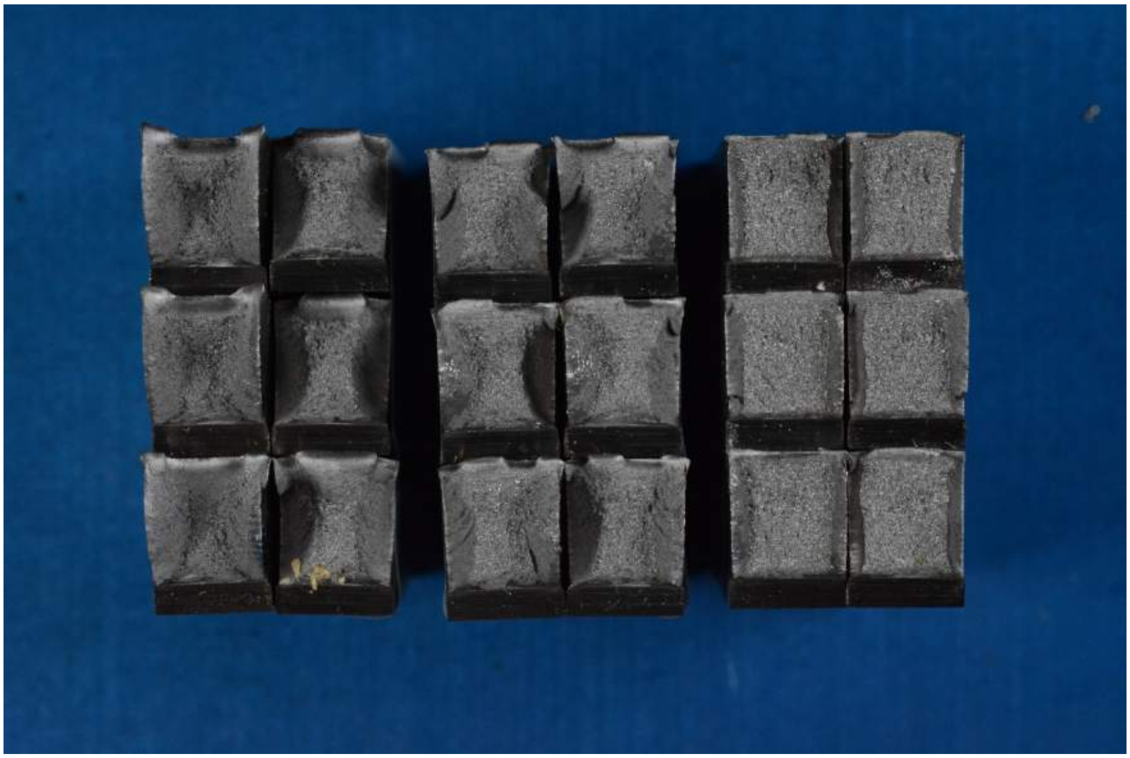


Figure J-8 - 3/4-Sized Charpy fracture surfaces for Custom 630 H1100. From left to right, test temperature was 90°F, room temperature, and -30°F.

Figure J-9 - Full-Sized Charpy fracture surfaces for Alloy 2507. From left to right, test temperature was 90°F, room temperature, and -30°F.

Figure J-10 - 3/4-Sized Charpy fracture surfaces for Alloy 2507. From left to right, test temperature was 90°F, room temperature, and -30°F.

MMR

A Subsidiary of THE MMR GROUP, INC.

Massachusetts Materials Research, Inc.

P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016

P.O. NO.: 14897

MMR NO.: 114564

MMR ID#: 1

SAMPLE IDENTIFICATION

Charpy Impact and Hardness testing of 2.25" threaded stock per Purchase Order instructions
ID#1: Plain

SUMMARY OF TESTING

The bar was sectioned in order to remove both full size and 3/4 size charpy impact specimens at a depth of .5" below the surface. We tested both sized specimens at three different temperatures for a total of six sets of tests. In addition, we made a Brinell hardness measurement at approximately mid-radius on a full diameter slice of the bar.

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	30.5
2	30.5
3	30.5
Average	30.5

(Test Temperature, Room - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	18.0
2	23.0
3	24.5
Average	22.0

(Test Temperature, -30°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	15.5
2	15.0
3	15.5
Average	15.5

MASSACHUSETTS MATERIALS RESEARCH, INC.

Thomas W. Baxter
Manager of Testing Services

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 1

SAMPLE IDENTIFICATION

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	29.5
2	28.5
3	29.5
Average	29.0

(Test Temperature, Room - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	25.5
2	23.5
3	25.5
Average	24.5

(Test Temperature, -30°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	11.5
2	11.5
3	11.5
Average	11.5

BRINELL HARDNESS - 363 HBW 10/3000

MASSACHUSETTS MATERIALS RESEARCH, INC.

Thomas W. Baxter
Manager of Testing Services

A Subsidiary of THE MMR GROUP, INC.

Massachusetts Materials Research, Inc.

P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 2

SAMPLE IDENTIFICATION Charpy Impact and Hardness testing of 2.25" threaded stock per Purchase Order instructions
ID#2: Galvanized

SUMMARY OF TESTING

The bar was sectioned in order to remove both full size and 3/4 size charpy impact specimens at a depth of .5" below the surface. We tested both sized specimens at three different temperatures for a total of six sets of tests. In addition, we made a Brinell hardness measurement at approximately mid-radius on a full diameter slice of the bar.

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	45.5
2	44.5
3	44.0
Average	44.5

(Test Temperature, Room - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	35.0
2	35.5
3	37.5
Average	36.0

(Test Temperature, -30°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	18.5
2	18.0
3	17.5
Average	18.0

MASSACHUSETTS MATERIALS RESEARCH, INC.

Thomas W. Baxter
Manager of Testing Services

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 2

SAMPLE IDENTIFICATION

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	33.0
2	32.5
3	33.5
Average	33.0

(Test Temperature, Room - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	22.5
2	24.5
3	23.0
Average	23.5

(Test Temperature, -30°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	12.5
2	12.5
3	13.0
Average	12.5

BRINELL HARDNESS - 341 HBW 10/3000

MASSACHUSETTS MATERIALS RESEARCH, INC.

Thomas W. Baxter
Manager of Testing Services

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 3

SAMPLE IDENTIFICATION
Charpy Impact and Hardness testing of 2.25" threaded stock per Purchase Order instructions
ID#3: Custom 450 - Blue

AMENDED REPORT DATE: 12/29/2016

SUMMARY OF TESTING
The bar was sectioned in order to remove both full size and 3/4 size charpy impact specimens at a depth of .5" below the surface. We tested both sized specimens at three different temperatures for a total of six sets of tests. In addition, we made a Brinell hardness measurement at approximately mid-radius on a full diameter slice of the bar.

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	58.5
2	60.5
3	58.0
Average	59.0

(Test Temperature, Room - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	55.5
2	51.5
3	52.0
Average	53.0

(Test Temperature, -30°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	25.0
2	28.5
3	26.0
Average	26.5

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

A Subsidiary of THE MMR GROUP, INC.

Massachusetts Materials Research, Inc.

P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016

P.O. NO.: 14897

MMR NO.: 114564

MMR ID#: 3

AMENDED REPORT
DATE: 12/29/2016

SAMPLE IDENTIFICATION

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	44.5
2	45.5
3	47.5
Average	46.0

(Test Temperature, Room - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	39.0
2	39.5
3	40.0
Average	39.5

(Test Temperature, -30°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	20.0
2	20.5
3	20.5
Average	20.5

BRINELL HARDNESS - 375 HBW 10/3000

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

Chemical analysis performed by Inductively Coupled Plasma/Optical Emission Spectrometer. Carbon, sulfur, nitrogen, hydrogen and oxygen performed by Leco Combustion. Mechanical and metallurgical testing performed per MMR Procedures.

A Subsidiary of THE MMR GROUP, INC.

Massachusetts Materials Research, Inc.

P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016

P.O. NO.: 14897

MMR NO.: 114564

MMR ID#: 3

ADDITION TO REPORT
DATE: 12/29/2016

SAMPLE IDENTIFICATION 2.25" threaded stock - Blue

CHEMISTRY

Element	Composition (%)
Carbon	.042
Columbium	.59
Chromium	14.58
Copper	1.46
Manganese	.41
Molybdenum	.74
Nickel	6.44
Phosphorus	.013
Sulfur	<.001
Silicon	.59
Aluminum	.01
Cobalt	.18
Vanadium	.09

According to the above test results, this sample conforms to the chemical requirements of UNS S45000.

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

The recording of false, fictitious or fraudulent statements or entries on the certificate may be punishable as a felony under federal law.

Chemical analysis performed by Inductively Coupled Plasma/Optical Emission Spectrometer. Carbon, sulfur, nitrogen, hydrogen and oxygen performed by Leco Combustion. Mechanical and metallurgical testing performed per MMR Procedures.

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 4
PAGE #: 1 of 3

SAMPLE IDENTIFICATION Charpy Impact and Hardness testing of 2.25" threaded stock per Purchase Order instructions
ID#4: Alloy 2507 - Green

AMENDED REPORT
DATE: 12/29/2016

SUMMARY OF TESTING

The bar was sectioned in order to remove both full size and 3/4 size charpy impact specimens at a depth of .5" below the surface. We tested both sized specimens at three different temperatures for a total of six sets of tests. In addition, we made a Brinell hardness measurement at approximately mid-radius on a full diameter slice of the bar.

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	264.0
2	264.0
3	264.0
Average	264.0

(Test Temperature, Room - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	263.5
2	264.0
3	264.0
Average	264.0

(Test Temperature, -30°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	257.5
2	260.5
3	263.5
Average	260.5

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016

P.O. NO.: 14897

MMR NO.: 114564

MMR ID#: 4

AMENDED REPORT
DATE: 12/29/2016

SAMPLE IDENTIFICATION

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	225.0
2	224.5
3	243.0
Average	231.0

(Test Temperature, Room - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	206.5
2	219.5
3	236.5
Average	221.0

(Test Temperature, -30°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	209.0
2	202.5
3	192.0
Average	201.0

BRINELL HARDNESS - 262 HBW 10/3000

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

Chemical analysis performed by Inductively Coupled Plasma/Optical Emission Spectrometer. Carbon, sulfur, nitrogen, hydrogen and oxygen performed by Leco Combustion. Mechanical and metallurgical testing performed per MMR Procedures.

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 4

SAMPLE IDENTIFICATION 2.25" threaded stock - Green

ADDITION TO REPORT
DATE: 12/29/2016

CHEMISTRY

Element	Composition (%)
Carbon	.015
Chromium	24.8
Maganese	.76
Molybdenum	4.14
Nickel	7.0
Phosphorus	.027
Sulfur	<.001
Silicon	.44
Aluminum	.07
Cobalt	.08
Copper	.15
Vanadium	.08
Tungsten	.01

According to the above test results, this sample conforms to the chemcal requirements of UNS S32750.

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

Chemical analysis performed by Inductively Coupled Plasma/Optical Emission Spectrometer. Carbon, sulfur, nitrogen, hydrogen and oxygen performed by Leco Combustion. Mechanical and metallurgical testing performed per MMR Procedures.

A Subsidiary of THE MMR GROUP, INC.
Massachusetts Materials Research, Inc.
P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 5

SAMPLE IDENTIFICATION
Charpy Impact and Hardness testing of 2.25" threaded stock per Purchase Order instructions
ID#5: Custom 630 - Yellow

AMENDED REPORT DATE: 12/29/2016

SUMMARY OF TESTING
The bar was sectioned in order to remove both full size and 3/4 size charpy impact specimens at a depth of .5" below the surface. We tested both sized specimens at three different temperatures for a total of six sets of tests. In addition, we made a Brinell hardness measurement at approximately mid-radius on a full diameter slice of the bar.

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	58.1
2	52.0
3	54.0
Average	54.5

(Test Temperature, Room - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	49.5
2	43.0
3	44.5
Average	45.5

(Test Temperature, -30°F - Full Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	23.5
2	25.0
3	22.0
Average	23.5

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

A Subsidiary of THE MMR GROUP, INC.

Massachusetts Materials Research, Inc.

P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION: Alan Humphreys

DATE: December 22, 2016

P.O. NO.: 14897

MMR NO.: 114564

MMR ID#: 5

AMENDED REPORT
DATE: 12/29/2016

SAMPLE IDENTIFICATION

CHARPY IMPACT (ASTM E23-12c)

(Test Temperature, 90°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	37.0
2	37.0
3	39.0
Average	37.5

(Test Temperature, Room - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	35.0
2	33.5
3	36.5
Average	35.0

(Test Temperature, -30°F - 3/4 Size Specimens)

Sample I.D.	Energy of Rupture (Ft/lbs)
1	17.0
2	17.0
3	12.5
Average	15.5

BRINELL HARDNESS - 352 HBW 10/3000

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

A Subsidiary of THE MMR GROUP, INC.

Massachusetts Materials Research, Inc.

P.O. BOX 810 • 1500 CENTURY DRIVE • WEST BOYLSTON, MA 01583 • TEL. 508-835-6262 • FAX 508-835-9025

ANALYTICAL REPORT

Simpson Gumpertz & Heger
41 Seyon Street
Building 1, Suite 500
Waltham, MA 02453

ATTENTION:
Alan Humphreys

DATE: December 22, 2016
P.O. NO.: 14897
MMR NO.: 114564
MMR ID#: 5

SAMPLE IDENTIFICATION

2.25" threaded stock - Yellow

ADDITION TO REPORT
DATE: 12/29/2016

CHEMISTRY

Element	Composition (%)
Carbon	.035
Columbium	.23
Chromium	15.3
Copper	3.98
Manganese	.72
Molybdenum	.14
Nickel	4.28
Phosphorus	.016
Sulfur	.027
Silicon	.34
Cobalt	.08
Vanadium	.06
Tungsten	.01

According to the above test results, this sample conforms to the chemical requirements of UNS S17400.

MASSACHUSETTS MATERIALS RESEARCH, INC.

Derek Thibault
Quality Assurance Manager

Chemical analysis performed by Inductively Coupled Plasma/Optical Emission Spectrometer. Carbon, sulfur, nitrogen, hydrogen and oxygen performed by Leco Combustion. Mechanical and metallurgical testing performed per MMR Procedures.

Appendix K – Galling Testing

Appendix K contains the following material related to galling testing:

- Tabulated individual test results for each specimen.

Dywidag Plain					
Load (lb)	406	296	254	202	154
Stress (ksi)	2.1	1.5	1.3	1.0	0.8
Result	Gall	Gall	Gall	Marginal	No Gall
				Threshold Galling Stress (ksi)	**0.91**

Dywidag Galvanized					
Load (lb)	254	204	157		
Stress (ksi)	1.3	1.0	0.8		
Result	Gall	Gall	No Gall		
				Threshold Galling Stress (ksi)	**0.92**

Custom 450					
Load (lb)	145	122	109	106	78
Stress (ksi)	0.7	0.6	0.6	0.5	0.4
Result	Gall	Gall	Gall	No Gall	No Gall
				Threshold Galling Stress (ksi)	**0.55**

Custom 630					
Load (lb)	176	108	102	81	
Stress (ksi)	0.9	0.6	0.5	0.4	
Result	Gall	Gall	No Gall	No Gall	
				Threshold Galling Stress (ksi)	**0.54**

Alloy 2507					
Load (lb)	198	154	146	122	103
Stress (ksi)	1.0	0.8	0.7	0.6	0.5
Result	Gall	Gall	Gall	No Gall	No Gall
				Threshold Galling Stress (ksi)	**0.68**

Appendix L – Pitting Corrosion Testing

Appendix L contains the following material related to pitting corrosion testing:

- Tabulated test results for each candidate material.

SIMPSON GUMPERTZ & HEGER

Engineering of Structures
and Building Enclosures

SHEET NO. __________

PROJECT NO. 141685.12

DATE 9 January 2017

CLIENT Alfred Benesch & Company

BY AOHumphreys

SUBJECT Pitting Corrosion Testing

CHECKED BY __________

Test Temperature (°C)	Test Temperature (°F)	Threadbar® Plain	Custom 450 H1050	Custom 630 H1100	Alloy 2507
0	32	General corrosion	No pitting	Pitting >1mil	-
5	41	General corrosion	Minor Pitting <1mil	Pitting >1mil	-
10	50	General corrosion	Pitting >1mil	Pitting >1mil	-
15	59	General corrosion	Pitting >1mil	Pitting >1mil	-
20	68	General corrosion	Pitting >1mil	Pitting >1mil	No Pitting
30	86	-	-	-	No Pitting
40	104	-	-	-	No Pitting
50	122	-	-	-	No Pitting
60	140	-	-	-	No Pitting
70	158	-	-	-	No Pitting
80	176	-	-	-	Minor Pitting <1mil
85	185	-	-	-	Pitting >1mil

Test Procedure (ASTM G48):
1 - Initial testing was conducted at 20°C (68°F).
2a - Materials that pitted were tested at decreasing 5°C (9°F) intervals until they did not pit or the lowest test temperature of 0°C (32°F) was reached.
2b - Materials that did not pit were tested at increased 10°C (18°F) intervals until pitting was observed.

Appendix M – Stress Corrosion Cracking Testing

Appendix M contains the following material related to stress corrosion cracking testing:

- Test report from Corrosion Testing Laboratories, Inc.

Corrosion Testing Laboratories, Inc.

January 6, 2017 **CTL REF #33507**

Alan O. Humphreys, Ph.D.
Simpson Gumpertz & Heger
41 Seyan Street
Building 1, Suite 500
Waltham, MA 02453

Re: <u>Stress Corrosion Cracking of 4 Alloys per ASTM G123</u>

Dear Dr. Humphries:

Presented herein are the results of the above referenced testing. This work was authorized per Simpson, Gumpertz & Heger (SGH) Purchase Order Number 14896.

SGH submitted four materials for corrosion testing to determine their resistance to stress corrosion cracking in a chloride environment. Each material was supplied as 2.75-inch diameter threaded rods approximately 24-inches long. They were identified as:

- Carbon Steel, CTL Sample #33507-1
- Custom 450 Stainless Steel (SS) , CTL Sample #33507-2
- Custom 630 SS, CTL Sample #33507-3
- 2507 Duplex Stainless Steel (DSS) , CTL Sample #33507-4

ASTM G123, *Standard Test Method for Evaluating Stress-Corrosion Cracking of Stainless Alloys with Different Nickel Content in Boiling Acidified Sodium Chloride Solution*, makes use of U-bend test specimens. While U-bend specimens provide a highly stressed specimen, measurement of the applied stress is unreliable. SGH requested C-rings be used which can be stressed more accurately. SGH requested an applied stress of 85% actual yield strength (AYS) and an exposure time of 14 days.

TEST PROCEDURES

Test Specimens

Four C-ring test specimens were prepared form each material per ASTM G38, *Standard Practice for Making and Using C-ring Stress-Corrosion Test Specimens*. The finished C-rings measured approximately 62 mm in diameter by 21 mm wide with a 1.5 mm wall thickness. The C-rings were cleaned with soap and water followed by a solvent rinse. The C-rings were assembled using C-276 hardware and ceramic insulators in the constant strain configuration depicted in Figure 3 of ASTM

G38. SGH supplied the AYS values for each material, **Table 1**. The desired stress (85% AYS) was applied by compressing the C-ring. The final compressed diameter for each C-ring was calculated using the equation in Annex A1 of ASTM G38.

Figure 1. As-received material.

TABLE 1
Applied Stress (ksi)

Alloy	AYS	85% AYS
Carbon Steel	154	130.9
Custom 450 SS	158	134.3
Custom 630 SS	150	127.5
2507 DSS	95	80.8

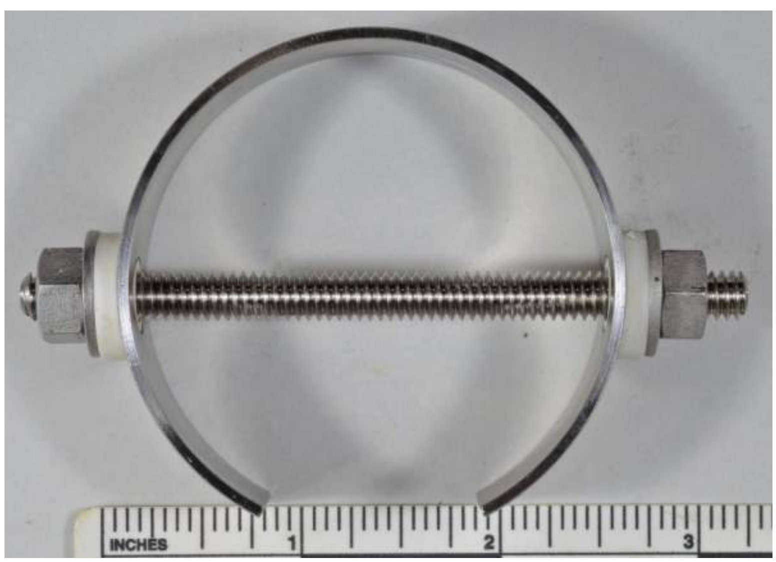


Figure 2. Typical C-ring assembly prior to stressing.

Test Solution
The acidified 25% sodium chloride solution was prepared using reagent grade sodium chloride and laboratory prepared de-ionized water (ASTM Grade IV). The prepared solution was acidified to a pH of 1.5 using reagent grade phosphoric acid.

Exposure
Each material was exposed in a separate test vessel. All four C-rings of the same material were exposed in the same test vessel. The test vessel consisted of a 2.5 Liter glass resin kettle that was filled with approximately 2-liters of solution. Each test vessel was fitted with a water-cooled condenser to minimize any evaporative losses. The test vessels were heated to boiling (approximately 109 to 110°C). Once the solution was boiling, the C-rings were immersed in the test solution.

Figure 3. Test Set-up

The C-rings were inspected every 6 hours during the first 24-hours of exposure, then daily afterwards. Once any cracks were observed, the cracked C-ring was removed from exposure.

RESULTS

Both the Custom 450 and Custom 630 SS C-rings failed within 12 hours of exposure. The carbon steel and 2507 DSS were still intact after 14 days of exposure.

Carbon Steel. The carbon steel specimens experienced general corrosion. At the end of the exposure, the C-rings were coated with a thin tenacious black deposit layer. These deposits were chemically removed using an inhibited acid solution. After cleaning, there was no visual indication of cracking on any of the C-rings, **Figure 4**.

Custom 450 SS. No cracks were observed after the initial 6-hour exposure period. At the twelve hour inspection, all four of the Custom 450 SS C-rings had experienced through wall cracking near the apex of the C-ring, **Figure 5**.

Custom 630 SS. No cracks were observed after the initial 6-hour exposure period. At the twelve hour inspection, all four of the Custom 630 SS C-rings had experienced shallow pitting and visible cracking, **Figure 6**. Crack depth on the edge of the specimens was approximately 70% of the wall thickness at the apex of the C-rings.

2507 DSS. No cracks were observed on any of the 2507 DSS C-rings during or after the 14-day exposure. After cleaning, the C-rings appeared unaffected by the exposure, **Figures 7**.

If you have any questions, please feel free to call.

Very truly yours,
Corrosion Testing Laboratories, Inc.

David L. Severance
Corrosion Technologist

Bradley D. Krantz
VP of Laboratory Services

Policy Statement

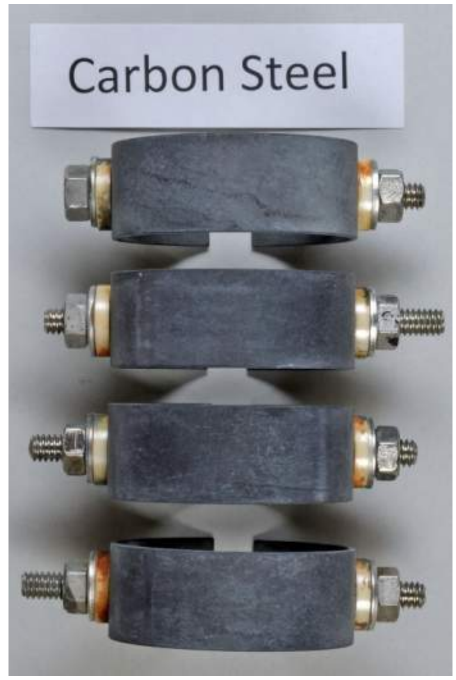
This study was performed and this report was prepared based upon specific samples and/or information provided to Corrosion Testing Laboratories, Inc. (CTL) by Simpson, Gumpertz and Heger. The information contained in this report represents only the materials tested or evaluated. Such work was performed in accordance with CTL's Quality Assurance Manual, Revision 13, issued 22 June 2009. The conclusions and opinions provided were developed within a reasonable degree of scientific certainty and are based upon materials and information provided to date. Should additional information become available (e.g., on further continued review of the material received or submission of additional samples for examination), we reserve the right to adjust our professional opinions.

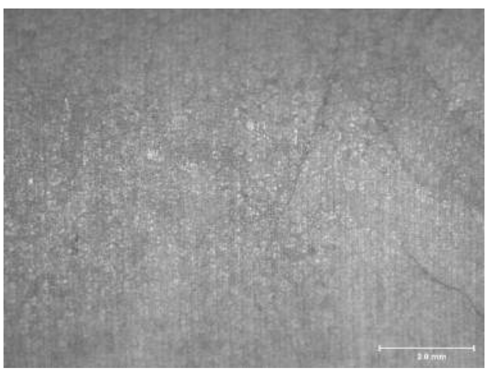
CTL assumes no responsibility for variations in sample or data quality (composition, appearance, performance, etc.) or any other feature of similar subject matter produced (measured, manufactured, fabricated, etc.) by persons or under conditions over which we have no control. This report may not be altered, added to or subtracted from and, if this does occur, CTL does not accept responsibility for such alterations, additions, or deletions. This report shall not be reproduced, except in full, without the written approval of CTL. All material that was received by CTL will be discarded six (6) months after this report has been issued, unless other arrangements have been agreed upon. All liquid, soil and gaseous samples that are received by CTL shall not be stored for more than thirty (30) days and shall be disposed of in accordance with applicable rules and regulations.

Simpson, Gumpertz, and Heger
January 6, 2017

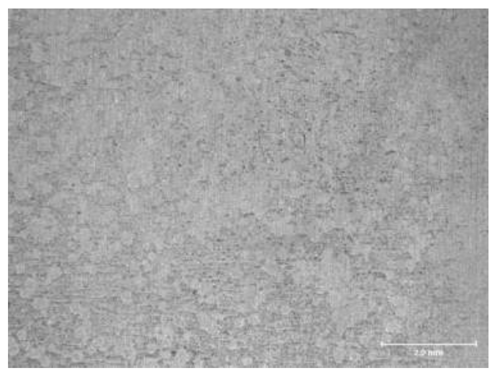
Pretest

Post Test

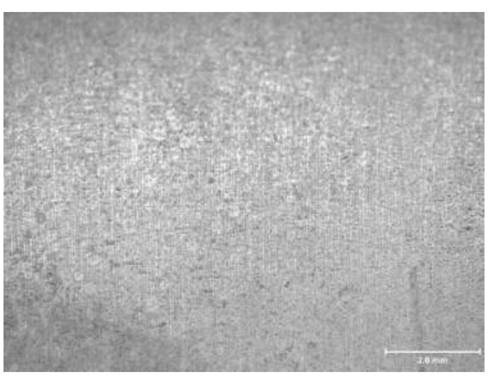




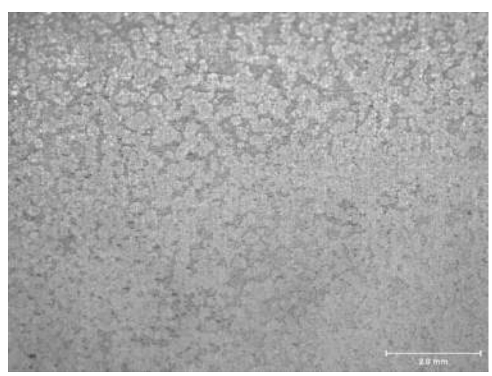
33507-1-1



33507-1-2



33507-1-3

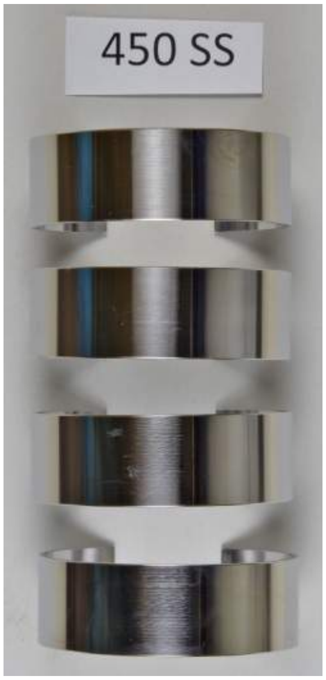


33507-1-4

Figure 4. Carbon Steel C-rings, Top: before and after exposure; Middle and bottom: Close-up (11X original magnification) of each C-ring after exposure for 14 Days per ASTM G123.

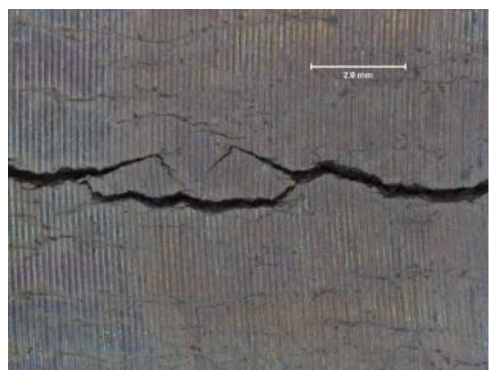
Simpson, Gumpertz, and Heger
January 6, 2017

Pretest



Post Test

33507-2-1



33507-2-2

33507-2-3

33507-2-4

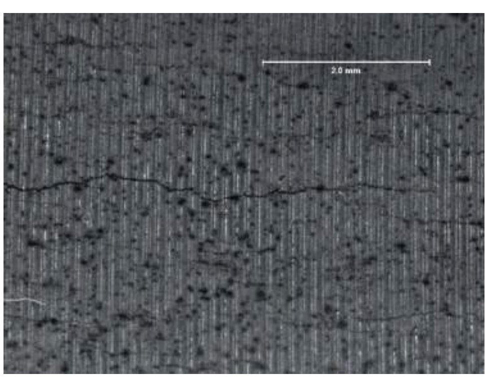
Figure 5. Custom 450 SS C-rings, Top: before and after exposure; Middle and Bottom: Observed cracks (11X original magnification) on each C-ring after exposure for 12 hours per ASTM G123.

Pretest

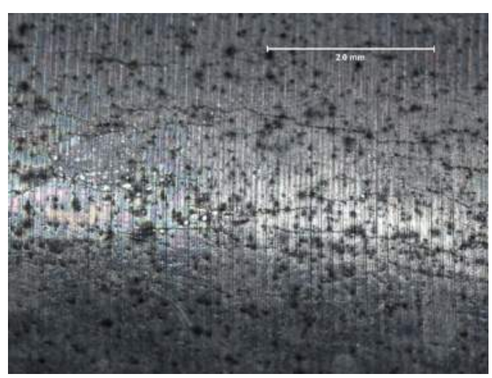
Post Test

33507-3-1

33507-3-2



33507-3-3

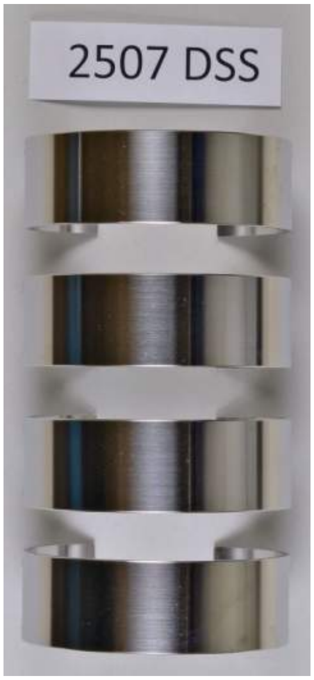


33507-3-4

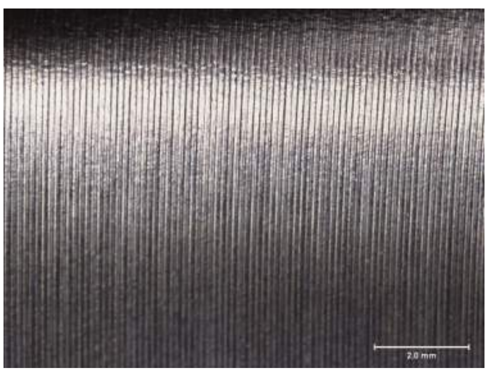
Figure 6. Custom 630 SS C-rings, Top: before and after exposure; Middle and Bottom: Observed cracks (20X original magnification) on each C-ring after exposure for 12 hours per ASTM G123.

Simpson, Gumpertz, and Heger
January 6, 2017

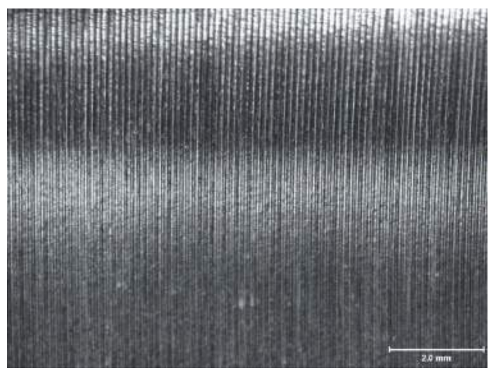
Pretest



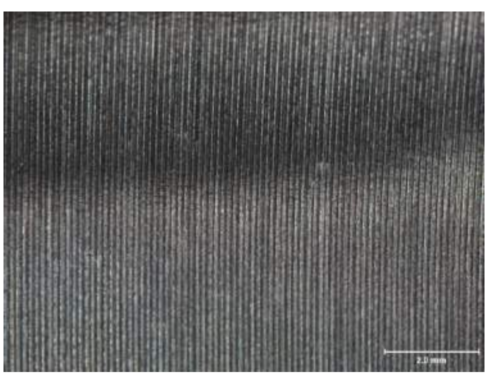
Post Test



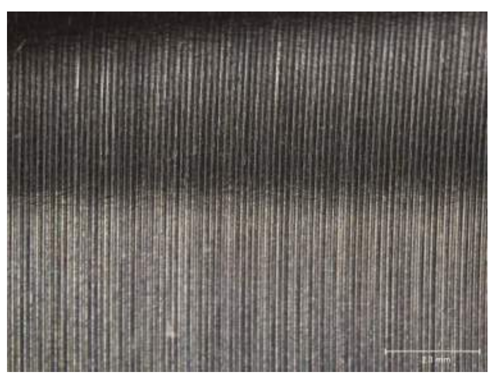
33507-4-1



33507-4-2



33507-4-3



33507-4-4

Figure 7. 2507 DSS C-rings, Top: before and after exposure; Middle and Bottom: close-up (11X original magnification) on each C-ring after exposure for 14 days per ASTM G123.

Appendix N – Hydrogen Embrittlement Testing

Appendix N contains the following material related to hydrogen embrittlement testing:

- Load vs. time curves for each material showing fast fracture and rising step load tests.
- Photographs of the bend specimen fast fracture strength (FFS) and rising step load (RSL) fracture surfaces.
- Scanning electron microscope images of the bend specimen fracture surfaces.

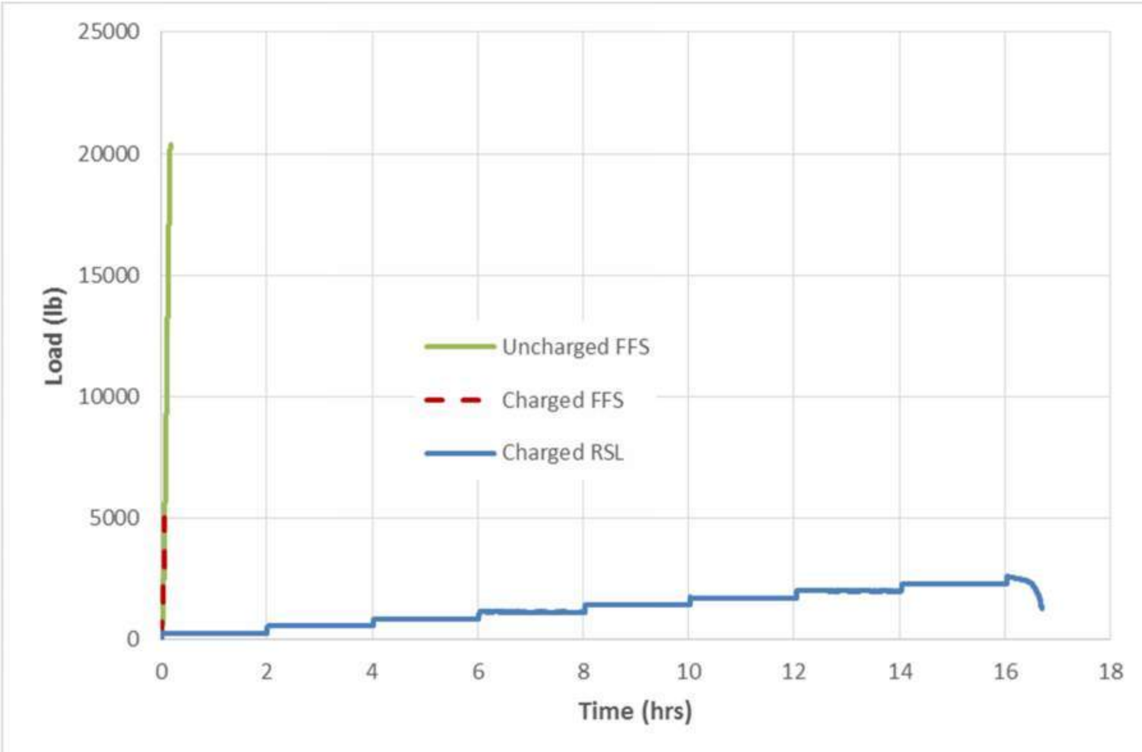


Figure N-1 – Threadbar® Plain load-time plot for hydrogen embrittlement testing.

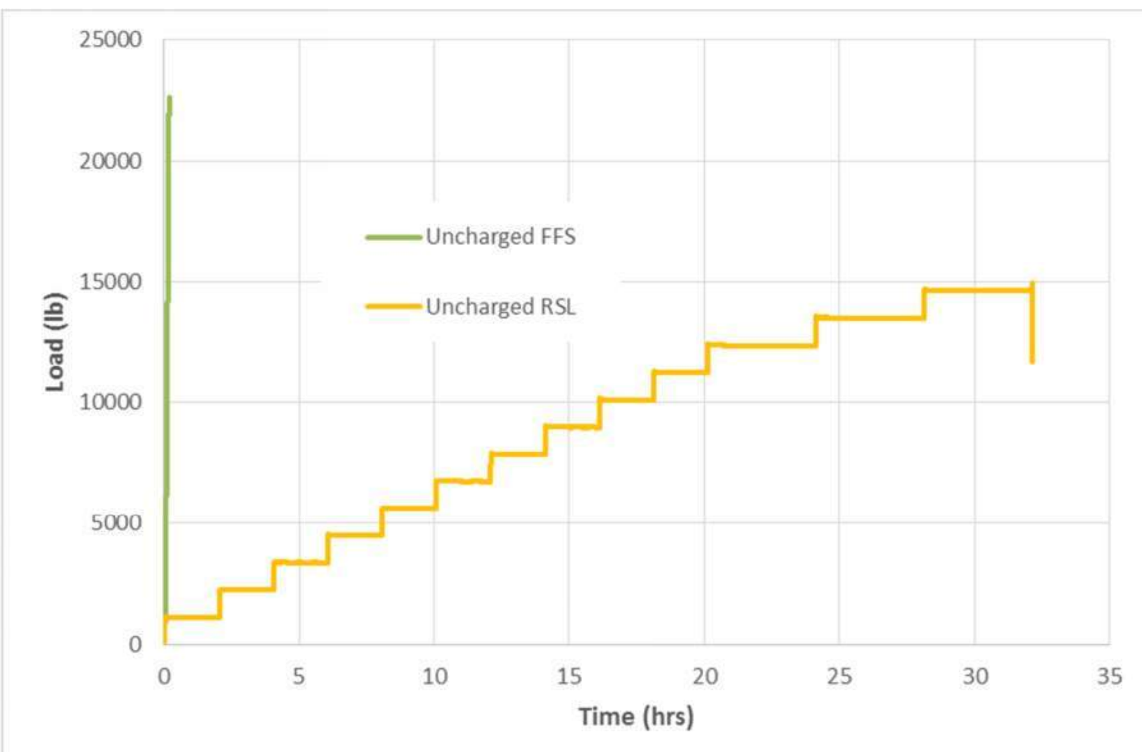


Figure N-2 – Threadbar® Galvanized load-time plot for hydrogen embrittlement testing.

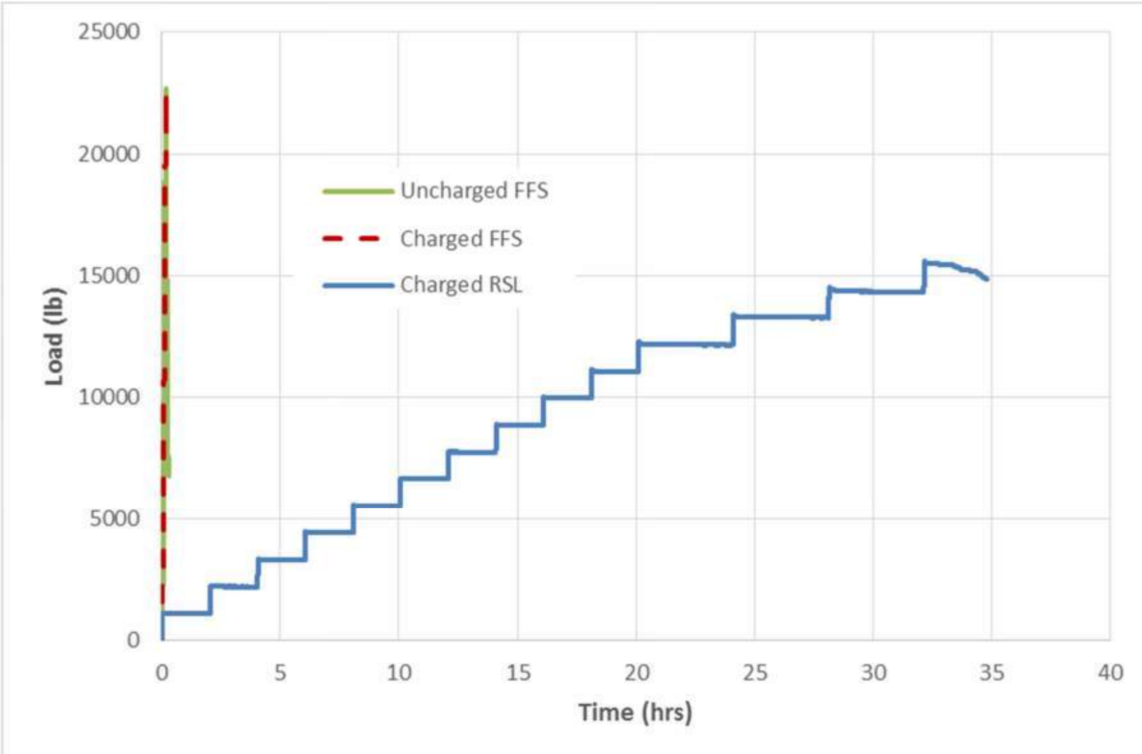


Figure N-3 – Custom 450 H1050 load-time plot for hydrogen embrittlement testing.

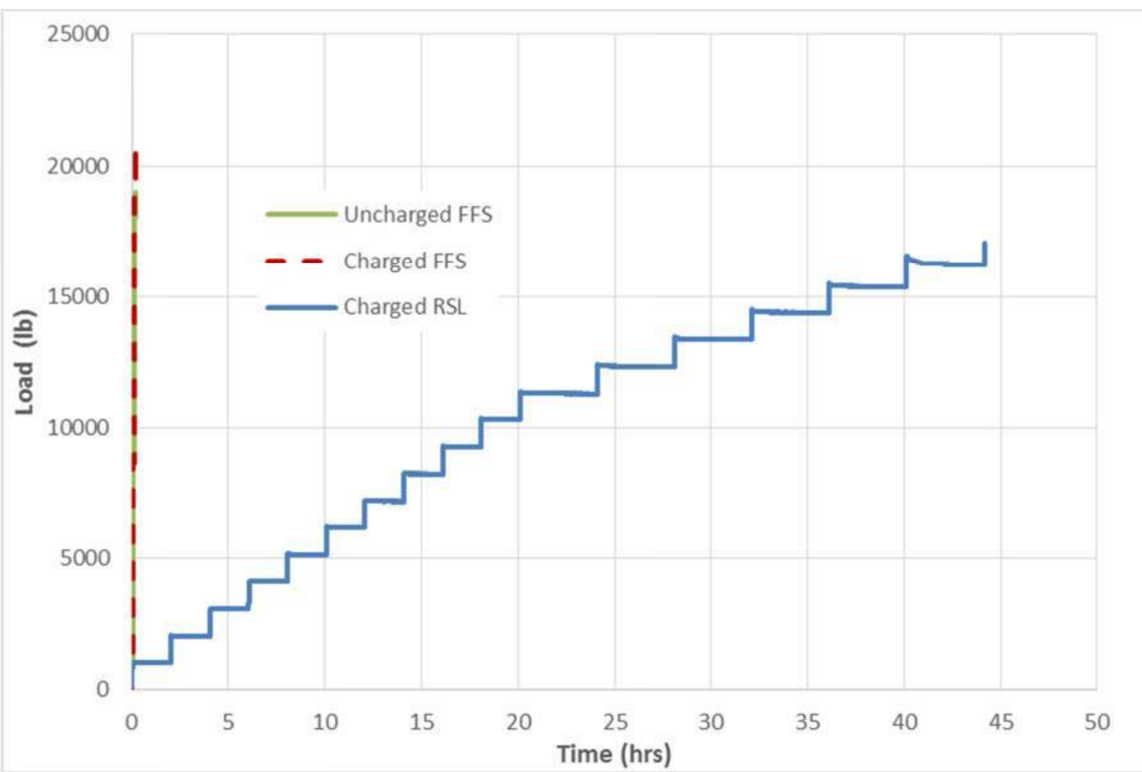


Figure N-4 – Custom 630 H1100 load-time plot for hydrogen embrittlement testing.

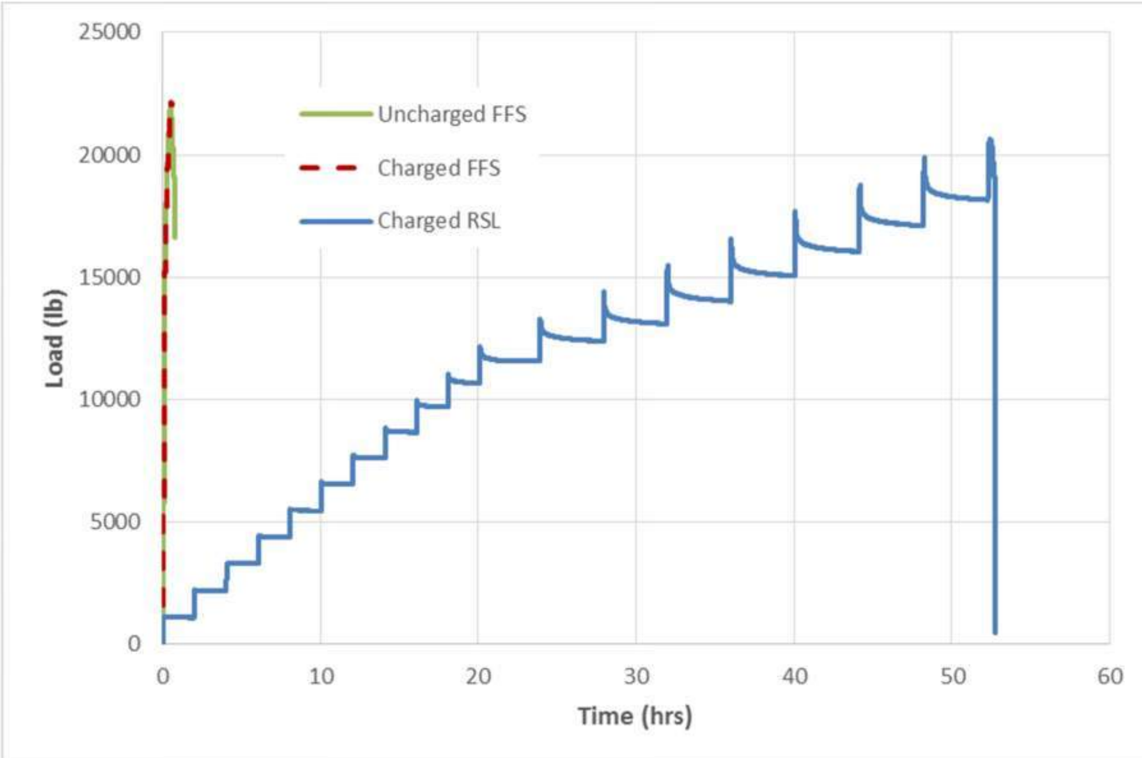


Figure N-5 – Alloy 2507 load-time plot for hydrogen embrittlement testing

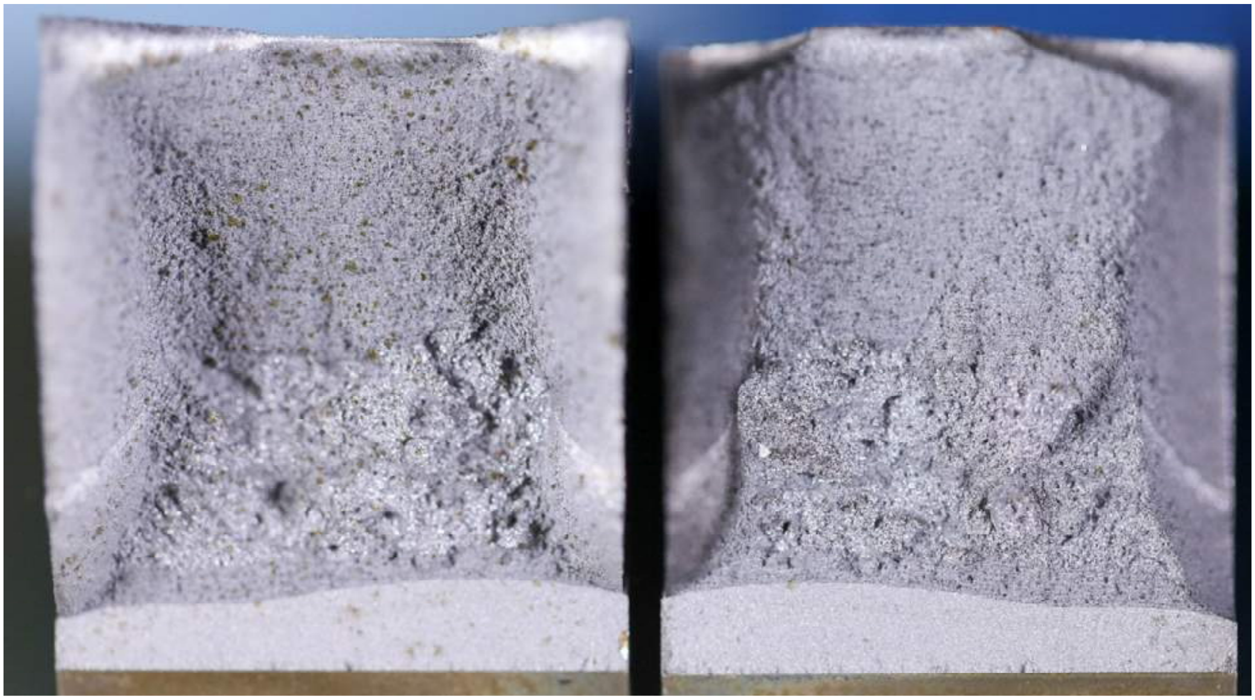


Figure N-6 – Threadbar® Plain uncharged FFS fracture surfaces.

Figure N-7 – Threadbar® Plain charged FFS fracture surfaces.

Figure N-8 – Threadbar® Plain charged RSL fracture surfaces.

Figure N-9 – Threadbar® Galvanized uncharged FFS fracture surfaces.

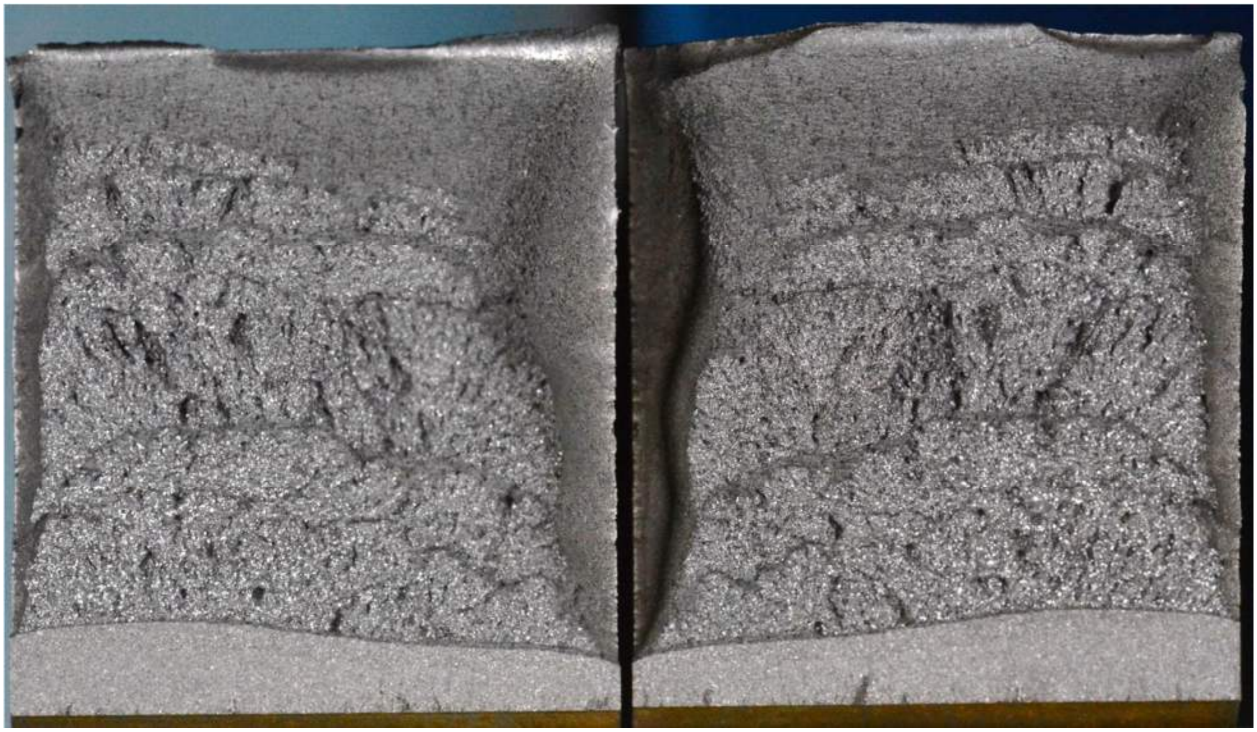


Figure N-10 – Threadbar® Galvanized uncharged RSL fracture surfaces.

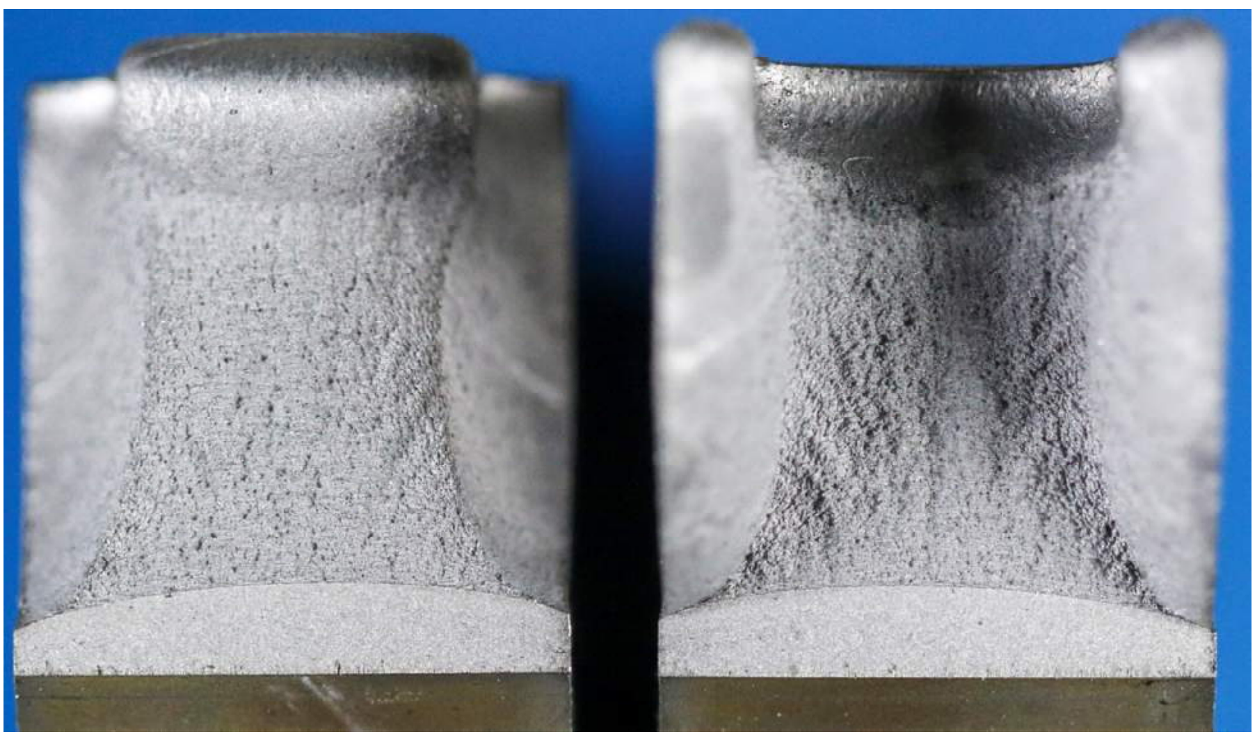


Figure N-11 – Custom 450 H1050 uncharged FFS fracture surfaces.

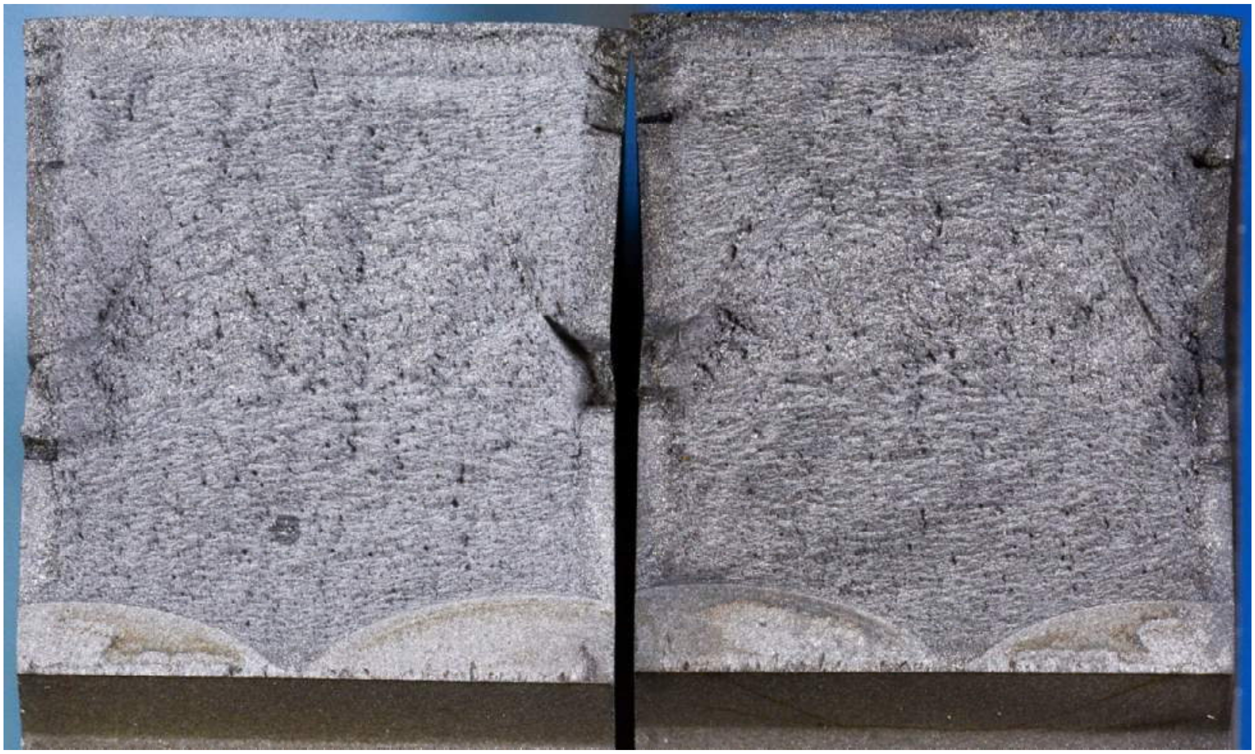


Figure N-12 – Custom 450 H1050 charged FFS fracture surfaces.

Figure N-13 – Custom 450 H1050 charged RSL fracture surfaces.

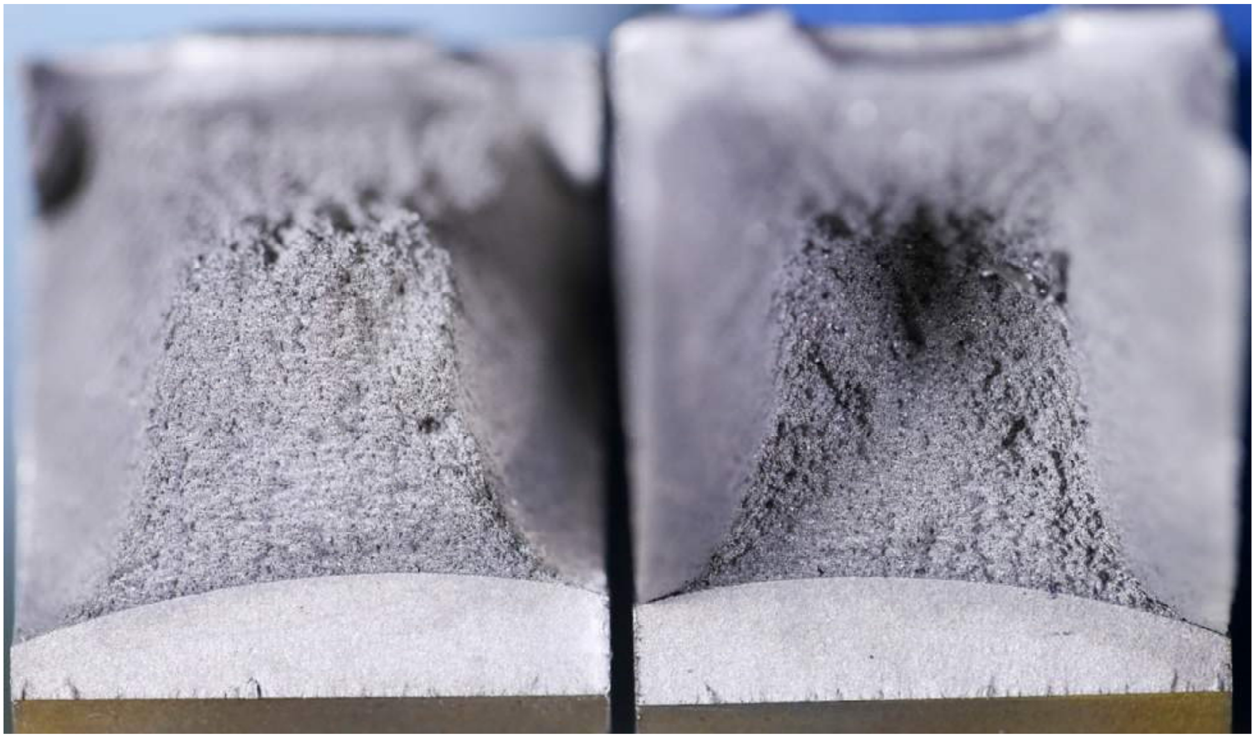


Figure N-14 – Custom 630 H1100 uncharged FFS fracture surfaces.

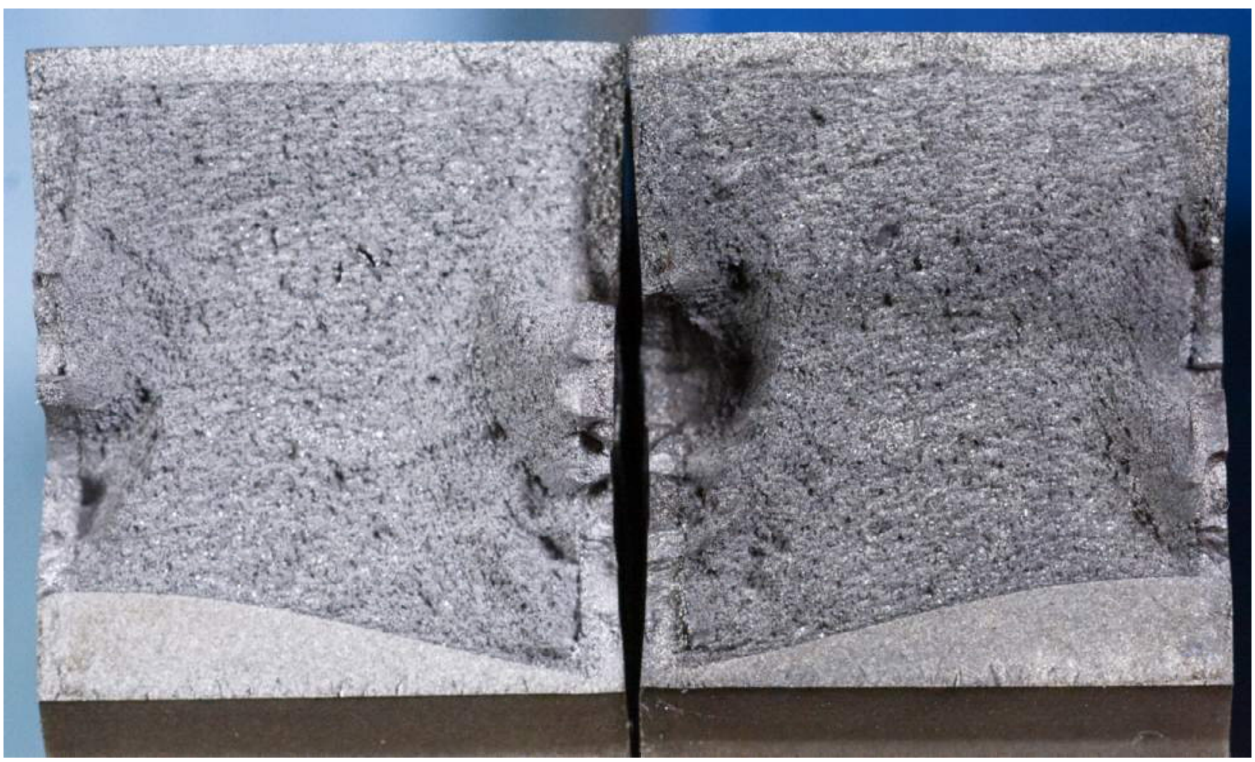


Figure N-15 – Custom 630 H1100 charged FFS fracture surfaces.

Figure N-16 – Custom 630 H1100 charged RSL fracture surface.

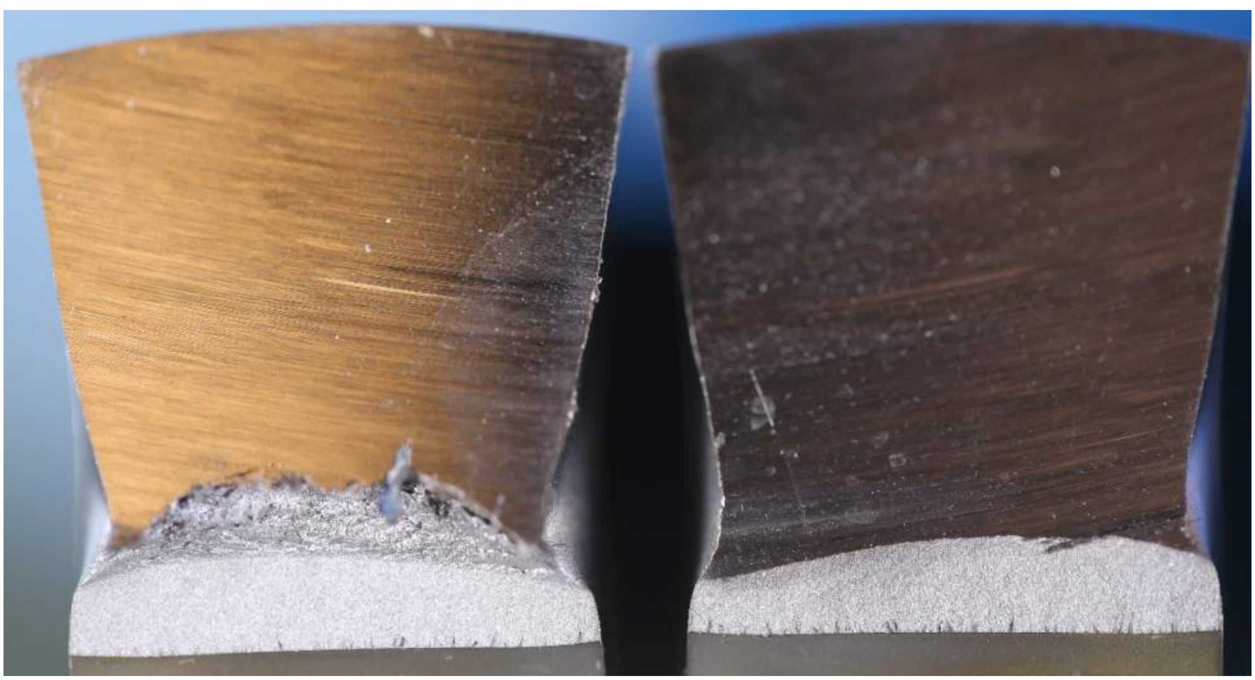


Figure N-17 – Alloy 2507 uncharged FFS fracture surfaces.

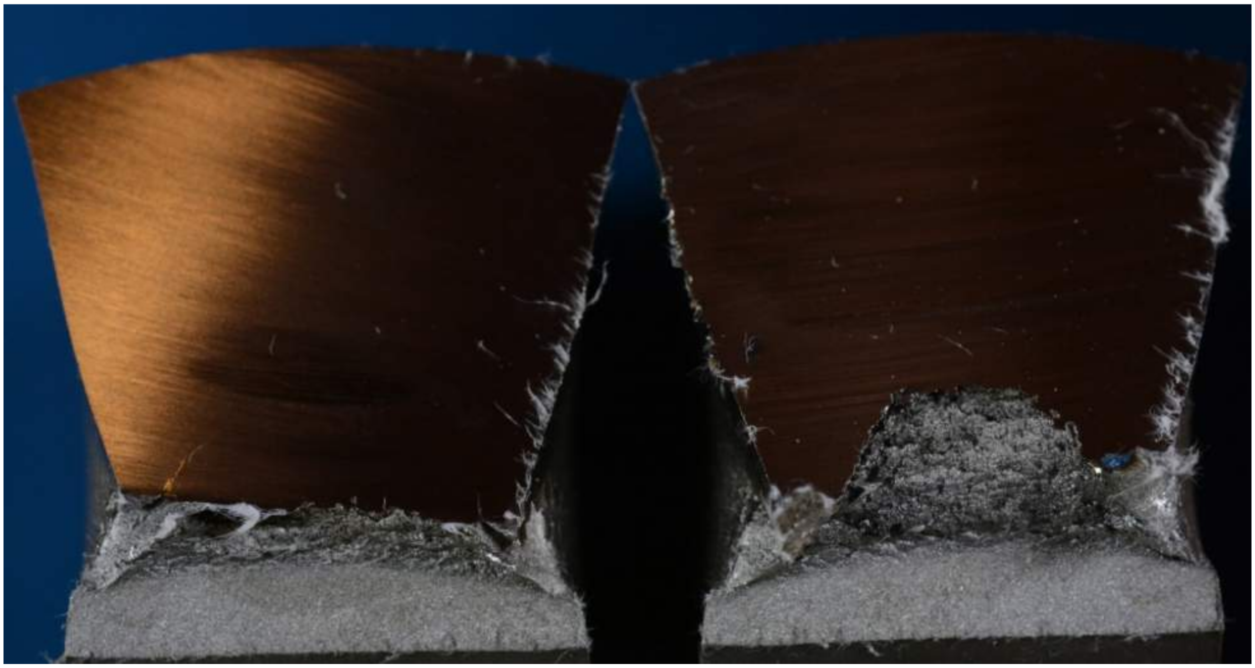


Figure N-18 – Alloy 2507 charged FFS fracture surfaces.

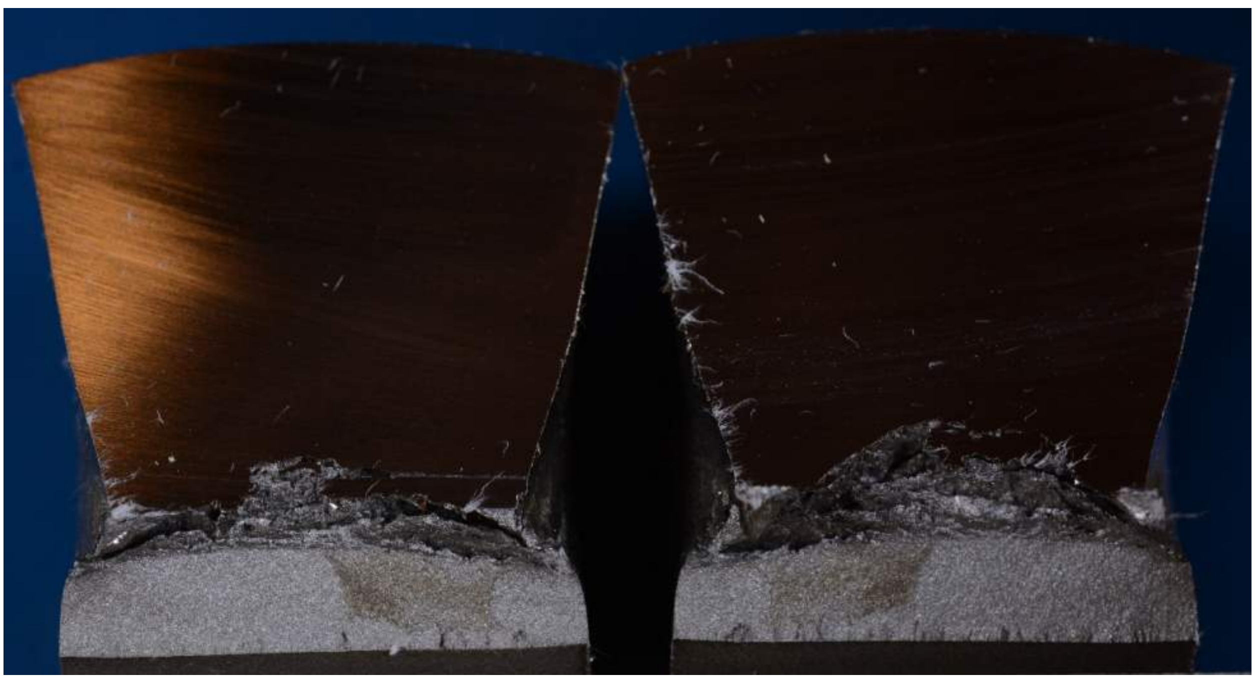


Figure N-19 – Alloy 2507 charged RSL fracture surfaces.

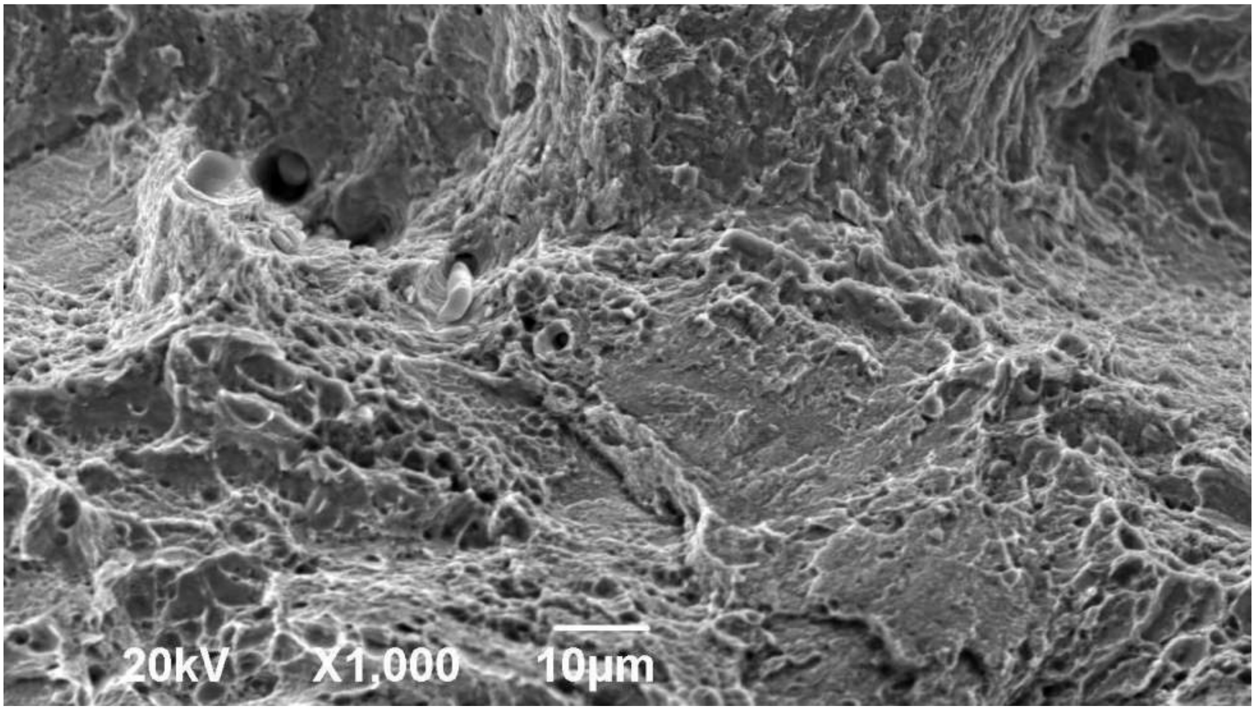


Figure N-20 – Representative region of fracture surface adjacent to end of precrack for Threadbar Plain, uncharged and FFS tested.

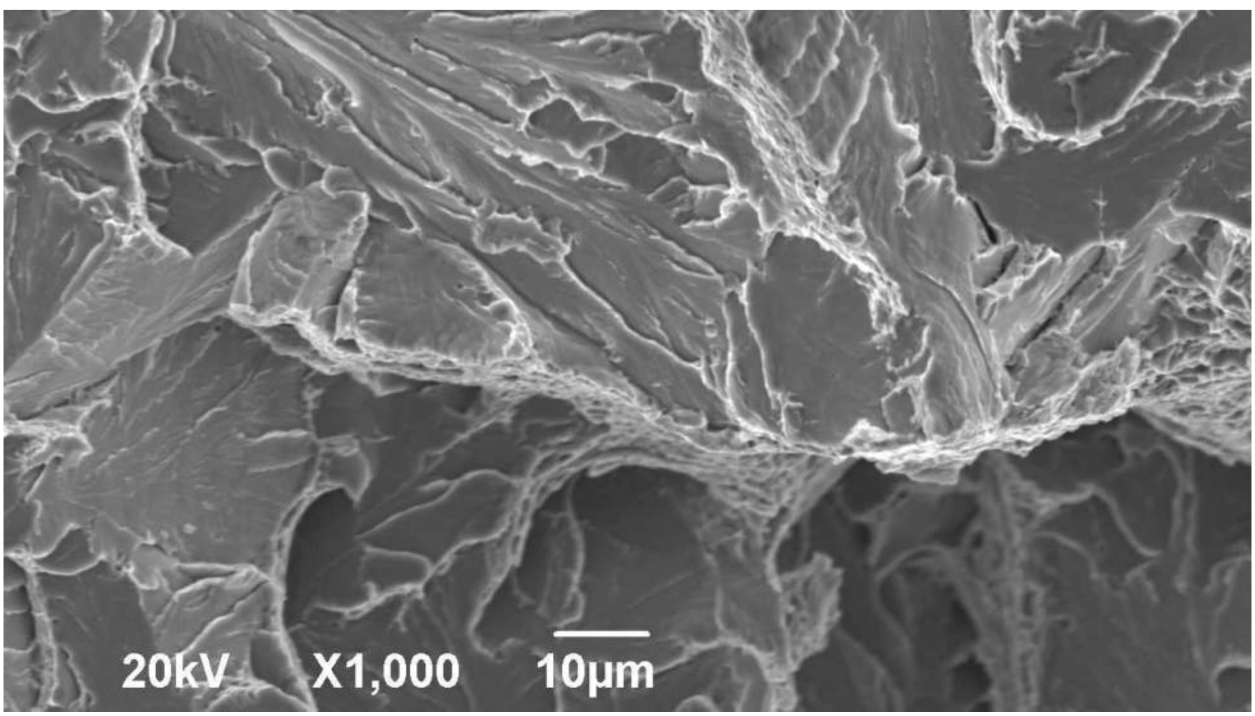


Figure N-21 – Representative region of fracture surface adjacent to end of precrack for Threadbar Plain, charged and FFS tested.

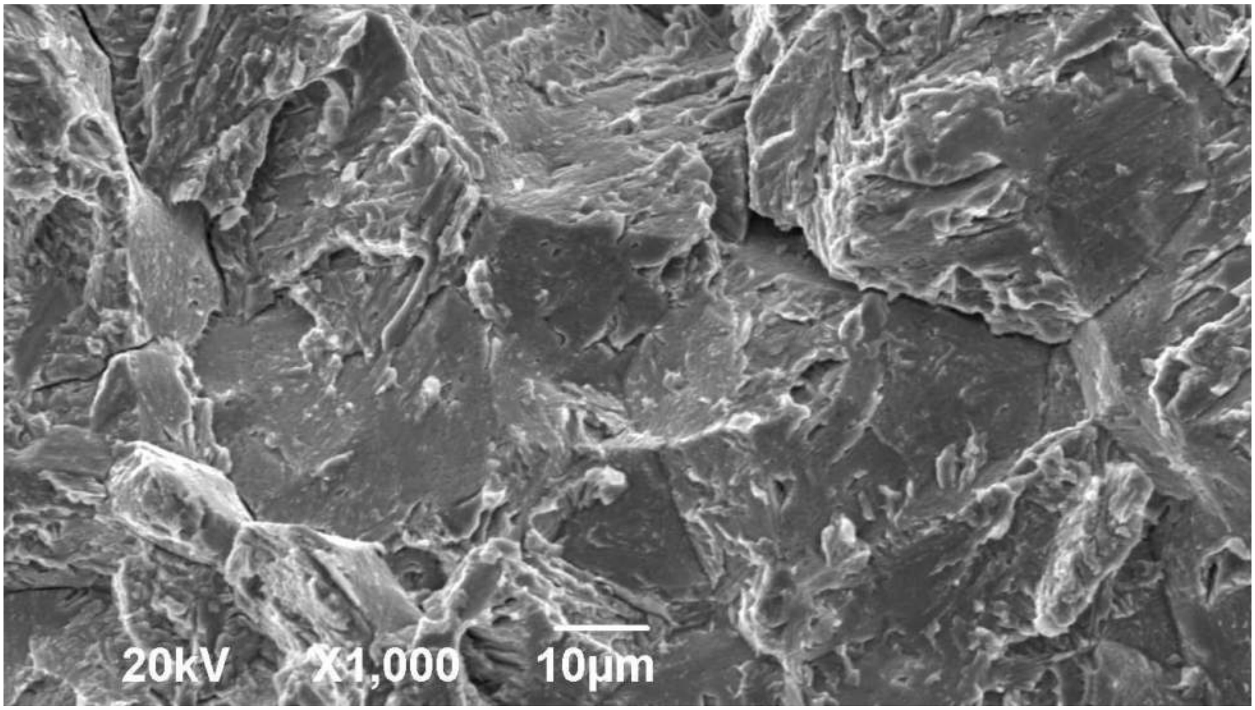


Figure N-22 – Representative region of fracture surface adjacent to end of precrack for Threadbar Plain, charged and RSL tested.

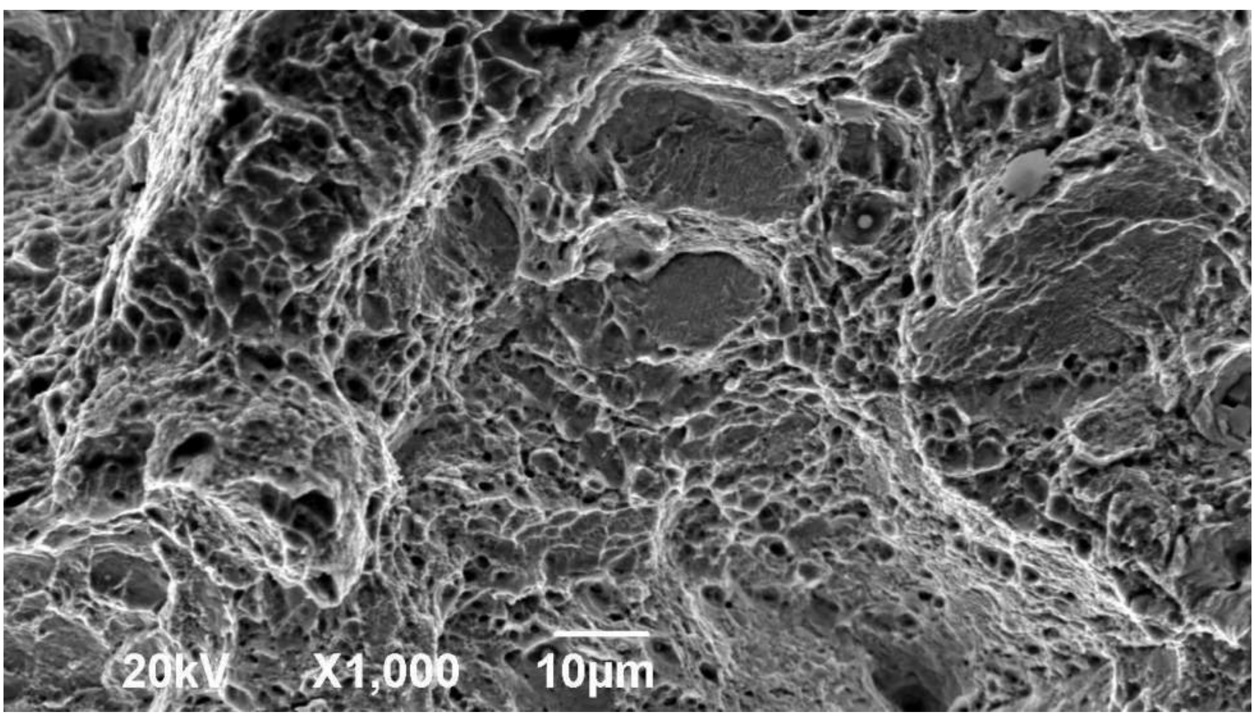


Figure N-23 – Representative region of fracture surface adjacent to end of precrack for Threadbar Galvanized, uncharged and FFS tested.

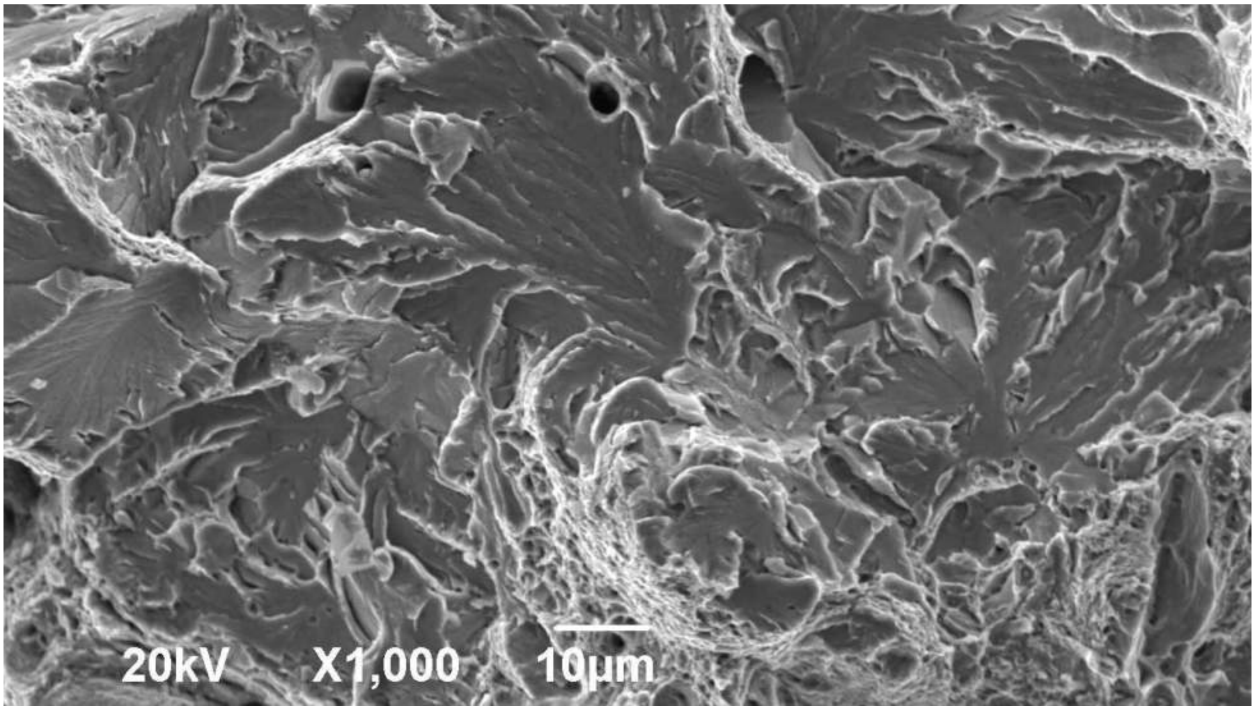


Figure N-24 – Representative region of fracture surface adjacent to end of precrack for Threadbar Galvanized, uncharged and RSL tested.

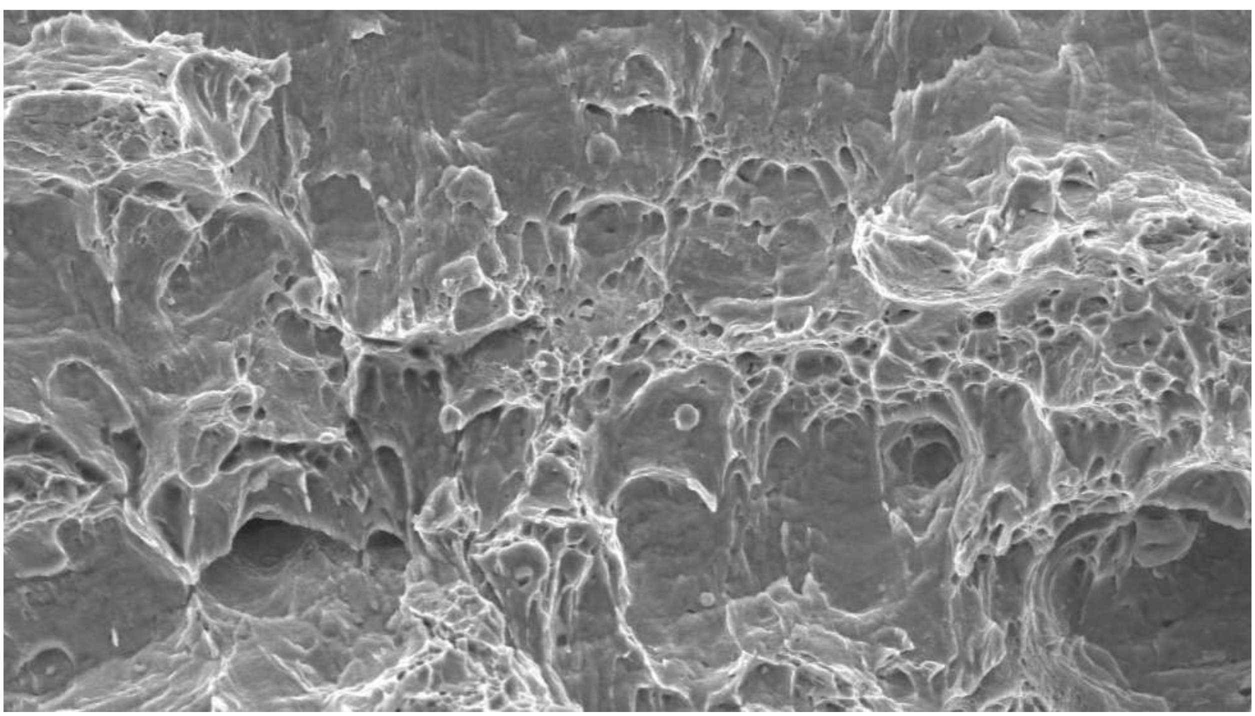


Figure N-25 – Representative region of fracture surface adjacent to end of precrack for Custom 450 H1050, uncharged and FFS tested.

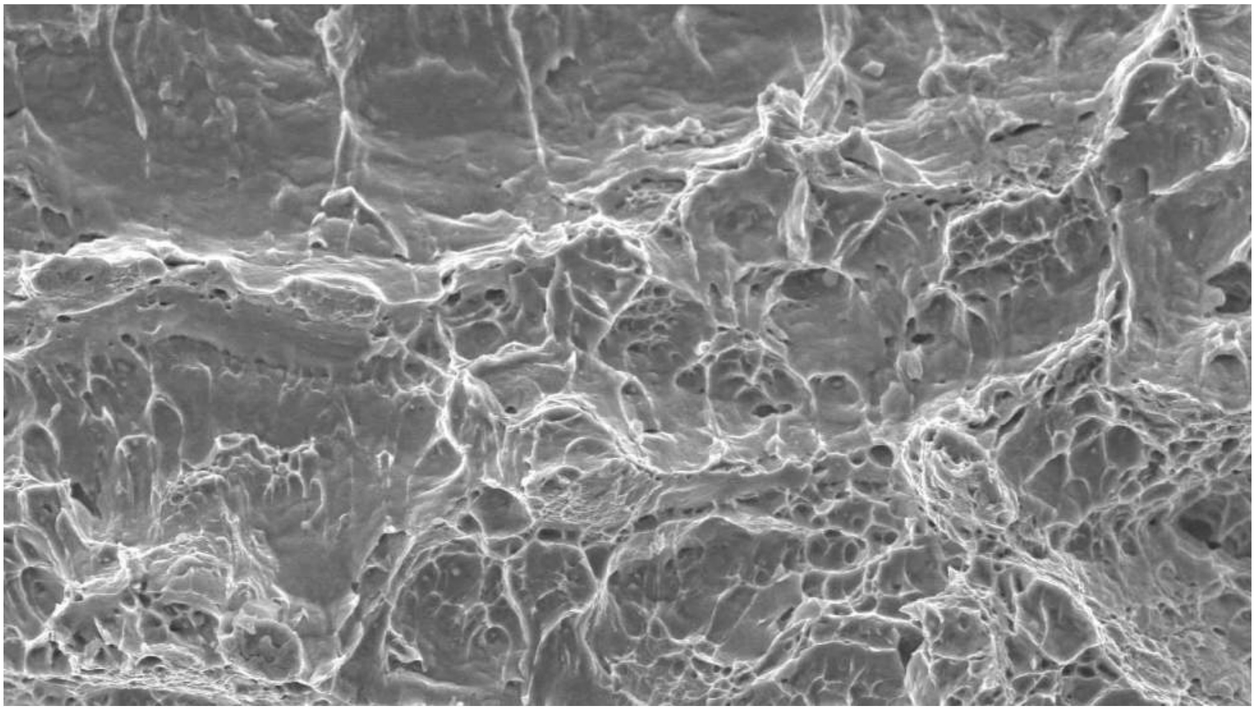


Figure N-26 – Representative region of fracture surface adjacent to end of precrack for Custom 450 H1050, charged and FFS tested.

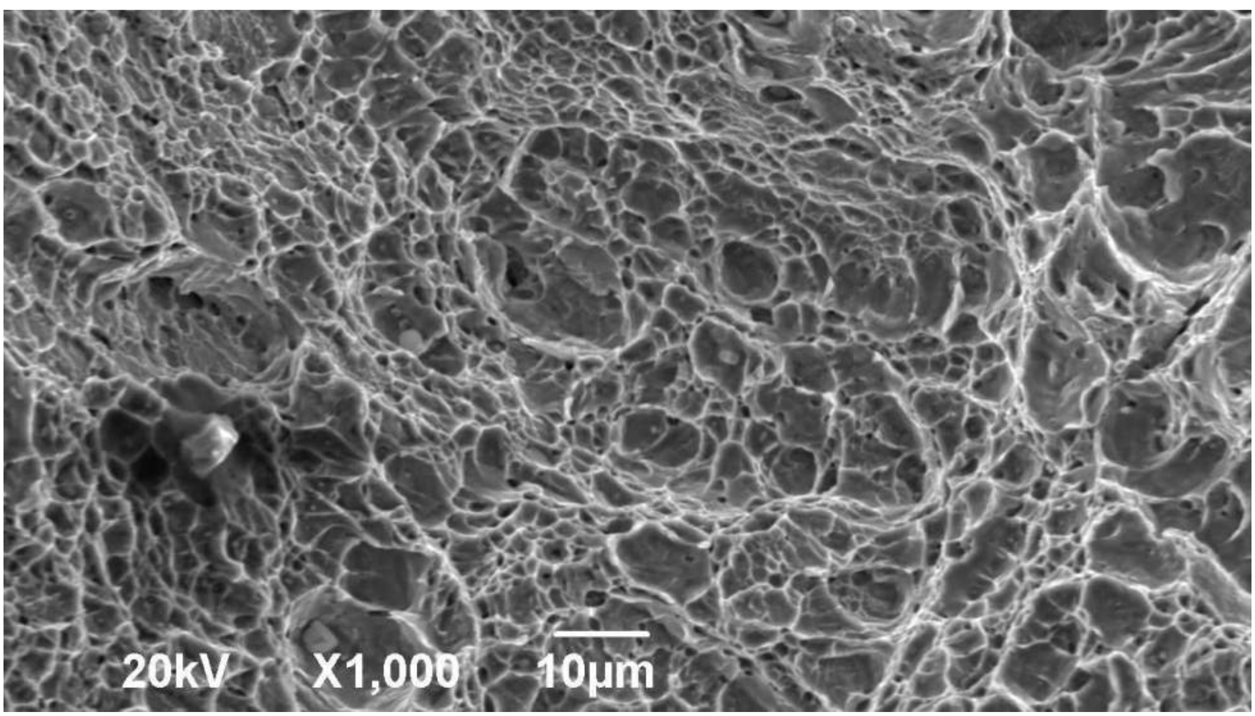


Figure N-27 – Representative region of fracture surface adjacent to end of precrack for Custom 450 H1050, charged and RSL tested.

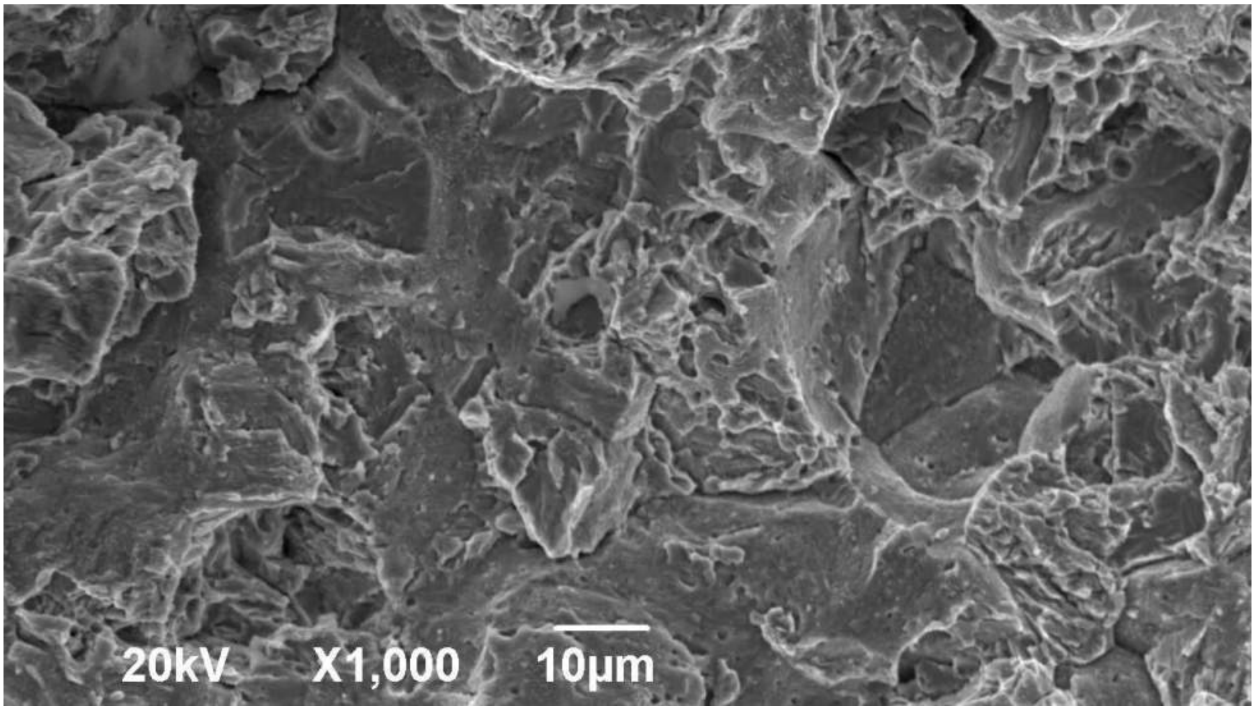


Figure N-28 – Representative region of middle of fracture surface at side of specimen for Custom 450 H1050, charged and RSL tested.

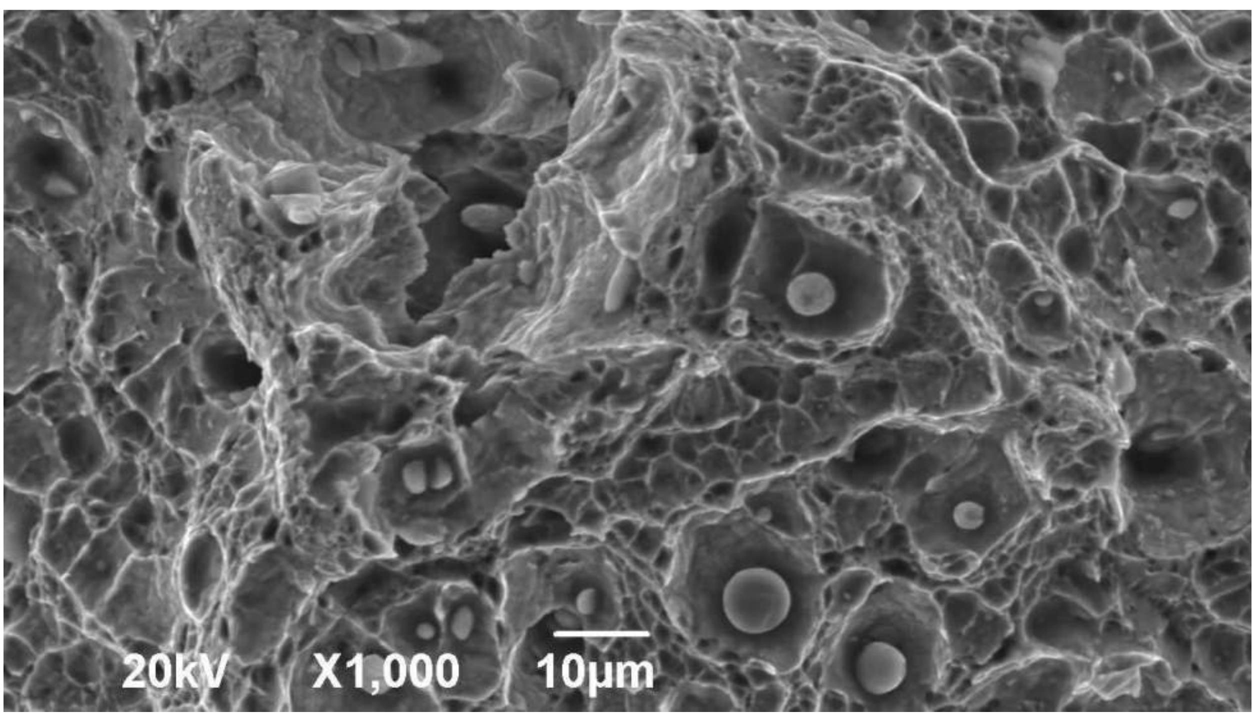


Figure N-29 – Representative region of fracture surface adjacent to end of precrack for Custom 630 H1100, uncharged and FFS tested.

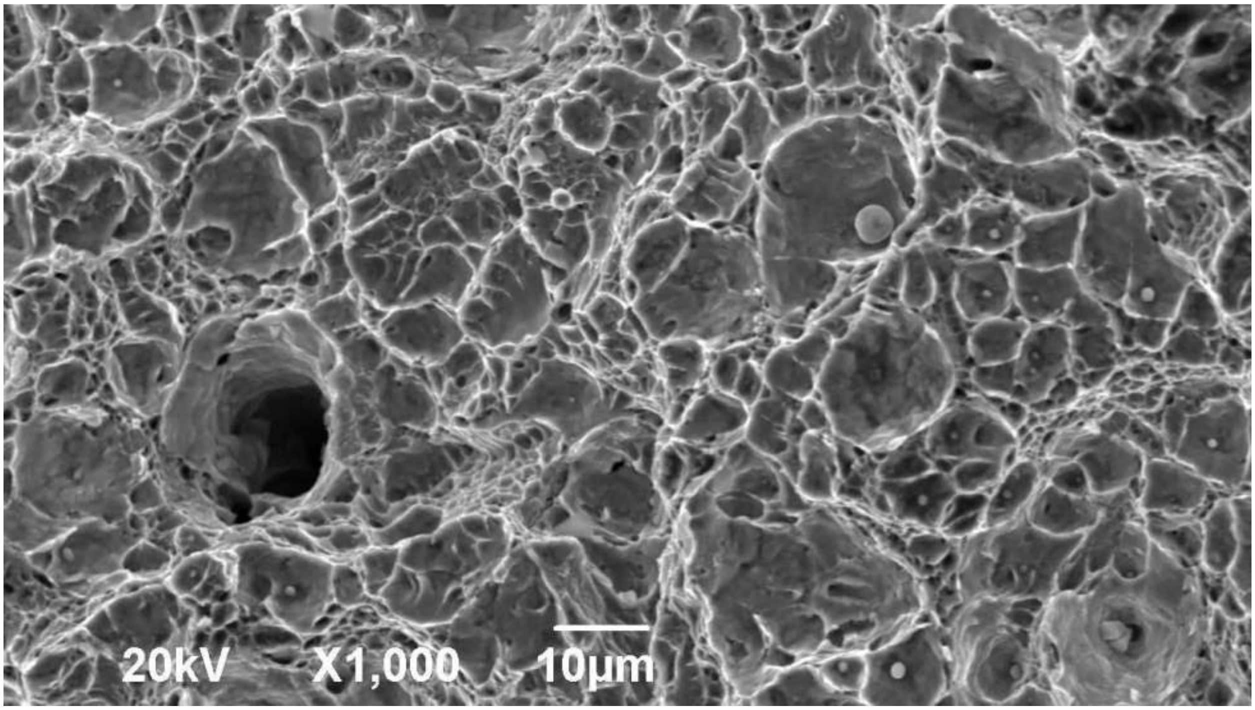


Figure N-30 – Representative region of fracture surface adjacent to end of precrack for Custom 630 H1100, charged and RSL tested.

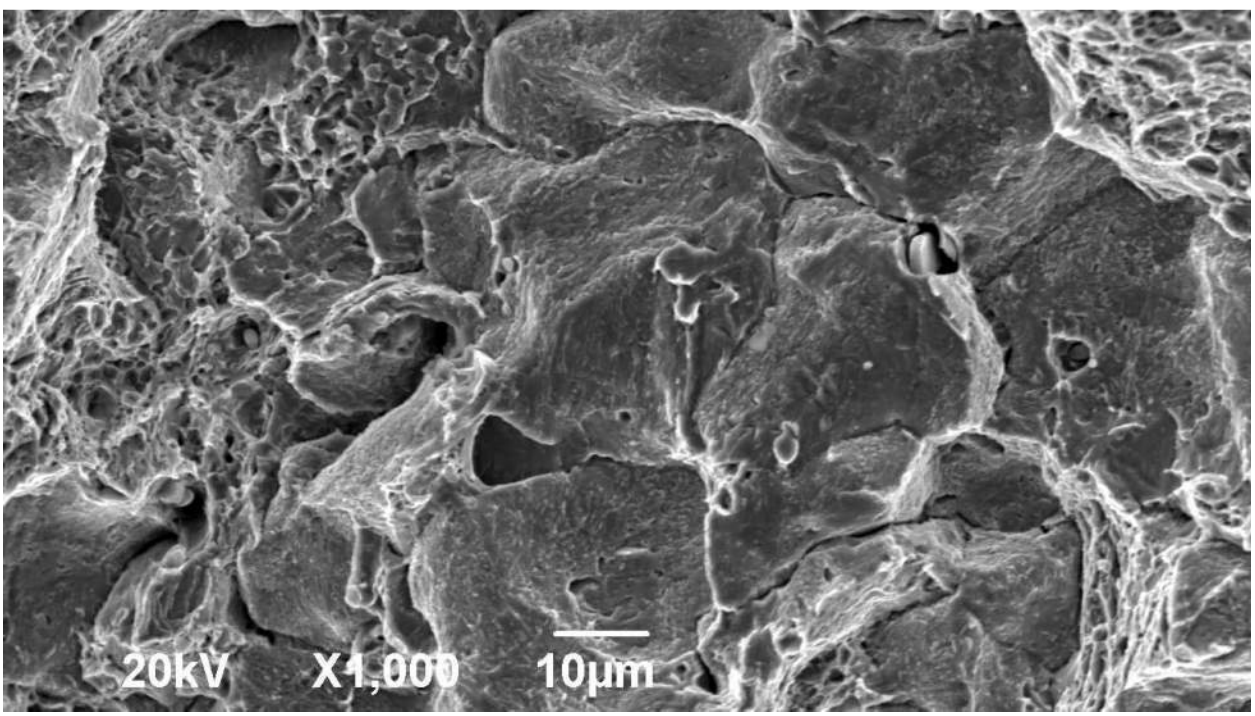


Figure N-31 – Representative region of middle of fracture surface at side of specimen for Custom 630 H1100, charged and RSL tested.

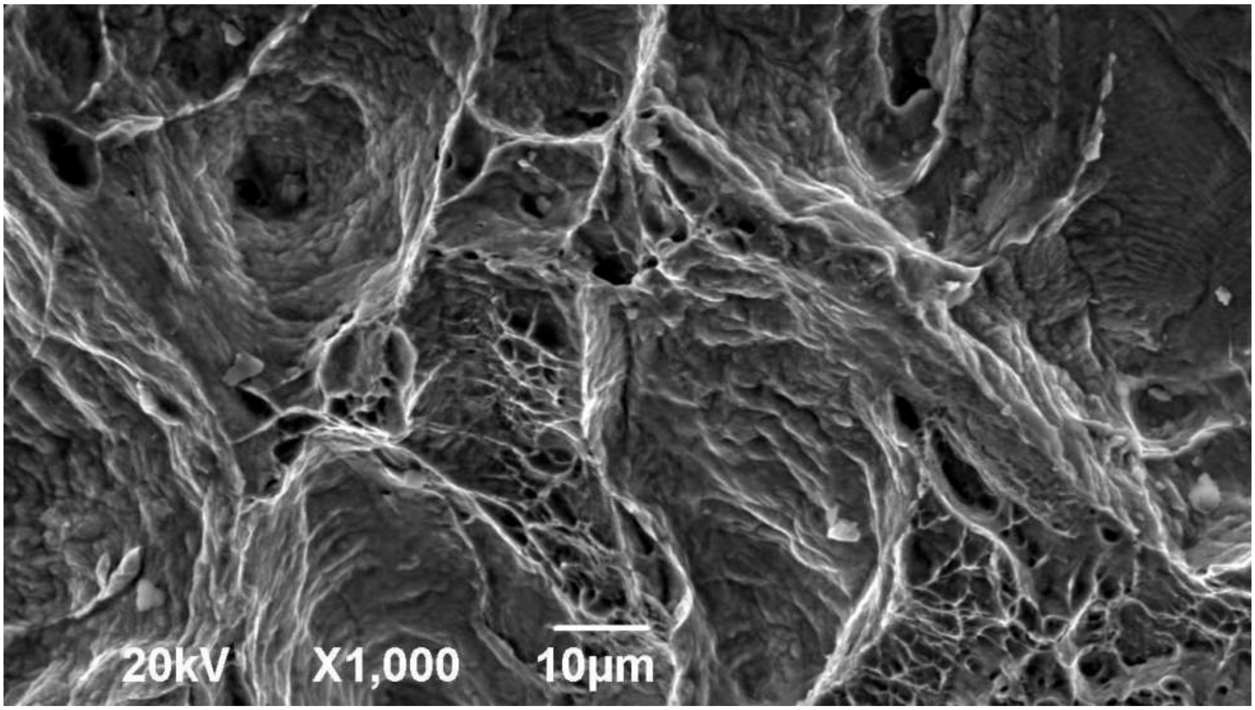


Figure N-32 – Representative region of fracture surface adjacent to end of precrack for Alloy 2507, uncharged and FFS tested.

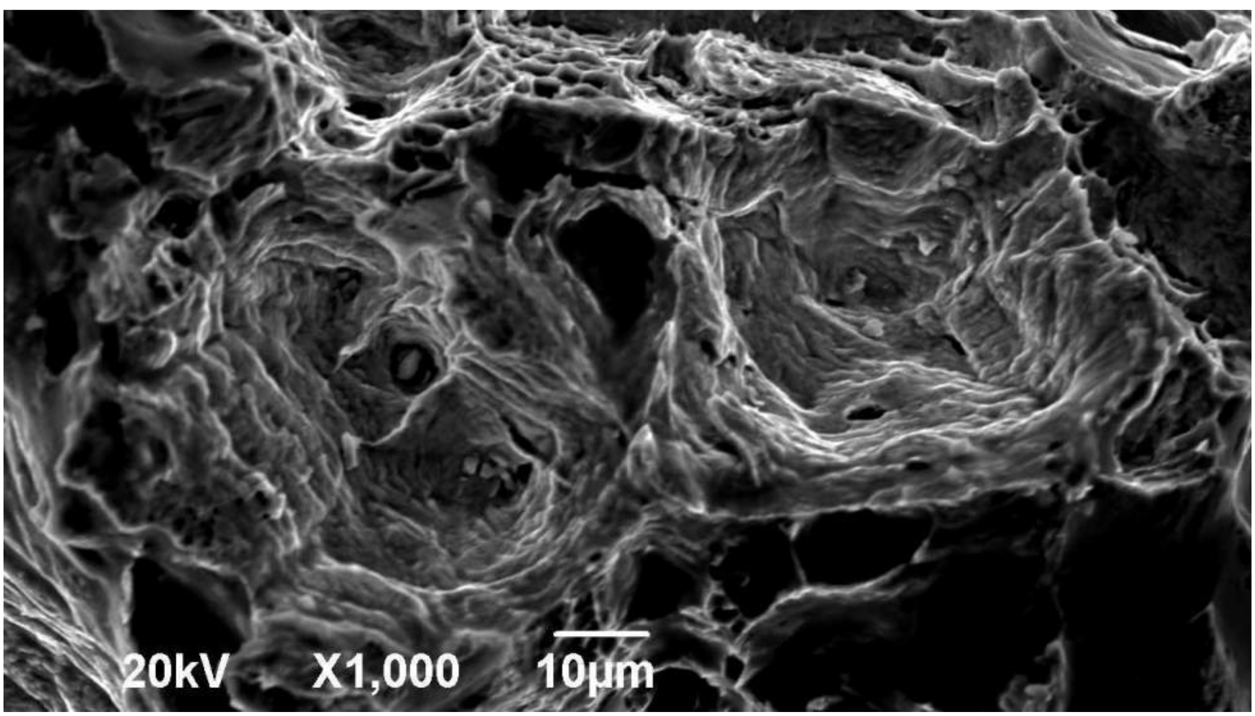


Figure N-33 – Representative region of fracture surface adjacent to end of precrack for Alloy 2507, charged and RSL tested.

Appendix O – Reference Material

Appendix O contains the following reference material related to the subject project:

- Information from Atlanta Rod and Manufacturing on Type 17-4 swedge bolts.

HERBERT C. BONNER BRIDGE

Posted on October 21, 2016 by Matt Brooks

Herbert C. Bonner Bridge

The Herbert C. Bonner Bridge is in North Carolina's beautiful Outer Banks. It carries approximately 2 million automobile passengers annually from Bodie Island to Pea Island, North Carolina. The original bridge was built in 1963, and

needed to be replaced with something that could withstand the region's harsh coastal environment.

A new 2.7-mile bridge is being built to span the Oregon Inlet. This bridge has a 100-year life-span and features high durability concrete, stainless steel rebar, and 17-4 stainless swedge bolts. Atlanta Rod was chosen to manufacture over 75,000 lbs. of 100% domestic 17-4 stainless swedge bolts in 2 ½" and 3" diameters. We also manufactured all the domestic 17-4 stainless heavy hex nuts to go with the bolts. All of the heavy hex nuts were precision forged in-house with machined threads, assembled onto the bolts, and shipped directly to the jobsite.

This entry was posted in Featured Projects. Bookmark the permalink.

← *2016 Vegas Fastener Show* *Goethals Bridge Project* →

Appendix P – Material Selection and Design Revisions

Appendix P contains the following information related to the material selection and design revisions:

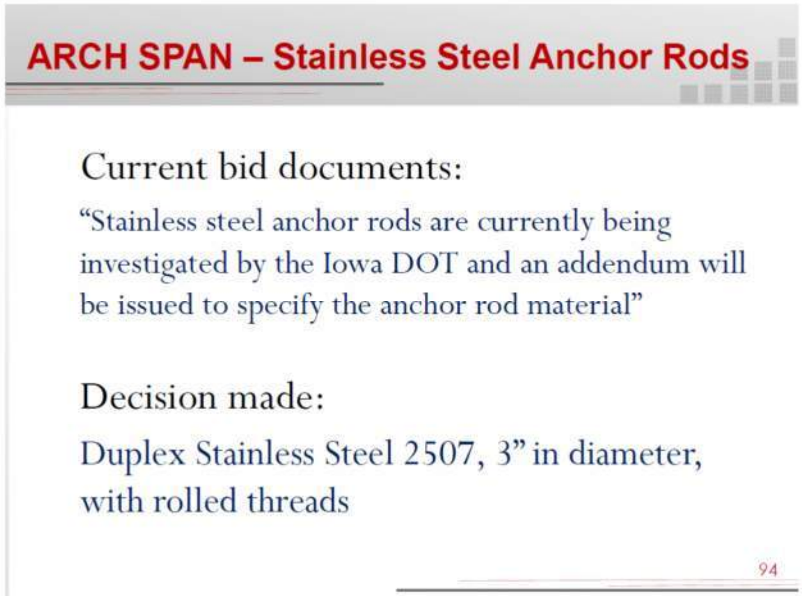
- Memorandum titled "I74 MRB Arch Rib Interface Post Tension Bars - Material Recommendation", prepared by Modjeski and Masters, Inc. to Alfred Benesch & Company dated 27 February 2017.

- Drawing Sheet Numbers 113, 113A, 114, and 115 prepared by Modjeski and Masters, Inc. for Iowa DOT Project Number IM-NHS-074-1(198)5--03-82 in Scott County. The drawings detail the Arch Rib – Concrete Interface Details, Arch Substructure. The drawings are noted to be "Changed by Addenda" on 23 March 2017.

- Special Provision prepared by Simpson Gumpertz & Heger Inc. for Iowa DOT Project Number IM-NHS-074-1(198)5--03-82 in Scott County. The Special Provision is SP-150263a titled *High-Strength, Stainless Steel Bars for Post-Tensioned Concrete*, with an effective date of April 25, 2017

The I-74 Bridge project is being administered by the Iowa DOT as the lead agency. The Letting Date is April 25, 2017. This revised Drawings and Special Provision were contained in a project addendum dated March 28, 2017 for Project No. 198.

Information from the Pre-Bid Meeting:



MEMORANDUM

DATE: February 27, 2017

TO: Alfred Benesch & Company

FROM: Modjeski and Masters, Inc.

RE: I74 MRB Arch Rib Interface Post Tension Bars – Material Recommendation

---

As a result of an investigation into anchor rod materials performed by SGH, and administrated by Alfred Benesch & Co., an alternative to conventional carbon steel A722 rods has been presented for use on the arch rib steel to concrete interface of the I74 MRB bridges. An evaluation of the changes required to implement Alloy 2507 Duplex Stainless Steel has been performed. Based on this evaluation, a recommendation to utilize 2507 anchor rods is made.

1 Material Characterization

Based on the results from the experimental program, SGH recommended the use of Alloy 2507 (A2507) due to its "*excellent toughness and resistance to pitting corrosion, stress corrosion cracking, and hydrogen embrittlement*" (Anderson, Neal S.; Brewe, Jared E.; Humphreys, Alan O.; Slavin, Chase M., 2017). However, concerns were raised regarding the structural performance of rods made of this material due to its lower strength (with respect to the minimum specified for conventional material, i.e. 150 ksi) and the inelastic behavior exhibited at jacking and service stress levels, see Figure 1. Additionally, the initial loads in the relaxation tests were smaller than those required by the corresponding Standard Specs and just one test (out of three) reached an initial stress similar to the design conditions.

To overcome these issues, the following measures were taken in order to proceed with the evaluation of A2507 as a potential candidate for the interface connection:

- Lower strength: SGH consulted the US manufacturer (Carpenter Technology) about the minimum strength that could be specified for this material. They concurred on a minimum tensile strength of 116 ksi. Moreover, to reduce the stress demands, a larger bar size that would require minimum changes in the current details was selected (3-inch outside diameter to the thread crests, $A_b = 6.14\ in^2$).
- Inelastic behavior: Tensioning the bars initially up to a higher stress to eliminate/minimize this nonlinear effect by strain hardening of the material. Currently, SGH is working on implementing a testing protocol to address this issue and will give recommendations to incorporate in the jacking procedure.

* *Relaxation*: In order to accommodate potential variations in relaxation, the design was bounded in terms of the PT losses. For relaxation, a minimum loss of 1.2% of the stress after seating was defined based on the test results at 24 hours for the case when an initial load similar to the anticipated effective jacking stress is reached (Test 1 in Figure 2). For the maximum boundary, a conservative loss of 5% after seating (almost twice the value obtained after the 1000 hr test) was assumed for design.

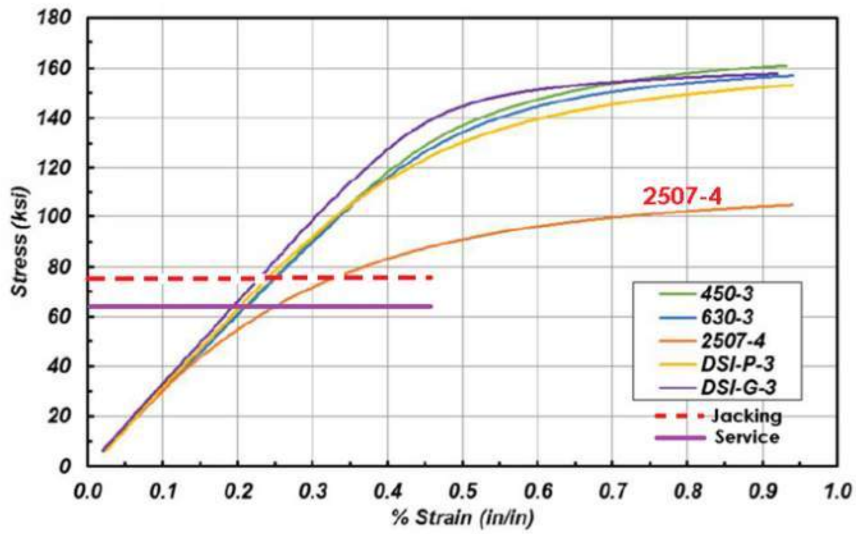


Figure 1. Stress-Strain Curve for Test Materials (SGH, 2017)

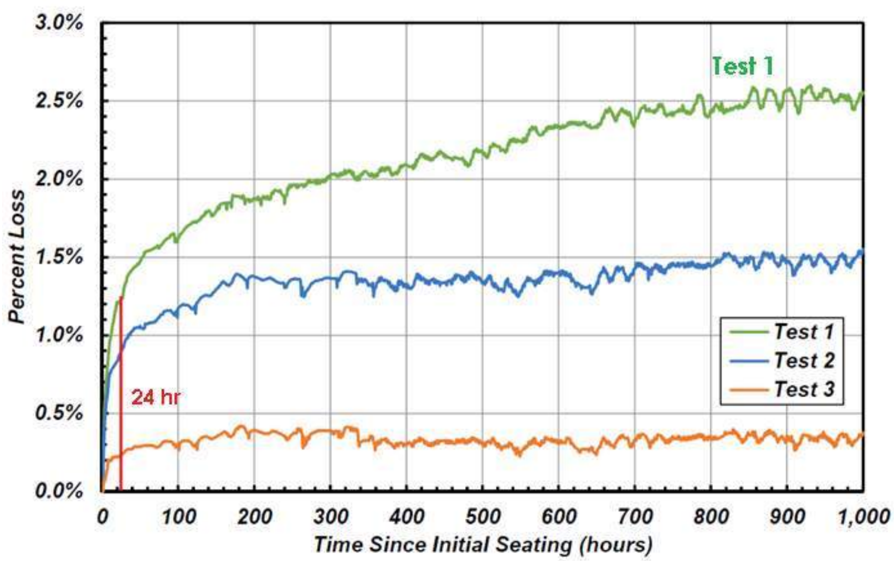


Figure 2. Relaxation Percent Loss for A2507 Tests (SGH, 2017)

2 Design Evaluation

The design of the interface connection was evaluated using A2507 3-inch anchor bars (A_b = 6.14 in^2) and incorporating the assumptions previously described. The results from the connection most susceptible to experiencing uplift (i.e. Arch Rib IC, no bike trail side) are presented in Table 1. The demand-to-capacity ratios were found satisfactory for the PT loss bounded design scenario.

As a result of the increased bar size, the connection details will be revised to accommodate the larger bar and corresponding accessories. Changes to the connection assembly include:

- Larger holes: Top anchor bearing plate
  Anchor bearing plate
  Template
  Bottom anchor bearing plate
- Thicker plates: Top anchor bearing plate

Additionally, MM has already incorporated the modifications required to the arch anchorage assembly to address the potential for corrosion resulting from contact between dissimilar metals (MM, 2016).

3 Recommendations

The testing done to-date has shown the Alloy 2507 duplex material to perform drastically better than conventional steel with respect to corrosion resistance. The lower strength of the material has been evaluated, and it has been determined that the arch anchorage design can be modified to accommodate it. We recommend that this material, in the form of anchor rods with a 3-inch outside diameter to the thread crests, with an effective area of 6.14 in^2 and a minimum strength of 116 ksi be used in place of the A722 anchor rods currently detailed in the design plans and specifications.

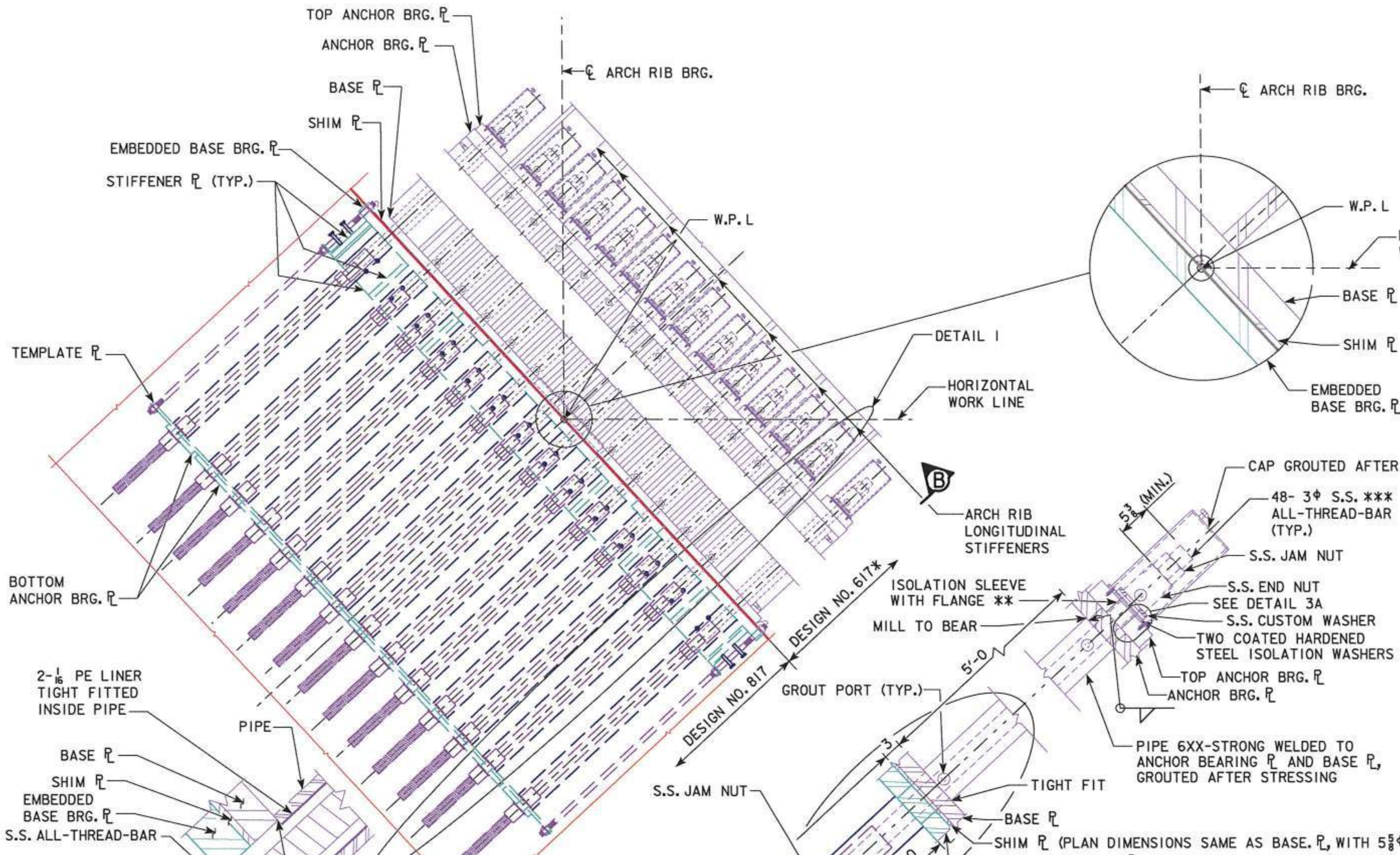
4 Works Cited

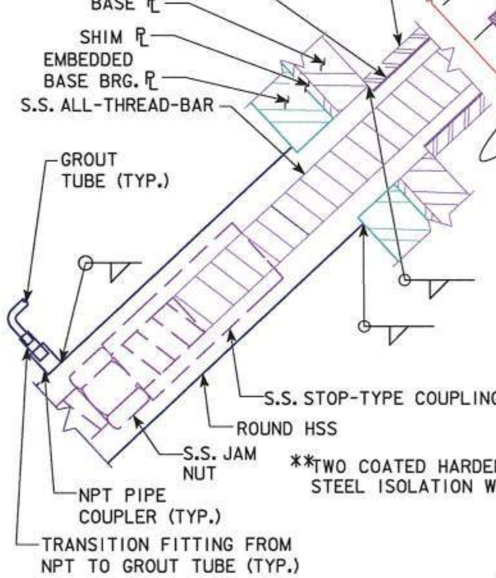
Anderson, Neal S.; Brewe, Jared E.; Humphreys, Alan O.; Slavin, Chase M. (2017). *Development of a New Generation, High-Strength P/T Anchorage Bar (Phase 2 Experimental Program).* Chicago, IL: SGH.

MM. (2016). *Memorandum: I-74 Arch Bridges – Stainless Steel Anchor Rod Alternative - Isolation of Dissimilar Metals.* Mechanicsburg: MM.

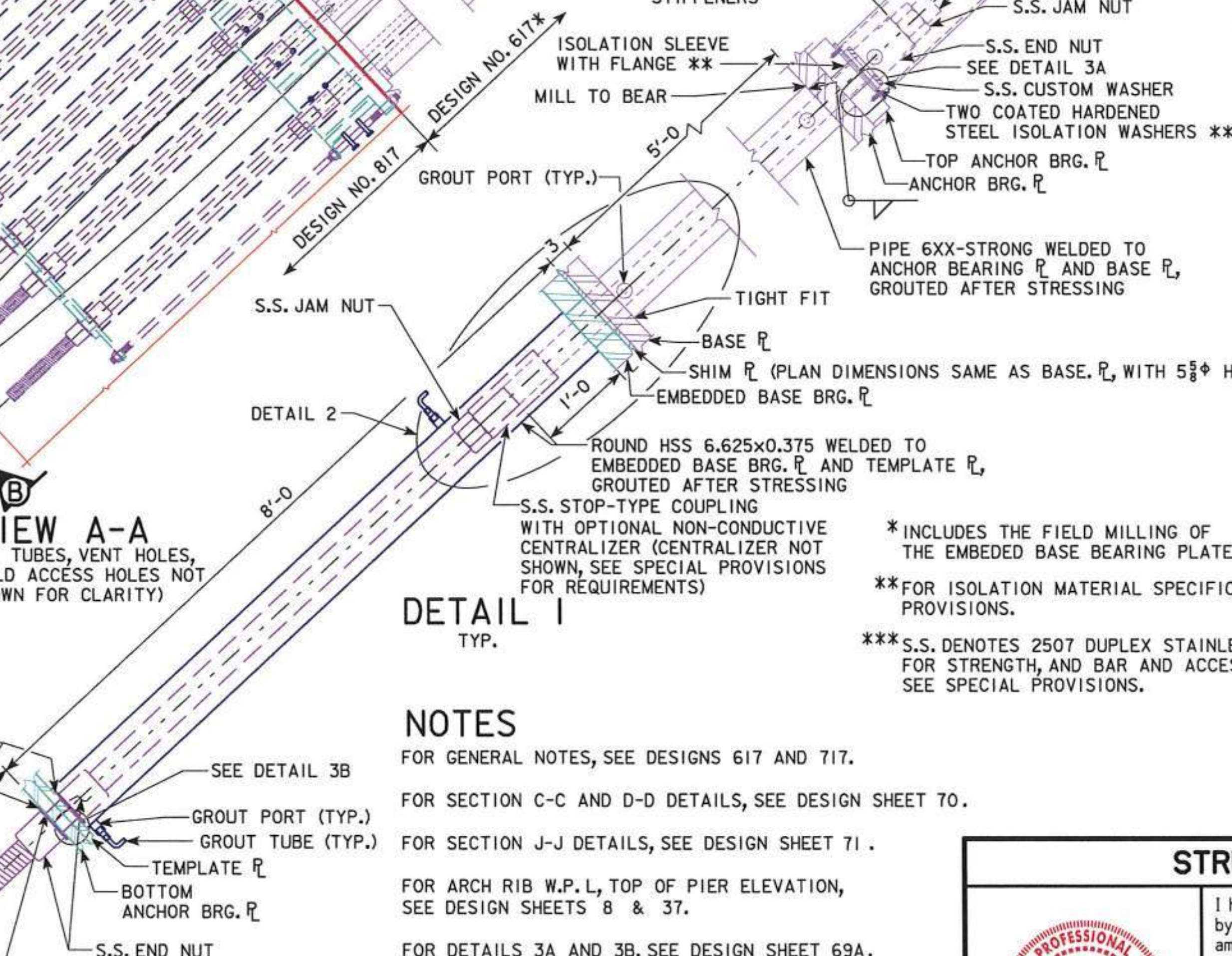
Table 1. Design Evaluation for Critical Connection

				A722 Gr. 150		**Alloy 2507**	
		Symbol	Units	Min. PT Loss	Max. PT Loss	Min. PT Loss	Max. PT Loss
Geometry	Thread Major Diameter	ϕ_{maj}	in	**2.75**	**2.75**	**3.00**	**3.00**
	Effective Bar Diameter	ϕ_{eff}	mm	65	65	71	71
			in	2.56	2.56	2.80	2.80
	Effective Bar Area	A_b	in^2	5.14	5.14	6.14	6.14
Properties	Minimum Ultimate Strength	F_u	ksi	**150**	**150**	**116**	**116**
			kips	772	772	712	712
	Yield strength	F_y	ksi	120	120	80	80
			kips	617	617	491	491
PT Losses	Instantaneous Loss	Δf_{inst}	ksi	6.0	11.7	5.9	11.7
	Long Term Loss	Δf_{LT}	ksi	5.2	14.3	6.0	13.3
	Relaxation	Δf_R	ksi	0.0	3.9	0.8	3.2
			$\%f_{pt}$	0.000	0.050	0.012	0.050
Operational Stresses	Jacking Stress	f_{pj}	ksi	90	90	76	76
			%Fu	0.60	0.60	0.65	0.65
			%Fy	0.75	0.75	0.95	0.95
			kips	463	463	464	464
	Stress after Instantaneous Loss	f_{pt}	ksi	84	78	70	64
			%Fy	0.70	0.65	0.87	0.80
			kips	432	403	428	392
	Effective Stress after Long Term Loss	f_{pe}	ksi	79	64	64	51
			%Fy	0.66	0.53	0.80	0.63
			kips	405	329	391	311
Critical Demands	Tensile capacity ($0.7F_u$, $0.7F_uA_b$)	T_r	ksi	106	106	81	81
			kips	544	544	496	496
	Maximum Tensile Effects	T_u	ksi	94	83	79	70
			kips	482	425	483	427
	Tensile Cap. Ratio	D/C		*0.89*	*0.78*	*0.97*	*0.86*



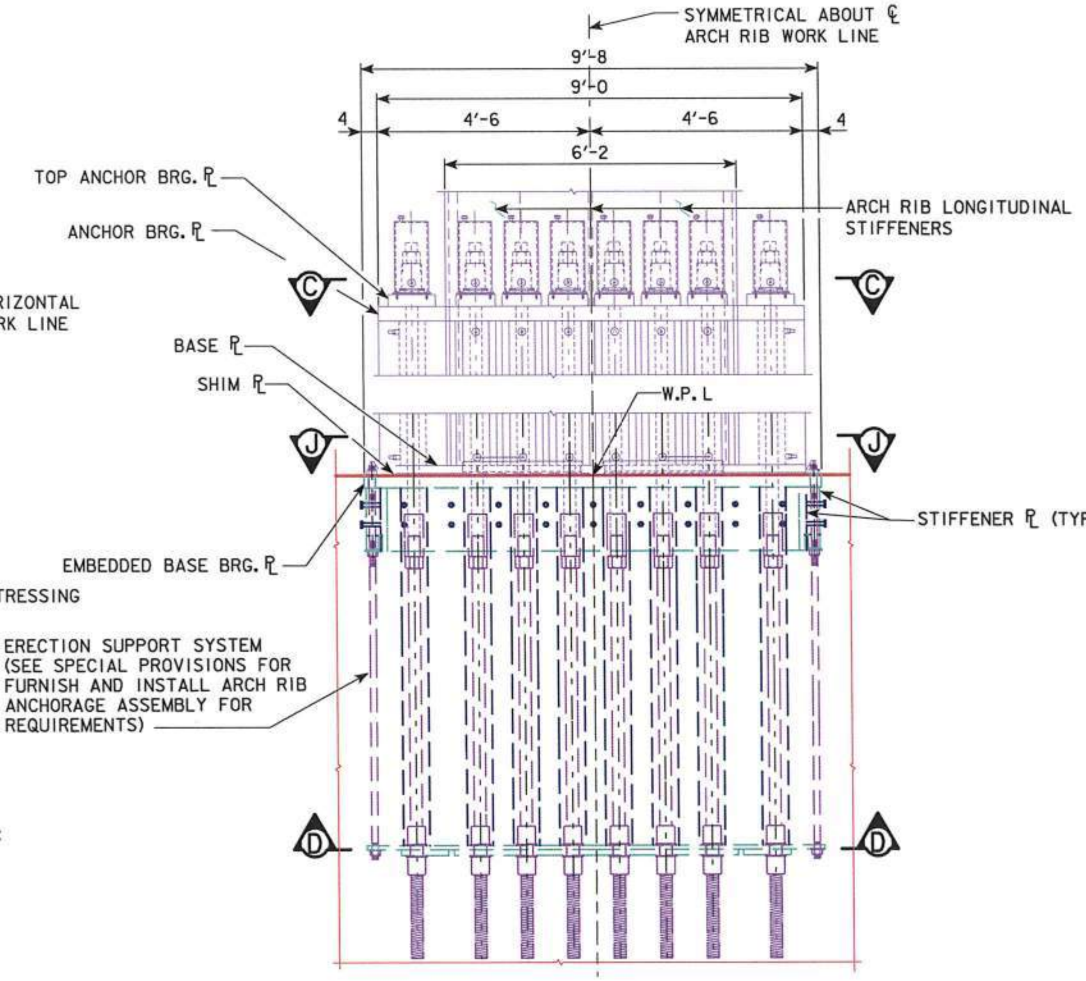


DETAIL 2



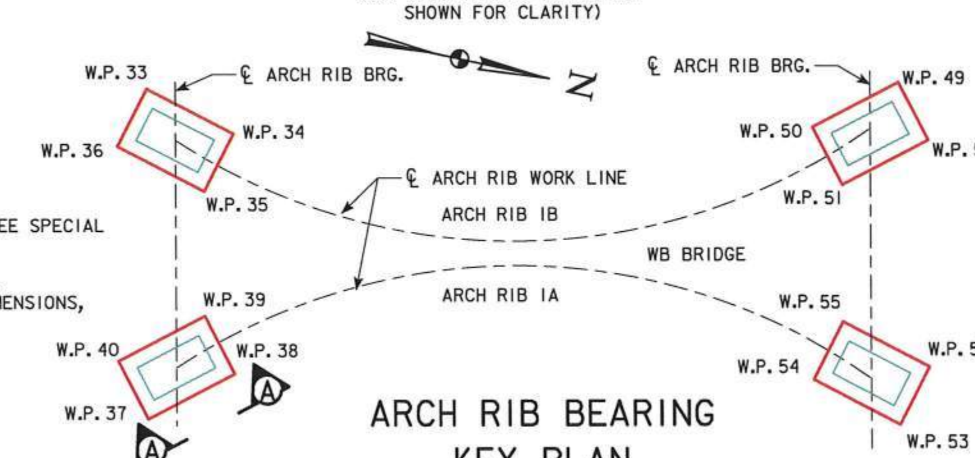
DETAIL I

TYP.



VIEW B-B

(GROUT TUBES, VENT HOLES, AND WELD ACCESS HOLES NOT SHOWN FOR CLARITY)



ARCH RIB BEARING KEY PLAN

(NOT TO SCALE)

* INCLUDES THE FIELD MILLING OF THE EMBEDED BASE BEARING PLATE.

** FOR ISOLATION MATERIAL SPECIFICATIONS, SEE SPECIAL PROVISIONS.

*** S.S. DENOTES 2507 DUPLEX STAINLESS STEEL FOR STRENGTH, AND BAR AND ACCESSORY DIMENSIONS, SEE SPECIAL PROVISIONS.

NOTES

FOR GENERAL NOTES, SEE DESIGNS 617 AND 717.

FOR SECTION C-C AND D-D DETAILS, SEE DESIGN SHEET 70.

FOR SECTION J-J DETAILS, SEE DESIGN SHEET 71.

FOR ARCH RIB W.P. L, TOP OF PIER ELEVATION, SEE DESIGN SHEETS 8 & 37.

FOR DETAILS 3A AND 3B, SEE DESIGN SHEET 69A.

FOR S.S. ALL-THREAD-BAR CAP AND S.S. CUSTOM WASHER DETAILS, SEE DESIGN SHEET 71.

FOR JACKING STRESS AND POST-TENSIONING OPERATIONS, SEE SPECIAL PROVISIONS.

FOR W.P. 33 THRU 40 AND 49 THRU 56, SEE DESIGN SHEETS 8 & 37.

MODJESKI and MASTERS
Experience great bridges.

STRUCTURAL DESIGN

LICENSED PROFESSIONAL ENGINEER THOMAS P. MURPHY 20338 IOWA

I hereby certify that this engineering document was prepared by me or under my direct personal supervision and that I am a duly licensed Professional Engineer under the laws of the State of Iowa.

Signature: [signature] Date: 3-23-2017

THOMAS P. MURPHY
Printed or Typed Name

License number 20338

My license renewal date is December 31, 2018

Pages or sheets covered by this seal: 113 - 115

SUBSTRUCTURE DESIGN FOR 0° SKEW

DUAL 795'-0 x 72' STEEL ARCH BRIDGE

ARCH RIB-CONCRETE INTERFACE DETAILS

ARCH SUBSTRUCTURE

STA. 6770+98.50, ℄ PROPOSED I-74 DECEMBER 2016

SCOTT & ROCK ISLAND COUNTIES

IOWA DEPARTMENT OF TRANSPORTATION - HIGHWAY DIVISION

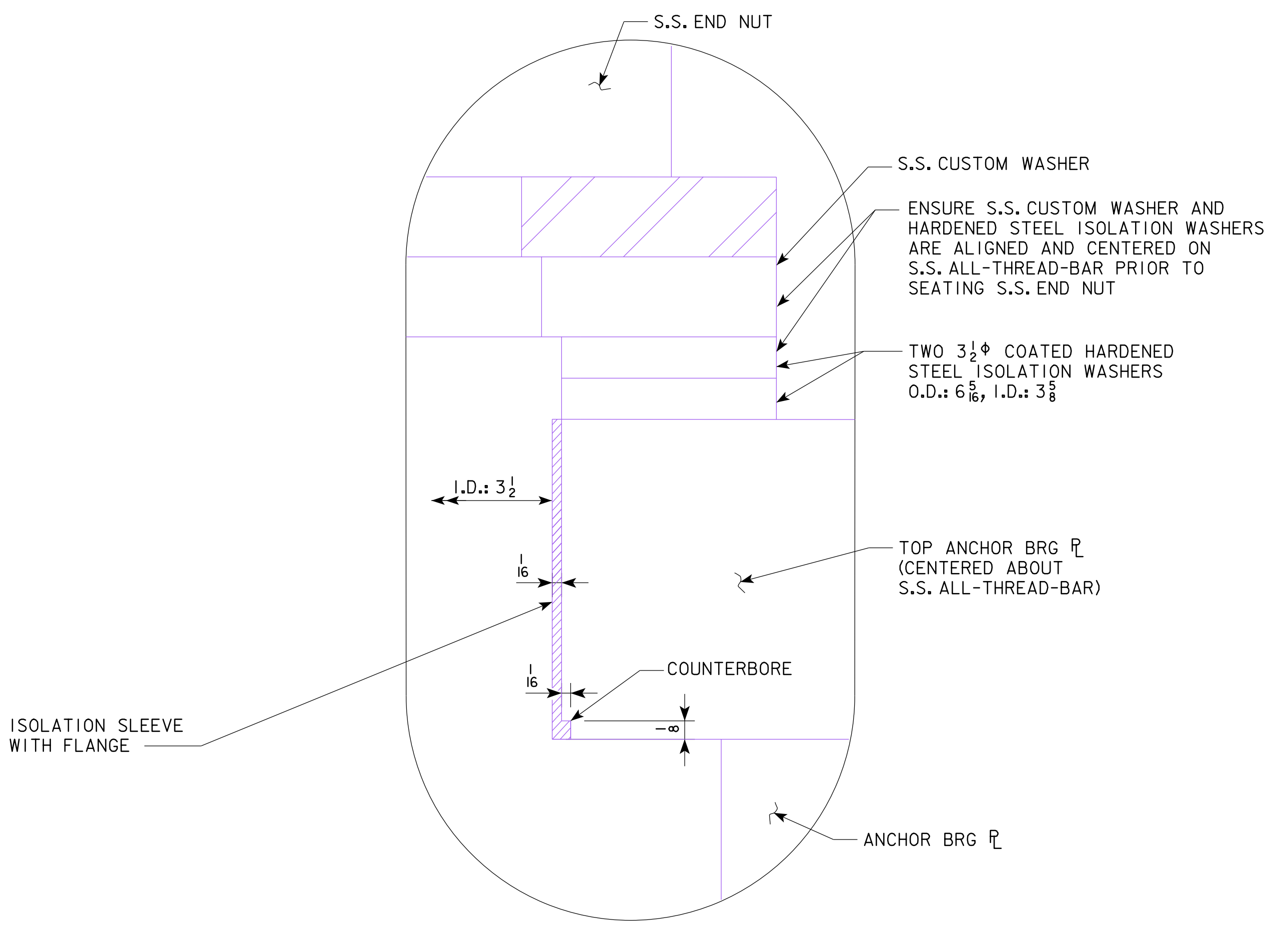
DESIGN SHEET NO. 69 OF 74 FILE NO. 30253 DESIGN NO. 817

DESIGN TEAM NYG/EAR/TJS	SCOTT COUNTY	PROJECT NUMBER IM-NHS-074-1(198)5--03-82	SHEET NUMBER 113

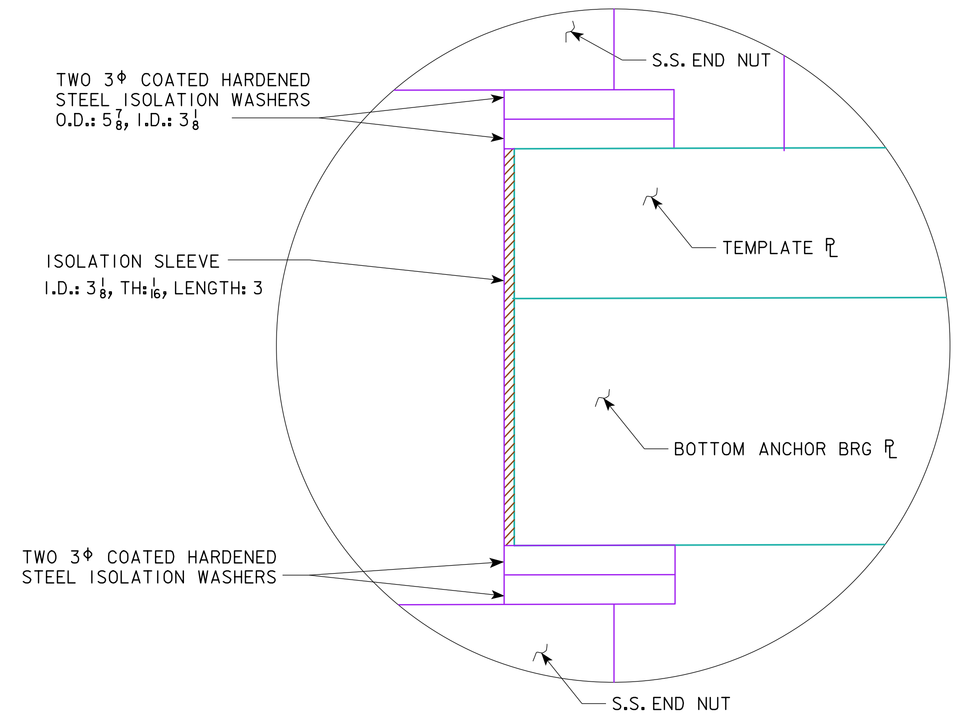
11:45:14 AM untitled c:\pwise_work\do_not_delete\dms05639\82074198.brg
MODEL: 824408S068A 3/23/2017

CHANGED BY ADDENDA

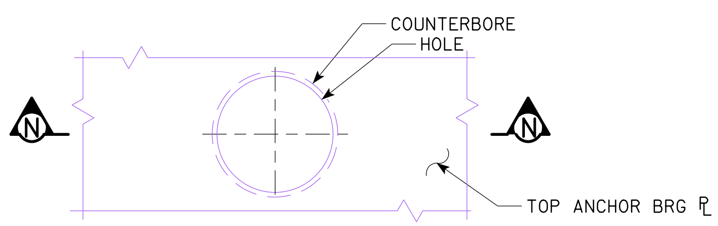
3/23/2017



DETAIL 3A

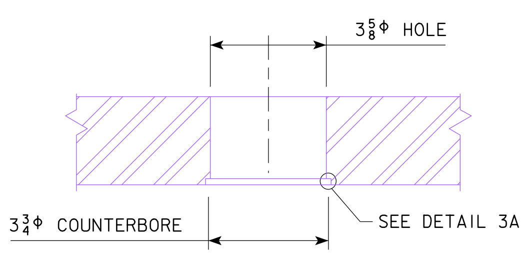


DETAIL 3B



PLAN

TOP ANCHOR BRG ℞



SECTION N-N

COUNTERBORE DETAIL

NOTES

FOR GENERAL NOTES, SEE DESIGNS 617 AND 717.

FOR LOCATION OF DETAILS 3A AND 3B, SEE DESIGN SHEET 69.

S.S. DENOTES 2507 DUPLEX STAINLESS STEEL.

SUBSTRUCTURE DESIGN FOR 0° SKEW

DUAL 795'-0 x 72' STEEL ARCH BRIDGE

ARCH RIB-CONCRETE INTERFACE DETAILS
ARCH SUBSTRUCTURE

STA. 6770+98.50, ℄ PROPOSED I-74 DECEMBER 2016

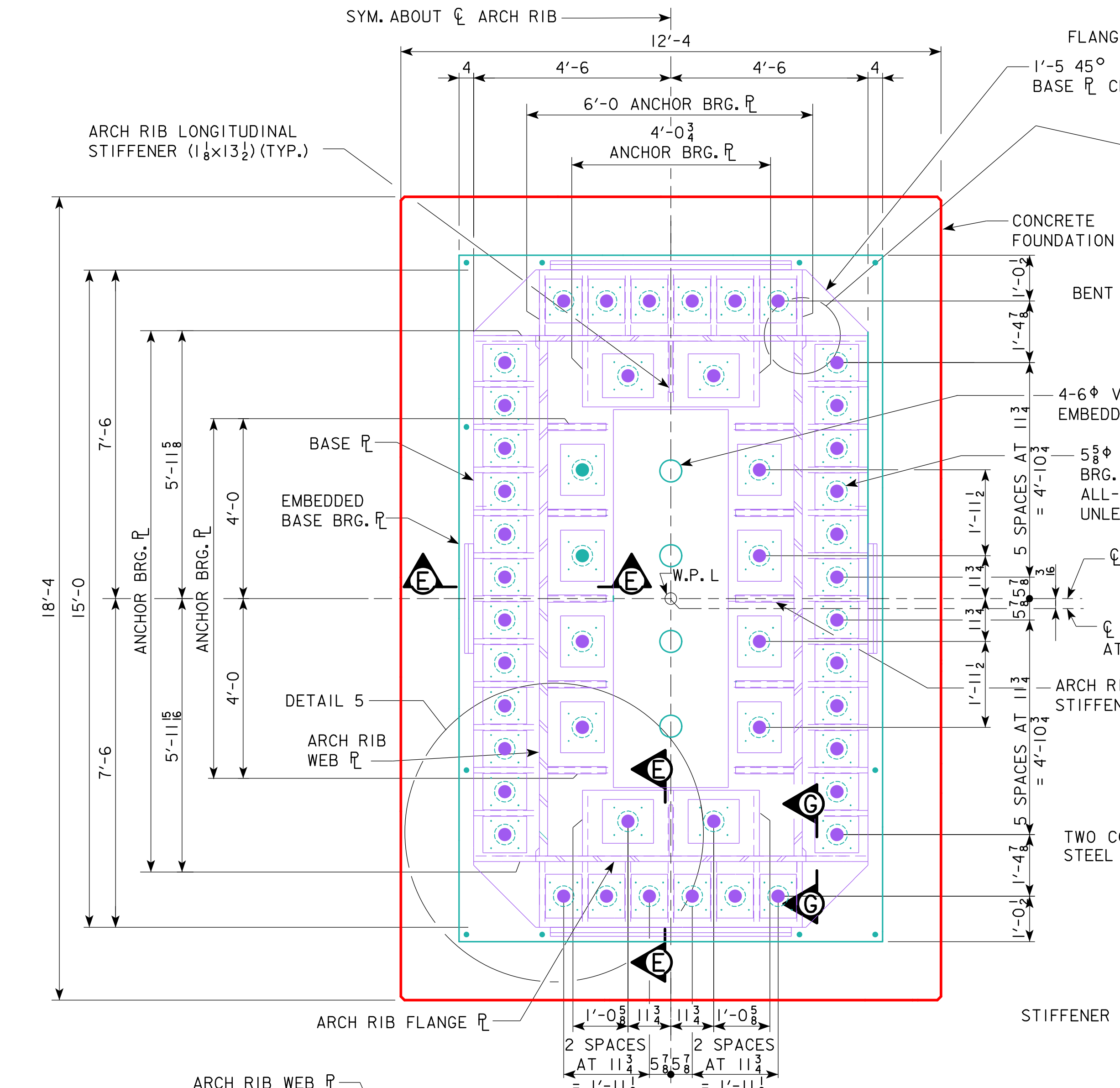
SCOTT & ROCK ISLAND COUNTIES

IOWA DEPARTMENT OF TRANSPORTATION - HIGHWAY DIVISION

DESIGN SHEET NO. 69A OF 74 FILE NO. 30253 DESIGN NO. 817

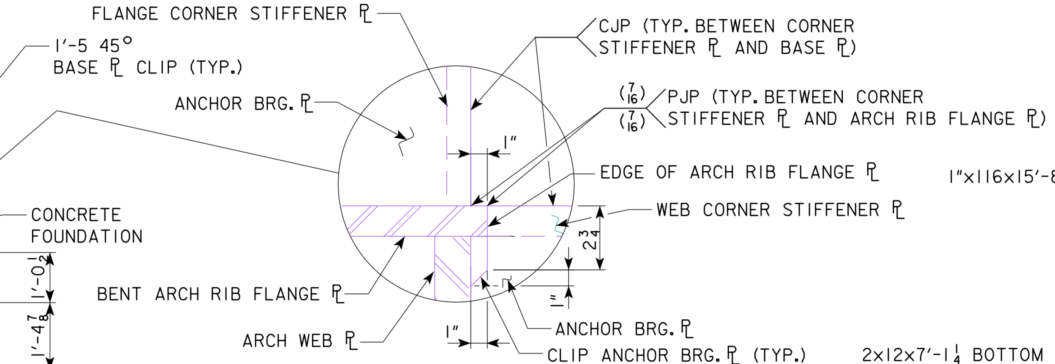
MODJESKI and MASTERS
Experience great bridges.

DESIGN TEAM NYG/EAR/TJS | SCOTT COUNTY | PROJECT NUMBER IM-NHS-074-1(198)5--03-82 | SHEET NUMBER 113A

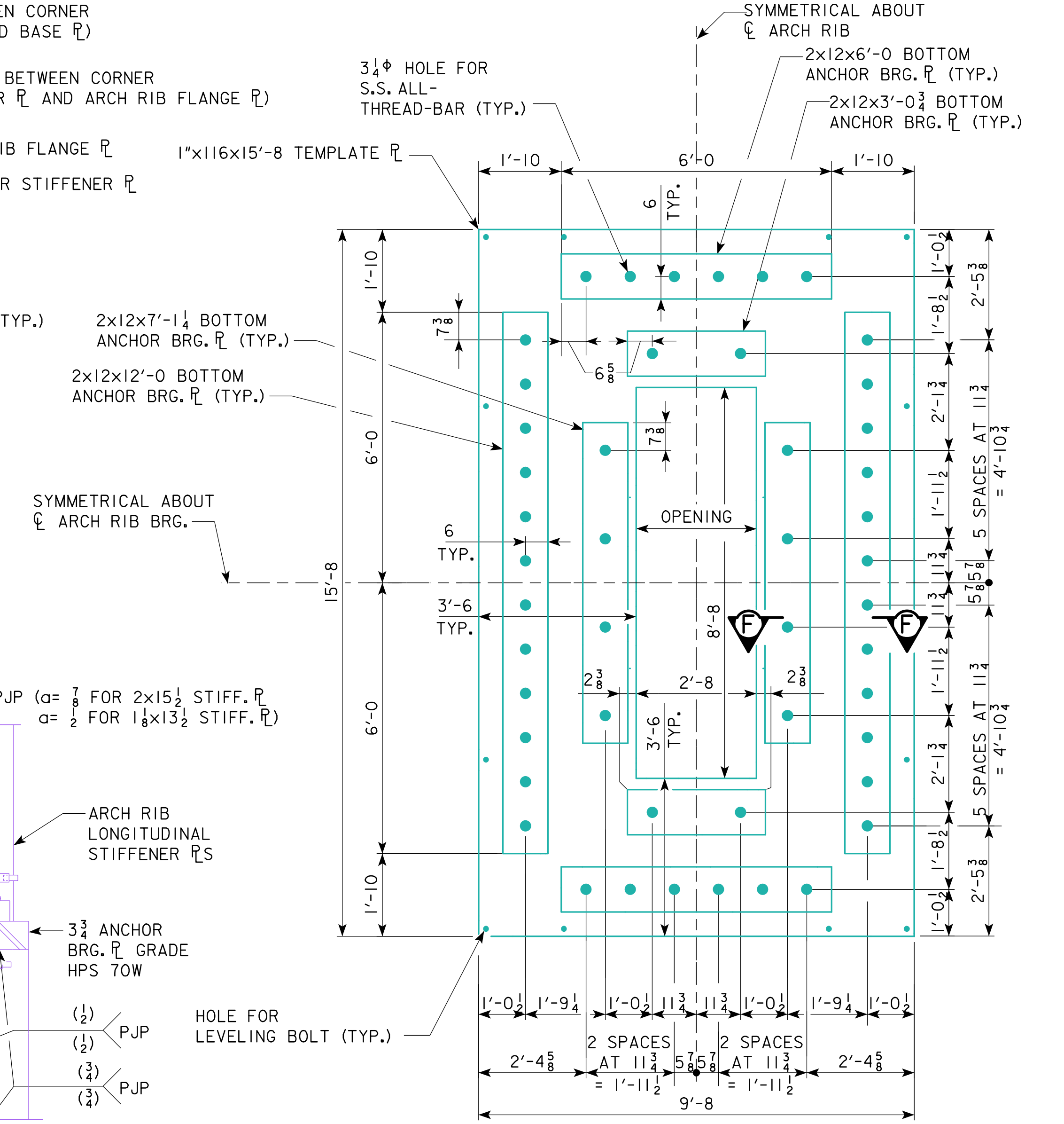


SECTION C-C

(PARALLEL TO BASE ℙ)

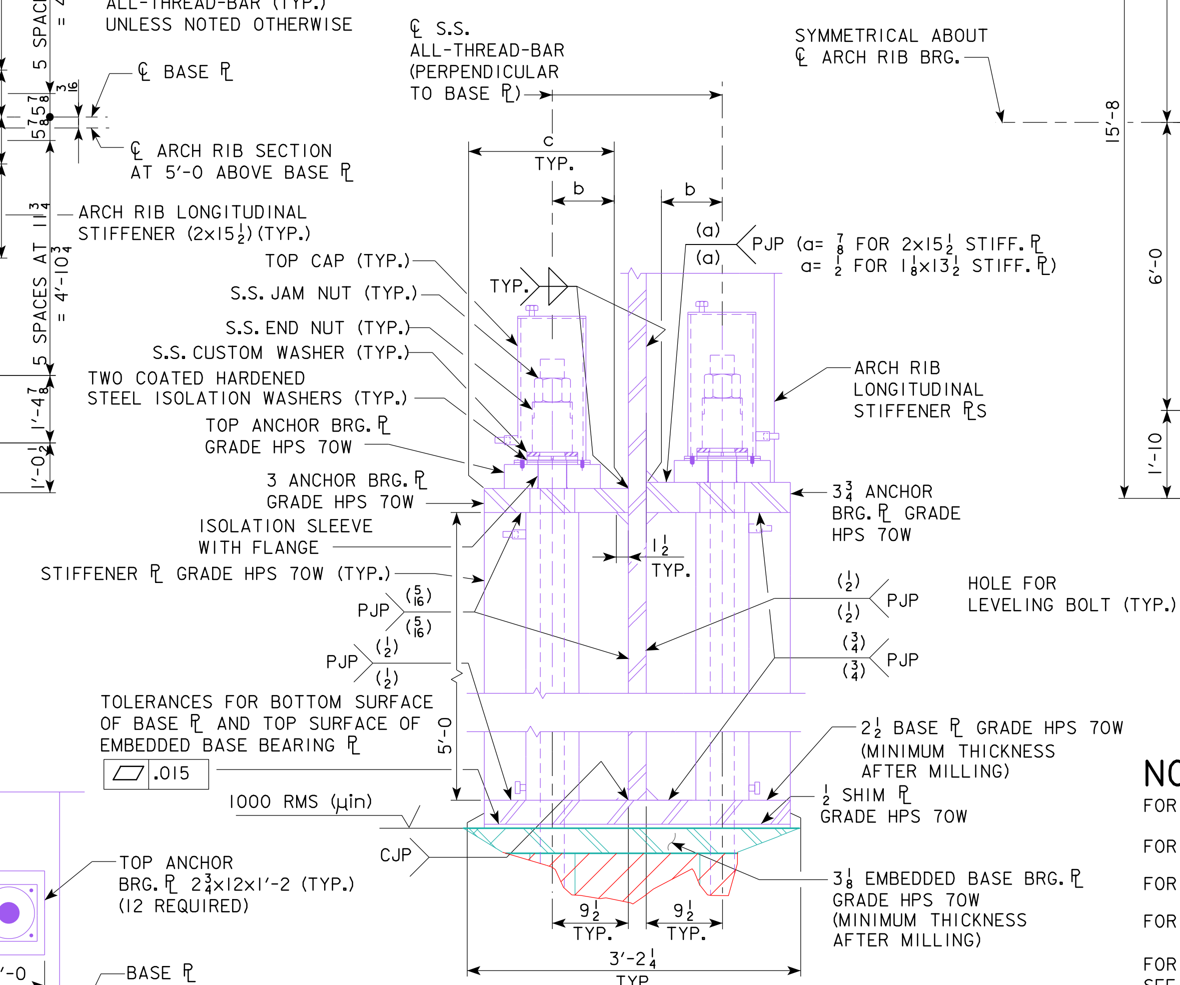


DETAIL 4



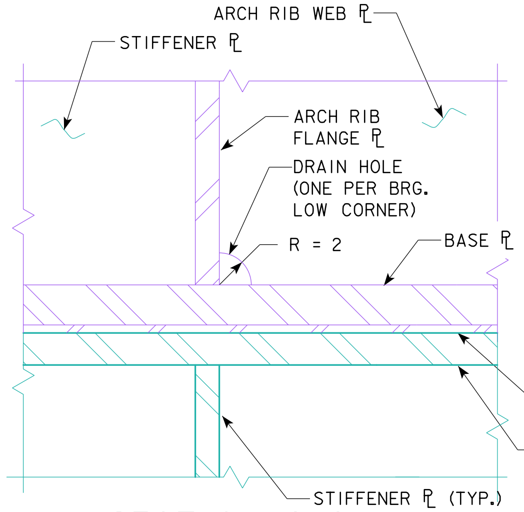
SECTION D-D

TEMPLATE AND BOTTOM ANCHOR BEARING ℙ



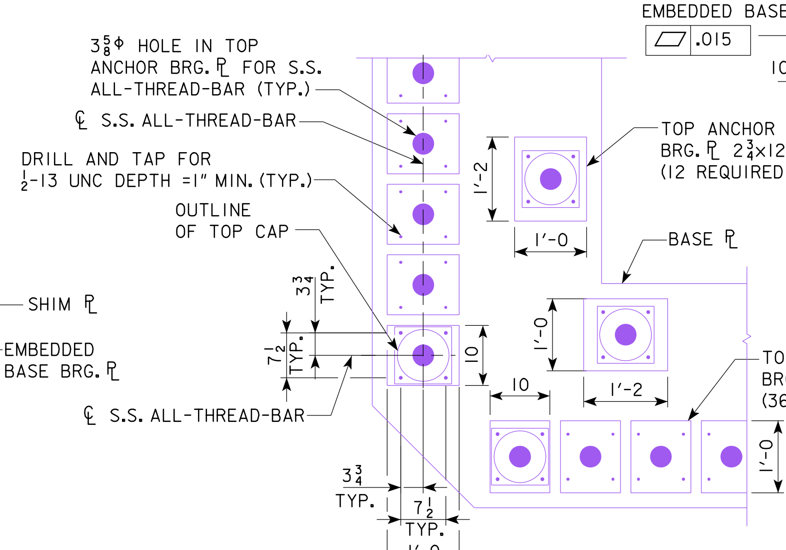
SECTION E-E

(FOR FLANGE AND BASE ℙ WELDS
AT CORNER STIFFENERS, SEE DETAIL 4)



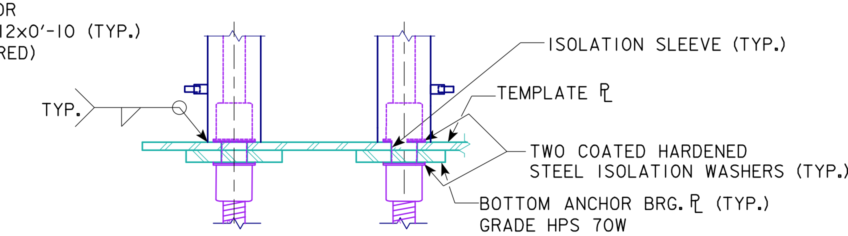
SECTION G-G

DETAIL LOCATED AT THE LOWEST
CORNER OF RIB FOR DRAINAGE
(BRG. W.P. 35, BRG. W.P. 51,
BRG. W.P. 39, AND BRG. W.P. 55)



DETAIL 5

(ARCH RIB AND ANCHOR BRG. ℙS
NOT SHOWN FOR CLARITY)



SECTION F-F

NOTES

FOR GENERAL NOTES, SEE DESIGNS 617 & 717.

FOR SECTIONS C-C AND D-D ORIGIN, SEE DESIGN SHEET 69.

FOR ARCH RIB W.P. L, TOP OF PIER ELEVATION, SEE DESIGN SHEETS 8 & 37.

FOR ISOLATION DETAILS, SEE DESIGN SHEET 69A.

FOR EMBEDDED BASE BEARING ℙ AND BASE ℙ DETAILS, SEE DESIGN SHEET 71.

FOR DISTANCES b AND c, FROM SECTION E-E, SEE DESIGN SHEET 71.

S.S. DENOTES 2507 DUPLEX STAINLESS STEEL.

SUBSTRUCTURE DESIGN FOR 0° SKEW

DUAL 795'-0 x 72' STEEL ARCH BRIDGE

ARCH RIB-CONCRETE INTERFACE DETAILS
ARCH SUBSTRUCTURE

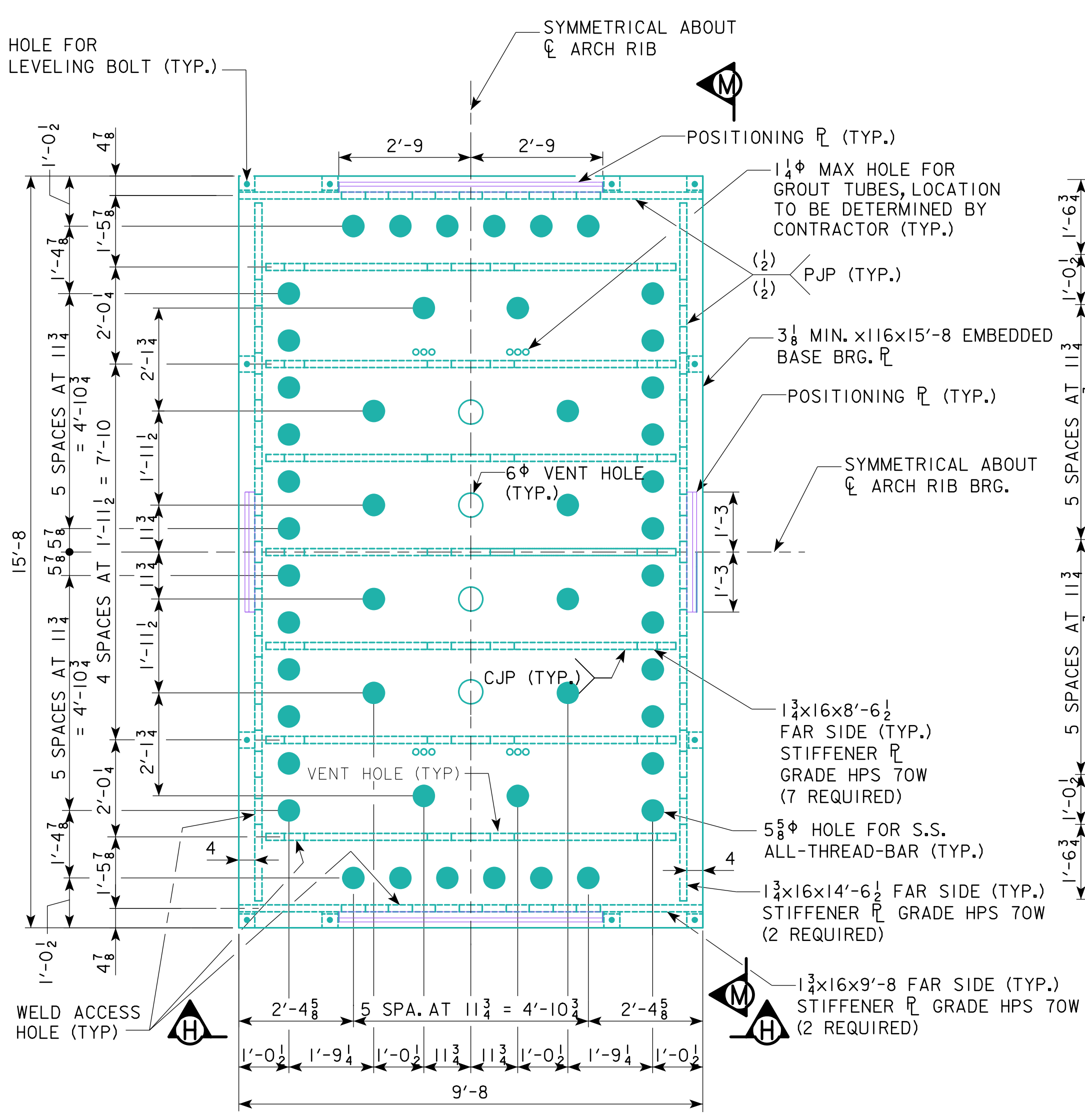
STA. 6770+98.50, ℄ PROPOSED I-74 DECEMBER 2016

SCOTT & ROCK ISLAND COUNTIES

IOWA DEPARTMENT OF TRANSPORTATION - HIGHWAY DIVISION

DESIGN SHEET NO. 70 OF 74 FILE NO. 30253 DESIGN NO. 817

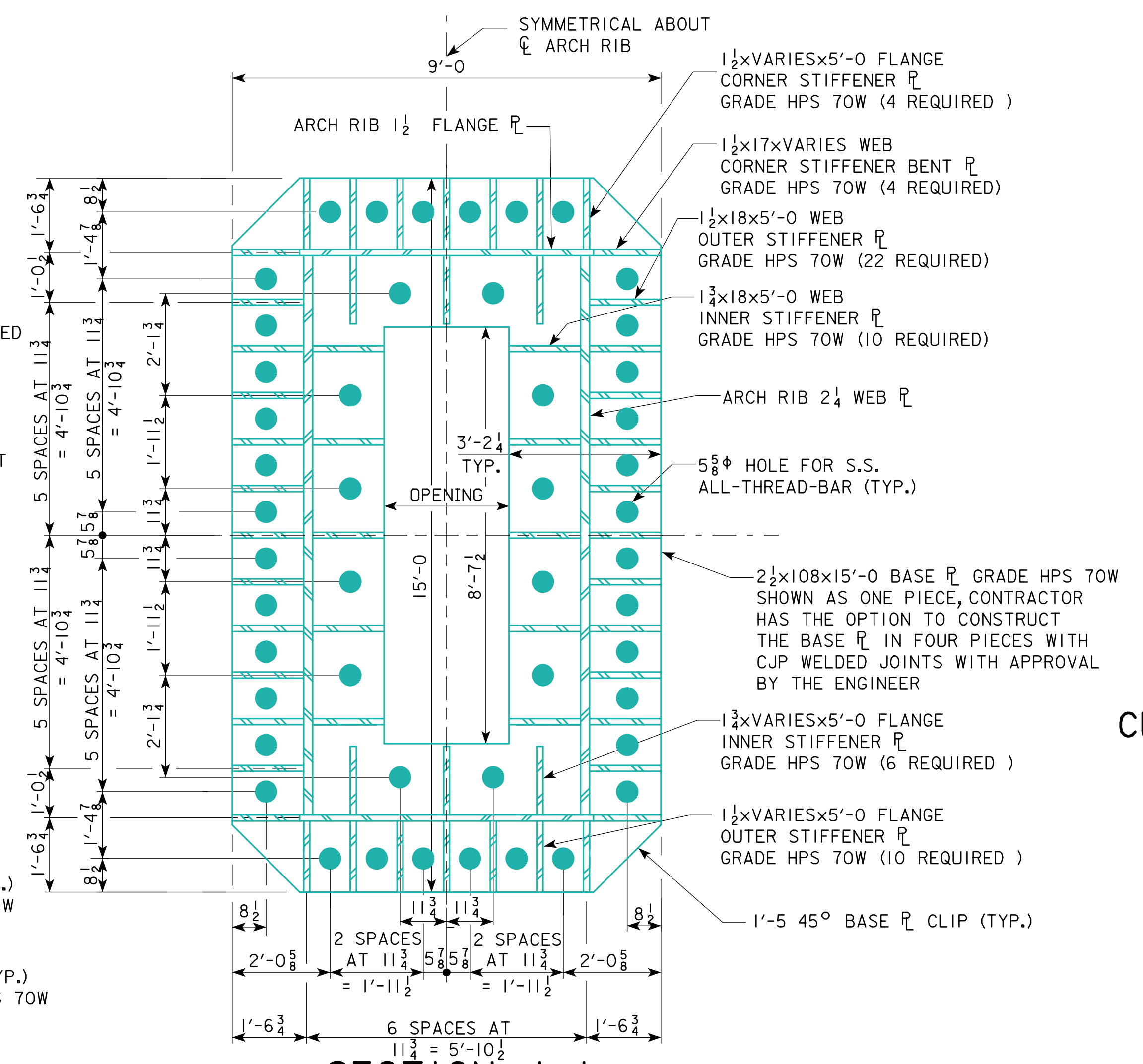
MODJESKI and MASTERS
Experience great bridges.



PLAN

EMBEDDED BASE BRG. ℙ

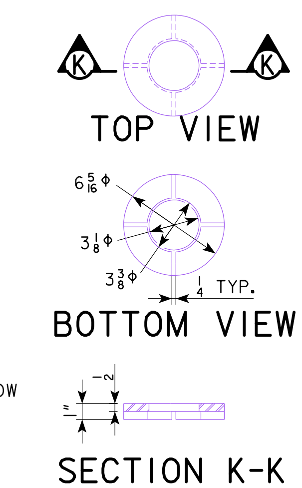
(SHEAR STUDS AND HSS NOT SHOWN FOR CLARITY)



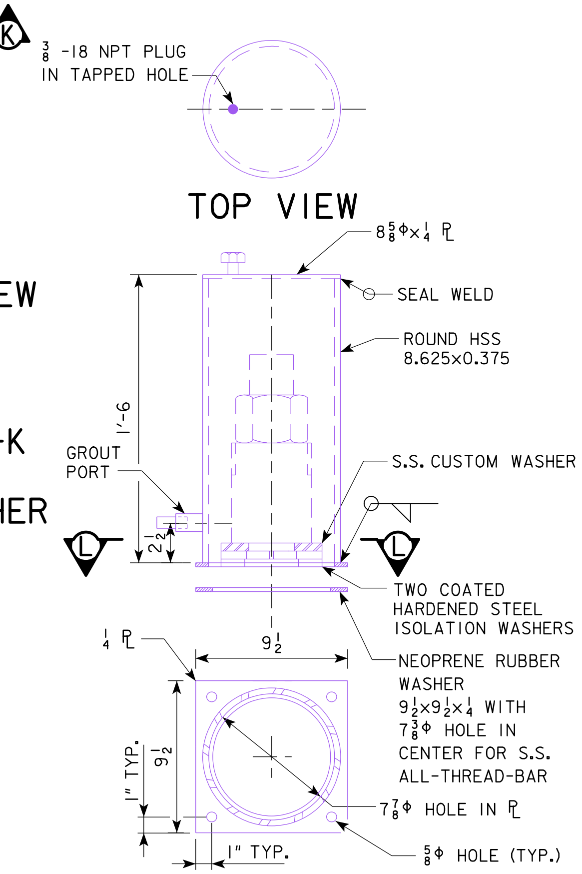
SECTION J-J

BASE PLATE

(CONCRETE FOUNDATION, EMBEDDED BASE BRG ℙ, HSS AND PIPE NOT SHOWN FOR CLARITY)



CUSTOM WASHER

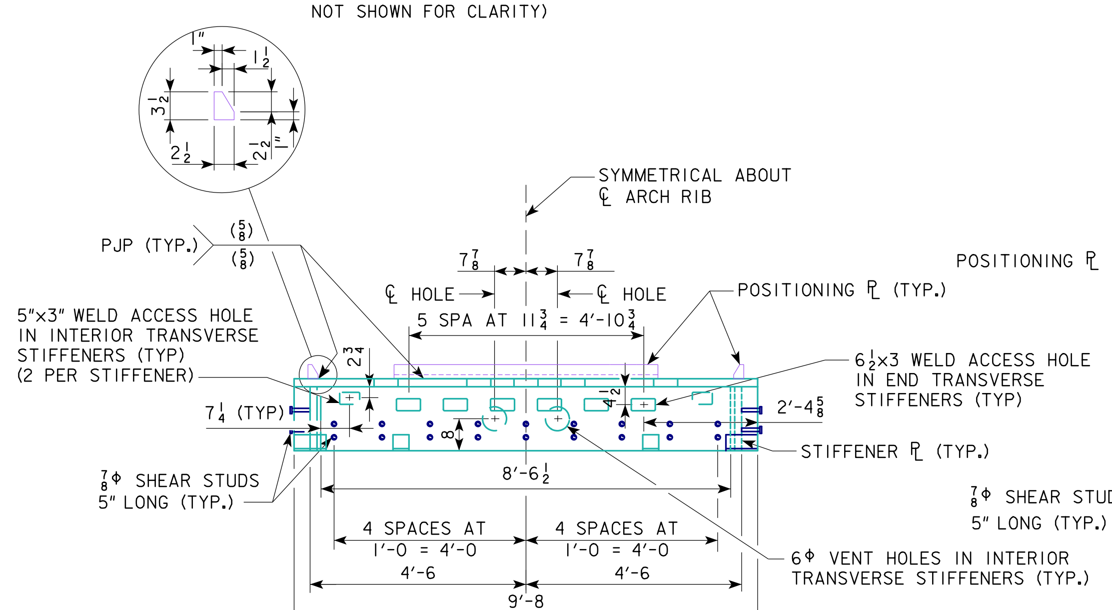


S.S. ALL-THREAD-BAR TOP CAP DETAILS

ANCHORAGE DIMENSIONS

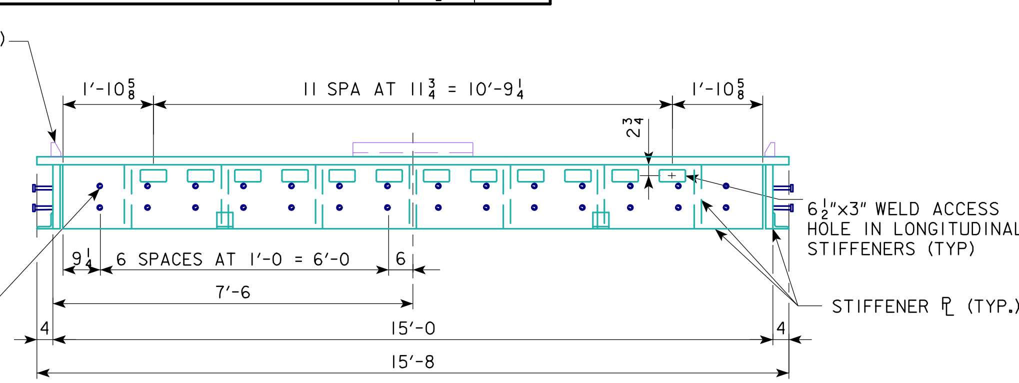
(SEE SECTION E-E PREVIOUS DESIGN SHEET)

LOCATION	"b"	"c"
ARCH RIB TOP FLANGE - OUTSIDE	9⅞	18⅜
ARCH RIB TOP FLANGE - INSIDE	9⅛	17⅝
ARCH RIB BOTTOM FLANGE - OUTSIDE	9 9/16	18 1/16
ARCH RIB BOTTOM FLANGE - INSIDE	9 7/16	17 15/16
ARCH RIB WEB - OUTSIDE	9½	18
ARCH RIB WEB - INSIDE	9½	18



VIEW H-H

(HSS NOT SHOWN FOR CLARITY)



VIEW M-M

(HSS NOT SHOWN FOR CLARITY)

NOTES:

FOR GENERAL NOTES, SEE DESIGNS 617 & 717.

PRIME MATING SURFACES OF BASE PLATE, EMBEDDED BASE BEARING PLATE, AND SHIM PLATE TO PROVIDE A CLASS A OR BETTER SLIP COEFFICENT.

POSITIONING ℙ'S ARE CONCEPTUAL AND ARE TO BE SUPPLIED AND INSTALLED IN DESIGN NO. 617.

FOR SECTION J-J ORIGIN, SEE DESIGN SHEET 69.

S.S. DENOTES 2507 DUPLEX STAINLESS STEEL.

WELD ACCESS HOLE CORNER RADIUS = 1" (TYP.)

SUBSTRUCTURE DESIGN FOR 0° SKEW

DUAL 795'-0 x 72' STEEL ARCH BRIDGE

ARCH RIB-CONCRETE INTERFACE DETAILS

ARCH SUBSTRUCTURE

STA. 6770+98.50, ℄ PROPOSED I-74 DECEMBER 2016

SCOTT & ROCK ISLAND COUNTIES

IOWA DEPARTMENT OF TRANSPORTATION - HIGHWAY DIVISION

DESIGN SHEET NO. 71 OF 74 FILE NO. 30253 DESIGN NO. 817

MODJESKI and MASTERS Experience great bridges.

DESIGN TEAM NYG/EAR/TJS | SCOTT COUNTY | PROJECT NUMBER IM-NHS-074-1(198)5--03-82 | SHEET NUMBER 115

SP- 150263a
(New)

SPECIAL PROVISIONS
FOR
HIGH-STRENGTH, STAINLESS STEEL BARS FOR POST-TENSIONED CONCRETE

Scott County
IM-NHS-074-1(198)5--03-82

Effective Date
April 25, 2017

THE STANDARD SPECIFICATIONS, SERIES 2015, ARE AMENDED BY THE FOLLOWING MODIFICATIONS AND ADDITIONS. THESE ARE SPECIAL PROVISIONS AND THEY SHALL PREVAIL OVER THOSE PUBLISHED IN THE STANDARD SPECIFICATIONS.

150263a.01 DESCRIPTION.
This Special Provision covers high-strength, stainless steel bars intended for use in post-tensioning (P/T) applications. This work consists of manufacturing, fabricating, furnishing and handling high-strength, stainless steel, all-thread bars and hardware for use as a P/T concrete anchor at the steel arch rib interfaces with Piers 12 and 13.

The P/T bars have continuous thread surface deformations, known as Type II bars. Stainless steel hardware shall include end nuts, coupling nuts, jam nuts, custom washers, temporary jacking hardware (stressing bars, stressing nuts, and stressing end nuts) and any miscellaneous stainless steel items needed to furnish a complete P/T anchorage bar assembly.

The specified stainless steel is 2507 Duplex Stainless Steel. Bars shall have a minimum tensile strength F_{ut} of 116,000 psi.

The Engineer will not consider alternate stainless steel alloys for this application. The stainless steel alloy used for the nuts, couplers, washers and other hardware shall match the threaded bar alloy to prevent dissimilar alloy contact.

A. Ordering Information: Orders for high-strength stainless steel bars under this Special Provision shall contain the following information:
- Project Title or Reference.
- Stainless steel alloy.
- Quantity of bars, coupling nuts, end nuts, and custom washers.
- Quantity of stressing bars, stressing nuts, and end nuts (not for final use in bridge).
- Size and length.

B. Commentary: This is a new application and new type of material for high-strength, stainless steel, all-thread bars for post-tensioned (P/T) concrete. As such, the Iowa DOT commissioned a research project for the development of the material application and stainless steel alloy selection. Where appropriate, the Iowa DOT has provided commentary from the researchers in various sections herein to relay experiences for the manufacture and fabrication of the bar. (Commentary is noted as such in parenthesis and provided in *italic* type face and highlighted in grey.)

150263a.02 DEFINITIONS.

Anchorages: An assembly of various hardware components that secures the stainless steel, all-thread-bars at their ends after they have been stressed and transfers a compressive force into the concrete or steel arch base.

Cold-Rolled Thread: A threading method that uses dies and pressure to displace rather than physically cut material to create threads. This is often used in conjunction with a slightly reduced diameter body.

Contamination: When carbon steel contacts a stainless steel, it can contaminate the stainless steel surface with free iron. This can de-passivate the protective oxide film of the stainless steel surface, leaving the material vulnerable to corrosion.

Coupling Nut: An internally threaded, longer-than-standard end nut used to connect two pieces of threaded material and develop the full tensile strength of the joined material. The threaded material engages the coupling nut for one-half the length on each end. This is also referred to as a stop-type coupling when a feature used to limit thread engagement is incorporated at the center of the nut length.

End Nut: An internally threaded product intended for use on external or male screw threads of the anchorage bar for the purpose of tightening or assembling two or more components.

Galling: A cold-welding process that can occur when the mating surfaces of male and female threads are placed under heavy pressure. During fastener tightening, high pressure can deform the mating threads and result in localized cold welding, leading to thread seizing.

Passivation: The process of forming an oxide film on a stainless steel surface by chemical treatment to improve corrosion resistance of the stainless steel material. The process is usually performed after the steel has been subjected to machining or contact with carbon steel.

Relaxation: An observed stress decrease in response to the same amount of strain generated in the structure, or simply creep within the steel under prolonged strain.

Right-Hand Thread: A screw thread that is screwed in or tightened-on clockwise. Right-hand threads are designated as RH or are not designated, as this thread pattern is most common.

Seating: Anchor seating is the total movement of a point on the post-tensioning bar during load transfer from the jack to the permanent anchorages. This is also known as seating loss in the bar, as some of the initial stressing load will be lost due to seating of the anchor plates, thread engagement and bearing within the lock-off nut, and immediate elastic relaxation of the metal.

Stop-Type Coupling: See Coupling Nut.

Stressing Nut: Similar to a coupling nut. Nut of the same stainless steel alloy as the threaded bar, used to post-tension the bar by threading on the exposed bar tail. The stressing nut usually has two or more parallel machined surfaces to allow for wrench-tightening / untightening. Nut may be hex-shaped in cross-section.

Tail: The length of threaded bar protruding from the end or lock-off nut, required to engage a temporary stressing nut used during the stressing operation.

150263a.03 MATERIALS.

A. Reference Documents.

1. **ASTM International.**

A276	Standard Specification for Stainless Steel Bars and Shapes
A370	Test Methods and Definitions for Mechanical Testing of Steel Products
A484	Standard Specification for General Requirements for Stainless Steel Bars, Billets, and Forgings
A722	Standard Specification for High-Strength Steel Bars for Prestressed Concrete (*covers carbon steel only*)
A751	Standard Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
A967	Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts
E10	Standard Test Method for Brinell Hardness of Metallic Materials
E18	Standard Test Methods for Rockwell Hardness of Metallic Materials
E23	Standard Test Methods for Notched Bar Impact Testing of Metallic Materials
E140	Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness
E328	Standard Test Methods for Stress Relaxation for Materials and Structures

2. **AASHTO.**

T244	Standard Method of Test for Mechanical Testing of Steel Products

B. Anchor Bar Fabricator: Furnish all components of the high-strength, stainless steel bar post-tensioning system from a single source, bar fabricator. The fabricator shall have experience in producing carbon steel P/T bars conforming to ASTM A722. Acceptable P/T bar fabricators are:

1. Dywidag Systems International (DSI), Bolingbrook, IL.
2. Williams Form Engineering Corp., Belmont, MI.
3. An approved equal.

C. Stainless Steel Supplier: Furnish all material of the high-strength, stainless steel bar post-tensioning system from a single source, supplier. Raw materials shall be sourced from a steel supplier subject to the Buy America provisions of the FHWA. Acceptable suppliers are:

1. Carpenter Technology Corporation, Philadelphia, PA. (*a contact familiar with this project is Kent Wilson, kwilson@cartech.com, 484-269-4130 cell*).
2. An approved equal.

D. All-Thread-Bars: All-thread, high-strength, stainless steel post-tensioning bars shall have the following requirements:

1. Stainless steel alloy - 2507 Duplex (UNS S32750).
2. Heat Treatment - Normal annealing as recommended by the manufacturer.
3. Minimum tensile strength, F_{ut} = 116 ksi.
4. Minimum yield strength, F_y = 80 ksi.
5. Length - as required for installation location.
6. Diameter - maximum 3 inch outside thread diameter.

7. Minimum effective tensile area – 6.14 square inches.

8. Finish - round with threads; passivated.

E. Coupling Nuts: Coupling nuts for joining two lengths of the all-thread bar shall develop the minimum specified tensile strength of the bar and have the following requirements:

1. Stainless steel alloy - 2507 Duplex (UNS S32750).

2. Heat Treatment - Normal annealing as recommended by the manufacturer.

3. Minimum tensile strength, F_{ut} = 110 ksi.

4. Minimum yield strength, F_y = 75 ksi.

5. Length - minimum of 12 inches.

6. Diameter - 5.0 inch outside diameter.

7. Finish - polished round and passivated.

8. Stop Pin - at mid-nut width and length to verify engagement of the two bar ends for stressing; pin shall be 2507 Duplex stainless steel.

F. End Nuts: End nuts for the all-thread bar shall develop the minimum specified tensile strength of the bar and have the following requirements:

1. Stainless steel alloy - 2507 Duplex (UNS S32750).

2. Heat Treatment - Normal annealing as recommended by the manufacturer.

3. Minimum tensile strength, F_{ut} = 110 ksi.

4. Minimum yield strength, F_y = 75 ksi.

5. Length - minimum of 5 inches.

6. Diameter - 5 inch outside diameter.

7. Finish - polished round and passivated.

G. Jam Nuts: Jam or stop nuts for the all-thread bar to be used at the end of the coupling nuts and end nuts shall have the following requirements:

1. Stainless steel alloy - 2507 Duplex (UNS S32750).

2. Heat Treatment - Normal annealing as recommended by the manufacturer.

3. Minimum tensile strength, F_{ut} = 110 ksi.

4. Minimum yield strength, F_y = 75 ksi.

5. Length - minimum of 3 inches.

6. Diameter - 5.0 inch outside diameter.

7. Finish - polished and passivated.

H. **Stressing Nuts:** Stressing nuts for joining two lengths of the all-thread bar during stressing shall develop the minimum specified tensile strength of the bar and have the following requirements:

1. Stainless steel alloy - 2507 Duplex (UNS S32750).
2. Heat Treatment - Normal annealing as recommended by the manufacturer.
3. Minimum tensile strength, F_{ut} = 110 ksi.
4. Minimum yield strength, F_y = 75 ksi.
5. Length - minimum of 12 inches.
6. Diameter - 5 inch outside diameter.
7. Finish - polished round and passivated.
8. Identification - label all stressing nuts with permanent paint in a conspicuous location to avoid their accidental use in the permanent bridge assemblies.
9. Visual Inspection Hole - provide at mid-nut thickness and length to verify engagement of the two bar ends for stressing.

I. **Custom Washers:** Custom washers as detailed on Drawing Sheet 139 shall have the following requirements:

1. Stainless steel alloy - 2507 Duplex (UNS S32750).
2. Heat Treatment - Normal annealing as recommended by the manufacturer.
3. Minimum tensile strength, F_{ut} = 110 ksi.
4. Minimum yield strength, F_y = 75 ksi.
5. Thickness - 1 inch.
6. Outside Diameter – 6 5/16 inches.
7. Inside Diameter - varies as 3 1/8 inches or 3 3/8 inches. Refer to drawing detail.
8. Finish - polished round and passivated.

J. **Fabrication.**

1. **Tolerance Levels:** The supplier shall specify minimum round bar tolerances for the plain bars to be ordered from the mill. In absence of specific tolerances for cold-finished bars, the permissible dimensional variations for cold-finished stainless steel bar shall not exceed the applicable tolerance levels or limits stated in ASTM A484 for inch-pound values.

2. **Thread Deformations**.
   a. All-thread post-tensioning bars shall have deformations spaced uniformly along the entire length of the bar. The thread deformations around the bar perimeter shall be similar in size and shape, and be continuous.

b. Threading shall be achieved by cold-rolling. The thread form, size, clearances, and tolerances shall be similar to that used in the prior bar testing research program, which was 3.5 threads per inch. Alternate thread form, size, clearance, and tolerances will require verification through full-size tension testing of the bar and nuts, and are subject to approval by the Engineer.

c. Threads on the bar and threading of the nuts shall mate to provide smooth installation of the nut on the bar with or without stress on the bar both before and after application of the pre-stretch load (refer to the Special Provision for Post-Tensioning of Arch Rib Bearings), which will cause inelastic deformation of the bar.

d. All threading shall have a right-hand (RH) thread orientation for all bars and nuts fabricated.

*(**Commentary**: Threading for the bar testing research program was performed by Dywidag Systems International (DSI). Minimum nut and coupling sizes provided in this special provision are based upon use of that thread. The stainless steel bars and nuts tested in the bar testing research program had a 3.5 threads per inch thread pitch. The various nut lengths specified above (Items D, E, F, & G) were tested and verified to develop the full-strength of the bar. Any significant deviation from the thread utilized in the bar testing research program will require approval by the Engineer. Moreover, verification by full scale tension testing of the bar and nuts to develop strength will be required for any thread form not conforming to that used during the bar testing research program. The draft final report is provided with this Special Provision for informational purposes only.)*

3. **Mechanical Coupling:** The bars shall have deformations arranged in a manner to permit coupling of the bars with a thread-on type coupling nut. It shall be the responsibility of the finished-bar manufacturer to demonstrate that a bar cut at any point along its length may be freely coupled to any other length of bar. Additionally, the coupled joint shall be capable of developing the minimum specified tensile strength of the coupled bars without coupler slip or thread tearing.

4. **Verification / Inspection.**

a. Coupling nuts shall be supplied with a 1/2 inch diameter hole at the center of the length and drilled full nut thickness. A 1/2 inch diameter, 2507 Duplex stainless steel stop pin shall be inserted and fixed in the coupler to provide a physical stop at the nut centerline to verify thread bar engagement at a splice. Welding of the stop pin is prohibited.

b. Stressing nuts shall be supplied with a 1 inch diameter, visual inspection hole at the center of the nut length and drilled full nut thickness.

5. **Finish:** The fabricated bars and nuts shall be free of defects injurious to the tensile properties and shall have a workmanlike finish.

6. End nuts shall have a minimum of two, parallel machined surfaces to allow for wrench-tightening, as required. As required, the top end nut shall have a hex pattern for tightening access while in the jacking frame. Indicate on the piece drawings the depth and length of the machined plane surface(s).

7. In as practical as possible, assign certain machines to fabricate stainless steels only, to prevent carbon steel contamination. Use the same preferred coolant to cut stainless steels, to the exclusion of all other metals.

K. Chemical Analysis.

1. A chemical analysis of each heat of steel shall be determined in accordance with ASTM A751. The manufacturer shall make the analysis on test samples taken during the pouring of the heat. The chemical composition determined shall be reported on the mill certificate for the heat.

2. The stainless steel shall conform to the chemical composition shown in Table 1, in accordance with ASTM A276:

Table 1 - 2507 Duplex Stainless Steel Chemical Requirements (Heat Analysis)

Element	Chemical Composition (%) [1]
Carbon (C)	0.030
Manganese (Mn)	1.20
Phosphorus (P)	0.035
Sulfur (S)	0.020
Silicon (Si)	0.80
Chromium (Cr)	24.0 to 26.0
Nickel (Ni)	6.0 to 8.0
Molybdenum (Mo)	3.0 to 5.0
Nitrogen (N)	0.24 to 0.32
Copper (Cu)	0.05

Note (1): Maximum, unless range specified.

3. In addition to the Table 1 requirements, the (% Cr) + (3.3 x % Mo) + (16 x % N) shall be greater than or equal to 41.

4. A product analysis may be made by the Engineer from the bar representing each heat of steel.

L. Mill Certification Material Analysis.

1. Tensile Testing: Tension tests shall be conducted in accordance with ASTM A370 or AASHTO T244 on machined specimens. Values reported shall include the following:
- Tensile Strength
- Yield Strength based on 0.2% offset
- Elongation in 2 inches.
- Percent Reduction in Area

2. Hardness Testing: Per Section K3 below, in accordance with ASTM E10 or E18.

3. Toughness Testing: Per Section K4 below, in accordance with ASTM E23 at -30°F or colder.

M. Fabricated Bar Verification Testing.

1. Tensile Properties.

a. Tension test specimens shall be the full section of the bar as fabricated in final form. The length shall be a minimum of 12 feet. Machined-reduced section test specimens are not permitted. Tension tests shall be conducted in accordance with ASTM A370 or AASHTO T244.

b. Area: All unit stress determinations shall be based on the nominal area determined from the bar weight [mass] less 3.5% for the weight [mass] of the deformations.

c. Threaded bars shall develop the specified tensile strength and yield strength of the original material.

d. Record the load-deformation curve up to 1% strain, using extensometers, LVDTs, or other elongation measurement means in either a 25 inch or 50 inch gage length.

2. Relaxation.

a. Full-size specimens shall be tested to determine their long-term relaxation under load. In addition to the following conditions, the general test procedures described in ASTM E328, Test Method A can be referenced.

- **b.** **Gage Length:** The gage length shall be at least 40 times the nominal bar diameter (**40*d*_b**).
- **c.** The temperature of the test specimen shall be maintained at 68°F ± 3.5°F. Any deviation from this mean temperature shall be accounted for in the test through thermocouples or temperature compensating load cells. In no instance shall the temperature drop below 45°F, unless the test is being performed at a lower specified design temperature.
- **d.** **Test Duration:** The relaxation test duration shall be 1000 hours.
- **e.** The test set-up shall consist of a stiff, stationary framework. End nuts shall be long enough to prevent nut failure during the test duration.
- **f.** The test specimen shall not be subjected to loading above 10% of its minimum breaking strength prior to the relaxation test.
- **g.** The stressing load shall be applied uniformly over a period of not less than 3 minutes and not more than 15 minutes.
- **h.** Load-elongation readings shall be taken when the test commences up to the target stressing load. Load-relaxation readings shall commence 1 minute after application of the total stressing load, after seating losses have occurred, if any. It shall be permitted to restress the test following initial readings to account for seating losses.
- **i.** Load-relaxation readings shall be taken no less than once per 2 hours for the test duration.
- **j.** Over-stressing of the test specimen beyond $0.9F_{pu}$ during application of the load shall not be permitted.
- **k.** The initial test load (after seating loss) shall be a minimum of 368 kips (60 ksi on a stress area of 6.14 square inches). The initial test load shall not exceed 430 kips (70 ksi on a stress area of 6.14 square inches). It should be noted that higher initial test loads will produce less favorable results. This test load shall be used to verify if the stressing level and associated relaxation losses are within the limits established by the design.
- **l.** The maximum permissible relaxation values are provided in Table 2:

Table 2 - Maximum Relaxation Values

Acceptance Criteria for 1000 Hour Relaxation Test Performed at 60 ksi Initial Stress (After Seating Losses) [1,2]	
Ratio of (100 hr Loss)/(1000 hr Loss)	**Maximum Permissible 1000 hr Loss (ksi)**
55.0%	0.95
65.0%	1.55
75.0%	2.36
85.0%	3.41

Note (1): Linear Interpolation is acceptable.

Note (2): For initial stress values exceeding 60 ksi, the maximum permissible 1000 hr loss may be increased by a ratio of (actual initial stress in test, ksi)/(60 ksi target initial stress)

- **m.** The Engineer reserves the right to modify the final P/T stressing values of the installed bars based on this testing.
- **n.** Failure to meet the relaxation limits above may result in rejection of the material.

3. Hardness.

- **a.** Hardness shall be reported across the section of the threaded bar, and at the inside and outside diameter of the end nuts and coupling nuts for fabricated material.
- **b.** Hardness testing shall be conducted in accordance with ASTM E10 or E18. Conversion factors per ASTM E140 shall be permitted to be used.
- **c.** The maximum hardness value of the fabricated material shall not exceed the value given in Table 3:

Table 3 - Maximum Hardness Values

Hardness Type	Maximum Value
Brinell	310
Rockwell C	33

4. **Fracture Toughness.**
   a. **Fracture Critical Tension Component:** The anchorage bars shall be considered fracture critical. Test specimens shall be procured from fabricated bars and impact tested in accordance with ASTM E23.
   b. **Impact Specimens**:
   - Specimens shall be standard-size or sub-size specimens, and indicated as such in the report.
   - The longitudinal axis of each specimen shall be parallel to the final direction of rolling of the bar or parallel to the longitudinal axis of the bar.
   - A minimum of three impact tests shall be taken from the center of the fabricated anchorage bar and tested.

   c. The minimum Charpy V-notch impact test results shall be as shown in Table 4:

Table 4 - Impact Test Requirements for P/T Bars

Minimum Energy Test Value, ft-lbs	Minimum Average Energy Value, ft-lbs
160	200 at -30°F

   d. The Charpy V-notch impact test results shall be reported to verify compliance with this Special Provision.

N. Number of Tests.

1. Hardness and impact testing shall be conducted in triplicate and considered as one set of tests. The number of test specimens shall consist of one set for every lot of 150 fabricated, all-thread bar(s) produced, or fraction thereof.

2. Tension and relaxation testing shall consist of testing three full-scale fabricated bars for the entire project, unless retesting is required.

3. Furnish all material samples for QA / QC testing at no additional cost to the Contracting Authority.

4. One set of dimensional property tests including bar weight (mass), and spacing, height and projected area of deformations shall be made of each bar size rolled from each heat.

*(**Commentary**: Any thread change will require experimental verification of the end and coupling nut's length and ability to develop the full strength of the bar. Fabricator shall submit their proposed testing program to verify.)*

O. Retesting.

1. If the minimum property of any test specimen is less than that specified, a retest shall be permitted.

2. If the results of a tension test specimen fail to meet specified requirements, two additional tests shall be made. If the tensile property in either of these tests is less than the minimum specified value, that heat shall be rejected.

3. If any test specimen fails because of mechanical reasons such as failure of testing equipment, it shall be discarded and another specimen taken.

4. If any test specimen develops flaws, it shall be discarded and another specimen of the same size bar from the same heat substituted.

P. Field Passivation: The citric acid solution for field passivation shall be:

1. *CitriSurf 77*, manufactured by Stellar Solutions, Inc., McHenry, IL 60050, (847) 854-2800.

2. *CitriSurf 2210 Gel*, manufactured by Stellar Solutions, Inc.

3. *Stainless Steel Passivation Kit*, manufactured by Caswell Plating Inc., Lyons, NY, (855) CASWELL.

4. An approved equal.

Q. Lubricants: As required, thread lubricants shall be used to prevent stainless steel galling. Suitable lubricants shall be PTFE-based (Teflon), non-silicone, dry lubricants such as:

1. *WD-40 Specialist Dry Lube PTFE Spray*, by WD-40 Corporation.

2. *B'LASTER Advanced Dry Lube w/Teflon*, by B'laster Chemical Corp.

3. *Dry PTFE Lubricant*, by Rust-Oleum Industrial Products.

4. An approved equal.

150263a.04 SUBMITTALS.

A. The high-strength stainless steel bars shall have the following submittal requirements for the plain parent bar(s) from the mill:

1. Mill Certificates for all steel heats used, including but not limited, to the following:
   - **a.** Heat and / or lot number.
   - **b.** Weight of material represented by the heat number.
   - **c.** Finished bar diameter.
   - **d.** Bar length represented by the heat.
   - **e.** Report on chemical composition.
   - **f.** Tensile properties, including tensile strength, yield strength, elongation in 2 inches, and reduction of area.
   - **g.** Hardness.
   - **h.** Charpy V-notch impact test.

2. Melt source.

3. Material description.

4. The raw source material is free from radioactive contamination. The finished material is free from mercury contamination.

B. Drawing Submittals: Piece drawings shall fully depict the part or assembly in plan, elevation, or sectional views with appropriate dimensional information. At a minimum, submit the following piece drawings for the high-strength stainless steel bar assembly:

1. End nut.

2. Coupling nut with stops.

3. Jam nuts.

4. Custom washer.

5. Full-length view of the bar with hardware denoted.

6. Details of the stainless steel jacking bar and nut assembly to install the bar.

C. **Verification Testing:** The high-strength stainless steel bars shall have the following submittal requirements for a minimum of three, full-size, fabricated, all-thread bar(s) produced:

1. Actual tensile properties of the fabricated bar, including:
   a. Yield strength from the 0.2% offset
   b. Tensile strength
   c. Elongation

2. Load-elongation behavior up to 1% strain.

3. Brinell or Rockwell C hardness reported across the section of the threaded bar, and at the inside and outside diameter of the end nuts and coupling nuts.

4. Charpy V-notch test results at a temperature of -30°F. Results shall be reported for standard-size or sub-size specimens.

5. Relaxation data for the 1000 hours relaxation test, including jacking load, initial test load, load at 100 hours, and load at 1000 hours for each bar tested. A graph showing all readings for load vs. time for each bar tested.

D. **Passivation Certification:** After all threaded bars, coupling nuts, end nuts, jam nuts, and custom washers have been fabricated, provide evidence of shop passivation of the stainless steel.

E. **Submittal Procedures**: Unless noted otherwise, submit the above in advance of the start of construction to allow a 30 calendar day review period. All submittals not approved and requiring resubmission shall be subject to the above review time period, with the review time beginning anew for each such submittal. Coordinate all submittals between various subordinates (contractors, suppliers, and engineers) to allow for a reasonable distribution of the review effort required by the Engineer at any given time. Do not install the work until the submittals have been approved.

F. **Lots and Identification:** A lot is that parcel of components as described herein. All all-thread-bars from each mill heat of steel shipped to the site shall be assigned an individual lot number and shall be tagged in such a manner that each such lot can be accurately identified at the job site. Submit records to the Engineer identifying assigned lot numbers with the heat of material represented. All unidentified all-thread-bars received at the site will be rejected. Also, loss of positive identification of these items at any time will be cause for rejection.

G. **Approval of Materials:** The approval of any material by the Engineer shall not preclude subsequent rejection if the material is damaged in transit or later damaged or found to be defective for any reason.

H. Clearly mark the shipping package or form with a statement that the package contains high-strength, stainless steel all-thread-bars and the type of care that is to be used in handling.

*(**Commentary**: The stainless steel alloy to be procured for this project will require sufficient lead time from the stainless steel mill manufacturer. The alloy is a special order and will likely require*

a mill order, with the appropriate end treatment. Some mills may also have a minimum order requirement. It is suggested that extra, production bars be procured to account for loss, or thread damage, etc.; the delay in procuring a small quantity of bars as the result of damage or poor planning can be significant. Moreover, the Contractor should plan to have sufficient stressing bars and nuts of the same stainless steel alloy.)

150263a.05 CONSTRUCTION.

A. Stainless Steel Passivation and Protection.

1. After fabrication, all stainless steel parts making up the anchor rod assembly shall be thoroughly cleaned with a degreaser or cleanser to remove contaminants, cutting fluids, roll-thread lubricants, etc. The stainless steel parts shall then be passivated in nitric acid per ASTM A967.

2. Following stainless steel post-tensioning bar installation, stressing, and lock-off, all exposed stainless steel parts for the final bridge anchorage shall be cleaned and field-passivated with citric acid-based solutions per ASTM A967. Parts for this treatment include the bar tails, end nuts used for lock-off, and seating plates. These parts shall be thoroughly cleaned with a degreaser or cleanser to remove contaminants, threading lubricants, etc.

3. Consult with the manufacturer of the citric acid-based solution for specific information regarding product use, concentrations, duration of treatment, and clean-up. Submit this information to the Engineer for use with field inspection.

4. **Mock-Up:** The Contractor shall select two bar tail regions from the installed anchor bar assembly on the abutment representative of stainless steel contamination requiring re-passivation.

a. The mock-up will be used to demonstrate the appropriate technique and methods to re-passivate the stainless steel in the field, including:

- Appropriate surface preparation.
- Thickness (gel), liquid concentration, or amount of material required.
- Means of containing the material on the sloped surface and preventing spillage on adjacent concrete, fiberglass, and (carbon) steel surfaces.
- Verification of approximate coverage rate.
- Required duration of the treatment at the given temperature.
- Clean-up and disposal procedures.

b. The mock-up shall be conducted on steel surfaces with a minimum temperature of 50°F and rising. Infrared temperature devices shall be used to verify temperature.

c. The Engineer must approve the mock-up location.

d. After successful completion of the mock-up verified means and methods for re-passivation, the Contractor shall submit the procedure for record.

e. The Contractor may wish to consider conducting additional mock-ups or tests on land prior to trials on the actual abutment face. The Contractor shall notify the Engineer and/or Department of these trials to witness the field testing.

f. The manufacturer of the citric acid solution shall be involved with any field trials of their material.

5. Citric acid-based solutions shall be stored on the job-site at temperatures between 50°F and 120°F in manufacturer-approved containers. Do not allow material to freeze.

6. Do not leave concrete or carbon steel surfaces exposed to citric acid-based solutions for any prolonged time period. Damage to these materials will occur with prolonged exposure.

B. Stainless Steel Galling Prevention.

1. As required during the stressing and lock-off operation, use a suitable lubricant to prevent stainless steel galling and aid in the turning of the end nut, coupling nut, and stressing nut.

2. The Contractor shall limit the use of a lubricant to the bar thread length actually engaging the nut. All excess lubricant on the bar tail shall be removed and stainless steel cleaned before field passivation.

3. Any lubricant used should not contain molybdenum disulfide or copper particles.

C. Handling and Storage.

1. After passivation, avoid contamination of the stainless steel surfaces with carbon steel material such as surfaces, tools, cutting debris and weld splatter. All parts shall be wood blocked, handled with nylon lifting straps, bundled with high-strength polyester strapping (i.e. *Tenax* or equivalent), etc. Contact with plain, carbon steel shall be avoided to prevent contamination.

2. Prevent contact of carbon steel tool surfaces (wrenches, pipe wrenches, etc.) with the stainless steel. As necessary, fabricate special wrenches from stainless steel to mitigate contamination of the nuts and anchor bar.

3. The transported stainless steel shall not come in direct contact with flatbed trailer surfaces without proper blocking. Tie downs on the flatbed trailer shall consist of nylon straps or chains padded with a nylon sleeve. Conventional, unprotected steel chains or steel cable tie downs are prohibited.

4. The stainless steel bars and hardware shall be stored above grade on the jobsite. Cover the bars and all hardware with tarpaulins. The Contractor shall be responsible for the security of the bars on the jobsite.

5. Any stainless steel part suspected of being contaminated or compromised during shipment, storage, or handling shall be re-passivated.

6. The Contractor shall protect the finished and exposed stainless steel post-tensioning bar installations in the abutment from contamination during the remaining construction operations on the bridge structure. This includes, but not limited to, weld splatter, steel cutting splatter, cutting, grinding, steel painting overspray, concrete placements in the vicinity of the abutment, temporary guying anchorages, etc.

7. Any installed stainless steel part suspected of being contaminated or compromised from nearby construction activities shall be cleaned and re-passivated with citric acid.

D. Field Cutting of Bars.

1. Only cut the ends of the all-thread-bars if the jacking forces and elongations are satisfactory and approval has been obtained from the Engineer.

2. Cut all-thread-bar tail protrusions that exceed 6 inches in length beyond the nut using an abrasive gas saw (i.e. *Partner Saw* or equivalent) with a blade solely dedicated to cutting the stainless steel bar.

3. After cutting, the cut surfaces should be passivated as per Section B above.

4. Flame or plasma cutting is strictly prohibited.

E. Inspection and Maintenance.

1. The Engineer shall have free entry, at all times while work on the contract is being performed, to all parts of the manufacturer's works that concern the manufacture of the material ordered. The manufacturer shall afford the Engineer all reasonable facilities to satisfy him that the material is being furnished in accordance with this Special Provision.

2. All tests (except product analysis) and inspection shall be made at the place of manufacture prior to shipment. Alternately, the tests shall be conducted at a laboratory (or at laboratories) suitable to perform the tests, prior to shipment. All testing shall be witnessed by a Professional Engineer licensed in the State of Iowa.

3. The Engineer shall reserve the right to perform any of the inspection set forth in the specification where such inspections are deemed necessary to assure that the material furnished conforms to prescribed requirements.

4. The Contractor shall leave any remaining stressing bars and hardware at the jobsite for potential future use at the bridge abutments. This material shall be labeled with permanent paint in a conspicuous location (end or side) stating “I-74 Arch Bridge Abutment, 2507 Duplex, Anchor Bar Hardware.” The Contractor shall coordinate the storage location with the Department.

150263A.06 METHOD OF MEASUREMENT.
No measurement shall be made.

150263A.07 BASIS OF PAYMENT.
No separate payment will be made per this Special Provision section. The payment for the requirements of this Special Provision shall be made in accordance with the Special Provisions for Furnish and Install Arch Rib Anchorage Assembly and the Special Provisions for Post-Tensioning of Arch Rib Bearings, as applicable.