Mechanical and bond properties of Grade 2205 duplex high-strength stainless steel strand

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■ This paper describes experimental testing to determine the mechanical and bond properties of Grade 2205 duplex high-strength stainless steel strand.

■ In addition to a review of existing research, tensile testing of 25 strand specimens and pullout testing of six strand specimens was conducted.

■ Results indicate that the high-strength stainless steel strands meet the minimum mechanical properties outlined in the recently published ASTM A1114 standard and the minimum pullout strength criteria recommended by the PCI Strand Bond Task Group and can be tensioned with typical chuck devices without adversely affecting strand strength.

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Stainless steel prestressing strands are a recently developed type of prestressing strand with high corrosion-resistance properties. For the construction of durable, low-maintenance concrete structures in extremely aggressive environments, they are being promoted as an alternative to carbon steel strands. Stainless steel strands' high corrosion-resistance properties are due to the high content of nickel, chromium, and molybdenum and low content of carbon in their chemical composition.[1] In addition to corrosion resistance, the chemical composition of the strand also affects its mechanical properties. The manufacturing process is another factor that influences the strand's mechanical properties and the shape of the stress-strain curve,[2] which can be determined from tensile tests.

In pretensioned concrete members, the prestressing force is transferred from strand to concrete through bonding. The strand is bonded to the concrete through mechanical bond and chemical adhesion on the surface of the strand.[3] After slippage occurs, the bonding is controlled by friction as well as mechanical bond. Bonding depends on many parameters, such as concrete strength, surface condition of the strand, and type and size of the strand. For the surface condition of the strand, any lubricant residue left from the manufacturing process can affect both the chemical adhesion and friction of the strand.[4] Because the surface of stainless steel strands does not rust as carbon steel strands do, they can be classified as smooth compared with carbon steel strands. Considering the differences between stainless steel and carbon steel strands, the same bond properties cannot be assumed to be applicable for both. There is little information available for the bond properties of stainless steel strands; therefore, the bond of stainless steel strands needs to be evaluated.

As with all new products, the lack of information on the mechanical and bond properties of Grade 2205 duplex high-strength stainless steel (HSSS) strands will delay their implementation in civil engineering applications despite their desirable corrosion resistance properties. Also, the mechanical properties and stress-strain behavior of the HSSS strands need to be known.

This paper presents the mechanical properties of 0.6 in. (15.2 mm) diameter HSSS strands. Twenty-five 0.6 in. diameter HSSS strands from two spools were tensile tested. A stress-strain equation was developed for the HSSS strands. The proposed equation satisfies the *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete* (ASTM A1114)[5] requirements and results in a stress-strain curve similar to the experimental data. This paper also evaluates the bond of 0.6 in. diameter HSSS strands determined by testing six HSSS strands following the *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand* (ASTM A1081).[6] Experimental bond values of 0.6 in. diameter HSSS strands were compared with values calculated using the proposed acceptance criteria by the PCI Strand Bond Task Group.[7] This study is part of a larger research project where 0.6 in. diameter HSSS strands were used in the fabrication of several American Association of State Highway and Transportation Officials (AASHTO) Type II girders; design, construction, and flexural behavior of the girders as well as transfer length of HSSS strands are discussed in detail in other publications.[8,9]

A brief background on stainless steel strands

Multiple types of stainless steel strands have been developed, and researchers have experimentally evaluated their mechanical properties and corrosion resistance performance. Moser et al.[2,10] conducted a preliminary investigation to evaluate the mechanical properties of six different HSSS wires and their corrosion resistance performance in alkaline and carbonated concrete solutions. The six stainless steel wires were austenitic Grades 304 and 316; martensitic Grade 17-7; and duplex Grades 2101, 2304 and 2205. Moser[2] proved that it is possible to obtain mechanical properties of carbon steel strand by tensile testing a single wire taken from the strand. Thus, Moser et al.[2,10] performed the tensile tests on a single wire for all six specimens and engineering stress-strain curves were plotted. The diameter of a single wire was 0.16 in. (4.1 mm), which is comparable to a single wire from a 0.5 in. (12.7 mm) diameter carbon steel strand. Mullins et al.[11] evaluated the mechanical and corrosion resistance properties of three different stainless steel strands (Grade 316, Grade XM29, and duplex Grade 2205) with Grade 270 carbon steel strand as the control. Schuetz[12] evaluated the mechanical properties of duplex Grades 2205 and 2304 prestressing strands.

Results from previous studies have revealed that all tested stainless steel strands, regardless of their type, had rounded stress-strain curves after the elastic modulus was deviated. The degree of roundedness, ultimate stress, ultimate strain, and corrosion resistance varied among strand types. Although Moser et al.[10] did not report directly on the differences in roundedness of the stress-strain curves for the six types of stainless steel strands that were studied, the degree of the roundedness can be identified in the report. The mechanical properties and stress-strain behavior of strands depend on many factors, such as chemical composition, heat treatment, and level of cold work.[13] The cold-drawing process is essential to achieve high tensile strength.[14] The early nonlinear stress-strain behavior of stainless steel strands is likely due to the presence of residual stress from the cold-drawing process.[2] Heat treatment reduces residual stresses, which increases the tensile strength and improves the stress-strain relationship below yield;[2] however, heat treatment reduces ultimate strain. Thus, unlike carbon steel strands, stainless steel strands have low ultimate strain and stress and have a rounded stress-strain curve with early nonlinearity. All previous research has concluded that Grade 2205 duplex HSSS is the best option for strands compared with other types of stainless steel because of its high mechanical and corrosion resistance properties, which can potentially improve long-term performance of bridge structures in extremely aggressive environments.

Comparison of carbon steel and stainless steel strands

The mechanical properties of stainless steel strands are different from those of carbon steel strands. The minimum required mechanical properties of carbon steel strands are specified by *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete* (ASTM A416)[15] for both Grade 250 and Grade 270 strands. The mechanical properties specified by ASTM A416[15] cannot be used for stainless steel strands because stainless steel strands are made from different alloys than carbon steel strands. Stainless steel strands are relatively new, and the need for a standard specification led to the development of ASTM A1114,[5] which was recently published. The new ASTM A1114[5] specifies the minimum acceptable mechanical properties of Grade 240 stainless steel strands. The decrease in the grade from 270 in ASTM A416[15] to 240 in ASTM A1114[5] is attributed to the chemical composition of the strand and the manufacturing process.[2] Some alloying elements used to make stainless steel strands control the ultimate tensile strength.

Table 1 lists the minimum requirements for ASTM A1114 Grade 240 strands and comparably sized ASTM A416 Grade 270 strands. ASTM A1114 provides mechanical properties for only two sizes of stainless steel strands, 0.52 and 0.62 in. (13.2 and 15.7 mm) diameter. The area and weight of Grade 240 stainless steel strands are equal to their counterpart

Table 1. Minimum required mechanical properties of strands

Parameter	ASTM A416 Grade 270		ASTM A1114 Grade 240	
Nominal diameter, in.	0.52	0.62	0.52	0.62
Area, in.^{2}	0.167	0.231	0.167	0.231
Load at 1% extension, kip	40.5	56.52	36.1	49.86
Breaking strength, kip	45.0	62.8	40.1	55.4
Elongation, %	3.5	3.5	1.4	1.4
Weight of strand, lb/1000 ft	570	780	570	780

Note: ASTM A416 = *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*; ASTM A1114 = *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 in.^{2} = 645.2 mm^2; 1 lb = 0.454 kg; 1 kip = 4.448 kN.

Grade 270 carbon steel strands. Stainless steel strands have lower load at 1% extension, breaking strength, and elongation compared with carbon steel strands. The most significant difference between carbon steel and stainless steel strands is elongation. The guaranteed elongation for stainless steel strands is only 40% of that for carbon steel strands.

The shape of the stress-strain curve for stainless steel strands is different from that for carbon steel strands. Carbon steel strands exhibit a linear plateau, whereas stainless steel strands exhibit almost no strain hardening and have rounded behavior in the plastic region (**Fig. 1**). The limited ductility in stainless steel strands significantly affects the design philosophy for concrete members prestressed with stainless steel strands.

Tensile tests

Specimen preparation

Two new 0.6 in. (15.2 mm) diameter HSSS strand spools were received at different times in ideal condition: free of rust and any visible defects. They were stored at the Florida Department of Transportation (FDOT) Structures Research Center and protected from oil, excessive bending, and any physical damage. A mill test certificate for each spool was provided by the manufacturer, specifying the mechanical properties and stress-strain relationship of the HSSS strands. The mechanical behavior of HSSS strands might vary from spool to spool for multiple reasons, such as the wire rod used to make prestressing strands not being perfectly identical from heat to heat, chemistry variances of the elements alloyed, and processing variances. Therefore, multiple samples from the two spools were tensile tested. Both spools were produced by the same manufacturer. The samples from the two spools are referred to as first spool and second spool throughout this paper.

Fifteen HSSS strand specimens were taken from the first spool. Ten specimens were taken from the beginning of the spool. Then the strand in the spool was used to fabricate several pretensioned concrete beams. Information regarding fabrication and testing of those beams can be found in another report.[8] The other five specimens were taken from the

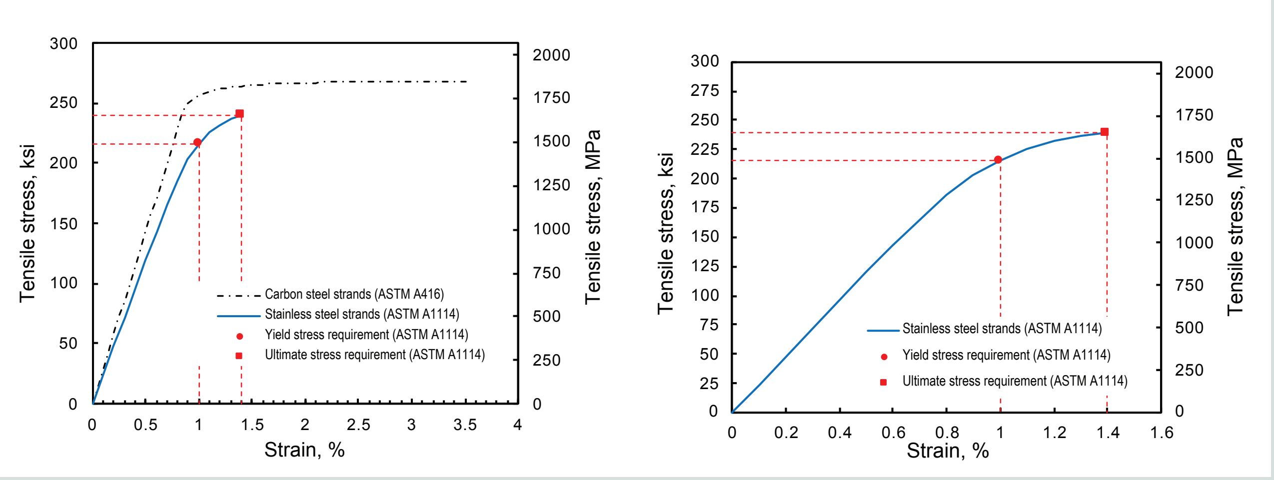
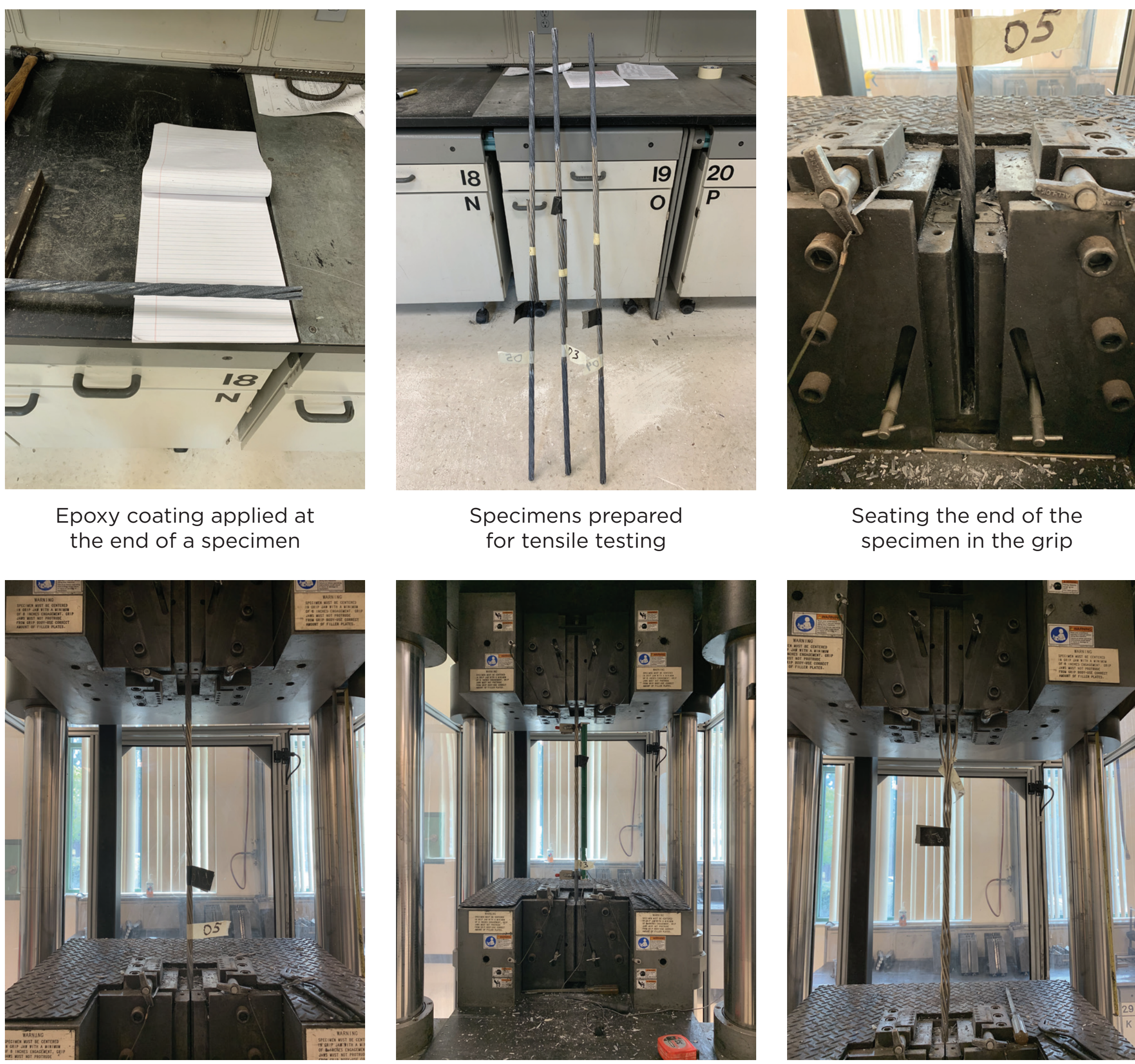


Figure 1. Comparison of stress-strain curves of stainless steel strands and carbon steel strands. Note: ASTM A416 = *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*; ASTM A1114 = *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete.*

additional length of strand in the precasting bed remaining after fabrication of the beams. Ten HSSS strand specimens were taken from the second spool. Five specimens were taken directly from the spool, and the other five specimens were taken from the strands in the precasting bed that remained after beam fabrication. All specimens were sent to the FDOT State Materials Office (SMO) for tensile testing.

Several methods can be used to grip the strands for the tensile test. The type of strand and tensile testing machine determine which gripping method to use. *Standard Test Methods for Testing Multi-Wire Steel Prestressing Strand* (ASTM A1061)[16] does not specify a single gripping method for all types of strands and tensile testing machines but rather leaves it to the tester to decide which method is more suitable. However, it does not allow the use of chuck devices as a primary gripping device in the tensile tests. HSSS strands exhibit grip slippage and complications with the gripping media, such as stress concentration and premature failure. Therefore, the ends of most of the strands were coated with high-modulus epoxy and 80 grit silicon carbide to create a friction grip and prevent grip slippage (**Fig. 2**). This coating approach seems to be one of the best available methods to transfer force from the grips to HSSS strands because it typically eliminates failure at the strands' ends. All specimens were tensile tested using the grout coating approach except for five specimens, which were taken directly from the first spool. Those specimens were tensile tested using chuck



Epoxy coating applied at the end of a specimen

Specimens prepared for tensile testing

Seating the end of the specimen in the grip

Strand preloaded to be aligned and seated in the grips

Extensometer attached to a strand to measure strain up to 1% elongation

Strand at failure

Figure 2. Preparation and testing of stainless steel specimens in tension. Note: Tensile tests were performed to determine the mechanical properties and stress-strain behavior of the stainless steel strands. Tensile tests were performed at the Florida Department of Transportation State Materials Office in Gainesville, Fla.

Table 2. Test matrix of the tensile test			
Number of specimens			
Source of strand	Beginning of spool		Remaining in bed
Testing method	Grout coating	Chuck devices	Grout coating
First spool	5	5	5
Second spool	5	n/a	5

Note: n/a = not applicable.

devices as a primary gripping device to determine whether chuck devices can be used in the casting yard to tension HSSS strands. **Table 2** shows the test matrix of the tensile tests in this experimental program.

Setup

Using grout coating approach A universal testing machine (UTM) was used for the tensile tests. The length of each specimen was 50 in. (1270 mm), and the strand length inserted in each grip was 8 in. (203 mm) (Fig. 2). This embedded length allowed for a full transfer of the load from the grips to the strand. A preload of about 10% of breaking strength was applied to align the strand and seat the ends in the grips (Fig. 2). After the strand was aligned and tight, a 24 in. (610 mm) extensometer was attached to the strand, leaving 5 in. (127 mm) clear distance between the jaws and the extensometer (Fig. 2). The extensometer measured strain up to about 1% extension with an accuracy of 0.01%, and then it was removed to prevent possible damage, as Grade 2205 HSSS strands have low ultimate strain. After the extensometer was removed, data collection was switched from the extensometer to the UTM and the specimen was reloaded. The UTM calculates strain by measuring displacement between the machine's crossheads.

Using chuck devices Chuck devices (wedges) are usually used in the field for normal strand tensioning procedures; however, ASTM A1061[16] clearly states that chuck devices shall not be used in the tensile test as a primary gripping device. Because stainless steel strands are relatively new to the construction industry and to ensure that regular chuck devices can be used to tension the HSSS strands in the casting yard, five 50 in. (1270 mm) HSSS strands were tensile tested using chuck devices as the primary gripping devices. The chuck devices were attached to the ends of the strands and neither epoxy nor 80-grit silicon carbide was used to coat the ends of the strands. The tensile tests were performed using a UTM. The strand was preloaded to 10% of breaking strength, and then an extensometer was attached. The UTM was unloaded at 1% extension to avoid damage when removing the extensometer. After the extensometer was removed, the data collection was switched to the UTM and the strand was reloaded again until failure.

Results

Using grout coating approach Tensile tests were performed on twenty 0.6 in. (15.2 mm) diameter HSSS strands, 10 from each spool. All specimens were tensioned until breakage, which

Table 3. Statistical summary of test results for specimens from the first spool

Specimen type	Specimen number	Yield strength (load at 1% extension), kip	Yield stress f_{py}, ksi	Breaking load, kip	Ultimate stress f_{pu}, ksi	$\frac{\text{Yield strength}}{\text{Specified breaking strength}}$, %	Elongation, %	Elastic modulus, ksi
Beginning of spool	1	52.52	228.34	60.25	261.93	94.80	1.87	24,100
	2	52.61	228.72	60.35	262.40	94.96	1.85	24,500
	3	52.50	228.27	60.12	261.40	94.76	1.83	24,600
	4	51.72	224.86	60.31	262.22	93.36	1.89	23,900
	5	52.47	228.11	60.07	261.16	94.71	1.86	24,400
Remaining in bed	6	53.41	232.23	60.14	261.47	96.41	1.76	25,200
	7	53.88	234.27	59.99	260.81	97.26	1.69	25,900
	8	53.43	232.32	60.36	262.43	96.44	1.80	25,200
	9	53.42	232.25	60.01	260.89	96.43	1.75	25,600
	10	53.41	232.23	60.11	261.35	96.41	1.78	25,800
Average		52.94	230.16	60.17	261.61	95.55	1.81	24,920
Standard deviation		0.667	2.900	0.139	0.602	1.14	0.064	716

Note: 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.

Table 4. Statistical summary of test results for specimens from the second spool

Specimen type	Specimen number	Yield strength (load at 1% extension), kip	Yield stress f_{py}, ksi	Breaking load, kip	Ultimate stress f_{pu}, ksi	$\frac{\text{Yield strength}}{\text{Specified breaking strength}}$, %	Elongation, %	Elastic modulus, ksi
Beginning of spool	1	51.06	223.96	56.87	249.42	92.12	1.62	24,500
	2	50.62	222.02	56.66	248.51	91.37	1.63	24,200
	3	50.18	220.10	56.77	248.97	90.58	1.71	24,200
	4	50.58	221.83	56.41	247.42	91.30	1.59	24,600
Remaining in bed	5	51.40	225.44	56.95	249.80	92.78	1.63	25,300
	6	52.06	228.33	57.12	250.52	93.97	1.59	25,300
	7	51.21	224.61	57.02	250.10	92.44	1.64	24,800
	8	51.84	227.37	57.22	250.97	93.57	1.66	25,400
Average		51.12	224.21	56.88	249.46	92.27	1.63	24,788
Standard deviation		0.645	2.831	0.262	1.150	1.09	0.036	494

Note: 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.

is defined as the failure state. Failure of all strands happened at one end, close to the jaw (Fig. 2). The failure of all strands was categorized as pure rupture. Statistical summaries of tested strands are presented in **Tables 3** and **4** for specimens from the first and second spools, respectively. Experimental results of two strands from the second spool were excluded from the summary in Table 4. The first specimen was excluded because the length of the specimen was shorter than the required length and the extensometer could not be installed to measure elongation. The second specimen was excluded because the specimen was not seated perfectly in the grips, which significantly affected the experimental results. The measured area for the strand from the first spool was 0.230 in.^{2} (148 mm^2), and the measured area from the second spool was 0.228 in.^{2} (147 mm^2).

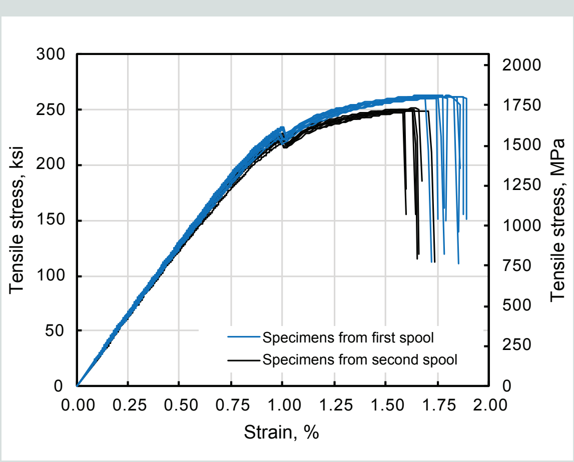


Figure 3. Stress-strain curves of the stainless steel strands from the tensile tests. Note: This figure can be used to determine mechanical properties of the tested stainless steel strands.

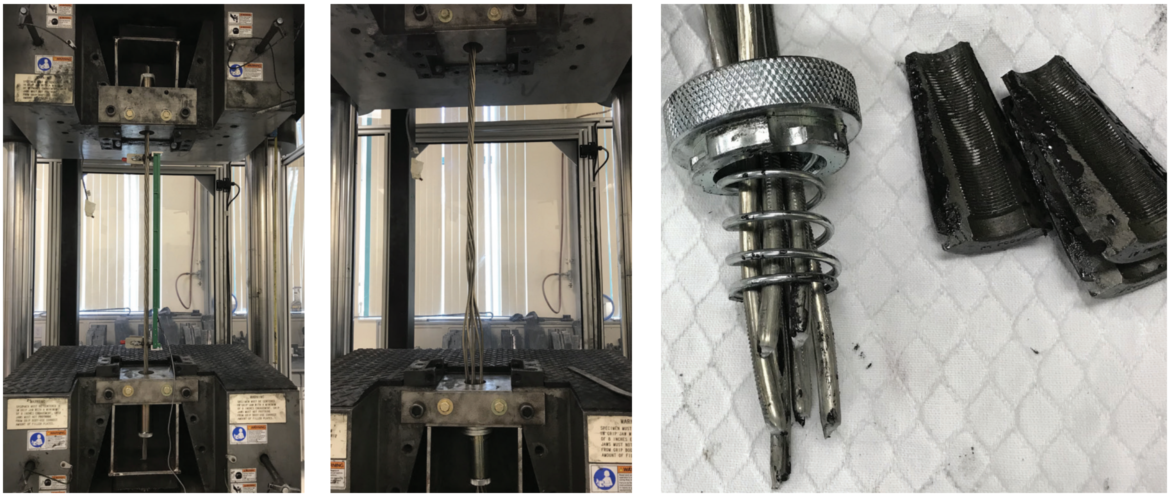
Figure 3 shows stress-strain plots of the tested HSSS strands. Note that the stress-strain behavior is different between specimens from the first spool and second spool. These differences can likely be attributed to multiple reasons, such as chemistry variances of the elements alloyed, processing variances, and the wire rod used to make the prestressing strands not being perfectly identical from heat to heat. Tensile test results showed that the HSSS strands exhibit early nonlinearity compared with carbon steel and a rounded stress-strain curve after the elastic modulus slope is deviated. Figure 3 shows a small drop in stress at about 1% strain. This drop occurred due to unloading the strand to remove the extensometer. It should be noted that this drop was inevitable, but it could have been minimized by more quickly removing the extensometer and reloading the UTM. After the drop, the strains were measured based on the crosshead displacement.

Table 5 gives the mechanical properties for 0.6 in. diameter high-strength stainless steel strands according to ASTM A1114[5] requirements, FDOT specification requirements,[17] mill certificates provided by the manufacturer for each spool, and average experimental results. All specimens from the first and second spools satisfied ASTM A1114[5] and FDOT requirements,[17] except for the area requirements. The measured average area of the specimens from both spools was slightly lower than the required value; the difference is insignificant. Note that the specified diameter of the tested specimens from both spools was 0.6 in. (15.2 mm), whereas ASTM A1114[5] provides minimum required mechanical properties for 0.62 in. (15.7 mm) diameter strands. The two spools used in the study were manufactured before the publication of ASTM A1114.[5] Specimens from the first spool had higher yield and breaking strengths, elongation, and elastic modulus than those from the second spool.

Table 5. Mechanical properties for 0.6 in. diameter high-strength stainless steel strands

		Area, in.²	Load at 1% extension, kip	Breaking strength, kip	Ultimate stress f_{pu}, ksi	Elongation, %	Elastic modulus, ksi
Standard requirements	ASTM A1114	0.2310	≥ 49.86	≥ 55.40	≥ 240	≥ 1.4	n/a
	FDOT	0.2310	≥ 49.86	≥ 55.40	≥ 240	≥ 1.4	n/a
First spool	Manufacturer's data	0.2328	52.92	59.76	256.65	1.90	24,300
	Average tensile tests	0.2300	52.94	60.14	261.61	1.81	24,950
Second spool	Manufacturer's data	0.2306	50.59	55.47	240.56	1.60	23,900
	Average tensile tests	0.2280	51.12	56.88	249.46	1.63	24,750

Note: ASTM A1114 = *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*; FDOT = Florida Department of Transportation; n/a = not applicable. 1 in.² = 645.2 mm²; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.



Tensile test of a specimen using chuck devices

Failure of the specimen at the chuck

Notching effect of grips on the stainless steel strands

Figure 4. Preparation and testing of stainless steel strands in tension using chuck devices. Note: Tests were performed at the Florida Department of Transportation State Materials Office in Gainesville, Fla.

Using chuck devices Tensile tests were performed on five 0.6 in. (15.2 mm) diameter HSSS strands from the first spool. **Figure 4** shows a stainless steel strand being tensile tested using chucks as the primary gripping devices. Failure of all five specimens happened at one end at the point where the chucks gripped the strands. Figure 4 also shows the notching effect of the grips, which resulted in failure of the strand. **Figure 5** shows the stress-strain curves of specimens tensile tested using grout coating and chuck devices. **Table 6** reports the average mechanical properties of tested strands. A reduction in all parameters was observed (breaking strength, load at 1% extension, ultimate strain, and modulus of elasticity) when strands were tensile tested with chuck devices. This is clear evidence that using chuck devices for tensile tests does not produce the full capacity of strands and should not be done, as stated by ASTM A1061.[16] The behavior of the strands before yielding was not significantly affected by using the chuck devices compared with the behavior after yielding (Fig. 5). Usually strands in the casting bed are tensioned within their elastic limit, below yield strength. Therefore, chuck devices (wedges) can be used to initially tension Grade 2205 HSSS strands for prestressed concrete member fabrication.

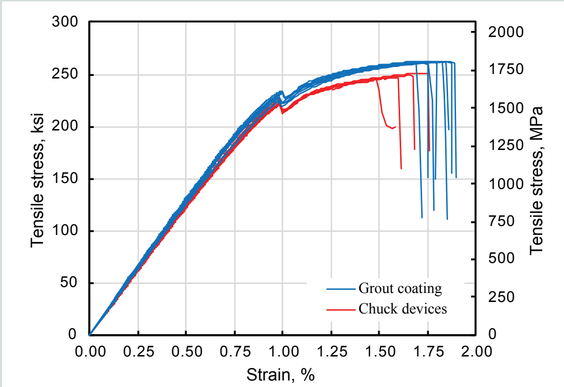


Figure 5. Stress-strain curves of stainless steel strands tested in tension using grout coating and chuck devices. Note: This figure shows the influence of using chuck devices on the mechanical properties of stainless steel strands.

Yield strength There are multiple methods to determine the yield strength of prestressing strands. The most common methods are the extension under load (EUL) and offset methods.[18] ASTM A416[15] and ASTM A1114[5] propose the EUL method for seven-wire prestressing strand. Those ASTM standards define the yield strength as the load when the total strain reaches 1%, and the yield strength must be at least 90% of the specified breaking strength, which is equal to 55.4 kip (246 kN) for 0.62 in. (15.7 mm) diameter stainless steel strands. Tables 3 and 4 show that all specimens from the first spool and the second spool adequately met the 90% yield strength requirement. Specimens from the first spool had an average yield strength of 95.55% of the specified breaking strength and standard deviation of 1.14% (Table 3). Table 4 shows that specimens from the second spool had an average yield strength of 92.27% of the specified breaking strength and standard deviation of 1.09%.

The offset method defines the yield stress as the intersection of the stress-strain curve with a line that starts at a specified strain value and runs parallel to the linear region of the stress-strain curve. *Eurocode 2: Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings*[19] specifies the initial strain value as 0.1%. This method is called the 0.1% offset method. The 0.2% offset method is recommended by the Korea Concrete Institute,[20] which specifies the initial strain value as 0.2%. Schuetz[12] suggests using the 1.2% extension method or 0.2% offset method to determine the yield strength of Grade 2205 stainless steel strands. In this research, yield strengths calculated using the 1.2% extension method or the 0.2% offset method were higher than 90% of the breaking strength, which satisfies the 90% yield strength requirement of ASTM A1114.[5]

Differences in tensile testing between carbon steel and HSSS strands The professional technician who performed the tensile tests at FDOT SMO reported multiple differences between tensile testing of carbon steel strands and HSSS strands. The differences are as follows:

Table 6. Mechanical properties of high-strength stainless steel strands tested using grout coating and chuck devices

Parameters	Using grout coating	Using chuck devices	Reduction, %
Area, in.^{2}	0.2328	0.2328	0
Load at 1% extension, kip	52.94	51.92	1.92
Breaking strength, kip	60.17	57.79	3.95
Elongation, %	1.81	1.60	11.60
Elastic modulus, ksi	24,950	23,900	4.09

Note: 1 in.^{2} = 645.2 mm^2; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.

- The HSSS strands kept their shape as bent on the spool, which resulted in difficulties seating both ends of the specimen in the top and bottom grips.
- The location of the break of the HSSS specimens was close to the grip in all specimens tested using the coating approach, while the carbon steel strands broke at random locations.
- The epoxy coating (Fig. 2) peeled from the HSSS specimens.
- The HSSS specimens failed more quickly than the carbon steel strands, and the plastic strain was much smaller than that of the carbon steel strands.
- Special attention was needed when removing the extensometer after reaching 1% extension because the HSSS specimens might break while removing the extensometer due to its short plastic strain.

Stress-strain model

Background

The stress-strain behavior of stainless steel strands is different from that of carbon steel strands. Therefore, a new stress-strain equation needs to be developed. The stress-strain formula is necessary for strength design and numerical analysis of prestressed concrete members. A widely accepted method for describing the stress-strain behavior of a material is the Ramberg-Osgood model.[21] The original model was developed for aluminum alloys and was not valid for materials with highly nonlinear stress-strain relationships. Since the development of the original model, many researchers have modified the model either for different materials or to better fit experimental tests. One of the most widely used analytical formulas, known as the power formula, was derived from the modified Ramberg-Osgood function. The power formula was proposed by Mattock[22] and has been proved suitable for highly nonlinear materials. It includes four curve-fitting constants, as shown in Eq. (1). The methodology behind this formula is to divide the stress-strain curve into two straight lines connected by a curve. The first line is for the elastic region, and the second line is for the inelastic region. As long as the actual stress-strain curve is available, the four curve-fitting variables can be calculated. The elastic modulus *E* is determined from the elastic region of the strand stress-strain curve. A detailed procedure for calculating curve-fitting constants for the power formula is given in Collins and Mitchell.[23]

$$\sigma = E \times \varepsilon \left\{ A + \frac{1-A}{\left[1+\left(B\times\varepsilon\right)^{C}\right]^{1/C}} \right\} \quad (1)$$

where

σ = stress in strand

ε = strain in strand

A = curve-fitting constant

B = curve-fitting constant

C = curve-fitting constant

Researchers have developed power formulas for all available low-relaxation carbon steel strand sizes. **Table 7** shows power formulas for three sizes of Grade 270 carbon steel strand.

Devalapura and Tadros[24] studied 56 stress-strain curves for low-relaxation Grade 270 carbon steel strand. Half of the stress-strain curves were obtained from the manufacturers, whereas the other half were obtained from testing by Devalapura and Tadros.[24] The specimens were made from different types of steel and were tested by different machines. A statistical lower-bound curve was derived from the 56 curves. The outcome of the study was proposed curve-fitting constants for the power formula for 0.5 in. (12.7 mm) diameter low-relaxation carbon steel strands.[24] The proposed power formula curve was as close as possible to the experimental lower-bound curve and satisfied the yield strength requirements of ASTM A416.[15] Collins and Mitchell[23] proposed curve-fitting constants for the power formula for 0.6 in. (15.2 mm) diameter Grade 270 carbon steel strand.

The power formula is not limited to specific strand diameters. Morcous et al.[25] recently proposed a power formula for 0.7 in. (17.8 mm) diameter Grade 270 carbon steel strand. The curve-fitting constants for the proposed power formula in the Morcous et al.[25] study were calculated after testing 40 strands from two different producers and using two different machines.

All proposed power formulas result in a conservative curve that lies below the actual stress-strain curves. This is mainly because the proposed power formulas were developed to fit the lower-bound curve of tested strands. The *PCI Design Handbook: Precast and Prestressed Concrete*[26] provides approximate stress-strain equations for seven-wire low-relaxation strands. The PCI equations are divided into two parts: the first part is for the elastic region, and the second one is for the plastic region.

Table 7. Stress-strain equations for low-relaxation Grade 270 carbon steel strands

Author	Diameter, in.	Modulus of elasticity, ksi	Proposed stress-strain equation
Devalapura and Tadros (1992)	0.5	28,500	$\sigma = E\times\varepsilon\left\{0.031+\frac{0.969}{\left[1+\left(112.4\times\varepsilon\right)^{7.36}\right]^{1/7.36}}\right\}$
Collins and Mitchell (1991)	0.6	29,000	$\sigma = E\times\varepsilon\left\{0.025+\frac{0.975}{\left[1+\left(118\times\varepsilon\right)^{10}\right]^{1/10}}\right\}$
Morcous et al. (2011)	0.7	28,500	$\sigma = E\times\varepsilon\left\{0.02+\frac{0.98}{\left[1+\left(\frac{E\times\varepsilon}{1.03\times f_{py}}\right)^{7.33}\right]^{1/7.33}}\right\}$

Note: E = modulus of elasticity of strand; f_{py} = specified yield stress of strand; ε = strain in strand; σ = stress in strand. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

Proposed stress-strain model

The format of the modified Ramberg-Osgood function, given in Eq. (1), was used to develop the stress-strain models of the two HSSS spools.

Tensile tests As mentioned, ten 50 in. (1270 mm) long specimens from each spool were tested in direct tension. The elastic modulus *E* was determined from the experimental data following ASTM A1061,[16] and the three coefficients (*A*, *B*, and *C*) in Eq. (1) were calculated to obtain a best fit with the lower-bound curve of the tested strands. **Table 8** summarizes the proposed coefficients.

Stress-strain equation for design ASTM A1114[5] requirements represent the minimum guaranteed mechanical properties for stainless steel strands. Thus, the proposed stress-strain equation for design purposes should represent the ASTM A1114[5] minimum requirements and have the same shape as the curve for the tested specimens. This means that for 1% strain and 1.4% strain, the proposed equation should result in a stress of 216 and 240 ksi (1490 and 1650 MPa), respectively. The curve-fitting constants in Eq. (1) were derived to adequately match the ASTM A1114[5] requirements and have the same stress-strain curve as the tested specimens. The proposed stress-strain equation for 0.6 in. (15.2 mm) diameter HSSS strands is given in Eq. (2).

$$\sigma = 24{,}000 \times \varepsilon \left\{ 0.06 + \frac{0.94}{\left[1 + \left(101 \times \varepsilon\right)^{6.45}\right]^{1/6.45}} \right\} \qquad (2)$$

Figure 6 provides a visual representation of the proposed equation along with two stress-strain sample curves from the experimental results, one from each spool. The proposed equation fits the lower-bound curve of the tested strands in the elastic region. This was achieved by taking the elastic modulus equal to 24,000 ksi (165,500 MPa). The proposed equation in the plastic region is parallel to the shape of the curves for the two spools in the plastic region. The proposed equation is conservative and underestimates the strand behavior of the two spools. It is conservative compared with the actual behavior of the HSSS strands because manufacturers will produce stainless steel strands that have mechanical properties greater than the minimum requirements of ASTM A1114.[5]

Table 8. Coefficients of modified Ramberg-Osgood function for tested high-strength stainless steel strands

Specimen identification	Coefficients		
	A	B	C
First spool	0.065	100	6.5
Second spool	0.050	102	7.0

Note: *A* = curve-fitting constant for stress-strain power formula; *B* = curve-fitting constant for stress-strain power formula; *C* = curve-fitting constant for stress-strain power formula.

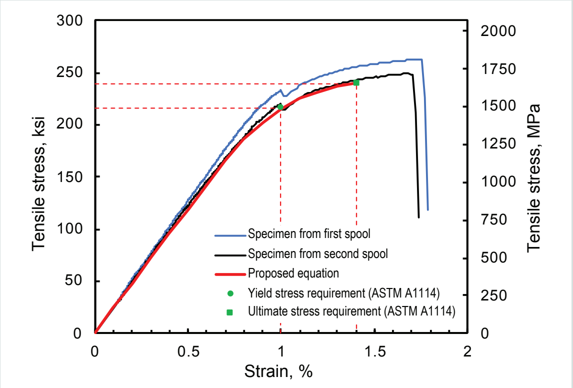


Figure 6. Comparison of the proposed equation for a stress-strain model with experimental stress-strain behavior of stainless steel strands. Note: ASTM A1114 = *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*.

Strand bond tests

A test procedure to measure the bond of prestressing strand is provided by ASTM A1081,[6] which was adopted from the North American Strand Producers,[27] where the strand is pulled out from a sand-cement mortar. In this study, the ASTM A1081[6] test method was used to evaluate the bond of 0.6 in. (15.2 mm) diameter HSSS strands in mortar.

Specimen preparation

The strand bond test was performed according to ASTM A1081 protocol.[6] The test requires a minimum of six strands and 15 mortar cubes. Six HSSS strands were taken from the first spool in as-received condition and protected from foreign substances. Six specimens were prepared by casting sand-cement mortar in a steel pipe around a single 0.6

Figure 7. Stainless steel specimens prepared for bond test.

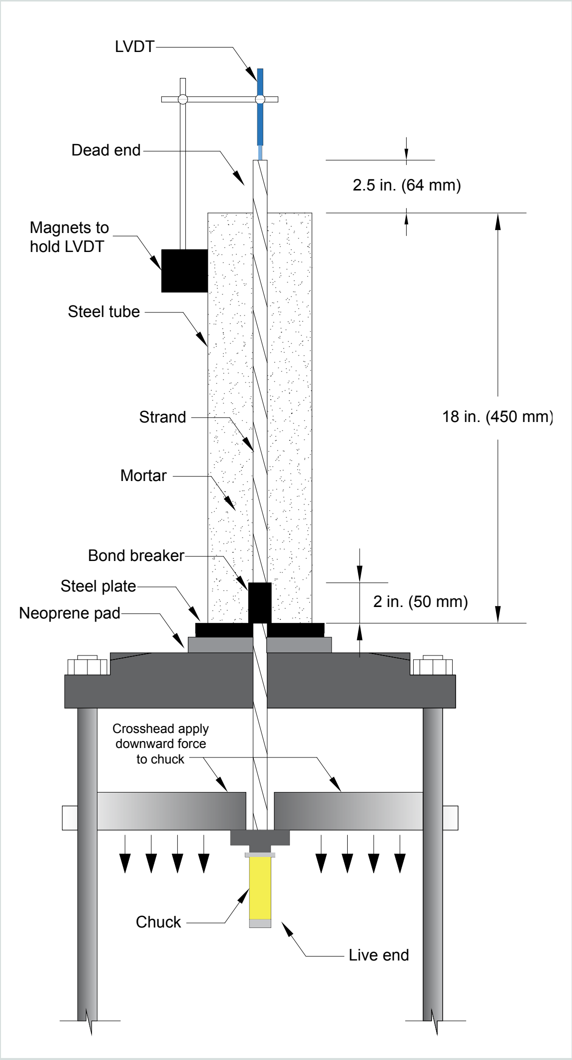


Figure 8. Test setup for the bond strength test following ASTM A1081. Note: Bond strength tests were performed to determine the bond strength of stainless steel strands. Bond strength tests were performed at the Florida Department of Transportation State Materials Office in Gainesville, Fla. ASTM A1081 = *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand*; LVDT = linear variable displacement transducer. 1 in. = 25.4 mm.

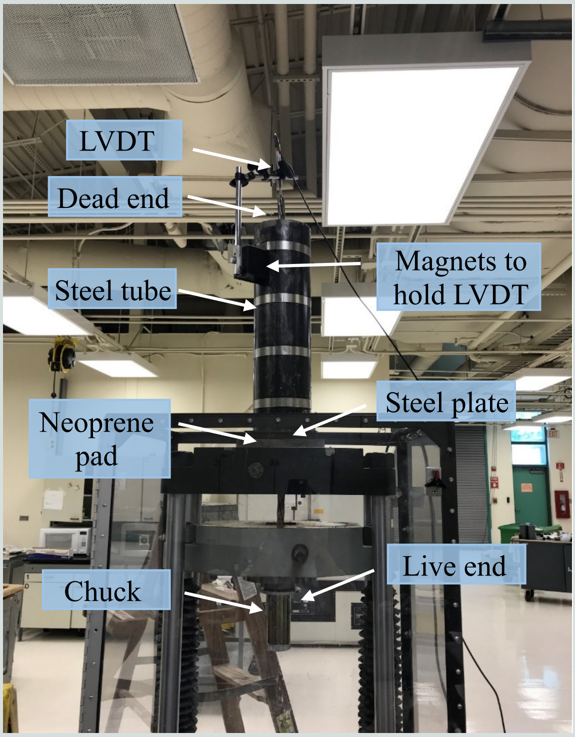


Figure 9. Specimen setup for standard test for strand bond. Note: LVDT = linear variable displacement transducer.

in. (15.2 mm) diameter HSSS strand (**Fig. 7**). The steel tube was 5 in. (127 mm) in diameter and 24 in. (610 mm) tall. A 2 in. (50 mm) long steel breaker was placed around the strand at the bottom of the steel tube immediately above the steel plate (**Fig. 8**). This steel breaker was used to debond the strand and reduce the confinement pressure acting on the strand. The specimens were cured in an environmental chamber until testing. The dimensions of the mortar cube were 2 × 2 × 2 in. (50 × 50 × 50 mm). Bond tests of strands were performed by professional technicians at the FDOT SMO in Gainesville, Fla.

Setup

Figure 8 shows the schematic test setup used for the ASTM A1081 bond test. The live end of the strand was connected to the gripping device where the force was applied. A linear variable displacement transducer was mounted at the dead end to measure displacement. The applied displacement rate of the gripping device was 0.1 in./min (2.5 mm/min), and the loading rate did not exceed 8500 lb/min (38 kN/min). **Figure 9** shows the testing apparatus used for the standard test for strand bond.

Results

Strand bond is defined as the pullout force at the live end that displaces the dead end of the strand by 0.1 in. (2.5 mm) (Fig. 9). Per ASTM A1081,[6] three mortar cubes shall be tested each hour at 22 to 26 hours after casting until they reach an average compressive strength of 4500 to 5000 psi (31 to 34 MPa), after which strand bond tests can be performed. Mortar mixture proportions were validated before the experiment, and the mortar was expected to have a compressive strength of 4500 to 5000 psi at 24 hours. Mortar strength has an influence on the bond of the strand. **Figure 10** shows the average compressive strength results of three mortar cubes and shows that the average hourly compressive strength of the mortar cube sets increased over time. The average hourly compressive strength of three mortar cubes for each group did not pass the minimum required compressive strength of ASTM A1081,[6] which is 4500 psi (31 MPa). The average compressive strength 26 hours after casting was 4452 psi (30.7 MPa), which was 98.93% of the minimum required strength. A mean mortar strength less than 4500 psi is acceptable by ASTM A1081[6] if the bond test result exceeds a minimum threshold value. Thus,

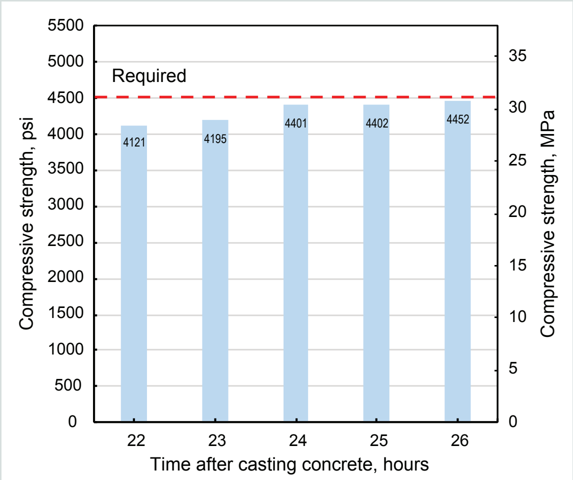


Figure 10. Compressive strength of concrete mortar cubes for bond strength tests of stainless steel strands.

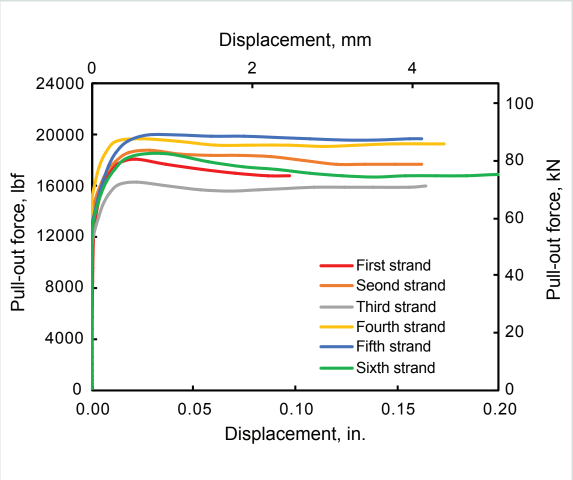


Figure 11. Pullout test results of 0.6 in. diameter high-strength stainless steel strands. Note: 1 in. = 25.4 mm.

the strand bond test was continued despite the minor under-strength of the mortar.

The bond tests of strands were started 26 hours after mortar casting, and six HSSS strands were tested. Each test was terminated after the strand slip exceeded 0.1 in. (2.5 mm) at the dead end, in accordance with ASTM A1081,[6] and the strand bond was taken as the average pullout force of the six strand specimens. Force-slip displacements were measured during the test. The pullout force at the chuck at the live end was measured concurrently with the movement of the strand at the dead end. **Figure 11** illustrates the force-displacement results for the six strands. The minimum and average pull-out force at 0.1 in. displacement were 15.80 and 17.88 kip (70.3 and 79.5 kN), respectively. The peak tensile force was reached when the slip displacement at the dead end was about 0.0223 in. (0.566 mm) (Fig. 11). The minimum and average peak forces were 16.30 and 18.63 kip (72.5 and 82.9 kN), which were about 3% and 4% greater than the minimum and average pullout forces at 0.1 in. (2.5 mm) displacement at the dead end, respectively.

ASTM A1081[6] does not specify a minimum threshold value for the bond of strand. In 2020, the PCI Strand Bond Task Group[7] recommended two acceptance bond threshold criteria for ASTM A1081.[6] The first criterion is that the minimum recommended average ASTM A1081[6] pullout value from six strands be 14.00 kip (62.3 kN), with no strand having a pullout value less than 12.00 kip (53.4 kN) at 0.1 in. (2.5 mm) displacement at the dead end. The second criterion is that the ultimate (high bond) recommended average pullout value from six strands be 18.00 kip (80.1 kN), with no strand having a pullout value less than 16.00 kip (71.2 kN). Note that those acceptance bond threshold values are for 0.5 in. (12.7 mm) diameter Grade 270 carbon steel prestressing strand conforming to ASTM A416.[15] For strands with either larger diameter or different grades, the PCI task group proposed an equation, which is given in Eq. (3).

$$(\text{Pullout value})_{\text{other sizes and grades}} = (\text{Pullout value})_{0.5\text{ in.}} \times 2 \times d_b \times \frac{f_{pu}}{270} \quad (3)$$

where

d_b = diameter of strand

f_{pu} = specified ultimate tensile stress of strand

Even though the recommended bond values were proposed for carbon steel strands conforming to ASTM A416,[15] they were used here for HSSS strand conforming to ASTM A1114.[5] In this study, the diameter and specified tensile strength for HSSS strand are 0.6 and 240 ksi (15.2 and 1650 MPa), re-

Table 9. Comparison of experimental results with values recommended by PCI Strand Bond Task Group

	Pullout force at 0.1 in. displacement, kip		Experiment / PCI	Ultimate pullout force (high bond), kip		Experiment / PCI
	Experiment	PCI		Experiment	PCI	
Minimum	15.80	12.80	1.23	16.30	17.07	0.96
Average	17.88	14.93	1.20	18.63	19.20	0.97

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

spectively. Using Eq. (3), the minimum recommended average pullout value for 0.6 in. diameter Grade 240 HSSS strand is 14.93 kip (66.4 kN), with no strand having a pullout value less than 12.80 kip (56.9 kN), and the ultimate (high bond) recommended average pullout value for 0.6 in. diameter Grade 240 HSSS strand is 19.20 kip (85.4 kN), with no strand having a pullout value less than 17.07 kip (75.9 kN).

Table 9 reports the pullout values obtained experimentally and those calculated using the approach proposed by the PCI Strand Bond Task Group.[7] The minimum and average experimental ASTM 1081[6] pullout values were 23.4% and 19.8% greater than the recommended values calculated using the PCI Strand Bond Task Group recommendations. Another comparison can be made with the ultimate (high bond) pullout values measured experimentally. The minimum and average peak forces (high bond ASTM A1081 value) were 95.5% and 97.0%, respectively, of the recommended values calculated using the PCI Strand Bond Task Group recommendations. Note that the PCI Strand Bond Task Group specified that either the minimum ASTM A1081 value or the high bond ASTM A1081 shall be satisfied. Therefore, it can be concluded that the 0.6 in. (15.2 mm) HSSS strand used in this study has an acceptable bond with concrete.

Conclusion

The use of stainless steel strands may enhance the durability of prestressed concrete members due to their high corrosion resistance. Many types of stainless steel strands have been developed, but researchers have found that Grade 2205 duplex HSSS strand is the best option due to its high mechanical and corrosion-resistance properties. This paper presents the experimental results of tensile and pullout testing to determine the mechanical and bond properties of 0.6 in. (15.2 mm) diameter Grade 2205 HSSS strands. The following conclusions were made:

- Twenty 0.6 in. diameter HSSS strands from two spools were tensile tested to determine the mechanical properties of the strand. The stress-strain behavior of specimens from the two spools was different. The difference can be attributed to multiple factors, such as the wire rod used to make prestressing strands not being perfectly identical from heat to heat, chemistry variances of the elements alloyed, and processing variances.

- The most recent ASTM A1114[5] specifies the minimum mechanical requirements of Grade 240 stainless steel strands. Specimens from both spools tested satisfied the minimum requirements specified by ASTM A1114,[5] except for the area requirement. The measured areas of the tested specimens were slightly lower than the value required by ASTM A1114[5] because the diameter of the tested specimens was 0.6 in., whereas ASTM A1114[5] provides minimum required mechanical properties for 0.62 in. (15.7 mm) diameter strands. Note that the tested strands were produced before the publication of ASTM A1114.[5]

- The stress-strain relationship of HSSS strands is fundamentally different from that of carbon steel strands. The HSSS strands have early nonlinearity with a rounded stress-strain curve in the plastic region. The HSSS strands exhibit almost no strain hardening compared with carbon steel strands. Compared with carbon steel strands, the currently available HSSS strands have lower ultimate strain and stress and elastic modulus. The most significant difference is in the elongation. The minimum required elongation of the HSSS strands is only 40% of that of the carbon steel strands.

- The stress-strain equation for prestressing strand is essential for the strength design and numerical analysis of prestressed concrete members. A stress-strain equation is proposed for the 0.6 in. diameter HSSS strands. The proposed equation satisfies the ASTM A1114[5] requirements, fits lower-bound curves of the tested strands in the elastic region, and has a stress-strain shape similar to those of the tested strands in the plastic region.

- Five 0.6 in. HSSS strands were tensile tested using chuck devices as the primary gripping devices. The objective of these tests was to verify that regular chuck devices can be used to tension HSSS strands in the casting yard. Experimental results showed that the mechanical properties of the HSSS strands are not significantly affected in the elastic region when chuck devices were used in the tensile tests. Thus, regular chuck devices can be used in the casting yard to tension HSSS strands. This conclusion is limited to straight strands; harped strands or multiple-strand tendons need further study.

- Bond of the 0.6 in. diameter HSSS strands was evaluated following ASTM A1081.[6] The minimum and average pullout forces at 0.1 in. (2.5 mm) end slip of six strands were 15.80 and 17.88 kip (70.3 and 79.5 kN), respectively. The minimum and average peak pullout forces of six strands were 16.30 and 18.63 kip (72.5 and 82.9 kN), respectively, which were about 3% and 4% greater than the minimum and average pullout forces at 0.1 in. end slip displacement, respectively. The peak pullout forces occurred when end slip displacement at the dead end was about 0.0223 in. (0.566 mm).

- Minimum threshold values for strand bond are not specified in ASTM A1081.[6] In 2020, two acceptance bond threshold criteria were recommended by the PCI Strand Bond Task Group[7] for ASTM A1081.[6] Experimental pullout forces of 0.6 in. diameter HSSS strands at 0.1 in. end slip were greater than the recommended values calculated using the PCI Strand Bond Task Group equation; however, experimental peak pullout forces of 0.6 in. diameter HSSS strands were less than the recommended values calculated using the PCI Strand Bond Task Group equation. The 0.6 in. diameter HSSS strand used in this study has an acceptable bond with concrete because it satisfied one of the two acceptance bond threshold criteria from the PCI Strand Bond Task Group.[7]

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References

1. Moser, R. D., P. M. Singh, L. F. Kahn, and K. E. Kurtis. 2012. "Chloride-Induced Corrosion Resistance of High-Strength Stainless Steels in Simulated Alkaline and Carbonated Concrete Pore Solutions." *Corrosion Science* 57: 241–253.

2. Moser, R. D. 2011. "High-Strength Stainless Steels for Corrosion Mitigation in Prestressed Concrete: Development and Evaluation." PhD diss., Georgia Institute of Technology, Atlanta, GA.

3. Riding, K. A., R. J. Peterman, and T. Polydorou. 2016. "Establishment of Minimum Acceptance Criterion for Strand Bond as Measured by ASTM A1081." *PCI Journal* 61 (3): 86–103. https://doi.org/10.15554/pcij61.3-02.

4. Polydorou, T., K. A. Riding, and R. J. Peterman. 2016. "Interlaboratory Study of the Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand." *PCI Journal* 61 (4): 53–64. https://doi.org/10.15554/pcij61.4-01.

5. ASTM Subcommittee A01.05. 2020. *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*. ASTM A1114. West Conshohocken, PA: ASTM International.

6. ASTM Subcommittee A01.05. 2015. *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand*. ASTM A1081. West Conshohocken, PA: ASTM International.

7. PCI Strand Bond Task Group. 2020. "Recommended Practice To Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand." *PCI Journal* 65 (6): 33–34.

8. Rambo-Roddenberry, M., and A. Al-Kaimakchi. 2020. *Stainless Steel Strands and Lightweight Concrete for Pretensioned Concrete Girders*. Tallahassee, FL: Florida Department of Transportation.

9. Al-Kaimakchi, A., and M. Rambo-Roddenberry. 2021. "Measured Transfer Length of 15.2-mm (0.6-in.) Duplex High-Strength Stainless Steel Strands in Pretensioned Girders." *Engineering Structures* 237: 112178. https://doi.org/10.1016/j.engstruct.2021.112178.

10. Moser, R. D., L. F. Kahn, P. M. Singh, and K. E. Kurtis. 2013. "Preliminary Studies of High-Strength Stainless Prestressing Steels." *ACI Special Publication* 291: 1–10.

11. Mullins, G., R. Sen, and A. Sagüés. 2014. *Design and Construction of Precast Piles with Stainless Reinforcing Steel*. Tallahassee, FL: Florida Department of Transportation.

12. Schuetz, D.P. 2013. "Investigation of High Strength Stainless Steel Prestressing Strands." MSc thesis, Georgia Institute of Technology, Atlanta, GA.

13. Gardner, L. 2005. "The Use of Stainless Steel in Structures." *Progress in Structural Engineering and Materials* 7 (2): 45–55.

14. Nürnberger, U., and Y. Wu. 2008. "Stainless Steel in Concrete Structures and in the Fastening Technique." *Materials and Corrosion* 59 (2): 144–158.

15. ASTM Subcommittee A01.05. 2017. *Standard Specification for Low-Relaxation Seven-Wire Steel Strand for Prestressed Concrete*. ASTM A416. West Conshohocken, PA: ASTM International.

16. ASTM Subcommittee A01.05. 2016. *Standard Test Methods for Testing Multi-Wire Steel Prestressing Strand*. ASTM A1061. West Conshohocken, PA: ASTM International.

17. Florida Department of Transportation (FDOT). 2020. *Standard Specifications for Road and Bridge Construction*. Tallahassee, FL: FDOT.

18. ASTM Subcommittee A01.13. 2017. *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*. ASTM A370. West Conshohocken, PA: ASTM International.

19. CEN (European Committee for Standardization). 2004. *Eurocode 2: Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings*. European Standard EN 1992-1-1. Brussels, Belgium: CEN.

20. Korea Concrete Institute (KCI). 2012. *The Korean Concrete Structure Design Code*. Seoul, Korea: KCI.

21. Ramberg, W., and W. R. Osgood. 1943. "Description of Stress-Strain Curves by Three Parameters." Technical

Note no. 902. Washington, DC: National Advisory Committee for Aeronautics.

22. Mattock, A. H. 1979. “Flexural Strength of Prestressed Concrete Sections by Programmable Calculator.” *PCI Journal* 24 (1): 32–54. https://doi.org/10.15554/pcij.01011979.32.54.

23. Collins, M. P., and D. Mitchell. 1991. Prestressed Concrete Structures. Englewood Cliffs, NJ: Prentice Hall.

24. Devalapura, R. K., and M. K. Tadros. 1992. “Stress-Strain Modeling of 270 ksi Low-Relaxation Prestressing Strands.” *PCI Journal* 37 (2): 100–106. https://doi.org/10.15554/pcij.03011992.100.106.

25. Morcous, G., A. Hatami, M. Maguire, K. E. Hanna, and M. K. Tadros. 2011. “Mechanical and Bond Properties of 18-mm- (0.7-in.-) Diameter Prestressing Strands.” *Journal of Materials in Civil Engineering* 24 (6): 735–744.

26. PCI. 2017. *PCI Design Handbook: Precast and Prestressed Concrete*. Chicago, IL: PCI. https://doi.org/10.15554/MNL-120-17.

27. Ramirez, J. A., and B. W. Russell. 2008. *Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete*. Washington, DC: National Cooperative Highway Research Program.

Notation

A = curve-fitting constant for stress-strain power formula

B = curve-fitting constant for stress-strain power formula

C = curve-fitting constant for stress-strain power formula

d_b = diameter of strand

E = modulus of elasticity of strand

f_{pu} = specified ultimate tensile stress of strand

f_{py} = specified yield stress of strand

ε = strain in strand

σ = stress in strand

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Abstract

The sustainability of concrete structures can be enhanced by using duplex high-strength stainless steel (HSSS) strands, due to their high corrosion resistance, in place of conventional carbon steel strands. This paper experimentally evaluates mechanical and bond properties of 0.6 in. (15.2 mm) diameter HSSS strands. Ten strands each from two spools were tensile tested to failure. The strands had lower yield and ultimate stresses, ultimate strain, and elastic modulus than carbon steel strands, and they met the minimum mechanical properties specified in the recently published ASTM A1114 *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*. HSSS strands exhibit nonlinear behavior beyond the elastic modulus. A stress-strain equation is proposed for 0.6 in. diameter HSSS strands, satisfying ASTM A1114 and in good agreement with experimental results. Five 0.6 in. diameter HSSS strands were tensile tested using standard chuck devices. The mechanical properties within the elastic region were not significantly affected by the use of chuck devices; therefore, chuck devices were deemed acceptable for use in the casting yard. The study was limited to straight strands. Six 0.6 in. diameter HSSS strands were tested for bond following ASTM A1081 *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand*. The minimum and average experimental pullout values were 15.80 kip (70.3 kN) and 17.88 kip (79.5 kN), respectively, which were 23.4% and 19.8%, respectively, greater than the minimum recommended values calculated using the PCI Strand Bond Task Group equation.

Keywords

Bond test, corrosion-resistant strand, stainless steel strand, stress-strain equation, tensile test.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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