# Transfer and development length of high-strength duplex stainless steel strand in prestressed concrete piles

Alvaro Paul, Lorintz B. Gleich, and Lawrence F. Kahn

- With increasing demand for bridge service lives of 100 or more years, engineers face a durability challenge regarding bridges in coastal regions, where accelerated deterioration is commonly observed.

- To develop more durable reinforcement, this research assesses the bond performance of duplex high-strength stainless steel (HSSS) 2205 strand in prestressed concrete piles by the experimental determination of the transfer and development length.

- It is possible that current codes may be used without modifications for design with duplex HSSS 2205 strand.

The long-term durability of prestressed concrete bridges exposed to marine environments is particularly challenging to achieve. Bridge piles located in the tidal zone face significant deterioration due to the combined action of harmful environmental factors, including dissolved ions in seawater, freezing and thawing cycles, wetting and drying cycles, and physical abrasion due to wave action.[1,2] Thus, modern requirements for bridge service lives beyond 100 years present a challenge for providing safe and durable bridges.[3]

A bridge survey showed that 30% of the inspected bridges in coastal Georgia exhibited visible damage, such as spalling or cracking caused by corrosion, to their prestressed concrete substructures, and the bridges had a substructure rating of 6 or less.[4] In addition, Kurtis et al.[5] estimated the service life of high-performance concrete structures with low (urban environment) and high (marine environment) chloride exposure using chloride permeability and surface resistivity data and service life modeling software. The predicted service life of a structure with high chloride exposure ranged from 21% to 31% of that of a structure with low chloride exposure.

Considering the limited-term performance of conventional prestressed concrete reinforcement in marine environments, the use of duplex high-strength stainless steel (HSSS) Grade 2205 (ASTM A276[6] designation UNS S31803) strand has been proposed as an alternative to improve the corrosion resistance of prestressed concrete piles.[7] Stainless steel has been used in reinforced concrete structures due to its higher corrosion resistance, even in extremely demanding environments.[7,8] However, different stainless steel alloy compositions have a wide range of mechanical properties and corrosion resistance.

Moser et al.[7] studied several stainless steel alloys to determine the most suitable for use in the high-strength prestressing strands of prestressed concrete piles. After this investigation, the duplex HSSS Grade 2205 was chosen as the most promising alloy. The duplex HSSS 2205 alloy, composed of ferrite and austenitic phases in approximately equal proportion, provides superior corrosion resistance compared with austenitic stainless steels Grades 304 and 316 after those alloys have been strain hardened to produce high-strength wire.[7] Schuetz et al.[9] showed that the tensile strength of the 7-wire strand made with the duplex HSSS 2205 alloy had an average tensile strength of 241.5 ksi (1665 MPa), an average ultimate strain of 1.6%, and stress relaxation less than 2.5% after the strand was subjected to a low-relaxation heat treatment process.

However, the performance of stainless steel strand in prestressed concrete piles had to be assessed prior to the material's implementation into substructure construction. The research presented in this article studied the transfer and development lengths of duplex HSSS 2205 strands in precast, prestressed concrete piles and compared those results with the transfer and development lengths measured on identical piles constructed with conventional strand to determine whether specifications given in both the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*[10] and the American Association of State Highway and Transportation Officials (AASTHO's) *AASHTO LRFD Bridge Design Specifications*[11] may be safely used for design with the stainless steel strand. In addition, expressions developed through previous studies for the estimation of transfer and development length are compared with the experimental results.

ACI 318-14 defines the transfer length $l_t$ as the "length of embedded pretensioned strand required to transfer the effective prestress to the concrete." The effective prestress is the stress in the strands after accounting for losses. Development length $l_d$ is defined as the sum of the transfer length and the flexural bond length, where the flexural bond length is defined as "the additional length over which the strand should be bonded so that a stress in the prestressing steel at nominal strength of the member ($f_{ps}$) may develop."

ACI 318-14 provides that the transfer length can be calculated using ACI Eq. (25.4.8.1).

$$l_t = \frac{f_{se}}{3000} d_b \qquad \text{(ACI 25.4.8.1)}$$

where

$d_b$ = diameter of the prestressing strand

$f_{se}$ = effective prestress in the prestressing steel

The AASHTO LRFD specifications suggest that the transfer length should be taken as 60 strand diameters ($60d_b$).

The AASHTO LRFD specifications provide that the development length can be calculated using Eq. (5.11.4.2-1).

$$l_d = \kappa\left(f_{ps} - \frac{2}{3} f_{pe}\right)d_b \qquad \text{(AASHTO 5.11.4.2-1)}$$

where

$\kappa$ = multiplier factor, equal to 1.6 when pretensioned member has a depth greater than 24 in. (610 mm) and 1.0 otherwise

$f_{ps}$ = stress in the prestressing steel at nominal strength of the member

$f_{pe}$ = effective prestress in the prestressing steel = $f_{se}$ in ACI 318-14

When $\kappa$ is 1.0, ACI 318-14 and AASHTO LRFD specifications expressions for development length coincide.

## Materials and methodology

### Properties of duplex HSSS 2205 strand

The low-relaxation duplex HSSS 2205 strands were produced under the same conditions as conventionally produced American Iron and Steel Institute (AISI) 1080 steel strands.[12] The ½ in. (13 mm) diameter, 7-wire HSSS 2205 prestressing strand was subjected to a stress relaxation process at 716°F (380°C) and a pull force of 40% ultimate tensile strength. The estimated cost of this duplex HSSS 2205 strand is six to eight times the cost of conventional steel strand.

The strand properties for the conventional AISI 1080 are $f_y$ (0.2% offset) of 254.7 ksi (1756 MPa) (standard deviation of 0.64 ksi [4.4 MPa]), $f_{su}$ of 281.8 ksi (1943 MPa) (standard deviation of 2.00 ksi [14 MPa]), ultimate strain of 5.89% (standard deviation of 0.59%), and elastic modulus of 29,400 ksi (203,000 MPa) (standard deviation of 130 ksi [900 MPa]). The same strand properties for duplex HSSS 2205 are $f_y$ (0.2% offset) of 228.7 ksi

(1577 MPa) (standard deviation of 2.35 ksi [16.2 MPa]), $f_{su}$ of 241.5 ksi (1665 MPa) (standard deviation of 0.07 ksi [0.5 MPa]), ultimate strain of 1.60% (standard deviation of 0.07%), and elastic modulus of 23,500 ksi (12,000 MPa) (standard deviation of 190 ksi [1300 MPa]).

Duplex HSSS 2205 strand has about an 11% lower tensile strength than conventional AISI 1080 steel strand. To account for this lower strength, the HSSS 2205 strands used for pile construction were ½ in. (13 mm) in diameter, compared with $^{7}/_{16}$ in. (11 mm) diameter conventional strands, which are standard for Georgia bridge pile construction.

Electrochemical cyclic potentiodynamic polarization tests (ASTM G61[13]) performed by Moser et al.[7] evaluated the corrosion resistance of both types of steel alloys when exposed to alkaline (pH ≈ 12.5) and carbonated (pH ≈ 9.5) solutions with variable chloride concentrations (0 to 1.0 M, where 0.5 M is considered seawater concentration). While the duplex HSSS 2205 strands showed no evidence of pitting or corrosion initiation under any of these conditions, conventional AISI 1080 steel strands had extensive corrosion damage under every condition except for the pH ≈ 12.5 alkaline solution with no chloride ions, which is the internal environment of uncarbonated reinforced concrete.

## Design of prestressed concrete piles

Five 70 ft (21 m) long and four 27 ft (8.2 m) long, 16 in. (410 mm) square, precast, prestressed concrete piles were fabricated. Each pile was reinforced with 12 strands with a 3 in. (76 mm) cover and with ASTM A1064[14] W3.4 (MW22) wire spiral reinforcement. Two 70 ft and two 27 ft long piles were fabricated with conventional $^{7}/_{16}$ in. (11 mm) diameter AISI 1080 strands and stressed to 70% of the experimental ultimate tensile strength $f_{si}$ (equal to 196 ksi [1351 MPa]). Three 70 ft and two 27 ft long piles were fabricated using ½ in. (13 mm) diameter duplex HSSS 2205 strand along with austenitic stainless steel Grade 304 wire spirals (**Fig. 1**). The duplex HSSS 2205 strands were stressed using the same total prestressing force as was used in the AISI 1080 piles. All piles were stressed from one end, referred throughout the article as the jacking end. In addition, the 27 ft specimens were fitted with no. 5 (16M) bar stirrups at 6 in. (150 mm) spacing and the top surface was roughened to serve as a composite beam for the development length tests. To maximize the strain levels in the prestressing strand during development length testing, a 27 in. (690 mm) deep concrete top section was later added to the 27 ft pile specimens (**Fig. 2**).

Construction of the piles with stainless steel reinforcement was completed with the same operations as for the conventionally reinforced piles. No difficulties were encountered when using the stainless steel strand and wire (that is, no special operations were required).

## Properties of concrete

The concrete mixture proportions used in the piles included the following:

- Type I/II cement (specific gravity = 3.14): 687 lb/yd$^3$ (408 kg/m$^3$)
- water (specific gravity = 1.00): 188 lb/yd$^3$ (112 kg/m$^3$)
- Class F fly ash (specific gravity = 2.26): 119 lb/yd$^3$ (70.6 kg/m$^3$)
- coarse aggregate (specific gravity = 2.65): 1870 lb/yd$^3$ (1109 kg/m$^3$)
- fine aggregate (specific gravity = 2.62): 1305 lb/yd$^3$ (774 kg/m$^3$)
- design air content: 4.0%
- retarder: 2.36 fl. oz./cwt (1.38 mL/kg)
- high-range water-reducing admixture: 6.45 fl. oz./cwt (3.75 mL/kg)
- air-entraining admixture: 0.46 fl. oz./cwt

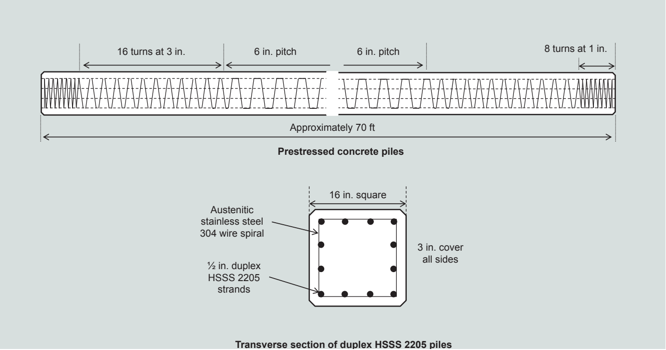

**Figure 1.** Typical configurations. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

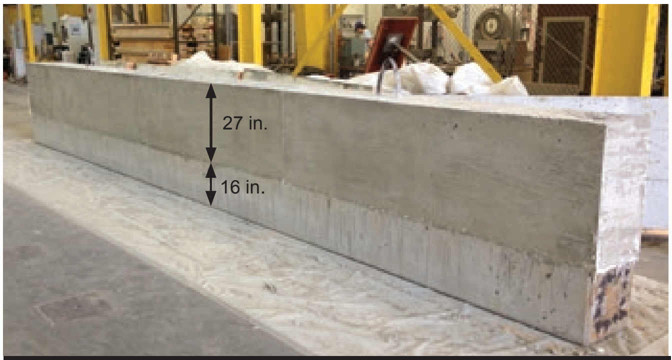

**Figure 2.** Development length testing specimen. Note: 1 in. = 25.4 mm.

This concrete had a water–cementitious material ratio *w/cm* of 0.23, 15% fly ash by weight replacement of cement (19.5% by volume), and a coarse aggregate size of no. 67 (maximum size of aggregate equal to ¾ in. [19 mm]). Mixture proportions complied with Georgia Department of Transportation (GDOT) Class AAA high-performance concrete, required for high-performance concrete used in precast, prestressed concrete bridge piles.

The design compressive strength of the concrete $f'_c$ used in the piles was 5000 psi (34 MPa). Nine 4 yd$^3$ (3 m$^3$) batches of concrete were produced at the plant. Cylinders were cast in the plant and kept in fog-room curing conditions (73.5 ± 3.5°F [23.1 ± 2.0°C], relative humidity > 98%) until testing. The average of at least three 4 × 8 in. (100 × 200 mm) cylinders was used to determine the compressive strengths at different times. The average compressive strength of concrete was 8001 ± 538 psi (55.2 ± 3.7 MPa) at 28 days, and 10,728 ± 450 psi (74.0 ± 3.1 MPa) during development length testing. In addition, the variability of the compressive strength of the piles was assessed by the identification of the concrete batches used in each specimen and was used to estimate the development length according to the specifications. The compressive strength of all concrete piles at strand release was 4020 psi (27.7 MPa).

## Driving of piles

Six months following pile construction, the five 70 ft (21 m) long piles were driven to refusal in the Savannah River using a D-30 diesel hammer (**Fig. 3**). **Table 1** shows the resistance capacities for each pile. All five piles exceeded the design capacity of 82 tons (164 kip). The stainless steel reinforced piles performed the same as the piles prestressed with conventional strand. One day after driving, the piles were extracted using a water jet system (Fig. 3). No cracking was observed except for a single transverse hairline crack in a conventionally reinforced pile.

## Transfer length

The transfer length of the strand in the piles was determined using the concrete surface strain and the 95% average maximum strain method.[15] Two rows of embedded

**Table 1.** Summary of pile-driving results for piles with both conventional and stainless steel strand

| Pile denomination | Travel for 10 blows, in. | Bearing capacity, ton |
|---|---|---|
| AISI 1080 no. 1, conventional | 1.75 | 97 |
| AISI 1080 no. 2, conventional | 1.25 | 112 |
| HSSS no. 1, duplex HSSS 2205 | 1.50 | 104 |
| HSSS no. 2, duplex HSSS 2205 | 1.50 | 104 |
| HSSS no. 3, duplex HSSS 2205 | 1.50 | 104 |

Note: AISI = American Iron and Steel Institute; HSSS = high-strength stainless steel. 1 in. = 25.4 mm; 1 ton = 8.896 kN.

**Figure 3.** Pile driving operation (left) and extraction of piles through water jet stream applied at the bottom of the pile (right).

**Figure 4.** Embedded elements left uniformly spaced points to be measured with a demountable mechanical gauge (left) and measurement of deformations at the surface of the piles (right).

detachable mechanical strain gauge points were installed at the surface of each end of each pile (**Fig. 4**). Detachable mechanical strain gauge points were placed along 8 ft (2.4 m) at each end of each pile; the points were spaced at 2 in. (50 mm) on center, starting at 1 in. (25 mm) from each end. Concrete surface strain measurements were taken before release of the strands, immediately after release, at 1 day, at 14 days, and periodically thereafter. The measurements taken at 14 days were considered for the calculation of the transfer length before driving. In addition, to understand the effect of driving on the transfer length, the same procedure was repeated after driving and extraction operations (273 days).

## Development length

The development length is the length of prestressing strand required to develop the design strength of the prestressing strand $f_{ps}$.[16] When the tension in the strand increases by the action of external forces, the bond stress also increases to maintain the equilibrium and to anchor the strand.[15] Thus, the development length can be defined as the minimum embedment required to avoid strand slip when the design stress of the strand is reached.[17] When a point load is applied at a longer distance from the end of the test beam than the development length, a flexural failure is expected. Otherwise, the strand may lose bond and slip and a shear

**Table 2.** Embedment lengths used for development length $l_d$ determination

| Pile | Embedment length, in. | ACI 318-14 $l_d$, % | AASHTO LRFD specifications $l_d$, % | Failure mode |
|---|---|---|---|---|
| **AISI 1080 no. 1, conventional** | 53.50 | 74 | 46 | Shear/bond |
| | 57.00 | 79 | 49 | Shear/bond |
| | 61.00 | 85 | 53 | Flexure |
| | 72.00 | 100 | 62 | Flexure |
| **Duplex HSSS 2205** | 57.00 | 73 | 46 | Shear/bond |
| | 61.75 | 79 | 49 | Shear/bond |
| | 69.00 | 88 | 55 | Flexure |
| | 79.75 | 102 | 64 | Flexure |

Note: AISI = American Iron and Steel Institute; HSSS = high-strength stainless steel. 1 in. = 25.4 mm; 1 ton = 8.896 kN.

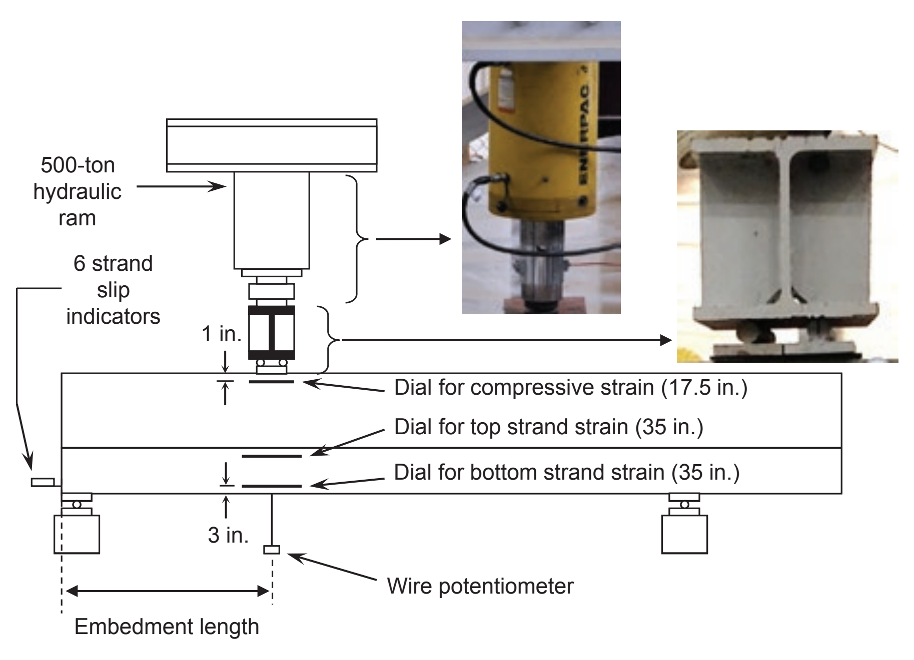

**Figure 5.** Setup for development length test. Note: Left and right supports correspond to a pin and a roller, respectively. Note: 1 in. = 25.4 mm; 1 ton = 8.896 kN.

failure may result. The criterion to define development failure during the test was considered a slip of a strand at the end larger than 0.01 in. (0.25 mm).[15,16,18]

The flexural test for the determination of the development length was performed on 27 ft (8.2 m) long piles after the addition of a top concrete section that increased the depth of the section to 43 in. (1100 mm) (**Fig. 5**). The 27 ft composite pile sections were simply supported and loaded at a variable embedment length with two point loads spaced 4 in. (100 mm) apart. **Table 2** gives the embedment lengths. The load was applied by a 1000 kip (4400 kN) hydraulic ram equipped with a 1000 kip load cell. A W10 × 77 (250 × 2000 mm) steel beam with stiffeners that was 24 in. (610 mm) long was placed under the load cell supported by two 1 in. (25 mm) diameter rollers. The vertical displacement of the pile at the position of load was recorded using a string potentiometer. Three mechanical gauges were attached to each side of the piles to estimate the strains in the prestressing strands and at the top section. Gauge lengths of 35 and 17.5 in. (890 and 445 mm) were used for the measurement of the strains in the concrete at the level of strands and at 1 in. below the top of the composite section.

At the end of the pile closer to the applied load, four dial gauges were epoxied to the bottom row of strands and two additional dial gauges were attached to the pile to determine strand slip. A strand slip higher than 0.01 in. (0.25 mm) indicated development failure.

Each beam was loaded monotonically in small deflection increments as described by Kahn et al.[19] The tests were stopped when the beam failed in either a flexural mode or shear/bond mode.

## Results and discussion

### Transfer length results

**Figure 6** shows typical smoothed concrete surface strain data plotted for specimen AISI 1080 no. 1 at the jacking end at 14 days. Using the 95% average maximum strain method,[15] the transfer length is determined as the distance from the end of the pile until the intersection of the increasing linear trend line and the 95% average maximum strain line.

Given that some of the piles showed strains before the constant strain plateau that are not clearly represented by a straight line and to avoid arbitrary interpretation of the data, the initial linear trend was calculated using the ordinary least squares method with a zero intercept. The surface strains from each pile end resembled those in Fig. 6.

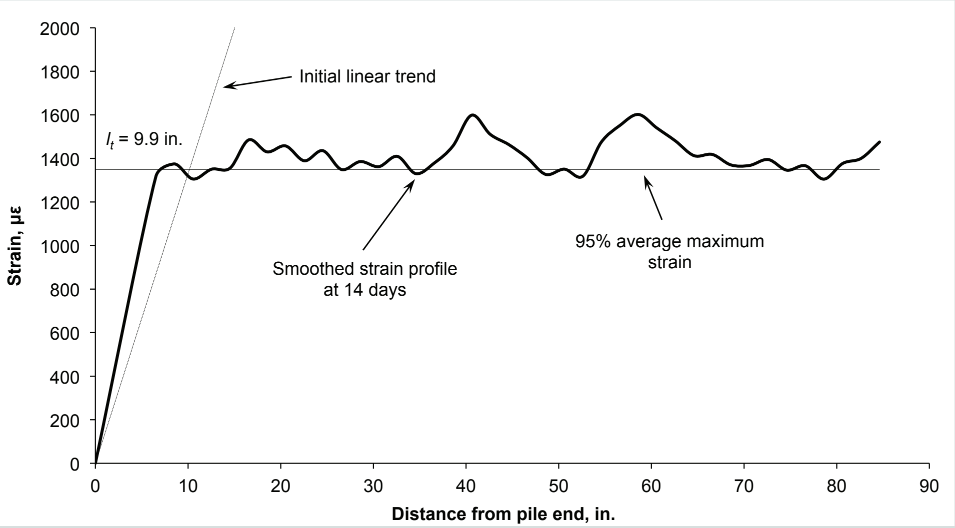

**Figure 6.** Determination of transfer length from the smoothed strain profile for pile AISI 1080 no. 1 jacking end at 14 days after release. Note: AISI = American Iron and Steel Institute; $l_t$ = transfer length. 1 in. = 25.4 mm.

**Table 3** shows the transfer length results for every pile end at 14 and 273 days (after driving and extraction). Experimental transfer lengths are compared with predicted values by AASHTO LRFD specifications and ACI 318-14. In each case, the jacking end of the pile was the one that was hit by the pile-driving hammer.

The average transfer lengths of the ½ in. (13 mm) diameter HSSS 2205 strands and AISI 1080 conventional 7/16 in. (11 mm) strands were lower than the respective AASHTO LRFD specifications and ACI 318-14 calculated values. At 14 days for the AISI 1080 strands, the average transfer lengths were 68% and 66% of the AASHTO LRFD specifications and ACI 318-14 lengths, respectively. At 14 days for the duplex HSSS 2205 strands, the average transfer lengths were 57% and 74% of the lengths predicted by the AASHTO LRFD specifications and ACI 318-14 equations, respectively. Also, individual results at 14 and 273 days ranged from 33% to 97% of the AASHTO LRFD specifications prediction. The transfer

**Table 3.** Summary of transfer length $l_t$ results at days 14 and 273 after driving

| Pile | Day 14 (before driving) | | Day 273 (after driving) | |
|---|---|---|---|---|
| | $l_t$, in. | % AASHTO LRFD specifications value* | $l_t$, in. | % AASHTO LRFD specifications value* |
| AISI 1080 no. 1 jacking end | 9.9 | 38 | 10.0 | 38 |
| AISI 1080 no. 1 anchorage end | 22.2 | 85 | 22.0 | 84 |
| AISI 1080 no. 2 jacking end | 13.4 | 51 | 12.3 | 47 |
| AISI 1080 no. 2 anchorage end | 25.5 | 97 | 16.4 | 62 |
| AISI 1080 average | 17.8 | 68 | 15.2 | 58 |
| HSSS 2205 no. 1 jacking end | 9.8 | 33 | 10.3 | 34 |
| HSSS 2205 no. 1 anchorage end | 15.6 | 52 | 11.5 | 38 |
| HSSS 2205 no. 2 jacking end | 17.3 | 58 | 23.7 | 79 |
| HSSS 2205 no. 2 anchorage end | 24.7 | 82 | 24.0 | 80 |
| HSSS 2205 no. 3 jacking end | 13.6 | 45 | 13.3 | 44 |
| HSSS 2205 no. 3 anchorage end | 21.7 | 72 | 20.9 | 70 |
| HSSS 2205 average | 17.1 | 57 | 17.3 | 58 |

Note: AISI = American Iron and Steel Institute; HSSS = high-strength stainless steel. 1 in. = 25.4 mm.

* The AASHTO LRFD specifications transfer length for AISI 1080 is 26.3 in. (25.5 in. for ACI 318-14) and for HSSS 2205 is 30.0 in. (21.2 in. for ACI 318-14).

**Table 4.** Comparison of experimental transfer length $l_t$ with code values and research proposed expressions

| | Duplex HSSS 2205 | | AISI 1080 steel | |
|---|---|---|---|---|
| | $l_t$, in. | Difference, % | $l_t$, in. | Difference, % |
| Experimental | 17.1 | n/a | 17.8 | n/a |
| ACI 318-14 (2014) | 21.2 | +24.1 | 25.5 | +43.5 |
| AASHTO LRFD specifications (2013) | 30.0 | +75.2 | 26.3 | +47.9 |
| Zia and Mostafa (1977) | 22.3 | +30.2 | 26.8 | +50.7 |
| Martin and Scott (1976) | 40.0 | +133.6 | 35.0 | +97.2 |
| Russell and Burns (1993) | 31.9 | +86.1 | 38.2 | +115.2 |
| Deatherage et al. (1994) | 23.9 | +39.6 | 27.9 | +57.0 |
| Mitchell et al. (1993) | 20.5 | +19.7 | 23.9 | +34.6 |
| Buckner: design (1995) | 23.9 | +39.6 | 27.9 | +57.0 |
| Buckner: best fit (1995) | 14.6 | -14.7 | 17.0 | -4.1 |
| Lane (1998) | 32.0 | +87.2 | 42.1 | +137.2 |
| Meyer: design (2002) | 30.6 | +78.8 | 26.8 | +50.9 |
| Meyer: best fit (2002) | 25.0 | +46.0 | 21.9 | +23.2 |
| Ramirez and Russell (2008) | 20.0 | +16.8 | 17.5 | -1.4 |

Note: AISI = American Iron and Steel Institute; HSSS = high-strength stainless steel; n/a = not applicable. 1 in. = 25.4 mm.

lengths of conventional steel strands were less than those calculated by the ACI 318-14 equation, but two of the six HSSS 2205 $l_t$ measurements were up to 16% greater than the calculated ACI 318-14 value. In the case of pile HSSS 2205 no. 2, one end showed a transfer length higher than the ACI 318-14 prediction before driving, while both ends showed a higher transfer length after driving. Pile HSSS 2205 no. 2 was not easily removed from the form bed during fabrication, and additional mechanical hammering was required. This early disturbance and vibration of the pile may have contributed to the higher transfer length values.

Transfer length results showed high variability, with values ranging from 9.8 to 24.7 in. (250 to 627 mm) for the HSSS 2205 strand. The transfer length of pretensioned elements may be influenced by strand diameter, specimen cover, and concrete strength at strand release; and it is usually higher at the cut end.[20,21] To account for these variables, several expressions have been proposed in previous studies.[10,11,15–17,22–27] **Table 4** shows the comparison between experimental results and the predicted transfer length by some of these expressions, where difference corresponds to the percentage variation of the calculated value with respect to the average 14-day experimental result. Thus, a positive difference between experimental $l_t$ and a proposed equation indicates that the equation is a conservative prediction.

Equations based only on the diameter of the prestressing strand (such as AASHTO LRFD specifications and Martin and Scott[23]) are overly conservative for duplex HSSS 2205 strand. These equations consider the increase of the transfer length when strands with higher diameter are used. In this case, the same jacking force was applied to the piles; therefore, a lower initial prestress was applied to duplex HSSS 2205 strands.

Expressions using stress in prestressing strand after release $f_{si}$ (stress after losses due to elastic shortening) and concrete strength at release $f_{ci}$ provide better agreement with experimental transfer lengths than the predictions using the effective stress of the prestressing strand after all losses $f_{se}$. The transfer length of pretensioned members is directly related to the stress of prestressing strand right after or at release and inversely related to the strength of concrete at release.[20,28] The use of these parameters can account for the use of nonconventional strands.

Transfer length results also show noticeably longer values of $l_t$ at the anchorage ends. Flame cutting of the tensioned strand was performed at the anchorage end, which may explain this difference. Longer transfer lengths at the cut end of prestressed concrete elements has been reported in previous research.[20–22,29] It has been suggested that localized slip or concrete damage can occur at the cut end because of the high strain energy released after the cutting of the fully tensioned strand.[29,30]

## Development length results

Flexural failures during development length tests consisted of ductile behavior with yielding and rupturing of pre-

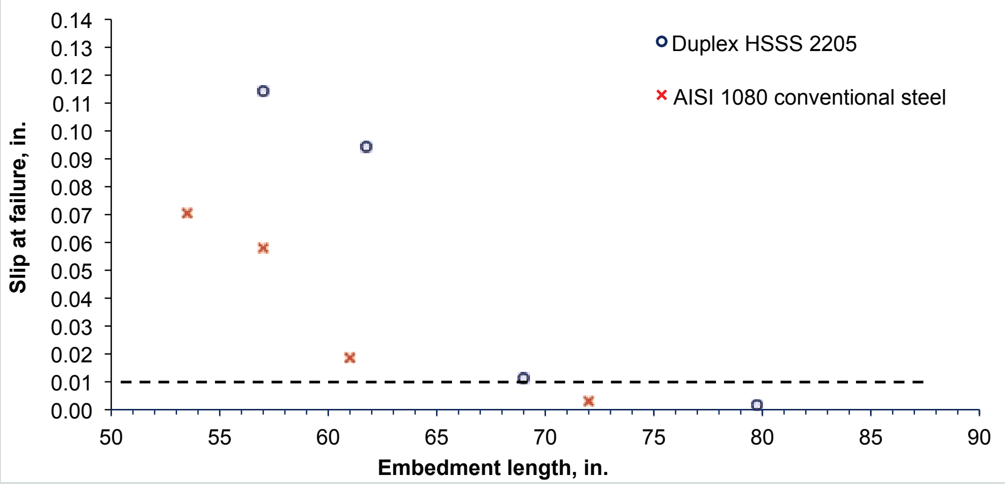

**Figure 7.** Slip at failure. Note: Dashed line shows the assumed slip failure limit and defined flexure and shear failure of piles. 1 in. = 25.4 mm. AISI = American Iron and Steel Institute; HSSS = high-strength stainless steel.

stressed reinforcement. Shear/bond failures were evident when large inclined cracks were present and when the end slip of the bottom strands exceeded 0.01 in. (0.25 mm).

Displacements measured by the dials epoxied to the strands were subtracted from those measured by the dials epoxied to the ends of the piles. The relative displacement of the strand with respect to the pile was the strand slip. **Figure 7** shows the slip at failure for each embedment length.

When the $l_d$ calculated using the ACI 318-14 equation was used as embedment length, negligible strand slips were observed (0.002 and 0.003 in. [0.050 and 0.08 mm] for duplex HSSS 2205 and conventional steel strands, respectively). Embedment lengths of 85% of $l_d$ for conventional steel strands and 88% of $l_d$ for duplex HSSS 2205 strands corresponded to strand slip at failure closest to 0.01 in. (0.25 mm), while embedment lengths corresponding to 79% and 74% of the predicted $l_d$ by ACI 318-14 for HSSS 2205 and conventional strand, respectively, exhibited strand slip that well exceeded the 0.01 in. (0.25 mm) limit.

The experimental development length was selected as the lowest embedment length in which the strand slip was

**Table 5.** Comparison of experimental development length $l_d$ with code values and research proposed expressions

| Source | Duplex HSSS 2205 | | AISI 1080 steel | |
|---|---|---|---|---|
| | $l_d$, in. | Difference, % | $l_d$, in. | Difference, % |
| Experimental | 69.0 | n/a | 61.0 | n/a |
| ACI 318-14 (2014) | 78.3 | +13.4 | 72.0 | +18.1 |
| AASHTO LRFD specifications (2013) | 125.2 | +81.4 | 115.3 | +89.0 |
| Zia and Mostafa (1977) | 93.5 | +35.6 | 85.0 | +39.3 |
| Martin and Scott (1976) | 115.3 | +67.1 | 141.5 | +132.0 |
| Russell and Burns (1993) | 52.3 | -24.2 | 55.4 | -9.2 |
| Deatherage et al. (1994) | 109.4 | +58.6 | 97.7 | +60.2 |
| Mitchell et al. (1993) | 59.5 | -13.8 | 55.7 | -8.6 |
| Buckner (1995) | 94.6 | +37.1 | 165.5 | +171.4 |
| Lane (1998) | 93.0 | +34.8 | 88.5 | +44.3 |
| Meyer: design (2002) | 84.9 | +23.1 | 71.0 | +16.4 |
| Meyer: best fit (2002) | 76.7 | +11.2 | 63.9 | +4.7 |
| Ramirez and Russell (2008) | 50.0 | -27.5 | 43.8 | -28.3 |

Note: AISI = American Iron and Steel Institute; HSSS = high-strength stainless steel; n/a = not applicable. 1 in. = 25.4 mm.

less than 0.01 in (0.25 mm) and in which the member failed in a flexural, rather than shear or bond, mode. From Table 3, the shortest embedment length that led to a flexural failure with no strand slip was 61 in. (1550 mm) for piles made with conventional 1080 strand and was 69 in. (1750 mm) for piles made with HSSS 2205 strand. This meant that the experimental development length of conventional AISI 1080 strand was 85% of the predicted value by ACI 318-14 and 53% of the predicted value by the AASHTO LRFD specifications. The experimental development length of duplex HSSS 2205 strand was 88% of the predicted value by ACI 318-14 and 55% of the predicted value by the AASHTO LRFD specifications. Thus, the use of both the ACI 318-14 and AASHTO LRFD specifications equations to estimate the development lengths of duplex HSSS 2205 strands gave values that were greater than the experimental values; therefore, the equations are conservative.

**Table 5** shows the comparison between experimental results and the predicted development length by previous researchers. Good approximations of development length consider the nominal diameter of strand $d_b$, the stress in the strand after transfer $f_{si}$, the effective stress after prestress losses $f_{pe}$ or $f_{se}$, and the stress in the strand at the nominal strength of the member $f_{ps}$. Concrete strength at strand release $f'_{ci}$ is also considered by some of the conservative theoretical relations.

## Conclusion

To evaluate the bond performance of duplex HSSS 2205 prestressing strands, transfer and development lengths measured on prestressed concrete piles were compared with those with conventional AISI 1080 steel strands and to transfer and development lengths calculated based on ACI 318-14 and AASHTO LRFD specifications. The following conclusions were drawn from the experimental research:

- The calculated transfer length of duplex HSSS 2205 strand was similar to that of conventional AISI 1080 strand in prestressed concrete piles.

- The measured transfer lengths of stainless steel and conventional strands in piles were negligibly affected by pile driving and extraction. The average change in transfer length for all of the piles was a decrease of 3.6%.

- The measured transfer lengths at 14 days for duplex HSSS 2205 strand were 74% and 57% of the lengths calculated based on the requirements of ACI 318-14 and the AASHTO LRFD specifications, respectively.

- Experimental development lengths of duplex HSSS 2205 strands were found to be 88% of the value computed by ACI 318-14, and 55% of the value computed by the AASHTO LRFD specifications. Thus, the development length of duplex HSSS 2205 strand can be conservatively estimated using equations given by the AASHTO LRFD specifications and ACI 318-14.

These conclusions show that the transfer and development lengths of duplex HSSS 2205 prestressing strand may be calculated conservatively with the current methods and that these calculated values may be used to assess the behavior of the piles after they have been driven.

## Acknowledgments

The research reported herein was sponsored by GDOT through research project 11-34 task order 02-105. Paul Liles, assistant division director of engineering, and Ben Rabun, state bridge engineer, provided many valuable suggestions throughout the study. Richard Potts and Joe Shepherd of Standard Concrete Products and Bill Johnston of TIC Marine and Heavy Civil Corp. were helpful with all construction operations. Kimberly Kurtis, a professor in the School of Civil and Environmental Engineering at the Georgia Institute of Technology, provided many valuable suggestions throughout the study. The opinions and conclusions expressed herein are those of the authors and do not represent the opinions, conclusions, policies, standards, or specifications of GDOT, the Federal Highway Administration, or other cooperating organizations.

## References

1. Aïtcin, P. C. 2003. "The Durability Characteristics of High Performance Concrete: A Review." *Cement and Concrete Composites* 25 (4): 409–420.

2. Mehta, P. K. 1991. *Concrete in the Marine Environment*. New York, NY: Elsevier Science Publishers Ltd.

3. Azzinamini, A., E. Power, G. Myers, H. Ozyildirim, E. Kline, D. Whitmore, and D. Mertz. 2013. *Design Guide for Bridges for Service Life.* Washington, DC: National Academy of Sciences.

4. Moser, R., P. Singh, L. Kahn, P. Singh, and K. Kurtis. 2011. *Durability of Precast Prestressed Concrete Piles in Marine Environment: Reinforcement Corrosion and Mitigation, Part 1*. GDOT (Georgia Department of Transportation) research project no. 07-30. Atlanta, GA: GDOT.

5. Kurtis, K. E., L. F. Kahn, and E. Nadelman. 2013. *Viability of Concrete Performance-Based Specification for Georgia DOT Projects*. Atlanta, GA: GDOT.

6. ASTM International Committee A01. 2016. *Standard Specification for Stainless Steel Bars and Shapes*. ASTM A276/A276M-16a. West Conshohocken, PA: ASTM International.

7. Moser, R., P. Singh, L. Kahn, and K. Kurtis. 2012. *Durability of Precast Prestressed Concrete Piles in Marine Environment, Part 2, Volume 2: Stainless Steel Prestressing Strand and Wire*. FHWA-GA-12-1026. Atlanta, GA: GDOT.

8. Hartt, W. H., R. G. Powers, D. K. Lysogorski, V. Liroux, and Y. P. Virmani. 2007. *Corrosion Resistant Alloys for Reinforced Concrete*. FHWA-HRT-07-039. Washington, DC: FHWA (Federal Highway Administration).

9. Schuetz, D., L. Kahn, K. Kurtis, P. Singh, and R. Moser. 2012. "Preliminary Studies of the Mechanical Behavior of High-Strength Stainless Steel Prestressing Strands." Paper 70. In *2012 PCI Convention and National Bridge Conference September 29–October 2, 2012, Nashville, Tennessee, Proceedings Disc*. Chicago, IL: PCI. CD-ROM.

10. ACI (American Concrete Institute) Committee 318. 2014. *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*. Farmington Hills, MI: ACI.

11. AASHTO (American Association of State Highway and Transportation Officials). 2013. *AASHTO LRFD Bridge Design Specifications*. 6th ed. Washington, DC: AASHTO.

12. ASTM International Committee A01. 2015. *Standard Guide for Specifying Harmonized Standard Grade Compositions for Wrought Carbon, Low-Alloy, and Alloy Steels*. ASTM A1040-10(2015)e1. West Conshohocken, PA: ASTM International.

13. ASTM International Committee G01. 2014. *Standard Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements for Localized Corrosion Susceptibility of Iron-, Nickel-, or Cobalt-Based Alloys*. ASTM G61-86(2014). West Conshohocken, PA: ASTM International.

14. ASTM International Committee A01. 2016. *Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete*. ASTM A1064/A1064M-16b. West Conshohocken, PA: ASTM International.

15. Russell, B. W., and N. H. Burns. 1993. *Design Guidelines for Transfer, Development and Debonding of Large Diameter Seven Wire Strands in Prestressed Concrete Girders*. FHWA/TX-93+1210-5F. Austin, TX: Texas Department of Transportation.

16. Meyer, K. F. 2002. "Transfer and Development Length of 0.6-inch Diameter Prestressing Strand in High Strength Lightweight Concrete." PhD diss., Georgia Institute of Technology, Atlanta, GA.

17. Buckner, C. D. 1995. "A Review of Strand Development Length for Pretensioned Concrete Members." *PCI Journal* 40 (2): 84–105.

18. Dill, J. C. 2000. "Development Length of 0.6-inch Diameter Prestressing Strand in High Performance Concrete." MSc diss., Georgia Institute of Technology, Atlanta, GA.

19. Kahn, L. F., J. C. Dill, and C. G. Reutlinger. 2002. "Transfer and Development Length of 15-mm Strand in High Performance Concrete Girders." *Journal of Structural Engineering* 128 (7): 913–921.

20. Oh, B. H., and E. S. Kim. 2000. "Realistic Evaluation of Transfer Lengths in Pretensioned, Prestressed Concrete Members." *ACI Materials Journal* 97 (6): 821–830.

21. Oh, B. H., E. S. Kim, and Y. C. Choi. 2006. "Theoretical Analysis of Transfer Lengths in Pretensioned Prestressed Concrete Members." *Journal of Engineering Mechanics* 132 (10): 1057–1066.

22. Zia, P., and T. Mostafa. 1977. "Development Length of Prestressing Strands." *PCI Journal* 22 (5): 54–65.

23. Martin, L. D., and N. L. Scott. 1976. "Development of Prestressing Strand in Pretensioned Members." *ACI Journal* 73 (8): 453–456.

24. Deatherage, J. H., E. G. Burdette, and C. K. Chew. 1994. "Development Length and Lateral Spacing Requirements of Prestressing Strand for Prestressed Concrete Bridge Girders." *PCI Journal* 39 (1): 70–83.

25. Mitchell, D., W. D. Cook, A. A. Khan, and T. Tham. 1993. "Influence of High Strength Concrete on Transfer and Development Length of Pretensioning Strand." *PCI Journal* 38 (3): 52–66.

26. Lane, S. N. 1998. *A New Development Length Equation for Pretensioned Strands in Bridge Beams and Piles*. FHWA-RD-98-116. Washington, DC: FHWA.

27. Ramirez, J. A., and B. W. Russell. 2008. *Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete*. National Cooperative Highway Research Project report 603. Washington, DC: Transportation Research Board.

28. Barnes, R. W., J. W. Grove, and N. H. Burns. 2003. "Experimental Assessment of Factors Affecting Transfer Length." *ACI Structural Journal* 100 (6): 740–748.

29. Kaar, P. H., R. W. LaFraugh, and M. A. Mass. 1963. "Influence of Concrete Strength on Strand Transfer Length." *PCI Journal* 8 (5): 47–67.

30. Russell, B. W., and N. H. Burns. 1997. "Measurement of Transfer Lengths on Pretensioned Concrete Elements." *Journal of Structural Engineering* 123 (5): 541–549.

## Notation

$d_b$ = nominal diameter of prestressing strand

$f'_c$ = design compressive strength of concrete at 28 days

$f'_{ci}$ = compressive strength of concrete at strand release

$f_{pe}$ = effective prestress in the prestressing steel (AASHTO LRFD specifications)

$f_{ps}$ = stress in the prestressing steel at nominal strength of the member

$f_{se}$ = effective prestress in the prestressing steel (ACI 318-14)

$f_{si}$ = stress in prestressing strand after strand release

$l_d$ = development length

$l_t$ = transfer length

$w/cm$ = water–cementitious material ratio

$\kappa$ = multiplier factor = 1.6 when pretensioned member has a depth greater than 24 in. (610 mm) and 1.0 otherwise

## About the authors

Alvaro Paul, PhD, is an assistant professor in the Facultad de Ingeniería y Ciencias Aplicadas at Universidad de los Andes, Chile, in Santiago.

Lorintz B. Gleich, MSc, PE, a captain in the U.S. Army, is an assistant professor in the Department of Civil and Mechanical Engineering at the U.S. Military Academy at West Point, N.Y.

Lawrence Kahn, PhD, PE, is professor emeritus in the School of Civil and Environmental Engineering at the Georgia Institute of Technology in Atlanta, Ga.

## Abstract

With increasing demand for bridge service lives of 100 years or more, engineers face a durability challenge regarding bridges in coastal regions, where accelerated deterioration is commonly observed. To develop more-durable reinforcement, this research assesses the bond performance of duplex high-strength stainless steel (HSSS) 2205 strand in prestressed concrete piles by the experimental determination of the transfer and development length. The average transfer length of piles reinforced with duplex HSSS 2205 strand was 74% and 57% of the transfer length calculated based on ACI 318-14 and AASHTO LRFD specification requirements, respectively. In addition, driving the piles to refusal had little effect on the transfer length. The experimental development length of piles using duplex HSSS 2205 strand was 88% and 55% of the transfer length calculated based on ACI 318-14 and AASHTO LRFD specifications requirements, respectively. These results suggest that the current codes may be used without modifications for design with duplex HSSS 2205 strand.

## Keywords

Bridge, bridge pile, corrosion protection, development length, stainless steel, transfer length.

## Review policy

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

## Reader comments

Please address reader comments to journal@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal,* 200 W. Adams St., Suite 2100, Chicago, IL 60606.