9-1-2000

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Published version. *ACI Structural Journal,* Vol. 97, No. 5 (September 2000): 774-782. DOI.

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 97-S79

Excessive Strand End Slip in Prestressed Piles

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This paper presents the results of a research project that investigated excessive strand end slip observed recently in some prestressed piles. From measurements taken in the field, it is apparent that the problem of excessive initial strand slip is independent of pile shape and size. Strand end slip is evident in piles of different manufacturers in different states in the Southeast. Excessive strand end slip was found in both the top and bottom of the cross section of the piles, although the top portion of the cross section generally exhibited much higher initial slip. Several preventive measures can be adopted to reduce the excessive strand end slip. These preventive measures include: a) proper concrete mixture proportioning to reduce top bar effect; b) use of higher-strength concrete with the lowest possible slump and setting time; c) assessment of the condition of the strands prior to installation to insure excellent bond characteristics; d) gradual release of prestress, with an optimal release sequence; and e) use of adequate vibration to ensure consolidation.

The strand end slip measured at five prestressing plants in the Southeast is considerably higher than the allowable end slip and is expected to affect the pile performance. If the strand slip theory is adopted, the strand development length increases substantially due to the excessive strand end slip. A top bar effect factor similar to the one used in reinforced concrete design is recommended. To maintain the excellent quality of precast and prestressed concrete products, manufacturers should adopt a dynamic quality control process that follows the rapid changes in the industry. More tests are necessary to ensure excellent quality, such as the Moustafa or an equivalent test, to assess the bond capabilities of the strands, end slip measurements, and direct measurement of the transfer length. Installation of piles should proceed in a manner to alleviate the top bar effects by placing piles alternately in their best and worst directions.

Keywords: pile; prestress; slip; strand.

INTRODUCTION

Prestressed concrete piles have been used in a wide variety of structures and loading conditions. Although they are primarily compression members, piles are subjected to tensile stresses caused by bending during lifting and placing as well as in service, especially during earthquakes.

Prestressed concrete piles are not susceptible to rot and wood borers, as are timber piles, or to corrosion, as are steel piles. Additionally, prestressed concrete piles can be designed to withstand the high compressive forces of large marine structures as well as the lateral loads associated with wind, waves, and earthquakes. Because of these advantages, prestressed concrete piles have become a standard item in bridge construction.

Recently, inspectors of the South Carolina Department of Transportation (SCDOT) observed a strand end slip problem involving 610 mm (24 in.) octagonal piles being cast at the Socastee bridge location near Conway, South Carolina.[1] It was estimated that the top strands were slipping by as much as 38 mm (1.5 in.) when cut to transfer the prestressing force. Although some end slip is expected, the amount encountered on this job was particularly large and difficult to explain. It is interesting to note that the strands, which were located near or below the midheight of the cross section of the piles, showed much smaller end slip.

In a pretensioned member, the prestressing force is applied by releasing the pretensioned strands from the prestressing frame. As the strands try to shorten, compressive force is applied to the concrete. The prestressing force is transferred to the concrete through bond between strands and concrete. When the strands are cut, some small end slip is expected due to loss of stress within the transfer length. The uniqueness of the reported case is the amount of end slip and that the end slip occurred mainly in the uppermost region of the cross section. The top strand end slip reported is approximately 25 to 38 mm (1 to 1.5 in.),[1] significantly greater than the 1.3, 2.0, and 2.3 mm (0.05, 0.08, and 0.09 in.) predicted by Balazs,[2] Brooks et al.,[3] and Anderson and Anderson,[4] respectively.

This paper describes research to determine the magnitude and causes of the excessive strand end slip and identifies possible solutions.

RESEARCH SIGNIFICANCE

This paper presents a top bar effect problem in prestressed concrete structural elements. Top bar effect is recognized in reinforced concrete practice, but not in the prestressed concrete industry. Strand end slip field measurements depicting the top bar effect phenomenon in prestressed concrete piles manufactured in the Southeast are presented and discussed. The effects of excessive strand end slip on pile performance are presented. Practical recommendations for reducing such effects are included.

STRAND END SLIP MEASUREMENTS

To get a better understanding of the situation, strand end slip measurements were taken at four additional prestressing plants in the Southeast.[1] The purpose of these measurements was to answer several questions. What strand end slip values were actually being experienced in the field? Was the problem limited to the 610 mm (24 in.) octagonal piles like those found at the Socastee bridge location, or was excessive end slip present in other pile types as well? Did strand arrangement or pile size affect the end slip? Does end slip vary with the pile manufacturer?

The piles studied are cast in prestressing beds, which can be over 61 m (200 ft) long. The individual piles are separated on the casting bed by removable header plates that are placed before the prestressing strand. Header plate movement is re-

ACI Structural Journal, V. 97, No. 5, September-October 2000.
MS No. 99-226 received November 15, 1999, and reviewed under Institute publication policies. Pertinent discussion will be published in the July-August 2001 *ACI Structural Journal* if received by March 1, 2001.

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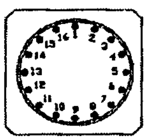
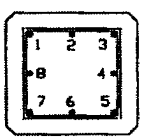
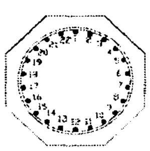
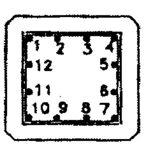
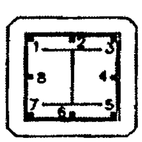
stricted by wooden blocks wedged into place to prevent movement during the casting process. This arrangement provides enough distance between the piles to take measurements at several places along the bed. The strand cutting sequence varied from manufacturer to manufacturer. All strands, however, were flame-cut, which resulted in a sudden release.

End slip was measured immediately after transfer by marking the strands 76 mm (3 in.) from the concrete surface or header plates before the strands were released. The header plates were pushed away from the concrete surface in most cases. In cases that header plate removal was not feasible, precautions were taken to ensure that the header plates did not move relative to the concrete surface. After the strands were flame-cut, the new distance from the marking to the concrete surface or header plate was measured. The difference in the two measurements was taken as the end slip of the strand into the concrete. Measurements were taken by quality control personnel from each plant and by SCDOT inspectors. Strand end slip measurements were taken from piles produced at five different plants. Petrou and Joiner[1] reported the design specifications and measurement positions relative to the pile's position in the casting bed. Table 1 provides a summary of the plant data collected by Petrou and Joiner. Strand and end slip measurements were collected for 23 piles. As can be seen in Table 1, excessive strand end slip is evident in all the piles sampled. The end slip occurs in both

Table 1—Average strand end slip measurements reported by Petrou and Joiner[1]

Plant	Strand location	Stressed end of stressing bed, mm (in.)	Anchor end of stressing bed, mm (in.)	Top slip / Bottom slip
Plant 1 	Top: average of strands 1, 2, 3, 15, and 16	11 (0.45)	10 (0.39)	1.18 stressed end 1.15 anchored end
	Bottom: average of strands 7 to 11	10 (0.38)	9 (0.34)	
Plant 2 	Top: strands 1 to 3	17 (0.67)	16 (0.63)	5.15 stressed end 1.91 anchored end
	Bottom: strands 5 to 7	3 (0.13)	8 (0.33)	
Plant 3 	Top: strands 1 to 6 and 18 to 22	38 (1.50)		N/A
	Bottom	Not observed		
Plant 4 	Top: strands 1 to 4	20 (0.78)	21 (0.83)	2.44 stressed end 4.15 anchored end
	Bottom: strands 7 to 10	8 (0.32)	5 (0.20)	
Plant 5 	Top: strands 1 to 3	8 (0.33)	10 (0.39)	1.27 stressed end 1.50 anchored end
	Bottom: strands 5 to 7	7 (0.26)	7 (0.26)	

the top and the bottom regions of the cross section, with the top strands generally exhibiting higher initial slip.

Top strand end slip is calculated based on the average slip of strands, which are located in the top region of the cross section. Bottom strand end slip is calculated based on the average slip of strands, which are located in the bottom region of the cross section. The average ratio of top strand end slip to bottom strand end slip is 2.12 for all piles sampled, demonstrating that the top strands are slipping much more than the bottom strands.

Plant 3 was producing octagonal piles for the Socastee bridge near Conway, South Carolina. This plant terminated its operation after that project. The octagonal prestressed piles from Plant 3, shown in Fig. 1, are 610 mm (24 in.) in width and cast in 21.3 m (70 ft) lengths. The prestressing strands are arranged in a circular pattern with a radius of 241 mm (9.5 in.). Each of the twenty-two 12.7 mm (1/2 in.) strands is prestressed with approximately 153.5 kN (34.5 kips) force. The observed end slip of the top strands was approximately 25 to 38 mm (1 to 1-1/2 in.). No detailed end slip measurements are available.

Two short sample lengths of pile were cast for testing the capacity of the strands used in Plant 3. The first length was 3.7 m (12 ft) long and the second was 1.3 m (52 in.) long. The 3.7 m (12 ft) long pile was cast without spiral reinforcement to determine the effect of the confining steel on the end slip. The 1.3 m (52 in.) long pile was cast with spirals having a 51 mm (2 in.) pitch, similar to the production piles. Once the concrete was cured, the strands were subjected to a pullout force. The results of these pullout tests for the 3.7 m (12 ft) and 1.3 m (52 in.) lengths are shown in Table 2 and 3, respectively.

Table 2 and 3 clearly show the weaker bond strength in strands cast at the top of the section versus strands cast at the bottom of the section. Strands at the top of the cross section exhibited bond failure, while strands at the bottom of the section, except for Strand 13, failed by breaking. Several of the strands in the 1.3 m (52 in.) pile with spirals slipped at an applied force of less than 44.5 kN (10,000 lb), while the corresponding strands in the pile without spirals slipped at loads over 133.5 kN (30,000 lb).

BOND MECHANISMS

From the plant measurements, it is apparent that the problem is not limited to one particular size or type of pile as was originally reported. To determine possible causes and solutions for the excessive strand end slip, the nature of the bond between prestressing steel and concrete must first be explored and understood. Once the nature of the bond is understood, several factors affecting that bond can be determined and investigated. A significant amount of research has been conducted on bond and how bond affects the ultimate strength of a member.[5-17]

Steel-to-concrete bond is achieved primarily by three factors:[16,17]

1. Adhesion of the concrete and steel interfaces;
2. Friction between the concrete and steel; and
3. Mechanical resistance due to interlocking of the twisted strand wires and the surrounding concrete.

The first of these factors, the adhesion of the concrete and steel interface, occurs where the concrete paste molds into and fills the rough surface of the steel, thereby creating an adhesion between the concrete and steel. Most prestressing steel, however, is very smooth, and such a mechanism alone would not be expected to produce adequate bond strength. Additionally, this type of bond mechanism can only be present when there is no end slip.[16,17] Because strand end slip is a universal phenomenon at detensioning of pretensioned members, adhesion cannot account for the bond strength in this region. The no-slip condition is only met in the middle of a member; therefore, adhesion could not be expected to contribute to bond strength over the transfer length.

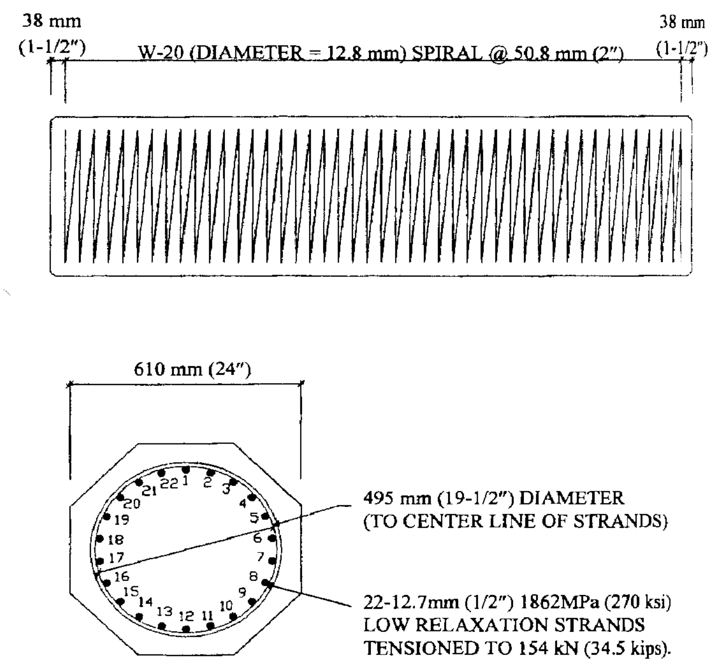
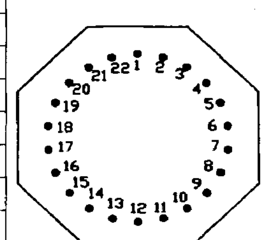


Fig. 1—Plan and cross section of 610 mm (24 in.) octagonal pile from Plant 3.

Table 2—Test results from 3.7 m (12 ft) pile without confining reinforcement

Strand no.	Load at first slip, kN (kips)	Maximum load, kN (kips)	Comments	Strand arrangement
1	177.9 (40)	191.3 (43)	Strand failure	
2	Not recorded	66.7 (15)	Bond failure	
3	15.6 (3.5)	51.2 (11.5)	Bond failure	
4	17.8 (4)	68.9 (15.5)	Bond failure	
5	66.7 (15)	126.8 (28.5)	Bond failure	
6	71.2 (16)	195.7 (44)	Strand failure	
7	93.4 (21)	197.9 (44.5)	Bond failure	
12	No slip	193.5 (43.5)	Strand failure	
18	No slip	200.2 (45)	Strand failure	
20	Not recorded	195.7 (44)	Strand failure	
22	155.7 (35)	177.9 (40)	Bond failure	

Friction between the concrete and steel is the primary bond mechanism in pretensioned concrete. The normal forces required to develop frictional resistance result from the Hoyer Effect. Steel strand has a reduced diameter under tension due to Poisson's effect and the tightening of the strand bundle; releasing the tension, therefore, allows the strand to return to its original diameter. In prestressed concrete, the swelling of the strand is prevented by the hardened concrete. The pressure created as the strand tries to swell produces the normal forces needed to create a friction reaction. The friction bond is affected by the surface characteristics of the steel, the coefficient of friction between the steel and the concrete, and the strength of the concrete.[16,17]

The third bond mechanism is the mechanical interaction between the prestressing strand and the concrete.[16,17] In all piles being evaluated, the prestressing steel is a seven-wire strand. This strand consists of a central wire spiral wrapped by six outer wires. This spiral wrapping produces crevices for the cement paste to work its way into, creating a mechanical connection between the concrete and the strand. The Hoyer Effect helps the mechanical bond, because the expansion of the steel improves the connection between the concrete and steel. Mechanical bonding, however, is not a dependable bond mechanism according to Martin and Scott.[18]

PROBABLE CAUSES OF EXCESSIVE STRAND END SLIP

Strand end slip occurs as a result of the loss of prestress within the transfer length, and it is estimated[3,4] to be around 2.5 mm (0.1 in.) for a 12.7 mm (1/2 in.) strand. Any additional strand end slip is considered excessive. Several factors have been identified that may weaken the bond between concrete and steel and so contribute to the excessive strand end slip. These factors include concrete strength and consistency, steel surface conditions, tension release mechanism, top bar effect, and transverse steel arrangement. Each of these factors will be evaluated to determine its relative significance.

Concrete strength and consistency

The compressive strength of the concrete at prestress transfer is at least 25.9 MPa (3750 psi) for all the piles in this study. This strength is less than the 27.6 MPa (4000 psi) recommended by Li and Liu,[19] but is greater than the 24.1 MPa (3500 psi) minimum concrete strength at release recommended by PCI[20] and AASHTO.[21] Additionally, this strength is reached in approximately 24 h, indicating a 28-day concrete strength well within the 34.5 to 55.2 MPa (5000 to 8000 psi) range recommended by PCI and others.[19-21]

The relative importance of concrete strength to bond is not completely clear from the literature. Kaar et al.[22] found no distinct correlation between concrete strength and strand development length for concrete strengths between 10.3 and 34.5 MPa (1500 and 5000 psi). Others, however, concluded that concrete strength does have an influence on development length.[2,17,23,24] FHWA researchers recently formulated new transfer and development length equations[25] that include the compressive strength as a major parameter

$$L_t = \frac{4f_{pt}d_b}{f'_c} - 5 \tag{1}$$

$$L_d = \left[\frac{4f_{pt}d_b}{f'_c} - 5\right] + \left[\frac{6.4(f_{ps} - f_{se})d_b}{f'_c} + 15\right] \tag{2}$$

The influence of concrete strength on the strand end slip may help to explain the higher end slip values of the top strands because the concrete at the top of the cast is expected to have significantly lower strength.

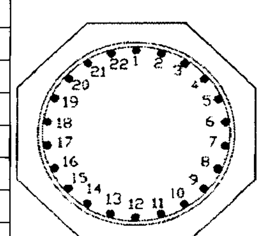
It has been shown in the literature,[26-28] for reinforced concrete beams, that the longer the concrete remains plastic, the lower the bond strength and the greater the top bar effect. The lowest-slump concrete with the shortest setting time that can still be properly consolidated should be used to obtain the best concrete-steel bond strength. Revibration appears also to improve bond strength for top-cast bars in high-slump concrete.[26] If used, revibration should be limited to the upper portions of placement.

Strand bond quality

A strand with a roughened surface has better bond characteristics.[17,24] Oils or other coatings will affect the bond characteristics by reducing the coefficient of friction between the concrete and steel. Recent research has shown that strands from different manufacturers display radically different bond characteristics.[29] The strand bond quality cannot explain the higher strand end slip observed in the top of a cross section since a strand for a single pile would likely come from the same stock or roll. One would not expect to see any significant or consistent variation in the bond quality of strands placed in the top versus the bottom of the cross sec-

Table 3—Test results from 1.3 m (52 in.) pile with spiral confining reinforcement

Strand no.	Load at first slip, kN (kips)	Maximum load, kN (kips)	Comments	Strand arrangement
1	22.5 (5)	48.9 (11)	Strand slipping excessively at 40 kN (9 kips)	
3	13.3 (3)	20.0 (4.5)	Bond failure	
8	44.5 (10)	193.5 (43.5)	Strand failure	
9	115.6 (26)	195.7 (44)	Strand failure	
12	124.5 (28)	193.5 (43.5)	Strand failure	
13	111.2 (25)	142.3 (32)	Bond failure	
15	173.5 (39)	200.2 (45)	Strand failure	
18	33.4 (7.5)	102.3 (23)	Bond failure	
19	40.0 (9)	104.5 (23.5)	Bond failure	
20	15.6 (3.5)	28.9 (6.5)	Bond failure	
22	13.3 (3)	22.2 (5)	Bond failure	



tion. Therefore, the strand bond quality is not, by itself, a major cause of the increased end slip of top strands.

Tension release mechanism

The tension release mechanism also does not provide a suitable answer to the excessive end slip. The fabricators of the piles studied used flame-cutting to release the tendons and transfer the prestressing force. This common method results in a sudden release of prestress. While it has been determined that a sudden release will increase the development length of a strand,[24,30,31] adequate results have been obtained using this method. As with the other factors discussed, if a sudden tension release was alone responsible, the lower strands should be slipping as much as the top strands. Again, this factor does not provide the answer by itself.

Top bar effect

According to ACI Code[32] and AASHTO[21] provisions, a top bar is any reinforcement having more than 12 in. of fresh concrete cast below it. Top bar effect is the most important factor contributing to the excessive end slip of top strands. This is the only factor related to the position of a strand in the cross section of a member. Measurements of prestressed strand end slip consistently show higher end slip in the top of a cross section, regardless of cross-sectional shape or strand arrangement.[1,30,33] In reinforced concrete design, the importance of top bar effects has been accounted for in the ACI Code[32,34,35] since 1951. The development length of top cast bars in reinforced concrete is increased by a factor of 1.3 (ACI Code[32]) or 1.4 (AASHTO[21]). The bond between prestressing strands and concrete is even more important in prestressed concrete since the prestressing force is transferred to the concrete by this bond. It is reasonable, therefore, to increase the development length of strands used in pretensioned members by a factor similar to that used for reinforced concrete elements.

Transverse steel arrangement

The pitch of spiral reinforcement near the ends of piles is typically very small and may inhibit the flow of concrete around the prestressing strands. Figure 2 shows that strands in the top of a cross section may have two zones of weaker concrete that inhibit good bond. The transverse steel arrangement, therefore, does influence the development length and end slip. Spiral pitches of 25 to 51 mm (1 to 2 in.) near the ends of pile segments, however, have been recommended practice for decades.[18,36,37] This smaller spacing is needed near the ends of the pile to provide the strength to resist the forces encountered during driving. Thus, while confining steel spacing is a factor in bond between steel and concrete, its use is required and the spacing is governed by other concerns.

PRETENSIONING LOSSES

Prestress losses arising from the excessive end slip must be determined to evaluate the effect on the piles' capacity.

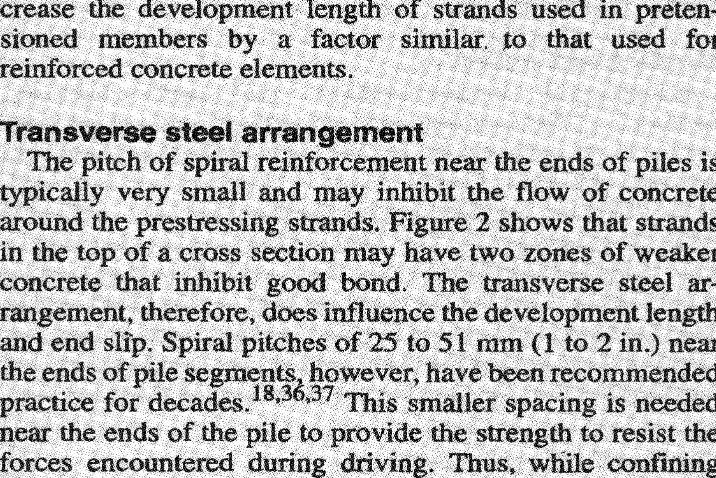


Fig. 2—Top and bottom strands showing areas of weak concrete.

Prestress losses in pretensioned concrete can be classified into two categories based on their time of occurrence. The first category consists of initial losses, which occur immediately after the transfer of the prestressing force. The second type of losses are time dependent, and occur over time after the prestressing force is transferred. Initial losses include elastic shortening of the concrete and initial strand end slip, while time dependent losses include creep and shrinkage of concrete and relaxation of the steel strands. Some relaxation of steel occurs before the transfer of the prestressing force.

Total expected losses are specified by both ACI-ASCE and by AASHTO.[21] An ACI-ASCE Joint Committee suggested losses to be around 241.3 MPa (35,000 psi), which does not include strand end slip losses. AASHTO recommends keeping total losses under 310.3 MPa (45,000 psi) for concrete with $f_c' = 34.5$ MPa (5000 psi).

Strand end slip losses

A realistic method of calculating prestressing loss due to strand end slip is based on a strand slip theory discussed in papers by Brooks et al.[3] and Anderson and Anderson.[4] The theory is based on the idea that the initial slip is a direct indication of the bond quality of the concrete. The slip, therefore, is directly related to the transfer length and flexural bond length.

Using a linear variation of stress from the free end of the member to the transfer length l_t', the average strand force over the transfer length $F_{i\,(ave)}$ can be set to the initial force immediately after transfer F_i, divided by 2. The initial strand slip at the end δ can be related to the average force by the steel strains

$$\delta = \frac{F_i l_t'}{2A_{ps}E_s} \tag{3}$$

Substituting the steel stress $f_{si} = F_i/A_{ps}$ and solving for the transfer length l_t' yields the following equation

$$l_t' = \frac{2\delta E_s}{f_{si}} \tag{4}$$

By setting Eq. (4) equal to the transfer length specified by the ACI Code,[32] an allowable end slip δ_{all} can be calculated

$$\delta_{all} = 0.024\frac{f_{se}f_{si}d_b}{E_s} \tag{5}$$

For the 610 mm (24 in.) octagonal piles, with f_{si} = 1396.2 MPa (202.5 ksi), f_{se} = 1189.4 MPa (172.5 ksi), and E_s = 193,000 MPa (28,000 ksi), the allowable slip is 2.5 mm (0.10 in.). The coefficient of Eq. (5) becomes 0.167 when U.S. units are used.

When the transfer length increases, the flexural bond length also increases.[3] The ACI Code[32] specifies the flexural bond length to be equal to $0.145(f_{ps} - f_{se})d_b$ and the transfer length to be $0.048(f_{se}d_b)$, where f_{ps} is the stress in prestressed reinforcement at nominal strength and d_b is the strand diameter. Rearranging the transfer length equation and solving for the diameter of the strand yields

$$d_b = \frac{20.7 l_t}{f_{se}} \tag{6}$$

The coefficient of Eq. (6) becomes 3.0 when U.S. units are used. Substituting this expression into the equation for the flexural bond length and substituting the new transfer length calculated by the strand slip theory results in the new flexural bond length l_b' given by the following equation

$$l_b' = 3.0\frac{(f_{ps}-f_{se})}{f_{se}}l_t' \quad (7)$$

The strand stress that can be developed f_{dev} depends on the position in the member. Assuming a linearly increasing transfer length, the developable stress f_{dev} at a distance x from the free end of the member, less than or equal to l_t', is

$$f_{dev} = \frac{x}{l_t'}f_{se} \quad \text{where } x \le l_t' \quad (8)$$

For cases where the point of interest is between the new transfer length l_t' and the new development length $(l_t' + l_b')$ and assuming a linearly varying flexural bond length

$$f_{dev} = f_{se} + \frac{(x-l_t')}{l_b'}(f_{ps}-f_{se}) \quad \text{where } l_t' \le x \le l_d' \quad (9)$$

And, if the distance from the free end is greater than the new development length l_d' the developable stress is given by

$$f_{dev} = f_{ps} \quad \text{where} x \ge l_d' \quad (10)$$

Applying the previous equations to the 610 mm (24 in.) octagonal piles with d = 38 mm (1.5 in.), f_{si} = 1396.2 MPa (202.5 ksi), f_{se} = 1189.4 MPa (172.5 ksi) and E = 193,000 MPa (28,000 ksi), yields a developable stress of 345.3 MPa (50.1 ksi) at the section 3.05 m (10 ft) from the end of the pile. This indicates a considerable loss of prestress at a distance where under normal bond conditions the developable stress f_{dev} should be equal to f_{ps}.

INFLUENCE OF END SLIP ON ULTIMATE CAPACITY OF PILE

At Plant 2, end slip measurements were taken from 457 mm (18 in.) square piles. The prestressing strands are arranged in a square pattern and are prestressed at 150.3 kN (33.8 kips) each (refer to figure inserted in Table 1). The piles are cast in 12.5 m (41 ft) lengths. Design drawings are shown in Fig. 3. Strands are numbered to correspond with the numbering in Table 1.

The axial load-moment interaction diagrams for this pile calculated by a program developed by the authors are shown in Fig. 4. In this program, the stresses in the strands are determined by Eq. (8) to (10). It is assumed that the stress in the strands upon reaching their developable stress remains constant. These interaction diagrams are drawn for a section 1800 mm (71 in.) from the pile end where strands with ACI limited end slip can fully develop their strength. The strand end slip values used for the analysis are those measured at the stressed end of the stressing bed (Table 1). Figure 4 shows that extensive end slip can dramatically reduce the ultimate capacity of the pile, particularly in the region of behavior where the pile is expected to perform.

Because of the top bar effect, the prestress loss of strands at the top part of the section will be larger than the prestress loss of strands at the bottom part of the section. There will be extra prestressing force (bottom prestressed force minus top prestressed force) at the bottom part. This produces a moment that causes tensile stress in the upper part of the section and compressive stress in the bottom part of the section. When the pile is installed, if the applied moment has the same direction as the moment produced by the top bar effect, the ultimate capacity of the pile will be decreased. This is called worst direction in this paper. On the other hand, if the directions of applied moment and the moment produced by top bar effect are opposite, the ultimate capacity of the pile will be increased under most loading conditions. This is called best direction in this paper.

It can be seen in Fig. 4 that the best direction moment capacity can be considerably greater than that of the worst direction. Additionally, Fig. 4 illustrates the effect of the excessive strand end slip. Both best and worst direction moment capacities are less than the assumed ACI moment capacity. In the case plotted (Plant 2), the observed end slips

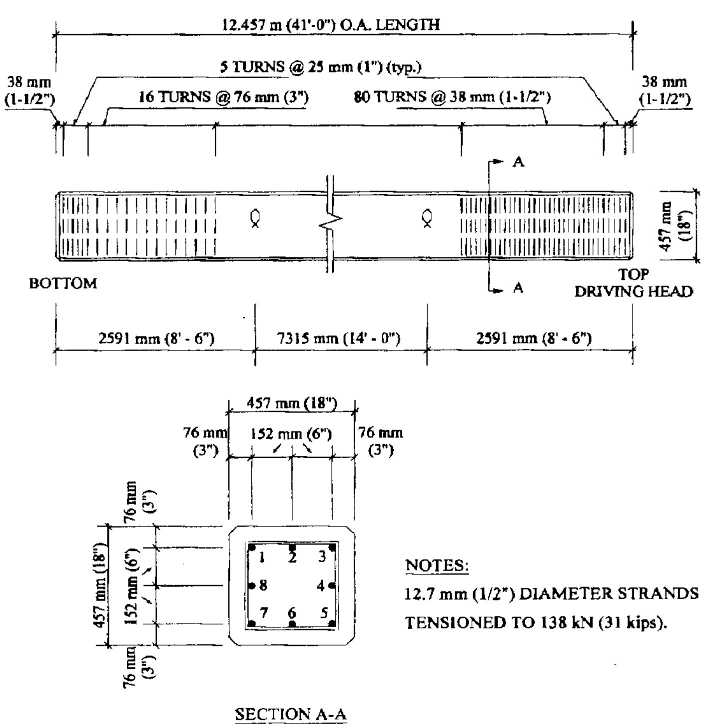


Fig. 3—Design of piles from Plant 2.

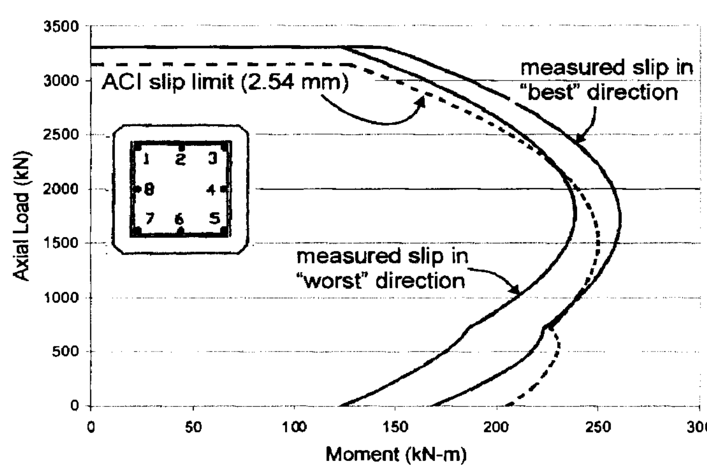


Fig. 4—Factored axial load-moment interaction diagram for Plant 2.

exceeded ACI permitted end slips by 670 and 130% for the top and bottom strands, respectively (Table 1).

By accepting that there is a top bar effect in prestressed concrete piles, it is recognized that there will be an initial or residual moment introduced to the piles. This residual moment results in a best and worst direction for the orientation of the piles. As such, the casting orientation of the piles should be noted and piles should be installed in a manner to alleviate this effect. Placing all piles in a footing in the same orientation may be detrimental to the capacity of the footing.

EUROCODE EC2

To this point, the discussion has been made with respect to the ACI 318 Code,[32] AASHTO,[21] and American practices and experience. It is illustrative to also look at the European code and experience. In the following, the notation of Eurocode EC2[39] is kept.

In the Eurocode EC2, distinction is made between the transmission length l_{bp} (over which the prestressing force P_0 is fully transmitted to the concrete), the dispersion (or development) length $l_{p,eff}$ (over which the concrete stresses gradually disperse to a distribution across the concrete section in agreement with the hypothesis that plane sections remain plane), the anchorage length l_{ba} (over which the tendon force in the ultimate limit state is fully transmitted to the concrete), and the neutralized zone $l_{bp,0}$ (over which the tendon stress is zero due to either purposely debonding or debonding resulting from the sudden release of the tendons). Figure 5 shows the definitions and design value of l_{bp} in Eurocode EC2. The transmission length (which is equivalent to the transfer length l_t in ACI notation) is influenced by the size and type of the tendon, the surface condition of the tendon, the concrete strength at transfer, and the degree of compaction of the concrete. Values are based on experimental data or experience with the type of tendon used. In the absence of any other information, values of the ratio l_{bp}/d_b range from 30 to 75 and are inversely proportional to concrete strength.

The design value $l_{bp,d}$ of the transmission length may be 0.8 or 1.2 times l_{bp}, depending on which value is more critical for the situation examined. The transmission length is the distance from the free end to the section where the concrete stresses due to the prestress along the top of the cross section may be considered as uniform. For rectangular cross sections and straight tendons situated near the bottom of the section, the dispersion length can be established as

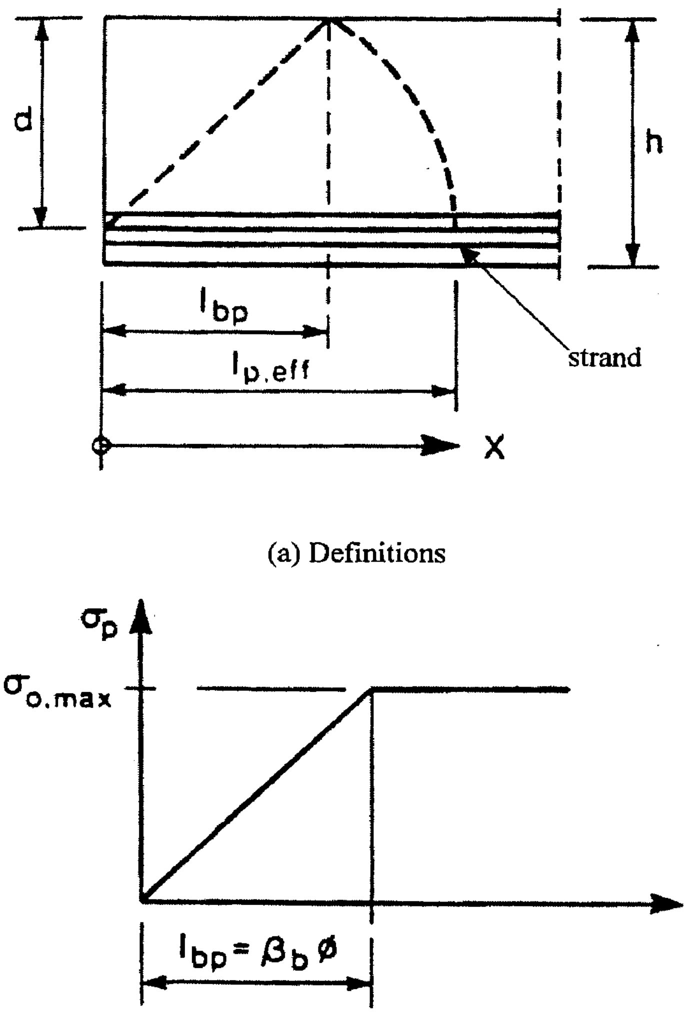
$$l_{p,eff} = \sqrt{l_{bp,d}^2 + d^2} \qquad (11)$$

Transmission length, anchorage length, and dispersion length are taken from the start of the effective bond that is after the end of neutralized zone. No value is given in EC2[39] for the length of the neutralized zone for the case of sudden release of the tendons. In the Greek code,[40] which is very similar to the EC2, a value of $10d_b$ is suggested for the length of the neutralized zone. Top bar effects are accounted for by considering a reduction in bond stress of 30%, which results in an increase of the transmission length by a factor of approximately 1.4. A top bar is defined as a bar that is in the top half of a concrete member with a thickness more than 250 mm (10 in.). For members with a thickness more than 600 mm (24 in.), a top bar is one that is within 300 mm (12 in.) of the top surface.

The Eurocode EC2 is not very different from the ACI Code concerning the transmission (transfer) length. In practice, it is suggested by the Eurocode EC2 that the transmission length be verified by in-place measurements, indicating a lack of confidence in the analytical expressions predicting the transmission length. In European practice, the gradual release of the tendons is preferred to a sudden release. If a sudden release technique is used, then special attention is paid to the cutting sequence.

CONCLUSIONS AND RECOMMENDATIONS

Although this study is based on measurements for a limited number of pile manufacturers in one region in the U.S. during a specific time period, it helps to emphasize a major point: to maintain the excellent quality of the precast and prestressed products the manufacturers should adopt a quality control process that follows the rapid changes in the industry. Concrete, as a material, changes continuously; the manufacturing process of prestressing strands is modified periodically. These changes are necessary to improve the quality and lower the cost of the precast and prestressed products. Some of these changes can be detrimental, however, if they pass unnoticed, for the quality and safety of the precast and prestressed products. Merely checking the strength of the concrete before release is no longer sufficient. More tests are necessary to ensure excellent quality, such as the Moustafa[29] or an equivalent test, to assess the bond capacity



(a) Definitions

(b) Design value of l_{bp}

Fig. 5—Transfer of prestress in pretensioned elements from Eurocode EC2.[40]

of the stands, end slip measurements, and direct measurement of the transfer length.

Some other conclusions can be summarized:

1. The allowable end slip for the investigated prestressed piles is estimated to be approximately 0.1 in. (2.54 mm). The strand end slip measured at the five prestressing plants in the Southeast is typically considerably higher than the allowable end slip;

2. No single factor seems to be sufficient by itself to cause the excessive end slip observed in these piles. Therefore, a combination of factors must be responsible. Top bar effect is the most important factor contributing to excessive end slip of top strands. Further experimental investigation is necessary to quantify the contribution of each factor to the strand end slip;

3. The problem of excessive end slip is independent of pile shape and size. The end slip is evident in piles of different manufacturers in different states in the Southeast. Excessive end slip was found in both the top and bottom of the cross section of the piles, although the top portion of the cross section generally exhibited much higher initial slip. A top bar factor similar to the one used in reinforced concrete design is recommended;

4. If the strand slip theory is adopted, the strand development length increases substantially due to the excessive strand end slip. The ultimate strength of the pile is reduced in the development length region making the safety of the pile, in some cases, questionable. Such results suggest that strand end slip measurements should be added to the quality control procedures of pile manufacturers and that a criterion for pile rejection should be sought; and

5. The Eurocode EC2 is not very different from the ACI Code concerning the transmission (transfer) length. In practice, it is suggested by the Eurocode EC2 that the transmission length be verified by in place measurements, indicating a lack of confidence in the analytical expressions predicting the transmission length. In European practice, the gradual release of the tendons is preferred to a sudden release. If a sudden release technique is used, then special attention is paid to the cutting sequence. A top bar factor of approximately 1.4 is applied to pretensioned members, much like the 1.3 factor applied to reinforced concrete in the U.S.

The following preventive measures are recommended to reduce the possibility of excessive strand end slip:

1. Use an appropriate concrete mixture proportion to reduce the top bar effect. Generally, such concrete will be of higher strength and have the lowest practical slump and setting time;

2. Assess the surface condition of the strands prior to installation to ensure excellent bond characteristics. For good bond, the strand should be free of oily residue and material latency;

3. Provide a gradual release of prestress. It is preferable that all strands be gradually released simultaneously (using a strongback and hydraulic system, for instance); if this is not possible, an optimal release sequence, minimizing internal stresses in the pile, should be used; and

4. Vibration should be adequate to ensure consolidation. Revibration should be avoided. The authors are currently involved in related research whose aim is to determine optimal vibration characteristics.

Additionally, in applications were the top bar effects may impact the capacity of the structure, piles should be installed in a manner alleviating these effects by placing piles alternately in their best and worst directions.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the South Carolina Department of Transportation (SCDOT) under Contract No. 573-1-24-95. The contents of this paper reflect the views of the authors, who are responsible for the findings and conclusions presented herein, and do not necessarily reflect the views of SCDOT. The assistance of the prestressed concrete manufacturers is greatly appreciated. Special thanks are due to Richard Pool of the University of South Carolina and Aly A. Hussein of SCDOT for their assistance.

NOTATIONS

A_{ps} = area of prestressed reinforcement in tension zone
d = distance from extreme compression fiber to centroid of tension reinforcement
d_b = nominal strand diameter
E_s = Young's modulus of strands
f_c' = specified compressive strength of concrete
f_{dev} = developable stress at point along length of pile
f_{ps} = stress in prestressed reinforcement at nominal strength
f_{pt} = stress in prestressed reinforcement prior to transfer of prestress
f_{se} = effective prestress after allowance for all prestress losses
f_{si} = stress in prestressed reinforcement at time of initial prestress, immediately after release in pretensioned member
F_i = initial force immediately after transfer
$F_{i\,(ave)}$ = average strand force over transfer length
h = overall thickness of member
l = length of pile as cast
l_b' = flexural bond length from strand slip theory
l_{ba} = anchorage length
l_{bp} = transmission length in Eurocode EC2
$l_{bp,0}$ = length of neutralized zone at ends of pretensioned members in Eurocode EC2
$l_{bp,d}$ = design value of transmission length in Eurocode EC2
l_d' = development length from strand slip theory
$l_{p,eff}$ = dispersion (or development) length in Eurocode EC2
l_t = transfer length from ACI provisions
l_t' = transfer length from strand slip theory
L = transfer length equation proposed by FHWA
L_d = development length equation proposed by FHWA
P_0 = prestressing force in Eurocode EC2
x = distance from free end to determine f_{dev}
β_b = transmission length coefficient
δ = free end slip
δ_{all} = allowable free end slip
Δf_{slip} = change in stress due to slip distributed over l
Δl = change in length
ϕ = nominal strand diameter

REFERENCES

1. Petrou, M. F., and Joiner, W. S., "Continuing Investigation of Strand End Slip in 24 Inch Octagonal Prestressed Concrete Piles," *Final Report* FHWA-SC-96-04, South Carolina Department of Transportation, May 1996.

2. Balazs, G. L., "Transfer Control of Prestressing Strands," *PCI Journal*, V. 37, Nov.-Dec. 1992, pp. 60-71.

3. Brooks, M. D.; Gerstle, K. H.; and Logan, D. R., "Effect of Initial Strand Slip on the Strength of Hollow Core Slabs," *PCI Journal*, V. 33, Jan.-Feb. 1988, pp. 90-111.

4. Anderson, A. R., and Anderson, R. G., "An Assurance Criterion for Flexural Bond in Pretensioned Hollow Core Units," ACI JOURNAL, *Proceedings* V. 73, No. 8, Aug. 1976, pp. 457-464.

5. Buckner, C. D., "A Review of Strand Development Length for Pretensioned Concrete Members," *PCI Journal*, V. 40, Mar.-Apr. 1995.

6. Burns, N. H., and Pierce, D. M., "Strength and Behavior of Prestressed Concrete Members with Unbonded Tendons," *PCI Journal*, V. 13, Oct. 1967, pp. 15-29.

7. Cousins, T. E.; Johnston, D. W.; and Zia P., "Development Length of Epoxy-Coated Prestressing Strand," *ACI Materials Journal*, V. 35, No. 4, July-Aug. 1990, pp. 309-318.

8. Cousins, T. E.; Johnston, D. W.; and Zia P., "Transfer Length of Epoxy-Coated Prestressing Strand," *ACI Materials Journal*, V. 35, No. 3, May-June 1990, pp. 193-203.

9. Edwards, A. D., and Picard, A., "Bonding Properties of 1/2 in. Diameter Strands," ACI JOURNAL, *Proceedings* V. 69, No. 11, Nov. 1972, pp. 684-689.

10. Hanson, N. W., and Kaar, P. H., "Flexural Bond Tests of Pretensioned Prestressed Beams," ACI JOURNAL, *Proceedings* V. 55, No. 7, Jan. 1959, pp. 783-802.

11. Janney, J. R., "Report of Stress Transfer Length Studies on 270k Prestressing Strand," *PCI Journal*, V. 8, No. 2, Feb. 1963, pp. 41-45.

12. Lane, S. N., "Development Length of Prestressing Strand," *Public Roads—A Journal of Highway Research and Development, Federal High-*

way Administration, V. 54, No. 2, Sept. 1990, pp. 200-205.

13. Martin, L. D., and Korkosz, W. J., "Strength of Prestressed Members at Sections Where Strands Are Not Fully Developed," *PCI Journal*, V. 40, No. 5, Sept.-Oct. 1995, pp. 58-66.

14. Russell, B. W., and Burns, N. A., "Design Guidelines for Transfer, Development and Bonding of Large Diameter Seven-Wire Strands in Pretensioned Concrete Girders," *Research Report* No. 1210-5F, Center for Transportation Research, University ofTexas at Austin, 1993, 286 pp.

15. Shahawy, M. A.; Moussa, I.; and Batchelor, B., "Strand Transfer Lengths in Full Scale AASHTO Prestressed Concrete Girders," *PCI Journal*, V. 37, No. 3, May-June 1992, pp. 84-96.

16. Abrishami, H. H., and Mitchell, D., "Bond Characteristics of Pretensioned Strand," *ACI Materials Journal*, V. 90, No. 3, May-June 1993, pp. 228-235.

17. Janney, J. R., "Nature of Bond in Pretensioned Prestressed Concrete," ACI JOURNAL, *Proceedings* V. 50, No. 9, May 1954, pp. 717-736.

18. Martin, L. D., and Scott, N. L., "Development of Prestressing Strand in Pretensioned Members," ACI JOURNAL, *Proceedings* V. 73, No. 8, Aug. 1976, pp. 453-456.

19. Li, S., and Liu, T. C., "Prestressed Concrete Piling-Contemporary Design Practice and Recommendations," ACI JOURNAL, *Proceedings* V. 67, No. 3, Mar. 1970, pp. 201-220.

20. PCI Committee on Prestressed Concrete Piling, "Recommended Practice for Design, Manufacture and Installation of Prestressed Concrete Piling," *PCI Journal*, V. 38, No. 2, Mar.-Apr. 1993, pp. 14-41.

21. American Association of State Highway and Transportation Officials (AASHTO), *Standard Specifications for Highway Bridges*, 16th Edition, Washington D.C., 1996.

22. Kaar, P. H.; LaFraugh, R. W.; and Mass, M. A., "Influence of Concrete Strength on Strand Transfer Length," *PCI Journal*, V. 8, No. 5, Oct. 1963, pp. 47-67.

23. Mitchell, D.; Cook, W. D.; Khan, A. A.; and Tham T., "Influence of High-Strength Concrete on Transfer and Development Length of Pretensioning Strand," *PCI Journal*, V. 38, No. 3, May-June 1993, pp. 52-66.

24. Zia, P., and Mostafa, T., "Development Length of Prestressing Strands," *PCI Journal*, V. 22, No. 5, Sept.-Oct. 1977, pp. 54-65.

25. Lane, S. N., "A New Development Length Equation for Pretensioned Strands in Bridge Beams and Piles," *Publication* No. FHWA-RD-98-116, Federal Highway Administration, McLean, Va., Dec. 1998.

26. Donahey, R. C., and Darwin, D., "Bond of Top-Cast Bars in Bridge Decks," ACI JOURNAL, *Proceedings* V. 82, No. 1, Jan.-Feb. 1985, pp. 57-66.

27. Altowaiji, W. A. K.; Darwin, D.; and Donahey, R.C., "Bond of Reinforcement to Revibrated Concrete," ACI JOURNAL, *Proceedings* V. 83, No. 6, Nov.-Dec. 1986, pp. 1035-1042.

28. Brettmann, B. B.; Darwin, D.; and Donahey, R. C., "Bond of Reinforcement to Superplasticized Concrete," ACI JOURNAL, *Proceedings* V. 83, No. 1, Jan.-Feb. 1986, pp. 98-107.

29. Logan, D. R., "Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications," *PCI Journal*, V. 42, No. 2, Mar.-Apr. 1997, pp. 52-90.

30. Deatherage, J. H.; Burdette, E. G.; and Chew, C. K., "Development Length and Lateral Spacing Requirements of Prestressing Strand for Prestressed Concrete Bridge Girders," *PCI Journal*, V. 39, No. 1, Jan.-Feb. 1994, pp. 70-83.

31. Hanson, N. W., "Influence of Surface Roughness of Prestressing Strand on Bond Performance," *PCI Journal*, V. 14, No. 1, Jan.-Feb. 1969.

32. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-99) and Commentary (318R-99)," American Concrete Institute, Farmington Hills, Mich., 1999, 391 pp.

33. Chew, C. K., "Development Length of Prestressing Strand," Doctoral dissertation, University ofTennessee, Knoxville, May 1991.

34. Jeanty, P. R.; Mitchell, D.; and Mirza, M. S., "Investigation of 'Top Bar' Effects in Beams," *ACI Structural Journal*, V. 85, No. 3, May-June 1988, pp. 251-257.

35. Clark, A. P., "Comparative Bond Efficiency of Deformed Concrete Reinforcing Bars," *Journal of Research*, National Bureau of Standards, V. 37, RP 1755, Dec. 1946, pp. 399-407.

36. Lin, T. Y., and Talbot, W. J., "Pretensioned Concrete Piles—Present Knowledge Summarized," *Civil Engineering*, May 1961, pp. 53-57.

37. Strobel, G. C., and Heald, J., "Theoretical and Practical Discussion of the Design, Testing and Use of Pretensioned Prestressed Concrete Piling," *PCI Journal*, V. 6, Sept. 1961, pp. 22-33.

38. ACI-ASCE Joint Committee 423, "Tentative Recommendations for Prestressed Concrete," ACI JOURNAL, *Proceedings* V. 54, No. 7, Jan. 1958, pp. 548-578.

39. ENV 1992-1-1 Eurocode 2: Design of Concrete Structures.

40. *New Greek Code for the Design and Construction of Concrete Structures*, May 1995.