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Top Bar Effects in Prestressed Concrete Piles

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The top bar effect in reinforced concrete is a widely recognized phenomenon. Currently, the ACI Building Code prescribes a 30% increase in the development length of top-cast reinforcing bars. No such provision is required for strands in prestressed concrete members. In this paper, the top bar effect for prestressing strands is introduced. Parameters affecting top bar phenomena in prestressed concrete piles are identified, and strategies for reducing this effect are presented. Finally, for the first time, the application of a top bar effect factor for prestressed concrete development length calculations, similar to the one applied in reinforced concrete structural elements, is proposed.

Keywords: bar; pile; prestressed concrete; slip.

INTRODUCTION

The influence of the casting position of reinforcing bars on their bond characteristics has been recognized since the early 1900s. Many researchers have reported the effects of casting position on the bond characteristics of reinforcing steel. They have performed experiments on pullout specimens that included reinforcing bars placed vertically in the formwork, and bars placed horizontally at the bottom (bottom-cast) and top (top-cast) of the formwork. Some researchers have performed beam tests that compared the behavior of bottom-cast and top-cast flexural reinforcement.1

In the case of a vertically oriented reinforcing bar, it has been concluded that the settlement of the concrete results in better consolidation of the concrete above the bar deformations than below the deformations. This means that some settling of aggregate is prevented by the bar deformations. Therefore, the bond strength is somewhat greater when the bar is pulled against, rather than with, the direction of casting. The lower bond strength of top-cast compared with bottom-cast horizontal bars is attributed to the greater settlement of concrete immediately below the top-cast bars and to a 10 to 20% lower tensile strength of the concrete at the top of the casting.

Based on tests carried out by Clark,2 the top bar effect was introduced into the ACI Building Code in 1951,3 in the form of allowable bond stresses at working loads. The allowable bond stress for a top-cast bar was 0.7 times the allowable stress for a bottom-cast bar. The 1963 ACI Building Code4 introduced ultimate strength design and used an ultimate bond stress expression with the same top bar bond stress-reduction factor as the 1951 ACI Code.

The 1971 ACI Building Code5 replaced the earlier bond stress calculation with an expression for development length. In this code and in the 1983 ACI Building Code6 the top bar effect is accounted for by multiplying the calculated development length by a factor of 1.4, which corresponds to the top bar bond stress reduction factor of 0.7 from the previous ACI Building Codes. In 1979, ACI Committee 4087 proposed that the top bar factor should be 1.3.

In 1988, Jeanty, Mitchell, and Mirza8 published an article investigating the top bar effect in beams. They tested full-size, 18 x 9 in. (457 x 229 mm) beam specimens to study the effects on the responses of top-cast versus bottom-cast bars, embedment length of the test bars, and the presence of transverse reinforcement crossing the plane of potential splitting.

From these tests, it was concluded that beams with bottom-cast bars showed improved behavior in terms of cracking, stiffness, strength, and deformation response over the companion beams with top-cast bars. For this series of beams, both with and without transverse reinforcement crossing the plane of splitting, the top bar factor was found to be approximately 1.22. The presence of transverse reinforcement across the plane of potential splitting was shown to reduce the required development length for both bottom-cast and top-cast bars by 20%.

Based on the tests of Jeanty, Mitchell, and Mirza, the top bar factor was reduced from 1.4 to 1.3 in the 1989 ACI Building Code.8 This factor is currently used for reinforced concrete design.9

The strand development length equation recommended for prestressed concrete elements, however, does not include a top bar factor. Measurements of prestressed strand end slip, a measure of the resulting development length, consistently show higher end slip in the top of a cross section regardless of cross-sectional shape or strand arrangement.10-12

In the most recent study,12 strand end slip measurements were taken at five prestressing plants in the southeastern U.S. Strand end slip measurements were collected for 23 piles. Excessive strand end slip, at times exceeding 0.75 in. (19 mm), was evident in all piles sampled. End slip occurs in both top and bottom regions of the cross section, with the top strands generally exhibiting higher initial slip.

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

The results of an extensive laboratory study on strand end slip problems are presented in a report by Petrou et al.13 This manuscript focuses on the top bar effects in prestressed concrete piles. Aspects of development and transfer lengths associated with strand end slip will be discussed in a subsequent manuscript.14
or 0.75 strand. All strands were prestressed to 203 ksi (1397 MPa), in. (cross-sectional area = 0.085 in.
strand, with the exception of Piles 22 and 23, which had 3/8
properly termed the top-cast bar effect. Precast piles, although
Piles have the simplest possible cross section for precast
vertical elements in a structure, are cast horizontally and thus
have both top-cast and bottom-cast strands. A laboratory in-
vestigation of full-scale prestressed concrete piles was carried
out to investigate strand development and top bar behavior.

RESEARCH SIGNIFICANCE

This paper demonstrates the presence of top bar effects in
prestressed concrete members. It attempts to identify the ma-
jor parameters controlling such phenomena and presents
strategies to reduce the top bar effect. It recommends, for the
first time, the introduction of a top bar effect factor in pre-
stressed concrete development length calculations similar to
the one applied in reinforced concrete structural elements.

EXPERIMENTAL INVESTIGATION

This study and the previously mentioned study of South-
east prestressing plants focus on prestressed concrete piles.
Piles have the simplest possible cross section for precast
members. It is also important to note that the top bar effect is
properly termed the top-cast bar effect. Precast piles, although
vertical elements in a structure, are cast horizontally and thus
have both top-cast and bottom-cast strands. A laboratory in-
vestigation of full-scale prestressed concrete piles was carried
out to investigate strand development and top bar behavior.

Pile test specimens

The pile specimen details used are shown in Fig. 1. It can
be noted that Pile 3 was discarded, as it experienced a flash
set during casting. The left-hand columns of Table 1 summa-
rize the variable parameters of the pile design and concrete
mixtures; these are discussed as follows. The 18 in. (457 mm)
square prestressed piles are typical of those used throughout
the southeastern U.S. Two 18 ft (5.5 m) long piles were cast
from each concrete batch in a 43 ft (13.1 m) prestressing bed,
with the exception of Pile 1, which was 40 ft (12.2 m) long
and cast on its own. All piles were prestressed with 8-1/2 in.
(cross-sectional area = 0.153 in.² [99 mm²]) Grade 270 strand,
with the exception of Piles 22 and 23, which had 3/8 in.
(cross-sectional area = 0.085 in.² [55 mm²]) Grade 270 strand.
All strands were prestressed to 203 ksi (1397 MPa), or 0.75f'c
Confining spiral reinforcement was provided by
each strand being individually stressed to 0.12f'c (5 kips),
and was measured in accordance with ASTM C 143.
Admixtures were provided by a ready-mix supplier as
indicated in Table 1. A retarder was used in Piles 4 through
7, 12 and 13, 18 and 19, and 22 and 23. A high-range water-
reducing (HRWR) agent was used in Piles 8 and 9.

With the exception of Piles 20 and 21, the minimum con-
crete compressive strength f'c at strand release was specified
to be 3500 psi (24.1 MPa). The measured compressive
strength and age of the concrete at strand release is given in
Table 1. The strand release sequence was varied. All strands
except those of Piles 24 through 27, and 32 and 33 were
flame-cut from each end of the prestressing bed simulta-
nenously. The traditional top-to-bottom sequence of cutting
was used for Piles 6, 7, 18, and 19. Otherwise, a radially
symmetric sequence, cutting strands in the order 2-6-3-7-1-
8-5-4 (Fig. 1) was used. The symmetric sequence was used to
minimize flexural stresses on the section resulting from the
unbalanced transfer of prestress force.

All strands of Piles 24 through 27, and 32 and 33 were
stressed and released simultaneously using a hydraulic gang
mechanism (Fig. 2). The gang stressing operation began with
each strand being individually stressed to 0.12f'c using a
Table 1—Pile specimen details and measured slip results

<table>
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<th>Pile</th>
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<th>Mixture</th>
<th>Slump, in.</th>
<th>Admixture</th>
<th>Spiral</th>
<th>f'_c, psi</th>
<th>Age, h</th>
<th>Sequence†</th>
<th>f_c, psi</th>
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<th>Bottom§</th>
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**S**
increased to 0.77. For this reason, the initial prestress was applied lock; hydraulic pressure was used to maintain the pretensioning of all eight strands simultaneously. A single 300 kip (1335 kN) hydraulic ram was used to complete the stressing against the gang-stressing bulkhead. A single standard single strand jack. The strand chucks were locked at each end of the strand jacking bulkhead. The strand chucks were locked at 0.014 in. (0.36 mm). Measurements were taken on all strands and the average end slip measured for all eight strands at both the north and south ends of each pile in the prestressing bed. The south end of each pile was the end closest to the strand jacking bulkhead. The right-hand columns of Table 1 report the average end slip measured for all eight strands and the top and bottom strand end slips. The top and bottom strand end slips are the average slips measured for the three top-cast (1, 2, and 3) and three bottom-cast (6, 7, and 8) strands, respectively. Finally, the ratio of top-to-bottom strand end slips is given in Table 1. This value is referred to as the \( \frac{t}{b} \) ratio. Figure 3 shows the top-versus-bottom strand end slip values for all piles tested. Table 2 shows the experimental values reported by Chew and those observed in the present study. Generally, excellent correlation between the studies can be seen. It can be noted that details such as the concrete slump, the presence of admixtures, and the method of strand release are not available for the data presented by Chew.

**Experimental Results**

### Strand End Slip Results

Once the pile concrete had achieved its release strength, the strands were simultaneously released using the hydraulic ram over approximately 270 s.

**Strand End Slip Determination**

Once the concrete was cast and hardened, the form bulkheads at the north and south ends of each pile in the bed were pulled back from the concrete surface. Steel plates with holes were fixed to each strand (the plates and a form bulkhead can be seen in Fig. 2). A depth gage with 0.001 in. (0.025 mm) precision was used to measure the distance from the fixed plates to the concrete surface. The plates remained in place during the release procedure, and a second measurement was made. In the case of the flame-cut strands, the cut was made a sufficient distance from the installed plates so as not to affect them in any way. The difference in these measurements before and after release represents the amount that the strand slipped into the concrete upon release. This value is called the end slip. All measurements were made within 2 in. of the concrete face and therefore include elastic shortening of the strand over this short gage length. The end slip values reported in Table 1 and throughout this paper include the elastic shortening over the gage length, estimated to be approximately 0.014 in. (0.36 mm). Measurements were taken on all eight strands at both the north and south ends of each pile in the prestressing bed. The south end of each pile was the end closest to the strand jacking bulkhead. The right-hand columns of Table 1 report the average end slip measured for all eight strands and the top and bottom strand end slips. The top and bottom strand end slips are the average slips measured for the three top-cast (1, 2, and 3) and three bottom-cast (6, 7, and 8) strands, respectively. Finally, the ratio of top-to-bottom strand end slips is given in Table 1. This value is referred to as the \( \frac{t}{b} \) ratio. Figure 3 shows the top-versus-bottom strand end slip values for all piles tested. Table 2 shows the experimental values reported by Chew and those observed in the present study. Generally, excellent correlation between the studies can be seen. It can be noted that details such as the concrete slump, the presence of admixtures, and the method of strand release are not available for the data presented by Chew.

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**Table 1 (cont.)—Pile specimen details and measured slip results**

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<th>Admixture</th>
<th>Spiral</th>
<th>( f'_c ), psi</th>
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<td>48 Gang</td>
<td>3720</td>
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<td>4.0</td>
<td>None</td>
<td>No</td>
<td>5740</td>
<td>48 Gang</td>
<td>3720</td>
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\(^{\dagger}\)N = north end of pile; S = south end.

\(^{1}\)Release sequences: Sym. = 2-6-3-7-1-8-5-4; Gang = slow gang release of all strands simultaneously.

\(^{2}\)Average of Strands 1, 2, and 3.

\(^{3}\)Average of strands 6, 7, and 8.

\(^{4}\)Pile No. 1 was 40 ft long.

\(^{5}\)Piles 22 and 23 had 3/8 in. diameter strand.

\(^{6}\)Concrete at free surface cracked near south end of Piles 26 and 32, thus the top slip results are larger than if the concrete had not cracked.

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**Fig. 3—Top and bottom strand end slip values.**
As noted in the text, some of large \( t/b \) ratios are not representative due to very small bottom slip values.

### Concrete slump

Concrete slump was determined according to ASTM C143-00 “Standard Test Method for Slump of Hydraulic Cement Concrete.” As can be seen in Table 1, 28-day concrete strength was maximized using a 4 in. (101.6 mm) slump. As expected, concrete strength decreased as the slump was either increased or decreased from 4 in. In general, as concrete slump increases, strand end slip increases. Slump, however, has little effect on the \( t/b \), although the piles with higher slump appear to have a slightly lower and less variable \( t/b \).

The improved \( t/b \) for higher-slump concrete may result from the decreased amount of vibration necessary to place the more workable mixture. Vibration has been shown to cause settlement of aggregate and to cause air and water to rise in the mixture, which results in a better concrete on the bottom of the cast and a poorer quality at the top. If this were the case, one would expect a higher \( t/b \) for concrete requiring more vibration. Therefore, although higher-slump concrete may not result in the same final concrete quality, it may help to mitigate the top bar effect by reducing the need to vibrate.

### Admixtures in concrete

There are insufficient data to discuss the effects of adding HRWR to the concrete mixture; however, there was no detrimental effect resulting from its inclusion in Piles 8 and 9.
Comparison of the results of Piles 16 and 17 with those of 6 and 7 demonstrates that the presence of retarder increases the average strand slip and the range of \( t/b \)s calculated. The presence of retarder appears to affect the relative strand end slips, increasing somewhat the top strand end slip. It is believed that this is a result of the retarder affecting the viscosity and yield stress of the plastic concrete mixture, allowing the aggregate to settle more than when retarder is not present.\(^{15}\) In this case, top strand slip and thus the \( t/b \), are increased.

**Presence of confining reinforcement**

Piles 12 and 13 were cast from the same batch of concrete. The piles were identical except for the fact that Pile 12 had no confining reinforcement, while Pile 13 had the typical confining reinforcing details shown in Fig. 1. The average measured strand slips were the same for each pile (0.101 in. [2.54 mm]) and very close to the average for all the piles. The \( t/b \)s for Piles 12 and 13 were 3.8 and 4.3, respectively. Similar results are seen for Piles 30, 31, 32, and 33, companion specimens also having one pile each without confining reinforcement.

The \( t/b \)s for Piles 4 and 5, which also have no spiral reinforcement, were slightly below the average for all piles. These observations suggest that the presence of congested confining reinforcement can prevent adequate vibration and trap rising air against the top strands. Therefore, in the presence of confining reinforcement, the \( t/b \) would be expected to increase, as the concrete-to-strand interface of the top strand is inferior.

**Strand diameter**

In Piles 22 and 23, a 3/8 in. diameter (cross-sectional area = 0.085 in.\(^2\) [55 mm\(^2\)]) strand was used in place of the 1/2 in. (cross-sectional area = 0.153 in.\(^2\) [99 mm\(^2\)]) strand used elsewhere. The strands were stressed to the same 0.75\( f_{pu} \). Average measured strand end slip was 0.049 in. (1.24 mm), approximately 50\% of that measured for the 1/2 in. strand. This result is reasonable because the actual bond stress is reduced for the 3/8 in. strand. As with the 1/2 in. strand, however, a significant top bar effect was exhibited with the average \( t/b \) greater than 3.

**Flame-cutting release sequence**

Most piles had their strands flame-cut in a symmetric pattern (Strands 2-6-3-7-1-8-5-4, refer to Fig. 1). A symmetric release pattern minimizes flexural stresses in the pile. Piles 6 and 7 and 18 and 19, however, were flame-cut in the more practical top-to-bottom pattern (Strands 1-2-3-4-5-6-7-8). The stresses resulting from the top-to-bottom cutting pattern may tend to increase the top strand slip, exaggerating the top bar effect and increasing the \( t/b \). When cutting from the top down:

1. The top strands are cut, resulting in an increase of compression in the concrete at the top of the pile and thus a slight relaxation of the top strands. A corresponding increase in tension results in the still-tensioned bottom strands. This increase in tension has the effect of reducing the externally applied prestressing force in the bottom strands; and
2. As the lower strands are cut, the top compression is relieved and the top strands see an increase in tension force that may further increment the slip resulting from their original release. Similarly, due to the original decrease in prestressing force, the bottom strands exhibit slightly less slip.

This sequence of events results in a greater \( t/b \), but likely no significant change to the average observed end slip. This is indeed the case with Piles 6 and 7 and 18 and 19. The average end slip is 0.132 in. (3.35 mm), only slightly greater than the overall average. The \( t/b \)s, however, are significantly greater than the average. The exceptionally high observed \( t/b \)s for these piles may have resulted from the combination of events discussed previously, particularly as the measured bottom strand slips were very low.

**Effect of gang tensioning/releasing**

Slow simultaneous tensioning and release of all eight strands, called gang tensioning/releasing, has the effect of lowering the measured end slip slightly and the \( t/b \) significantly. The average end slip for the gang-released piles (24 through 27, and 32 and 33) is 0.094 in. (2.38 mm), slightly lower than the observed average. The average \( t/b \), however, is 1.63—significantly lower than the average. As mentioned previously, Piles 26 and 32 exhibited cracking at their south ends, likely resulting from form-induced restraint at release. These south-end results from these piles were not included in the averages presented previously.

The lowest observed \( t/b \) (1.03 and 1.14) were observed in Piles 26 and 27, respectively. A comparison of the gang released piles to those that were flame-cut clearly shows that the sequence and manner of strand release has a significant influence on the top bar effect.

**SUMMARY AND CONCLUSIONS**

Strand end slip measurements were made on 32 18 in. (457 mm) square prestressed concrete piles. The following parameters were varied to investigate their effect on the observed strand end slip:

1. Concrete slump was varied from 3.5 to 5.5 in. (89 to 140 mm);
2. Ten piles were cast with concrete using a retarder admixture;
3. Two piles were cast with concrete using a HRWR;
4. Five piles were cast without spiral reinforcement confining the strand;
5. Strand diameter was reduced from 1/2 to 3/8 in. (12.7 to 9.5 mm) for two piles;
6. Two strand-cutting sequences were used: top-down and a symmetric sequence;
7. The prestress of six piles was released using a slow (gang) release method rather than flame cutting; and
8. The concrete strength at release varied from 1711 to 5769 psi (11.8 to 39.8 MPa). The 28-day strength varied from 4490 to 9350 psi (31.0 to 64.5 MPa).

Based on the observed strand end slip data, the following conclusions are made:

1. Strands at the top of the pile cross section exhibited strand end slip values consistently higher than the generally accepted value of 0.1 in. (2.54 mm), while bottom strands exhibited values consistently lower. Strand end slip values lower than the allowable are practically obtainable for all strands if certain recommendations are adopted;
2. Regardless of parameters tested, top-cast strands exhibit greater end slip than bottom-cast strands. This phenomenon is known as the top bar effect in reinforced concrete, and appears also to exist for prestressed concrete. An increase in the development length used for design should be introduced to account for this effect. This increase is analogous to the top bar factor of 1.3 used for the design of reinforced concrete members;
3. For the range of slump values considered, increased concrete slump results in greater strand end slip. There also appears to be an optimal slump to minimize the top bar effect. This slump is approximately 4 in. (102 mm);

4. The presence of retarder increases the top strand end slip while having little effect on the bottom strand slip. This increases the average end slip in the pile and worsens the top bar effect disparity in the pile;

5. The presence of HRWR has no observable effect on either the end slip or top bar effect. It is noted that only two piles tested were made using HRWR;

6. Low concrete strength at release increases the strand end slip. Top-strand end slip is increased to a greater degree than bottom-strand slip; thus, the top bar effect is worsened when the concrete strength at release is low. This effect is likely caused by the gradient of concrete strength through the depth of the section being more significant at lower strengths due to variation of temperature and curing conditions through the depth of the member. No significant effects due to release strength are observed for release strengths greater than approximately 3500 psi (24.1 MPa);

7. Spiral confining reinforcement may prevent good compaction around strands. Due to geometry, this effect is more significant for top strands. Thus, the top bar effect may be worsened by the presence of confining reinforcement. End slip values, however, are not significantly affected by the presence of confining reinforcement. This may result from some mechanical interaction between the spiral and strand that helps to transfer prestress and limit slip;

8. A top-down cutting sequence tends to increase the already larger top strand end slip, worsening the top bar effect. Therefore, cutting the strands in a symmetric manner around the pile can reduce the top bar effect. It is better to start the strand release with a strand at the bottom; and

9. Releasing the prestress forces in a slow manner (gang tensioning) reduces strand end slip and appears to minimize the top bar effect.

**RECOMMENDATIONS**

Based on the observations and conclusions presented, it is recommended that a top bar effect factor, similar to that used for top-cast bars in reinforced concrete, be adopted in the determination of development length of prestressing strand. Additionally, the following recommendations are based on the conclusions of this study;

1. Wherever practical, the slump of concrete mixtures used for prestressed concrete pile construction should be limited to 4 in. (102 mm);

2. The use of retarder should be avoided in concrete mixtures prepared for prestressed concrete pile construction;

3. Concrete compressive strength at release should be maintained above 3500 psi (24.1 MPa);

4. Strands should be released in a symmetric manner starting at the bottom of the pile;

5. Vibration should be monitored very carefully since it controls aggregate settlement;

6. Slow (gang) release is preferred to sudden release (flame cut); and

7. Strand end slip measurements should be adopted as a quality control tool. Strand bond quality should be also checked periodically.

**ACKNOWLEDGMENTS**

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**REFERENCES**


3. ACI Committee 318, “Building Code Requirements for Reinforced Concrete (ACI 318-51) and Commentary (318R-51),” American Concrete Institute, Farmington Hills, Mich., 1951.


5. ACI Committee 318, “Building Code Requirements for Reinforced Concrete (ACI 318-71) and Commentary (318R-71),” American Concrete Institute, Farmington Hills, Mich., 1971.

6. ACI Committee 318, “Building Code Requirements for Reinforced Concrete (ACI 318-83) and Commentary (318R-83),” American Concrete Institute, Farmington Hills, Mich., 1983.


