3-1-2002

Top Bar Effects in Prestressed Concrete Piles

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Published version. *ACI Structural Journal*, Vol. 99, No. 2 (March 1, 2002): 208-214. DOI.

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 99-S23

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 Code[4] 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 Code[5] replaced the earlier bond stress calculation with an expression for development length. In this code and in the 1983 ACI Building Code,[6] 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 408[7] proposed that the top bar factor should be 1.3.

In 1988, Jeanty, Mitchell, and Mirza[1] 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,[1] 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]

ACI Structural Journal, V. 99, No. 2, March-April 2002.
MS No. 01-187 received June 15, 2001, and reviewed under Institute publication policies. Pertinent discussion will be published in the January-February 2003 *ACI Structural Journal* if received by September 1, 2002.

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RESEARCH SIGNIFICANCE

This paper demonstrates the presence of top bar effects in prestressed concrete members. It attempts to identify the major 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 prestressed concrete development length calculations similar to the one applied in reinforced concrete structural elements.

EXPERIMENTAL INVESTIGATION

This study and the previously mentioned study of Southeast prestressing plants[12] 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 investigation 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 summarize 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 mm^2]) Grade 270 strand, with the exception of Piles 22 and 23, which had 3/8 in. (cross-sectional area = 0.085 in^2 [55 mm^2]) Grade 270 strand. All strands were prestressed to 203 ksi (1397 MPa), or $0.75f_{pu}$. Confining spiral reinforcement was provided by smooth 0.28 in. (7 mm) diameter wire with a yield strength of 82 ksi (565 MPa). Not all piles were provided with confining spirals, as indicated in Table 1. SCDOT Highway Class X (now called Class 5000) or Class D (now called Class 4000) concrete was provided by a local ready-mix supplier. Class X concrete is a Type III mixture with a minimum specified 28-day compressive strength of 5000 psi (34.5 MPa) and is designed to achieve 3500 psi (24.1 MPa) within 72 h. Class D concrete is a Type I mixture with a minimum specified 28-day compressive strength of 4000 psi (27.6 MPa). Class D would not typically be used for prestressed piles, but

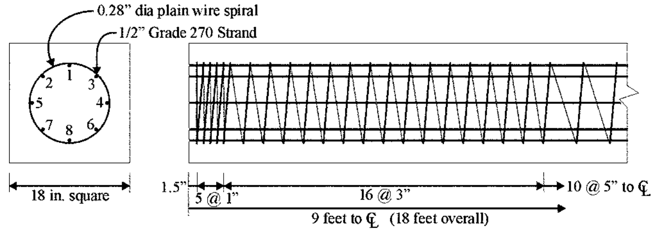

Fig. 1—Pile test specimen details and strand numbering.

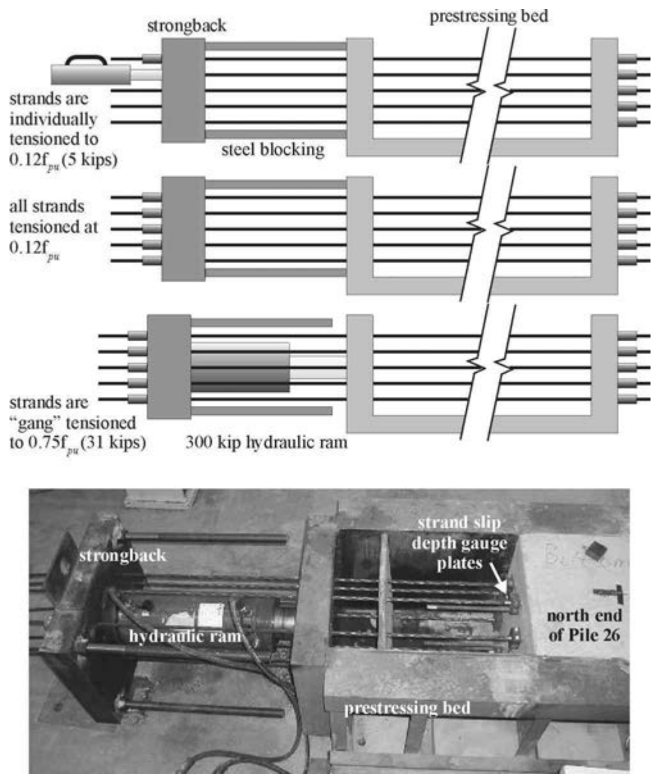

Fig. 2—Gang tensioning procedure and setup.

has been included herein for comparison. As indicated in Table 1, most batches easily achieved their design strengths; concrete slump also varied from 3.5 to 5.5 in. (90 to 140 mm) 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 concrete 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 simultaneously. 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 $0.12f_{pu}$ using a

Table 1—Pile specimen details and measured slip results

Pile	End[*]	Mixture	Slump, in.	Admixture	Spiral	f_c', psi	Strand release			Strand end slip, in.			
							Age, h	Sequence[†]	f_c, psi	Average	Top[‡]	Bottom[§]	t/b ratio
1[‖]	N	X	4.0	None	Yes	7990	145	Sym.	4790	0.066	0.080	0.049	1.64
	S									0.071	0.082	0.066	1.25
2	N	X	3.5	None	Yes	7480	46	Sym.	4320	0.022	0.031	0.009	3.44
	S									0.021	0.034	0.013	2.59
4	N	X	5.0	Retarder	No	6510	51	Sym.	3550	0.187	0.271	0.114	2.37
	S									0.084	0.139	0.028	5.04
5	N	X	5.0	Retarder	No	6510	51	Sym.	3550	0.052	0.067	0.029	2.35
	S									0.174	0.259	0.095	2.73
6	N	X	5.0	Retarder	Yes	7220	68	t-b	4080	0.207	0.293	0.140	2.10
	S									0.100	0.166	0.049	3.39
7	N	X	5.0	Retarder	Yes	7220	68	t-b	4080	0.080	0.162	0.015	10.54
	S									0.172	0.262	0.086	3.03
8	N	X	4.5	HRWR	Yes	6700	27	Sym.	5670	0.094	0.127	0.066	1.91
	S									0.045	0.064	0.017	3.76
9	N	X	4.5	HRWR	Yes	6700	27	Sym.	5670	0.045	0.074	0.024	3.11
	S									0.091	0.125	0.063	1.97
10	N	X	3.5	None	Yes	6700	43	Sym.	4500	0.092	0.115	0.076	1.51
	S									0.046	0.067	0.013	5.18
11	N	X	3.75	None	Yes	6770	43	Sym.	4500	0.038	0.052	0.037	1.40
	S									0.101	0.136	0.074	1.83
12	N	X	4.0	Retarder	No	7840	48	Sym.	3900	0.141	0.199	0.075	2.67
	S									0.061	0.107	0.022	4.85
13	N	X	4.00	Retarder	Yes	7840	48	Sym.	3900	0.070	0.134	0.025	5.35
	S									0.133	0.205	0.063	3.28
14	N	D	4.0	None	Yes	7840	43	Sym.	3540	0.164	0.230	0.102	2.26
	S									0.078	0.108	0.033	3.31
15	N	D	4.0	None	Yes	7840	43	Sym.	3540	0.147	0.208	0.083	2.49
	S									0.060	0.093	0.043	2.18
16	N	X	5.5	None	Yes	6310	168	Sym.	5770	0.144	0.220	0.082	2.68
	S									0.075	0.133	0.049	2.75
17	N	X	5.5	None	Yes	6310	168	Sym.	5770	0.066	0.102	0.051	1.98
	S									0.144	0.203	0.088	2.30
18	N	D	3.5	Retarder	Yes	6680	49	t-b	3580	0.175	0.277	0.090	3.06
	S									0.092	0.174	0.012	15.10
19	N	D	3.5	Retarder	Yes	6680	49	t-b	3580	0.070	0.136	0.003	45.44
	S									0.163	0.261	0.084	3.11
20	N	D	4.5	None	Yes	7660	12	Sym.	1710	0.234	0.314	0.195	1.61
	S									0.084	0.185	0.031	5.96
21	N	D	4.5	None	Yes	7660	12	Sym.	1710	0.066	0.109	0.022	4.97
	S									0.195	0.293	0.099	2.97
22[#]	N	X	4.0	Retarder	Yes	9350	48	Sym.	4380	0.038	0.063	0.019	3.36
	S									0.050	0.079	0.040	1.98
23[#]	N	X	4.0	Retarder	Yes	9350	48	Sym.	4380	0.056	0.118	0.015	7.89
	S									0.050	0.069	0.053	1.29
24	N	X	5.5	None	Yes	4490	72	Gang	3420	0.102	0.143	0.071	2.03
	S									0.105	0.141	0.066	2.15
25	N	X	5.5	None	Yes	4490	72	Gang	3420	0.087	0.114	0.063	1.80
	S									0.097	0.133	0.058	2.28
26	N	X	5.5	None	Yes	6500	66	Gang	3830	0.080	0.088	0.085	1.03
	S									0.165[**]	0.301[**]	0.075[**]	4.01[**]
27	N	X	5.5	None	Yes	6500	66	Gang	3830	0.081	0.086	0.075	1.14
	S									0.090	0.095	0.083	1.14
28	N	X	4.5	None	Yes	8610	72	Sym.	4060	0.068	0.081	0.057	1.43
	S									0.057	0.099	0.028	3.51
29	N	X	4.5	None	Yes	8610	72	Sym.	4060	0.044	0.047	0.044	1.08
	S									0.073	0.087	0.061	1.41

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

Pile	End*	Mixture	Slump, in.	Admixture	Spiral	f_c', psi	Strand release			Strand end slip, in.			
							Age, h	Sequence†	f_c, psi	Average	Top‡	Bottom§	*t/b* ratio
30	N	X	3.5	None	Yes	7130	72	Sym.	3730	0.087	0.094	0.080	1.17
	S									0.029	0.064	0.021	3.07
31	N	X	3.5	None	No	7130	72	Sym.	3730	0.037	0.061	0.034	1.20
	S									0.089	0.112	0.072	1.57
32	N	X	4.0	None	Yes	5740	48	Gang	3720	0.099	0.123	0.079	1.56
	S									0.146§	0.260§	0.058§	4.46§
33	N	X	4.0	None	No	5740	48	Gang	3720	0.103	0.131	0.079	1.67
	S									0.098	0.119	0.085	1.41

*N = north end of pile; S = south end.
†Release sequences: Sym. = 2-6-3-7-1-8-5-4; Gang = slow gang release of all strands simultaneously.
‡Average of Strands 1, 2, and 3.
§Average of strands 6, 7, and 8.
||Pile No. 1 was 40 ft long.
Piles 22 and 23 had 3/8 in. diameter strand.
**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.

standard single strand jack. The strand chucks were locked at this stress level against the gang-stressing bulkhead. A single 300 kip (1335 kN) hydraulic ram was used to complete the tensioning of all eight strands simultaneously.

The gang mechanism used did not have a positive mechanical lock; hydraulic pressure was used to maintain the prestress force. For this reason, the initial prestress was increased to $0.77f_{pu}$ to account for losses in the hydraulic system. The hydraulic pressure was monitored from the time of initial stressing to the time of release. An initial loss of prestress of $0.02f_{pu}$ occurred within 1h of tensioning; afterwards, no further significant losses occurred. Based on this observation, the strands were gang-tensioned at least 2 h prior to placing the concrete. It is noted that for a gang tensioning mechanism to be practical in the field, a positive mechanical locking device needs to be available.

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

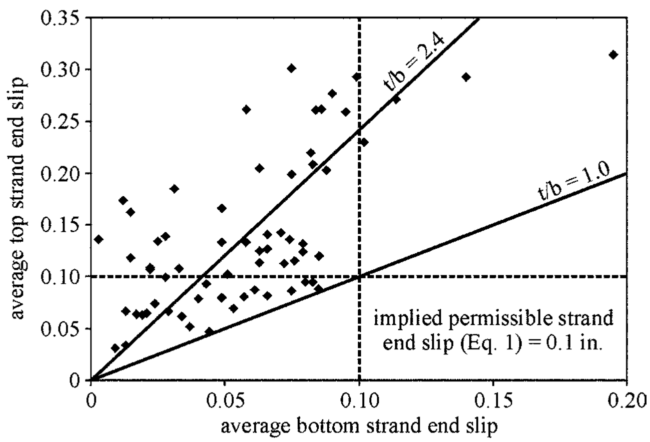

Fig. 3—Top and bottom strand end slip values.

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 *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[10] 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

The average strand end slip measured was 0.095 in. (2.41 mm). The average top-strand slip was 0.140 in. (3.56 mm), and the average bottom-strand slip was 0.058 in. (1.47 mm). Although one might expect greater slip values at the ends of the piles closest to the flame-cutting or at the ends closest to the gang release mechanism, no significant difference was found. There is no significance as to where the measurements were taken, whether from the north or south ends of the piles. As can be seen in Fig. 3, top-strand slip regularly exceeded the implied[13] permissible strand slip of 0.1 in. (2.54 mm), while the bottom-strand slip typically did not.

Table 2—Summary and comparison of results from this study and that of Chew[10]

Parameter	Present study	Chew[10]
Number of piles in study	32	22
Range of concrete strength, f_c', psi	5740 to 9350	5130 to 7980
Average concrete strength, f_c', psi	7070	6180
Range of concrete strength at strand release, f_c', psi	3420* to 5770	3360 to 5550
Average concrete strength at strand release, f_c', psi	4000	4830
Range of average strand end slip, in.	0.021 to 0.314	0.020 to 0.181
Average top strand end slip observed in study, in.	0.140	0.233
Range of bottom strand end slip, in.	0.003 to 0.195	0.020 to 0.141
Average bottom strand end slip observed in study, in.	0.058	0.083
Range of *t*/*b* ratios	1.03 to 45.44†	1.49 to 5.11
t/b ratio	2.4	2.8

*Piles 20 and 21 intentionally released early at a release strength of 1710 psi.
†As noted in the text, some of large *t/b* ratios are not representative due to very small bottom slip values.

t/*b* ratio results

The observed top-bottom (*t*/*b*) strand-slip ratios vary from 1.03 (Pile 26) to well over 3.0. Some of the very high *t*/*b*s calculated in Table 1 (Piles 7, 18, and 19) are indicative of very low measured bottom-strand end slips and should not be considered representative. Additionally, during the gang release of Piles 26 and 32, the concrete at the top surface near the south end of these piles cracked. It is believed that these cracks were caused by the formwork restraining the shortening of the piles. As a result, the top-strand end slip values for these piles are unrepresentatively large.

Based on average top- and bottom-strand end slip values given previously, the average *t*/*b* is 2.4. The results shown in Table 1 and those reported previously by Chew[10] demonstrate very clearly that there is a top bar effect present in prestressed concrete. This top bar effect is analogous to that recognized for reinforced concrete and is influenced by many of the same factors.

FACTORS AFFECTING TOP BAR PHENOMENA

The following sections discuss the effects of varying parameters on the measured end slip and *t*/*b* values.

Twenty-eight-day concrete strength

Twenty-eight-day concrete compressive strength ranged from 4490 to 9350 psi (31.0 to 64.5 MPa). Strand end slip values are not significantly affected by 28-day compressive strength, although some of the higher-strength piles (Piles 22, 23, 28, and 29) did exhibit lower and more consistent end slips. The *t*/*b*, on the other hand, appears to increase slightly with increased 28-day compressive strength. This change in the *t*/*b* generally results from a relative decrease in the bottom strand slip measurements for higher concrete strengths.

Concrete strength at strand release

As may be expected, end slip is reduced at higher release strengths. At release strengths close to the recommended value of 3500 psi (24.1 MPa), however, strand end slip varies considerably, although the average slip is generally acceptable. This suggests that, for standard prestressing practice, typical variations in concrete strength at release do not affect the expected strand end slip beyond the reasonable expected variance. Concrete strength at strand release appears to have little effect on the *t*/*b* and, again, large variations are seen close to the recommended release strength. While higher release strengths appear to reduce strand end slip, this effect is not significant at release strengths moderately greater than the recommended value of 3500 psi. It is believed that 3500 psi is an acceptable and practical prescribed release strength.

To investigate the effect of early release or a low release strength, Piles 20 and 21 were intentionally released at 12 h after having achieved a compressive strength of only 1710 psi (11.8 MPa). In this case, the average top- and bottom-strand end slips were 0.225 and 0.087 in. (5.71 and 2.21 mm), respectively, approximately 55% greater than the average top and bottom slips for all the piles. 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.

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[15] 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 $0.75f_{pu}$. 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*s (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

The authors acknowledge the financial support by 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 the SCDOT. The assistance of the prestressed concrete manufacturers is greatly appreciated.

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