BEARING ZONE CRACKING OF PRECAST PRESTRESSED GIRDERS DUE TO SLIDING FRICTION

Lawrence F. Kahn, PhD, PE, Georgia Institute of Technology, Atlanta, GA
Patrick J. Kelly, Pruitt Eberly Stone Inc., Atlanta, GA

ABSTRACT

Experience has shown that the bearing zones of long, heavy precast prestressed girders were cracking on the precasting bed after cut-down of the strands. Use of steel plates, Teflon pads and other devices was seen to reduce this cracking which was believed to be caused by sliding friction. This research quantified this sliding friction and measured the effectiveness of several friction reducing techniques. The five method tested in the laboratory and at a precast plant using BT-72 girders were the following: an oil coated steel surface (control), embedded steel plate with an oil coated surface, embedded steel angle with an oil coated surface, teflon pad, and a wax lubricant. For the 124-ft long girders, researchers measured concrete strain in the bearing region, camber, and girder slide. These field results were compared to the sliding friction coefficients found in the laboratory, and the results agreed. The embedded steel plate with oil coated surface reduced friction the greatest and eliminated cracking; the steel angle provided nearly the same friction and cracking reduction; and the teflon pad and wax lubricants provided significantly reduced friction compared to the standard oil-coated steel surface, although some cracking still persisted. As the use of high performance concretes and longer span girders increases, it is recommended that some type of friction reducing technique is used to eliminate bearing zone cracks.

KEYWORDS: Prestressed Concrete, Precast Concrete, Girders, Construction, Cracking, Lubricants, Bearing, Friction

INTRODUCTION

Precast concrete producers have satisfied the needs of bridge designers by providing longer span pretensioned bridge girders through utilization of larger diameter strands and higher strength concretes. Standard shape AASHTO and Bulb-T girders are now regularly constructed with lengths exceeding 125 ft. These long girders weigh considerably more than the 90-ft. girders built just 15 years ago. In Georgia, that added weight has created a problem: the bearing ends of girders sometimes crack due to tension created by the friction between the girder and prestressing bed as the girder slides after cut-down of the prestressing strands.

As shown in Figure 1, the weight of the girder rests on the very edge of the girder; vertical/diagonal cracks form in this bearing zone. Research[1, 2] has found that these cracks occur within the transfer length of the strand and that these cracks extend the transfer length beyond that found in girders without such cracks. Further, such cracking has required costly field repairs of spalled end-zones in Georgia bridges[1].

Figure 1. Bearing zone cracking due to sliding friction after strand cut-down.

The Georgia Department of Transportation (GDOT) in cooperation with Standard Concrete Products, Atlanta, and with Georgia Tech conducted a pilot research program to investigate methods to reduce the cracking in the girders by reducing the sliding friction between the girders and the steel bed. The study investigated five friction reducing techniques: use the current method of oil on the steel bed, a teflon pad which has been used on some projects, a wax lubricant, an embedded steel plate like that specified by the South Carolina DOT, and an embedded steel angle like the ones used at corners of reinforced concrete corbels. Additional longitudinal reinforcing bars were not used because they would not decrease friction, and they would only restrain crack size and not prevent crack formation. The investigation included a laboratory portion which measured the sliding friction of a concrete block on steel surface and a field portion which used the different methods on 124-ft long PCI BT-72 girders.

FRICTION REDUCING TECHNIQUES

The basic friction reducing technique was the application of a mineral oil base form release lubricant which is commonly used at Standard Concrete Product (SCP) plants. The second method was the use of a 0.02-in. thick teflon coated magnetic pad, similar to common household magnetic "stick-ons". Such pads have been successfully used by SCP for construction of large girders including those used for the Atlanta Hartsfield-Jackson Airport fifth runway. Figure 2 shows the teflon pad in the laboratory and on the precasting bed.

Figure 2. Teflon coated magnetic pad used in laboratory (left) and field (right).

The third technique was an application of a wax emulsion (RA5840 by Cellulose Solutions, Dothan, Alabama) which had been used successfully as a release agent. The fourth technique was the use of an embedded, galvanized steel plate as illustrated in Figures 3 and 4. This embedded plate is nearly identical in design to that commonly used for bridge girders by the South Carolina DOT.

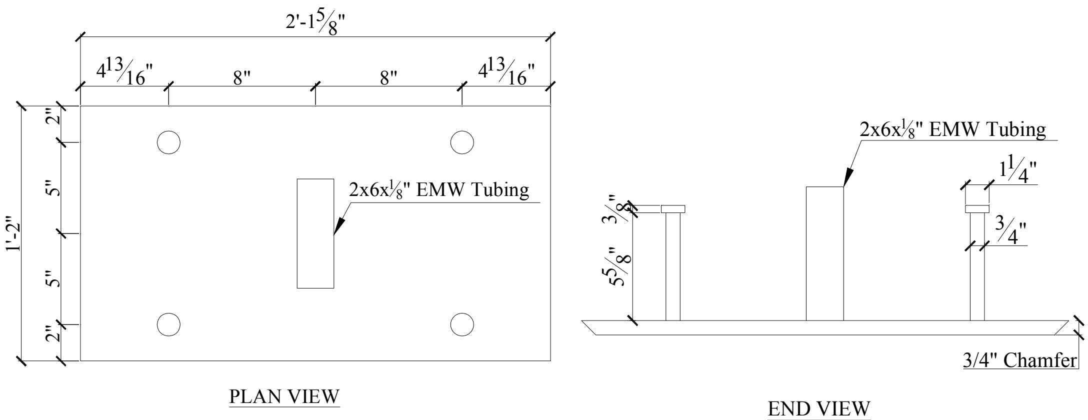

Figure 3. Drawing of embedded steel plate with 4- ¾" diameter studs and slot for restraining dowel.

Figure 4. Galvanized embedded steel plate on prestressing bed.

The fifth technique was the use of a galvanized embedded steel angle shown in Figure 5. The angle was considered as a low-cost alternative to the embedded steel plate.

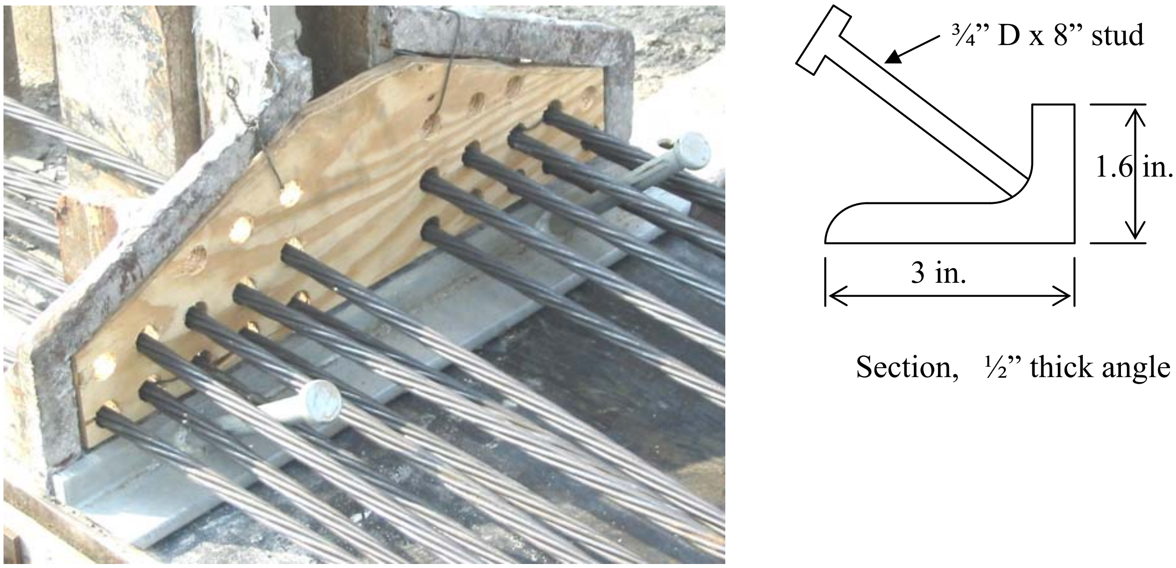

Figure 5. Embedded galvanized steel angle with two ¾-in. diameter studs

LABORATORY INVESTIGATION

The laboratory investigation measured the sliding friction between a concrete block and the top of a steel wide-flange beam. The test set-up is shown in Figure 6. The top surface of the steel beam was either clean and dry, coated with oil, coated with wax, or had a teflon-coated magnetic pad adhered to its surface. One concrete block had a plain bottom surface while a second had a steel plate embedded at the bottom. The blocks measured 26-in. wide x 16-in. x 16-in.

Both string potentiometers and an LVDT were used to measure the displacement of the sliding concrete block; a load cell accurate to 1 lb. measured the sliding force. At least three sliding friction tests were conducted for each surface condition. It was judged that an embedded steel angle would have the same sliding resistance as an embedded steel plate; therefore, the embedded angle was not tested in the laboratory. For the laboratory and field tests, the "control" was considered the oil coated steel surface.

The hydraulic ram was activated and pushed the concrete block steadily along the steel beam. The load cell continuously measured the force required to move the block over a sliding distance of approximately two inches, and the potentiometers and the LVDT measured that displacement. The coefficient of static friction, μ_s, was calculated with Equation (1) for each test and by using the greatest value from the load cell produced during the test and dividing by the normal force of the block used in the test[3]. The concrete block with no embedded steel plate weighed 563 lbs. and the concrete block with the embedded steel plate weighed 598.5 lbs.

$$\mu = F_s/N \tag{1}$$

where: μ = friction coefficient
F_s = force of sliding friction, highest lateral force measured
N = normal force in contact with the sliding surface

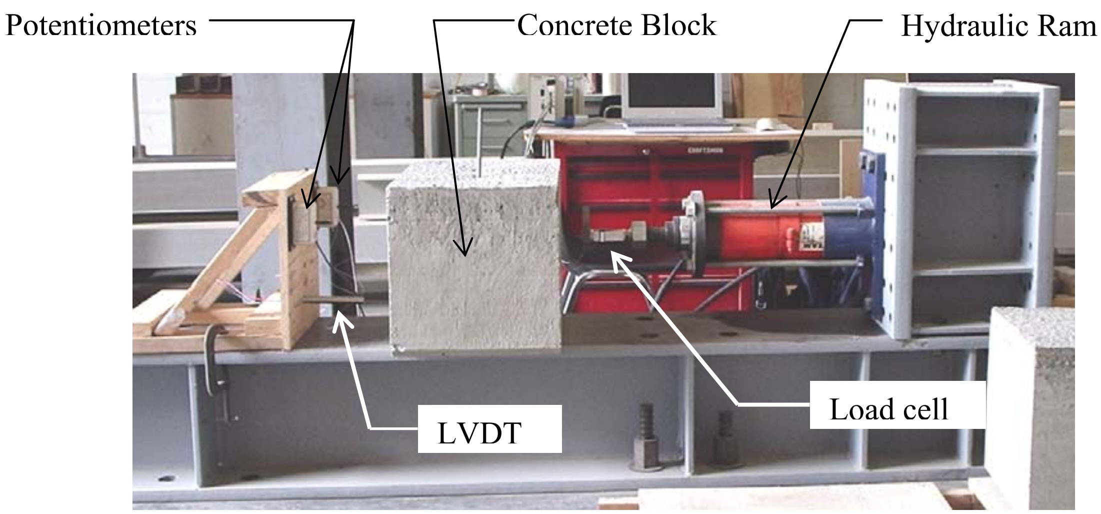

Figure 6. Laboratory sliding friction test set up.

Table 1 presents the average results from the laboratory tests. The embedded steel plate with oil-coated steel surface showed the lowest sliding friction, less than one-half that found for that using concrete on an oil-coated surface.

Table 1. Average sliding friction, μ_{ave}, results

Friction surface	Coefficient of Variation	μ_{ave}	$\mu_{ave}/\mu_{control}$
Clean & Dry	10.9%	0.514	116 %
Oil Lubricant, Control	12.4%	0.445	100 %
Teflon Pad	23.7%	0.265	60 %
Wax Lubricant	5.6%	0.232	52 %
Steel Plate, dry surface	2.2%	0.225	50 %
Steel Plate and Oil	3.2%	0.206	46 %

FIELD INVESTIGATION

Field tests were conducted at Standard Concrete Products plant in Atlanta, GA. Tests were conducted on 12 individual prestressed concrete BT-72 girders which were being cast for a GDOT bridge. Three 124-ft. long girders were poured at a time on a casting bed at the plant. The five friction reducing techniques used for the girders were: oil coated steel bed (control), teflon pad, wax lubricant, steel plate with oil, and steel angle with oil. The teflon pad was used at each end of four girders while the other methods were used at both ends of two girders each.

Three methods were used to measure the effectiveness of each friction reducing technique. Longitudinal strain was measured over a 10-in. gauge length at the center of gravity of the prestressing strands, approximately 4 ½ in. above the bottom of the girder at both ends on each side of the 12 girders. Figure 7 shows the epoxy bonded strain points for use with a DEMEC gauge. The distance between the gauge points was measured before cut-down (initial), after cut-down while the girder was on the bed, and after the girder was moved off the bed. The initial measured DEMEC gauge distance was subtracted from the measured DEMEC guage distance after cut-down and after the girder was moved off the bed, then divided by the initial length to compute the strains ε_{bed} and ε_{move}, respectively. After cut-down, a "zero" difference in strain between on and off the bed would indicate zero sliding friction restraint; similarly a ratio of $\varepsilon_{bed}/\varepsilon_{move}$ equal to 1 would indicate no friction restraint.

Figure 7. Strain measuring gauge points 4 ½" above bottom of girder and line for sliding

The sliding at each end of a girder was measured to determine the approximate change in length (ΔL) of the girder immediately before and after cut-down while the girder remained on the bed. The larger the value of ΔL compared from one girder to another indicated less resistance to sliding. A straight vertical line was drawn on the bottom flange of the concrete girders and continued to the outside face of the steel casting bed to measure any sliding movement.

The camber of each girder was measured on and off the bed (Δ_{bed} and Δ_{move}) using an electronic total station. Again, a small difference in camber would indicate little friction resistance; similarly a ratio of $\Delta_{bed}/\Delta_{move}$ equal to 1 would indicate no friction restraint. The weight of each girder was determined by measuring the unit weight of each batch of concrete used in each girder and by knowing the volume of each. The tensioning force in each strand was known, so an approximate initial sliding force could be computed.

Tables 2 and 3 summarize the results from the girder tests.

Table 2. Girder results for the five friction reducing techniques

Friction Technique	Girder Weight (kip)	Prestressing Force (kip)	Strain Average $\varepsilon_{bed}/\varepsilon_{move}$	Sliding ΔL (in)	Camber $\Delta_{bed}/\Delta_{move}$
Oil-1	97.01	1460.70	50%	1.28	61%
Oil-2	96.75	1355.70	56%	1.19	85%
Teflon Pad-1	97.01	1438.80	50%	1.53	65%
Teflon Pad-2	96.75	1438.80	66%	1.30	72%
Teflon Pad-3	95.77	1438.80	56%	0.86	65%
Teflon Pad-4	98.09	1357.50	56%	1.22	83%
Wax-1	95.39	1460.70	70%	2.81	68%
Wax-2	97.01	1460.70	75%	1.56	62%
Steel Plate-1	96.75	1355.70	85%	1.56	91%
Steel Plate-2	98.09	1357.50	80%	1.41	-
Steel Angle-1	96.75	1355.70	91%	1.41	93%
Steel Angle-2	98.09	1357.50	85%	1.41	95%

The oil-coated surface showed the highest restraint to movement; it had the lowest $\varepsilon_{bed}/\varepsilon_{move}$ ratio, a low value for ΔL, and the $\Delta_{bed}/\Delta_{move}$ ratio was nearly as low as that found for the girders with the teflon pads. The teflon pad was the least effective "new" technique in limiting the additional strain in the girders after they were moved off the casting bed as determined by girder strain. The $\varepsilon_{bed}/\varepsilon_{move}$ ratio averaged 8% greater than oil; although the $\Delta_{bed}/\Delta_{move}$ ratio averaged only 3% greater.

Table 3. Average girder results for the five friction reducing techniques

Friction Technique	Average Weight (kip)	Average Prestressing Force (kip)	Strain Average $\varepsilon_{bed}/\varepsilon_{move}$	Average Sliding ΔL (in)	Camber Average $\Delta_{bed}/\Delta_{move}$
Oil (Control)	96.88	1408.20	53%	1.23	73%
Teflon Pad	96.90	1418.48	57%	1.23	71%
Wax	96.20	1460.70	73%	2.19	65%
Steel Plate with Oil	97.42	1356.60	83%	1.48	91%
Steel Angle with Oil	97.42	1356.60	88%	1.41	94%

The wax lubricant was the second least effective new technique. The end strain and ΔL showed better results than the teflon pad technique, but the camber differences were about the same as those found using the pads. The embedded steel plate with oil was the second most effective technique in limiting the additional strain in the girders after they were moved off the casting bed as determined by girder strain. The $\varepsilon_{bed}/\varepsilon_{move}$ ratio averaged 57% greater than that found using oil, the ΔL was 20% greater, and $\Delta_{bed}/\Delta_{move}$ ratio averaged 25% greater than oil only.

The embedded steel angle was the most effective technique in limiting the additional strain in the girders. The $\varepsilon_{bed}/\varepsilon_{move}$ ratio for the angles averaged 66% greater than using oil alone, the ΔL was 15% greater, and $\Delta_{bed}/\Delta_{move}$ ratio averaged 29% greater than oil only.

These quantitative results match the findings from the laboratory sliding friction tests. The embedded steel sliding on an oiled surface had substantially less sliding resistance than plain concrete on the oiled surface alone. Yet, the qualitative findings are even more important. Figure 1 shows bearing zone cracking at the end of an oil-only girder; this occurred at each end of the two girders. Figures 8 and 9 show typical cracking at the end of the teflon pad and wax emulsion girders, respectively. The cracks varied: a crack would initiate at the bottom between one and six inches from the end; the angle varied from about 45 degrees to vertical, and the crack either crossed the entire bottom flange or just cut diagonally to spall the corner of the bottom flange.

No cracking was observed in any girder using the embedded steel plates. A very small crack occurred at one side of one end of the Angle-1 girder (Figure 10). The release strength of the Angle-1 girder was 5,900 psi while that of Angle-2 girder was 7,900 psi; the added tensile strength may have prevented the cracking from occurring in the Angle-2 girder.

The embedded plate and embedded angle well protected the bearing zones of the BT-72 girders. Qualitatively, the steel plate provided the best friction reducing technique because it prevented cracking in the bearing zone region.

Figure 8. Cracking in Teflon Pad-2, typical

Figure 9. Cracking in Wax-1, typical

The researchers noted that the position of the girders along the prestressing bed and whether the girder end was toward or away from the active, jacking location did not affect the strain or cracking results. The cause for the high variation in the results for the oil, wax, and teflon pad girders compared to that for the embedded steel plate and angle is unknown.

Figure 10. Cracking at one location in Angle-1 girder

ANALYSIS OF RESULTS

A simple analysis was conducted to determine the stress at which the sliding friction cracks developed. The analysis was based on assuming a linear tensile stress in the concrete girder from the bottom surface to zero stress at the top of the crack as shown in Figure 11. This analysis was intended to just find the friction force which caused cracking and not to be used for design.

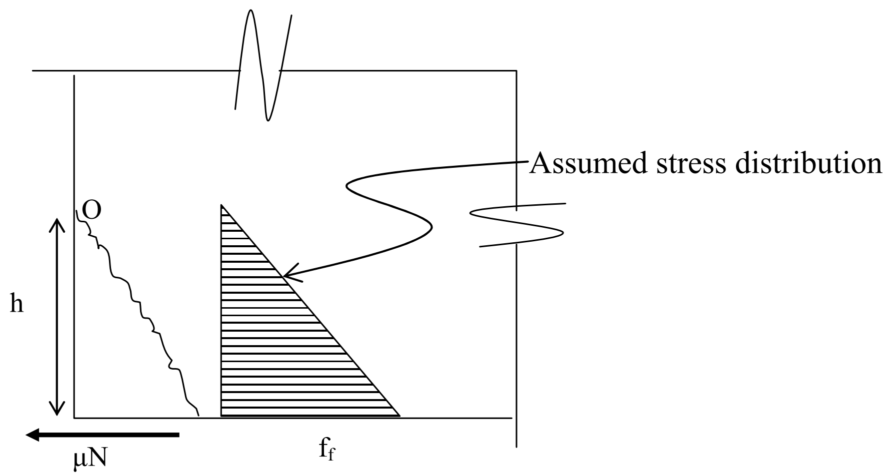

Figure 11. Schematic of cracking stresses at bottom, end of girder

The stress caused by the friction force was calculated as follows:

$$\sum M_o = \mu N{*}h = 0$$
$$f_f = M_o/S$$

where: μ = μ_{ave} found in laboratory tests
N = half the girder weight (bearing load at each end)
h = approximate average height of crack for each girder as measured
M_o = moment about point O at the top of the crack
S = $bh^2/3$ (section modulus below the crack about the base of the section)
b = width of the bottom flange (26 in. for all girders)
f_{ci} = girder initial compressive strength at the time strands were cut

Table 4 gives the results of this simple analysis which uses the friction coefficients from the laboratory tests, the crack height measured in the girders, the girder release strengths, and the girder calculated weights. In each case, the calculated flexure stress, f_f, was greater than the assumed initial tensile stress capacity, $3\sqrt{f_{ci}}$. Within the first few inches of the end of the beam, the precompression of the concrete was not considered significant; and after cracking, was not present.

Table 4. Simple analysis results

Girder Friction	μ	N (kip)	h (in)	S (in^3)	f'_{ci} (psi)	f_f (psi)	$3\sqrt{(f'_{ci})}$ (psi)	Cracked?
Oil-1	0.445	48.51	6	312	7600	415	262	yes
Oil-2	0.445	48.37	6	312	5900	414	230	yes
Pad-1	0.265	48.51	5	216.67	7500	297	260	yes
Pad-2	0.265	48.37	5	216.67	7500	296	260	yes
Pad-3	0.265	47.89	5	216.67	7500	293	260	yes
Pad-4	0.265	49.04	5	216.67	7700	300	263	yes
Wax-1	0.232	47.69	4	138.67	7600	319	262	yes
Wax-2	0.232	48.51	4	138.67	7600	325	262	yes
Plate-1	0.206	48.37	0	0	5900	0	230	no
Plate-2	0.206	49.04	0	0	7700	0	263	no
Angle-1	0.206	48.38	4	138.67	5900	287	230	yes
Angle-2	0.206	49.04	0	0	7700	0	263	no

The tensile capacity of $3\sqrt{f_{ci}}$ seemed appropriate because the beams that cracked had a calculated stress larger than this value in all cases, and that value has been used as a design standard. This simplified analysis was used to determine what weight of a girder could be cast without bearing zone cracking. The initial concrete strength f_{ci} was taken as 7,500 psi; the depth of the crack is taken as 6 in.; the width of the bottom flange as the 26 in.; and the coefficient of friction for an oiled steel bed form as $\mu = 0.445$. Then the maximum N value was computed using the relations given above as 30,380 lbs. The total weight of the beam would be 60,760 lbs which would be equivalent to a 78-ft long BT-72. Further research is needed to determine if other girders with weights in excess of about 61 kips have experienced bearing zone cracking.

The steel plate performed well because the plate acted as reinforcement which transferred the tensile forces caused by the sliding friction force, μN, to the studs as illustrated in Figure 12. Because the studs were embedded 3 and 14 in. within the precompressed concrete, they transferred the tensile forces without exceeding that precompression. The embedded angle performed similarly where the head of the diagonal stud transferred the tension to the precompressed concrete about 8 in. within the section.

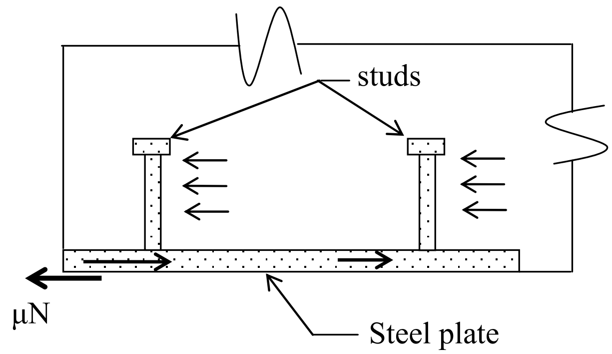

Figure 12. Schematic of tension force transfer in the embedded steel plate

CONCLUSIONS AND RECOMMENDATIONS

This pilot study showed that the teflon coated magnetic pad, wax emulsion, embedded steel plate, and embedded angle each significantly reduced sliding friction between the precast concrete unit and an oiled steel surface as compared to the friction between plain concrete and an oiled steel surface. The field study showed that the embedded steel plate and the embedded steel angle were the most effective in reducing and eliminated cracking in the bearing zone region. It was estimated that the embedded steel reduced the sliding friction to less than one-half of that found with an oiled surface alone.

The authors recommend that a friction reducing technique be used for pretensioned girders weighing more than about 61 kips. The embedded steel plate was easy to install in the field and provided excellent bearing zone reinforcement; such a plate is recommended for long-span, heavy weight girders. The steel angle was also easy to install and performed well.

REQUEST

The research presented herein was only a pilot study. The authors request that the reader submit recommendations for reducing and eliminating bearing zone cracks to the first author at his email address, Lawrence.Kahn@ce.gatech.edu. Your experience with such cracking would enhance the research and provide a better understanding of the cracking mechanism.

ACKNOWLEDGEMENTS

The research presented in this paper was sponsored by the Georgia Department of Transportation under Georgia DOT Task Order No. 02-20, Research Project No. 05-14.

Valuable support and guidance from the Georgia DOT were provided by Messrs. Paul Liles and Myron Banks. At Standard Concrete Products, Messrs. Craig Thompson, David Hennessey, and Richard Potts were particularly helpful and cooperative. Georgia Tech students John Bunyasaranand, Jonathan Hurff, Felix Kim, Ben Allread, and Andreas Willecke assisted in the field and laboratory portions of this research. Drs. Russell Gentry and Kimberly Kurtis assisted in planning and conducting the research. Mr. Allan Short, Cellulose Solutions, Daphne, Alabama, provided a variety of wax emulsions for investigation.

REFERENCES

Kelly, Patrick, "Bearing Zone Cracking of Precast Prestressed Concrete Bridge Girders," masters thesis, Georgia Institute of Technology, Atlanta, GA, 2007, pp 237

Slapkus, Adam, "Evaluation of Georgia's High Performance Concrete Bridge," masters thesis, Georgia Institute of Technology, Atlanta, GA, 2002, pp. 352

Persson, B. N. J. and E. Tosatti, ed. *Physics of Sliding Friction*, Kluwer Academic Publishers. Dordrecht, The Netherlands, 1996. pp. 69-89