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Precast Concrete Panel Thickness for Epoxy-Coated Prestressing Strands

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Interim Report for HR-353

by

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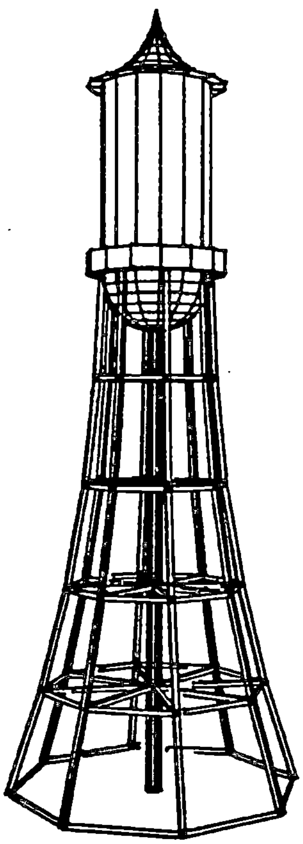

Submitted to the
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Table of Contents

ABSTRACT

A recommended minimum thickness for prestressed concrete (P/C) bridge deck panels containing 3/8-in. diameter, 270-ksi, low-relaxation, grit-impregnated, epoxy-coated prestressing strands is being evaluated by testing prototype panel specimens. As of January 1994, specimens from ten castings have been tested. The specimens in the first five castings were constructed to establish a preliminary minimum thickness for P/C panels. The specimens in the last five castings were constructed to 1) confirm the minimum panel thickness requirement, 2) measure the development length of epoxy-coated strands in specimens containing multiple strands, 3) measure the development length of uncoated strands in specimens containing multiple and single strands, 4) observe if concrete cracks form in thin panel specimens that have a raked top surface and are reinforced with welded wire fabric and either epoxy-coated or uncoated strands, 5) measure the transfer length for specimens containing a single uncoated strand, and 6) observe the seating characteristics of the grips used for uncoated strand and epoxy-coated strands. These tests have produced several initial findings. The preliminary recommended thickness for P/C panels containing grit-impregnated, epoxy-coated strands is 3 in. and the tentative development length for uncoated and coated multiple strands is approximately 45 in. and 24 in., respectively. Further tests will address confirmation of the recommended P/C panel thickness and establish the transfer and development lengths of single and multiple, uncoated and grit-impregnated epoxy-coated strands.

INTRODUCTION

Composite prestressed concrete (P/C) bridge decks have been constructed on secondary roads in Iowa for many years. These slabs consist of P/C panels and a reinforced concrete (R/C) topping slab. The panels replace the lower concrete portion, including the longitudinal and transverse reinforcement, in a conventional full-depth R/C deck. The construction of this type of deck system has been permitted by the Iowa Department of Transportation (Iowa DOT) as an alternate to a full-depth R/C slab, if the panel bridge deck system has performance characteristics comparable to those for a full-depth slab. For full-depth slabs, the Iowa DOT requires that all reinforcing bars be epoxy-coated for corrosion resistance. Presently, the composite slab alternate design uses epoxy-coated reinforcement for the top layer of longitudinal and transverse bars in the topping slab and uncoated prestressing strands and welded wire fabric in the P/C panels. To produce a composite slab with reinforcement corrosion protection comparable to that for a full-depth slab, the Iowa DOT authorized an investigation to study the feasibility of using epoxy-coated prestressing strands and welded wire fabric in P/C panels.

PROJECT SCOPE

The primary objective of this research is to establish a recommended minimum thickness for P/C bridge deck panels which contain 3/8" diameter, 7-wire, 270-ksi, low-relaxation, grit-impregnated, epoxy-coated prestressing strands and epoxy-coated welded wire fabric. The strands are spaced at 6 in. on center and are positioned at the mid-thickness of the panel. To accomplish this objective, an evaluation of the short-term bond performance of these strands is being undertaken by visual inspection of specimen surfaces to detect any concrete cracking and by measuring transfer and development lengths for the prestressing strands. For comparative purposes, specimens which contain the same diameter and type of uncoated prestressing strands are being tested. The transfer length for a strand is the concrete embedment length necessary to fully transfer a prestressing force from the strand that has been stressed to 75 percent of its minimum ultimate tensile strength into the concrete; and the development length for a strand is the total concrete embedment length necessary to achieve the nominal moment strength of the member when the strand reaches its minimum ultimate tensile strength.

In addition to the primary objective, there are two secondary objectives to this research. First, to determine the influence of multiple strands on the transfer and development lengths. Second, to monitor the seating characteristics of the wedge-shaped grips used for epoxy-coated and uncoated strands. The length of the grip and the length of the teeth in the wedges of the grips used with epoxy-coated strand are longer than those used for uncoated strand.

LITERATURE REVIEW

Epoxy-coated prestressing strands were first introduced by Florida Wire & Cable Company in 1984. Both smooth-surfaced and grit-impregnated, epoxy-coated strands are available. Dorsten et al [1] performed bond transfer length and pull-out tests of smooth-surfaced, epoxy-coated; and grit-impregnated, epoxy-coated, 1/2-in. diameter, 270-ksi, low-relaxation prestressing strands. Based on their test results of single strand specimens, they concluded that the transfer and development lengths for grit-impregnated, epoxy-coated strand are equal to or less than those lengths for uncoated strand of the same diameter. Because concrete splitting occurred across the width of some of their specimens that contained a grit-impregnated, epoxy-coated strand when the strand was released, these researchers suggested that more concrete cover may be required for epoxy-coated strands compared to the cover needed over uncoated strands. They also stated that strands without grit embedded in the epoxy coating were not suitable for bonded tendons, since little bonding strength was developed between the concrete and the smooth coating.

Cousins et al [2-4] also investigated the bond characteristics of epoxy-coated and uncoated strands in single strand specimens. They tested 270-ksi, low-relaxation strands with 3/8-in., 1/2-in., and 0.6-in. diameters. The 1/2-in. diameter strands had three grit densities of epoxy coating. During their tests, longitudinal splitting occurred in two of their transfer length specimens which contained a grit-impregnated, epoxy-coated strand. They concluded that these coated strands have shorter transfer and development lengths than those lengths for uncoated strands of the same diameter. Their test results also indicated that transfer and development lengths increased as the strand diameter increased, but decreased as the grit density increased.

In 1992, Lane [5] finished a research program that involved testing 50 rectangular beams prestressed by uncoated and epoxy-coated strands. This program, which was sponsored by the Federal Highway Administration (FHWA), was intended to establish if the American Association of State Highway and Transportation Officials (AASHTO) Specification [6] Eq.(9-32) for prestressing strand development length is valid for 270-ksi, coated and uncoated strands. Three diameters of 270-ksi, low-relaxation strands were used. Lane reported that the AASHTO transfer length of 50 strand diameters is conservative for specimens which contained one epoxy-coated strand, while this length is unconservative for specimens which contained four epoxy-coated strands, one uncoated strand, or four uncoated strands. And, the AASHTO Eq.(9-32) for strand development length is conservative for specimens with one epoxy-coated strand, four epoxy-coated strands, or one uncoated strand, while this equation is unconservative for specimens with four uncoated strands.

To date, our literature review has not revealed any studies that addressed the bonding performance of epoxy-coated strands in thin P/C bridge deck panels used in composite slab construction.

WORK ACCOMPLISHED

In December of 1992, the experimental portion of the research program began with the construction of a large prestressing frame. Two plan views for the frame illustrating two possible combinations of header locations, are shown in Fig. 1. The main members of the frame are two, 30-in. deep by 54-ft. long, steel

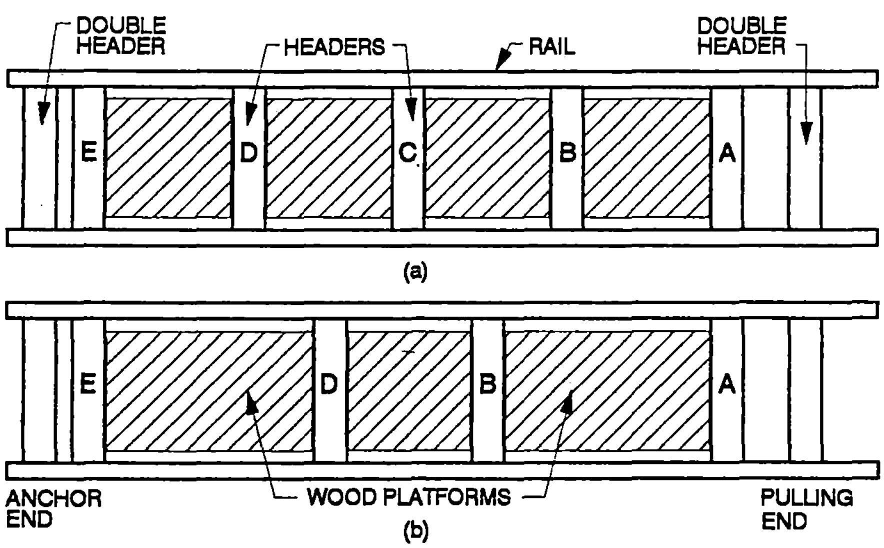


Figure 1. Plan views for prestressing frame: (a) Header locations for four bays of equal length; (b) Header locations for two end bays of equal length and one shorter middle bay.

I-shaped rails spaced 9 ft. - 3 in. on center and 28-in. deep, steel I-shaped headers that span between the rails. The headers may be positioned at different locations along the frame length to accommodate various specimen lengths. Double headers are provided at the designated strand anchor and pulling ends. The single headers at the ends of the specimens are oriented horizontally and their flanges have been slotted to allow for up to eight prestressing strands spaced at 6 in. on center to pass just above their webs. Steel shelf angles have been welded to the flanges of these headers to support wood platforms, which provide the formwork for the bottom of the specimens. Wood sideforms were constructed to establish the specimen widths and thicknesses.

By January 1994, a total of ten specimen castings have been completed. Four castings involved uncoated strands, and six castings involved epoxy-coated strands. In an effort to closely match the concrete used in the P/C panels, which are manufactured at Iowa Precast Concrete in Iowa Falls, IA, careful attention was given to the concrete mix design. The specific mix design that is being used in this research contains:

1. 1721 lb/yd^3 course aggregate (Martin-Marietta 1/2-in. limestone chips),
2. 1046 lb/yd^3 fine aggregate (Hallett Ames concrete sand),
3. 705 lb/yd^3 cement,
4. 0.39 water/cement ratio,
5. 6 percent air entrainment, and
6. water reducer and plasticizer to give 4 to 5 in. slump.

Even though a ready-mix producer has furnished the concrete for all of the castings, some inconsistencies in the workability and strength of the concrete have been experienced. We have attributed these problems to the small quantities of concrete ordered for each casting. A brief description of the purpose of each casting is given in the following paragraphs.

Cast No. 1: This casting was conducted to identify any problems in the electrical instrumentation and the casting procedures.

Cast Nos. 2 and 3: These castings established a preliminary estimate of the minimum recommended thickness for panels reinforced with epoxy-coated prestressing strands. Each casting had six specimens 2.5-in. thick and six specimens 3-in. thick. All specimens were 12-in. wide and reinforced with two prestressing strands spaced at 6-in. on center at the mid-thickness of the cross section. The top surface of the specimens was cast smooth to permit for visual inspection of concrete cracks. None of these specimens contained welded wire fabric (WWF). Visual inspection of the 2.5-in. thick specimens immediately after the epoxy-coated strands were cut revealed numerous longitudinal concrete cracks. Each crack was located directly above a strand. None of the 3-in. thick specimens experienced concrete cracking; therefore, a 3-in. minimum panel thickness was tentatively selected.

Cast No. 4: To confirm a 3-in. panel thickness, twelve 3-in. thick by 12-in. wide by 7-ft long smooth surfaced specimens containing epoxy-coated strands and no WWF were constructed. After prestressing the specimens, visual inspection of concrete surfaces revealed that concrete cracking did not occur.

Cast No. 5: Since the previous specimens were narrow in width compared to bridge deck panels, the possibility that wider 2.5-in. thick specimens reinforced with epoxy-coated strands would not crack needed to be investigated. Hence, this casting was made with four 2.5-in. thick by 36-in. wide, smooth surfaced, specimens that were reinforced with six epoxy-coated strands. WWF was not used in these specimens. After the strands were cut, longitudinal cracking was observed over many of the outside strands confirming that the 2.5-in. thickness was not adequate to transfer the prestressing force from the epoxy-coated strands.

Cast Nos. 6 and 7: The smooth surfaced specimens in these castings were made to establish a preliminary development length of uncoated prestressing strands and to confirm that concrete cracking would not occur along the transfer length. Each casting produced two 6-in. thick by 36-in. wide by 11 ft - 9 in. long development length specimens and one 3-in. thick by 36-in. wide by 6 ft - 9 in. long transfer length specimen. The six prestressing strands spaced 6-in. on center were positioned 2-in. above the bottom of the development length specimens and at mid-thickness of the transfer length specimen. Again, these specimens did not contain any WWF. The measured development length of the uncoated strands were found to be about 20 percent shorter than the length established by Cousins [3,4] and, as anticipated, cracks were not detected in the transfer length specimens.

Cast No. 8: The 3-ft wide panel specimens in this casting were made to measure the development length of epoxy-coated prestressing strands and to observe if a raked top surface on a specimen containing a layer of epoxy-coated 6x6-D6xD6 WWF placed on top the strands would affect concrete crack resistance. Two 6-in. thick by 11 ft - 9 in. long development length specimens and one 2.5-in. thick by 6 ft - 9 in. long transfer length specimen were produced. The six epoxy-coated prestressing strands were positioned as they were for cast nos. 6 and 7. The measured development length for these epoxy-coated strands were in close agreement to the length measured by Cousins [3,4]. Again, concrete cracking above the outside prestressing strands was noted in the 2.5-in. thick transfer length specimen after strand release.

Cast No. 9: Except for the thickness of the transfer length specimens, the specimens in this casting were identical with those in cast no. 8. To increase the concrete cracking resistance, the thickness of the transfer length specimens was increased from 2.5 in. to 3 in. The measured epoxy-coated strand development length for these specimens was in close agreement with Cousins [3,4] and concrete cracks were not observed in the 3-in. thick transfer length specimen.

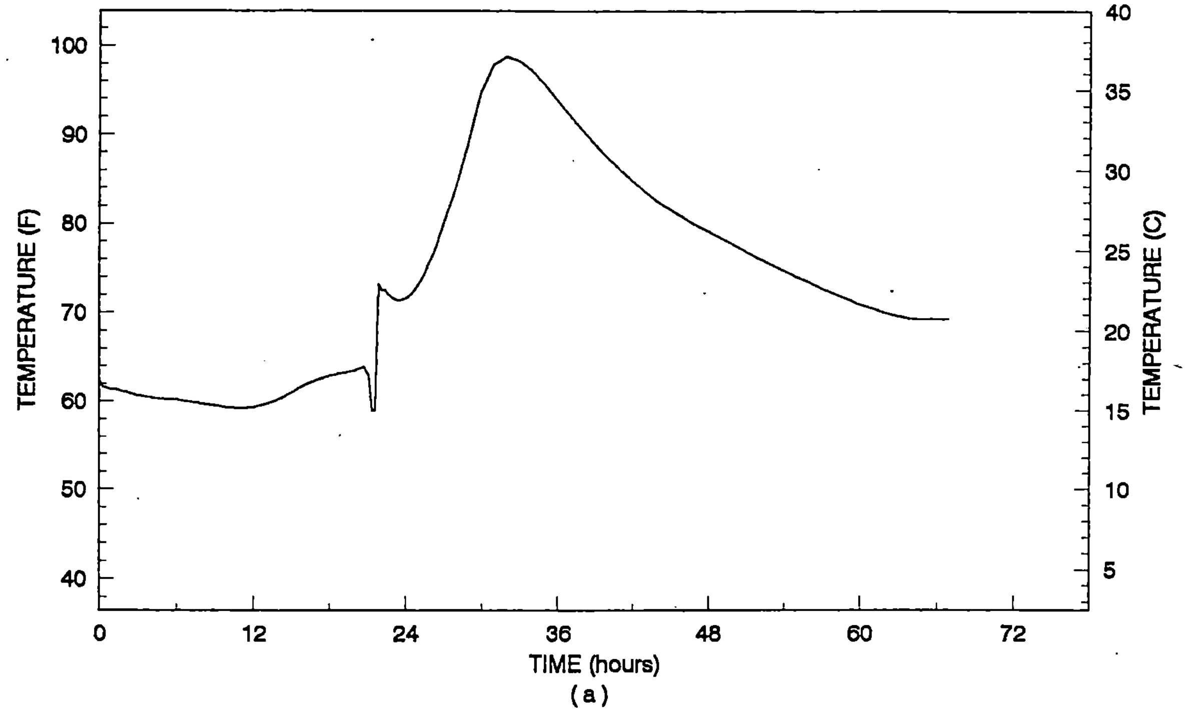
Cast no. 10: This casting had three purposes. First, to measure the development length of uncoated prestressing strands in 4-in. wide by 6-in. thick, single strand specimens, identical in cross-section to those used by Cousins [3,4], and to investigate the reason for the 20 percent difference in the measured uncoated strand development length established in this research with that obtained by Cousins. Second, to measure the development length of uncoated strands in 6-in. wide by 6-in. thick, single strand specimens. This width represents the tributary width for one strand in a P/C bridge deck panel. And third, to measure the strand transfer length in two, 4-in. wide by 3.5-in. thick, single strand specimens with polyester-mold embedment strain gages that were positioned at regular intervals on alternating sides of the strand. Development length testing showed that the development lengths of the single strand specimens were longer than that for the multiple strand specimens and that strands in the 4-in. wide specimens had longer development lengths than that for the 6-in. wide specimens. The axial strains measured immediately after prestressing the transfer length specimens were used to establish the strand transfer length. The distance from the end of the specimen to a point at which the strains became constant was defined as the transfer length.

PRELIMINARY RESULTS

•Strand Force Variation

In order to control the prestressing force for the specimens, strand forces were periodically monitored. Figure 2 illustrates how temperature variations (Fig. 2a) affects the strand prestress force (Fig. 2b). Before casting of the concrete, the strand temperature is identical to the laboratory room temperature. During this time, the prestressing force in the strands changes with time due to moderate room temperature changes and strand relaxation. After the concrete for the specimens has been cast, the strand temperature is significantly affected by the temperature of the surrounding concrete. The heat of concrete hydration causes the strand temperature to rise for about ten hours. This temperature increase produces a decrease in the prestressing force in a strand. A minimum strand force occurs when the concrete temperature is at a maximum. As the concrete temperature decreases, the strand prestressing force increases and approaches the value present just prior to casting of the concrete.

Figure 3 shows a typical fluctuation in the strand forces during the progressive cutting of the strands, when the prestressing bed contained six strands. An abrasive saw blade was used to cut the strands to obtain the effect of sudden release of a strand prestressing force. This method of cutting produces the most severe release condition for prestressing a concrete section. The notation along the curves indicate the cutting sequence. The number represents the strand number and the letter corresponds to the prestressing frame header designation (Fig. 1) at which a strand has been cut. For example, the notation 4B signifies that a cut was performed on strand no. 4 at header B. The strand forces shown in Fig. 3 were measured at header A. The strand force fluctuation is a characteristic of any prestress bed. For this research, the



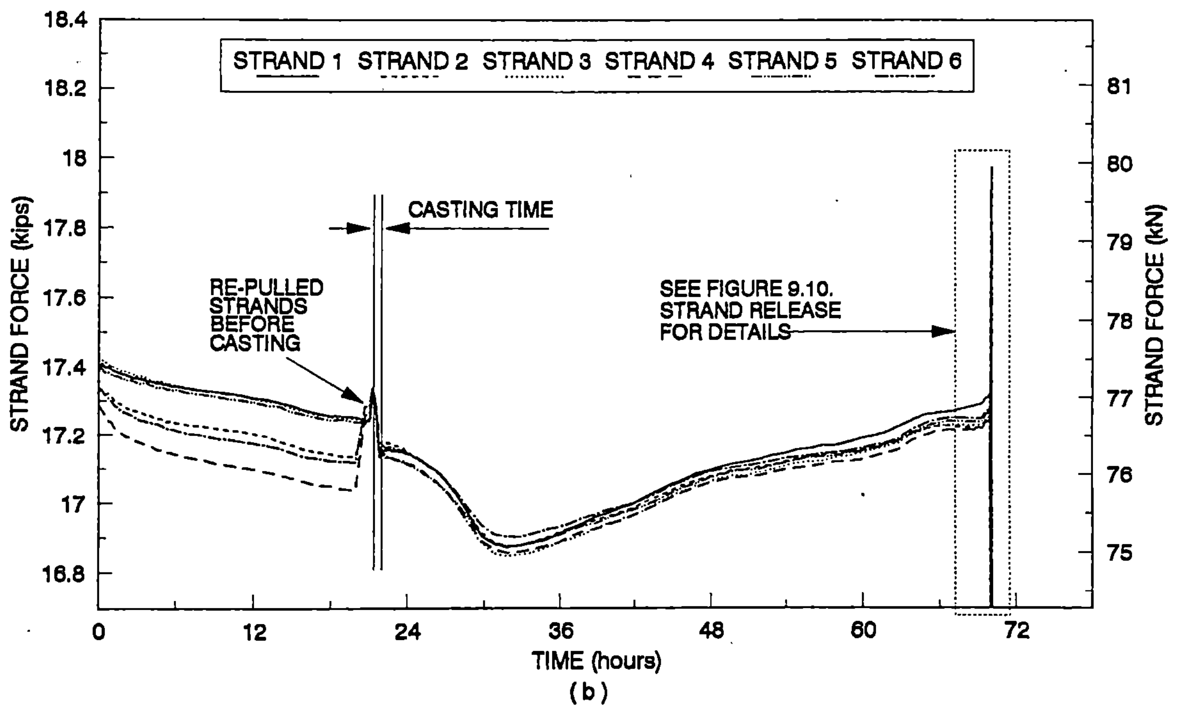


Figure 2. Typical strand temperature and force versus time relationships: (a) strand temperature versus time; (b) strand force versus time.

range of force variation is about one kip, representing about six percent of the initial strand prestressing force. The range of force fluctuation would decrease with longer strands and more rigid anchorages in a prestress bed.

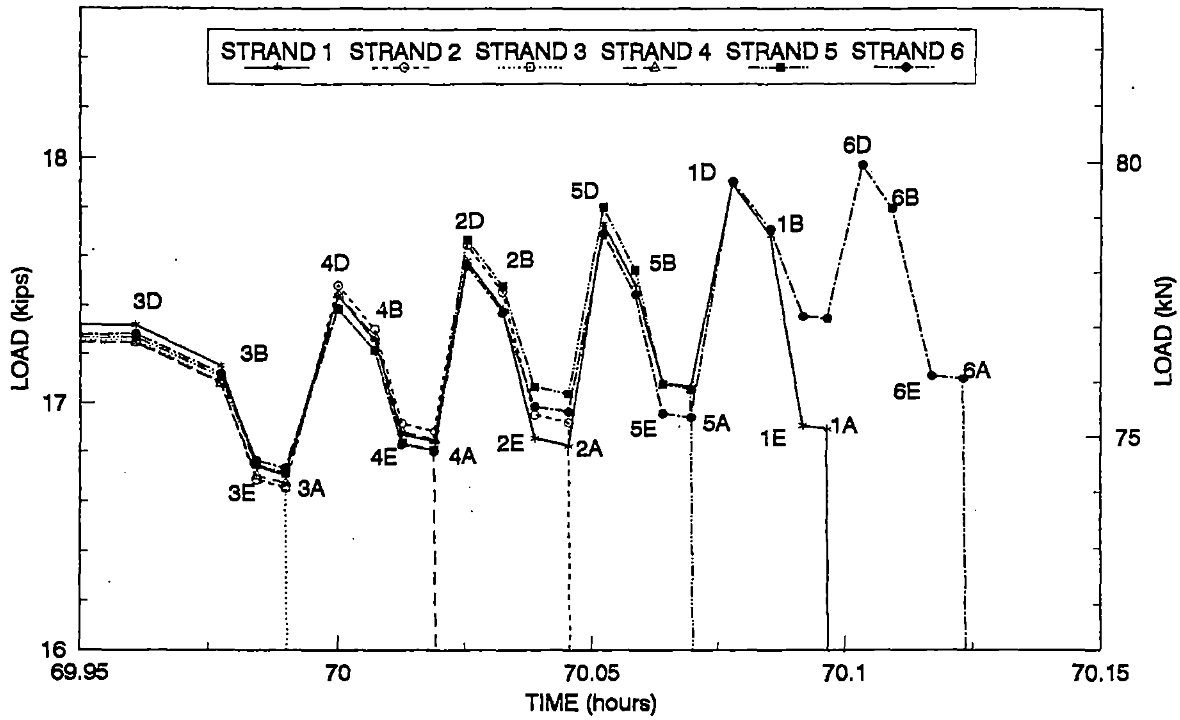


Figure 3. Typical strand force versus time relationship during release.

- <u>Panel Thickness</u>

The initial results of the tests to determine the recommended thickness for a P/C bridge deck panel are summarized in Table 1. The specimen width, b, and thickness, h, are listed in the second and third columns in the table. The strand type notation U and C listed in column 5 refers to uncoated and grit-impregnated, epoxy-coated strands, respectively. The notation listed in column 7 specifies if a particular specimen contained welded wire fabric and had a raked top surface (N = no and Y = yes). If welded wire fabric was present in a specimen, the coating on the fabric matched the coating for the prestressing strands. The concrete compressive strength, f'_{ct}, when the strand were cut is listed in column 8.

Table 1. Specimen parameters and concrete cracking occurance.

CAST NO. (1)	b (in.) (2)	h (in.) (3)	NO. OF SPECI-MENS (4)	STRAND TYPE (5)	NO. OF STRANDS (6)	WWF & R/S (7)	f'_{ct} (psi) (8)	NO. OF CRACKED SPECIMENS (9)
1	12	2.5	3	U	2	N	4074	NONE
	12	3.0	3	U	2	N	4074	NONE
	12	3.5	3	U	2	N	4074	NONE
	12	4.0	3	U	2	N	4074	NONE
2	12	2.5	6	C	2	N	4574	4
	12	3.0	6	C	2	N	4574	NONE
3	12	2.5	6	C	2	N	4520	4
	12	3.0	6	C	2	N	4520	NONE
4	12	3.0	12	C	2	N	6941	NONE
5	36	2.5	4	C	6	N	4634	4
6	36	3.0	1	U	6	N	2917	NONE
7	36	3.0	1	U	6	N	3892	NONE
8	36	2.5	1	C	6	Y	4149	1
9	36	3.0	1	C	6	Y	4586	NONE

Concrete cracking was not observed in the 2.5-in. thick specimens which contained uncoated strands nor in the 3-in. thick specimens which contained epoxy-coated strands. However, a considerable amount of concrete cracking occurred in the 2.5-in. thick specimens reinforced with epoxy-coated strands. Therefore, for a P/C bridge deck panel prestressed with epoxy-coated strands, a preliminary minimum thickness of 3 in. is recommended to prevent concrete splitting at strand release. Additional testing is required to confirm this thickness, since the recommendation is based on results obtained from only four tests that have been conducted on 3-in. thick specimens reinforced with epoxy-coated strands.

● Transfer Length

Two transfer length measurements have been made on single strand specimens in Cast No. 10. The transfer length specimen parameters and the preliminary values of transfer length, L_t, obtained from these specimens are given in Table 2. The length L_t was obtained by plotting concrete strains measured by the embedment gages after the strand was cut.

Table 2. Specimen parameters and transfer lengths.

SPECIMEN NUMBER (1)	b (in.) (2)	h (in.) (3)	STRAND TYPE (4)	NO. OF STRANDS (5)	f'_{ct} (psi) (6)	L_t (in.) (7)
10-3.5TU-6	4	3.5	U	1	4014	34
10-3.5TU-7	4	3.5	U	1	4014	35

For specimen no. 10-3.5TU-7, Fig. 4 shows the concrete strain data and two visual "best fit" straight lines that have been drawn through the data points. According to a linear strain distribution model for prestressing a specimen, the concrete strain increases linearly from zero at the free end to a maximum value at the end of the strand transfer length, after which the strain remains constant. The test results closely match this mathematical model. The average transfer length of the epoxy-coated strand in these specimens was 34.5 in.

● Development Length

Strand development lengths were established by measuring the distance from the load point in a cross-bending test to the closest end of a specimen at which a strand bond failure was detected by strand slippage. The maximum length

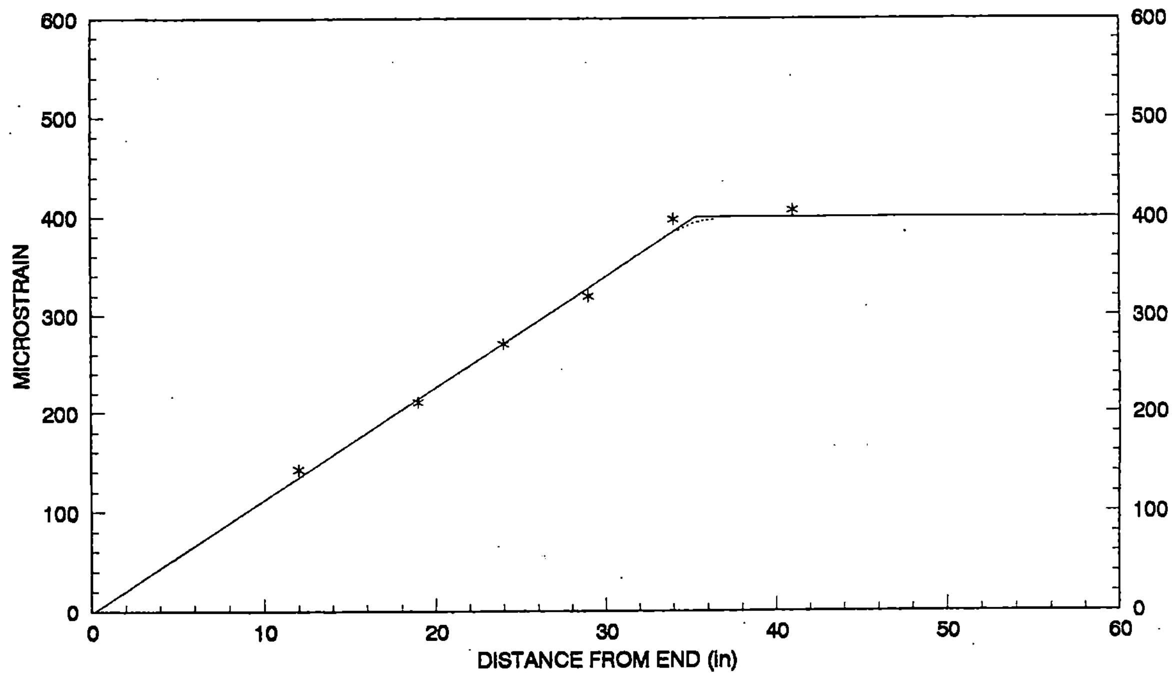


Figure 4. Transfer length test of Specimen No. 10-3.5TU-7.

obtained while a specimen still experienced a strand bond failure was considered to be the strand development length. A strand was considered to have slipped if its relative longitudinal displacement with respect to the concrete surface at the end of the specimen is more than 0.01 of an inch. All of the prestressing strand development length specimens were 6-in. thick. Specimens containing uncoated strands were 4, 6, and 36-in. wide and specimens with epoxy-coated strands were 36-in. wide. The strands were positioned at 2 in. above the bottom of the specimens. Additional parameters for the strand development length specimens are given in Table 3. The end of the specimen closest to the applied load is referenced by the header designation in the prestressing bed (Fig. 1). This end is listed in column 2 in the table. The concrete compressive strength, f'_{cd}, when the development length tests were conducted is given in column 6. The

Table 3. Specimen parameter and development lengths.

SPECIMEN NUMBER (1)	END (2)	b (in.) (3)	STRAND TYPE (4)	NO. OF STRANDS (5)	f'_{cd} (psi) (6)	LOAD POINT (in.) (7)	MODE OF FAILURE (8)
6-6.0DU-1	A	36	U	6	2967	50	F
6-6.0DU-3	D	36	U	6	2967	30	B
6-6.0DU-3	E	36	U	6	2967	40	B
7-6.0DU-1	A	36	U	6	4891	45	B/F
7-6.0DU-3	D	36	U	6	4891	42	B
7-6.0DU-3	E	36	U	6	4891	45	F
8-6.0DC-1	A	36	C	6	5149	28	F
8-6.0DC-1	B	36	C	6	5149	26	F
8-6.0DC-3	D	36	C	6	5149	21.5	S/B
8-6.0DC-3	E	36	C	6	5149	24	S/B
9-6.0DC-1	A	36	C	6	5832	26	F/S
9-6.0DC-1	B	36	C	6	5832	24	F/S
9-6.0DC-3	E	36	C	6	5832	25	F/S
10-6.0DU-1	A	4	U	1	5534	70.5	F
10-6.0DU-2	A	4	U	1	5534	65	B
10-6.0DU-3	A	4	U	1	5534	60	B
10-6.0DU-3	B	4	U	1	5534	56	B
10-6.0DU-4	B	4	U	1	5534	54	B
10-6.0DU-9	D	6	U	1	5220	50	B
10-6.0DU-9	E	6	U	1	5220	54	F
10-6.0DU-10	D	6	U	1	5220	54	F/B
10-6.0DU-11	D	6	U	1	5220	46	B
10-6.0DU-11	E	6	U	1	5220	44	B
10-6.0DU-12	D	6	U	1	5220	42	B
10-6.0DU-12	E	6	U	1	5220	42	B

distance between the load point and the closest end of a specimen is listed in column 7. Modes of failure for a particular specimen, which were classified as bond, flexural, combined bond and flexural, combined shear and bond, or combined flexural and shear (B, F, B/F, S/B, or F/S, respectively), are listed in column 8.

The preliminary results for prestressing strand development length, L_d, are:

For uncoated strands,

36"x6" panels L_d=45 in.

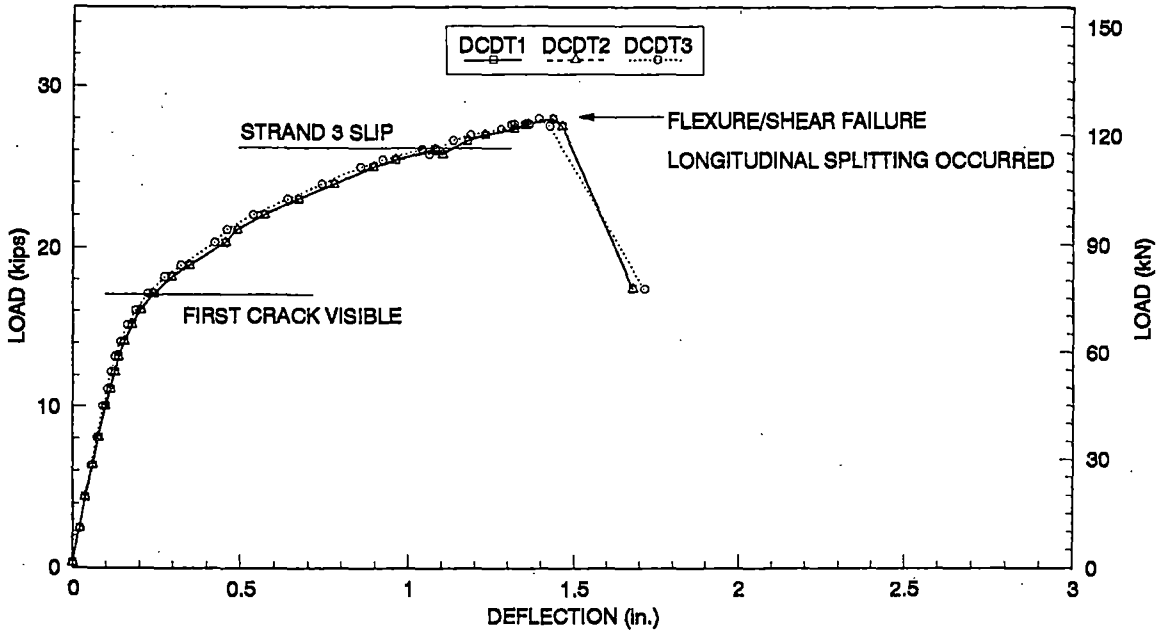
6"x6" beams L_d=54 in.

4"x6" beams 60 in.$<L_d<$70.5 in.

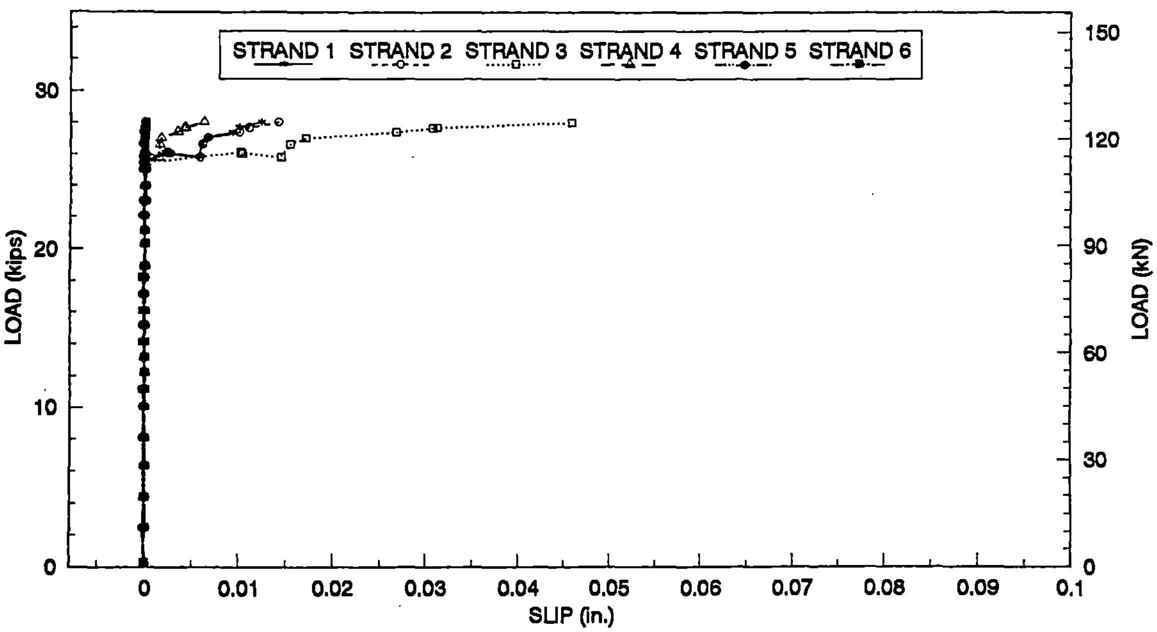
For epoxy-coated strands,

36"x6" panels L_d=24 in.

Figure 5 shows displacement results for a typical development length test on a 36-in. wide specimen. The load versus load point deflection relationship and the load versus strand slip, measured at end of the specimen nearest the load point, are shown in Figs. 5(a) and 5(b), respectively. In this test, strands 1, 2, and 3 slipped, while the other three strands did not experience slip before a combined flexure and shear failure of the specimen occurred. Before any concrete flexural cracks in this specimen were observed, the load-deflection relationship remained linear, indicating that the specimen had a constant flexural rigidity, EI. After concrete cracks developed in the specimen, the reduction in EI was reflected by the reduced slopes in the load-displacement relationship.



(a)



(b)

Figure 5. Typical development length test results with load at 24 in. from end B: (a) Load versus deflection; (b) Load versus strand slip at end B.

WORK REMAINING

- Additional tests will be conducted to confirm that a 3-in. thick P/C panel is adequate for strand release when grit-impregnated, epoxy-coated prestressing strands are used.
- The data collected from cast nos. 6, 7, and 10 involving uncoated strands indicate that strand development length for multiple-strand specimens are shorter than that for single strand specimens. Future castings will be conducted to confirm this trend and to establish if the same phenomenon holds true for epoxy-coated strands.
- Additional strand transfer length testing with embedment strain gages in single strand and multiple strand specimens will be performed for both uncoated and epoxy-coated strands.

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the Highway Division of the Iowa DOT.

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