DEVELOPMENT LENGTH OF STRANDS IN PRESTRESSED PANEL SUBDECKS

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A Study of Prestressed Panels and Composite Action in Concrete Bridges Made of Prestressed Beams, Prestressed Subdeck Panels, and Cast-in-Place Deck

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ABSTRACT

This report describes the results of field and laboratory studies of prestressed concrete panels of the type proposed for use as a new method of highway bridge construction. Twenty panels, utilizing two different strand sizes, concrete types and panel lengths were considered. Study objectives included the determination of the development length of the prestressing strands shortly after fabrication and the effect of cyclic loading on this development length. Changes in panel stiffness as a result of fatigue loading were also monitored.

Test results showed that an average of 22 in. of development length was required for 3/8 in. diameter, 7-wire strands pretensioned with a force of 13.75 kips. An average development length of 34 in. was required for 1/2 in. diameter strands pretensioned with a force of 27.50 kips.

Cyclic loading was found to have negligible effect on strand development length or on panel stiffness.

SUMMARY

A recent innovation in prestressed concrete highway bridge construction utilizes concrete panels as bottom forms for a conventional cast-in-place deck. These panels, which are precast and prestressed, subsequently form a composite unit through bond to the cast-in-place deck to carry vehicular loads.

The work reported herein describes tests conducted on the prestressed panels to determine the prestress strand development length required for such members, and to observe the effects of cyclic loading on development length of strands and on panel stiffness.

Twenty specimens were utilized in the testing program. All were 3-1/4 in. thick, and were prestressed with either 3/8 in. or 1/2 in. diameter 7-wire strands. Both normal weight and lightweight concrete were used. Copper tubes containing strain gages were embedded in each specimen to measure longitudinal prestress strain at points along the length of the panel. The strains were used to determine the development length required by the strands.

An average development length of 22 in. was required for the 3/8 in. diameter strands, and 34 in. was needed for the strands with 1/2 in. diameters. The type of concrete used had little effect on development length, especially for those specimens with the larger strand. Cyclic loading was found to have negligible effect on strand development length or on panel stiffness.

IMPLEMENTATION STATEMENT

The work reported herein is the second phase of a three-phase investigation which is to include load tests of a full-scale model of the prestressed panel-cast-in-place slab type construction. Therefore a statement concerning the implementation of this type of bridge construction will be deferred until the completion of this study.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

I. INTRODUCTION

A recent innovation in prestressed concrete highway bridge construction incorporates a concrete panel subdeck. These panels, which are precast and prestressed, are normally three to four inches thick, and four to six feet wide. Their length is dependent upon the lateral spacing of the prestressed concrete beams and is chosen so that the panel will span the opening between two adjacent beams and have an adequate bearing area on their top flanges. The prestressed panel initially serves as a bottom form for a conventional cast-in-place slab usually three to five inches thick, and subsequently becomes an integral part of the bridge deck through the bond between the cast-in-place concrete and the top face of the panel. Several bridges of this type built in Illinois about 1956 used 2-1/2 in. thick panels with a 5 in. thick cast-in-place deck.[8*] The structural action of this two-element bridge deck in transmitting vehicular wheel loads laterally to adjacent beams is assumed to be identical to that of a monolithic slab of equal thickness. Earlier studies[3,11] have been made verifying this assumption, and attention is now being focused on the structural integrity of the prestressed panel, both at the time of construction when it serves as a form to support cast-in-place concrete, and afterward when it works in conjunction with the cast-in-place slab to transmit loads.

In order for the prestressed panel to perform satisfactorily, it must develop and retain a prescribed level of precompression. This,

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*Superscripts refer to entries in the List of References.

in turn, is dependent upon the characteristics of stress transfer between the prestressing strands and the panel concrete. It is known that in pretensioned prestressed members, some finite distance from each of its ends is necessary for transfer of stress between strand and concrete. For relatively short concrete members, such as the panels under investigation here, this distance or development length is of primary concern. If the development length is quite long, only a small midspan segment of panel will receive the full prestress force. If the bending moment for which the panel is designed should occur toward the end of the panel, it can result in cracking of the panel under service load conditions. If the development length of the strands at the time of fabrication of the panel is satisfactory, but service conditions to which it is subjected cause a substantial increase in this length, unexpected cracking may also occur.

The research program described in this report was undertaken to determine development length of prestressing strands in prestressed panels similar to those currently being used in a few highway bridges[3] in the state of Texas. Both initial development length and the development length after repeated transverse loading were studied. Measurements were also taken to determine if stiffness of a panel was altered by repeated loading.

II. PREPARATION AND INSTRUMENTATION OF PANELS

A total of 20 panels, using two different sizes of seven-wire prestressing strand and two different types of concrete, were fabricated by a commercial supplier for the testing program. The panels were divided into five groups of four specimens each, and their properties are summarized in Table 1. The first number in a panel designation is its length in inches; the letters which follow denote normal weight or lightweight concrete; and the last two numbers denote the strand diameter in eighths of an inch and the specimen number, respectively.

TABLE 1. PROPERTIES OF TEST PANELS

Panel Designation	Dimensions	Number and Size of Strands	Type of Concrete
68 LW3-1,2,3,&4	68" x 22" x 3-1/4"	4-3/8" diameter	Lightweight
68 NW3-1,2,3,&4	68" x 22" x 3-1/4"	4-3/8" diameter	Normal weight
68 LW4-1,2,3,&4	68" x 22" x 3-1/4"	2-1/2" diameter	Lightweight
68 NW4-1,2,3,&4	68" x 22" x 3-1/4"	2-1/2" diameter	Normal weight
108 NW4-1,2,3,&4	108" x 22" x 3-1/4"	2-1/2" diameter	Normal weight

Each of the test panels was provided with two small metal instrumentation tubes to measure the development length of the strands. Electrical resistance strain gages were mounted at equal intervals along the inside of the tube, which was embedded in the center of the panel, parallel to the strands, as shown in Figs. 1 and 2. The longitudinal strain induced

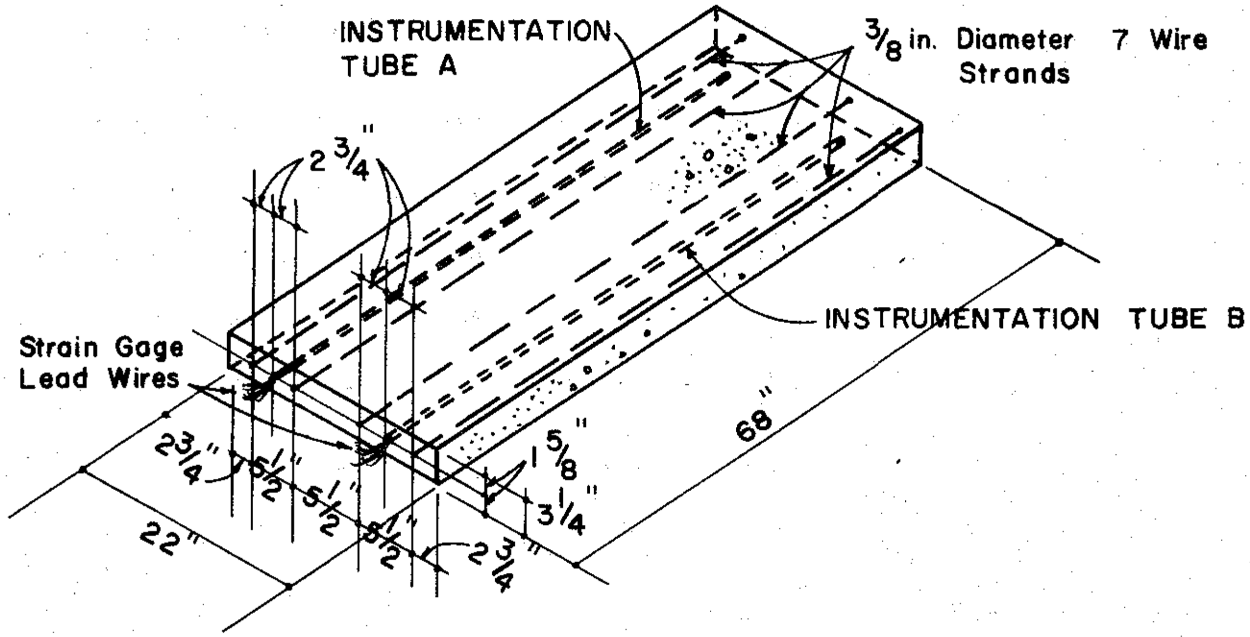


FIGURE 1. INSTRUMENTATION TUBES IN PANEL WITH 3/8 IN. DIAMETER STRANDS

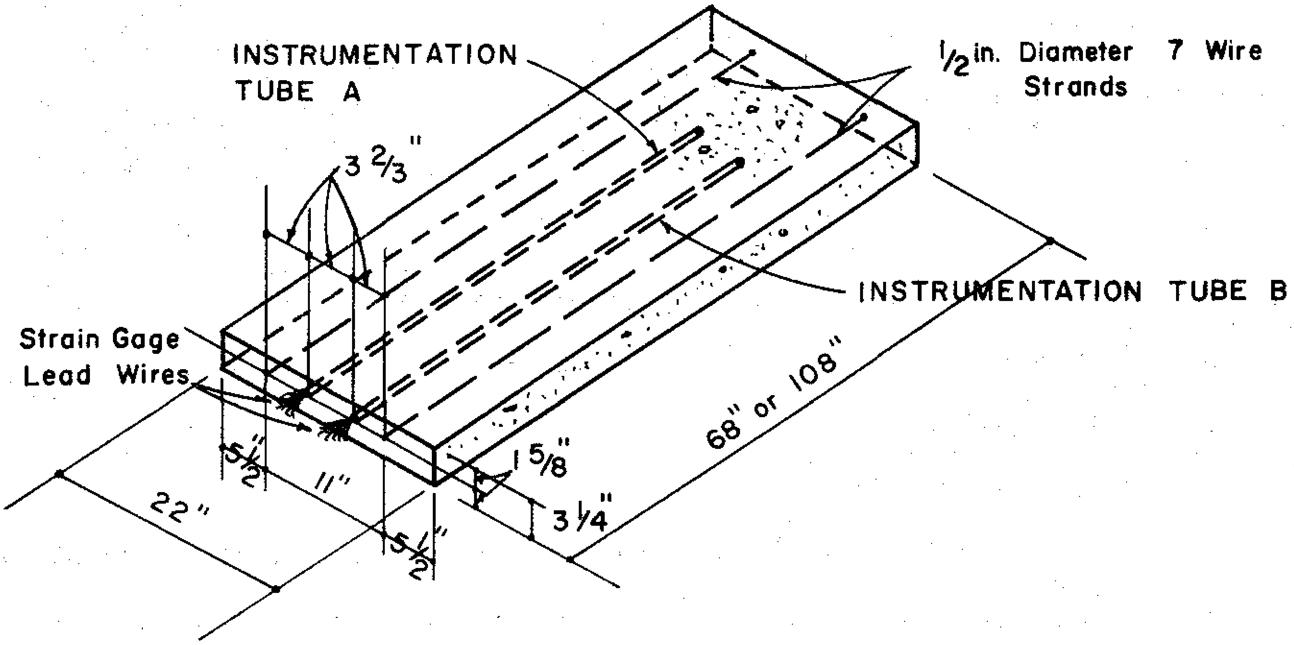


FIGURE 2. INSTRUMENTATION TUBES IN PANEL WITH 1/2 IN. DIAMETER STRANDS

in the concrete by transfer of force from the strands was measured by the gages in the embedded instrumentation tubes. The point at which the strain readings reached a constant value marked the end of the transfer zone, and the development length was determined by measuring the distance from the end of the panel to this point.

2.1 Fabrication of Instrumentation

The instrumentation tubes were constructed from .018 in. thick copper strips, one in. wide and 58 in. or 78 in. long, depending on whether the tube was to be used in a 68 in. or 108 in. long panel. Ten strain gages were used in those tubes placed in the 68 in. panels and 15 gages were used for the 108 in. panel instrumentation tubes. In both cases the gages were spaced at 4 in. intervals, beginning 4 in. from the end of the panel. The strain gages used were TML type FLA 6-11 electrical resistance gages with 6 mm. gage length, manufactured by Tokyo Sokki Kenkyujo Co. Ltd. They were attached to the copper tubes using Eastman 910 contact cement. Small, stranded, plastic insulated lead wires were attached to each gage and cut so they extended approximately two feet beyond the end of the strip. Figure 3 shows an instrumentation tube at this stage of construction. An initial coat of Bean Gagekote #5 waterproofing was next applied to each gage and its lead wire terminals. The flat copper strip was then curled to form a tube, and a second application of waterproofing was made, completely covering all gages and lead wires within the tube. The outside surface of the tube was scraped and then cleaned with acetone and metal conditioner to remove any waterproofing that might interfere with the

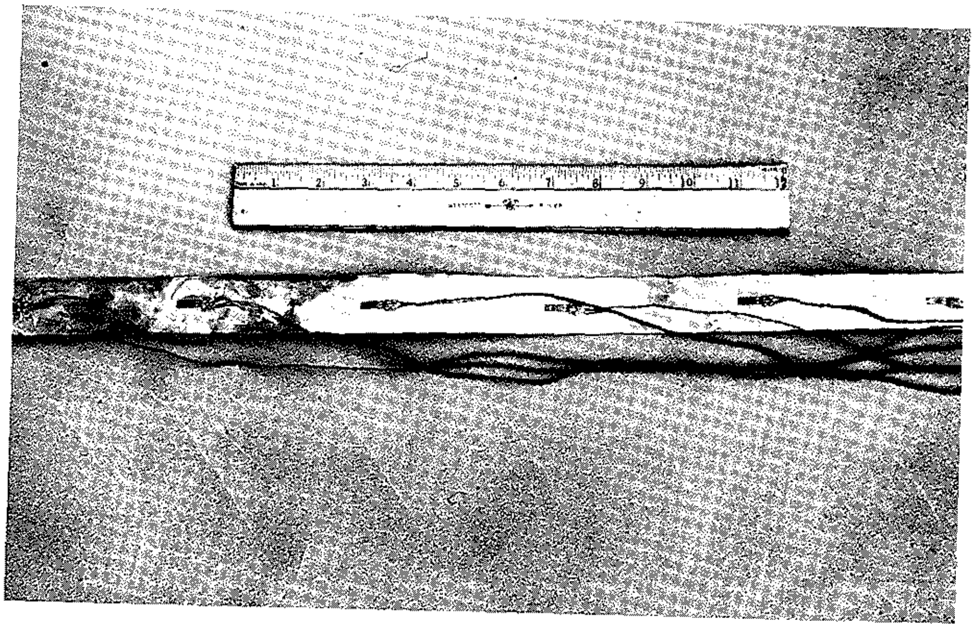


FIGURE 3. INSTRUMENTATION TUBE WITH STRAIN GAGES IN PLACE

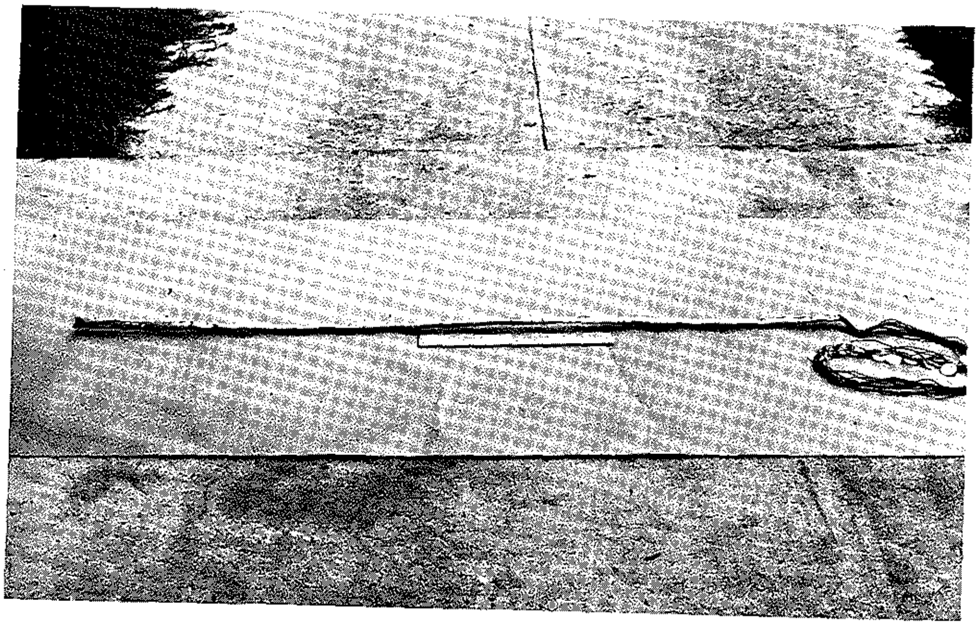


FIGURE 4. COMPLETED INSTRUMENTATION TUBE

bond between the copper tube and the surrounding concrete. As a final step, the outside of the tube was roughened with a metal rasp to improve bonding characteristics. Pullout tests indicated that copper tubes prepared in this manner required approximately 4 in. of embedment length to develop the strength of the tube. Figure 4 shows a completed instrumentation tube.

2.2 Fabrication of Panels

The panels used in this test program were produced by a commercial fabricator in Dallas, Texas. TTI personnel installed the instrumentation and collected data in the field.

The 20 panels were cast in two lines; one line consisting of normal weight and light weight 68 in. panels with four 3/8 in. diameter strands and the other containing 68 in. normal weight and light weight and 108 in. normal weight panels with two 1/2 in. diameter strands. A compression stress of approximately 700 psi in the concrete after release was obtained by tensioning the 3/8 in. diameter strands with a force of 13.75 kips each and the 1/2 in. diameter strands with 27.50 kips. The surface of the strands was clean and rust free.

After the strands were tensioned in the prestressing bed, bulkheads were installed to form the individual panels and the instrumentation tubes were set in place. Short lengths of No. 3 reinforcing bar were tied laterally underneath the prestressing strands at 18 in. intervals, and the tubes were secured to them with tie wire. The strain gage lead wires protruding from the end of each tube were passed through holes in the bulkheads and placed in plastic bags for protection. Figures 5 and 6 show instrumentation tubes in the casting bed for 3/8 in. diameter and 1/2 in. diameter strands, respectively.

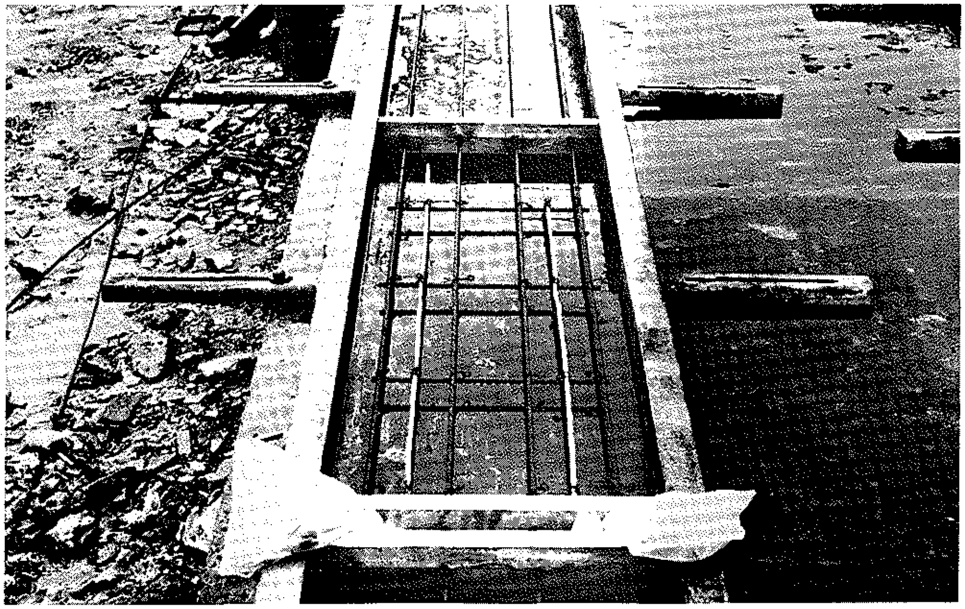


FIGURE 5. INSTRUMENTATION TUBE INSTALLED IN PANEL WITH 3/8 IN. DIAMETER STRANDS

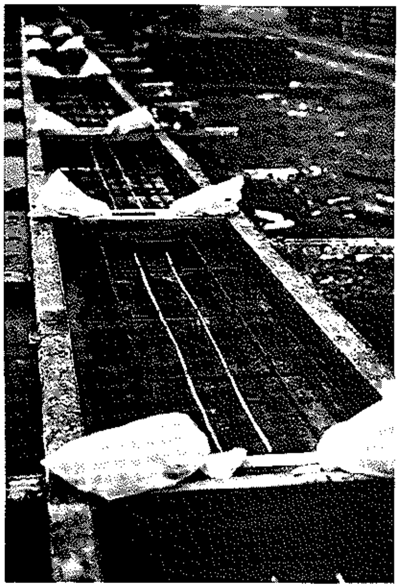


FIGURE 6. INSTRUMENTATION TUBE INSTALLED IN PANEL WITH 1/2 IN. DIAMETER STRANDS

After all instrumentation was in place, the casting operation began. The concrete was placed in the forms and vibrated into place, with care being taken that the instrumentation tubes were not dislodged from their mid-depth position in the panels. Standard test cylinders were made from both the lightweight and normal weight batches of concrete to use in determining compressive strength at time of release of the strands. A photograph of the pouring operation, in progress, is shown in Fig. 7. After the pour was completed, the panels and test cylinders were allowed to cure for approximately four hours at prevailing moisture and temperature conditions. Tarpaulins were then placed over the panels and cylinders, and approximately 12 hours of steam curing was applied following Texas Highway Department requirements[9]. At the end of the curing period, three cylinders from each concrete batch were tested, giving an average compressive strength of 5300 psi for the lightweight and 5100 psi for the normal weight concrete. The tarps were removed from the panels, and the first set of readings were taken from the gages. The prestressing strands were then released by gradually reducing the ram force at the jacking end of the bed. A second set of strain readings was taken from the panels as soon as the release was completed. The cables between panels were cut with a torch and the panels were removed from the casting beds and prepared for shipment to the laboratory at College Station.

III. TESTING PROGRAM

The testing program was carried out in two phases and with two different objectives. The first phase was conducted in the field to

FIGURE 7. CASTING OPERATION

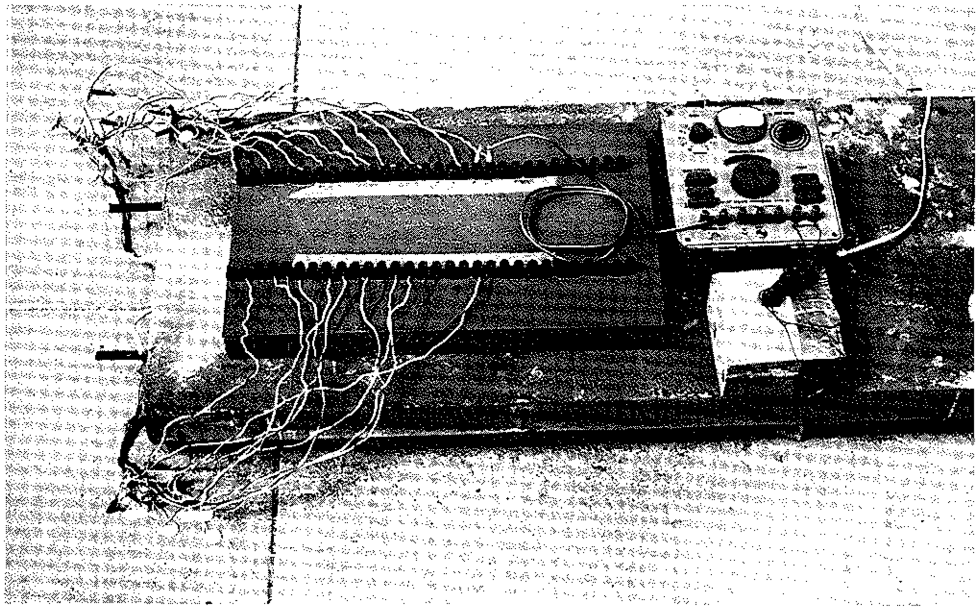


FIGURE 8. EQUIPMENT FOR MEASURING STRAINS IN THE FIELD

determine the length of transfer required for the various strand sizes and concrete types. The second phase was carried out in the laboratory and was designed to study the effect of fatigue loading on the serviceability of the panels; specifically, what effect would fatigue loading have on the transfer length of strands and on the stiffness of the panel.

3.1 Initial Development Length of Strands

Two sets of strain readings taken from the instrumentation tubes in the field made it possible to determine the development length of the prestressing strands in one end of each panel. The first set of readings was taken prior to the release of the prestressing strands. The second set was taken after the strands had been released.

The strain readings taken before and after release were obtained while the panels remained in the casting bed. A Baldwin-Lima Strain Indicator was used for strain readings sensitive to changes in strain of 5 micro-inches per inch. A strain gage mounted on a short copper strip and embedded in a 6 in. x 6 in. x 3 in. concrete block was used as a temperature compensating gage in the strain measuring circuit. Gage circuits were individually completed by a banana plug connection to the strain indicator. Figure 8 shows the equipment in readiness for taking a series of readings.

3.2 Fatigue Loading of Panels

The fatigue loading phase of this study was conducted in the McNew Laboratory at Texas A&M University. Loads were applied by a Gilmore pulsating loader. Three specimens out of each group of four listed in Table 1 were tested.

The 68 in. long panels were tested with simple support conditions and a span of 5 ft-2 in. A concentrated force, with sinusoidal varying magnitude, was applied at the midspan point of the specimen. This resulted in both upward and downward displacements at a frequency of 15 cps. The panels rested in the testing machine on a specially constructed frame which provided a simple support condition for both upward and downward force. The load was applied through a collar clamped to the panel at midspan. As shown schematically in Fig. 9, a dial gage, sensitive to .001 in., was positioned on an aluminum channel at the center of the panel to measure midspan deflection. A transducer, made from a spring steel cantilever beam and instrumented with electrical resistance strain gage, and linked to an oscilloscope was also attached at midspan to obtain a more accurate midspan deflection reading while the panel was under cyclic loading. Static strain readings from the gages in the instrumentation tubes were taken using a Budd Digital Strain Indicator and two Budd Switch and Balance units. Strains could be measured to 1 micro-inch per inch using this equipment. Figure 11 shows one of the 68 in. long panels in the testing machine.

Each of the test specimens were subjected to two million cycles of load applied continuously, with the exception of periodic pauses to record strain and deflection data, over approximately a 42 hour period. The amplitude of the sinusoidal varying force applied to the 68 in. long panels was selected to produce bending stresses of zero and 1400 psi at midspan. The stress at the top and bottom of the panel, with no load applied, was 700 psi compression due to prestressing. On the downward stroke of the load, a compression stress was superimposed at the top face of the panel, while a tensile stress of equal magnitude was superimposed at the bottom face. The

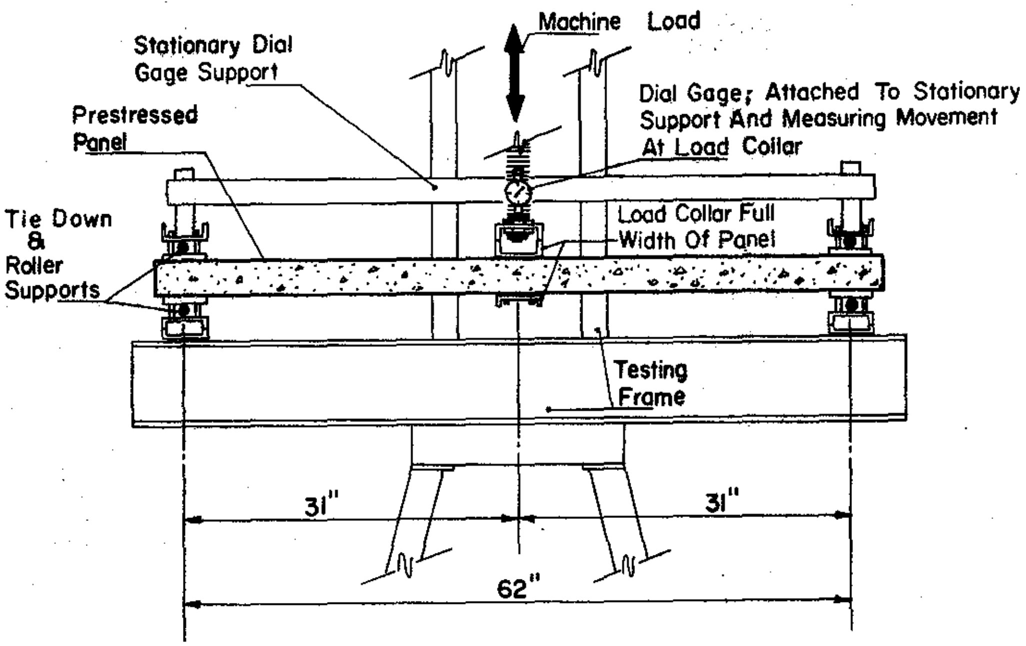


FIGURE 9. TEST SETUP FOR FATIGUE LOADING OF 68 IN. LONG PANELS

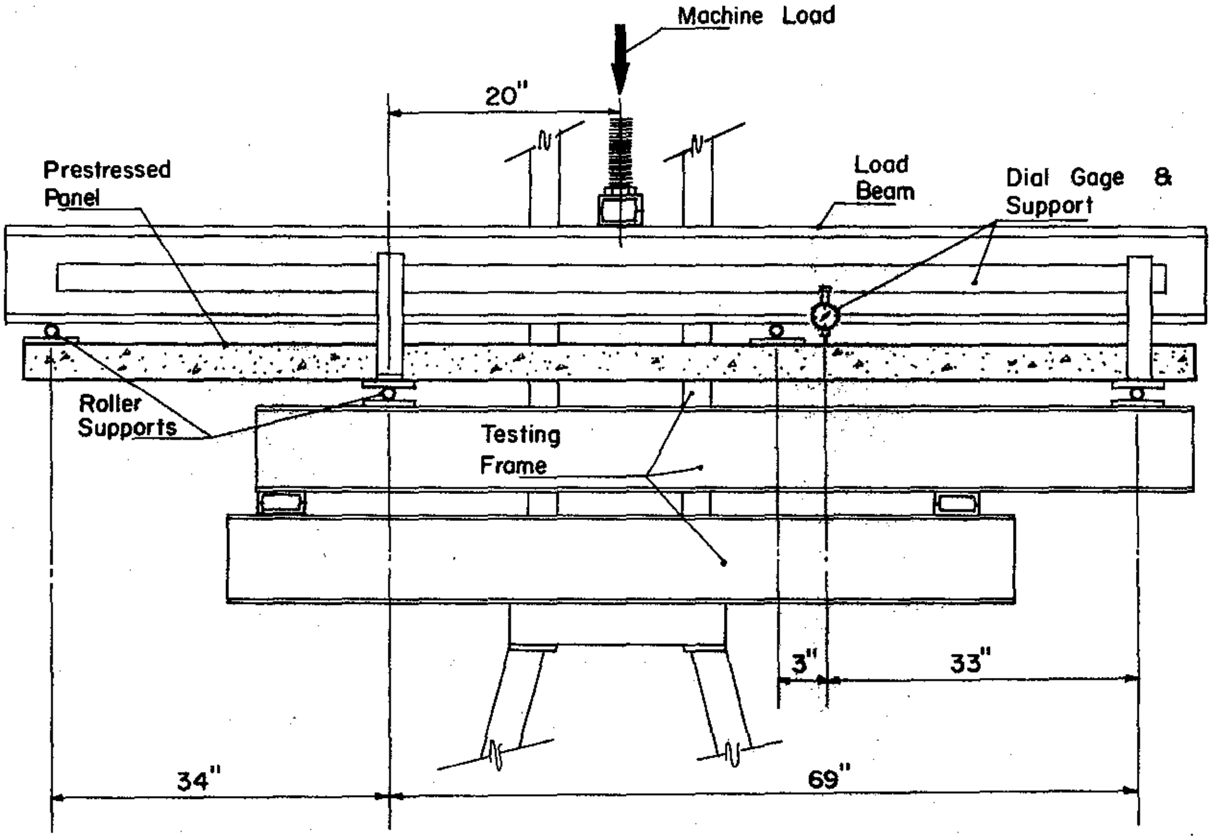


FIGURE 10. TEST SETUP FOR FATIGUE LOADING OF 108 IN. LONG PANELS

net result was an increase in compression stress at the top face and a decrease in compression at the bottom. The amplitude of the load was selected to produce a superimposed stress of 700 psi, so that when it was directed downward with maximum value, a net stress of 1400 psi compression was produced at the top face of the panel and a stress of zero at the bottom face. During the upward stroke, the situation was reversed, resulting in a net stress of zero at the top face of the panel and 1400 psi compression at the bottom. Thus, during one complete cycle of load, the stresses at the top and bottom faces of the panel varied between zero and 1400 psi compression. The required force amplitude was determined indirectly, through measurement of midspan deflection. The midspan deflection required to produce a superimposed stress of 700 psi was computed from the load-stress relation

$$\Delta = \frac{L^2 \sigma}{6\ t\ E}$$

where

L = clear span of 62 in.

σ = superimposed stress of 700 psi

t = panel thickness of 3 1/4 in.

E = modulus of elasticity

Stress-strain tests on standard cylinders cast in the field with the panels yielded average modulus values of 5,600,000 psi for the normal weight specimens and 3,900,000 psi for the light weight specimens. During the tests, the amplitude of the force was adjusted, holding the frequency constant at 15 cps, until the deflection computed from the above relation was registered

FIGURE 11. TESTING MACHINE WITH 68 IN.
LONG PANEL IN PLACE

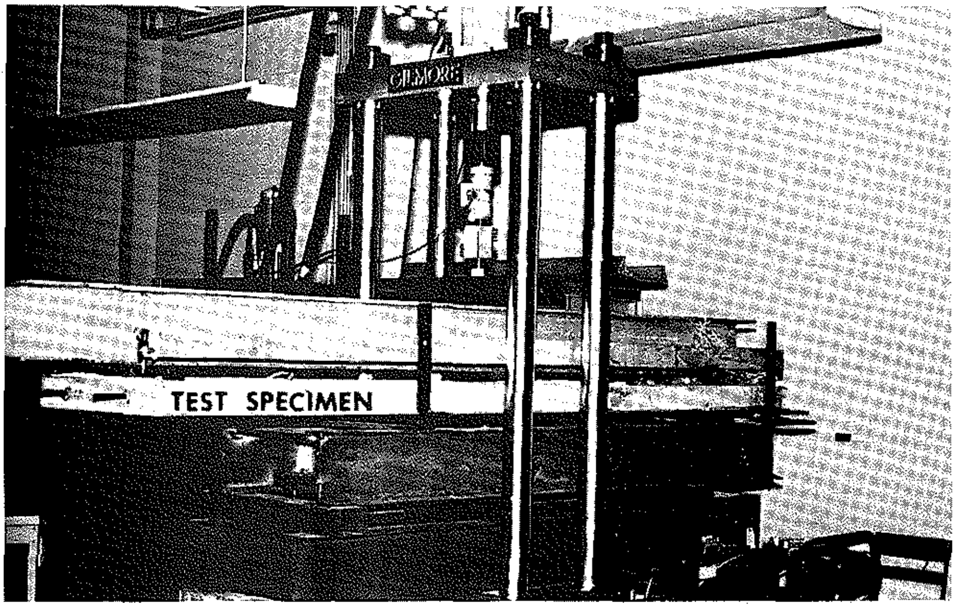


FIGURE 12. TESTING MACHINE WITH 108 IN.
LONG PANEL IN PLACE

by the midspan deflection transducer.

The loading arrangement for the 108 in. panels is shown in Fig. 10. The panels were simply supported, with an overhang, to simulate the condition of a panel on the outermost line of beams in a bridge. Two concentrated forces were applied to these panels; one at the overhanging end and the other at a point between supports. This arrangement subjected the panel simultaneously to both positive and negative bending moments. The concentrated forces underwent a half-sine variation in magnitude at 15 cps, thus causing only downward deflections. The deflection of the panel was measured at the point of maximum deflection between supports, which was 33 in. to the right of the right-most support. The magnitude of the load was altered so as to produce a compressive stress of 1400 psi at the top of the panel and zero stress at the bottom, at the point of maximum moment. The maximum bending moment occurred beneath the load point, 36 in. to the right of the right-most support (see Fig. 10). Figure 12 shows one of the 108 specimens under load.

Two sets of data were collected from each specimen tested. Before the cyclic loading was begun, the strain gages in the instrumentation tubes were connected to a digital strain indicator through a 10 channel switch and balance unit. Each channel was balanced, so that a zero value of strain was indicated for each gage. After loading of the panel was begun, strain readings were taken from all gages at one hundred thousand cycle intervals. Changes in these readings reflected changes in the development length of the strands due to cyclic loading.

The second set of data collected consisted of load-deflection readings taken at five hundred thousand cycle intervals. The static machine load required to cause .005 in. increments in downward displacement at midspan were recorded while varying the total midspan deflection from zero to .025 in. for normal weight concrete specimens and from zero to .035 in. for light weight concrete specimens. These readings, which were made for both the 68 in. and 108 in. long panels, were taken to study the effect of cyclic loading on panel stiffness.

IV. TEST RESULTS

4.1 Initial Development Length of Prestressing Strands

The difference in strain readings taken immediately before and immediately after release were used in determining the development length of prestressing strands. The point along the panel where the difference in strain readings became constant marked the end of the strand development zone. A plot of compressive strain vs. distance from the end of the panel was made for both instrument tubes of each panel and the development length was estimated from it. Figures 13 through 17 show typical plots for one of the panels from each of the five groups of test specimens. Table 2 summarizes the development lengths found for each of the panels, and Table 3 contains the average development lengths of various groupings of test specimens.

4.2 Fatigue Loading of Panels

Three of the four specimens in each group were tested. The data collected in this phase was used to determine if cyclic loading caused any slippage and increase in strand development length, and to see if panel stiffness was reduced. The trends in the data taken from each of the test specimens were essentially the same, and the data from specimen 68 NW4-2 has been chosen for detailed examination, it being typical of the other panels tested.

Figures 18 through 22 show plots of strain reading vs. number of cycles of load, for specimen 68 NW4-2. The symbols "A" and "B" were

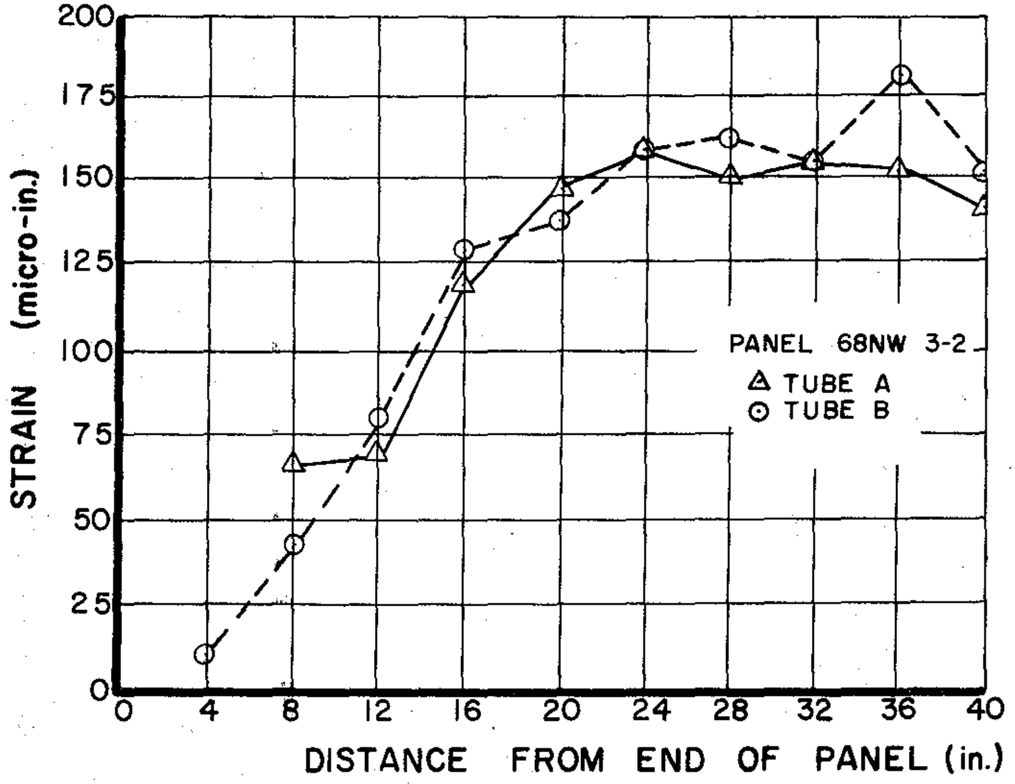


FIGURE 13. STRAIN VS. DISTANCE FROM END OF PANEL FOR SPECIMEN 68 NW3-2

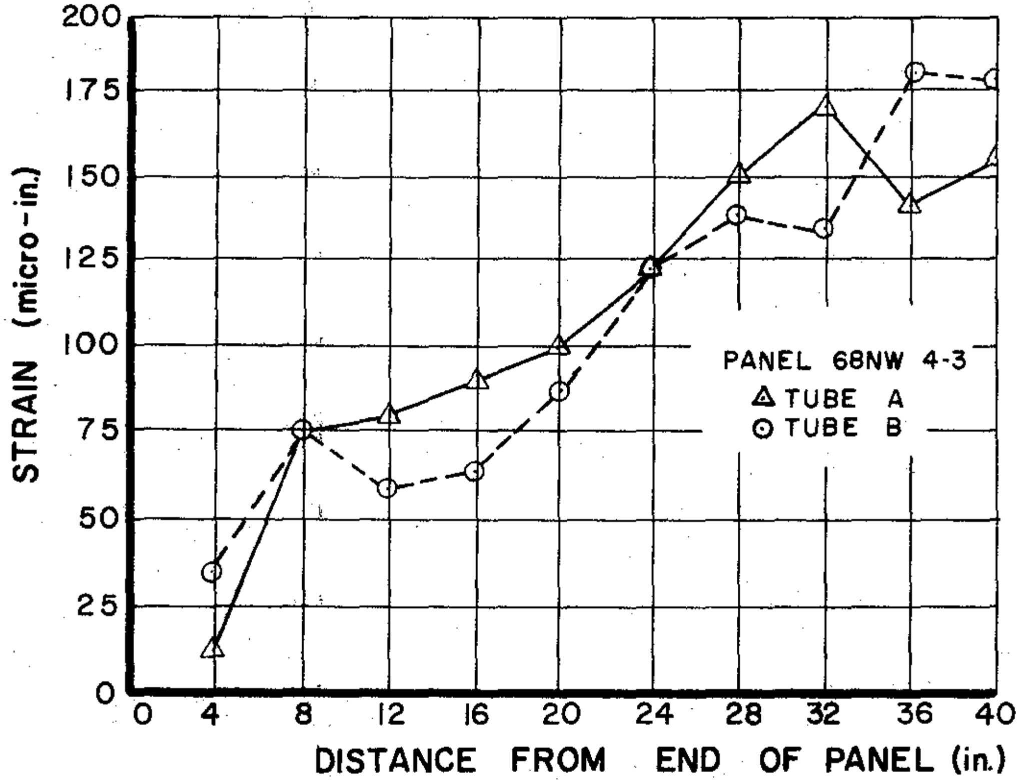


FIGURE 14. STRAIN VS. DISTANCE FROM END OF PANEL FOR SPECIMEN 68 NW4-3

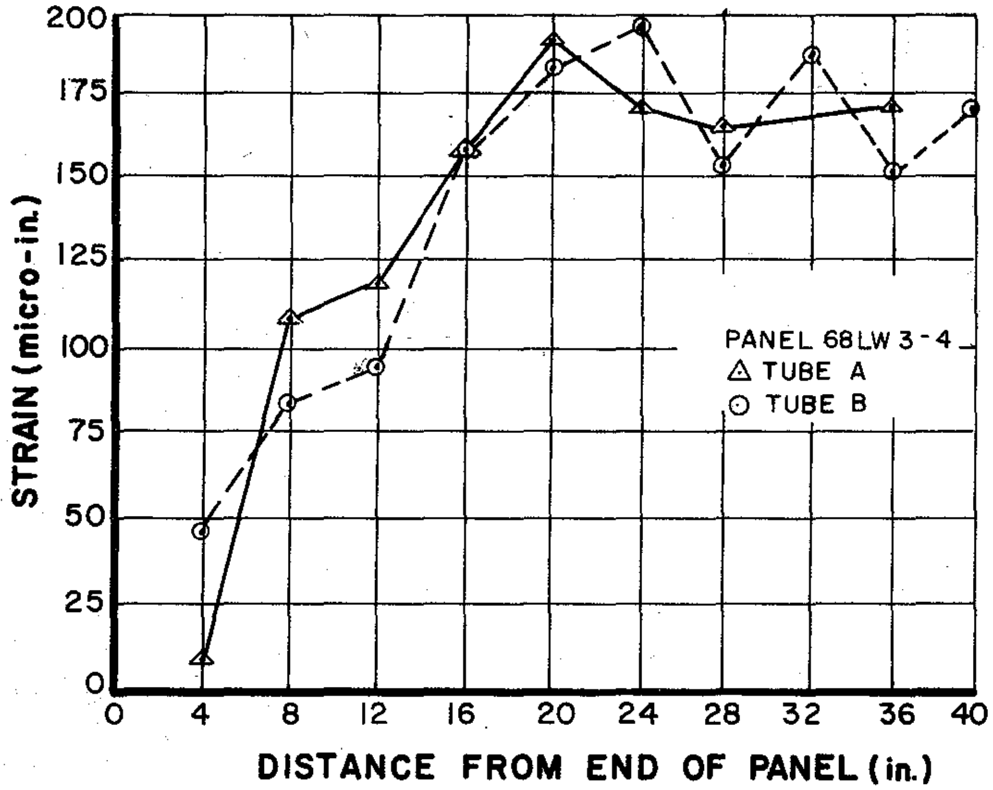


FIGURE 15. STRAIN VS. DISTANCE FROM END OF PANEL FOR SPECIMEN 68 LW3-4

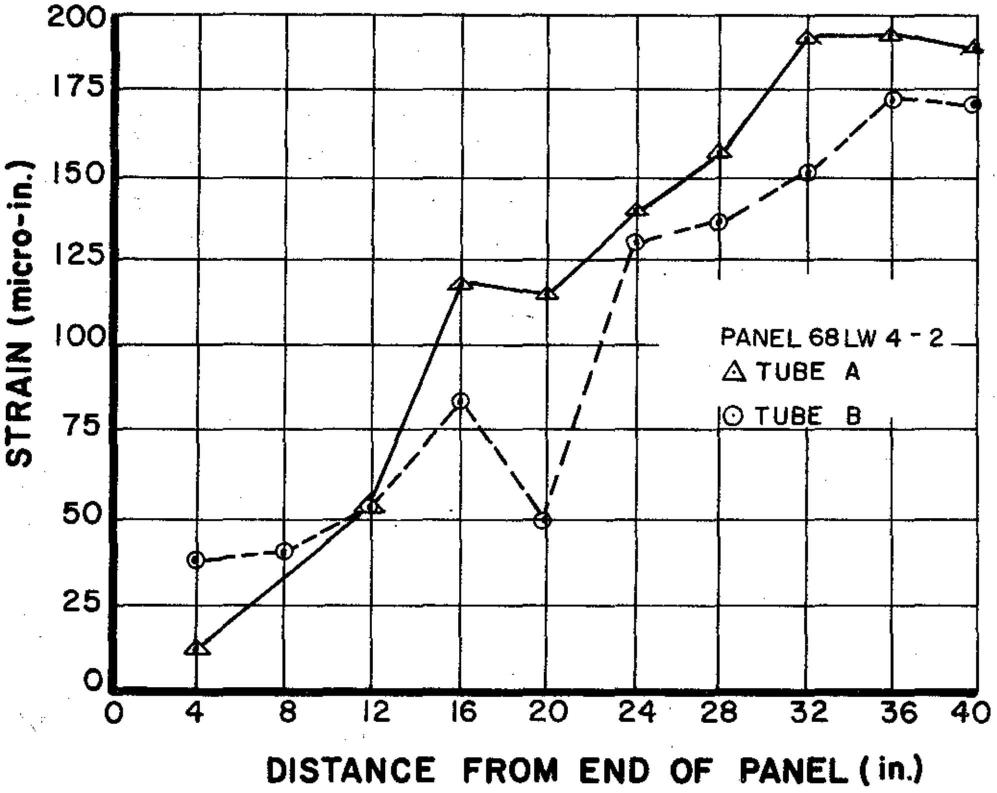


FIGURE 16. STRAIN VS. DISTANCE FROM END OF PANEL FOR SPECIMEN 68 LW4-2

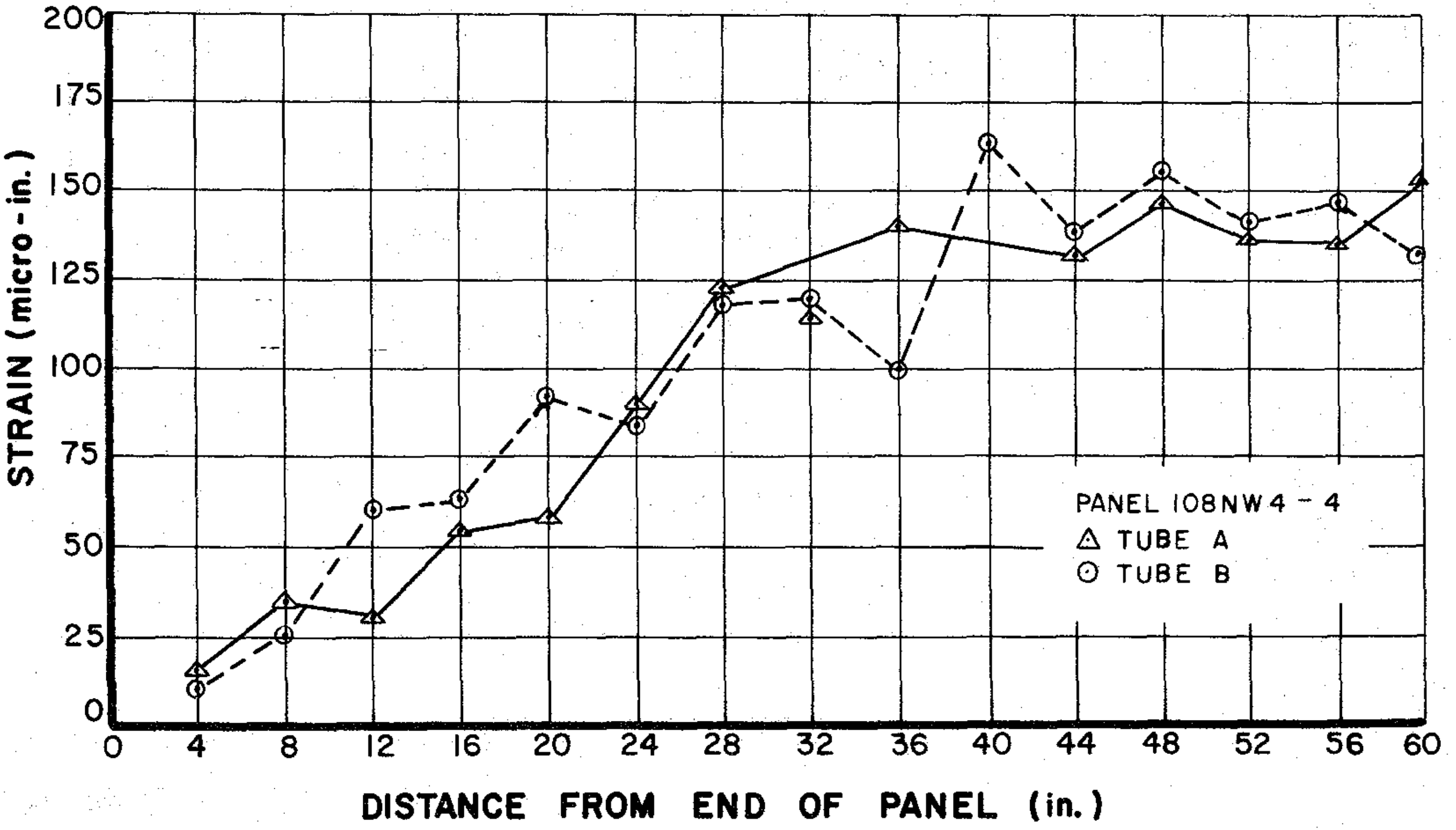


FIGURE 17. STRAIN VS. DISTANCE FROM END OF PANEL FOR SPECIMEN 108 NW4-4

TABLE 2. DEVELOPMENT LENGTH OF STRANDS

Panel Designation	Development Length (in.)
68 LW3-1	22.0
3-2	24.0
3-3	28.0
3-4	22.0
68 NW3-1	20.0
3-2	24.0
3-3	18.0
3-4	20.0
68 LW4-1	32.0
4-2	34.0
4-3	32.0
4-4	32.0
68 NW4-1	34.0
4-2	34.0
4-3	34.0
4-4	32.0
108 NW4-1	36.0
4-2	34.0
4-3	40.0
4-4	38.0

TABLE 3. AVERAGE DEVELOPMENT LENGTH OF STRANDS

Panel Description	Average Development Length
All 68 LW3- specimens	24.0
All 68 NW3- specimens	20.0
All 68 LW4- specimens	32.0
All 68 NW4- specimens	33.0
All 108 NW4- specimens	37.0
All specimens with 3/8 in. strands	22.0
All specimens with 1/2 in. strands	34.0

used to distinguish gages in one tube from those in the other. Gages were numbered consecutively from 1 to 10, starting with the gage nearest the end of the panel. For this specimen, all ten gages in each instrumentation tube were functioning throughout the test program. Up to three gages were lost in some panels. Reasons for the losses are not known, but it is believed that either breaks in lead wires or failure of waterproofing caused the trouble. No readings from malfunctioning gages are shown in the plots for determining development lengths or for variations in strain vs. loading cycles.

Early in the program it was noted that after cycling began, there was a pronounced increase in strains recorded from every gage over the first two hundred to four hundred thousand cycles, at which point all readings began to drop and continued to do so for another several hundred thousand cycles, leveling off again at about one half million cycles. This pattern is shown in Figs. 18 through 22 for specimen 68 NW4-2.

The uniform change in all gage readings suggested a temperature effect not compensated by the circuitry used with the instrumentation. A check was made to determine the effect that change of temperature of a panel had on gage readings. An instrumented panel was subjected to several known temperature changes. The results indicated that an increase in temperature caused an increase in strain reading, while a decrease in temperature caused a reduction in strain reading. With the direction of change known, it was decided to monitor the surface temperature of specimen 68 NW4-2 during testing. A thermometer with

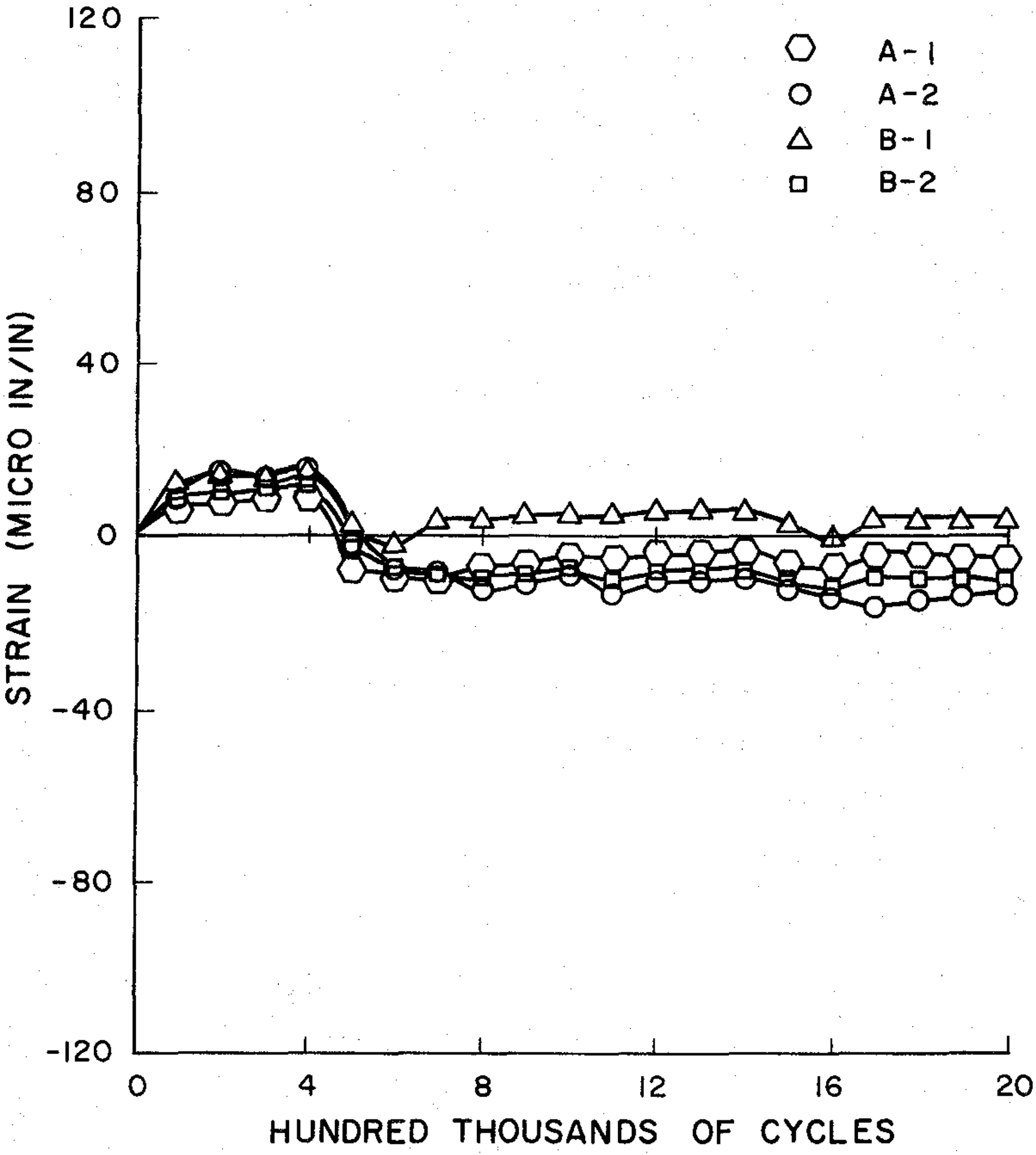


FIG. 18 PANEL 68NW4-2
STRAIN VS. NO. CYCLES

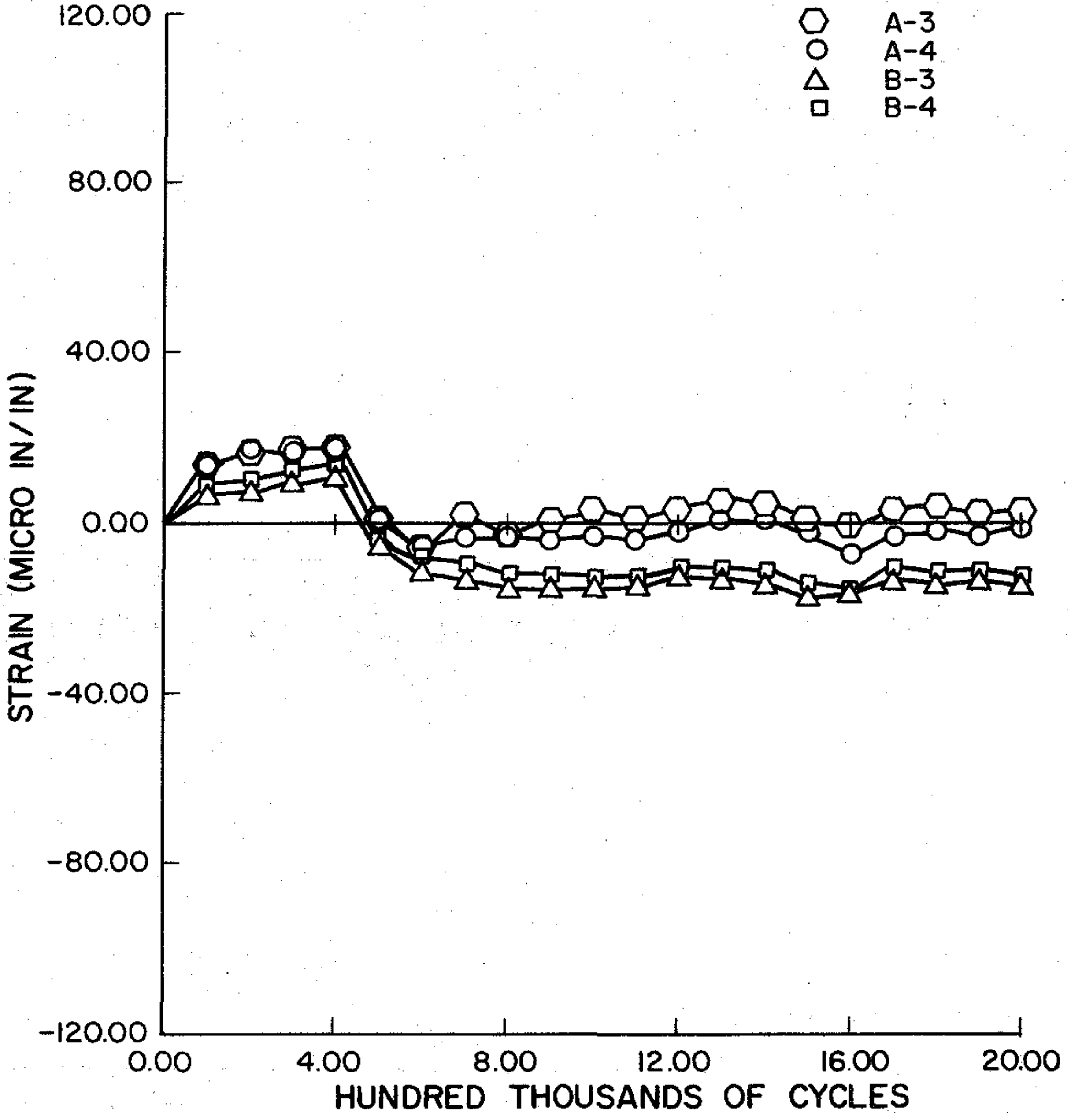


FIG. 19 PANEL 68NW4-2
STRAIN VS. NO CYCLES

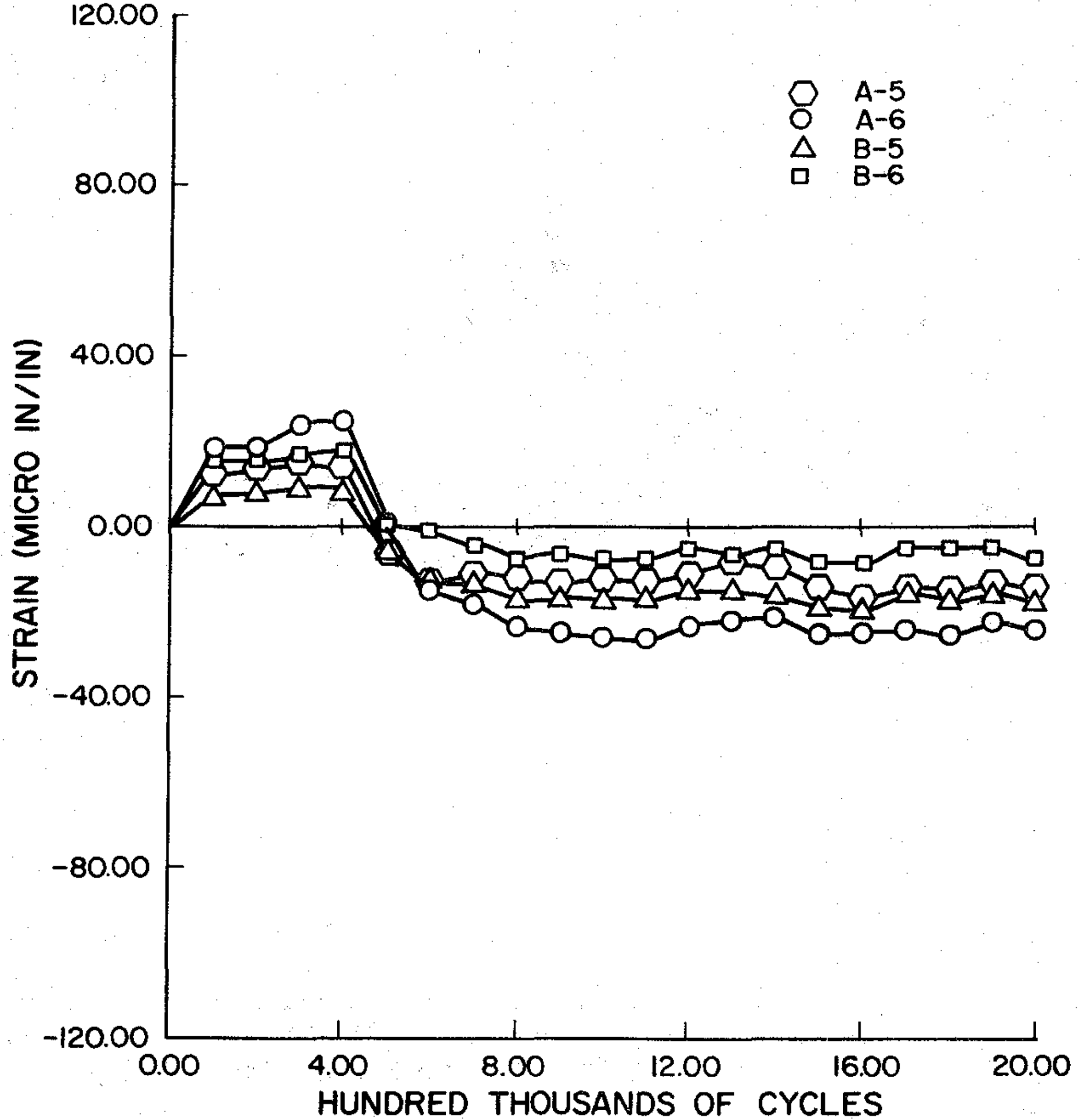


FIG. 20 PANEL 68NW4-2
STRAIN VS. NO. CYCLES

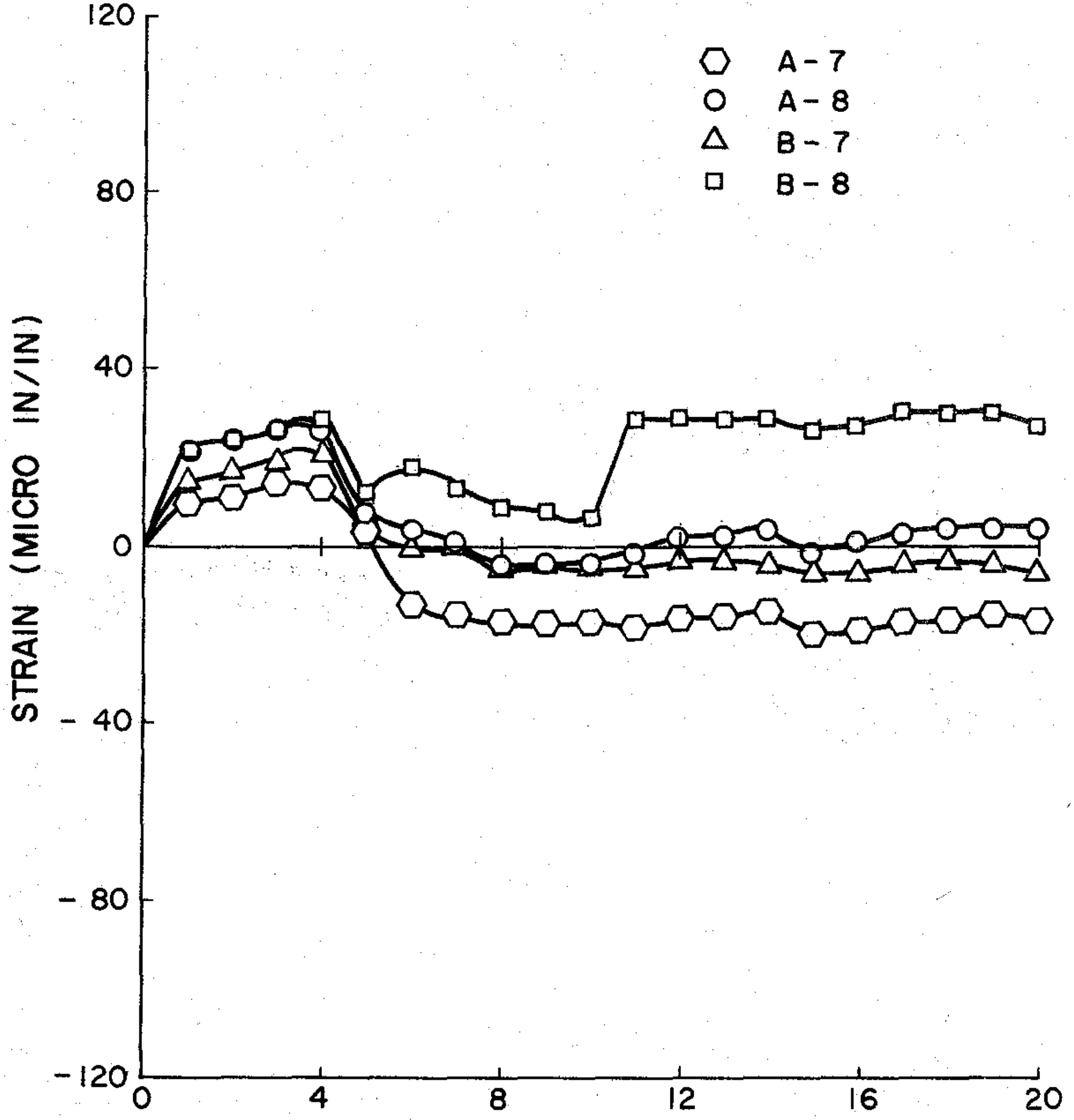


FIG. 21 PANEL 68NW4-2
STRAIN VS. NO. CYCLES

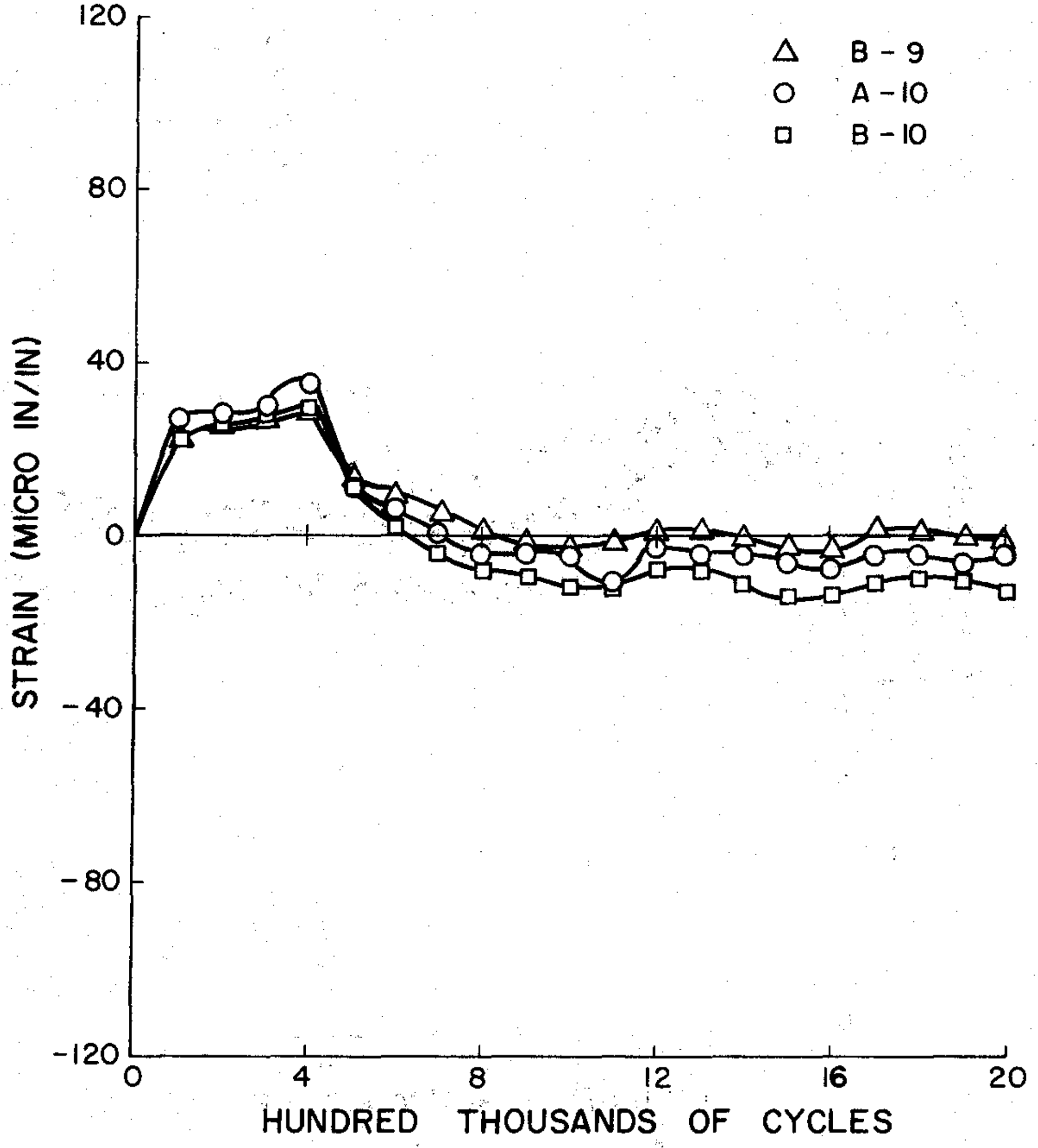


FIG. 22 PANEL 68NW4-2
STRAIN VS. NO. CYCLES

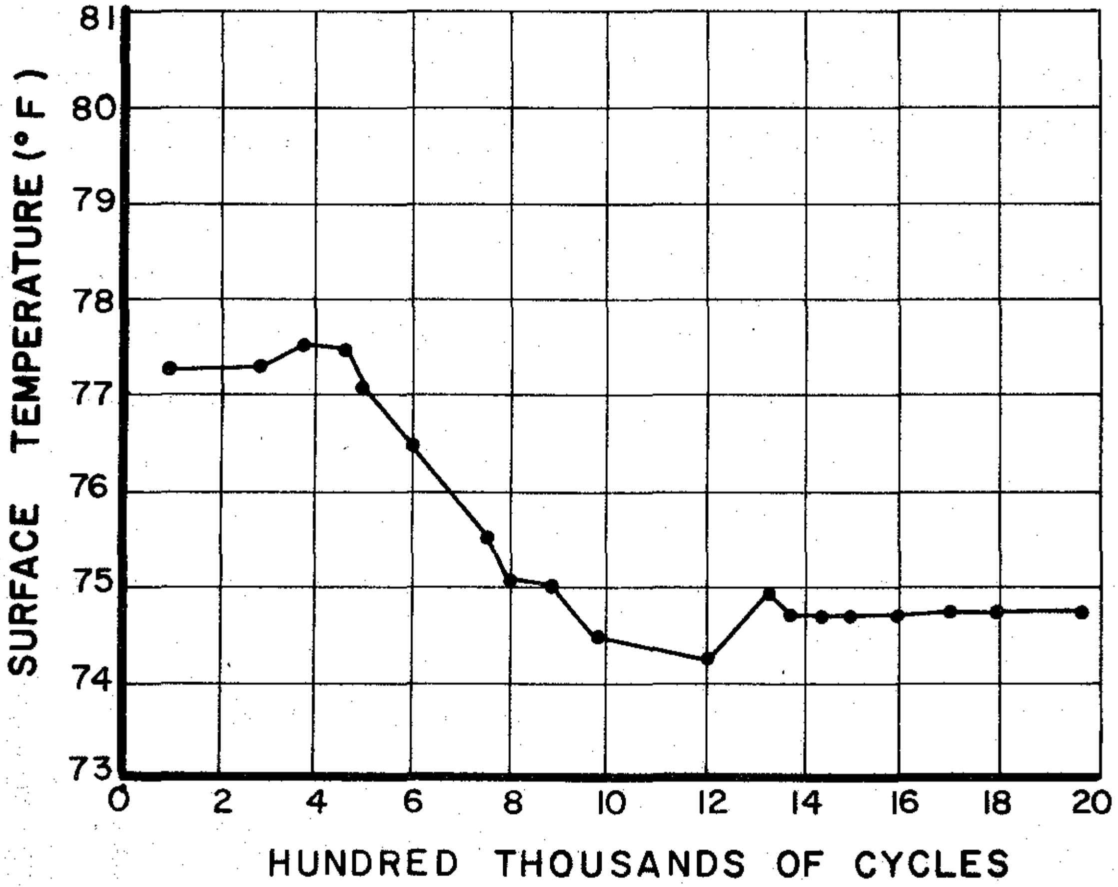


FIGURE 23. SURFACE TEMPERATURE VS. NUMBER OF CYCLES FOR SPECIMEN 68 NW4-2. AMBIENT TEMPERATURE EQUAL TO 77° F.

one degree Fahrenheit divisions, and estimable to a quarter of a degree, was placed on the top face of the panel, approximately 6 in. from midspan toward the uninstrumented end. It was secured to the concrete surface with a waterproofing compound and then covered with a block of styrofoam to give added insulation from variations in room temperature. Periodic temperature readings were taken throughout the test, and the resulting temperature record is presented graphically in Fig. 23. A comparison of the fluctuations in temperature with the trends of change in gage readings shown in Figs. 18 through 22 show strong correlation.

On the basis of the test of specimen 68 NW4-2 it was decided that the cause in variation of strain readings was a result of temperature changes in the specimen due to cyclic loading and not the result of slip of the prestressing strands. Rather violent fluctuations in strain reading were occasionally observed in some of the test specimens, but subsequently proved to be the result of malfunctions in instrumentation rather than the result of strand slippage.

Machine load vs. midspan panel deflection tests were run at five hundred thousand cycle intervals to determine if any significant loss in panel stiffness occurred as a result of cyclic loading. The test consisted of incrementation of a static load sufficient to cause a .005 in. increment in deflection, up to a total deflection of .025 in. for normal weight concrete specimens and .035 in. for light weight specimens. The resulting load-deflection data was plotted and the slope of the line obtained before cyclic loading began was compared with the slopes of the lines taken at 1 and 2 million cycles. A decrease in slope indicates a reduction in the bending resistance of the panel. The reduction in stiffness for the 15 panels tested ranged from 3 to 14%, with the latter value obtained for specimen 68 LW4-1. The load-deflection plots for this specimen are shown in Fig. 24.

V. DISCUSSION OF RESULTS

The results of this testing program indicate that cyclic loading which induces bending stresses no larger than usual static design stress levels had negligible effect on the development length of prestressing strands in panels of the type tested. Negligible loss of panel stiffness occurred as a result of cyclic loading.

Tables 2 and 3 summarize the initial strand development lengths found in this study. An average length of 22 in. was required by specimens containing 3/8 in. diameter strands, while 34 in. was the average distance needed to develop strands of 1/2 in. diameter. Prior research[5] has shown that the development length required for 7-wire strand is dependent on several factors, some of the more important being, (1) surface condition of strand, (2) method of releasing prestress force, (3) initial stress in strand before release, and (4) strand size. The surface condition of strands used in commercial yards varies widely, and the degree of rusting and surface roughness varies with the conditions and length of storage prior to use. A review of the studies cited in the list of references indicates that rusted strands require shorter development lengths. The method of releasing the prestress force has a pronounced effect on strand development length. Flame cutting of the strands produces a sudden release

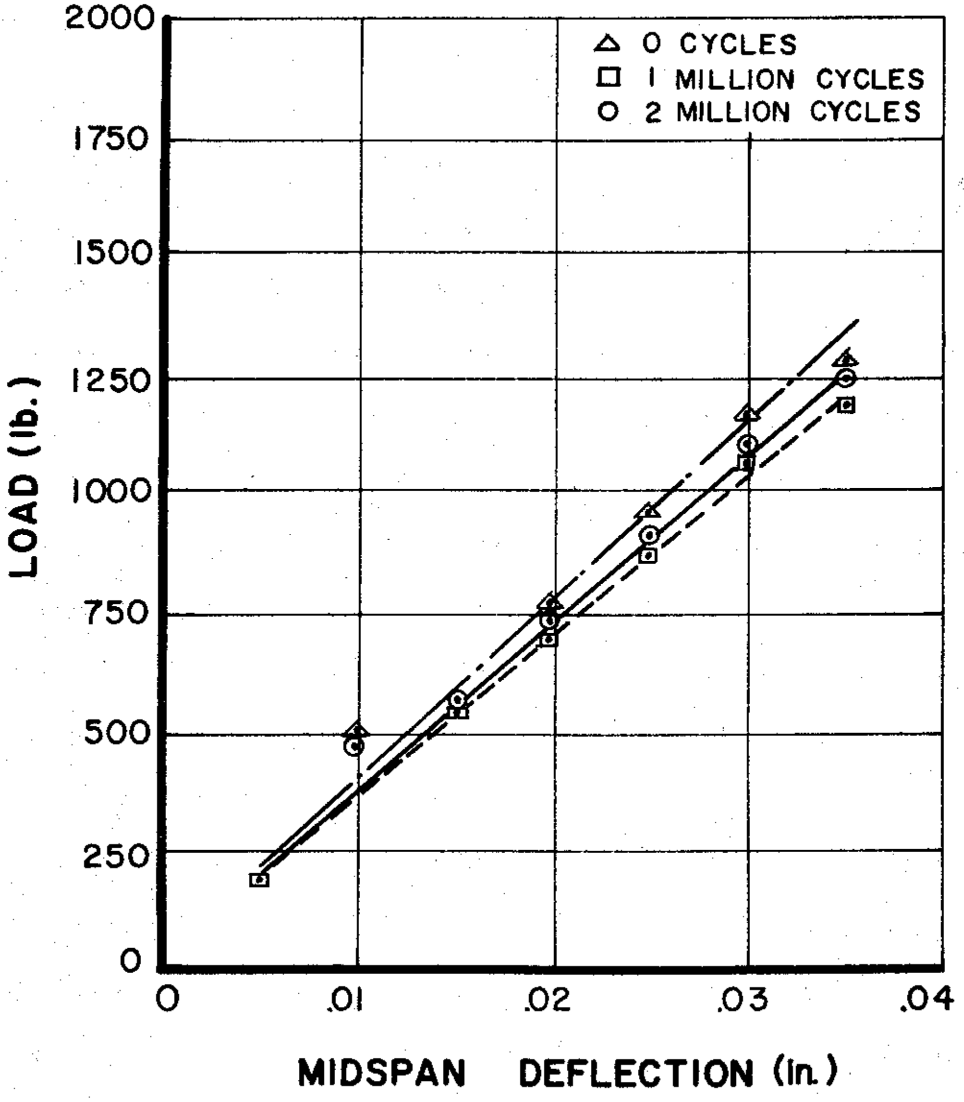


FIGURE 24. LOAD VS. MIDSPAN DEFLECTION FOR
SPECIMEN 68 LW4-1

of force and results in longer development lengths for strands, while a gradual release, by slowly reducing the jacking force used to stress the strands, results in shorter lengths. The magnitude of this effect can be observed for one study by Kaar, et.al.,[4] in the summarized data contained in Table 4. In the Kaar tests direct comparisons were made between development lengths of strands in either end of specimens for which release at one end was by flame cutting. Little study has been devoted to the influence of initial prestress force on the development length of strands of given size, although one investigation[4] has found that development length is approximately proportional to initial force.

Table 4 cites some other tests conducted to determine development length required for different sizes of strand under various conditions. It is apparent that there is considerable variation in reported development lengths. Even in tests where significant factors were essentially the same, a sizeable variation was observed (compare, for example, the tests of references 2 and 4 in Table 4). The development lengths found in this study; 22 in. average for 3/8 in. diameter strands and 34 in. for 1/2 in. diameter strands, are toward the upper range of values reported in other tests.

The development length of 32 to 33 in. for all 68 in. long test specimens with 1/2 in. diameter strands as compared with 37 in. for 1/2 in. strands in the 108 in. long panels raises the possibility that in the shorter panels, slip of the strand occurred along the entire length of the strand. If significant slip in the shorter panels

TABLE 4. SUMMARY OF DEVELOPMENT LENGTHS FROM OTHER STUDIES

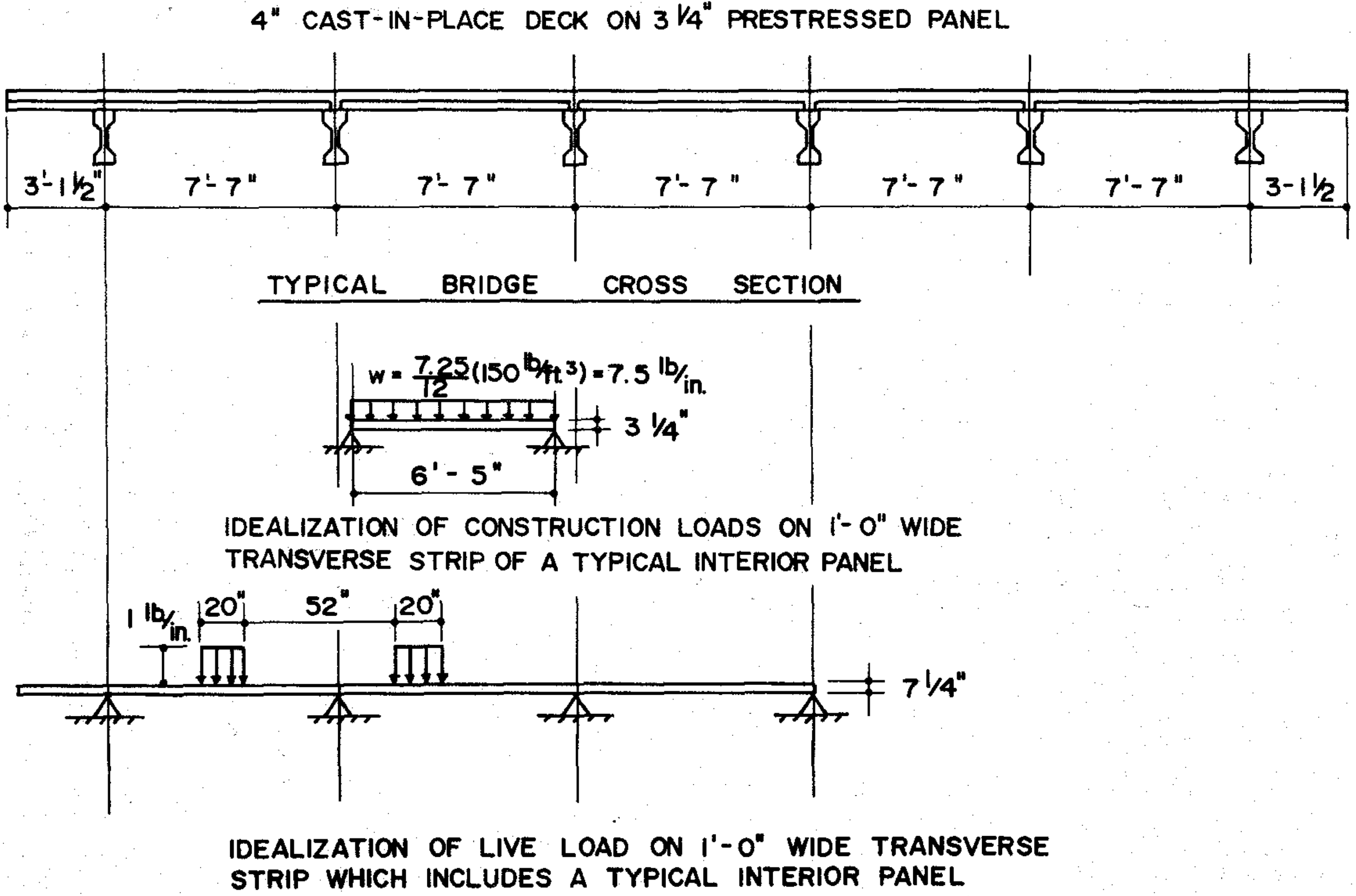
Reference	7 Wire Strand Diameter (in.)	Initial Prestress Force (kips)	Strand Surface Condition	Concrete Strength (psi)	No. of Specimens	Method of Release	Average Development Length (in.)
Over & Au[6]	3/8	12.8	clean, nonrusted	4200	not stated	not stated	30
	1/2	24.4	clean, nonrusted	5500	not stated	not stated	35
Kaar, LaFraugh & Mass[4]	3/8	15.0	clean, nonrusted	varied from** 1700 to 5000	6	flame-cut "dead" end*	23
	3/8	15.0	clean, nonrusted	varied from** 1700 to 5000	6	flame-cut "cut" end*	27
	1/2	25.0	clean, nonrusted	varied from** 1700 to 5000	10	flame-cut "dead" end*	35
	1/2	25.0	clean, nonrusted	varied from** 1700 to 5000	10	flame-cut "cut" end	42
Hanson[2]	1/2	24.0	clean, nonrusted	5000	1	flame-cut "dead" end	22
	1/2	24.0	clean, nonrusted	5000	1	flame-cut "cut" end	26
Preston[7]	1/2	25.0	clean & bright	4200	2	not stated	30
	1/2	29.0	clean & bright	4100	2	not stated	30
	1/2	29.0	medium coat of rust	4100	2	not stated	20
George[1]	3/8	14.0	not stated	4000 to 5000	6	not stated	10

**Results of these tests showed concrete strength to have little effect on transfer length.

had occurred, a substantially lower level of concrete stress, and hence strain, would be expected at the midspan of the shorter panels than at the center of the 108 in. panels. From the plots of compression strain in the panel vs. the distance from the end of the panel, no such trend was observed. Thus, it appears that for the shorter panels, only a few inches near midspan received the full prestress force.

The effect of the reduced level of precompression in the strand development zone can be examined by investigating the bending stresses in a panel from a typical bridge caused by both construction and vehicular loads. One such bridge is that of the Texas Highway Department crossing the Nueces River on U. S. Highway 90 in Uvalde County, Texas. This bridge consists of five prestressed concrete beams spaced laterally at 7 ft-7 in. centers and with an 80 ft-0 in. span. The prestressed panels are 3-1/4 in. thick, have a clear span between beams of 6 ft-5 in. and are designed for a 990 psi compression stress after losses. The bridge has a 4 in. thick cast-in-place deck, as seen in the section in Fig. 25.

The stresses in the panel can be estimated by considering a one foot wide transverse strip cut from the bridge and computing the bending moments acting on this strip as a result of the loads. During construction, the panel acts as a simply supported beam, carrying its own weight plus the weight of the 4 in. thick cast-in-place deck. This condition gives the uniformly distributed load of 7.5 lb/in. shown in Fig. 25. The one foot wide strip with a composite section of prestressed panel and cast-in-place slab is designed to sustain



TYPICAL BRIDGE CROSS SECTION

IDEALIZATION OF CONSTRUCTION LOADS ON 1'-0" WIDE TRANSVERSE STRIP OF A TYPICAL INTERIOR PANEL

IDEALIZATION OF LIVE LOAD ON 1'-0" WIDE TRANSVERSE STRIP WHICH INCLUDES A TYPICAL INTERIOR PANEL

FIGURE 25. IDEALIZATION OF ONE FOOT WIDE TRANSVERSE STRIP FROM BRIDGE

a positive moment at midspan computed from[10]

$$M = 0.8\ ((S + 2)/32)\ P \cdot I \qquad (1)$$

where S is the clear span, P is the wheel load from the rear axle of an HS20 truck and I is a factor to account for impact. Taking S as 6.43 ft, P equal to 16,000 lbs and I as 1.30 gives a midspan moment of 52,600 in.-lb/ft. The maximum value of positive moment at points in the strand development zone rather than at midspan are of interest here, and were obtained from the idealization shown in Fig. 25. The transverse strip was assumed to act as a beam continuous over four supports and carrying a portion of the wheel loads from the rear axle of an HS20 truck. The wheels are assumed to transmit load over two 20 in. segments that are 6 ft-0 in. apart, center-to-center. More than a single one foot wide strip is effective in transmitting wheel loads laterally to the beams and taking 16,000 lbs as evenly distributed over a 20 in. segment would overestimate the bending moments that are produced. Therefore, for this analysis, a uniformly distributed unit load of 1 lb per in. was assumed, and an envelope of maximum positive moment for the center span of the three span idealization was produced by moving the block loading arrangement across it. At any point along the span, the ordinate of this curve (see Fig. 27) gives the value of the largest positive moment that occurs at that point. The unit load envelope was then scaled so that the maximum positive moment at midspan was equal to that given by Equation (1). This envelope is shown at the bottom of Fig. 27.

A comparison can now be made between the bending moment at points in the strand development zone produced by the loads, and the bending moment required to produce a specified stress at the bottom face of the prestressed panel at that point. Considering first the case of moments caused by construction loads, the moment at points along the panel due to the uniformly distributed load of 7.5 lb/in. have been plotted in Fig. 26. Taking the maximum permitted stress in the prestressed panel as zero,[10] the moment required to produce this stress at any point a distance x from the left end of the panel is given by

$$M = -2h_P^2 \cdot s_P \qquad (2)$$

where s_P is the precompression stress, given by;

$$s_P = \begin{cases} -990\ x/L_d & ;\ 0 \leq x \leq L_d \\ -990 & ;\ L_d \leq x \leq L-L_d \\ -990\ (L-x)/(L-L_d) & ;\ L-L_d \leq x \leq L \end{cases} \qquad (3)$$

L equals 77 in., the clear span of the panel and h_P equals the 3-1/4 in. panel thickness. Equation (3) assumes a linear variation of precompression stress over the development zone, which is in agreement with the results of these tests (refer to Figs. 13 through 17). The two dotted curves shown in Fig. 26 are plots of Equation (2), using L_d equal to 22 in. for 3/8 in. diameter strands and 34 in. for 1/2 in. diameter strands. A comparison of the bending moment required to bring the maximum stress in the panel to zero with the moment produced by the construction load indicates that at all points along the panel, there is a considerable margin of safety against overstress.

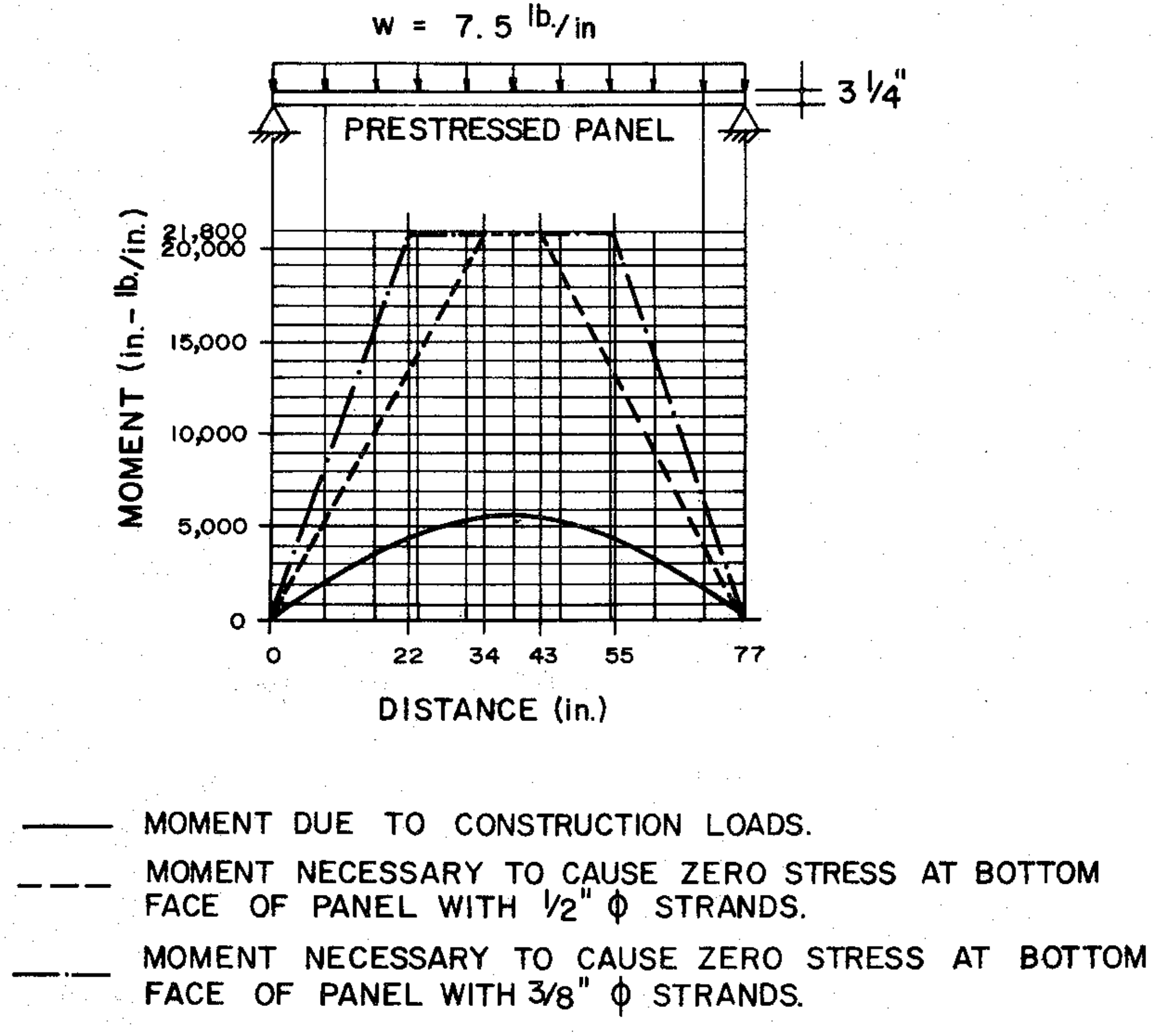


FIGURE 26. PRESTRESS AND CONSTRUCTION LOAD MOMENTS ON SIMPLY SUPPORTED PANEL

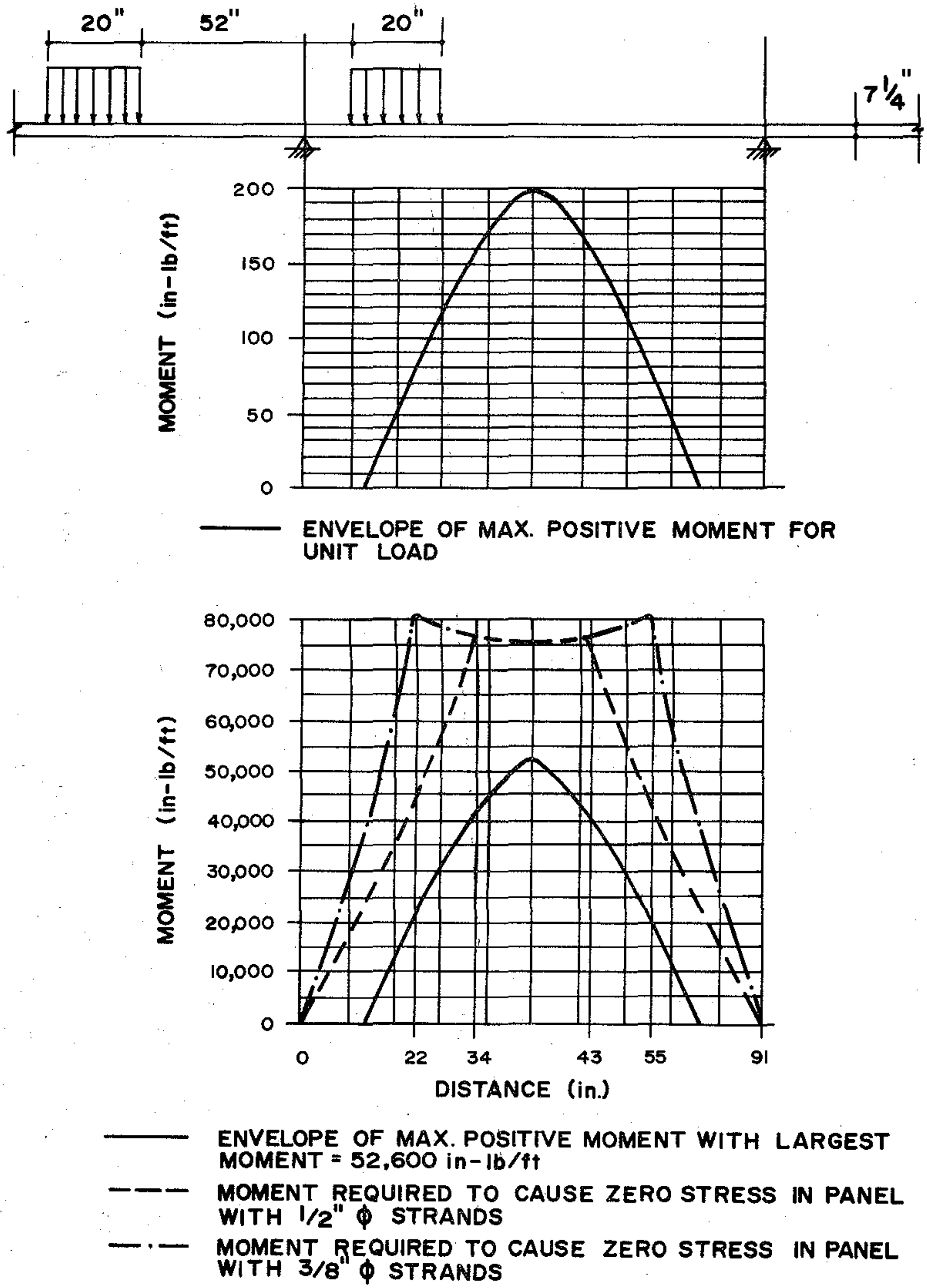


FIGURE 27. PRESTRESS AND WHEEL LOAD MOMENTS FOR TRANSVERSE STRIP

The same comparison between moment required to cause a maximum stress of zero in the prestressed panel and that produced by the loads has been made in Fig. 27 for the case of wheel loads being carried by a one foot wide transverse strip with a composite section consisting of the panel plus the 4 in. thick cast-in-place deck. The solid curve shown is the envelope of maximum positive moments scaled so that the midspan moment coincides with the value given by Equation (1). For the composite cross section, the bending moment required to produce a zero stress in the bottom face of the panel at a point a distance x from the left end of the center span is given by

$$M = [-s_p + M_d/2h_p^2]\ 2h_c^2 \tag{4}$$

where s_p is given by Equation (3) with L equal to 91 in., the center-to-center spacing of the beams, M_d is the moment due to the 7.5 lb/in. distributed load and h_c equals 7-1/4 in., the thickness of the composite section. The two dotted curves in Fig. 27 are plots of Equation (4) for L_d equal to 22 in. and 34 in. A comparison of the bending moment curves of Fig. 27 shows that the wheel loads will produce no tensile stresses in the panel.

CONCLUSIONS

The prestressed concrete panel, as a separate structural element, performs well under cyclic loading at a low stress level. From the 15 panels tested, no evidence of slippage of prestressing strand was found after 2 million cycles of midspan load.

In regard to the development length of strands in these panels, it was found that:

1. The type of concrete used, i.e., either normal weight or lightweight has little effect on development length.
2. For the 20 panels, some being lightweight and others normal weight concrete, an average of 22.0 in. of development length was necessary for 3/8 in. diameter 7-wire strands stressed to an initial stress of 162 ksi. An average length of 34 in. was found for 1/2 in. diameter strands, stresses to an initial stress of 180 ksi.

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