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PROBABLE FATIGUE LIFE
OF
PRESTRESSED CONCRETE BEAMS

PART I: BEAM TESTS

by

R. F. Warner

C. L. Hulsbos

Part of an Investigation Sponsored by:

Pennsylvania Department of Highways
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SYNOPSIS

An investigation was conducted into the fatigue life of pretensioned prestressed concrete flexural members failing by fatigue of the prestressing steel. The work consisted of a series of static and fatigue tests on prestressed concrete beams, an experimental study of the fatigue properties of 7/16-inch diameter seven-wire prestressing strand, and a theoretical analysis of the stresses and deformations in prestressed concrete members subjected to repeated flexural loadings. The results of the study of the strand fatigue properties, together with the theoretical analysis, provide a method for estimating probable

fatigue life of beams subjected to repeated loadings of either constant or varied magnitude.

The investigation will be described in four parts. In this first part, static and fatigue tests on eight prestressed concrete beams of rectangular section are reported. The prime purposes of these tests were to provide detailed information on the behavior of flexural members under repeated loadings and to obtain test data to check the accuracy of the method presented in succeeding parts for estimating beam fatigue life.

INTRODUCTION

When prestressed concrete was introduced as a new method of construction, the possibility of its having poor fatigue properties was a matter of concern to many engineers. A number of beam fatigue tests were therefore conducted in Europe(1,2,3) and later in the United States(4,5). Although these initial investigations were little more than acceptance tests, they indicated that fatigue failure would not be a practical problem provided that the repeated loadings do not cause cracking of the concrete. Since this condition was realized in the designs at that time, interest in fatigue failure declined and subsequent work has not been sufficiently extensive to provide answers to the many questions concerning the effects of fatigue loading.

Unfortunately, the lack of information on the fatigue resistance of prestressed concrete members has made necessary the retention in design specifications of the stipulation of no cracking under load. This in turn places restrictions on possible improvements and refinements to design procedures. At present, for example, the economic use of partial prestressing techniques is often impossible because of code limitations on allowable bottom fiber concrete stresses.

Before current code requirements can be changed, additional information must be obtained on the behavior of prestressed concrete under fatigue loading. Knowledge of fatigue failure - which until recently was almost completely contained in the negative statement that fatigue failure will not occur if the loads do not cause cracking - must obviously be broadened to allow quantitative estimates to be made of fatigue life and safety under general loading conditions.

The possible modes of failure in fatigue of prestressed concrete flexural members are comparable in some ways to the corresponding modes of failure under static loading. Thus, beams may be described as "under-reinforced", "over-reinforced", or "balanced", depending upon whether the primary failure takes place in the steel, in the concrete, or in the two materials more or less simultaneously. It should be noted that an under-reinforced beam with respect to fatigue failure is not necessarily under-reinforced from the point of view of static ultimate strength.

In certain circumstances it may be possible also for a progressive bond failure to occur along the length of the beam as a result of fatigue loading. Bond-fatigue failure, like bond failure under static loading, will occur only in regions where relatively steep moment gradients exist; it is therefore unlikely in flexural members in which the moment-to-shear ratio is large, and is more conveniently treated in association with a study of shear failure. In dealing with the basic modes of fatigue failure in flexure, attention may therefore be restricted to fatigue in the tension steel and in the concrete compression region.

In 1958, a bibliography and review of research on concrete fatigue was published(6) which indicates that earlier studies of fatigue failure in prestressed concrete beams have consisted, in the main, of small experimental programs of beam fatigue tests. Because of the isolated nature of this work, the conclusions have often been limited to the performance of a particular type of beam under a particular condition of loading.

Probably the most significant conclusion which can be drawn from previous experimental work is that if a fatigue failure occurs in a beam of normal design it is likely to be due to a fatigue failure of the prestressing strand. A shear fatigue failure is the next most common type of failure reported in the literature.

Previous research into fatigue failure of prestressed concrete beams has been restricted to the rather idealized situation of constant cycle repeated loadings. In practice, it is far more usual for successive loadings to differ in magnitude. Consequently, a typical load history consists of a number of different loads each with a different frequency of occurrence. Studies of the fatigue properties of prestressed concrete members under varied loading patterns have not previously been made, and important practical questions concerning the effect on fatigue life of a relatively small number of high overloads regularly mixed with the design loadings have not been answered.

An investigation of the fatigue life of prestressed concrete beams failing by fatigue of the prestressing steel is described in this and three succeeding papers. From an experimental study of the fatigue properties of prestressing strand and a theoretical analysis of the stresses and deformations in a concrete flexural member under repeated loadings, a method is developed for estimating the fatigue life of beams subjected to either constant-cycle or varied repeated loadings. In addition, results are given of static and fatigue tests conducted on eight prestressed concrete beams of rectangular section. The prime purpose of the beam tests was to obtain experimental data to check the accuracy of the method developed for predicting beam fatigue life. The beam tests are described in this part of this four part paper.

Two beams were tested to failure statically, three were tested in fatigue under constant cycle loading, and three were tested in fatigue with varied repeated loading. Beam fatigue test data from previous investigations provide very little quantitative information on behavior under repeated loadings and so in this investigation particular attention was given to measurements of beam deflections and concrete deformations. Fatigue loading was in all cases continued beyond the first wire failures to determine also the post-failure behavior of the beams.

NOTATION

b	width of beam
d	effective depth of beam
f'_c	ultimate strength of the concrete
F_{se}	prestressing force in test beam just prior to first load cycle
h	full depth of concrete section
M_{ol}	cracking moment in first load cycle
M_{ult}	static ultimate moment of beam
N	number of cycles
p	reinforcement ratio; $p = \frac{A_s}{bd}$
$\Delta\epsilon_c$	inelastic concrete strain at the steel level due to creep and shrinkage
ϵ_{ce}	elastic concrete strain at the steel level due to prestressing force F_{se}
ϵ_{se}	steel strain corresponding to prestressing force F_{se}
ϵ_{si}	steel strain corresponding to initial prestressing force F_{si}
$\Delta\epsilon_{su}$	strain increment at the cracked section corresponding to M_{ult}
ϵ'_u	concrete top fiber strain at M_{ult}

TEST SPECIMENS

The eight test beams were all twelve feet long, with a rectangular cross section approximately six inches wide and twelve inches deep. The longitudinal reinforcement consisted of three 7/16-inch diameter prestressing strands placed at the depth of eight inches below the top surface of the beam. In the first four beams manufactured, the nominal effective prestressing force in the strand was 60 percent of its static strength; in the other four beams the nominal value was 40 percent. The specimens were thus divided into two groups of four: F1 through F4, and F5 through F8. Apart from static tests to failure on one specimen from each group, the beams in the first group were used for the constant cycle fatigue tests, those in the second for the cumulative damage tests.

Full details of the specimens are contained in Fig. 1 and Table 1. Actual dimensions of the beams given in Table 1 vary slightly from the nominal values. The effective prestressing forces, shown as F_{se} in Table 1, also differ somewhat from the nominal values because of variability of creep and shrinkage effects in the concrete. Strains in the steel due to initial and effective prestressing forces, ϵ_{si} and ϵ_{se}, are shown in Table 1 together with elastic and creep strains in the concrete at the steel level, ϵ_{ce} and $\Delta\epsilon_c$. Since it was impossible to test all the beams at the same time, the effect of variations in age was minimized by commencing the tests approximately 150 days after manufacture of the specimens. Actual ages at time of commencement of test are shown in Table 4.

Six two-leg stirrups of 3/4-inch intermediate grade reinforcing bar were placed in the end regions of each beam at six inch spacings, as shown in Fig. 1.

Materials

The concrete used in the beams was made from 3/4-inch maximum size crushed limestone, Lehigh river sand, and type III, high early strength Portland Cement. Sieve analyses of the aggregates are shown as grading curves in Fig. 2. The fineness modulus of the sand was 2.65. The specific gravities of sand and coarse aggregate were 2.65 and 2.69, respectively.

The same nominal concrete mix was used throughout, although slight changes were made in the water content of different mixes to adjust for variations in the moisture content of the sand. An attempt was made to keep the slump at approximately two inches. The concrete was mixed in six cubic foot batches in a horizontal drum, positive action mixer for three minutes and then transported in buggies to the prestressing bed. Five batches of concrete were used in the manufacture of each group of four beams.

In Table 2, details are given of the mix quantities and the regions in the test beams were the different batches were used. In order to obtain greater uniformity, concrete from only one batch was placed in the test region of each beam. Results of static tests conducted at the time of the beam tests on three cylinders from each batch are also contained in Table 2.

The strand reinforcement used in the experimental work of this investigation was obtained in two lots from one manufacturer. They were purchased as typical samples of seven-wire prestressing strand and had gone through the normal manufacturing processes of extrusion, cold drawing, spinning, and stress relieving. Lot I was used in the manufacture of the test beams and also for a small number of static and fatigue tests to determine its properties; the strand in Lot II was used in the experimental study of strand fatigue properties which will be described in Part II. The results of four static ultimate strength tests conducted on specimens from Lot I are contained in Table 3, and a typical load-strain curve is shown in Fig. 3.

Manufacture of Test Beams

The beams were manufactured four at a time in a prestressing frame erected on the dynamic test bed in Fritz Engineering Laboratory. Three strands running the length of the frame were positioned and tensioned to the required initial prestressing force. Formwork and stirrups were assembled for four beams end to end along the strands, and the concrete was placed. After the concrete had set, the side forms were removed and the beam surfaces were prepared for deformation measurements. The concrete was then covered and kept moist. At an age of approximately five days the strand forces were gradually released and the strand between the beams was burned off close to the concrete. The beams were stored for thirty days at a temperature of approximately 70 degrees F. under wet burlap and moisture-proof plastic sheeting. After this initial period of curing they were stored in the laboratory at room temperature and humidity.

Measurement of Prestressing Force and Losses

During the prestressing operations the force in each strand was measured with dynamometers placed at both ends of the strands.

A ten inch gage length Whittemore deformeter was used to measure elastic, creep, and shrinkage strains on the sides of the beams. When the concrete had hardened, grids of small aluminum targets were cemented to both sides of the beams in the test region in the pattern shown in Fig. 4. The beams lay in an east-west direction during casting and testing and the regions covering the gage lengths for deformation measurements were labelled R1 to R6 as shown in Fig. 4. Grid points were placed at the steel level on the north and south sides of the beam in the six regions. Additional grid points were placed in Regions R3 and R4 at six different levels, as shown in Fig. 4, so that the vertical distribution of strain could also be measured. Elastic and inelastic strains in the concrete, obtained from deformeter readings made before and after release and during the curing process, were used to determine the elastic and inelastic concrete prestress losses. The same grid of points was used for deformation measurements during testing of the beams.

TEST PROCEDURE

All static and fatigue tests were conducted in the loading frame shown in Fig. 5. The beams were supported on a ten foot span with a pin support at one end and a rocker at the other. Two equal loads were applied symmetrically to the beams through steel distributor plates four inches wide and three-quarters of an inch thick which were grouted to the top surface of the concrete at sections three feet from each support. Two twenty-two kip capacity Amsler jacks with spherical seatings at each end were used to apply both the static and dynamic loadings.

Static ultimate strength tests were conducted on beams F3 and F6; beams F1, F2, and F4 were tested in fatigue with constant cycles of loading; beams F5, F7 and F8 were tested in fatigue with a varied pattern of loading.

Static Ultimate Strength Tests

For the static tests to failure, a pendulum dynamometer was connected to the loading jacks to deliver pressure and also to measure load.

Loads were applied to the beams in two kip increments. Concrete deformations were measured on the grid shown in Fig. 4 at each load increment; deflections were measured at the load points and at the centerline with Ames dial gages in contact with the lower surface of the test beam. As the loading became high, considerable creep occurred, and in order to obtain relatively steady readings a period of time was allowed to ellapse between the application of a load increment and the measurement of deformations and deflections. The loading was increased until failure took place.

Constant Cycle Fatigue Tests

An Amsler pulsator was used to apply varying pressure to the jacks during the beam fatigue tests. All constant cycle loading was applied at 250 cycles per minute.

Prior to the commencement of each fatigue test, two static tests were conducted on the beam to loads slightly higher than the maximum value to be used in the repeated load cycle. Fatigue loading was also interrupted at regular intervals in order to make additional static tests. Deformation and deflection measurements made during the static load tests indicated accurately the changes in the response of the beam which had occurred in the previous sequence of fatigue loading. Crack development was recorded in each static test during an inspection of the beam while under maximum load. The fatigue loading was continued, with interruptions only for static tests, until failure.

Ames dial gages were used to measure deflections during both the static and fatigue loading. When not in use the gages were taped down out of contact with the moving test beam. Extreme deflections under dynamic load were obtained by untaping the gage, holding the plunger, and allowing it to extend slowly upwards until it made contact with the lower surface of the test beam in its position of maximum deflection.

In order to preserve the centering of the jacks on the distributor plates and the beam on its supports, a minimum load of 4.5 kips per jack was always maintained on the beam. An attempt was made to obtain the same load cycle in all three constant cycle tests so that three replications would be obtained of the one fatigue test. A comparison of dynamic deflection readings with the load deflection curves obtained during the static tests provided an accurate measure of the actual loadings, including inertial effects, on the beams. Details of the applied loadings are contained in Table 4.*

Cumulative Damage Tests

The cumulative damage tests were conducted in the same manner as the constant cycle tests, except that the fatigue loading varied between a constant minimum level and three different maximum levels. In order to mix the three load cycles evenly and at the same time have a repeated loading pattern which could be followed by the fatigue equipment, the load cycles were arranged in blocks which were repeatedly applied to the beam until completion of the test. Each block contained a total of 30,000 load cycles. As shown in Fig. 6, the load block contained, in order, 18,000 repetitions of the smallest load cycle, 9000 repetitions of the intermediate load, and 3000 repetitions of the maximum load cycle. Since the size of one load block was always very small with respect to the fatigue life of the beam, an even distribution of the three different loadings throughout the loading history was obtained.

The cumulative damage tests were conducted using an Amsler pulsator. Since there was no programming arrangement on this equipment, all load changes were made manually. It was found that an experienced operator could change the loading from one level to the next within 200 cycles.

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* In succeeding parts of this paper, the following terminology will be used: The smallest most frequently occurring load will be referred to as the "design" or "predominant" loading P_{pred}; the larger loadings in the block will be referred to as "overloadings", P_{01}, P_{02} ---. This notation is used in Table 4.

Static tests to loads slightly higher than the maximum load cycle were conducted prior to, and interspersed through, the fatigue loading in the manner described for the constant cycle tests. A minimum loading of 3.8 kips per jack was maintained on the beams to preserve centering. The fatigue loading was applied to beams F7 and F8 at the rate of 250 cycles per minute, to beam F5 at 500 cycles per minute. Apart from the regular static tests, rest period of from four to six hours were introduced in each 24 hour period.

A comparison of dynamic readings with static load-deflection curves again provided an accurate measure of the loadings actually applied to the beams. An attempt was also made in these tests to obtain the same loadings on all three beams, but the initial theoretical estimate of the inertial loading effect for beam F5, tested at 500 cycles per minute, proved to be slightly inaccurate. The maximum load cycle applied to F5 was for this reason approximately 0.2 kips smaller than that used in F7 and F8. Values of the actual loadings are given in Table 4.

BEAM TEST RESULTS

Static Tests to Failure

Beams F3 and F6, which were tested statically, failed in a manner typical of under-reinforced beams by yielding of the steel and then crushing of the concrete in the compression fibers. Cracking moments M_{ol} and ultimate moments M_{ult} are given in Table 1.

The centerline deflections of the two beams are plotted against load in Fig. 7. In the higher load range, F6, which had the lower prestressing force, deflected considerably more than F3, although its ultimate load is actually slightly higher.

The crack patterns for the beams are shown in Figs. 8 and 9. Cracks were restricted almost entirely to the pure moment region. However, one inclined crack formed in the east shear span of each beam, but never at any time did shear failure appear likely. A strong tendency was observed in these tests, and also in the initial static tests conducted on the fatigue specimens, for the flexural cracks to follow a more or less vertical path to the level of the steel reinforcement, then to branch into two opposing inclined cracks. The tendency is clearly seen in the recorded crack patterns.

The observed crack development on the north and south sides were quite similar and concrete deformations at corresponding gage lengths on either side of the beams were nearly equal. Average top fiber concrete strains, extrapolated from the deformation readings in the Regions R3 and R4 are shown in Fig. 10. Maximum and minimum values of concrete deformations at the steel level were recorded in Regions R5 and R6 in beam F3, and in the Regions R3 and R1 in beam F6; they are plotted against load in Fig. 11. Since at least one crack had formed within every gage length in each beam tested statically, measured concrete deformations were distributed approximately linearly with respect to depth.

Beam Behavior under Fatigue Loading

Beam behavior under fatigue loading followed a common pattern in all six fatigue tests and will be described in terms of deflections, deformations, and cracking patterns. Beams F2 and F7 have been chosen as typical, and detailed data for only these beams are presented in this paper. Similar test data for the other beams are available in Reference 7.

Deflections increased quite considerably under fatigue loading, particularly in the early load cycles. Deflections observed during the periodic static tests on beams F2 and F7 are shown, together with dynamic deflections, in Figs. 12 and 13. In the figures, triangles are used to represent test points for the first static load cycle so that they will not be confused with test points for the second load cycle. Dynamic deflections are shown by dashed lines. The three dashed lines shown in Fig. 13 correspond to the three different maximum load levels used in the cumulative damage tests. In the constant cycle tests, where the fatigue loading was more severe, deflections continued to increase, though at a decreasing rate, until the failure of the first wire. In the cumulative damage tests there was a tendency for the deflections to settle down to steady values. During the test of beam F8 deflections actually began to decrease slightly after 600,000 cycles of loading.

Concrete deformations measured on the sides of the beams were greatly influenced by the presence or absence of flexural cracks. When there were no cracks in a particular gage section, tensile deformations tended to be very small, and were little influenced by fatigue loading. In beam F7, for example, cracks did not form in Region R3 and at a load of 10.5 kips the deformations at the steel level in this gage length were one-tenth of those in other regions, as is shown in Fig. 14. Also in beam F2, absence of cracks in Region R5 resulted in relatively low deformations, as shown in Fig. 15. In Fig. 16 the distributions of concrete deformations in beam F7 for the Regions R3 and R4 are plotted. Whereas the distribution is approximately linear for the section containing a flexural crack, there is a sharp discontinuity in the distribution below the neutral axis in Region R3 because of the absence of cracks in this section and the presence of cracks in adjacent sections. Concrete deformations at the steel level in the failure region at various stages of fatigue loading are shown in Figs. 17 and 18. Values for zero load have been obtained by extrapolation and are plotted as dashed lines. Average top fiber concrete compressive strains, measured in the failure region, are shown in Figs. 19 and 20. Again, values for zero load have also been obtained by extrapolation and are plotted as dashed lines.

The patterns of cracking which formed during the initial static tests were similar to those observed in the static ultimate tests. Although some extension of the existing cracks took place, particularly in the early load cycles, no new cracks formed in any of the beams as a result of repeated loadings. Most of the crack extension had taken place when approximately thirty thousand cycles of loading had been applied. Subsequent development was almost nil until after some wires had snapped. The cracking patterns for all beams are shown in Figs. 8 and 9.

It is thus seen that after a short initial period in which deflections, deformations, and crack heights increased considerably, the beams settled down to give a fairly consistent and constant response to load. This was particularly so for beams F5, 7, and 8, on which the fatigue loading was less severe. No prior indication was given in any of the beams of the imminence of wire fatigue failure.

The fracture of one of the wires of the seven-wire strand in the beam could always be detected by a distinctive sound, together with a small but sudden increase in maximum deflection and a slight fall-off in load. The region containing the wire failure was determined from the deformation readings taken in the next static test. After sudden increases in deflection and deformations which accompanied the initial wire failure, the beams again settled down with a consistent response to loading, but with slightly decreased rigidity. A considerable number of cycles often separated the first and second wire failures, but the interval separating successive failures tended to decrease as the number of failed wires increased. Thus the post-failure behavior of the beams consisted of an increasing rate of change in deflections, increased permanent set, and decreasing rigidity. When the wires began to fail in the beams the cracking patterns again began to extend. A tendency was noted for those cracks which had already become inclined during the initial static loading to take almost horizontal paths and link together to form a continuous pattern running through a considerable portion of the test section at a level a little below the neutral axis. This tendency was particularly pronounced in beam F1 and is recorded in the completed cracking pattern for that beam in Fig. 8. Fatigue loading was continued on F7 until so many wires had broken that the static strength of the specimen had been reduced to the value of the maximum applied dynamic load. This test was terminated when concrete crushing was observed in the top fibers of the beam. Another beam, F8, was tested statically to failure after 5 wires had snapped due to fatigue loading, its static ultimate strength is recorded in Table 1. The tests were continued on the other beams until four or five wires had failed.

Beam Fatigue Test Results

The results of the beam fatigue tests are recorded in Table 4. Values of the applied loading have been obtained by comparing dynamic deflections with the load-deflection curves obtained at regular intervals during the static tests, and are average values taken over the entire history of loading up to failure. The terms N_1, N_2, etc. in Table 4 refer to the number of load cycles at which the first, second, etc. wire failure took place.

CONCLUDING REMARKS

The beam fatigue tests have indicated that the response of a prestressed concrete beam may vary considerably as a result of fatigue loading. This variation is probably due to creep effects. Changes in the concrete stress-strain relations, and progressive bond failure between the tension steel and the surrounding concrete in the vicinity of the tensile cracks. Most of the variation in beam response, however, occurred in the very early loading cycles, and, after an initial sequence of repeated loadings representing perhaps ten percent of the fatigue life, the beam settled down to a fairly regular and consistent response to load.

When the fatigue loading was particularly severe, a continuous change in beam response may occur up to failure as shown by the test results of beams F1, F2, and F4. Such severe fatigue loading would rarely be encountered under field conditions, and in most cases it can probably be assumed that the beam response is constant.

Fatigue failure occurred by successive fractures of the individual wires of the strand. A considerable number of load cycles separated the first and second steel failures, but the interval separating successive failures tended to decrease as the number of failed elements increased. Failure of each steel element was accompanied by a corresponding decrease in beam rigidity.

When the total area of steel reinforcement is contained in a small number of elements, it is advisable to associate beam fatigue failure with failure of the first steel element. When there are a large number of steel elements present in the section, beam fatigue failure may better be defined arbitrarily as the failure of some proportion of the elements. The proportion would be chosen from a consideration of allowable decreases in beam rigidity and factor of safety against static load which could be allowed to occur as a result of the steel failures.

If the fatigue life of a prestressed concrete beam is governed by the fatigue life of the tension steel, it should be possible to estimate the beam fatigue life provided that information is available on the fatigue properties of the prestressing steel and that the steel stresses in the beam which result from the applied loading can be calculated.

The second of this series of papers will describe an experimental investigation into the fatigue properties of 7/16-inch diameter prestressing strand.

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TABLE 1 - PRESTRESSED CONCRETE TEST BEAM PROPERTIES

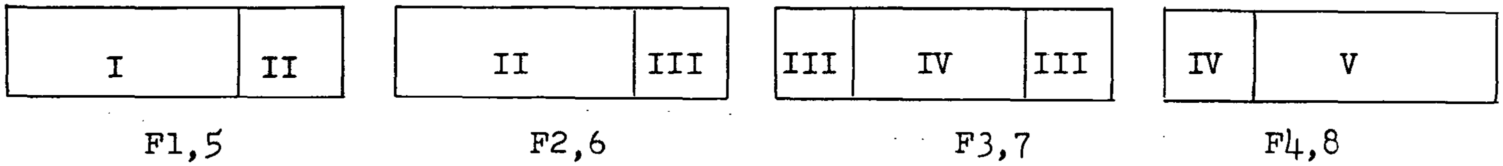
Beam	b (in.)	d (in.)	h (in.)	f'_c* (ksi)	p	ϵ_{si}	ϵ_{ce}	$\Delta\epsilon_c$	ϵ_{se}	F_{se} (kips)	M_{o1}	ϵ'_u	ϵ_{su}	Mult Static
F1	6.12	8.09	12.12	7.04	.00661	670	22	68	580	51.0	309.6			
2	6.06	8.09	12.12	7.21	.00669	670	23	71	576	50.6	308.0			
3	6.19	8.00	12.06	6.98	.00660	670	24	71	575	50.6	316.6	233	436	536.4
4	6.00	8.00	12.06	6.98	.00681	670	24	70	576	50.6	300.5			
F5	6.09	8.12	12.12	6.42	.00660	515	17	62	436	37.8	263.3			
6	6.19	8.00	12.06	6.88	.00660	510	16	63	431	37.5	257.5	264	605	545.4
7	6.31	8.00	12.06	6.22	.00648	500	16	70	414	35.6	248.4			
8	6.25	8.00	12.06	6.83	.00653	500	16	65	419	36.0	241.2			(503.0)

*Average f'_c in test section

Notes: All strains in in/in x 10^{-5}

All moments in in-kips

TABLE 2 - DETAILS OF CONCRETE MIXES



Concrete Batch Distribution

Beams	Batch	Cement lb.	Water lb.	Sand lb.	Gravel lb.	Slump in.	Static Strength of Cylinders at Time of Beam Tests			
							1	2	3	Mean f'_c
F1-4	I	148	66.5	386	386	2	7240	7360	6460	7020
	II	148	64.1	386	386	1-3/4	7090	7450	7150	7230
	III	148	64.8	386	386	2	6040	6310	6070	6140
	IV	148	65.2	386	386	2-1/2	6900	6915	7100	6970
	V	148	64.4	386	386	2-1/4	6990	7100	6860	6980
F5-8	I	148	73	386	386	2-5/8	6270	6570	6490	6440
	II	148	70	386	386	2	7230	6640	6770	6880
	III	148	69	386	386	2-1/4	6550	6610	6560	6570
	IV	148	66	386	386	2-1/8	6310	6050	6440	6270
	V	148	65.5	386	386	1-7/8	6670	6650	6820	6710

TABLE 3 - STATIC TESTS, LOT I STRAND

Specimen No.	P_{ult}, lbs.
BS-1	27,300
BS-2	27,300
BS-3	27,400
BS-4	27,500

TABLE 4 - BEAM FATIGUE TEST RESULTS

Beam	Age (days)	Rate of Loading cpm	Jack Loads, kips*				Failure Section	Wire Failures, Million Cycles				
			P_{min}	P_{pred}	P_{o1}	P_{o2}		N_1	N_2	N_3	N_4	N_5
F1	167	250	4.50	12.10	-	-	W	0.225	0.233	0.258	0.258	0.258
2	170	250	4.50	12.10	-	-	E	0.164	0.200	0.215	0.226	0.226
3	161		(Static Test)				L	(Crushing of Concrete Top Fiber)				
4	169	250	4.50	12.10	-	-	W	0.139	0.146	0.164	--	--
F5	180	500	3.80	7.08	9.14	10.17	W	1.947	2.516	2.817	2.817	2.820
6	156		(Static Test)				L	(Crushing of Concrete Top Fiber)				
7	196	250	3.80	7.05	9.09	10.37	L	1.167	1.437	1.467	1.552	1.580
8	168	250	3.80	7.12	9.08	10.43	E	1.136	1.557	1.586	1.587	--

*Including dynamic effect, estimated from deflection readings

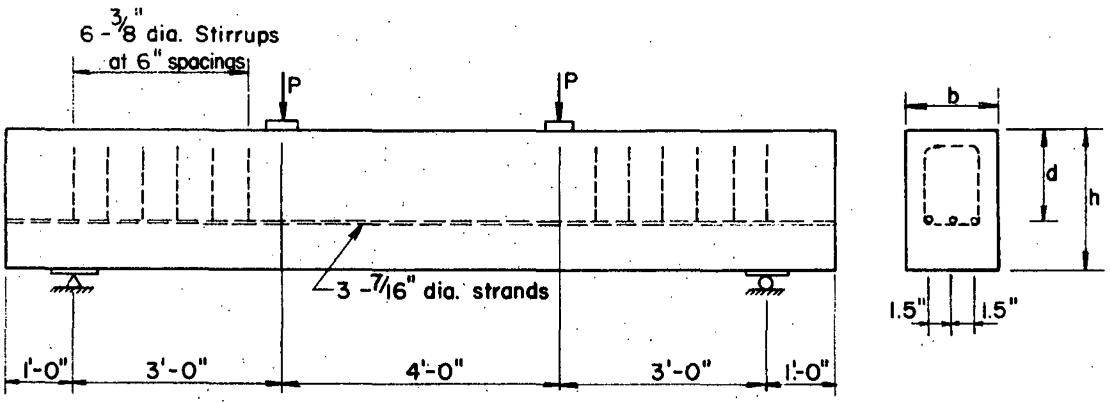


FIG. 1 - DETAILS OF BEAM TEST SPECIMENS

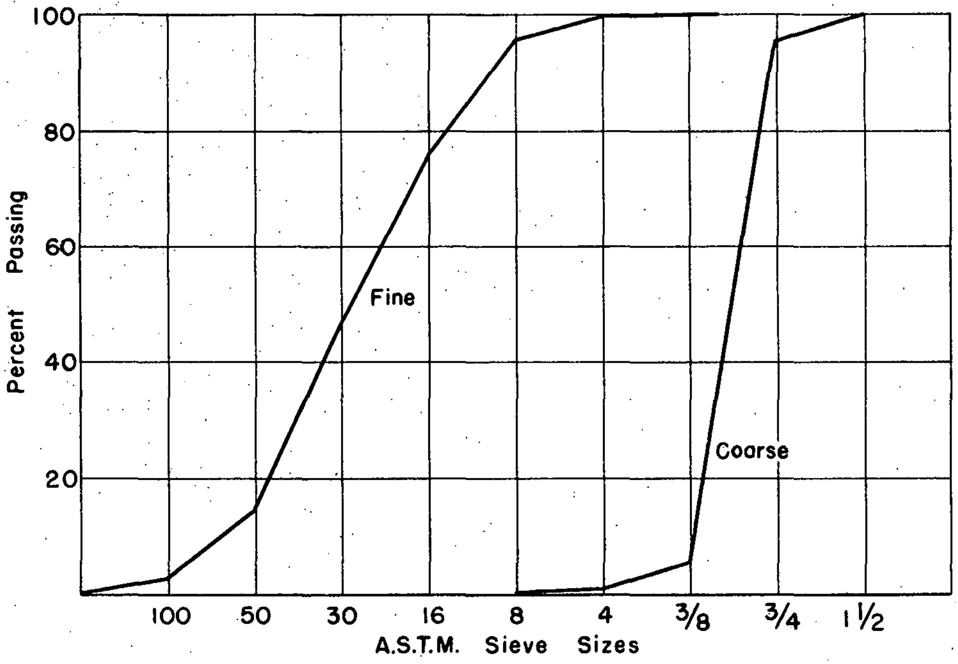


FIG. 2 - GRADING CURVES FOR FINE AND COARSE AGGREGATES

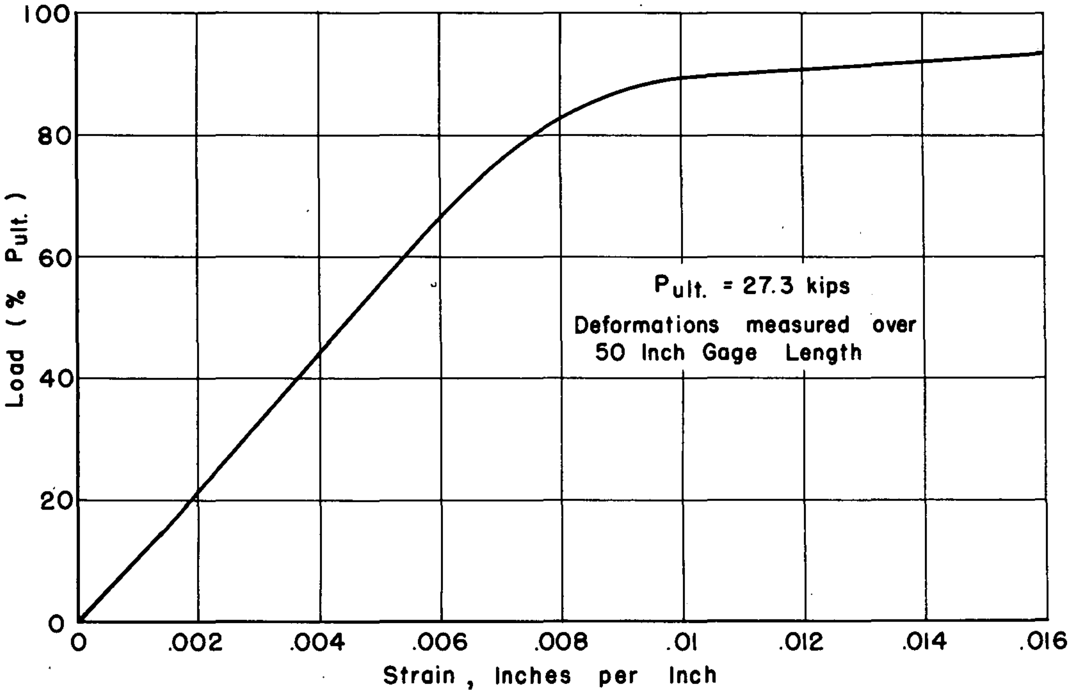


FIG. 3 - LOAD VERSUS STRAIN, 7/16 INCH DIA. STRAND - LOT I

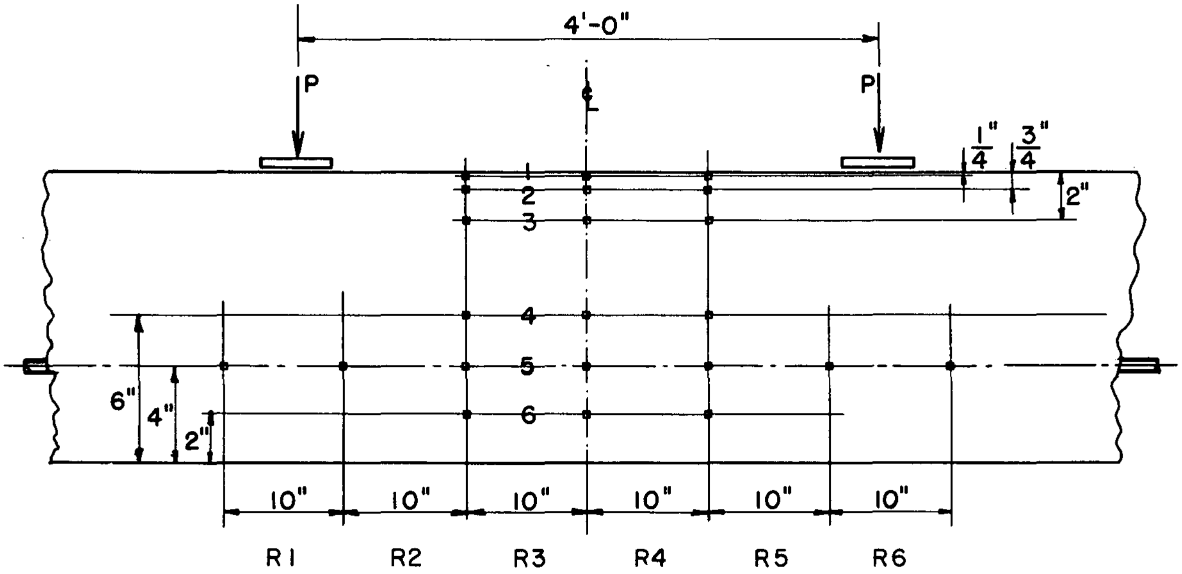


FIG. 4 - GRID LAYOUT FOR MEASUREMENT OF CONCRETE DEFORMATIONS (SOUTH FACE)

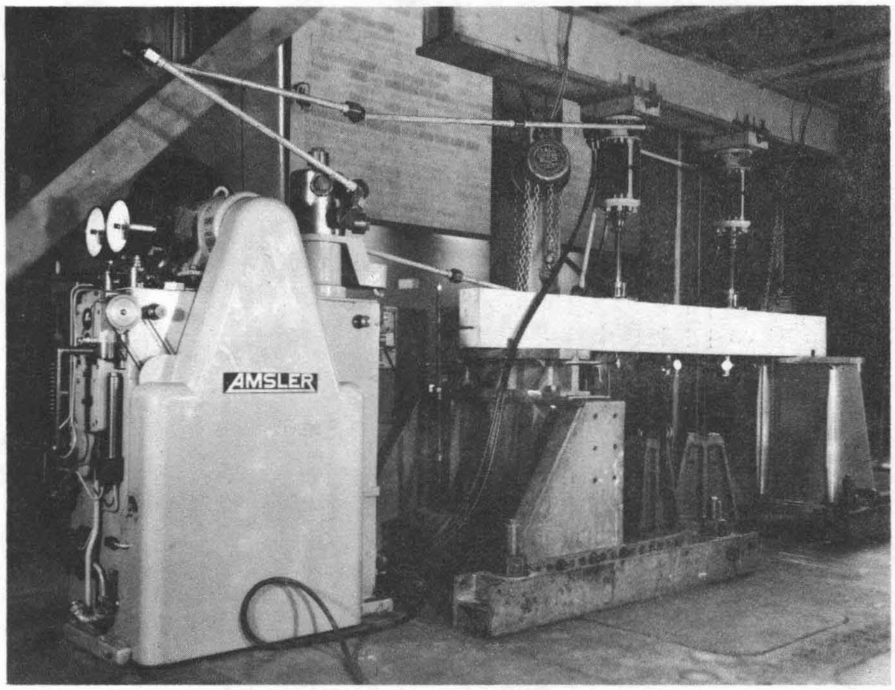


FIG. 5 - BEAM TEST SET-UP

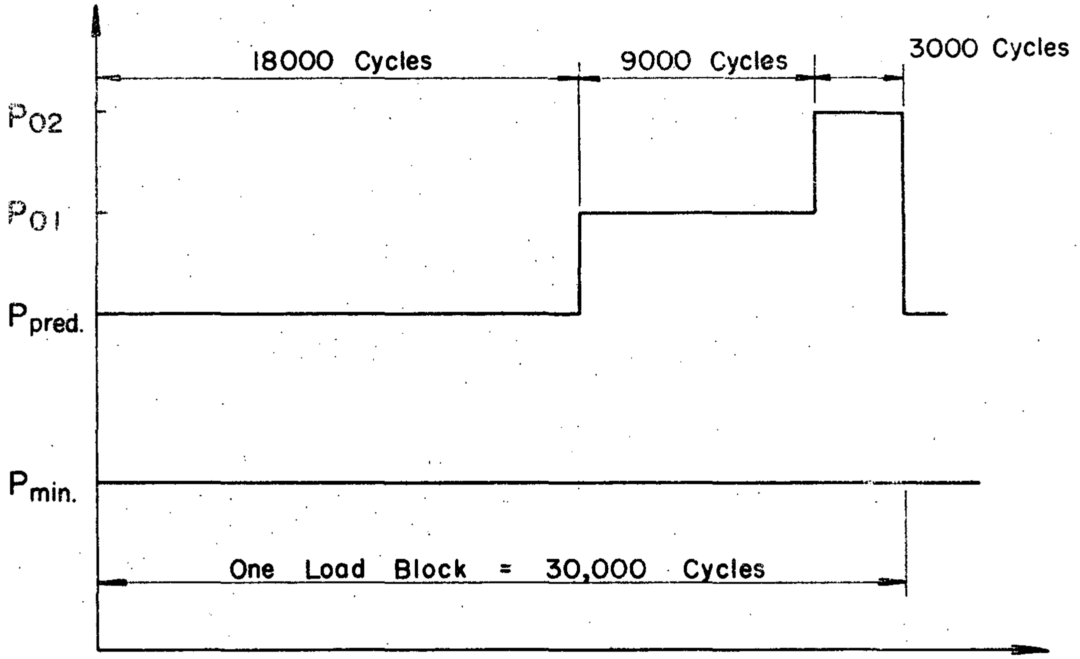


FIG. 6 - LOAD BLOCK FOR BEAM CUMULATIVE DAMAGE TESTS

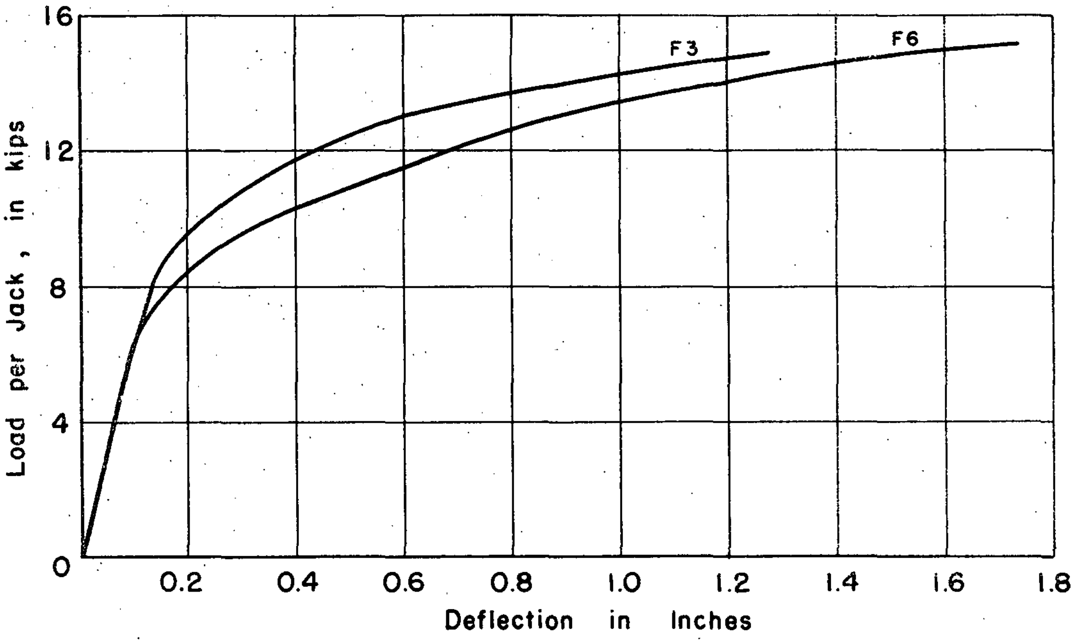
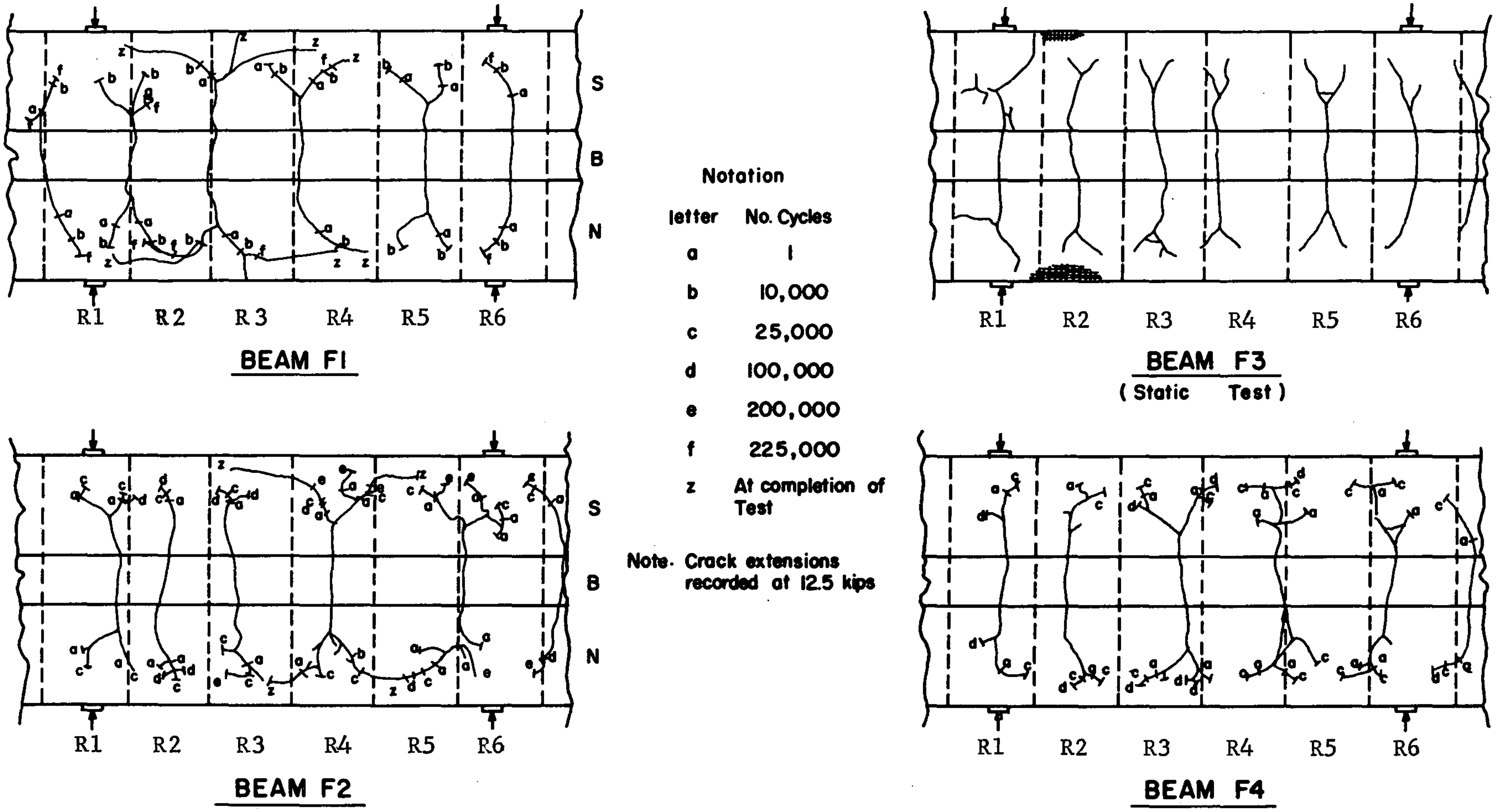


FIG. 7 - CENTER-LINE DEFLECTIONS, STATIC ULTIMATE TESTS - F3, F6



BEAM F1

BEAM F2

BEAM F3
(Static Test)

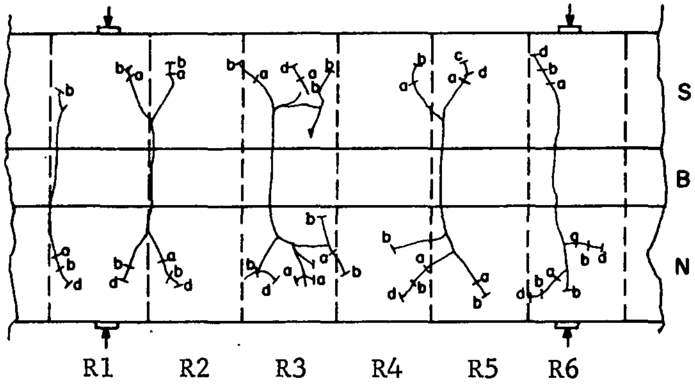
BEAM F4

Notation

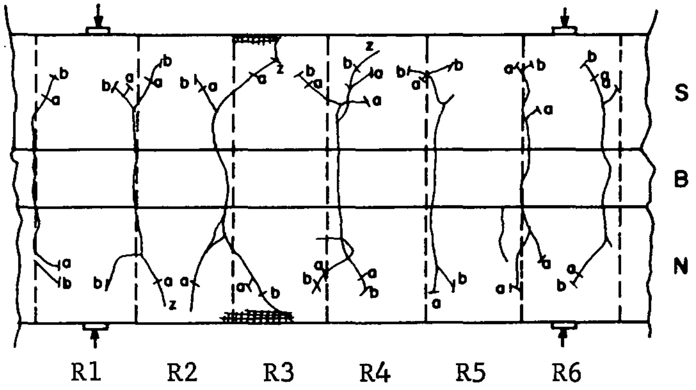
letter	No. Cycles
a	1
b	10,000
c	25,000
d	100,000
e	200,000
f	225,000
z	At completion of Test

Note. Crack extensions recorded at 12.5 kips

FIG. 8 – CRACKING PATTERNS



BEAM F5

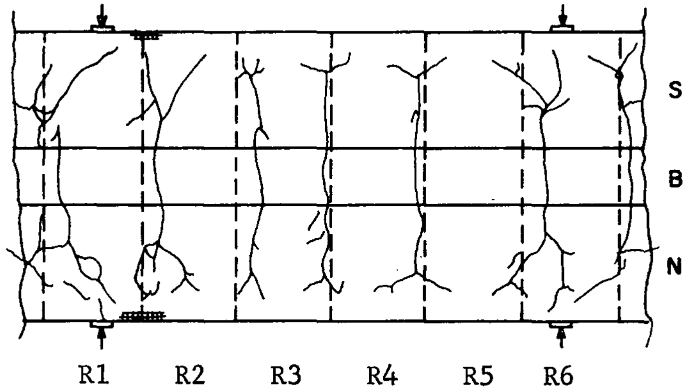


BEAM F7

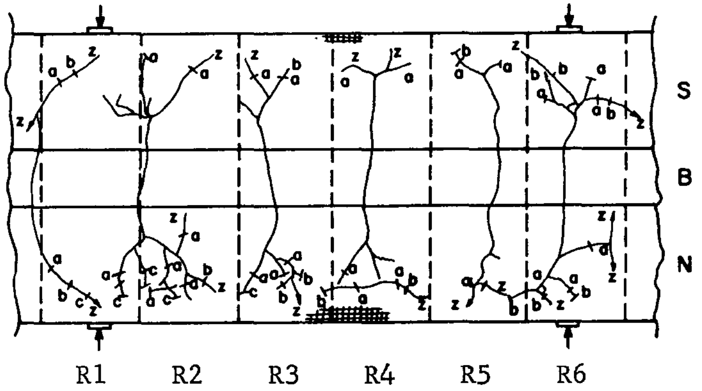
Notation

letter	No. Cycles
a	1
b	30,000
c	90,000
d	1,200,000
z	At completion of Test

Note: Crack extensions recorded at 10.5 kips



BEAM F6
(Static Test)



BEAM F8

FIG. 9 - CRACKING PATTERNS

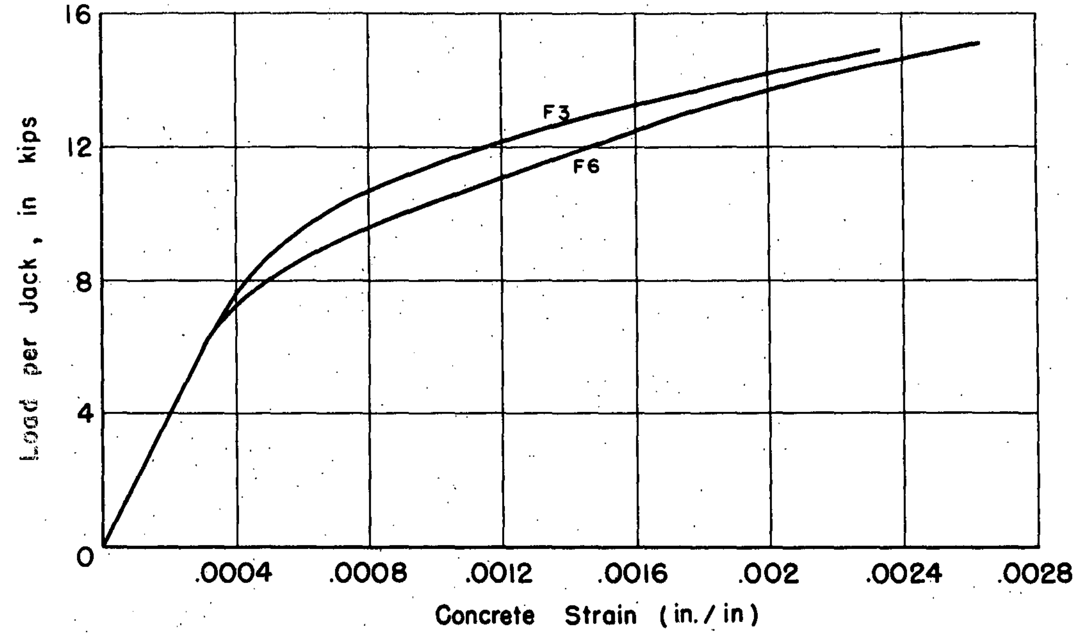


FIG. 10 - TOP FIBER CONCRETE COMPRESSIVE STRAINS, STATIC ULTIMATE TESTS — F3, F6

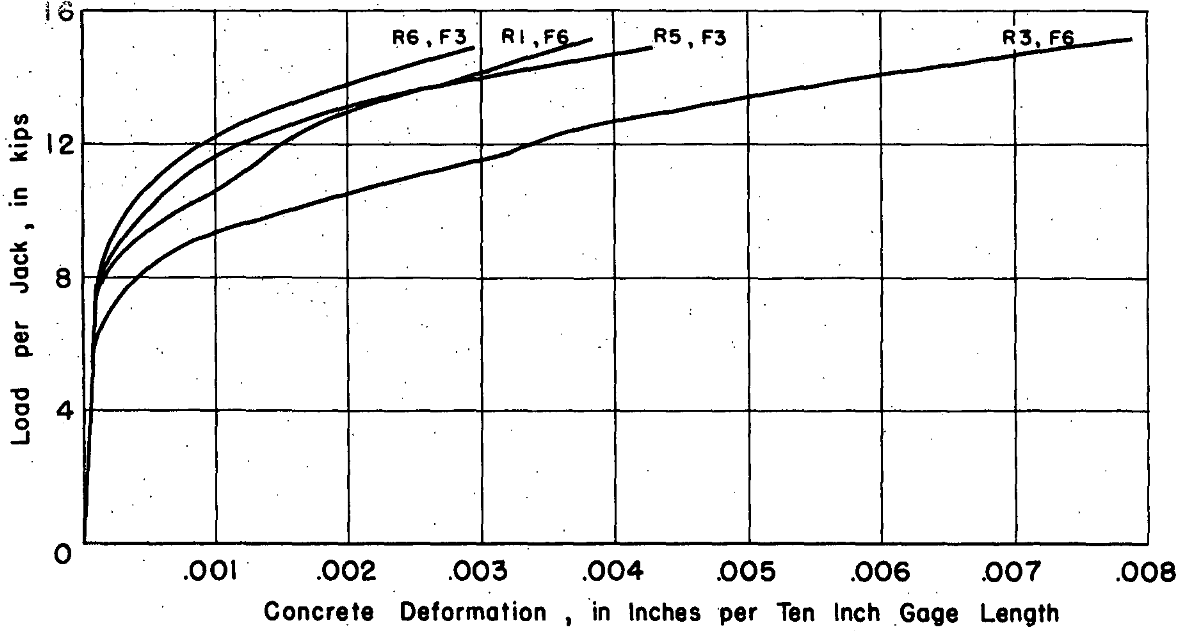


FIG. 11 - CONCRETE DEFORMATIONS AT THE STEEL LEVEL, STATIC ULTIMATE TESTS — F3, F6

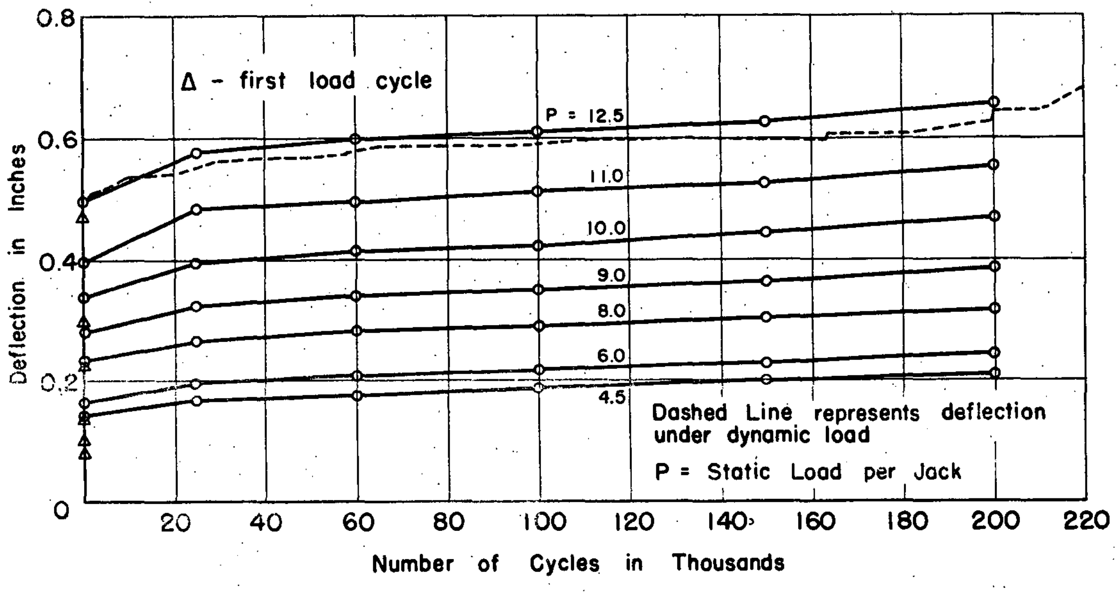


FIG. 12 – MID-SPAN DEFLECTIONS, STATIC AND DYNAMIC LOADS – BEAM F2

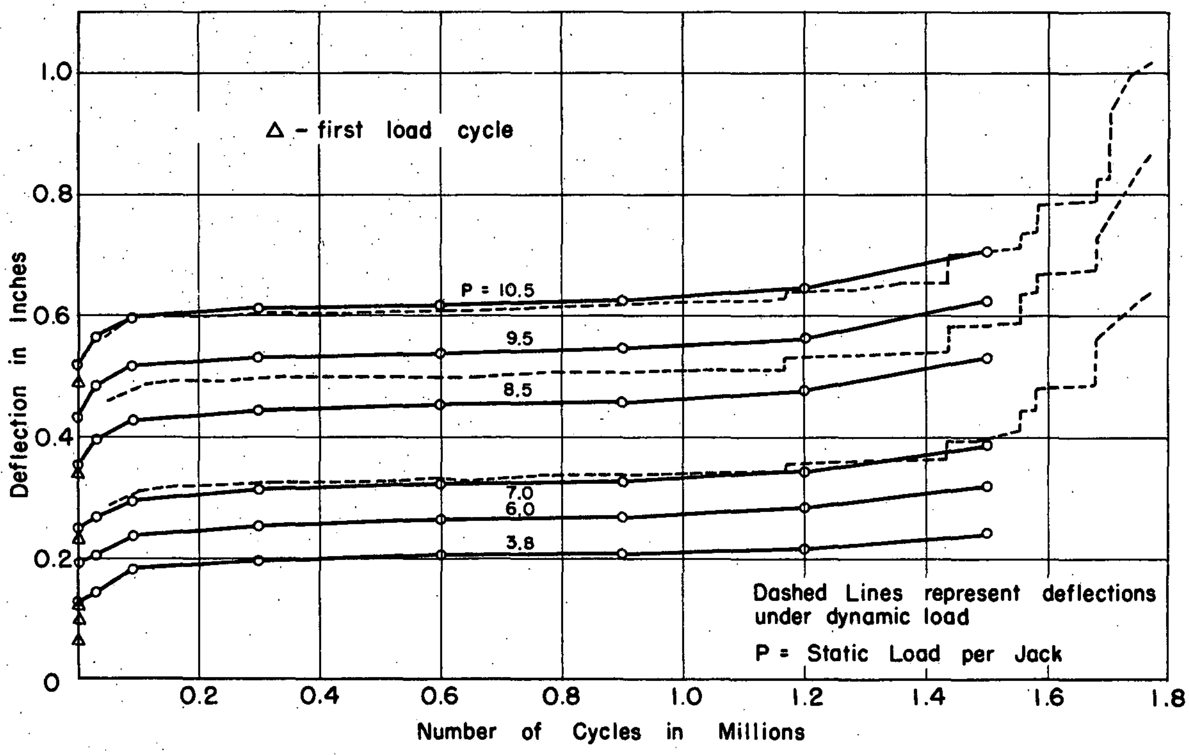


FIG. 13 – MID-SPAN DEFLECTIONS, STATIC AND DYNAMIC LOADS – BEAM F7

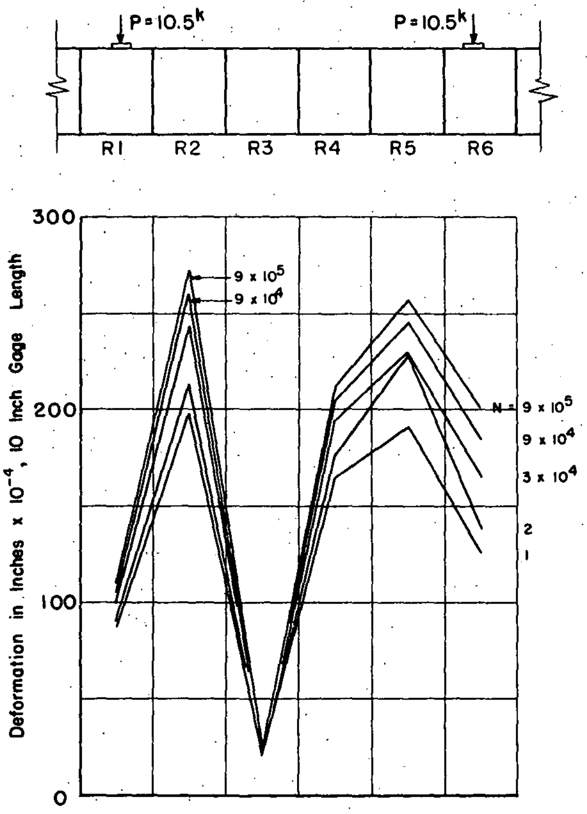


FIG. 14 -CONCRETE DEFORMATIONS AT THE STEEL LEVEL - BEAM F7

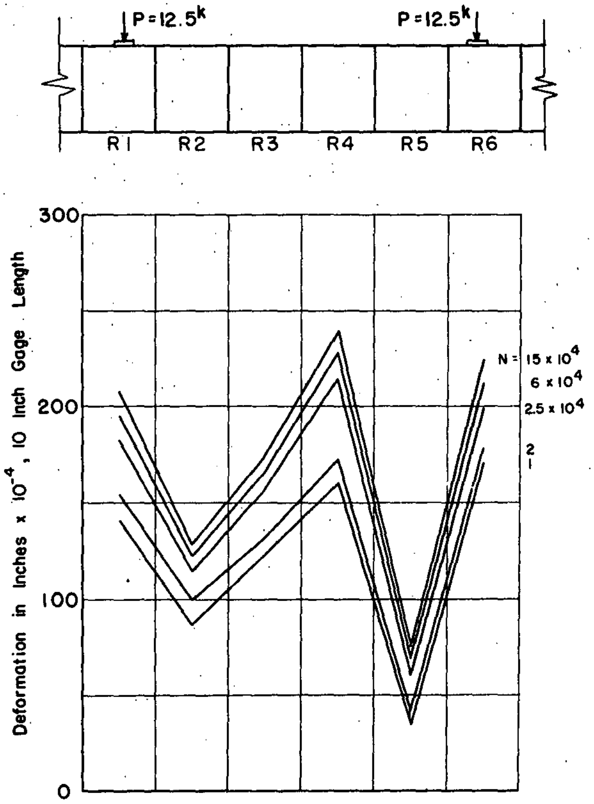
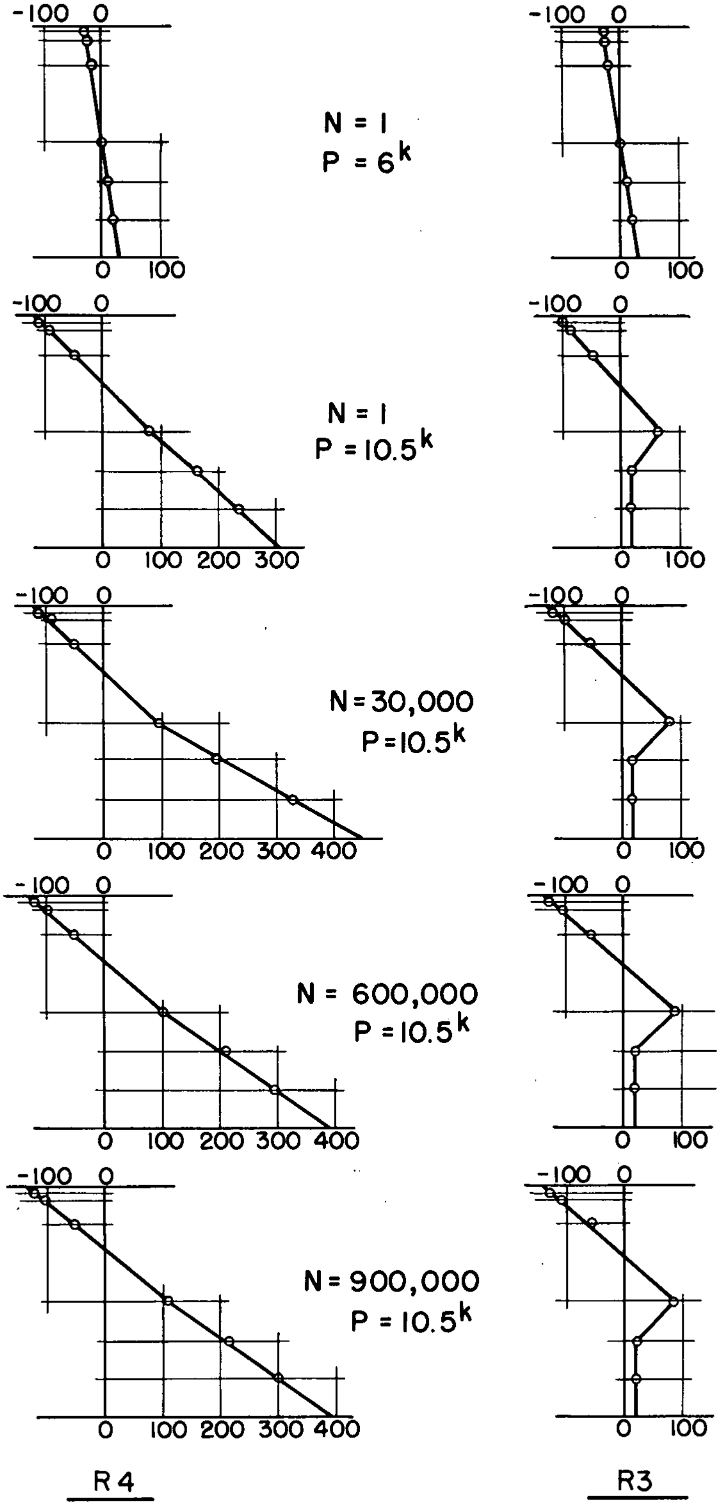


FIG. 15 -CONCRETE DEFORMATIONS AT THE STEEL LEVEL - BEAM F2



Note: All deformations in Inches x 10^{-4}, per 10 Inch Gage Length

FIG. 16 - CONCRETE DEFORMATIONS IN REGIONS R3 AND R4, BEAM F7

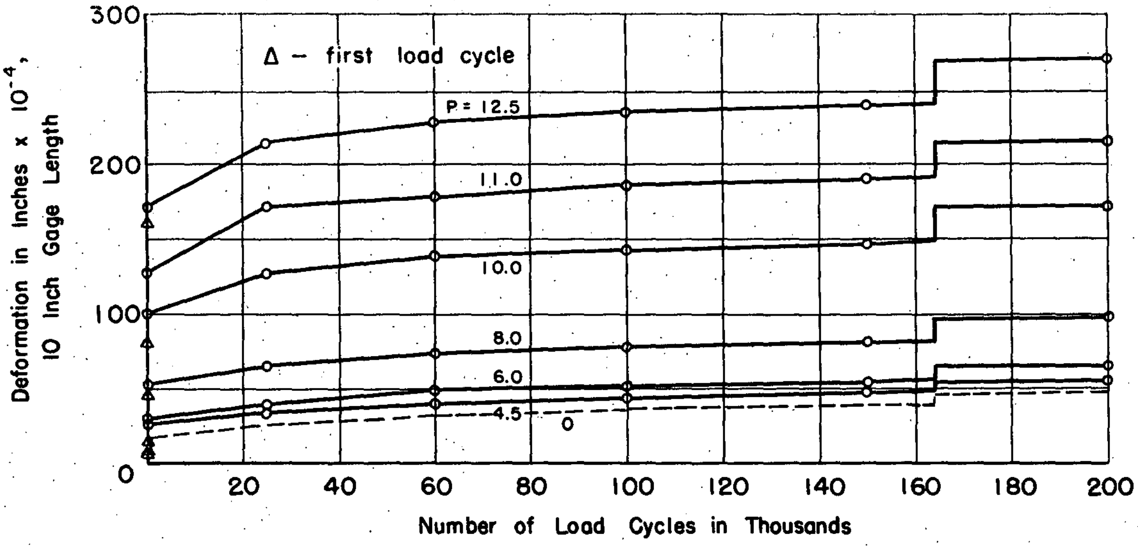


FIG. 17 - CONCRETE DEFORMATIONS AT STEEL LEVEL, REGION R4 - BEAM F2

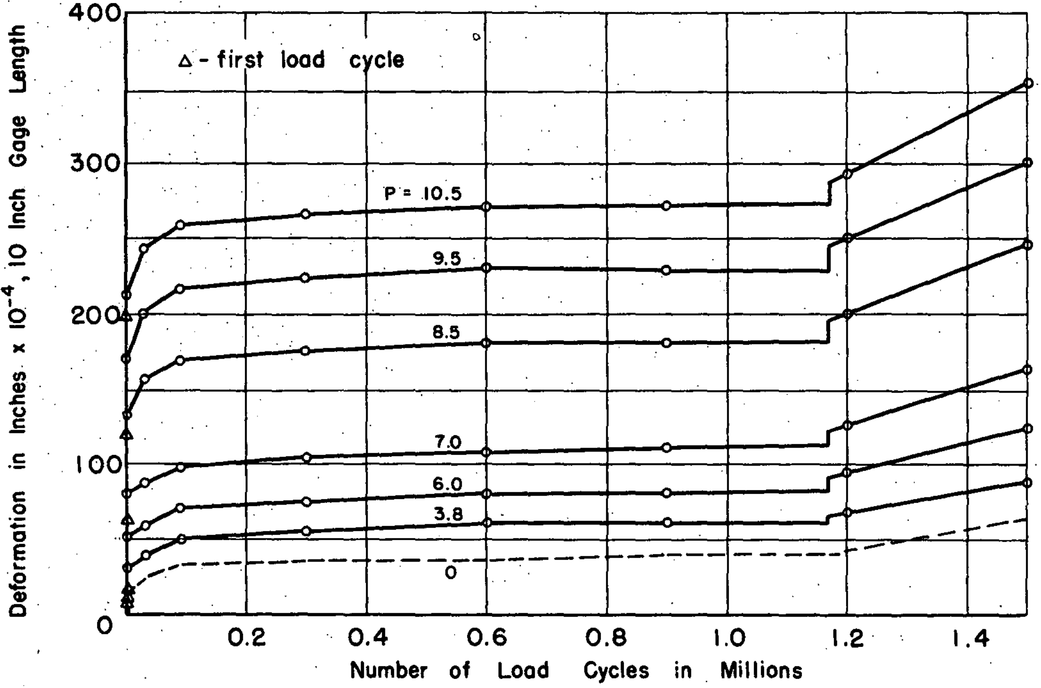


FIG. 18 - CONCRETE DEFORMATIONS AT STEEL LEVEL, REGION R2 - BEAM F7

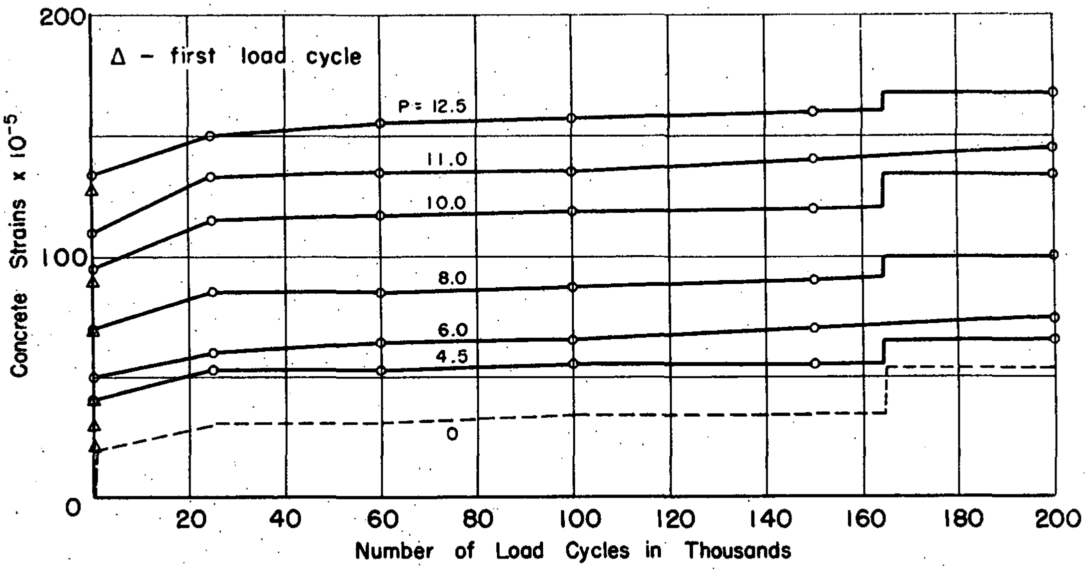


FIG. 19 -TOP FIBER CONCRETE COMPRESSIVE STRAINS, REGION R4 - BEAM F2

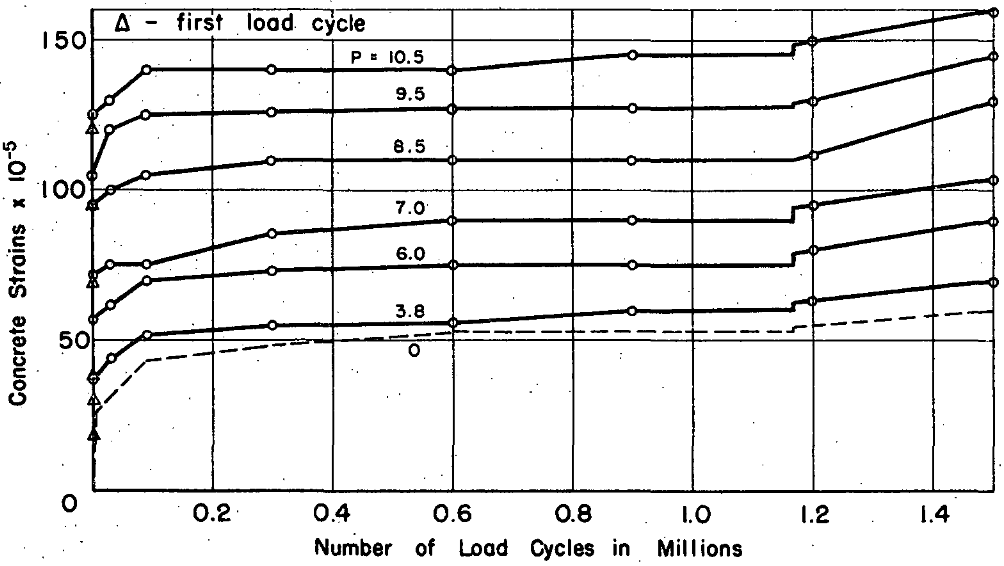


FIG. 20 -TOP FIBER CONCRETE COMPRESSIVE STRAINS, REGION R3 - BEAM F7