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BEHAVIOR OF INSTRUMENTED PRESTRESSED CONCRETE PAVEMENT AT NAS LEMOORE, CALIFORNIA

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

BEHAVIOR OF INSTRUMENTED PRESTRESSED CONCRETE PAVEMENT AT NAS LEMOORE, CALIFORNIA

Y-R011-01-013

Type C

by

J. A. Bishop

OBJECT OF TASK

To gather information about the behavior of a functional, prestressed concrete taxiway by installing instruments and obtaining test data during and after constructio

ABSTRACT

Longitudinal and transverse post-tensioning loads and the distribution of these forces along the lengths of tendons were defined by calibrated links or couplers installed in the tendons.

Strains induced in the concrete by stressing and existing for several months after stressing were measured by Carlson strain meters embedded in the concrete adjacent to instrumented couplers.

A load test resulted in the definition of a deflection pattern and the measurement of pressures under the load.

There was apparently a substantial amount of friction between longitudinal tendons and their ducts as indicated by the difference in tendon force between ends and center. Couplers installed in transverse tendons which were encased in rigid aucts and stressed from one end only did not indicate a large friction loss from one end of the tendons to the other.

Tendon forces decrease, and compressive strains in the concrete increase, with time under the influence of slab shrinkage and increased pavement temperatures.

A load test shows that the six-inch thickness of prestressed concrete pavement is the equivalent of at least eleven inches of conventional concrete pavement.

BACKGROUND

The application of the prestressing technique to concrete pavement for roads and airfields dates from the middle 1940's with the design and construction of a runway at the Orly Aerodrome near Paris.[1] Since that work a number of investigative efforts[2] have been undertaken in England, Belgium, and a few other countries. In the United States, however, relatively little in this field was accomplished until 1952. In that year the Bureau of Yards and Docks initiated a research and development program on prestressed concrete pavement as part of its continuing effort to develop pavement to accommodate high performance aircraft. The preliminary studies resulted in the construction of an experimental pavement slab at the Patuxent River Naval Air Station, Maryland and an extensive test program was conducted on this slab from 1953 to early 1955.[3] Much information on the use of prestressed concrete in airfield pavement was obtained from this study. In an effort to augment the knowledge gained, the Bureau, in 1958, authorized the prestressing and the instrumenting of a 75 foot by 512 foot taxiway to be constructed at NAS Lemoore, in California. The taxiway was to be a functional part of the Air Station, not an experiment, and any instrumentation undertaken could not interfere with either its construction or its operational use. The principal reason for instrumenting the taxiway was to gather information about the behavior of prestressed concrete pavement which would be useful in the construction of future prestressed pavement.

A corollary purpose of the instrumentation was the collection of data which would be useful to the designer and the contractor in the control of the construction of this particular pavement.

The data to be obtained by this investigation included strains (converted to stresses if possible) induced in the concrete by prestressing, the distribution of prestressing forces along the tendons, the behavior of the pavement under loading, and the magnitude of pressures under the slab caused by loading.

Details of the instrumentation scheme were developed by NCEL in concert with the Public Works Office of the Twelfth Naval District, and the pavement designer, the firm of Porter, Urquhart, McCreary and O'Brien. The Structures Division of NCEL had experience in instrumenting structural members both in experimental investigations and actual construction, and the same techniques employed were to be adapted to this pavement wherever practicable. With a view toward establishing a satisfactory instrumentation program the results of the Navy's experimental project at Patuxent River NAS were studied as were those of other prestressed pavement investigations conducted in various parts of the world.

INSTRUMENTATION PLAN

For economic reasons it was not feasible to completely instrument the entire pavement, so representative instrument locations were selected as indicated in Figure 1, which is a layout of the taxiway showing the location of the various instruments. The middle one of three lanes was chosen for the major share of the instrumentation. It was uniformly six inches thick over nearly two thirds of its length. The other lanes were tapered from six inches at their inner edges to nine inches at the outside to accommodate the anchorages necessary in the transverse prestressing. The end thirds of each lane were tapered for this same reason.

Three longitudinal tendons and three transverse tendons were instrumented, and near each instrument, a meter was installed for indicating concrete strains induced by prestressing. Pressure transducers were installed under the pavement near the center of the middle lane.

TENDON FORCE MEASUREMENTS

Figures 2-6 are photographs of the couplers used to measure tendon forces at various stages of preparation. The following paragraph, is quoted from the Specifications covering the fabrication of the couplers:

> "The configuration of the coupler shall be such that there are no points of stress concentration. The design and selection of material shall be such that the working stress will be approximately 50 per cent of the yield strength. Silicone oil shall not be used at any stage in the fabricating, finishing, or shipping of the couplers. The finish of the coupler surface shall be the equivalent of that designated by Mil-Std-10A as 125. Variation of details will be permitted to conform to prestressing system used."

Four AB-7 electrical resistance strain gauges were applied to each coupler as shown in Figure 3 to form a balanced Whetstone bridge, and were connected to 10 feet of lead wire. They were then waterproofed and wrapped for protection during the field installation. Instrumented couplers were calibrated in a 400,000-pound, Baldwin, universal, testing machine. During calibration 400 feet of lead wire was temporarily attached to the short lead of each coupler so that the sensitivity of the unit would resemble that which it would have after installation in the slab. A calibration curve for each coupler was established for loads of 0 to 80,000 pounds, the upper limit being considerably higher than the largest load expected to be applied in the field. Strains resulting from the loading of the couplers were measured on a Baldwin-Lima-Hamilton Type M-Indicator.

CONCRETE STRAIN MEASUREMENTS

For indicating strains in the concrete during and after prestressing, Model SL-10, Carlson Elastic Wire Strain Meters, designed for embedment in concrete, were selected because they are small enough to use in relatively thin concrete sections. A strain meter was installed near each of the tendon couplers. The Carlson meters were carefully aligned parallel to the prestressing tendons and were suspended at the midpoint of the pavement section with fine wires attached to tendon sheaths, or reinforcing steel where this was used (such as at the ends or edges of the pavement). Figure 7 is a close-up view of a Carlson meter in position, and Figure 8 shows three, transversely oriented units at the edge of the slab. Fresh concrete was placed around the strain meters by hand and each was carefully protected to insure its safety during vibrating and finishing of the concrete.

PRESSURE CELLS

Before completion of the cement-treated base, two "blockouts" were made to accommodate two pairs of pressure cells. In each blockout one cell was placed so that its face was level with the bottom of the base course. On top of these cells, base course material was placed to the depth of the finished cement-treated base. A polyethylene sheet was used as the friction breaking layer (See Figure 9). The second cells were installed with their faces against the polyethylene sheet and immediately over those under the base. The two pairs were 8.33 feet apart and were located under the center lane as indicated on Figure 1.

These cells consisted of a Type 4-312A CEC, pressure pickup fitted to one face of a bellows-type case which was completely filled with water and soluble oil. Thus, load exerted against the face of the bellows was transmitted undiminished to the diaphragm of the pickup. Each bellows was 6 inches in diameter and 1 inch thick. Figure 10 is a view of the pickup alone and the assembled cell.

INSTRUMENT CABLE CONDUITS

Recording and indicating instruments were located in a control house remote from the prestressed taxiway. A single underground master conduit which branched at the edge of the pavement into feeder conduits contained the lead wires for the individual instruments. These feeder conduits were positioned before the cement treated base was constructed, and blockouts were left at the locations of the instruments. In eack blockout sufficient lead wire was coiled to permit ease of connectior to the instruments. Cement-asbestos conduit (transite) was used throughout and all joints were wrapped to insure watertightness.

TEST SPECIMENS

Before the Government accepted any prestressing steel, the manufacturer provided specimens from each "heat" for test purposes. Of interest particularly were the modulus of elasticity, the unit elongation, and the yield and ultimate strengths of the prestressing tendons.

During placement of the concrete, concrete specimens were taken to provide information necessary on the days on which prestressing would take place. Cylinders to be used for establishing a modulus of elasticity needed to compute stresses in the concrete were "field cured" -- that is, at the job site and under the same conditions as the pavement proper. Beams and prisms of the concrete were also made but information from the tests of these was not related to the instrumentation.

Cylindrical specimens of the grout used to fill the sheaths encasing the uninstrumented prestressing tendons were made at the time of grouting.

PRESTRESSING

Instrumented longitudinal tendons were the first to be stressed in the schedule established by the contractor. In order to insure that the amount of load applied at each end was sufficient to provide the necessary loads over the lengths of tendons, a "jack verification" step was conducted using data from the instrumented couplers. Predetermined values of load were applied to hydraulic jacks at both ends of the slab in increments up to the greatest load expected ultimately to be applied. At the end of each load increment strains in the couplers at the center, quarter points, and ends were measured and converted to forces. These forces, together with measured elongation of the tendons, served as a basis for the loads to be applied in the subsequent stressing of the tendons. In other words the calibration of the gauges on the hydraulic jacks was verified on the instrumented tendons. The same general procedure was followed with the transverse tendons, but these were jacked from one end only. In Appendix A are given the pavement designer's instructions to the prestressing contractor on the jack verification procedure and the computation of the required jacking loads to be applied to the tendons. After stressing the instrumented tendons, data were taken to provide information on the adjustment of the loads as indicated by the couplers and the changes in concrete stresses as reflected by the strain meters. Readings were continued during the entire prestressing operation and periodically for several months after completion of the construction work.

Immediately after all longitudinal and transverse tendons had been stressed, and before the grouting of the ducts was begun, the pavement was subjected twice to wheel loadings to determine the magnitude of deflections. Both loadings were made on the center lane, one on the six-inch uniformly thick section over the pressure cells, and one near the north end where the pavement was approximately seven inches thick. In each case a 60,000-pound single-wheel load with a tire pressure of 200 psi was used. The load was applied in 10,000-pound increments and the deflection patterns were determined by dial extensometers (Ames dials) placed on a grid system about the point of load application.

RESULTS

Longitudinal Tendon Forces

Table I lists the tendon forces indicated by the instrumented couplers since the beginning of prestressing of the pavement.

Longitudinal tendon No. 17 exhibited representative forces and the forces indicated by its couplers have been plotted against time in Figures 11 and 12. Both these curves and Table I reveal a general decrease in tendon force with time, for while a load at the north end of the slab (coupler A-17) on the day of stressing is 70.4k, the load at this same point five months later dropped to 55.9k. This decrease, noted in all the couplers of tendon No. 17, occurs in all the other instrumented tendons.

Transverse Tendon Forces

Data provided by couplers in the transverse tendons are shown in Table I. Unfortunately some of the couplers installed in transverse tendons were damaged during construction with the result that no data were received from them. Information was obtained, however, from at least one coupler at each of the three transverse instrumentation positions.

It is seen from these data that, unlike the condition existing in the longitudin tendons, the tendon force is essentially constant from one side of the pavement to the other at the time of stressing. This may be because the transverse tendons were only 75 feet long and were encased in rigid ducts rather than the flexible ones used with the longitudinal tendons.

Since friction caused relatively little loss in tendon force over the length of transverse tendons, the data provided by the operable couplers may be averaged. These average coupler loads are plotted against time since stressing on Figure 11 and the reduction of loads with time is apparent.

Concrete Strains

The Carlson strain meters placed contiguous with tendon couplers in the pavement have provided data since the day of prestressing which is summarized in Table I The strains measured by the meters adjacent to longitudinal tendon No. 17 are plotte on Figure 13. On Figure 14 are plotted the strains indicated by meters oriented transversely. These figures also include a curve showing the average temperatures prevailing in the concrete at the times strains were measured. (Temperatures are obtained from the Carlson Meters).

It can be seen in Table II that strain meters A-17 and H-17 at the ends of the slab provided data at the end of the first day of prestressing, whereas those at interior locations did not do so for several days. This is not the case for the meters adjacent to transverse tendons. Transverse meters at the center of the middle lane reflected strains on the day after stressing.

All meters oriented longitudinally indicate that compressive strains in the concrete increase with time, while coupler forces decrease. The same general trend toward increasing compressive strains in a transverse direction is apparent also.

It should be noted here that strains only are plotted on Figures 13 and 14. That increasing strains do not, however, reflect increasing stresses will be pointed out in the Discussion.

Load Tests

Figure 15 is the pattern of maximum deflections resulting from the loading of the six-inch section of the pavement; Figure 16 shows the result of loading at the thickened end. It is seen that in the former, the maximum deflection is less than 0.04 inch, and in the latter, the maximum was approximately 0.03 inch. The positive numbers in Figures 15 and 16 indicate upward deflections at these points. The grid system of extensometers was not extensive enough to define the contours of zero deflection accurately, but these contours appear to be approximately 7 to 9 feet from the center of the load application areas.

The pressure cells, located under the slab and under the cement treated base course, provided the data about loading shown in Figure 17. The cell at the slab-base interface, when directly beneath the center of the wheel, (Curve B), indicated a pressure of 12 psi for a 60,000-pound wheel load, while 6.3 psi was recorded for the cell under the base course (Curve C). Both cells located 8.33 ft away from this pair indicated pressures of 0 psi under this same load. The manner in which the pressure on the lower of this remote pair of cells varies during loading is shown on Figure 17 (Curve D).

DISCUSSION OF RESULTS

As indicated in the tables and figures referred to above, there is a substantial amount of friction between longitudinal tendons and their ducts. This is not the case, however, for the transverse tendons and ducts, and the difference is believed to be not because the ducts were shorter, but because different types of ducts or sheaths were used. The transverse ducts, being relatively rigid, held the tendons in a straight line while the longitudinal ducts were flexible; they sagged considerably in their 37-inch span between the rigid transverse ducts. The designer recognized the presence of this friction (wobble effect) and accounted for it in his calculation of the jacking loads necessary to apply the required prestressing force to the pavement. His assumption of the magnitude of the friction was reasonably substantiated by the tendon force values obtained from the couplers (See Figure 18).

The diminishing of the tendon forces is attributed to several factors: increasing temperature of the pavement, shrinkage of the concrete, creep in the concrete, creep in the steel, and adjustment of the tendons in their ducts under warping and curling of the pavement and load on the slab. The first two of these can be reasonably estimated; creep in the concrete under the loads imposed on it is not considered particularly significant; nor is the creep in the steel.

The average ambient temperature in the area of NAS Lemoore has been increasing to the date of this report since the day of prestressing and the strain meters in the pavement reflect increased compressive strains. From the average pavement temperatures of Table I it is seen that an increase of approximately 47 degrees has taken place since the end of the first day of stressing. Thus both concrete and steel have expanded longitudinally and the net effect of the difference in coefficients of the expansion can be shown to be a "pulling away" of the steel from the concrete of approximately 0.29-inch. This is the equivalent of a release of about a 530-poun load in each tendon.

Specimens made when the concrete in the slab was placed, and stored under humidity conditions essentially the same as the slab, indicate that the concrete ha shrunk approximately 200 micro inches per inch since the day of stressing. Thus, the slab has shortened 512' x 12" x 200 x 10^{-6} = 1.23 inch. This is the equivalen of 4600 pounds released from the end of the slab. (This calculation ignores the ef of frictional forces between pavement and base which are mobilized by the shrinki or shortening of the slab. Actually the frictional pattern between slab and base is not known inasmuch as warping and curling of the slab would preclude a constant pattern.)

It is seen, therefore, that together, the temperature increase and shrinkage of the concrete account for 5.1k or nearly 40 per cent of the average decrease of longitudinal tendon force (in tendon No. 17) which has taken place since the day of stressing. As mentioned, it is believed that neither creep in concrete nor in ste would add appreciably to this percentage. The remainder of the decrease therefor must be due to the "adjusting" of the tendons in the ducts. Whether this adjustmen eventually becomes constant and further decrease will be due only to temperature and shrinkage (and creep) remains to be seen.

The same analysis was applied to transverse tendons forces and their decrease account for only a small fraction of the reduction with time.

The result of this diminution of tendon forces is a decrease in residual concre stresses regardless of the cause of the decrease. If the average force on each of th 33 longitudinal tendons was 70k at the time of stressing, the maximum concrete str at midlength of the slab would be 367 psi. A decrease of 13 or more per cent in tendon force (as has been experienced in tendon No. 17 since stressing) would decrease this concrete stress to approximately 320 psi. This would, if no other for were working, be apparent in decreasing compressive strains indicated by the Carl meters in the concrete. As is seen on Figure 13, however, indicated compressive strains are continually increasing. It is apparent, then, that shrinkage of the con- crete, which results in increasing strains, has a greater effect on the total indicat strains than does the combination of decreasing load and increasing temperature, both of which would result in decreasing strains. Warping and curling of the pave ment might also account for a small amount of the increase in indicated strains, si the bending of a Carlson meter will change the ratio of resistance of the two coils Because the direction (compression or tension) of the indicated strain, however, depends on the orientation of the meter, the effect of this factor probably can be neglected without serious consequence.

While the magnitudes of the strains in the concrete have been established, they cannot be converted directly to stresses because their separate causes cannot be distinguished. Nor can the load test of the prestressed taxiway be compared with a load test of an unstressed pavement, since in this case load testing before prestressing was impossible. While it is recognized that the results of one load test are not sufficient to warrant extensive conclusions regarding pavement action, the pressure and deflection data obtained will permit some observations.

On Figure 17 is plotted a pressure-deflection curve developed from data furnished by the pressure cell located in the slab-base interface directly beneath the center of the wheel, (Curve B). The deflections are maximum values, inferred from deflections measured close to both sides of the wheel since no deflections could be measured directly under the center of the load. Reasonably good proportionality appears to exist between deflection and pressures above 4 psi pressure.

Both the cell in the slab-base interface and the one under the base course directly beneath it responded immediately upon application of load. It is assumed that both the base and the slab deflected an equal amount, and the pressures indicated by the lower cell are plotted against the slab deflections on Figure 17 (Curve C). Above 3 psi, pressures and deflections are reasonably proportional.

Figure 17 also shows the pressures exerted on the cell under the base course 8.33 feet away from the center line of the loaded area; the pressures indicated are also plotted against deflections under the load. This curve reveals that, after the deflection under the load attained a value of 0.0125 inch, corresponding to a load of 20,000 pounds, the pressure on the cell began to decrease and continued to do so until the highest load, 60,000 pounds, had been applied, at which time the indicated pressure was zero. The cell above this one in the slab-base interface indicated a maximum pressure of less than 0.05 psi midway through the application of the first increment of load, 10,000 pounds, and then decreased to zero. This is reasonably consistent with the deflection pattern of Figure 15 which shows positive (+) deflections, indicating uplift, occurring approximately 8 feet from the center of the load.

On the basis of this it is considered safe to assume that the point of zero pressure of slab on base is located approximately 8 feet from the center of the load. Thus a comparison can be made of the prestressed pavement with conventional pavement from the standpoint of their respective radii of relative stiffness. For this purpose the analysis contained in Technical Publication NAVDOCKS TP-PW-4, dated 1 January 1953 is referred to. This states that when a uniform load is applied to the surface of a concrete pavement, there is a peak earth pressure at the interface between slab and base on the axis of loading; and that at a distance from this axis equal to twice the radius of relative stiffness the earth reaction is practically zero.

The radius of relative stiffness of the prestressed pavement is estimated to be 4 feet. This publication also tabulates values of radii of relative stiffness corresponding to different values of subgrade modulus and pavement thickness. If it is estimated that the subgrade modulus of the prestressed pavement is 200 pci, fo, example, it can be shown that the six-inch thickness is approximately the equivalent of 14-15 inches of conventional concrete pavement. If the subgrade modulus is assumed as 100 pci the prestressed pavement appears to be the equivalent of 11-12 inches of conventional pavement. Admittedly both of these assumed subgrade modulus values are conservative for the base course under the prestressed pavement is cement treated material. The tabulation of radius of relative stiffness values is based on a concrete modulus of elasticity of 4×10^6, but the Poisson's ratios are assumed equal.

No pressure cells were installed under the pavement at the location of the load test conducted in the thickened end of the taxiway. Under this test the maximum deflection was slightly less than was obtained in the loading of the uniform thickness portion of the slab as might be expected.

CONCLUSIONS

A number of conclusions may be drawn on the basis of the data and the performance of the instruments used in the prestressed pavement:

1. The couplers were properly designed and a link of this description is a satisfactory device for measuring prestressing forces, the distribution of these forces along the length of the tendons, and the adjustment of these forces with time.

2. Carlson strain meters are a satisfactory means of extracting strain data from pavement. They cannot, however, distinguish between the strains due to prestressing and those caused by other factors such as shrinkage and creep.

3. The pressure cells were properly designed and installed and they functioned satisfactorily, but they were too few to define a pressure pattern adequately

4. The use of flexible ducts results in a considerable diminution of prestressing load over the length of a tendon. This is apparently due to friction caused by sagging and misalignment. That this loss will occur can be predicted, however, and a correction can be applied to jacking loads to insure adequate concrete stresses remote from the point of load application (See Figure 18). Substantially less friction losses appear where rigid ducts are used.

5. Strains in the concrete caused by prestressing are not immediately apparent except in areas close to the point of load application. At remote locations, such as at the quarter point or the center, the slab must adjust for several days before the meters sense any strain due to load.

6. Compressive strains in the concrete continue to increase with time while tendon forces decrease.

7. The decrease of tendon forces with time is partially the result of a shortening of the slab because of shrinkage; some is due to increased pavement temperature coupled with a difference in coefficients of thermal expansion of concrete and prestressing steel; the major portion, however, is apparently the result of adjustment of the tendons in their ducts.

8. Load tests are valuable but should be made on the pavement before prestressing as well as afterward in order that the effect on prestressing can be directly evaluated.

9. Reasonably good proportionality appears to exist between deflection and pressure immediately under the pavement. This is true also of deflection and pressure under the base course.

10. On the basis of radius of relative stiffness, and assuming a relatively low subgrade modulus, the six-inch section of prestressed pavement is the equivalent of more than eleven inches of conventional pavement.

FUTURE WORK

It is planned to continue the observation of coupler and strain meter data on a bi-monthly basis during the remainder of the first year of the pavement life. After that data will be taken semi-annually for two years. Under this schedule the pavement will be exposed to three complete cycles of weather and will have been in operational use for approximately two years.

ACKNOWLEDGMENTS

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A

DATE	A-15	A-16	A-17	B-15	B-16	B-17	F-15	F-16	F-17	G-15	G-16
						LONGITUDINAL					
2-2-60			73.6			67.2			59.8		
			70.4			67.2			60.2		
*		30.9	69.8		35.1	66.7		39.5	61.9		35.4
		39.5	69.8		35.4	66.6		39.4	61.9		36.0
		49.8	69.7		44.4	66.5		39.9	61.9		44.3
		59.4	69.7		52.6	66.5		47.6	61.9		53.3
		68.7	69.6		61.2	66.4		55.1	61.8		61.4
		73.8	69.6		65.6	66.3		59.4	61.8		65.9
**		50.0	69.3		57.3	66.0		59.0	61.4		65.3
*	30.8	50.0	69.1	37.2	57.1	65.6	36.5	44.2	61.1	32.8	64.9
	39.3	49.9	69.0	37.3	57.1	65.6	36.5	44.1	61.1	38.2	64.9
	49.9	49.9	69.0	41.9	57.1	65.5	43.2	44.1	61.1	47.8	64.9
	59.9	49.9	69.0	50.1	57.0	65.5	51.4	44.1	61.0	57.7	64.8
2-2-60	69.5	49.9	69.0	58.0	57.0	65.4	60.4	44.1	61.0	66.7	64.7
2-2-60	74.6	49.9	68.9	62.1	57.0	65.4	60.3	44.1	61.0	66.5	64.7
2-2-60	71.6	49.9	68.9	62.0	57.0	65.4	60.2	44.1	60.1	66.4	64.7
2-2-60	70.4	49.6	68.1	61.7	57.0	65.2	59.8	58.4	60.7	65.6	64.3
2-3-60	70.4	50.4	68.2	62.5	57.6	65.8	60.8	59.7	62.1	66.0	64.8
2-3-60	70.1	50.4	67.7	62.3	57.5	65.5	60.7	59.7	62.0	65.7	64.6
2-4-60	70.0	50.4	67.7	62.7	57.6	65.7	61.1	60.0	62.5	65.7	64.6
2-5-60	69.8	50.3	67.4	62.5	57.2	65.4	60.8	59.7	61.9	65.4	64.5
2-5-60	69.6	50.1	67.2	62.3	57.0	65.2	60.7	59.5	61.6	65.3	64.1
2-8-60	69.2	49.8	66.7	62.0	56.7	64.7	60.3	59.2	61.2	64.9	64.0
2-8-60	69.1	49.8	66.4	61.9	56.7	64.6	60.3	59.2	61.2	65.2	64.1
2-9-60	69.0	49.6	66.4	62.1	56.7	64.7	60.4	59.2	61.1	64.9	64.0
2-9-60	69.0	49.6	66.4	62.1	56.6	64.6	60.3	59.2	61.0	64.9	64.0
2-9-60	68.9	49.5	66.4	62.1	56.6	64.6	60.3	59.2	61.1	64.9	63.9
2-9-60	68.9	49.5	66.3	62.1	56.7	64.6	60.3	59.2	61.1	64.8	63.9
2-9-60	69.3	50.0	66.6	62.1	56.8	64.6	60.3	59.2	61.1	64.8	63.8
2-9-60	69.4	50.0	66.6	62.2	56.8	64.6	60.4	59.2	61.2	64.8	63.9
2-11-60	69.0	67.6	66.3	60.7	65.4	63.1	59.0	60.4	59.5	63.5	64.5
2-13-60	68.6	66.0	65.9	60.7	64.6	62.6	58.6	60.2	59.4	63.0	63.9
2-17-60	68.5	65.4	65.8	60.5	63.8	62.3	58.5	59.7	60.0	63.0	63.5
3-2-60	68.1	67.3	65.2	60.0	61.8	61.2	58.0	59.2	59.7	62.3	62.6
3-31-60	65.0	59.8	63.3	58.4	58.6	58.9	56.7	58.1	57.1	58.9	59.7
5-2-60	61.9	56.0	61.9	56.7	56.7	57.1	55.9	57.4	55.6	58.2	56.7
5-3-60	62.7	56.2	62.4	57.5	57.6	58.0	56.8	58.5	56.7	59.0	57.6
6-6-60	57.9	49.8	59.1	53.0	53.5	54.0	54.0	55.5	52.9	53.1	50.0
7-11-60	55.4	46.0	55.9	49.3	51.4	51.2	52.1	53.3	51.1	47.0	44.7

* Note that loads on interior couplers are higher than on end couplers. I releasing of full prestressing load applied during jack verification.

** Difficulty with tendon locking device caused drop in load. Full load wa (2/11/60).

TABLE I

INSTRUMENTED TENDON LOADS (kips)

							TRANSVERSE									Average	
17	G-15	G-16	G-17	H-15	H-16	H-17	C-81	C-82	C-83	D-81	D-82	D-83	E-81	E-82	E-83	Temp°F	OP.
.8			69.7			74.1										46.1	Fu
.2			69.8			71.1											Ja
.9		35.4	68.9		31.2	70.2											Te
.9		36.0	68.8		40.6	70.2											"
.9		44.3	68.8		50.2	70.2											"
.9		53.3	68.8		60.8	70.1											"
.8		61.4	68.8		71.0	70.1											"
.8		65.9	68.7		76.2	70.1											Ful
.4		65.3	68.5		63.7	69.9											Jac
.1	32.8	64.9	68.2	31.0	63.4	69.8											Ten
.1	38.2	64.9	68.2	40.6	63.4	69.8											"
.1	47.8	64.9	68.1	50.6	63.4	69.7											"
.0	57.7	64.8	68.1	61.3	63.3	69.7											"
.0	66.7	64.7	68.0	70.9	63.3	69.7											"
.0	66.5	64.7	68.0	70.3	63.3	69.7											Ful
.1	66.4	64.7	68.0	68.8	63.3	69.7											Jac
.7	65.6	64.3	67.6	67.9	62.9	69.2										58.2	End
.1	66.0	64.8	67.9	67.8	63.2	69.1	51.8	50.9		51.7		50.2		50.8		47.7	Ten
.0	65.7	64.6	67.7	67.8	63.0	68.8										48.8	(Ja
.5	65.7	64.6	67.7	67.8	62.9	69.0										46.0	
.9	65.4	64.5	67.5	67.7	62.8	68.7										49.6	Str
.6	65.3	64.1	67.3	67.3	62.7	68.5	49.9	50.1	COUPLER DAMAGED	48.9	COUPLER DAMAGED	49.1	COUPLER DAMAGED	49.6	COUPLER DAMAGED	49.5	
.2	64.9	64.0	66.8	67.4	62.7	68.1	49.5	50.0		48.7		48.8		49.4		54.0	
.2	65.2	64.1	66.8	66.9	62.9	68.0										55.1	
.1	64.9	64.0	66.8	66.8	62.4	67.9										51.8	
.0	64.9	64.0	66.8	66.7	62.4	67.9											
.1	64.9	63.9	66.7	66.8	62.3	67.9											
.1	64.8	63.9	66.7	66.8	62.3	67.9											Str
.1	64.8	63.8	66.7	67.1	63.0	67.8											
.2	64.8	63.9	66.7	67.3	63.0	67.8											
.5	63.5	64.5	65.4	66.9	69.6	67.4	49.2	49.8		48.4		48.6		48.8		57.5	
.4*	63.0	63.9	65.1	67.9	68.7	67.1										60.4	
.0	63.0	63.5	64.9	66.3	64.5	66.8										60.7	Gro
7	62.3	62.6	64.1	65.5	67.8	66.4	48.7	48.9		47.7		48.0		48.5		61.7	
1*	58.9	59.7	62.3	65.4	66.0	64.9	47.3	48.2		46.0		47.0		45.9		76.1	
6	58.2	56.7	60.3	58.3	64.7	64.2	46.3	47.6				46.1				85.5	
7	59.0	57.6	61.2	55.9	65.2	64.5										68.0	
9	53.1	50.0	55.6	57.3	61.9	62.1	44.2	45.9				48.4				103.8	
1	47.0	44.7	51.2	51.0	58.3	59.9	41.6	44.1				40.6				105.5	

nd couplers. Interior couplers did not reflect complete
erification.

. Fuil load was not again applied until end of prestressing

B

C

ADS (kips)

...7	TRANSVERSE C-81	C-82	C-83	D-81	D-82	D-83	E-81	E-82	E-83	Average Temp°F	OPERATION
1										46.1	Full jacking load on tendon 17
1											Jack released
2											Tendon 16 jacked to 30k
2											" " " " 40k
2											" " " " 50k
1											" " " " 60k
1											" " " " 70k
1											Full jacking load on tendon16 75.5k
9											Jack released
8											Tendon 15 jacked to 30k
8											" " " " 40k
7											" " " " 50k
7											" " " " 60k
7											" " " " 70k
7											Full jacking load on tendom 15 75.5k
7											Jack released
2										58.2	End of work day
1	51.8	50.9	COUPLER DAMAGED	51.7	COUPLER DAMAGED	50.2	COUPLER DAMAGED	50.8	COUPLER DAMAGED	47.7	Tendons 81, 82, 83 fully stressed
8										48.8	(Jacking Load 52K)
0										46.0	
7										49.6	Stressing of transverse tendons
5	49.9	50.1		48.9		49.1		49.6		49.5	
1	49.5	50.0		48.7		48.8		49.4		54.0	
)										55.1	
)										51.8	
)											
)											
)											Stressing of longitudinal tendons
3											
3											
		49.2	49.8		48.4		48.6		48.8		57.5	
										60.4	
										60.7	Grouting of tendon ducts
	48.7	48.9		47.7		48.0		48.5		61.7	
	47.3	48.2		46.0		47.0		45.9		76.1	
	46.3	47.6				46.1				85.5	
										68.0	
	44.2	45.9				48.4				103.8	
	41.6	44.1				40.6				105.5	

ot reflect complete

til end of prestressing

A

LONGITUDINAL

DATE	A-15	A-16	A-17	B-15	B-16	B-17	F-15	F-16	F-17	G-15	G-16	G-[illegible]
2-2-60	0	0	0	0	0	0	0	0	0	0	0	0
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60												
2-2-60	-100	-75	-110									
2-3-60	- 91	-71	- 94									
2-3-60	- 99	-74	-103									
2-4-60	- 98	-78	-101									
2-5-60	- 98	-78	-105									
2-5-60	- 98	-79	-125									
2-8-60	-119	-68	-106									
2-8-60	-111	-91	-118									
2-9-60												
2-9-60												
2-9-60												
2-9-60												
2-9-60												
2-9-60	-108	-92	-118									
2-11-60	-114	-119	-124	-101	-112	-73	-105	-121	-118	-128	-132	-[illegible]
2-13-60	-124	-127	-134	-116	-127	-80	-112	-137	-111	-139	-138	-1[illegible]
2-17-60	-121	-126	-134	-130	-143	-90	-128	-160	-146	-145	-149	-1[illegible]
3-2-60	-125	-135	-147	-153	-178	-103	-151	-187	-165	-167	-179	-1[illegible]
3-31-60	-162	-236	-195	-197	-213	-180	-196	-240	-215	-209	-214	-1[illegible]
5-2-60	-188	-289	-211	-229	-261	-222	-227	-268	-254	-253	-250	-2[illegible]
5-3-60	-176	-215	-200	-169	-173	-155	-147	-187	-173	-168	-189	-1[illegible]
6-6-60	-233	-349	-263	-285	-297	-259	-268	-329	-312	-266	-286	-2[illegible]
7-11-60	-269	-354	-319	-340	-333	-313	-320	-369	-359	-281	-328	-3[illegible]

Minus (-) signs indicate compressive strains

B

TABLE II

STRAINS IN CONCRETE (10^{-6} in./in.)

15	G-16	G-17	H-15	H-16	H-17	C-81	C-82	C-83	D-81	D-82 (TRANSVERSE)	D-83	E-81	E-82	E-83	Average Temp°F
	0	0	0	0	0	0	0	0							46.1
			-103	-92	-110		-95	-65	-16	-22	-11	- 3	-71	-77	58.2
			- 97	-91	-109	- 1	-92	-74	- 1	-13	- 1		-66	-74	47.7
			-102	-95	-110	-64	-102	-75	- 8	-18	- 7	-73	-72	-80	48.8
			- 97	-94	-105	-71	- 96	-75	-64	-71	-52	-76	-71	-81	46.0
			-105	-94	-109	-69	-100	-75	-63	-71	-52	-81	-76	-84	49.6
			-105	-102	-117	-73	-100	-72	-63	-75	-56	-82	-80	-88	49.5
			-105	-1C2	-113	-74	-105	-71	-62	-73	-47	-86	-80	-88	54.0
			-123	-116	-135	-77	-113	-84	-84	-88	-65	-94	-92	-100	55.1
															51.8
															"
															"
															"
															"
			-117	-110	-129	-83	-111	-78	-79	-82	-64	-92	-87	-99	"
28	-132	-95	-124	-112	-139	-75	-117	-75	-62	-76	-50	-82	-79	-92	57.5
39	-138	-106	-141	-144	-154	-53	-118	-80	-46	-68	-45	-85	-82	-91	60.4
45	-149	-116	-140	-147	-154	-59	-123	-84	-58	-81	-53	-86	-82	-100	60.7
67	-179	-138	-158	-165	-171	-61	-122	-85	-88	-100	-67	-97	-94	-108	61.7
09	-214	-183	-204	-209	-225	-78	-148	-107	-128	-133	-157	-116		-132	76.1
53	-250	-230	-293	-231	-241	-119	-163	-120	-146	-140	-183	-134		-138	85.5
68	-189	-154	-201	-210	-225	-116	-155	-124	-125	-124	-170	-134	Meter Damaged	-128	68.0
66	-286	-265	-283	-294	-300	-161	-202	-161	-213	-203	-242	-175		-171	103.8
81	-328	-321	-348	-357	-374	-190	-243	-205	-305	-302	-295	-211		-210	105.5

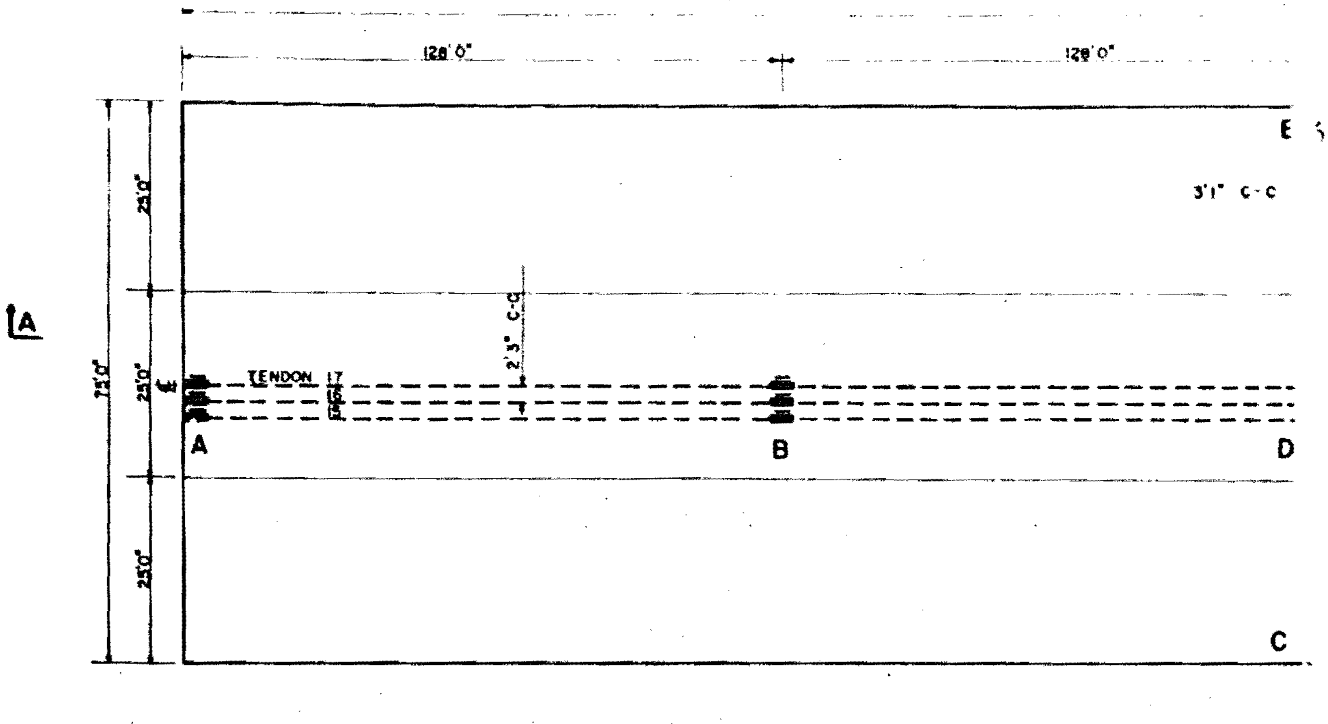
B C

0^{-6} in./in.)

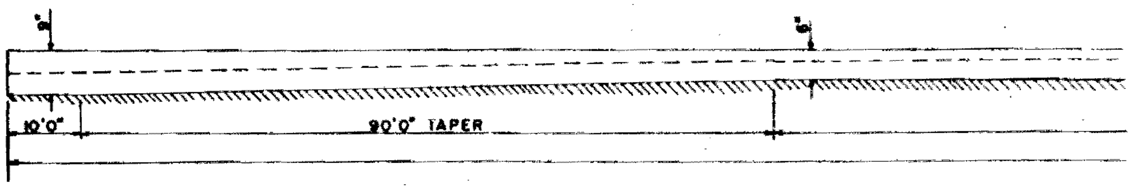
TRANSVERSE

C-82	C-83	D-81	D-82	D-83	E-81	E-82	E-83	Average Temp°F	OPERATION
0	0							46.1	Full jacking load on tendon 17
									Jack released
									Tendon 16 jacked to 30k
									" " " " 40k
									" " " " 50k
									" " " " 60k
									" " " " 70k
									Full jacking load on tendon 16 75.5k
									Jack released
									Tendon 15 jacked to 30k
									" " " " 40k
									" " " " 50k
									" " " " 60k
									" " " " 70k
									Full jacking load on tendon 15 75.5k
									Jack released
-95	-65	-16	-22	-11	- 3	-71	-77	58.2	End of work day
-92	-74	- 1	-13	- 1		-66	-74	47.7	Tendons 81, 82, 83 fully stressed
-102	-75	- 8	-18	- 7	-73	-72	-80	48.8	(Jacking Load 52K)
- 96	-75	-64	-71	-52	-76	-71	-81	46.0	
-100	-75	-63	-71	-52	-81	-76	-84	49.6	Stressing of transverse tendons
-100	-72	-63	-75	-56	-82	-80	-88	49.5	
-105	-71	-62	-73	-47	-86	-80	-88	54.0	
-113	-84	-84	-88	-65	-94	-92	-100	55.1	
								51.8	
								"	
								"	Stressing of longitudinal tendons
								"	
								"	
-111	-78	-79	-82	-64	-92	-87	-99	"	
-117	-75	-62	-76	-50	-82	-79	-92	57.5	
-118	-80	-46	-68	-45	-85	-82	-91	60.4	
-123	-84	-58	-81	-53	-86	-82	-100	60.7	Grouting of tendon ducts
-122	-85	-88	-100	-67	-97	-94	-108	61.7	
-148	-107	-128	-133	-157	-116		-132	76.1	
-163	-120	-146	-140	-183	-134	Meter Damaged	-138	85.5	
-155	-124	-125	-124	-170	-134		-128	68.0	
-202	-161	-213	-203	-242	-175		-171	103.8	
-243	-205	-305	-302	-295	-211		-210	105.5	

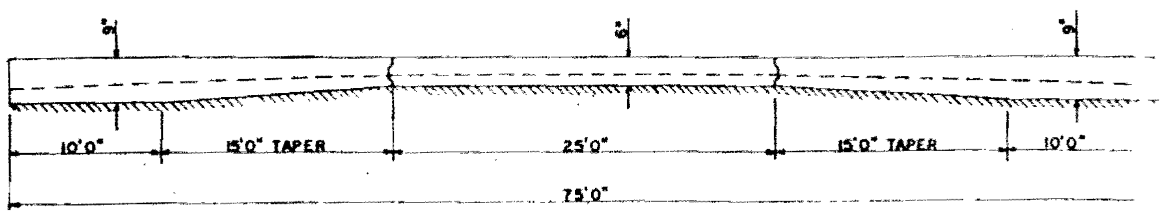
A



PLAN

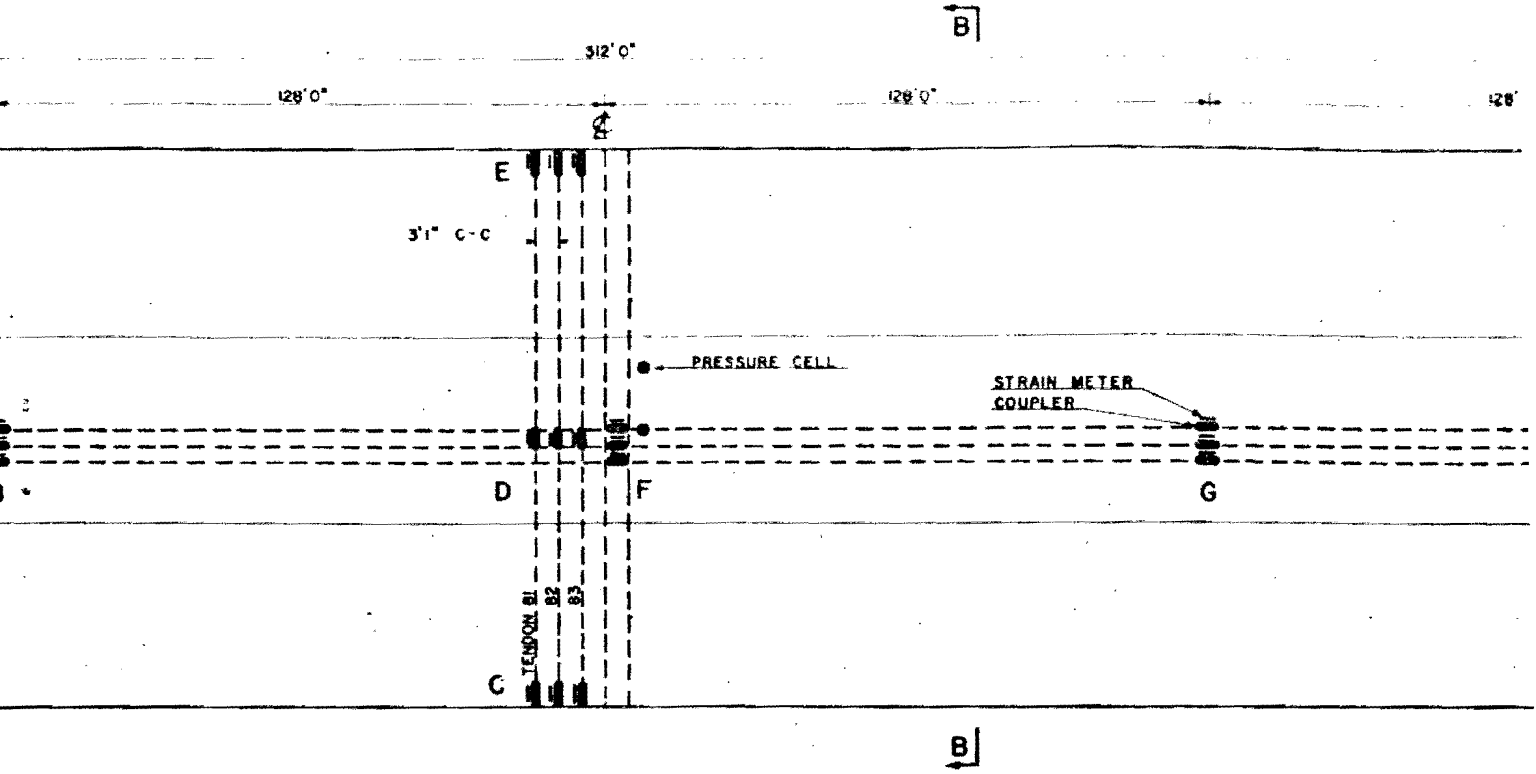


SEC



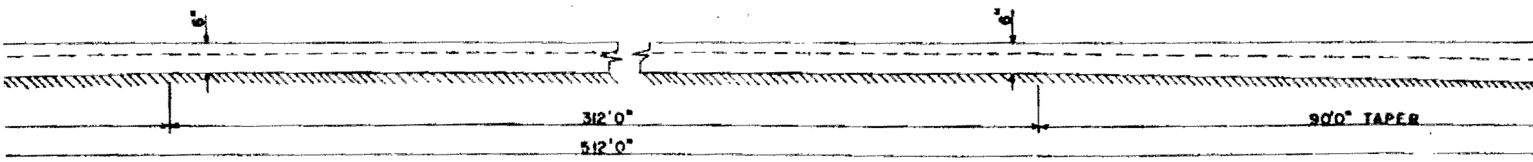
SECTION BB

B

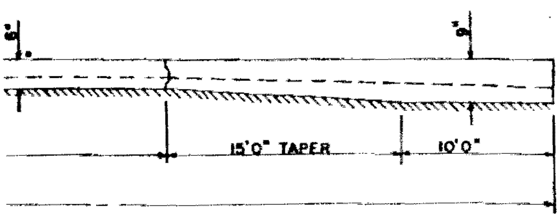


PLAN OF TAXIWAY

NO SCALE

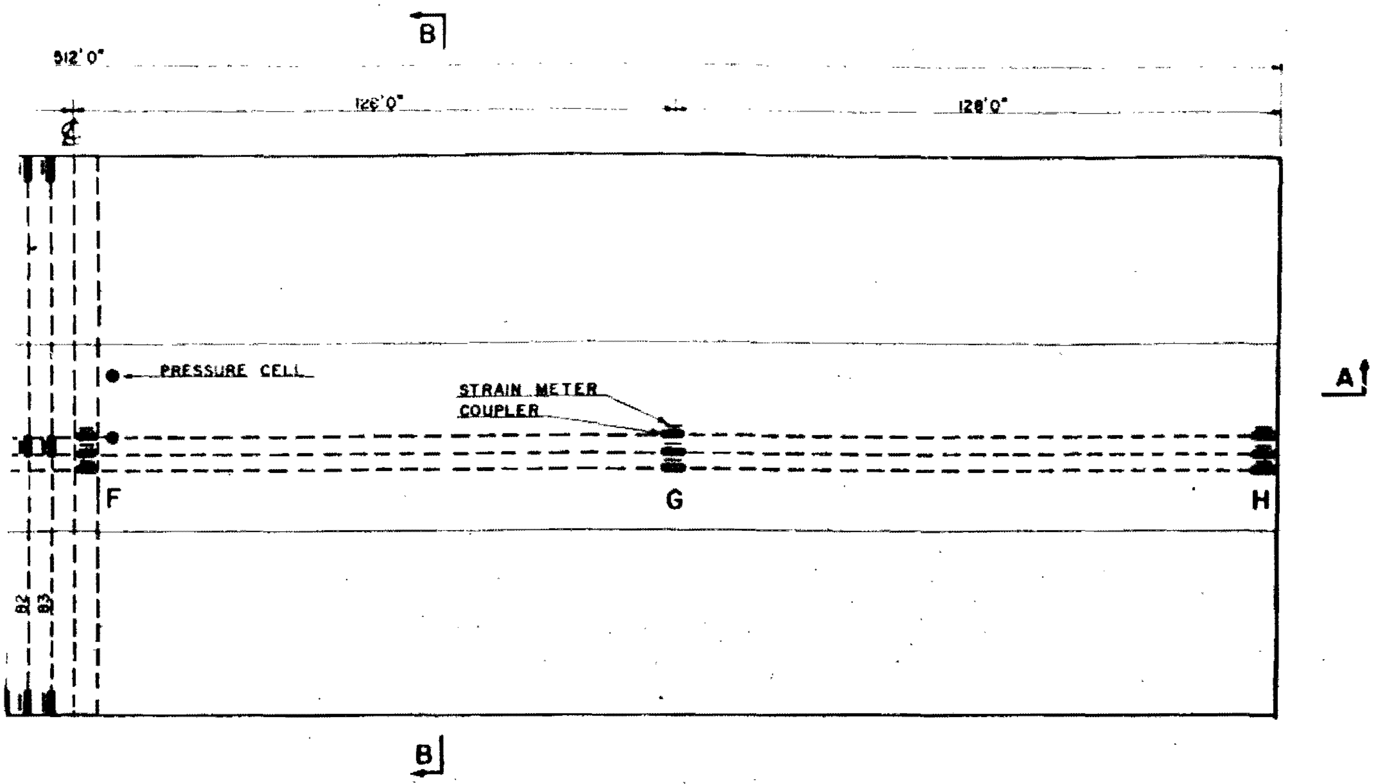


SECTION AA

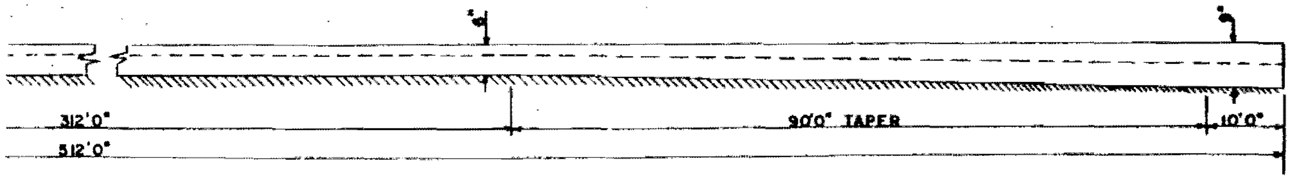


BB

B C



)F TAXIWAY
) SCALE



CTION AA

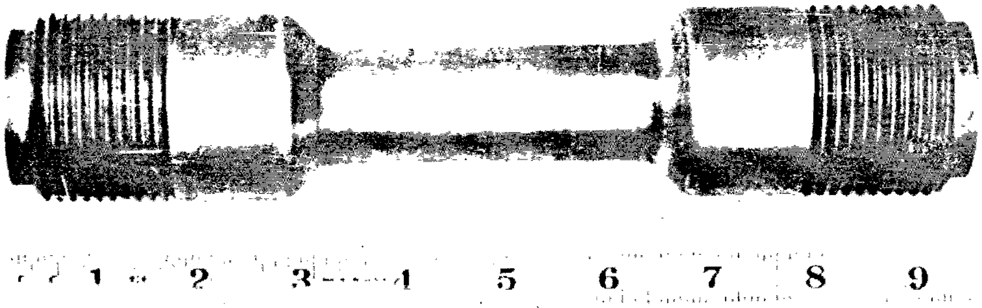


Figure 2. Coupler as manufactured.

Figure 3. 2-AB-7 gauges, 2-more opposite side.

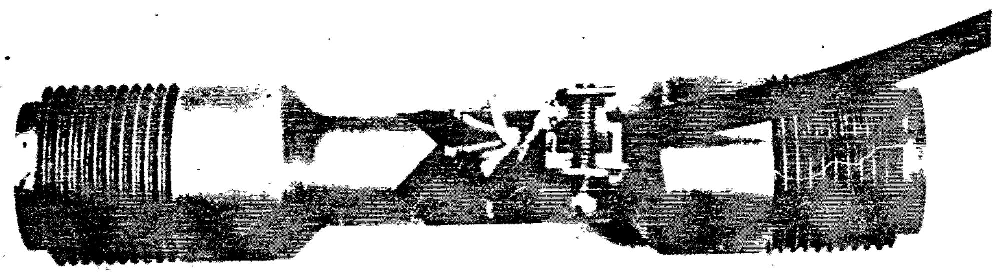


Figure 4. Gauges insulated and connected to leads.

Figure 5. Further waterproofing with petrosene wax.

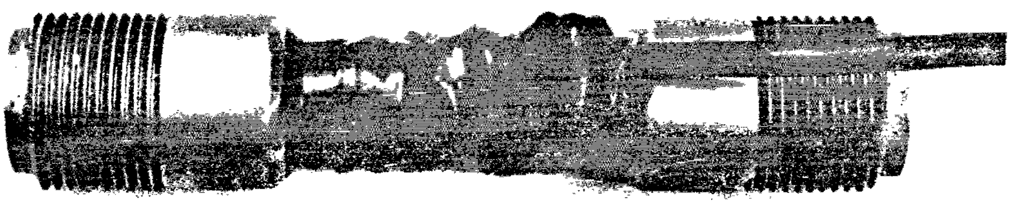


Figure 6. Final covering — scotch-electric tape

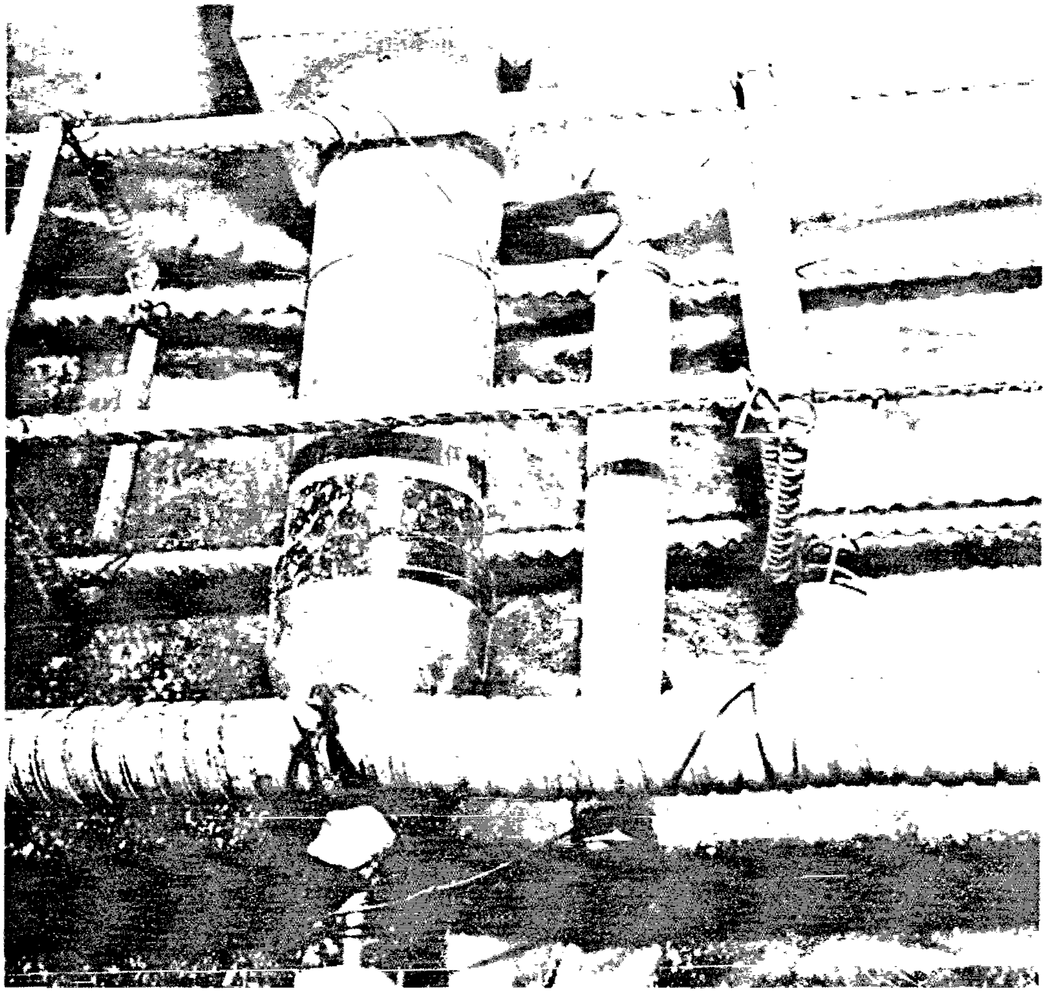


Figure 7. Close-up of carlson strain meter in place.

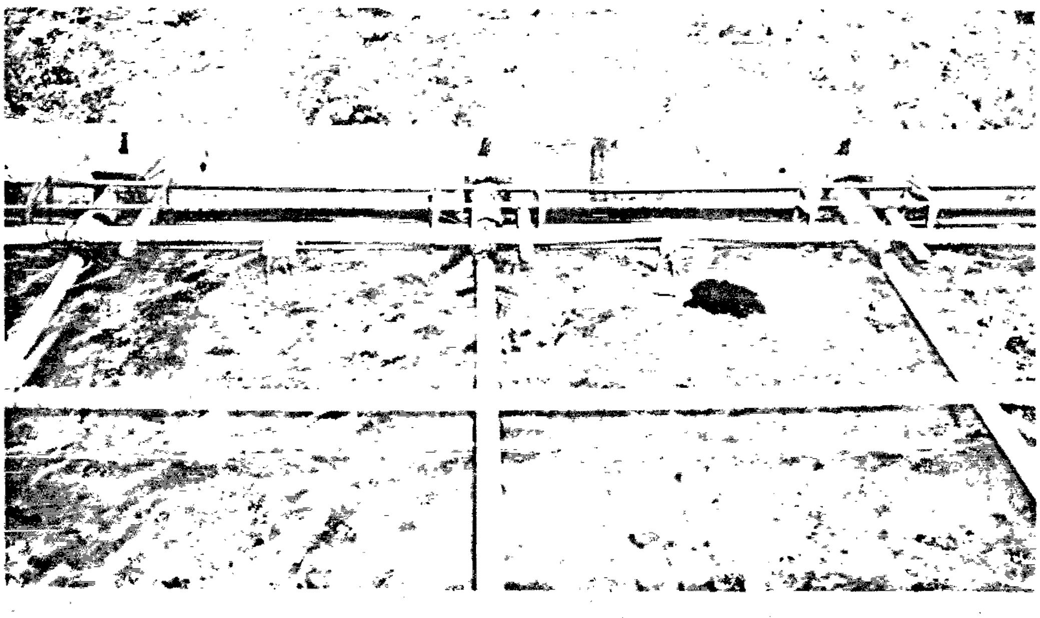


Figure 8. Carlson strai[illegible]

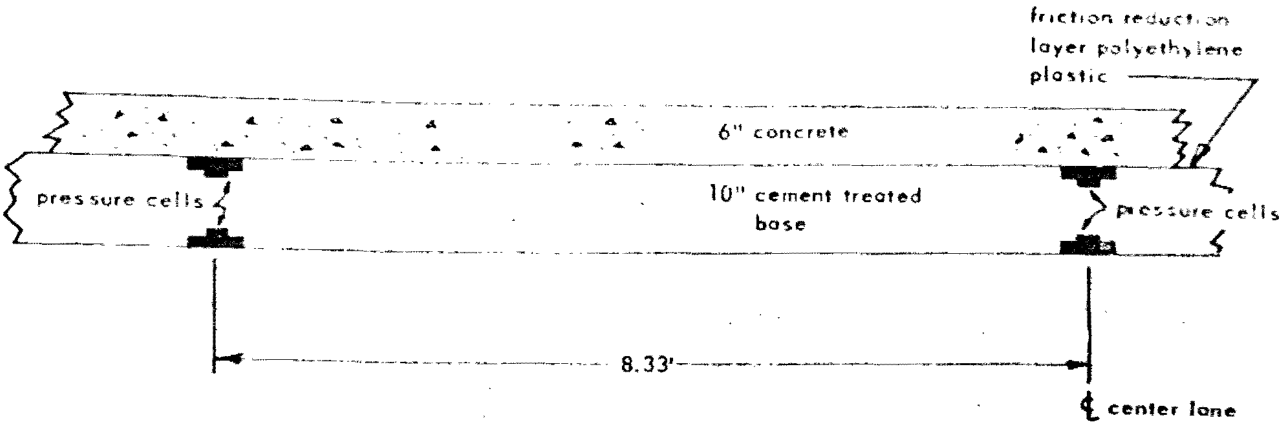


Figure 9. Arrangement of pressure cells.

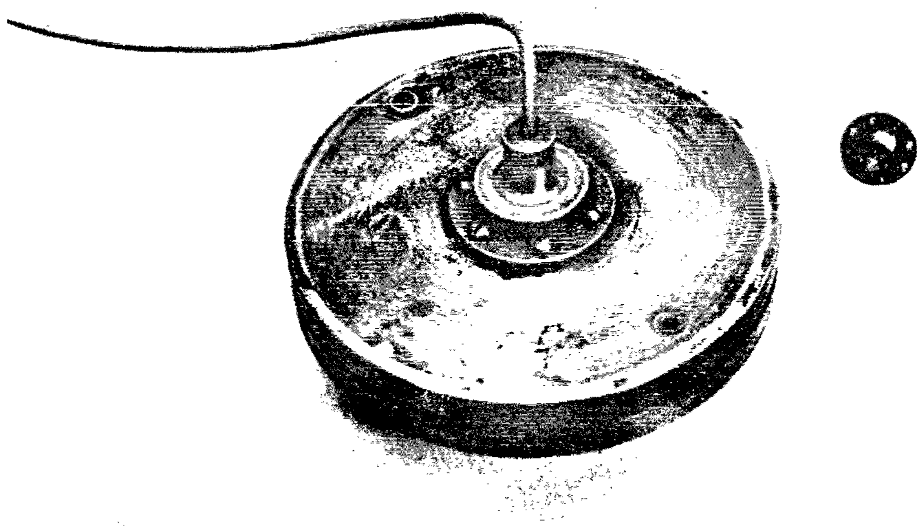
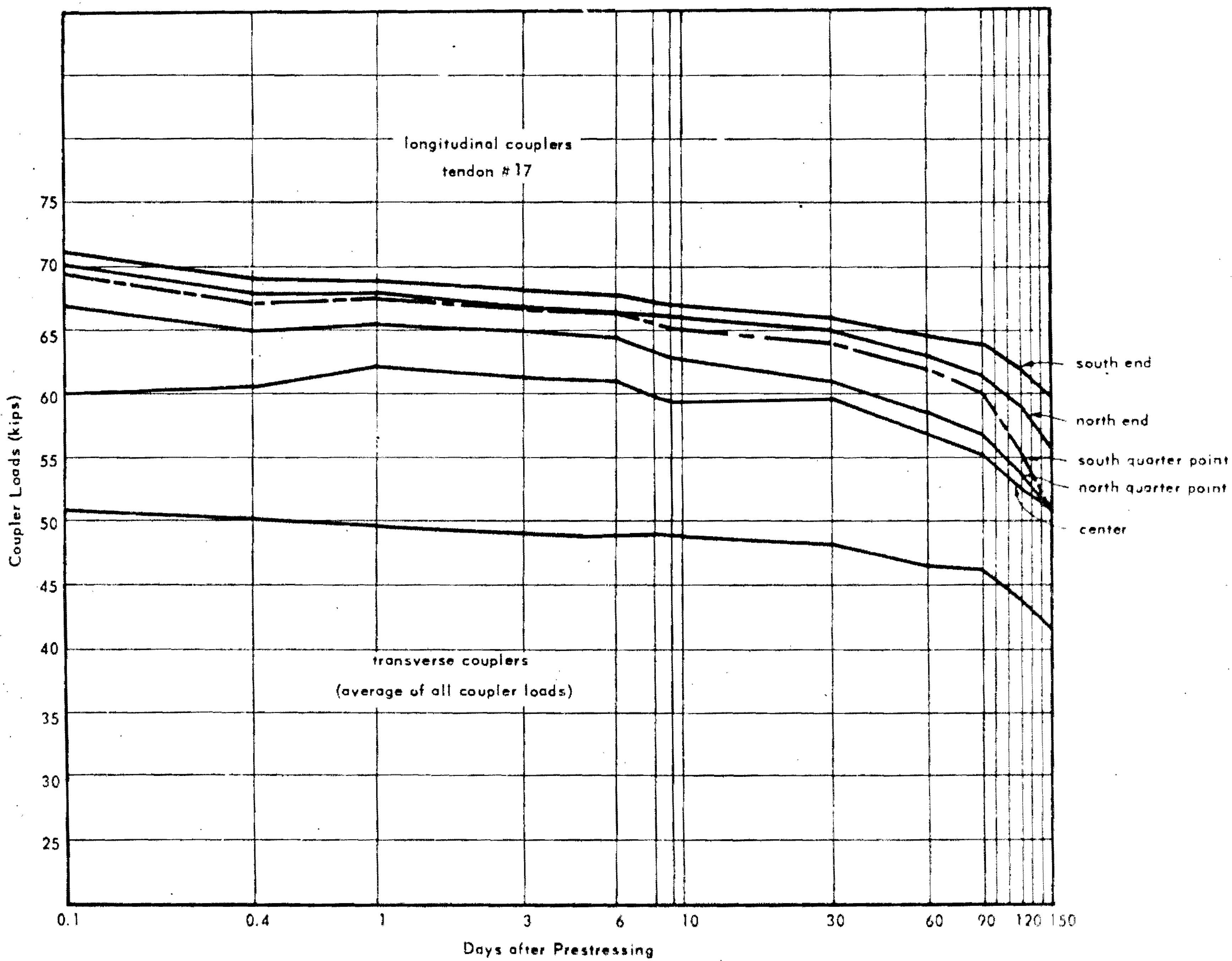


Figure 10. Pressure pickup and assembled cell.



longitudinal couplers
tendon # 17
transverse couplers
(average of all coupler loads)
south end
north end
south quarter point
north quarter point
center
Coupler Loads (kips)
75
70
65
60
55
50
45
40
35
30
25
0.1
0.4
1
3
6
10
30
60
90
120
150
Days after Prestressing

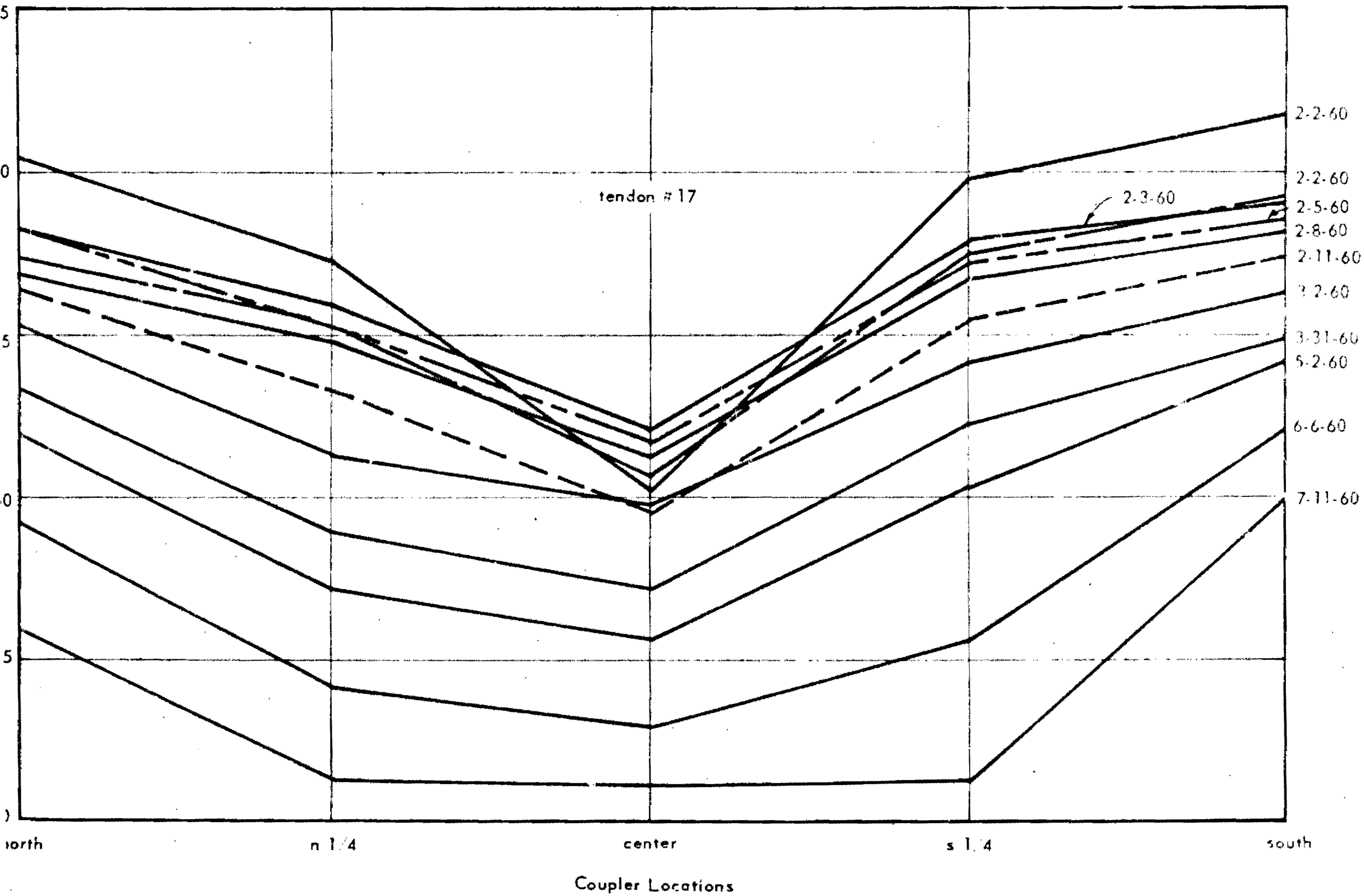


Figure 12. Longitudinal coupler loads.

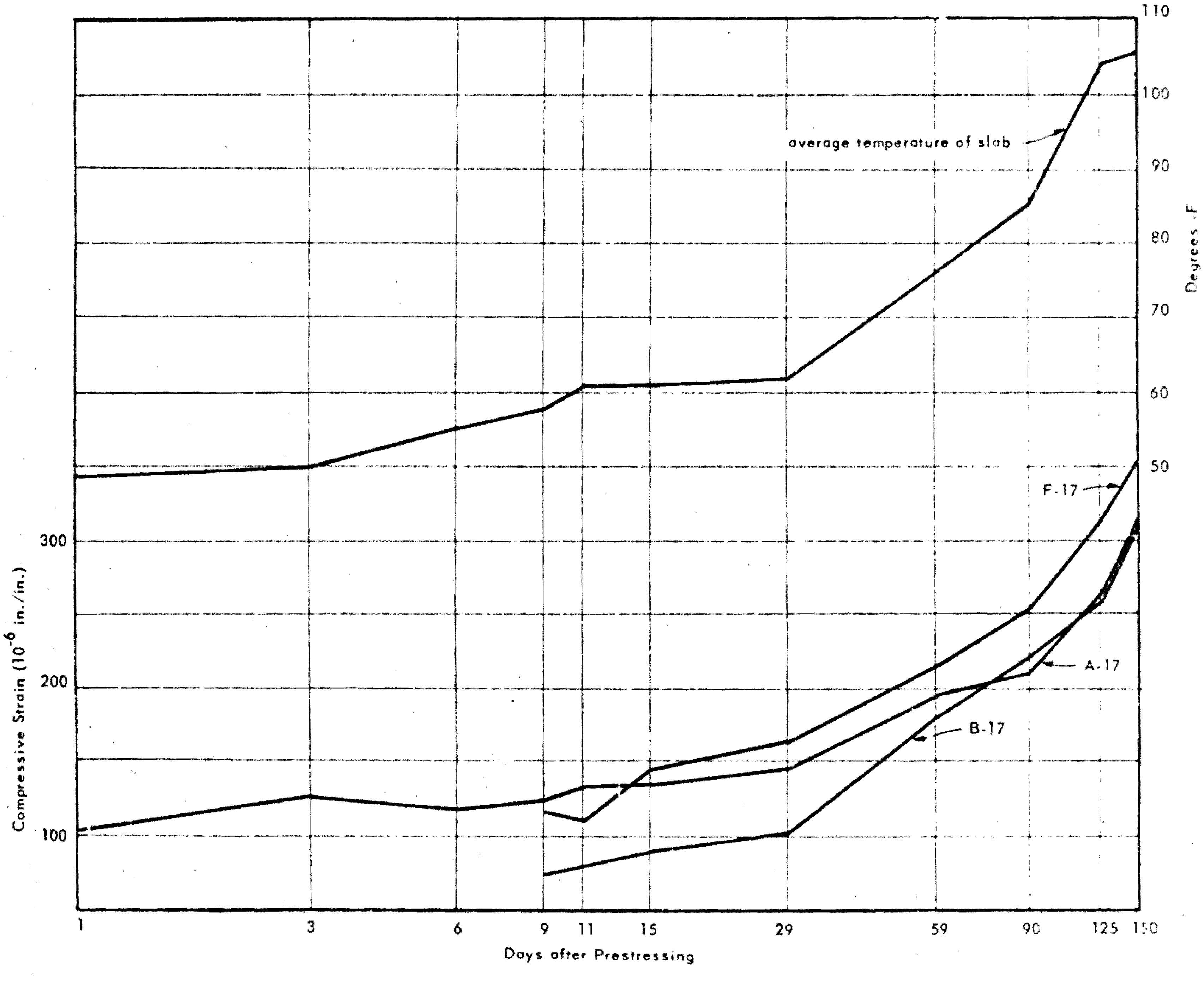


Figure 13. Strains in concrete (longitudinal).

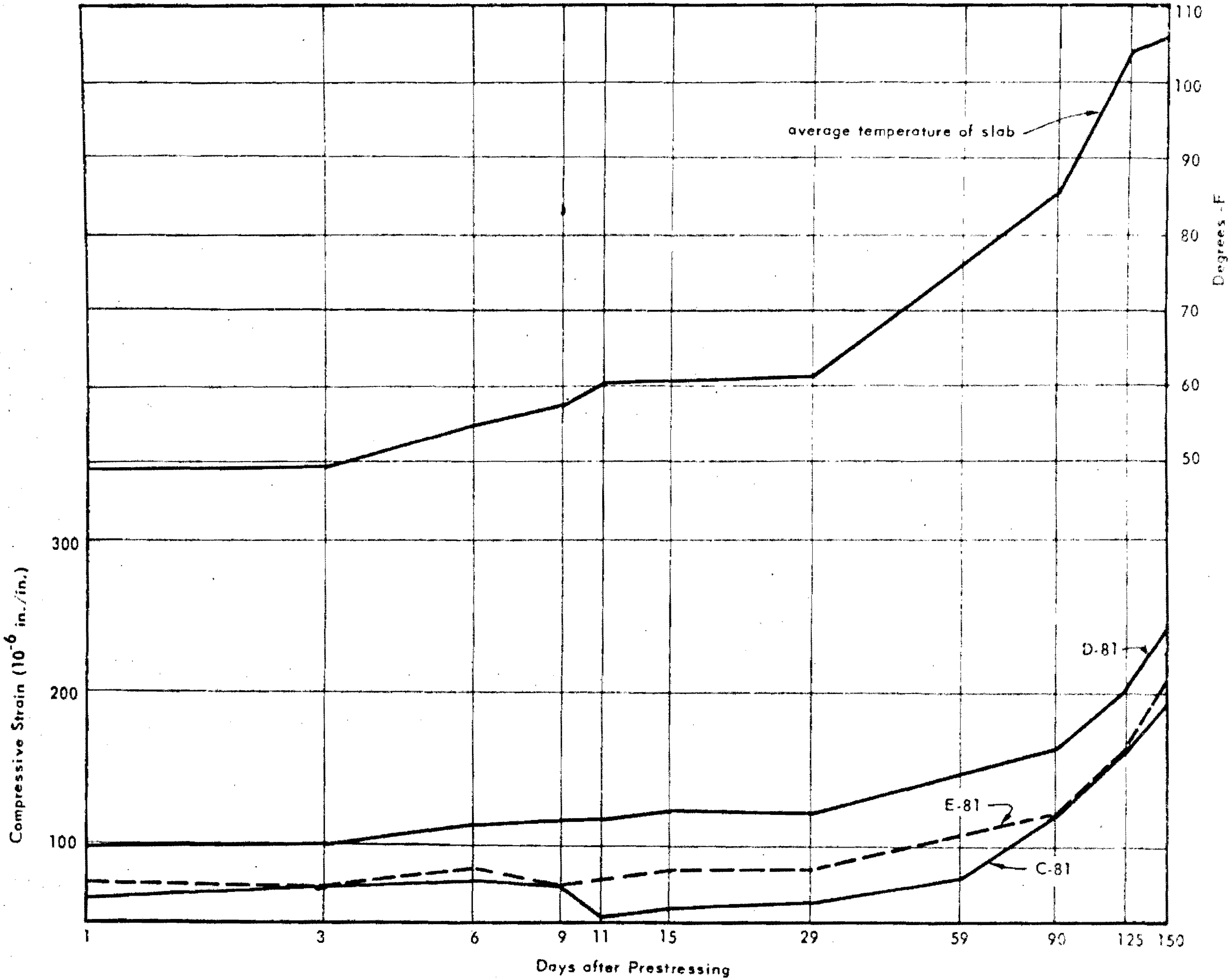


Figure 14. Strains in concrete (transverse).

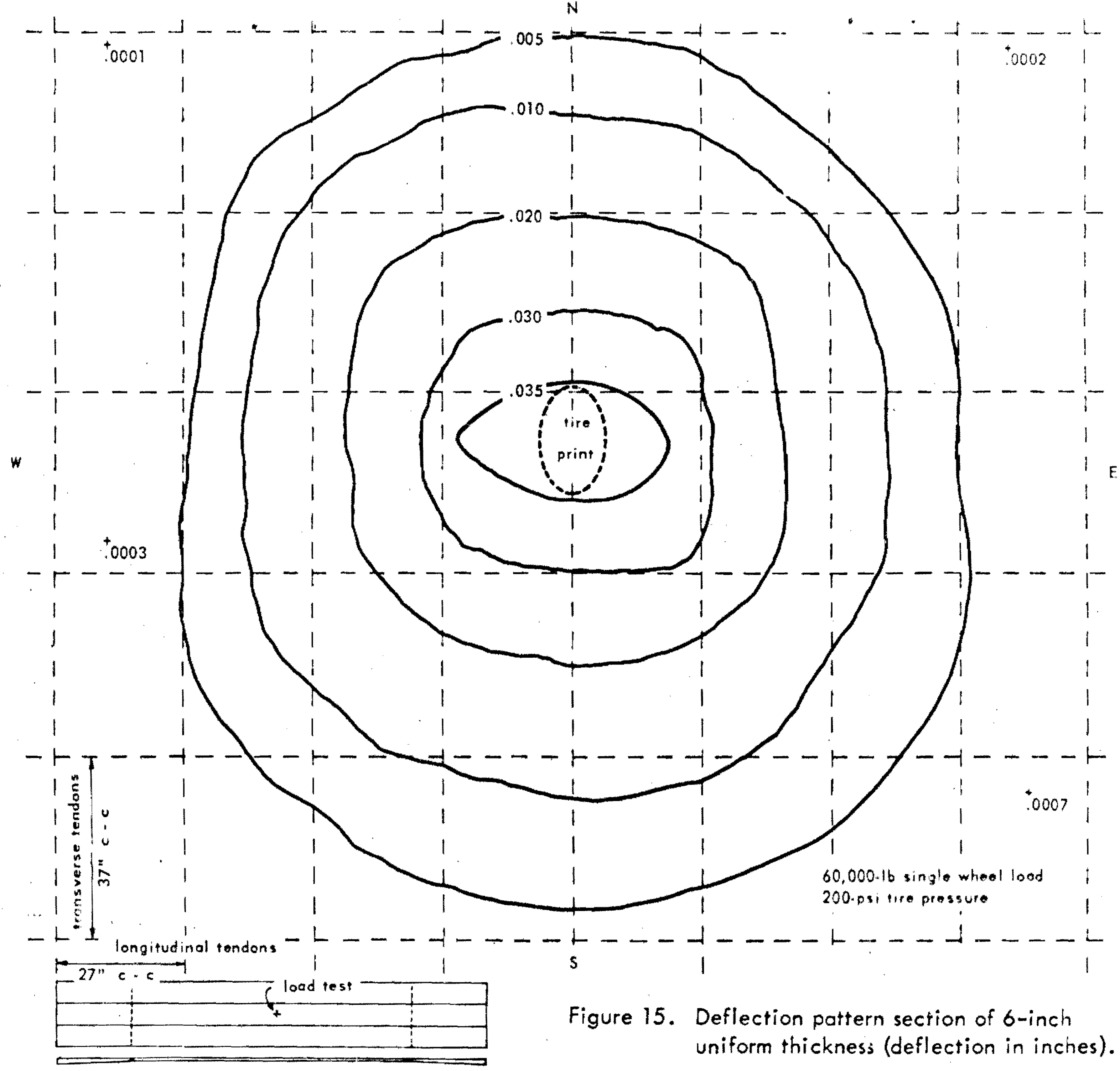


Figure 15. Deflection pattern section of 6-inch uniform thickness (deflection in inches).

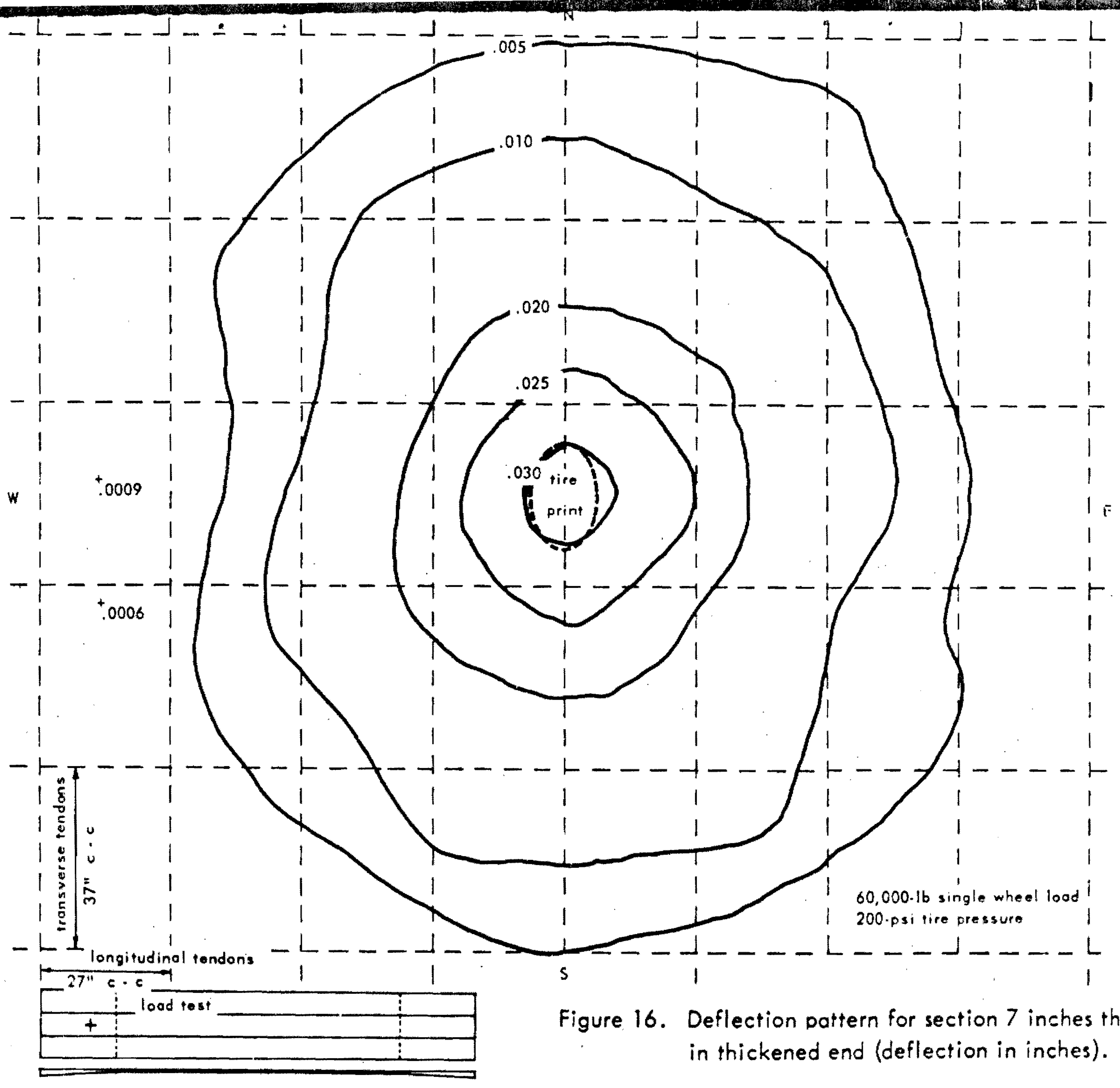
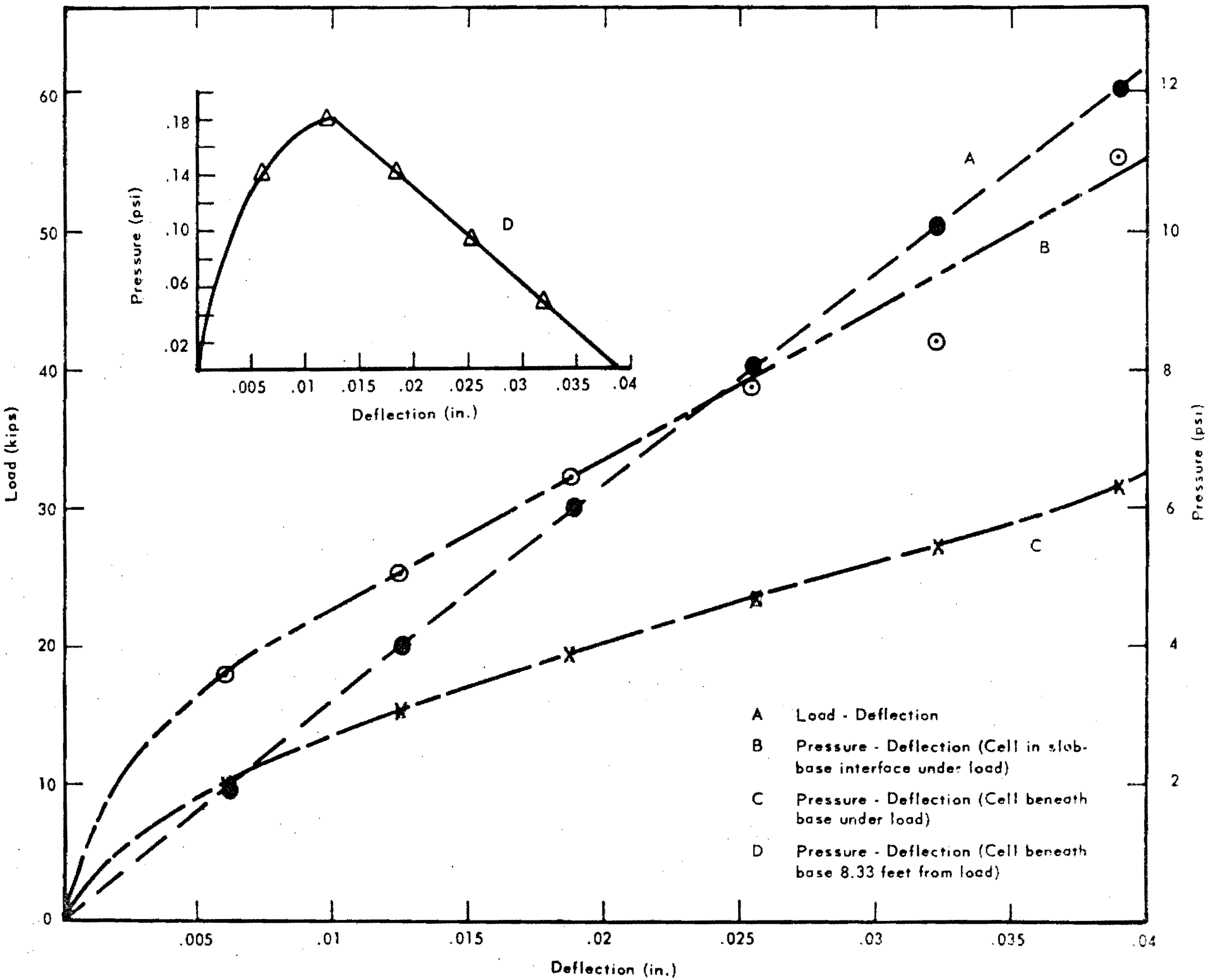


Figure 16. Deflection pattern for section 7 inches thick in thickened end (deflection in inches).



Pressure (psi)
.18
.14
.10
.06
.02
.005
.01
.015
.02
.025
.03
.035
.04
Deflection (in.)
D
A
B
C
Load (kips)
60
50
40
30
20
10
0
12
10
8
6
4
2
Pressure (psi)
.005
.01
.015
.02
.025
.03
.035
.04
Deflection (in.)
A Load - Deflection
B Pressure - Deflection (Cell in slab-base interface under load)
C Pressure - Deflection (Cell beneath base under load)
D Pressure - Deflection (Cell beneath base 8.33 feet from load)

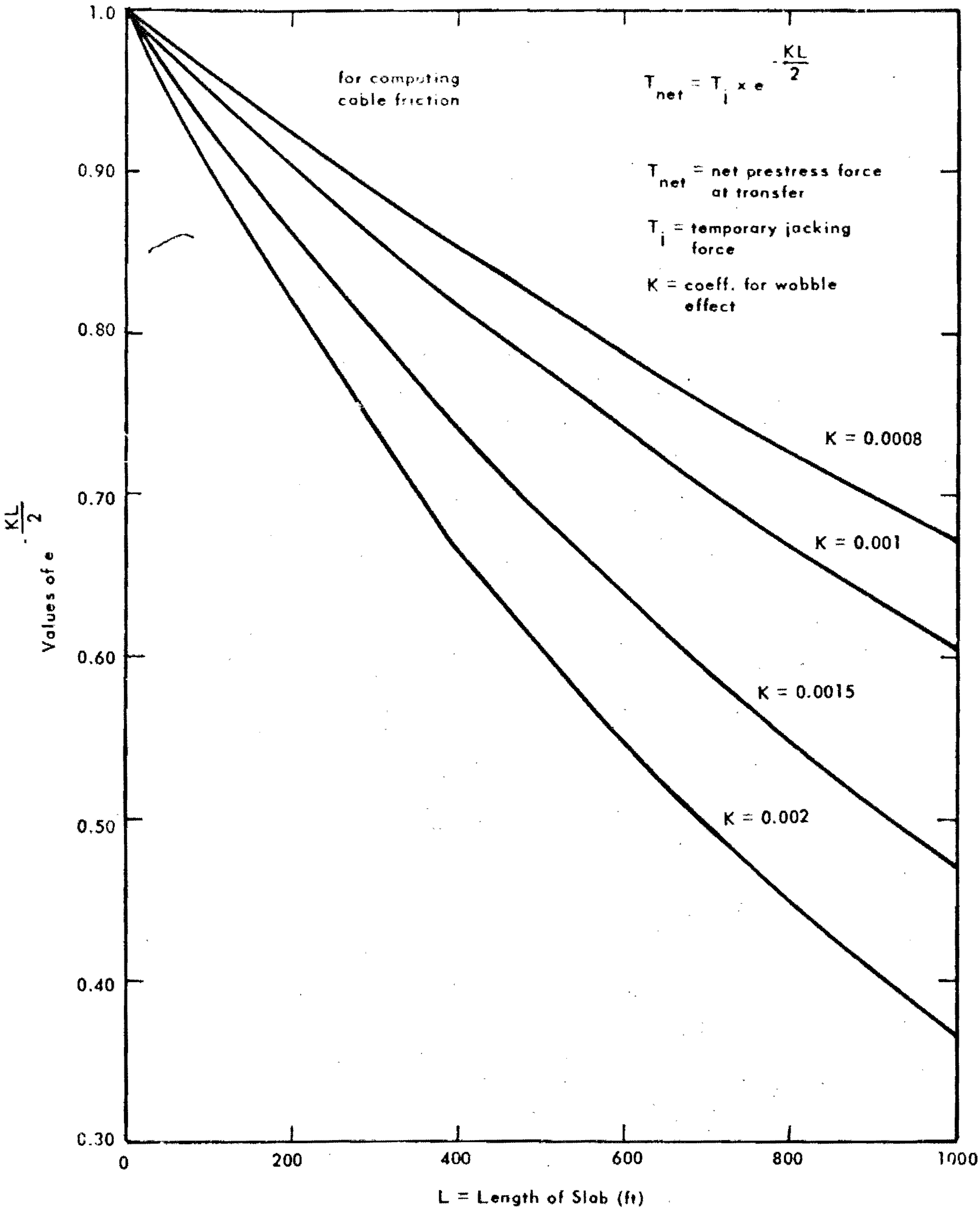
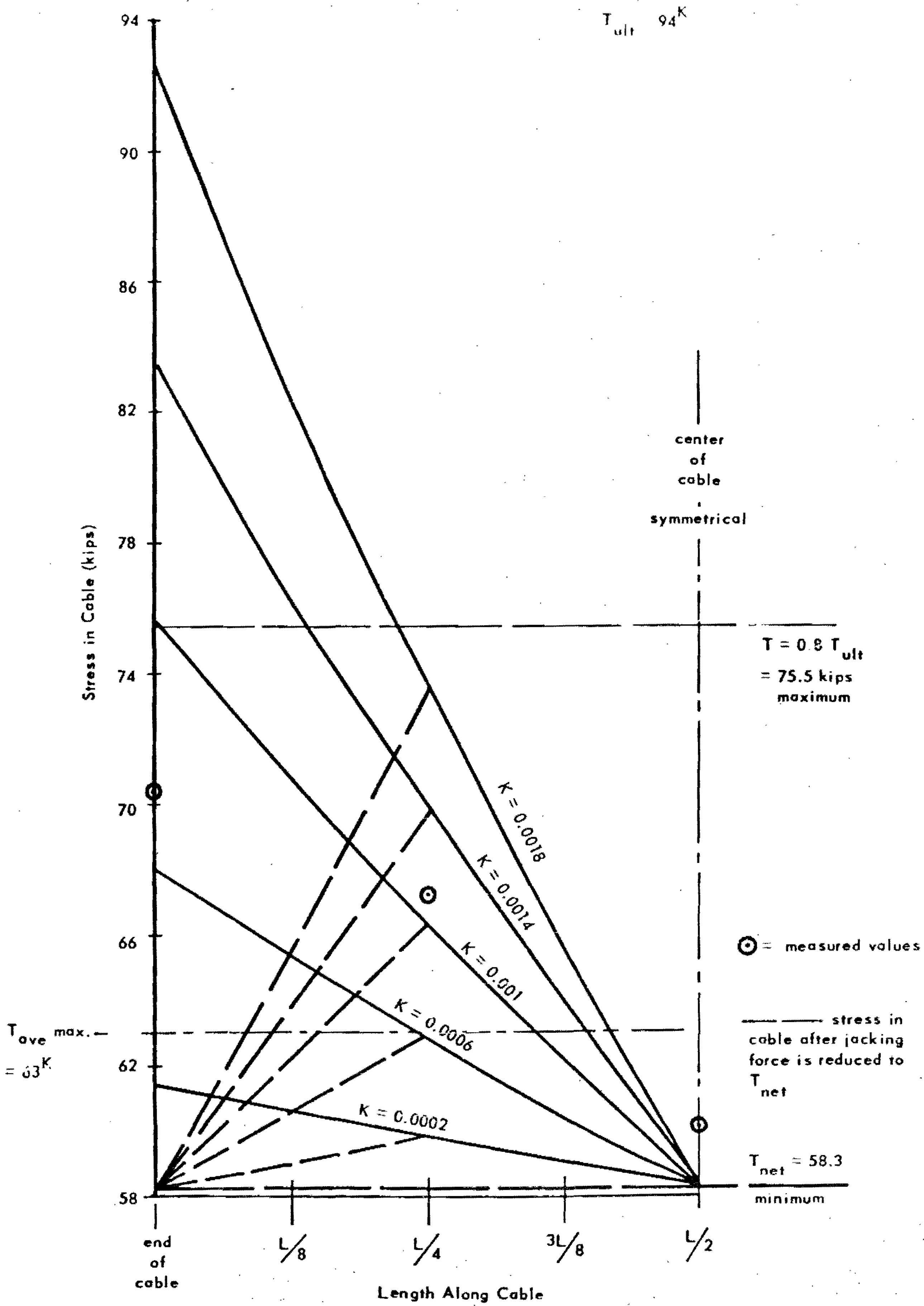
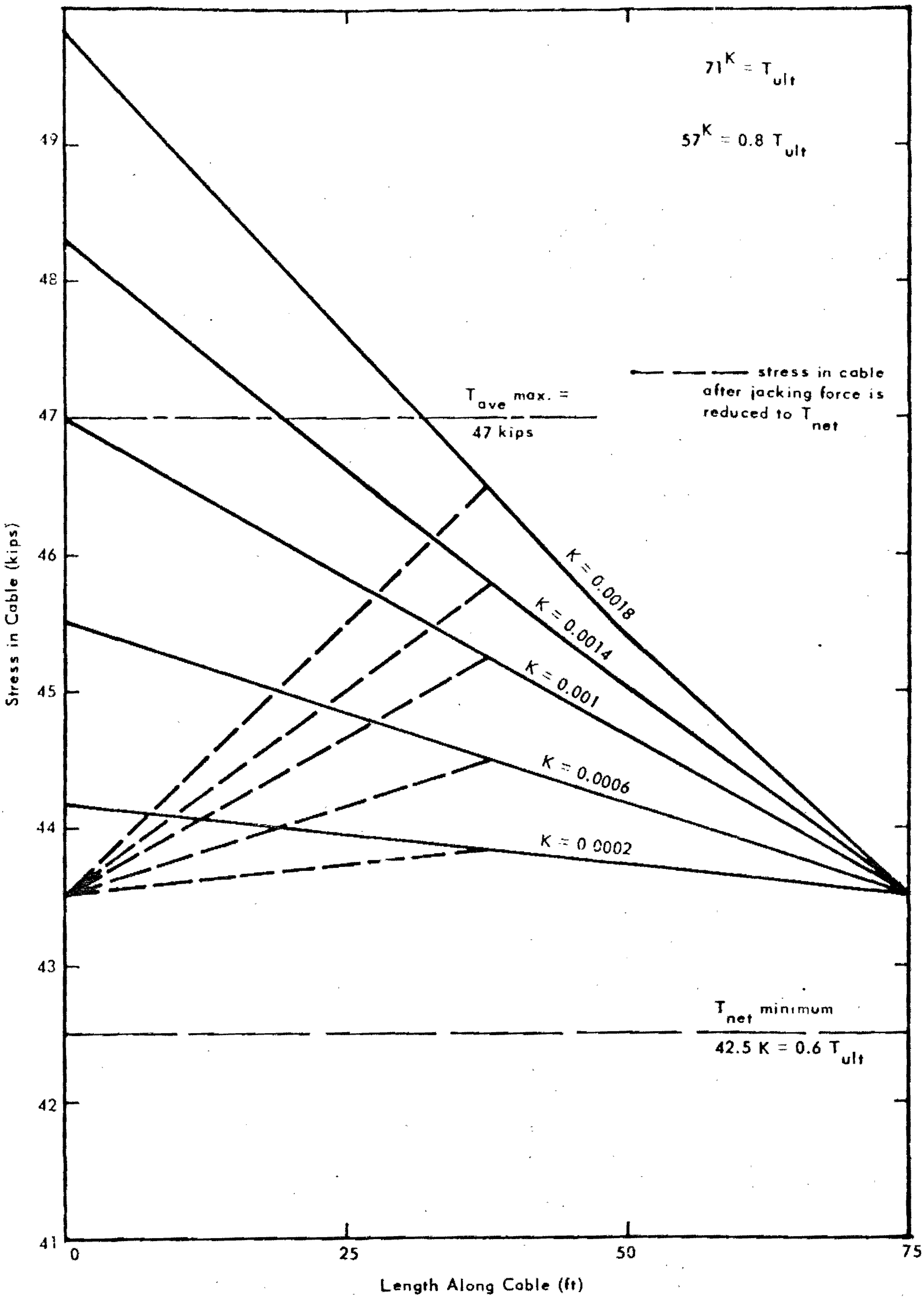


Figure 18. Variation of $e^{-\frac{KL}{2}}$ with K (wobble effect).



T ult 94K
94
90
86
82
78
74
70
66
62
58
Stress in Cable (kips)
center
of
cable
symmetrical
T = 0.8 T ult
= 75.5 kips
maximum
K = 0.0018
K = 0.0014
K = 0.001
K = 0.0006
K = 0.0002
= measured values
T ave max.
= 63K
stress in
cable after jacking
force is reduced to
T net
T net = 58.3
minimum
end
of
cable
L/8
L/4
3L/8
L/2
Length Along Cable



71K = T ult
57K = 0.8 T ult
stress in cable after jacking force is reduced to T net
T ave max. = 47 kips
K = 0.0018
K = 0.0014
K = 0.001
K = 0.0006
K = 0.0002
T net minimum
42.5 K = 0.6 T ult
Stress in Cable (kips)
Length Along Cable (ft)
41
42
43
44
45
46
47
48
49
0
25
50
75

Appendix A

The following information was provided the prestressing contractor by the pavement designer, the firm of Porter, Urquhart, McCreary and O'Brien.

1. Hydraulic Jacks

All jack gauges shall be verified on the instrumented test tendons by determining the applied force from the calibration curve, supplied by the prestressing subcontractor, and from the measured elongation. The computed stress should be checked against the stress measured in the test tendons.

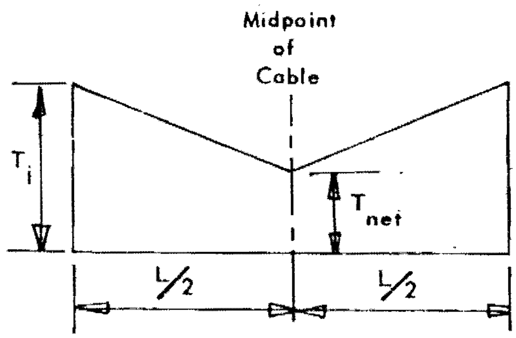
2. Friction

a. Longitudinal instrumented test tendons (3)

(1) Jack each end to 30 kips.

(2) Continue jacking in 10 kip intervals until load at each end reaches 75.5 kips.

(3) From the load applied at the ends and the load as measured at the center from the couplers compute value for K and the elongation as follows:



Cable stress when jacking is done from both ends.

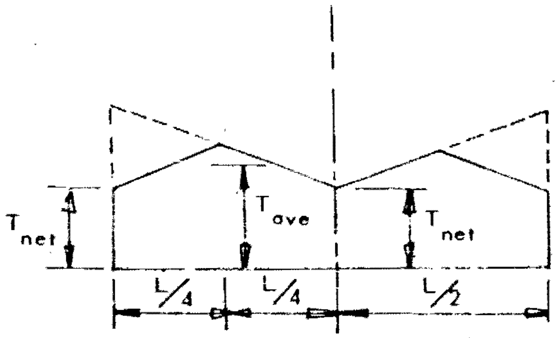
T_i = jacking force in kips

T_{net} - from center strain gauge

Computation for K:

$$\frac{T_i}{T_{net}} = \frac{KL}{e^2}$$

$$\therefore\ K = \frac{2}{L} \log_e \frac{T_i}{T_{net}}$$



Cable stress when jacking force is released.

Computation for elongation:

$$\Delta = \frac{\dfrac{T_i + T_{net}}{2} \times \dfrac{L}{2}}{E_s \; A_s} \quad \text{(at each end)}$$

$$E_s = 29.5 \times 10^6 \text{ psi}$$

$$A_s = 0.392 \text{ in}^2$$

$$\therefore \Delta = 1.32 \times 10^{-4} \; (T_i + T_{net})$$

(4) Compare the calculated elongation to the measured elongation.

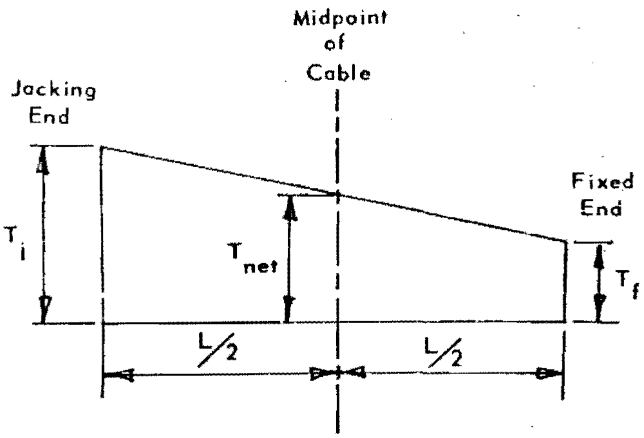
(5) For $T_i = 75.5$ kips, T_{net} must be $\geqq$ 58 kips.

(6) T_{net} must be such that $T_{net} + \dfrac{T_i - T_{net}}{4} = T_{ave} \leqq 63$ kips.

(7) Release jack load at each end to 30 kips.

(8) Continue jacking at <u>one</u> end only in 10-kip intervals until load at jacking end reaches <u>75.5</u> kips.

(9) Compute values for K, T_{net} and elongation as follows:



Cable stress after jacking from one end only.

Computation for K:

$$\frac{T_i}{T_f} = e^{KL}$$

$$\therefore K = \frac{1}{L} \log_e \frac{T_i}{T_f}$$

Computation for T_{net}:

$$T_{net} = T_i e^{-\frac{KL}{2}}$$

where K is that computed.

Computation for elongation:

$$\Delta = \frac{T_i + T_f}{2} \times L \times \frac{1}{E_s A_s}$$

$$E_s = 29.5 \times 10^6 \text{ psi}$$

$$A_s = 0.392 \text{ in}^2$$

$$\therefore \Delta = 2.65 \times 10^{-4} \quad (T_i + T_f)$$

Compare computed T_{net} with that measured from couplers.

(10) Compare computed elongation with the measured elongation.

(11) Limiting value for T_{net} and T_{ave} same as in (4) and (5) above.

b. Longitudinal non-instrumented tendons (3)

(1) Jack each end to 30 kips.

(2) Continue jacking at <u>one</u> end only in 10-kip intervals until load at at jacking end reaches 75.5 kips.

(3) Compute value for K, T_{net} and elongation as in a. (9) above. Compare computed elongation with measured elongation.

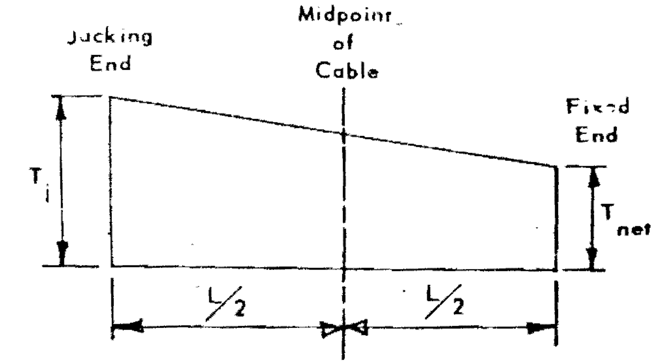
(4) Limiting value for T_{net} and T_{ave} same as above.

c. Transverse instrumented test tendons (3)

(1) Jack each end to 15 kips.

(2) Continue jacking at <u>one</u> end only in 10-kip intervals until load at jacking end reaches 47.0 kips.

(3) Compute values for K and elongation as follows:



Cable stress after jacking

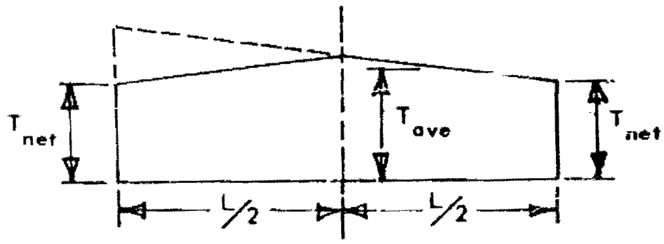
T_i = Load at jacking end

T_{net} = Load at fixed end

Computations for K:

$$\frac{T_i}{T_{net}} = e^{KL}$$

$$\therefore K = \frac{1}{L} \log_e \frac{T_i}{T_{net}}$$



Cable stress after release

Computation for elongation:

$$\Delta = \frac{T_i + T_{net}}{2} \times L \times \frac{1}{E_s \ A_s}$$

$$E_s = 29.5 \times 10^6 \text{ psi}$$

$$A_s = 0.295 \text{ in}^2$$

$$\therefore \Delta = 0.52 \times 10^{-4} \quad (T_i + T_{net})$$

(4) Compare the calculated and measured elongation.

(5) For T_i = 47 kips, T_{net} must be $\geqq$ 42.5 kips.

(6) T_{net} must be such that $T_{net} + \dfrac{T_i - T_{net}}{4} = T_{ave} \leqq 47$ kips

Instructions 2c.(1) through 2c.(6) were not followed inasmuch as transverse tendons were fixed at one end. Magnitude of jacking load (52K) was established by designer and Figure 3 was not used.