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TESTING AND EVALUATING PRESTRESSED CONCRETE BRIDGE DECKS WITH FIBERGLASS COMPOSITE CABLES

(Final Report)

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by

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ABSTRACT

Advanced composite materials such as fiberglass and graphite do not have corrosion problems like steel. Hence, they are studied in this project for their feasibility to use in prestressed concrete bridge decks. The mechanical properties of these cables were tested and compared with steel cables. A combination test was developed to evaluate the quality of prestressing cables. The fiberglass and graphite cables have successfully completed this test.

The concrete environment with sodium chloride solution on these cables was tested and the short term study did not produce any damage to fiberglass cables. The pull out strength and slip critical beam tests did not show any damage to bond between cables and concrete. The transfer length and development length of fiberglass and graphite cables were determined and they were comparable with steel cables. The prestressing losses for fiberglass and graphite cables were less than steel cables. The flexural behavior of advanced composite cable prestressed beams was similar to steel cable prestressed beams up to the first crack. No damage was noticed on any of the beams due to cyclic loading. It seems feasible to use fiberglass and graphite cables for prestressing concrete units in lieu of steel cables.

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Chapter 1

INTRODUCTION

1.1 General

Bridge deck deterioration, due to corrosion of reinforcements, is a serious problem in this country and abroad. Several methods of preventing corrosion have been tried including cathodic protection, and most of the them are not cost effective or satisfactory. Application of deicing salts in the northern parts of the U.S.A. accelerates the deterioration problem. An alternative material to steel for reinforcement is an urgent necessity to improve the durability of bridge decks. Some of the advanced composite materials developed by defense industries attracted several researchers in the U.S.A. and abroad as these materials do not have corrosion problems and will provide extended life for the bridge deck. However, these materials are more suitable for prestressing cables than for regular reinforcement. The low relaxation steel cables available today possess a tensile ultimate strength of 270 ksi. and Young's modulus of 28.5 million psi. Advanced composites such as fiberglass (S-2) and graphite pultruded rods have a tensile strength of 270 to 300 ksi. and Young's modulus between 9 and 24 million psi. These materials are very promising and need to be evaluated.

This study was initiated in 1989 by South Dakota Department of Transportation to evaluate fiberglass (S-2) cables for prestressing bridge decks. This study also included a comparative study of graphite and other advanced composite materials for prestressing cables. Several states have now initiated research in this area but are having problems with anchoring the cables as they are very brittle in nature. Dr. Iyer at South Dakota School of Mines and Technology, has developed a special anchorage system for these cables as early as 1987, and hence was able to further this project without any serious problems. The Florida DOT is now in its second year of study for prestressed piles in a marine environment, using fiberglass cables with anchorage developed by Dr. Iyer.

1.2 Review of Literature

The Corp of Engineers (1,2) in the 1960's tried to use fiberglass cable for prestressing concrete and was not successful in getting a satisfactory anchorage system. Several researchers were interested in developing various fiber composite cables for prestressing in Europe. Gerritse and Werner (3) were involved in aramid fibers, whereas Wolff and Miesseler (4) were involved in polyglass cables. In Japan, Kakihara (5) developed an improved version of aramid cables known as AFRP rods. Graphite cables were also developed in Japan and were introduced in Europe through BASF for civil engineering application. In 1987, (6) Dr. Iyer developed an anchorage system for fiberglass cables and used them for prestressing beams with existing facilities at prestressed concrete plants. This anchorage was unique as it uses the steel chucks used for prestressing steel cables.

Miesseler and Wolff in 1986, were responsible for building the first prestressed concrete bridge for heavy road traffic loads in Dusseldorf, Germany. They used polyglass cables for beams and conventional steel reinforcements for the decking and other structures. They used the post tension method of prestressing for their work. Very little work has been reported in the pretensioning area with these composite cables for prestressing. This study at SDSM&T concentrated on bridge decks with the pretensioned method of prestressing.

1.3 Objective and Scope

The main objective of this study was to test and evaluate fiberglass (S-2) and graphite cables for prestressing concrete bridge decks. In order to achieve the above objective, a comprehensive laboratory test program was developed to study the following:

1. Appropriate test methods to evaluate the mechanical properties of these cables and compare them with steel cables. (Test methods include static, cyclic, sustained, and creep test on cables.)
2. The influence of concrete environment on the S-2 glass and steel for bond between concrete and the cables.
3. Prestressing techniques and the losses of prestressing.
4. The anchorage system developed by Dr. Iyer for prestressing fiberglass cables.

5. Determination of transfer length, development length and failure mode of beams by slipping of cables and/or failure of concrete.
6. The influence of salt solution on the strength of prestressed concrete beams (glass and steel) with time.
7. The behavior of S-2 glass and graphite prestressed beams under static and cyclic flexural loading, and compare with steel prestressed beams.

On the basis of the above tests, design guidelines were developed for beams prestressed with fiberglass or graphite cables.

1.4 Testing Program

A laboratory testing program was developed to reflect the needs of the actual condition of the prestressed concrete bridge deck using these advanced composite cables. Steel cables were used as control specimens. In the pretensioned method, the cables are stretched using jacks and end anchorages to an initial stress level and the concrete is placed in position. It will take from 24 to 48 hours for the concrete to develop the required minimum strength before the cables can be cut. Hence, a short term load test is needed to evaluate the cables. After cutting the cables, the cables will transfer the force to the concrete by bond, and hence bond strength between concrete and cable needed to be evaluated. These beams are subjected to flexural loading due to live loads. Several combinations of the loading were simulated in the laboratory to study the effect of real loading conditions on the behavior and failure modes.

On the basis of the above needs, the following tests were conducted.

1. A series of tests were used to evaluate the quality and mechanical properties of pultruded rods and cables.
2. Quality control tests were used to assure the minimum strength requirements of cables.
3. Testing the anchorage system.
4. Pull out tests to evaluate the bond strength between cable and concrete with and without sodium chloride solution.
5. Effect of sodium chloride on the ultimate flexural strength of prestressed concrete beams with fiberglass cables.
6. Static, cyclic, and sustained flexural loading tests on beams prestressed with fiberglass and graphite cables were conducted to study the failure modes.
7. Companion test specimens with steel cables were used for direct comparison.
8. Sanded graphite cables were used to make comparison with unsanded graphite cable performance.
9. The transfer, development length, and losses of prestressing were determined for each cable material.

Chapter 2

PREPARATION AND TESTING OF CABLES AND ANCHORAGE

2.1 Materials

2.1.1 Resin & Fibers

The vinyl ester resin system was used for making pultruded rods with S-2 fiberglass and graphite fibers. The pultruded rods were manufactured by Polygon with a nominal diameter of 0.125 in. The fiber volume used was approximately 65 percent. In a separate study conducted at Owens-Corning the vinyl ester resin system 8084 was selected on the basis of its resistance to sodium chloride solution under continuous stress condition. Properties of the resin system are shown in Table 2.1.1.1. Details of the fiber and resin system used for making pultruded rods are shown in the Table 2.1.1.2. Properties of different fibers used are shown in Tables 2.1.1.3 and 2.1.1.3A. Low relaxation steel (ASTM A416-88-b) of 3/8 in. and 1/2 in. diameter cables were used for these tests. Properties of steel are shown in Table 2.1.1.4.

2.1.2 Pultruded Rods and Cables

Pultruded rod specimens of 3 ft. 6 in. lengths from every batch of rods supplied were tested for ultimate tensile strength to evaluate the quality of the material manufactured by Polygon. These rods were tested as per ASTM D3916 (7) and the results are shown in Table 2.1.2.1. The aluminum tabs were used for gripping these rods.

Seven pultruded rods of nominal diameter 0.125 in. were used to make cables with approximately one twist/ft. All these cables were strengthened by a proprietary method developed by Dr. Iyer. Steel chucks were used to grip the ends of the cables for all the tension tests and for pulling the cables to make prestressed concrete beams. All the cables and anchorage systems were prepared in the Civil Engineering laboratory. Tension tests were conducted on cables to evaluate the properties of the material as well as the anchorage system.

2.1.3 Concrete

Ready mixed concrete was used for making all specimens. Type III cement was used and the mix was designed to provide an ultimate compressive strength of 5000 psi. The slump and air content of concrete, and air temperature were recorded for each batch of concreting. Test cylinders were made to test the strength of concrete to determine the time of release of prestressing. Mix details are shown in Table 2.1.3.1. The prestressed concrete industry uses steam curing in the plant to accelerate the strength development of concrete. In the laboratory, a special curing was used in lieu of steam curing. This special fast curing process involves covering the concrete with wetted burlap and a polyethylene sheet. Electric heating blankets with temperature control (maximum 120^0F) were laid over the plastic sheet, and the heating blankets were covered with an industrial insulation blanket to prevent the heat from escaping into the atmosphere. The concrete temperature and the surroundings were monitored using thermocouples. The test cylinders were cured with the beams for the same conditions.

2.2 Testing of Cables and Anchorage

Several trial tension tests were conducted on S-2 glass cables with a special anchorage system to monitor the quality control of the manufactured pultruded rod and the anchorage, in order that the ultimate stress reached the manufacturer's recommended value without any failure near the chucks. These trial test results are not shown in this report. No standard test method was available for evaluating composite cables and hence a test procedure was developed in this project.

Two types of tests were conducted on fiberglass, graphite, and steel cables to evaluate the performance of the cables and the anchorage system. The first test was a static tension test; the second was a combination of static tension followed by sustained load and cyclic tension-tension load tests. After two million cycles, the same specimen was tested for the ultimate tensile strength. The fiberglass and graphite cables were subjected to a long term sustained tension load to study the creep and relaxation of the cables. After the creep test, the same specimens were tested for the ultimate strength.

2.2.1 Static Tension Tests

The static tension test was conducted on cables using the Tinius Olson Testing Machine with a maximum capacity of

300,000 lbs. Electrical strain gages* (EA-06-032 UW-120) were installed on the two rods in the cable to monitor the strain in the cables during the test. The lengths of the cables were approximately 36 to 42 inches and the nominal diameter of the cable was 3/8 in. General set up for the static tension is shown is Figure 2.2.1.1. All the cables failed somewhere near the middle without any failure near the anchorage. Two 0.6 in. diameter steel chucks at each end were used for all the tests. Typical stress-strain diagrams are shown in Figures 2.2.1.2 and 2.2.1.3. The test results are shown in Table 2.2.1.1.

Steel cables were gripped by reusable steel chucks and were tested for tensile strength as per ASTM 370 (19). A typical stress-strain diagram is shown in Figure 2.2.1.4.

A summary of tests results is shown in Table 2.2.1.2.

2.2.2 Combination Test-Static-Sustained-Cyclic- and Static Tension Test

A combination test was developed to simulate the stress conditions in the cables during the prestressing operation and applied loads in the beams. During the prestressing, the cables were pulled to an acceptable stress level (initial jacking force) and maintained at this level by the anchorage system. It takes 24 to 48 hours for the concrete to cure and to reach the required strength so that the cables can be cut from the anchorage system to apply the prestress on the beams.

* Supplied by Micro-Measurements Group

These beams were subjected to applied loads (live loads) and changes in the stress level in the cables. Hence, a combination test was developed to evaluate the cables and anchorage neglecting the losses due to shrinkage and creep in concrete during these tests.

One representative sample of S-2 glass, graphite, and steel cables was tested for the combination of static tension, sustained tension (about 48 hours) followed by a cyclic (tension-tension) test. After two million cycles the same specimen was tested for ultimate tensile strength. Strain gages were used to monitor the strain in the cables during the entire period of the combination test. A MTS closed loop testing machine was used to conduct these tests. The general set up of the test is shown in Figure 2.2.2.1. Special steel supports were attached to the machine as shown in the figure (2.2.2.1) to conduct these tests. A data acquisition system (MEGADEC*) was used to monitor automatically the strain and the load on the cables at regular intervals of time. The data was processed by an IBM compatible computer.

Trial combination tests with different minimum to maximum stress ratio in cyclic tests were conducted (8). Only the final test results are presented in this report. One representative sample of cable was tested from each material,

* MEGADEC-Data acquisition system supplied by Optim Electronics

namely steel, S-2 glass, and graphite. The maximum stress level for sustained load test and cyclic test was selected on the basis of initial prestressing force, which varies with the type of cable used for the test. Specimen identification and stress levels on different cables are shown in Table 2.2.2.1. A maximum load of 16,000 lbs. was applied on steel and graphite cables; whereas a maximum load of 10,000 lbs. was applied on S-2 glass cables.

All these specimens were subjected to a static tension up to the maximum load and kept at this load for a minimum period of 48 hours. The strains and loads were monitored at regular intervals. At the end of the sustained load test, the loads were released to zero and again loaded to the mean load level for the cyclic (tension-tension) test. The ratio (R) of minimum load to maximum load was kept close to 0.90. The load was varied sinusoidally at 7 cycles per second (7 H_z) for all the tests. The R value was selected on the basis of the beam tests conducted in this report under section 3.6.2. The number of cycles per second and sinusoidal variation were reasonable on the basis of variation expected in an actual bridge structure (9).

The cyclic loading was continued to complete the two million cycles or until the specimens failed during the tests. The surviving specimens were subjected to tension test up to failure after bringing the load to zero. The test results are shown in Tables 2.2.2.2 through 2.2.2.9. The modulus of elasticity of each cable before and after the cyclic load was calculated from the stress-strain diagram for various specimens during the combination tests.

The steel cable failed during the cyclic tests before completing the two million cycles, while graphite and fiberglass cables survived the two million cycles. During the ultimate tensile strength test, graphite and fiberglass specimens failed very close to the mid length, and away from the anchorage; steel specimens failed close to the anchorage. No slip was noticed at the special anchorage used for these tests. No significant change was noticed in strain readings during the sustained tension tests on graphite, steel, and fiberglass cables.

In the case of graphite cables, the two million cyclic loading does not have any significant effect, as the strain readings at 16,000 lbs. before and after the cyclic loading were very close. The modulus of elasticity remained the same before and after the two million cycles as can be seen from Figure 2.2.2.2. The steel cable could not complete the two million cycles and hence, a comparison was not possible. During the cyclic loading test the variation of strain was very minimal. In the case of graphite cables, the ultimate stress after two million cycles was 314 ksi. and was very close to the control specimens. The same test was conducted on S-2 glass cable with a maximum load of 10,000 lbs. instead of 16,000 lbs. The stress-strain diagram before and after two million cycles is shown in Figure 2.2.2.3. The two graphs deviate very little and the modulus changes were very small. The ultimate stress after two million cycles was 314 ksi. and was very close to the range of control specimens. Hence, the sustained load and cyclic load have very little effect on the properties of the graphite and fiberglass cables.

No failure was noticed in the special anchorage used for graphite and fiberglass cables during any of these tests. The special anchorage system, developed by Dr. Iyer in 1987, has performed very well and is very suitable for prestressing these advanced composite materials. The stress levels used for sustained and cyclic loads will be used for the initial prestressing of these cables for making prestressed concrete beams for future evaluation.

2.2.3 Long Term Sustained Tension Test (Creep Test)

The ability of fiberglass and graphite cables to retain the final prestressing force for a long period of time is important for prestressed concrete units. This property of retaining load with time is related to creep or relaxation of cables. Three fiberglass and three graphite cables of approximately 42 inches in length were prepared with special anchorage at the ends. The creep testing frame for testing concrete cylinders was modified and the cables were supported by a steel section as shown in Figure 2.2.3.1. Strain gages were installed in all three cables to monitor strain at regular intervals of time. A hydraulic jack was used to load the cables and lock the anchorage system to retain the stress in the cables. Final stress level in each cable is shown in Table 2.2.3.1. Strain readings were recorded every 24 hours for a week, every week for a month, and one reading per month. The relative humidity and room temperature were also recorded. This test for fiberglass was continued for one year. The strain variation with time on all the three cables are shown in Figure 2.2.3.2. The strain remained constant in all three cables for a one year period of testing. This shows that no damage was done to cables or anchorage during the sustained load test (creep test). After the creep test, the cables were tested for ultimate tensile strength. The strength was 257 ksi. and the cable failed in the middle. The stress-strain diagram before and after the creep test is shown in Figure 2.2.3.3. The modulus of elasticity did not change as the two diagrams were identical. In other words, no creep of cables or slippage of anchorage were noticed during this test.

The creep test on the graphite cables has been running for six months and is still in progress. The strain variations are shown in Figure 2.2.3.4. Within this limited time of study, no significant creep in these cables or slipping of anchorage was noticed under the sustained load test.

Chapter 3

PREPARATION OF SPECIMENS AND TESTING

3.1 General

A self straining steel frame was fabricated in the structural engineering laboratory at SDSM&T to act as a prestressing bed for making all the prestressed concrete beams for various tests. Pull out specimens of six inches in diameter were made using conventional concrete cylinder molds. Test cylinders were made as per ASTM C 192-81 standards for each placement of concrete. A 5000 psi. ultimate compressive strength concrete with Type III cement was used for casting all the specimens. Details of the curing method and mix properties details were reported earlier (section 2.13). Many trial tests were conducted before the prestressed test beams were made but only typical test results or summaries of the results are presented in this report. Three students are in the process of completing their Master's theses on the same subject (8,10,11). Details and complete test data are provided in these theses.

3.2 Prestressing Method

Pretension and post-tension methods are the two techniques used to prestress concrete with steel cables. The pretension method is more common in the U.S.A. for precast units and is used in this project. In the pretensioned method of prestressing, the cables are pulled to an acceptable stress level and kept at this stress level until the concrete has developed enough strength to release the prestress. A self straining steel frame as shown in Figure 3.2.1 was used to stress the cables and keep the anchorages in positions. Calibrated load cells were used to monitor the load in each cable in addition to the pressure gages in the jacks. Form work for the test beams were made of plywood and wood sections. A fast curing method as explained in section 2.1.3 was used for curing all concrete beams. Hydraulic jacks were used to apply force in the cable and generally the prestressing force was released after the concrete had reached an ultimate compressive strength of 4000 psi. Stresses in the cables were released by cutting the cables using a circular power saw. All the tools and equipment used for conventional steel prestressing were used for stressing advanced composite cables. Hence, the same bed and equipment were used for making prestressed concrete beams with steel cables. The main difference was the strengthening of the composite cables to use the steel chucks. This requires no modifications to the present prestressing plant making precast units. This was a great advantage in using the special anchorage system developed by Dr. Iyer.

3.3 Preparation of Specimens

In the pretension method of prestressing, the cable is in direct contact with concrete to provide the required anchorage or bond to develop the prestressing in the concrete. To study the bond between the cables and concrete, pull out specimens were prepared for different types of cables. The details of the pullout specimens are shown in Table 3.3.1. Forty eight 6 in. diameter and 12 in. height concrete cylinders with fiberglass cables embedded were cast for pull out test; additionally, 36 pull out specimens (6 in. diameter and 12 in. height) were made with steel cables of 1/2 in. diameter. Twenty four fiberglass and 12 steel specimens were subjected to eight percent sodium chloride solution with alternate wetting and drying cycles (one cycle per week). The remaining specimens were left in air at room temperature. This test was conducted to study the influence of deicing salt on the bond between concrete and cables. Eighteen beams of 6 in. wide by 4 in. deep and 72 in. long prestressed with fiberglass and twelve similar beams prestressed with 1/2 in. diameter steel cables were made. The details of the beams are shown in Table 3.3.2. Twelve fiberglass prestressed beams and six steel prestressed beams were subjected to eight percent sodium chloride solution with alternate wetting and drying cycles (one cycle per week). The remaining (six fiberglass and six steel beams) beams were left in air at room temperature. These specimens were prepared to study the influence of deicing on the ultimate flexural strength of these beams.

In addition to the thirty (18 plus 12) 6x4x72 in. beams, thirty two additional beams were made to study the failure mode of beams in flexure. The details of the beam sections and lengths are shown in Tables 3.3.3 and 3.3.4. Generally, fiberglass prestressed beam sections were 8 1/2 in. by 12 1/2 in.; whereas, graphite prestressed beam sections were 6 1/2 in. by 8 1/2. These were made on the basis of designs shown in Appendix C. Companion steel prestressed beams of the same sections were also made to compare the test results. After many trials and failures, a typical procedure was selected to make all the beams. The procedure used was similar to making steel prestressed concrete beams. Wooden forms were fabricated for various beams, and kept in position. The cables were placed in position with one end (dead end) having load cell and chucks (double chucks used for composite cables). The other end was pulled by a hydraulic jack. An initial tension of 500 to 1000 lbs. was applied to each cable so that the cables were tight in order to install the strain gages on the middle of the beams. M-Bond* 200 was used to bond the electrical strain gages to the individual rods of the cables.

The Micro-Measurement Vishay 220 system unit was used to measure the strains in the cables and concrete. Care was taken at every stage to see that the cables were anchored properly at the dead ends and at the jacking end. Load cell readings were monitored continuously to make sure no excess loading was applied to the cables. Cables were pulled slowly, one by one at 2000 lbs. intervals at regular sequence to reach the predetermined initial prestressing force for each cable.

* Supplied by Micro-Measurements

Generally 10,000 lbs. was used for fiberglass cables; whereas a 16,000 lbs. force was used for (3/8 in. diameter) steel cables. After reaching this required stressing of all the cables, the strain gages installed on the cables were covered with five minute epoxy and covered with a short plastic tube to protect the gage area. This was done just a few hours before placing the concrete so that the five minute epoxy had cured completely to provide the proper waterproofing to strain gages. Needle vibration was used to consolidate the concrete. Test cylinders were made to monitor the strength development of concrete.

Fresh concrete properties such as slump, air content, and temperature were tested for every concreting and typical results are shown in Table 2.1.3.1. All the specimens were marked on the surface before applying the fast curing described in section 2.13. At least one concrete cylinder was tested for ultimate compressive strength every 24 hours to monitor the strength development. When the strength reached 4000 psi. or above, the side form work and the curing were removed. Strain gages were installed on the concrete along the cable lines to measure transfer length. Strain readings before and after the release of prestress have provided the transfer length for each beam. The stress release was achieved by carefully cutting the cables with a circular power saw. After recording the strains in cables and concrete, the beams were carefully removed from the prestressing bed for storage or for further testing.

Four steel and fiberglass prestressed beams of five feet length were made in addition to the first series to study the slip failure condition with sodium chloride solution. Details of the beams are shown in Table 3.3.4. These fiberglass prestressed beams used fiberglass (E glass) stirrups and S-2 glass cables for stirrup holders; whereas the fiberglass and graphite beams cast previously used steel stirrups and stirrup holders. Details of the stirrups are shown in Tables 3.3.3 and 3.3.4.

3.4 Effect of Sodium Chloride Solution on Bond and Flexural Strength

3.4.1 Pull Out Test

The specimens kept in salt solution and in air were used to conduct the pull out test as per ASTM Standard (14). At regular intervals of time, the fiberglass and steel cable specimens were tested for bond by pull out test. The values were used for direct comparisons of the effect of sodium chloride solution on bond. Generally, the pull out test results did not represent the actual bond strength of the specimens (13). Half cell readings were also taken in the case of steel specimens. After the first month of tests, the height of the cylinders were reduced to 6 in. by saw cutting them. This reduced the embedment length to 6 in. to get a pull out failure, rather than partial cracking due to wedge action. After nine months of testing with reduced height, again the full height specimens were tested to see any differences in strength or behavior. The test results are shown in Table 3.4.1.1. No significant change in bond strength was noticed after nearly seventeen months of exposure to sodium chloride solution in either steel or fiberglass cables. This shows the concrete or concrete with deicer had very little effect on the bond between cable and concrete.

3.4.2 Flexural Test

Flexural tests were conducted on 6 in. x 4 in. x 72 in. prestressed beams by applying a central concentrated load on a simple span of 70 in. The load was applied using a Tinius Olson Testing Machine. The deflection of the beam and concrete strain at the top were recorded during the tests. The load at first crack and failure loads were recorded. Half cell readings were taken on beams prestressed with steel cables. The summary of the test results are shown in Table 3.4.2.1. All the beams failed in crushing of concrete, but no slip or failure of cables was noticed. No loss in bond was noticed and the stresses in the cables were not sufficient to create this failure mode. There was no significant reduction of ultimate load noticed in the case of the beams subjected to sodium chloride solution even though a slight reduction was noticed in beams kept in air. In the case of fiberglass prestressed beams, those with one inch eccentricity have a higher first crack and ultimate load compared to concentric (no eccentricity) beams. The half cell readings in steel beams jumped to -.500 volts within a month with sodium chloride solution; whereas the beams kept in air showed very small half cell readings of -.008 volt. The half cell readings remained more or less the same during the testing period. This indicated high activity of corrosion in steel beams, but the strength of the beams was not very much affected as the failure of the beams was mostly by crushing of the concrete. Deeper beam specimens were made with shorter lengths to study the bond/corrosion problem by using slip critical beams as described in the next section.

3.4.3 Slip Critical Beams

Three steel prestressed beams and three fiberglass prestressed beams of five feet lengths were subjected to eight percent sodium chloride solution with alternate wetting and drying cycles (one cycle per week). One steel prestressed and one fiberglass prestressed beam were tested for flexural strength without subjecting them to deicer as control specimens. Dial gages were attached to the ends of the cables to monitor the relative movement of the cables with respect to the end of the beams. This indicated any slip of the cables or bond failure between the concrete and the cables. All of these beams failed by slipping of the cable under the flexural load. There was no tension failure noticed in the cables or crushing of concrete, and the slipping of the cables started just after the first crack. One fiberglass prestressed beam and one steel prestressed beam were tested for flexural load at regular intervals to determine the load at slipping. The test results are shown in Table 3.4.3.1. There was no reduction in magnitude of slip critical loads on these beams with time of exposure to sodium chloride solution. Therefore, it can be stated that no bond damage happened due to sodium chloride solution on these cables. This agrees with the pull out test results reported in section 3.4.1.

3.4.4 Sustained Load Test

One pair of 5 ft. length prestressed steel beams and another pair of 5 ft. length fiberglass prestressed beams were used for the sustained flexural test. One beam was kept at the bottom and was subjected to sodium chloride solution and the other beam (out of the same pair) was kept at the top and was subjected to a concentrated load at the center with the two ends restrained by threaded rods. The central support was provided by a load cell to monitor the flexural load as shown in the Figure 3.4.4.1. The sustained load for the fiberglass beam pair was 8000 lbs. and for the steel beam pair it was 10,000 lbs. These loads were selected on the basis of the working load on the beams. Cable slips relative to the ends of the beams were monitored by using dial gages for the beams in the air. The beams in air were undergoing shrinkage; whereas, the beams in salt water were not subjected to any shrinkage. The beams in air lost stress in the cables, while no decrease of stress in cables was noticed in beams in salt water. After 140 days, these beams were tested for ultimate flexural strength. The summary of the test results is shown in Table 3.4.4.1. The slip loads on the beams subjected to salt solution were much higher than the beams kept in air. This clearly shows that short term exposure to salt solution did improve the bond and ultimate strength of the beams. The stresses in the cable did not show any increase in stress during the sustained flexural load test. Hence, in prestressed concrete beams the sustained working load will have very little effect on the behavior of beams.

3.5 Determination of Transfer Length

Transfer length is the distance from the end of the beams to the point where full prestressing force is transferred to the concrete section. This depends on the diameter of the cable and the effective prestressing force on the cable. According to the American Concrete Institute (12), the transfer length of steel cables is equal to one-third of the effective stress times the diameter of the cable. The transfer length also depends on the way in which the stresses are released from the cables to the concrete. According to Collins (page 106) (13), the flame cut cables will have a transfer length longer than the gradually released prestressed force. Again, the wedge action has an important effect on the transfer length and pull out strength. At the end of the prestressed concrete beams, the stress in the cables is zero and the full stress level builds towards the center of the beam. Hence, the Poisson's ratio effect is felt with larger diameter at the ends and lesser diameter towards the center.

This effect is also known as the wedge action in the pretensioned method of prestressing. This wedge effect will also affect the pull out test to crack the concrete cylinders longitudinally. One set of beams from fiberglass, steel, and graphite prestressed beams was used for determining the transfer length. Strain gage readings were recorded before and after the release of prestress in each case and the strain readings were plotted along the length of the beams as shown in Figures 3.5.1a, 3.5.1b, and 3.5.3. The distance from the ends of the beams to the point of constant strain was used as the transfer length in each case. The summary of transfer lengths for different beams is shown in Table 3.5.1.

3.6 Flexural Tests

Flexural tests were conducted on several prestressed beams to study the mode of failure. Two types of failure were expected on the beams under flexural loading (shear failure was prevented by using proper shear stirrups), namely the tension failure of cable, crushing of concrete and/or slipping of cables. The dimensions of the beams and the prestressing force were very critical with different types of cables used, when studying these failure modes. The slip critical beams were important for studying the development length and deterioration of bond between concrete and cable with the presence of sodium chloride solution. This test was described in section 3.4.3. The cyclic flexural loading was also conducted to study the failure mode.

On the basis of the ultimate tensile stress and the modulus of elasticity of the cable material, the ultimate failure strain of the cable in a prestressed beam was determined. Two lengths for the beams were used; one 8 ft. and the other a 5 ft. length. The 5 ft. length was designed on the basis of insufficient development length. The tension failure in the cable was designed by increasing the depth of the beam and the length of the beams. Beam sections are shown in Table 3.3.3.

3.6.1 Static Flexural Tests

The procedure for flexural tests was the same for testing all the beams with a simple span and a concentrated central load. The Tinius Olson Testing Machine with a maximum capacity of 300,000 lbs. was used for testing the beams. Electrical strain gages of 2 in. gage length (EA-20-CBW 120*) were installed on the top of the beam to monitor the concrete strain. Dial gages were installed to monitor the slip of the cables and the central deflection of the beams under the incremental loading condition. The first crack and ultimate loads were recorded and the crack pattern was marked with felt pen on the side of the beam. The summary of the test results is shown in Table 3.6.1.1. All the 5 ft. length beams failed by slipping of the cables. Some of the 8 ft. length beams failed by slipping while others failed by crushing of concrete

* Micro-Measurement Group

or they were very close to the development length. The unsanded graphite cable beams slipped even in the 8 ft. length beam and hence the development length should be more than 4 ft. The sanded graphite cable failed in tension of the cable/crushing of concrete. All the 5 ft. length steel cables failed by slipping; whereas the 8 ft. length cables failed by slipping/crushing of concrete. Comparing the same section of beams and lengths, the fiberglass and steel beams had similar modes of failure. Similarly comparing the same section of beams, the graphite and steel prestressed beams had similar failure modes. In respect to resistance to slipping, the sanded graphite cables prestressed beams were better than unsanded graphite cable beams. The load deflection diagram for steel and graphite prestressed beams is shown in Fig. 3.6.1.1. The load deflection diagram for steel and fiberglass beams are shown in Figure 3.6.1.2. The steel and fiberglass or steel and graphite are very comparable up to the first crack load; however, with loading above the first crack, the deflection of fiberglass beams was more than the steel prestressed beams. This was expected as the modulus of elasticity of fiberglass was one-third the modulus of steel cables.

3.6.2 Cyclic Flexure Test

The companion beams cast along with static test beams were used for the cyclic flexure test. Two 5 ft. beams and one 8 ft. beam were used for testing the cyclic flexural load on fiberglass prestressed beams. One 8 ft. steel prestressed beam was used for cyclic flexural loading. One sanded graphite and one unsanded graphite prestressed beam of 5 ft. lengths were tested for cyclic flexural loading. MTS-closed-loop-system testing machine was used for all the cyclic tests. Figure 3.6.2.1 shows the general set up of loading.

Electrical strain gages of 2 in. gage length (EA-06-20 CBW-120) were used to monitor the concrete compressive strain at the top and at mid span of the beams. Dial gages were used to measure the cable slips at the ends. The details of the beam dimensions and spans are shown in Table 3.3.3. All the beams were loaded up to the first crack and used a load less than first crack on the maximum load for cyclic loading. A two thousand pound load was used for minimum load from the stand point of testing. These loads were applied at the mid span as a line load. Seven cycles per second (7 Hz) with sinusoidal variation were used to apply the cyclic loading. The load variation and strain readings in the cables and concrete were monitored by using MEGADEC Data Acquisition System. After completing the two million cycles of loading, the load was brought to zero and again loaded up to failure. The test results are shown in Table 3.6.2.1.

3.7 Losses in Prestressing

The losses in the pretensioned method of prestressing included two types of losses. Anchorage losses and jack transfer losses can be controlled by the operation by applying higher stresses in the cable, as these are short term stresses. The elastic shortening, shrinkage and creep of concrete and relaxation of cables are the properties of concrete and cable material. Hence, they can be reduced by better mix design but cannot be controlled by the prestressing operation.

In this project, the length of the bed was nearly 30 ft. and the anchorage losses and jack transfer losses were very high (varies from 5.2 to 7.4 percent for all the cables). In the prestressing plant, the length of the bed is very long (200 to 400 ft.) and the percentage loss will be very small (1 percent). There was very little relaxation measured on fiberglass and graphite cables under creep test (ref. section 2.2.3) and hence the relaxation losses were nominal. For fiberglass cables, the elastic shortening was nearly one-third that of steel cables as the modulus of elasticity of fiberglass was nearly one-third that of steel. The elastic shortening of graphite cables was less than steel as the modulus of elasticity of graphite was nearly 80 percent of the modulus of steel. The summary of losses is shown in Table 3.7.1. The losses in prestressing due to elastic shortening vary from 1.1 to 2.4 percent in fiberglass, while the same losses in steel vary from 2.6 to 4.5 percent. This seemed to agree with the ratio in modulus of materials for the two cables. In the case of sanded graphite cables, the losses were 2.6 percent for the same cross sections of beam which were proportional to the modulus of the graphite cable.

3.8 Monitoring the Stresses in Advanced Composite Cables

Miesseler (4) has used fiber optics to monitor the stresses in fiberglass cables and crack development in concrete on the bridge at Duesseldorf, Germany. This bridge was built in 1986. Miesseler used fiber optics in combination with laser beam lights to measure the time of travel in the optical fiber by the laser beam light. A demonstration was arranged at SDSM&T in February 1991 to check this technology. There has been limited success in monitoring stresses by this method. This demonstration was conducted by FIMOD Corporation of Virginia on steel and concrete beams. Later, Dr. Iyer visited Canada and learned that the fiber optics in combination with laser beam lights can locate the break in the cable or crack in the concrete. This needs a special OTDR (to measure laser time lag in picoseconds) to locate the break in fiber optics. This investigation is in progress and the availability of fiber optics to resist stresses more than 100 ksi. is being examined. Preliminary tests are in progress with the cables (cable stress goes as high as 180 ksi.) to test this technology. Maybe in the future this can be used for monitoring cracks in concrete or breakage locations in cables.

Chapter 4

DISCUSSION OF TEST RESULTS

4.1 Cables and Anchorage System

The average mechanical properties of the pultruded rods and the cables seem to be good enough to be used for prestressing cables. The modulus of elasticity of fiberglass cable is approximately one-third that of steel and hence the losses in prestressing are lower than for the steel prestressed beams. Graphite cables have 80 percent of the modulus of steel and hence will have some reduction in losses. The combination test proved that the fiberglass and graphite cables are definitely better than steel (refer to Section 2.2.2). No relaxation (creep) was noticed in fiberglass and graphite cables. No anchorage failure was noticed in any of these tests. However, the special anchorage developed by Dr. Iyer in 1987, was very satisfactory in prestressing these advanced composite cables. An initial prestress level of 142 ksi. for S-2 fiberglass cable and 186 ksi. for graphite cables is recommended. A strict quality control was needed on the manufacturing of the pultruded rods to obtain the required mechanical properties.

4.2 Influence of Sodium Chloride Solution on Bond and Flexural Strength

The pull out test did not reveal any change due to the influence of 8 percent sodium chloride solution as the pull out loads did not change with exposure to salt. This indicates the relative bond strength between the cables and concrete did not deteriorate due to exposure to sodium chloride solution for a limited period of time. The ultimate flexural test results did not show any decrease in strength due to salt solution. Even though the corrosion was very active in steel prestressed beams, the flexural test results did not show any decrease in strength. This was mainly due to the failure mode of the 6x4x72 in. beam. All the failures were due to the crushing of concrete without any slip or cable failure. The depth of the beam was too small to create any high stresses in the cables to produce slip or cable failure.

The slip critical beam test was designed on the basis of the slip load on cables with insufficient development length. The 5 ft. length beams were used for these tests, so that the length of the beam was more than the transfer length and at the same time less than the development length. The dimensions of the beams were 8 1/2 in. width and 12 1/2 in. depth to create a high stress in the cable during the flexure test to develop a slip failure. This was very successful but the slip loads did not decrease due to the short term (150 days) exposure to salt solution. The sustained flexural load has not shown any decrease in strength for the beams subjected to salt solution. All the beams had one inch clear cover for the cables. In summary, the short term application of salt on prestressed concrete beams had very little effect on bond or slip critical strength of the beams.

4.3 Transfer and Development Lengths

The transfer lengths for fiberglass cables were 13.0 and 14.0 in. (35 to 37 times the diameter -0.375 in. of cable) and compares well with the ACI 318 equation of 13 and 14 inches. The unsanded graphite had partial slipping as the lengths of the beams were less than twice the transfer length. The transfer length measured was 32 in. and did not agree with the ACI-equation. The measured and ACI values of transfer lengths for steel cables agreed very well.

According to the ACI-equation, the development length of prestressed concrete beams with steel cables is given by [fps - 2/3 fse] d_b, where fps is the stress in the cable at flexural failure. Fse is the effective prestress in the cable. The d_b is the diameter of the cable. The strain in the cable at the point of slipping was measured using strain gages and the stress (fps) was calculated by multiplying the strain by the modulus of elasticity of the cable. Similarly, the stress (fse) was calculated by measuring the strain at the point of transfer of prestressing. Using these two stresses in the ACI-equation, the theoretical development length was calculated. The measured length will be half of the length of the beam subjected to flexural test with slipping mode of failure. The theoretical values and measured values were compared for various beams and are shown in Table 4.3.1. The theoretical (ACI) development length agrees with the experimental measured values for steel cables; however, the

ACI Code values did not agree with the measured values for fiberglass and graphite cables.

4.4 Flexural Behavior and Mode of Failure

For all the 5 ft. beams, the slip load was very close to the first crack. The load-deflection diagram for fiberglass and graphite beams compares fairly well with steel prestressed beams until the first crack for the same prestressing force. After the first crack, the fiberglass prestressed beams have more deflection. This was expected as the modulus of the fiberglass was one-third that of steel. Behavior of composite cable prestressed beams up to first crack was comparable to steel prestressed beams. Hence, working load deflections will be the same in both cases. Unsanded graphite cables needed more development length and the minimum length of the beams should be more than 8 ft. for pretensioned beams. Sanded graphite cables performed better than unsanded graphite cables.

All the cyclic test specimens survived the two million cycles except two 5 ft. length unsanded graphite prestressed beams as shown in Table 3.6.2.1. This again confirms that the unsanded graphite cables needed more development and transfer length. The limited number of beams tested for cyclic flexure did not show any trend in the behavior except that none of the 8 ft. beams failed during the cyclic loading; the first crack and slip load after the cyclic loading were comparable to the static loading on similar beams. The cyclic flexural loading (within the working load) did not damage these beams.

4.5 Losses in Prestressing

The anchorage losses measured were high, as the bed was short. The elastic shortening losses were comparable, with fiberglass having approximately one-third the losses of steel. It is anticipated that the shrinkage and creep losses in fiberglass prestressed beams will be one-third the losses of steel prestressed beams. Assuming the anchorage losses to be small (can be controlled), the other losses for fiberglass prestressed beams will be one-third the losses of steel prestressed beams. The graphite prestressed beams will have 80 percent of the losses of the steel prestressed concrete beams. The losses of advanced composite cable prestressed beams will be less than conventional beams.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

On the basis of various tests conducted on the cables and the prestressed concrete beams, the following conclusions are drawn.

1. The vinyl ester resin system for making pultruded rods (fiberglass and graphite fibers) was very satisfactory on the basis of its resistance to a corrosive environment (Section 2.1.1).
2. The ultimate tensile strength of fiberglass and graphite cables was better than or equal to the ultimate strength of steel cables (270 ksi.).
3. The modulus of elasticity of fiberglass cables was nine million psi.; whereas the modulus of elasticity of graphite was 24 million psi.
4. The combination test developed for testing the quality control of manufactured cables was very successful in evaluating the cables.
5. The anchorage system, developed by Dr. Iyer in 1987, for advanced composite cables, performed satisfactorily for all the tests and prestressing of the beams.
6. The pull out tests could be used for the purpose of comparison of different cables and did not measure the bond strength between cables and concrete.
7. The eight percent sodium chloride solution on prestressed

concrete beams (fiberglass and steel*) did not reduce the ultimate flexural strength of 6x4x72 in. beams or ultimate slip load on the 8 1/2 x 12 1/2 x 60 in. beams.

8. Fiberglass and graphite cables with the anchorage system successfully withstood the combination test (static-sustained-cyclic-tension test) and no damage was done to these cables.

9. The transfer length of fiberglass cable was found to be 37 times the diameter of the cable; whereas the transfer length of steel* cables was 45 times the diameter. The unsanded graphite cables had a transfer length of 42 in. (112 times the diameter).

10. For the stress levels tested, the measured development length of fiberglass and graphite beams did not agree with the ACI-equation. However, the measured development length for steel* prestressed beams agreed with the ACI-equation.

11. The losses in prestressing, other than anchorage losses, were less in fiberglass cables (1/3 of steel*) and graphite cables (8/10 of steel).

12. In comparison with steel* prestressed beams, the fiberglass and graphite prestressed beams behaved equally in static and cyclic flexural loading tests. The two million cycle flexural loading (within working stress) did not damage fiberglass or graphite prestressed beams.

* low relaxation steel (ASTM A416-88-b)

13. The working load deflection (before cracking) of fiberglass and graphite prestressed beams were the same. After cracking, the fiberglass and graphite prestressed beams show an increase in deflection with respect to steel* prestressed beams.

5.2 Recommendations

Fiberglass and graphite cables can be used for prestressing concrete with great care and supervision. The present prestressing plant facilities can be used with some minor modifications. These cables are very brittle and need to be handled very carefully.

Design guidelines in the Appendices are very simple to follow for advanced composite cable prestressed beams. The initial prestressing force for fiberglass and graphite are given with corresponding losses. This needs to be refined for use in the field or to simulate actual conditions.

A demonstration bridge using these materials is needed to evaluate the economics of this technology for bridge construction. A low risk, high volume bridge should be constructed to monitor the real loading and environmental effects on these new space-aged materials. The main property of their resistance to corrosion in a concrete environment is a great advantage in using these materials in bridge construction.

* low relaxation steel (ASTM A416-88-b)

This needs to be evaluated in the field with great care and continuous monitoring. Different materials, such as fiberglass, graphite, and Aramid cables need to be evaluated in the field with cost factors used to make a choice between these cables for future use. In this part of the U.S.A., we are having more problems with bridge deck deterioration and therefore, a bridge deck study is more appropriate than piles or beam studies. A demonstration bridge (deck slab) with these materials is to be constructed to study the above points.

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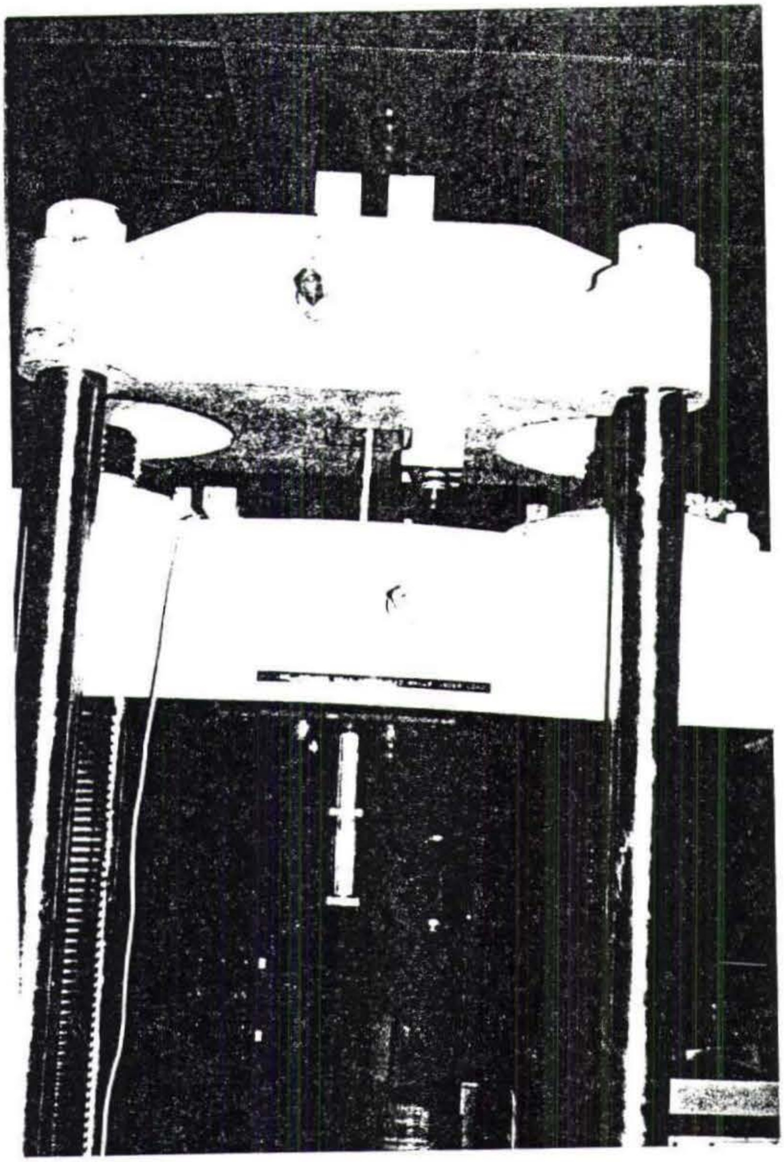


Fig. 2.2.1.1 STATIC TENSION TEST SETUP

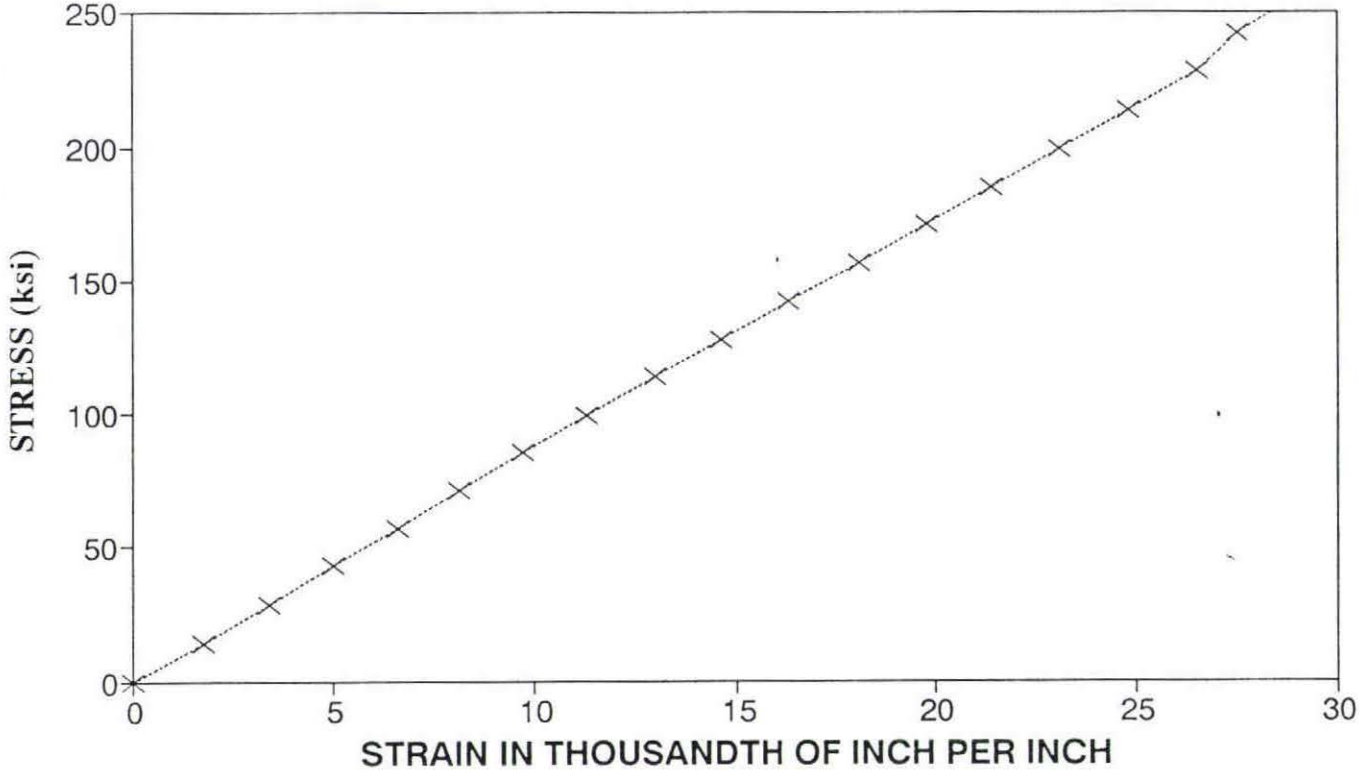


Fig-2.2.1.2 STRESS STRAIN DIAGRAM OF S-2 GLASS VINYLESTER(8084) CABLE VE#2

AREA OF CABLE = 0.0702 sq. inches. GAGE LENGTH = 40.0 inches.
FAILURE STRESS LEVEL = 289.88 ksi. MODULUS OF CABLE = 8.71 million psi.

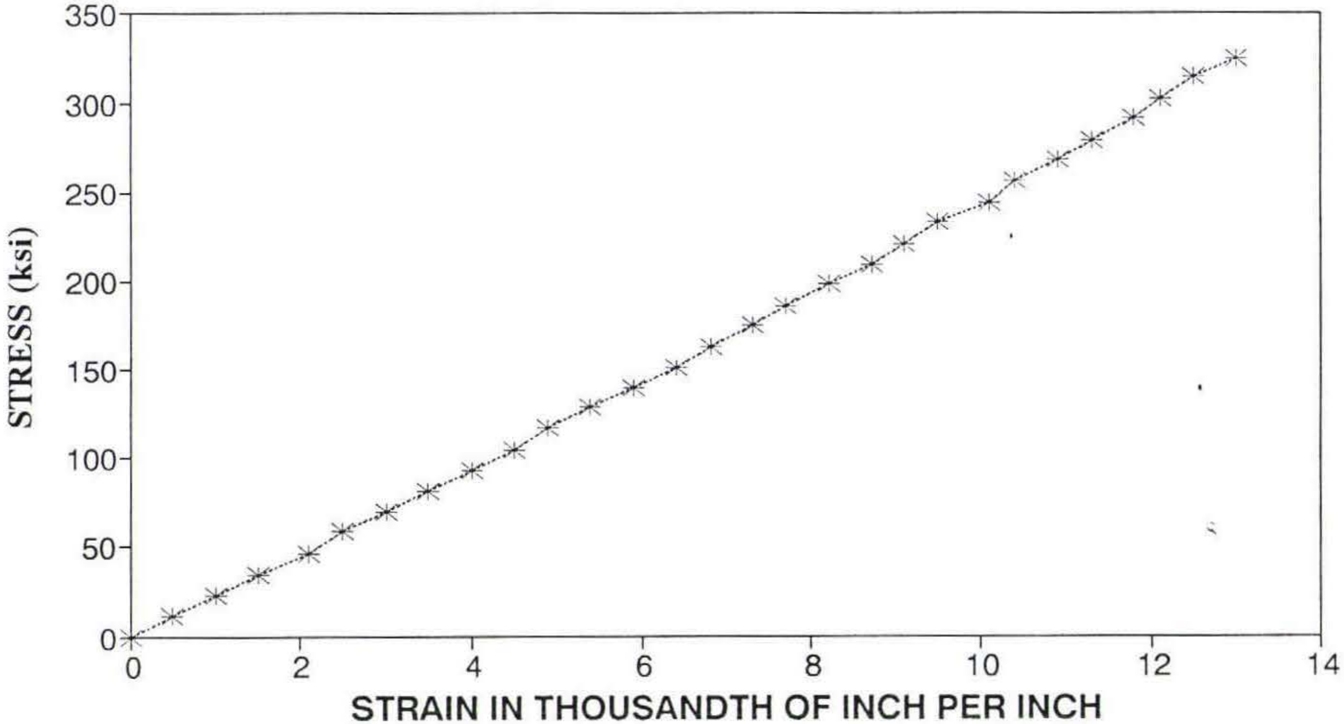


FIG-2.2.1.3 STRESS STRAIN DIAGRAM OF AS-4 GRAPHITE VINYLESTER(8084)CABLE G#1

AREA OF CABLE = 0.0859 Sq. Inches. GAGE LENGTH = 32 inches.

FAILURE STRESS LEVEL = 328.75 ksi. MODULAS OF CABLE = 24 million psi.

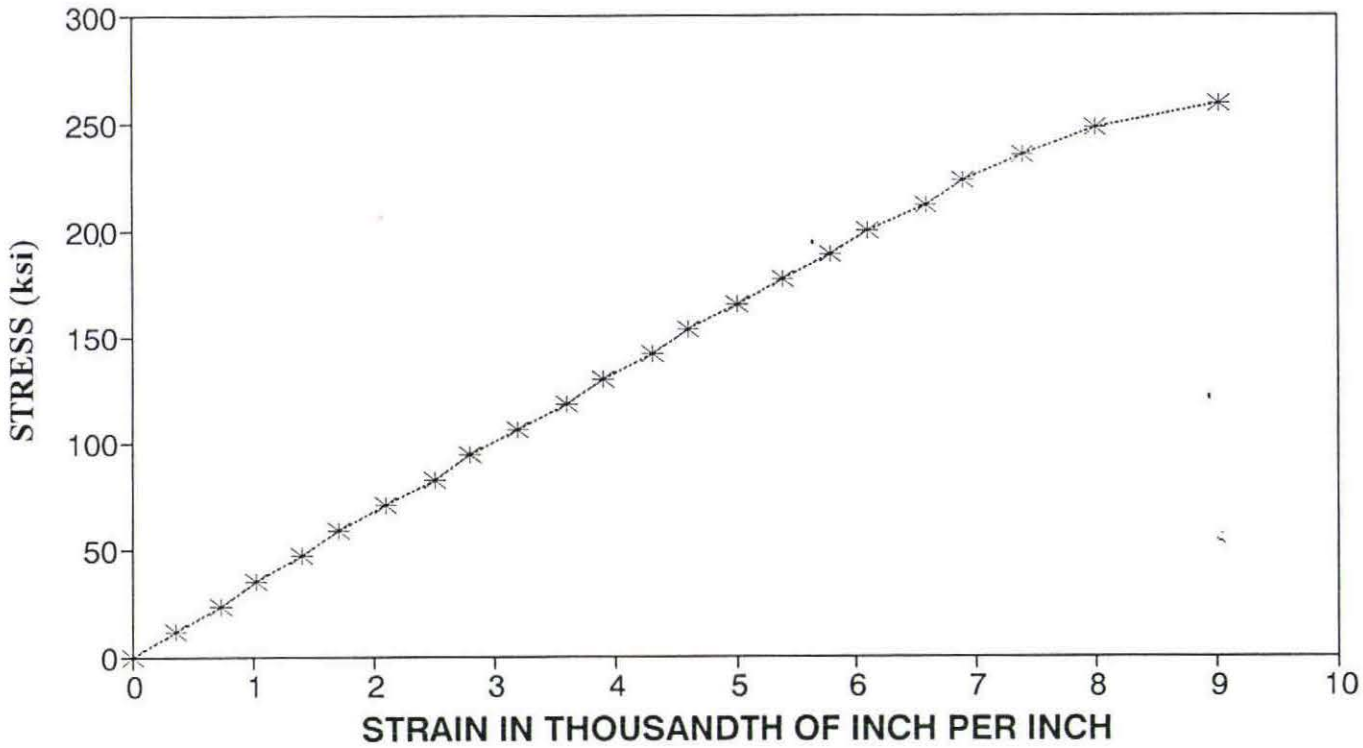


Figure. 2.2.1.4 STRESS - STRAIN DIAGRAM OF STEEL CABLE #3

AREA OF CABLE = 0.085 sq. inches. GAGE LENGTH = 25 inches.
FAILURE STRESS LEVEL = 273.53 ksi. MODULUS OF CABLE = 28.1 million psi.

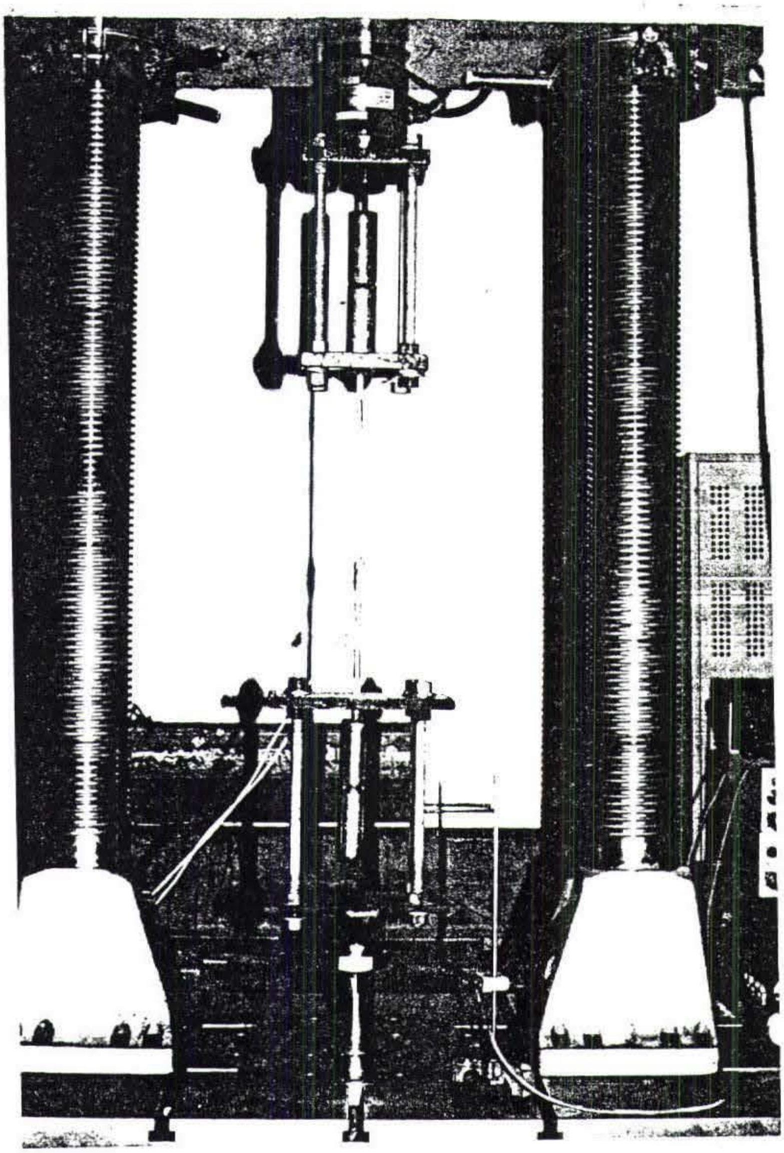


Fig. 2.2.2.1 GENERAL EXPERIMENTAL SETUP FOR CYCLIC AND SUSTAINED LOAD TEST

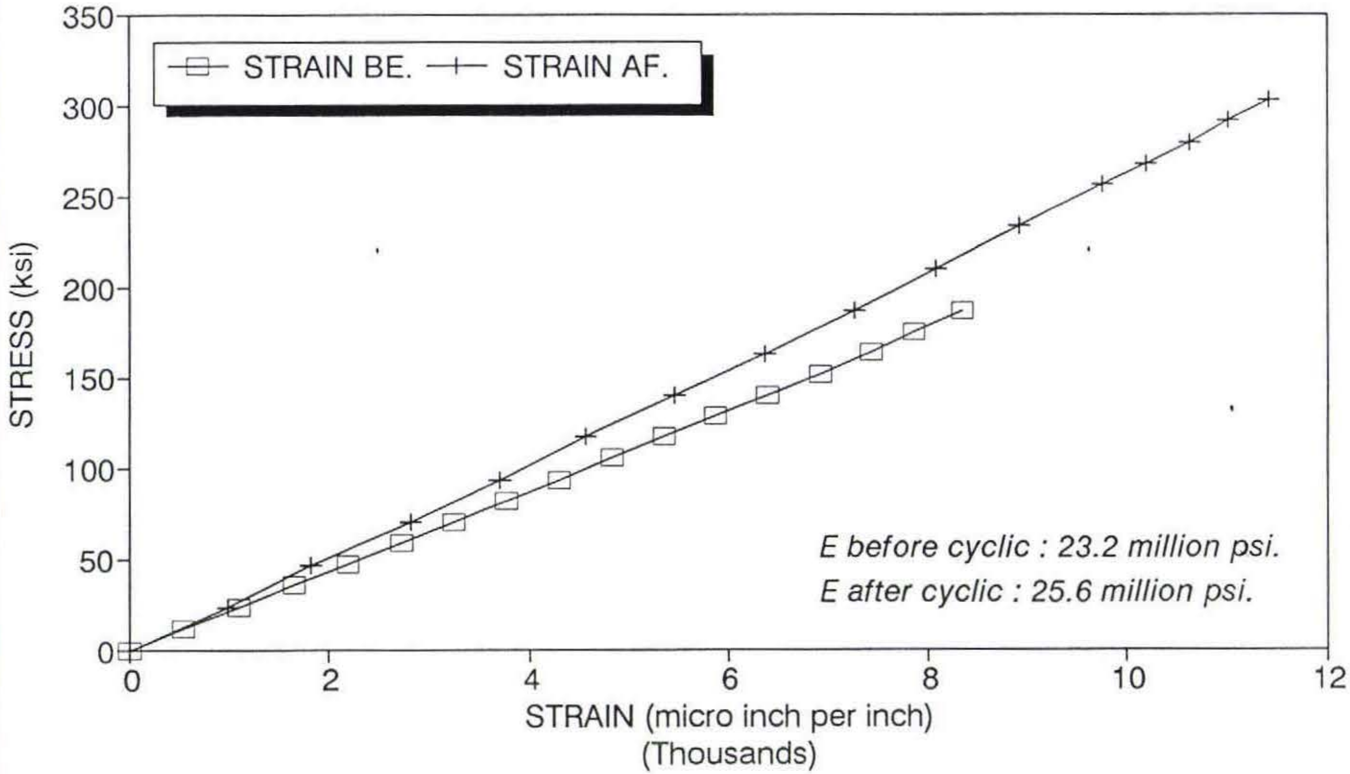


Fig. 2.2.2.2 STRESS-STRAIN DIAGRAM FOR
AS4-GRAPHITE VINYLESTER(8084) CABLE #G3

(BEFORE AND AFTER 2 MILLION CYCLES. FREQUENCY = 7 Hertz. MAXIMUM STRESS = 186 ksi . R = 0.90)

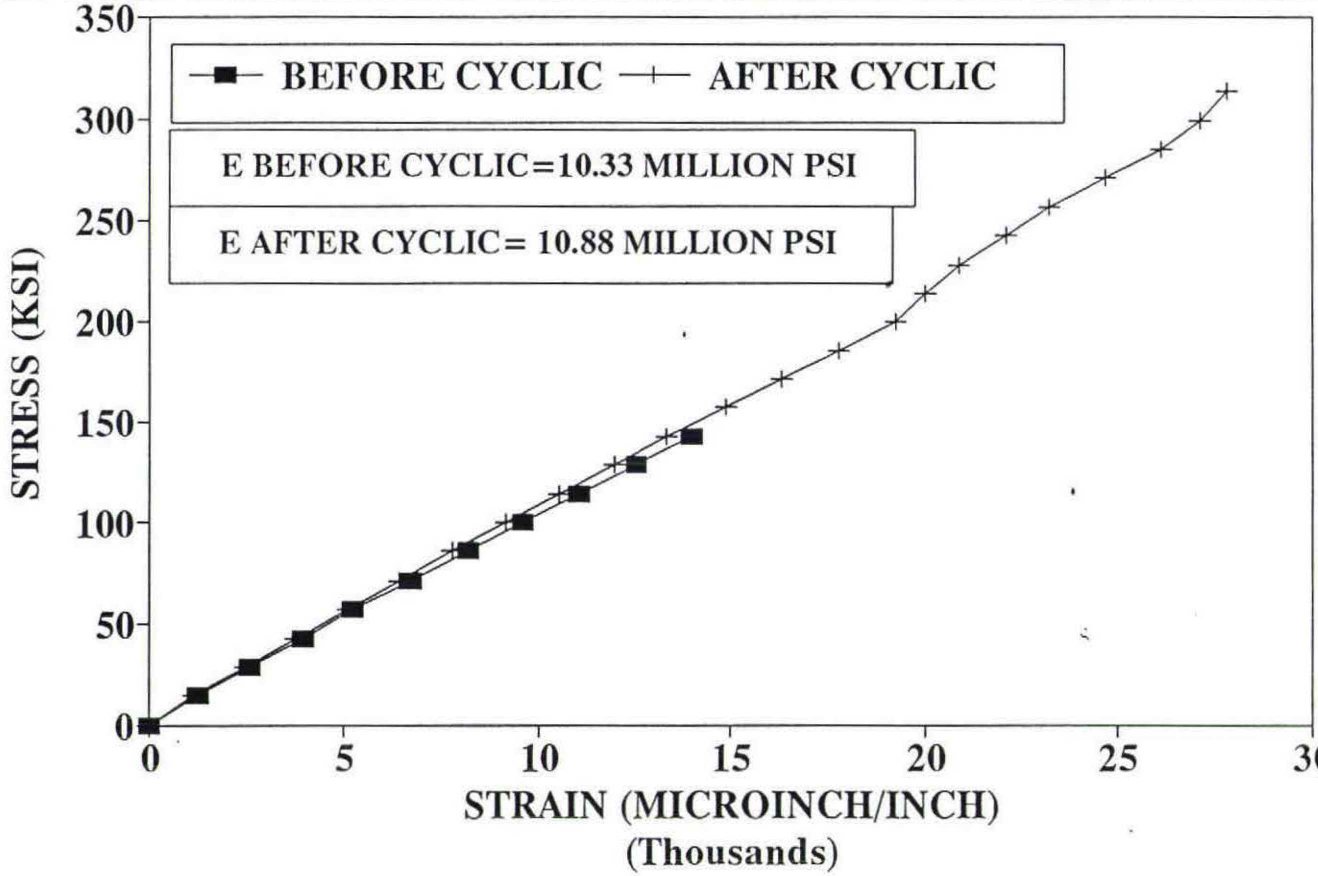


FIG-2.2.2.3 STRESS STRAIN DIAGRAM FOR S-2 GLASS CABLES

BEFORE AND AFTER CYCLIC TEST

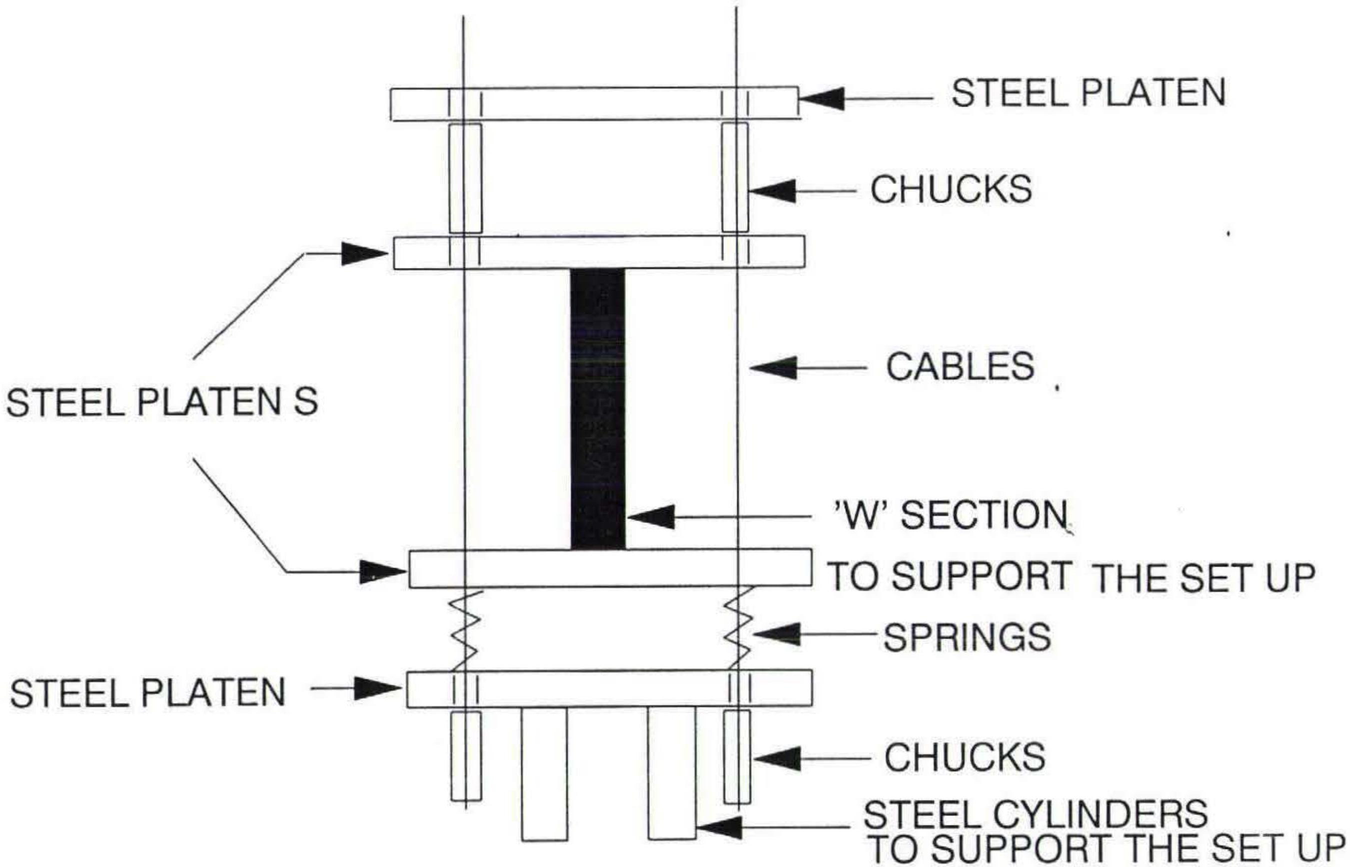


FIG-2.2.3.1 EXPERIMENTAL SET UP FOR CREEP TEST

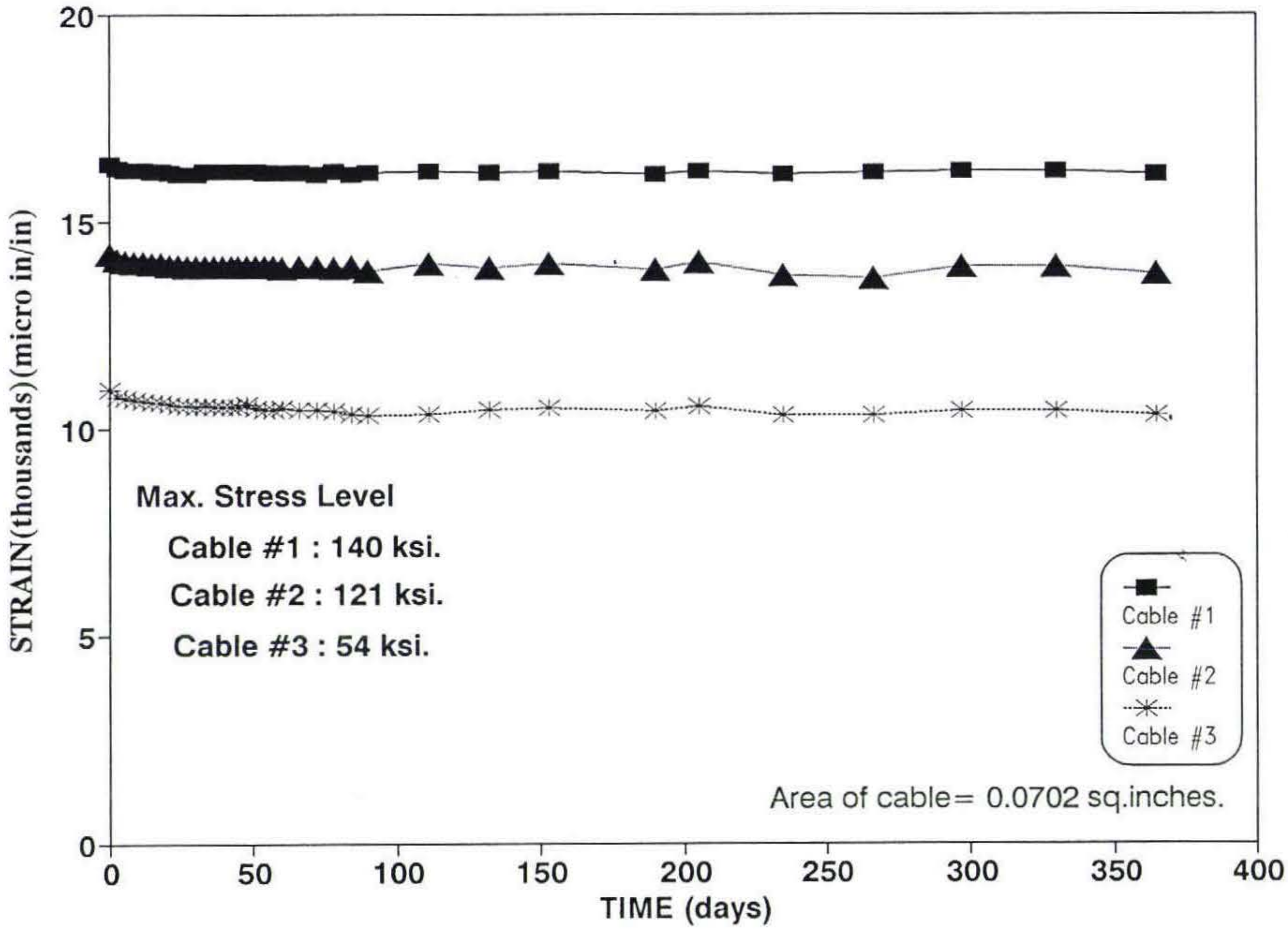


Fig. 2.2.3.2 STRAIN VARIATION IN S2 GLASS VINYLESTER CABLES SUBJECTED TO CREEP TEST

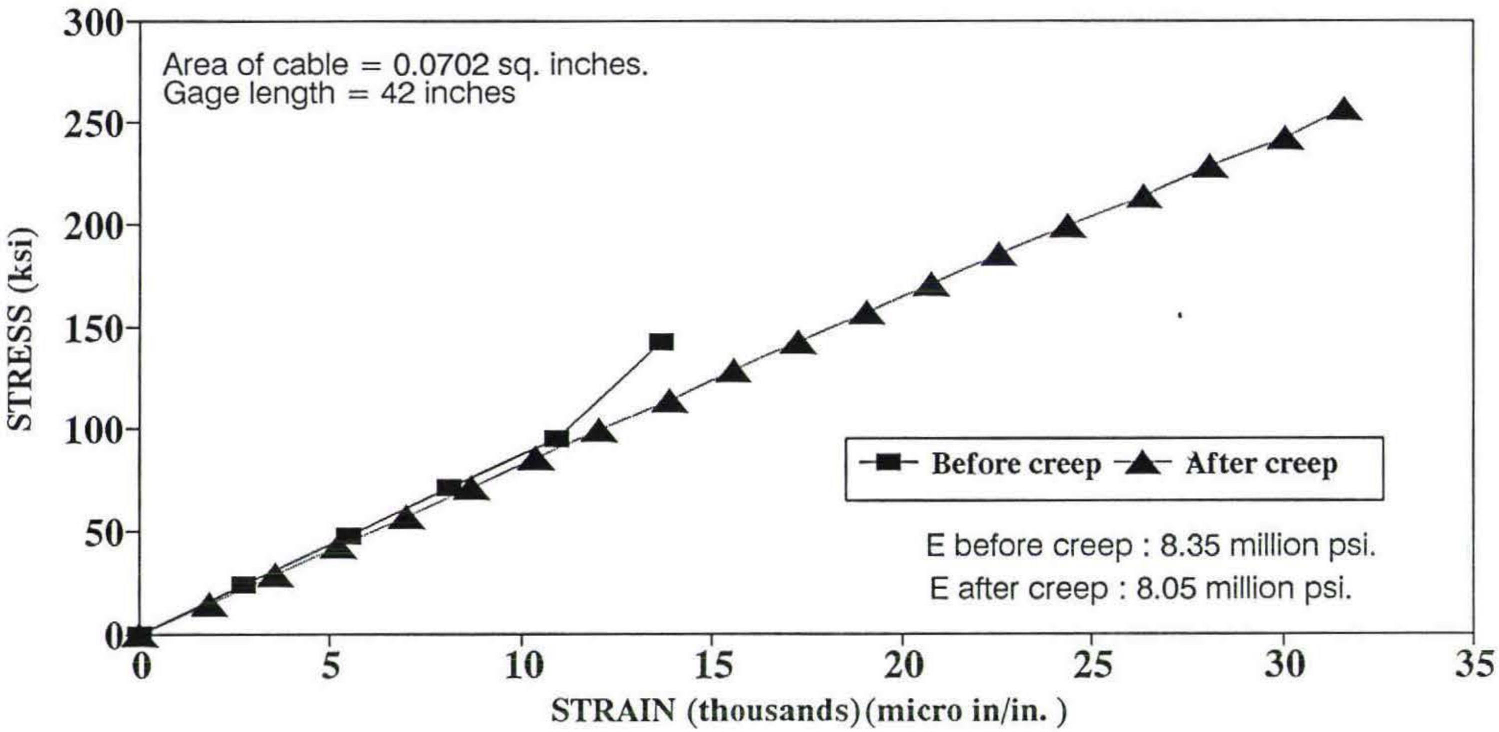


Fig.2.2.3.3 STRESS-STRAIN DIAGRAM FOR S2 GLASS VINYLESTER CABLE #2

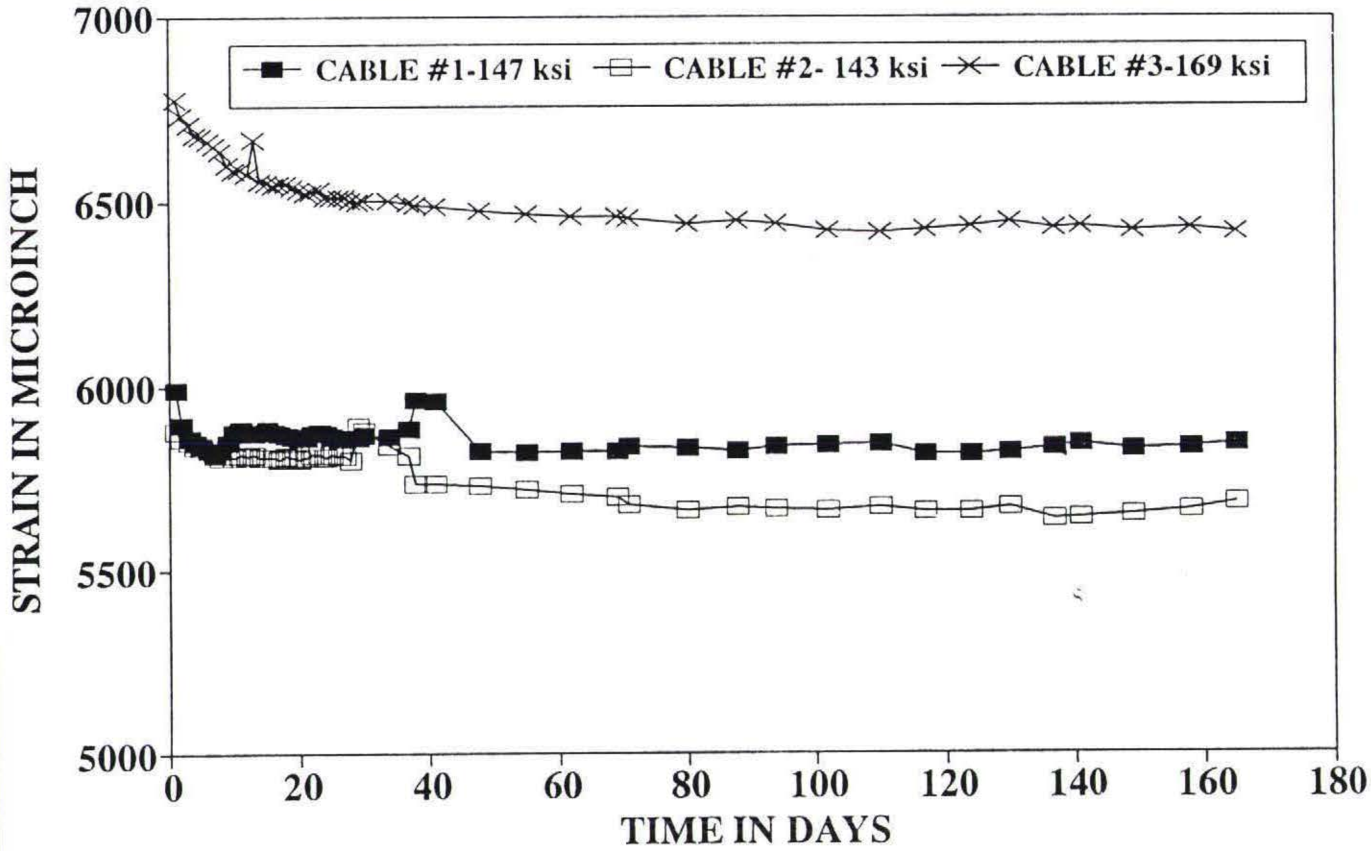


FIG-2.2.3.4 STRAIN VARIATION IN AS-4 GRAPHITE CABLES

SUBJECTED TO CREEP TEST (IN PROGRESS)

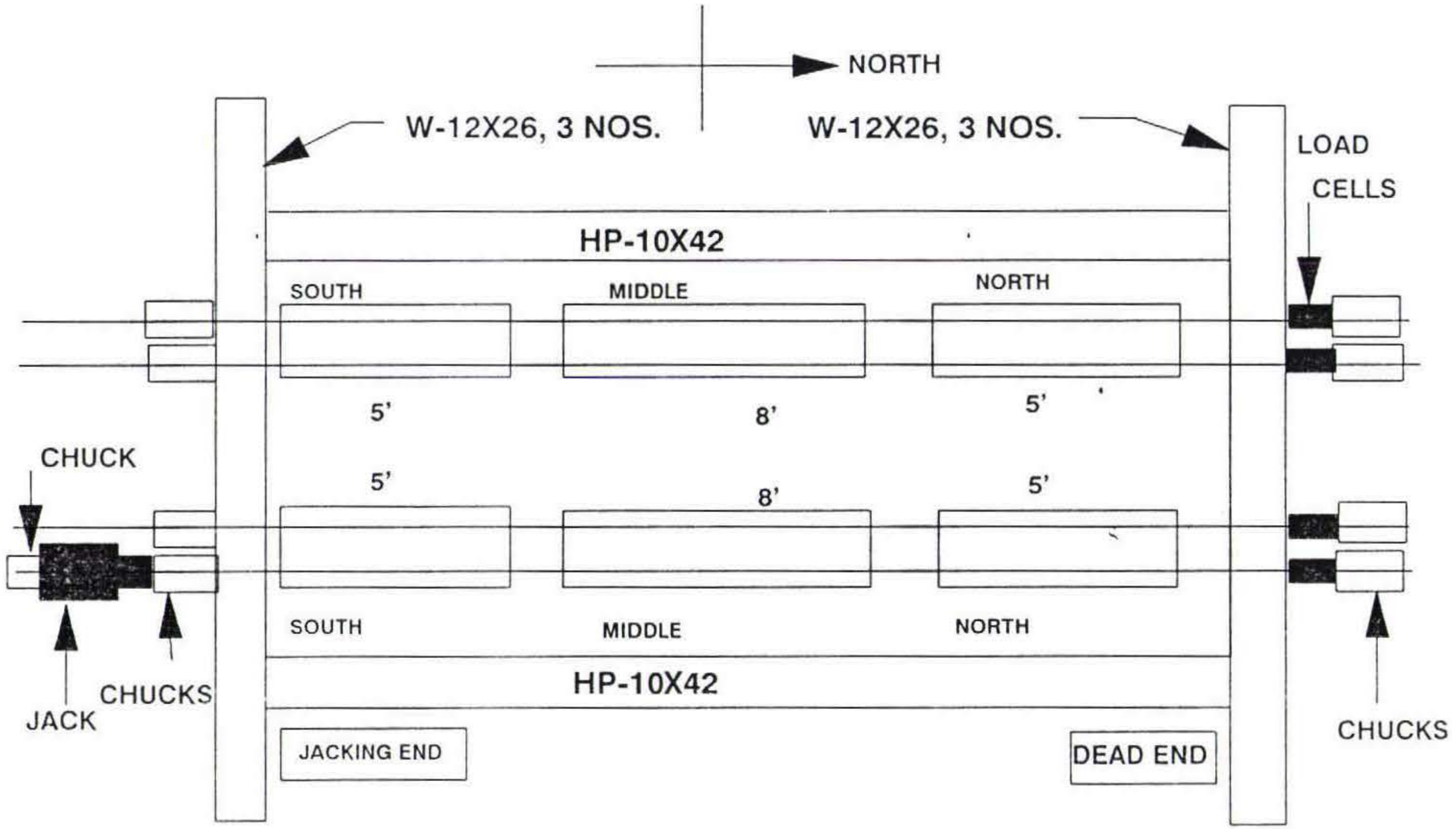


FIG-3.2.1 THE PRESTRESSING BED USED FOR PRESTRESSING CABLES

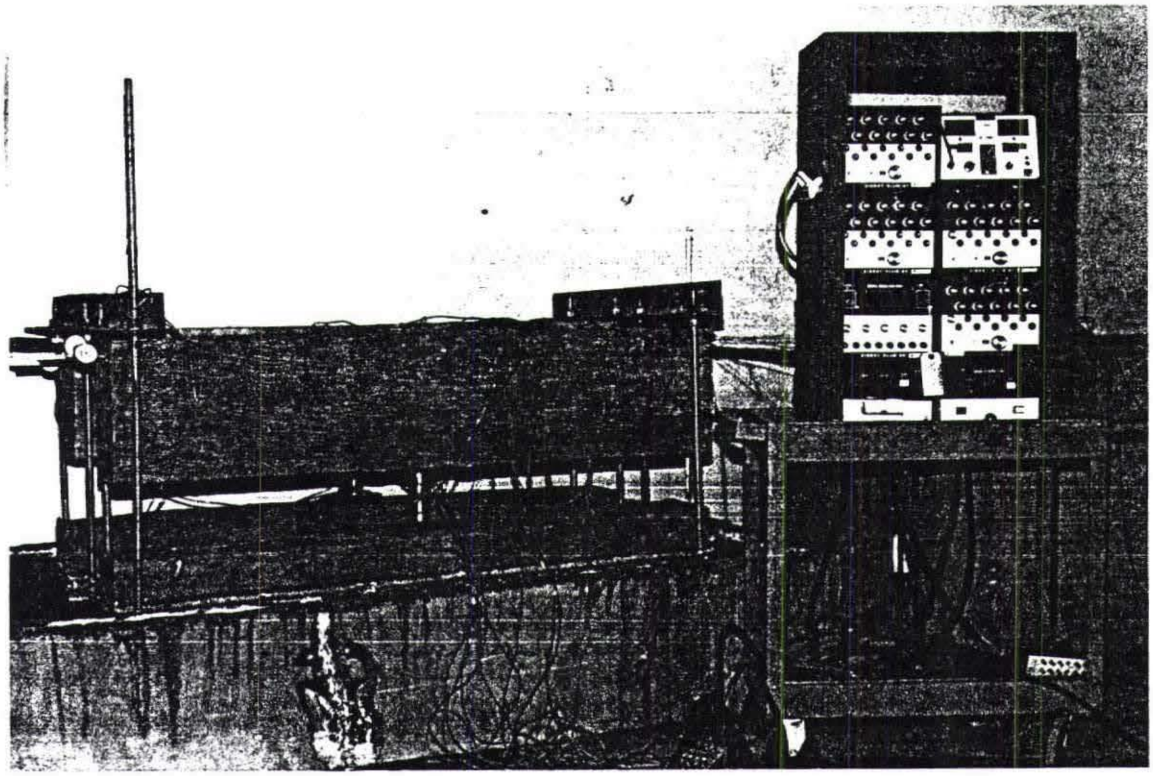


Fig. 3.4.4.1 SUSTAINED FLEXURAL TEST SETUP
(lower beams in salt & upper beams in air)

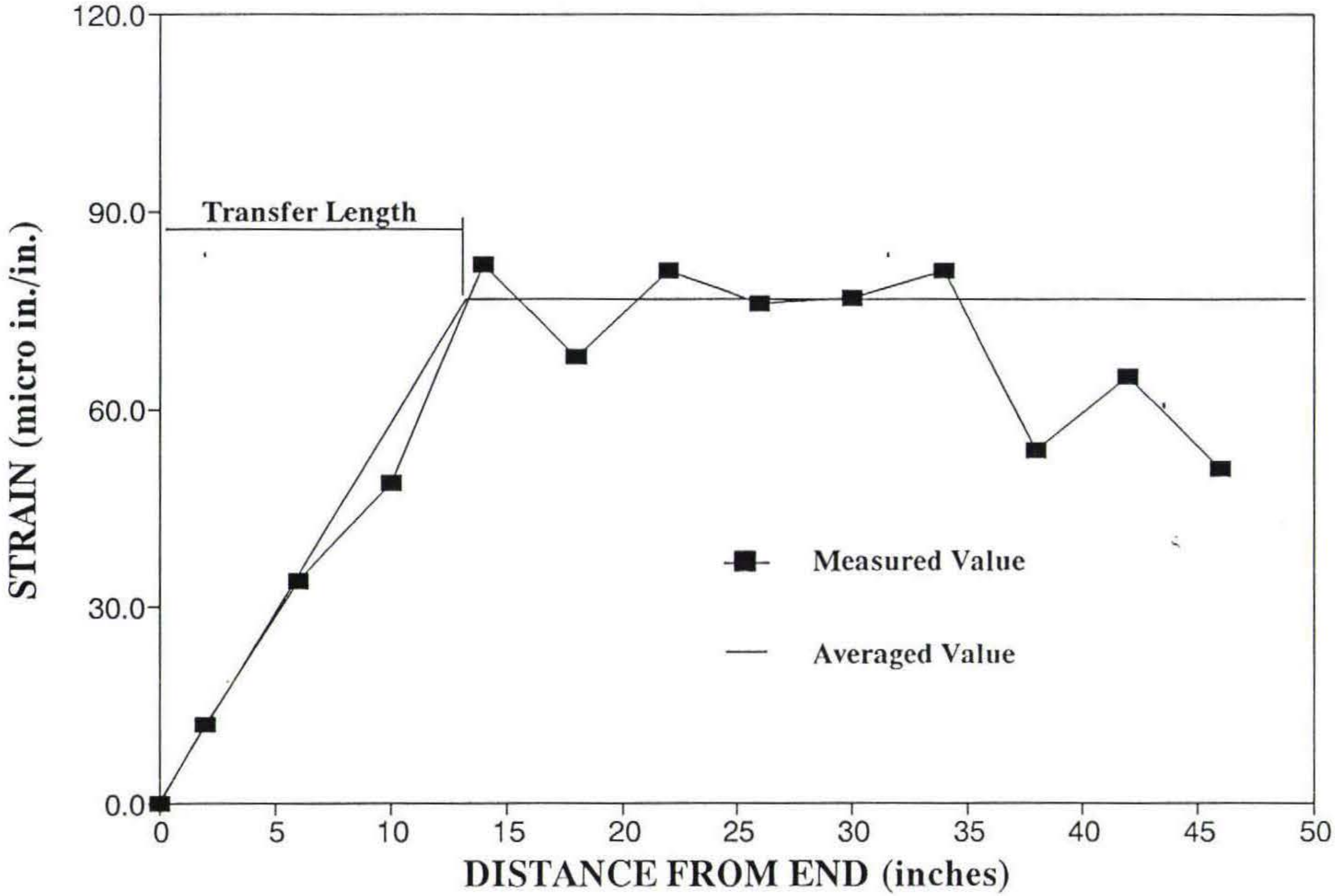


Figure 3.5.1a Transfer Length Test of Fiberglass Prestressed Beam (fse=109 ksi)

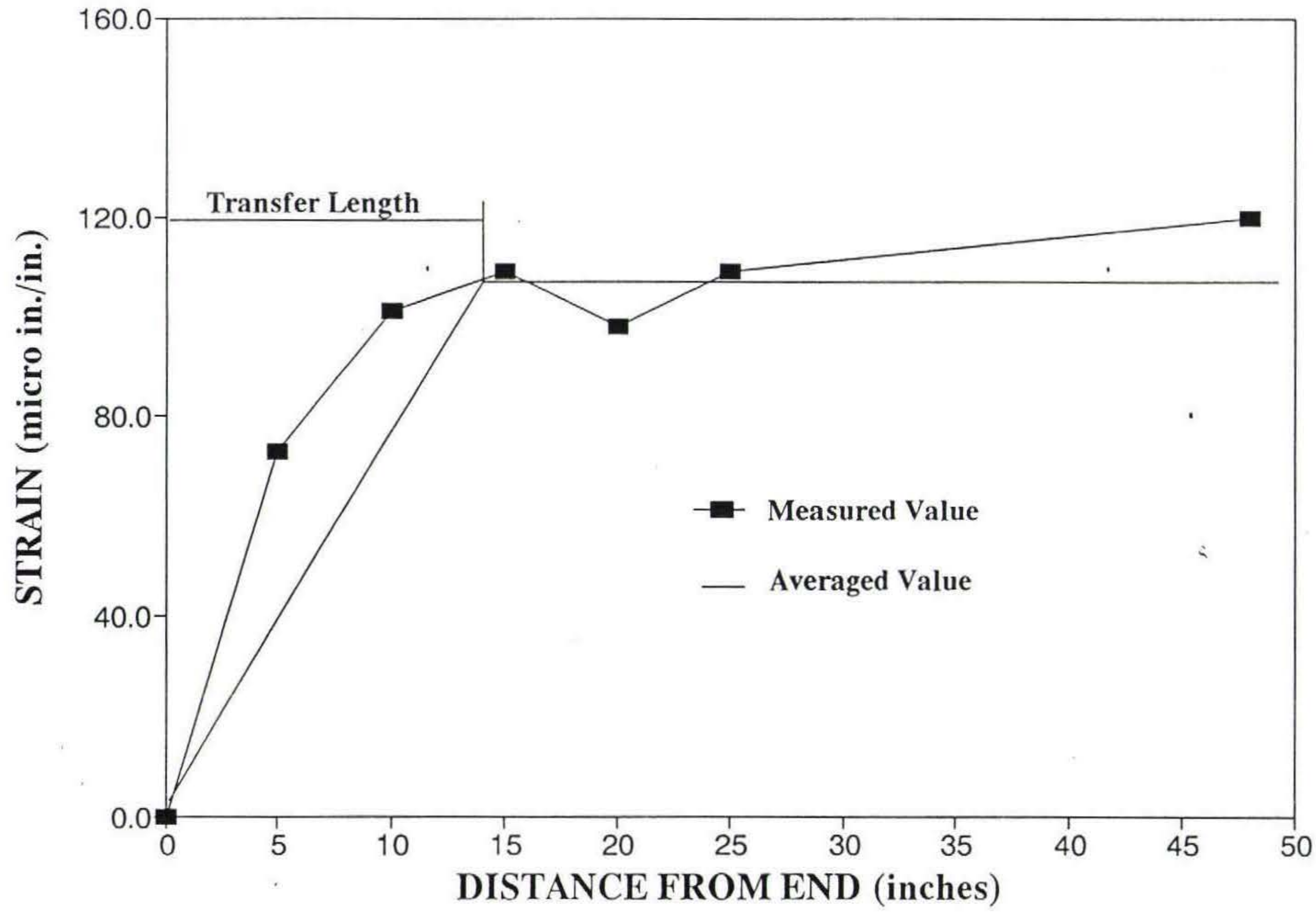


Figure 3.5.1b Transfer Length Test of Fiberglass Prestressed Beam (fse=116ksi)

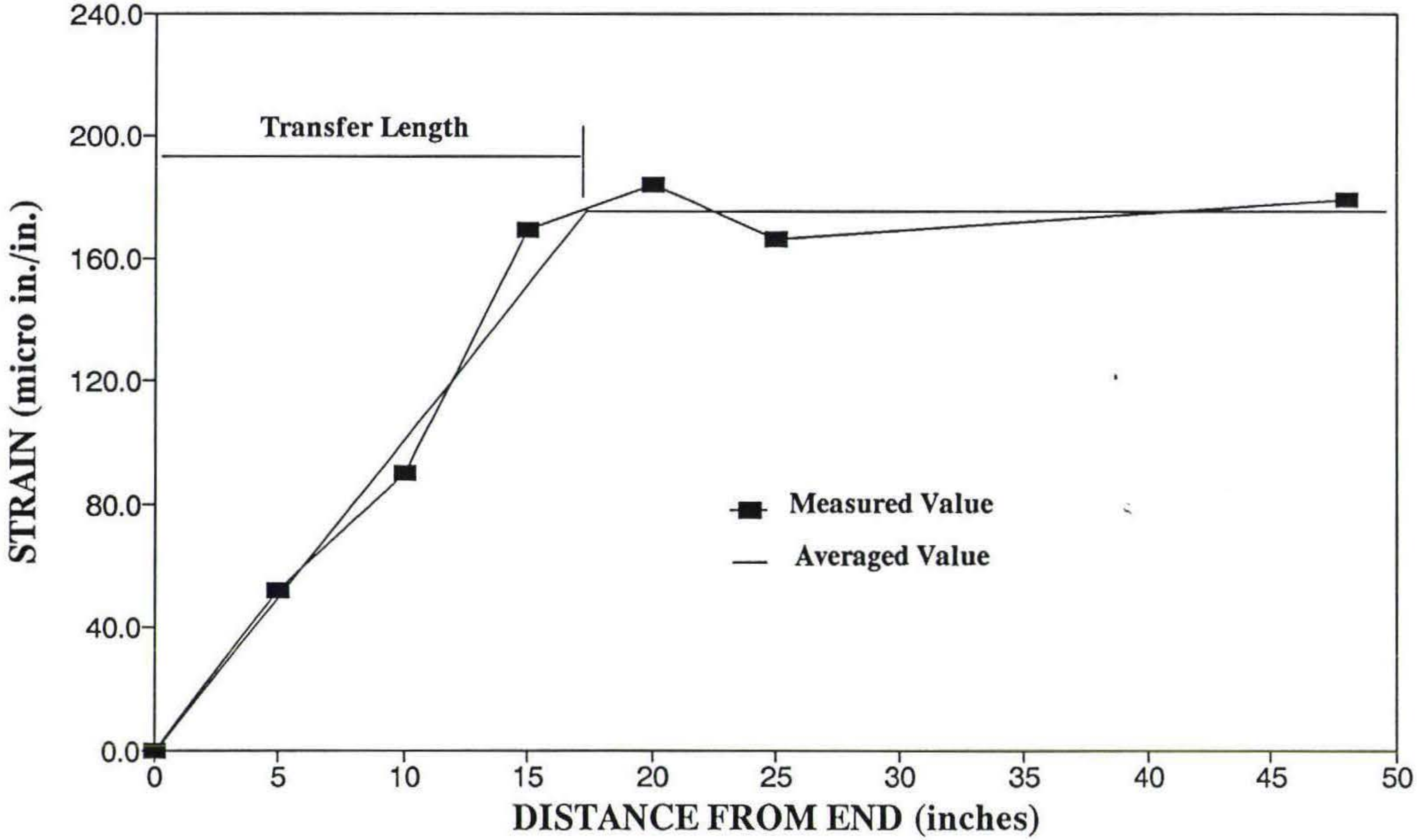


Figure 3.5.2 Transfer Length Test of Steel Prestressed Beam

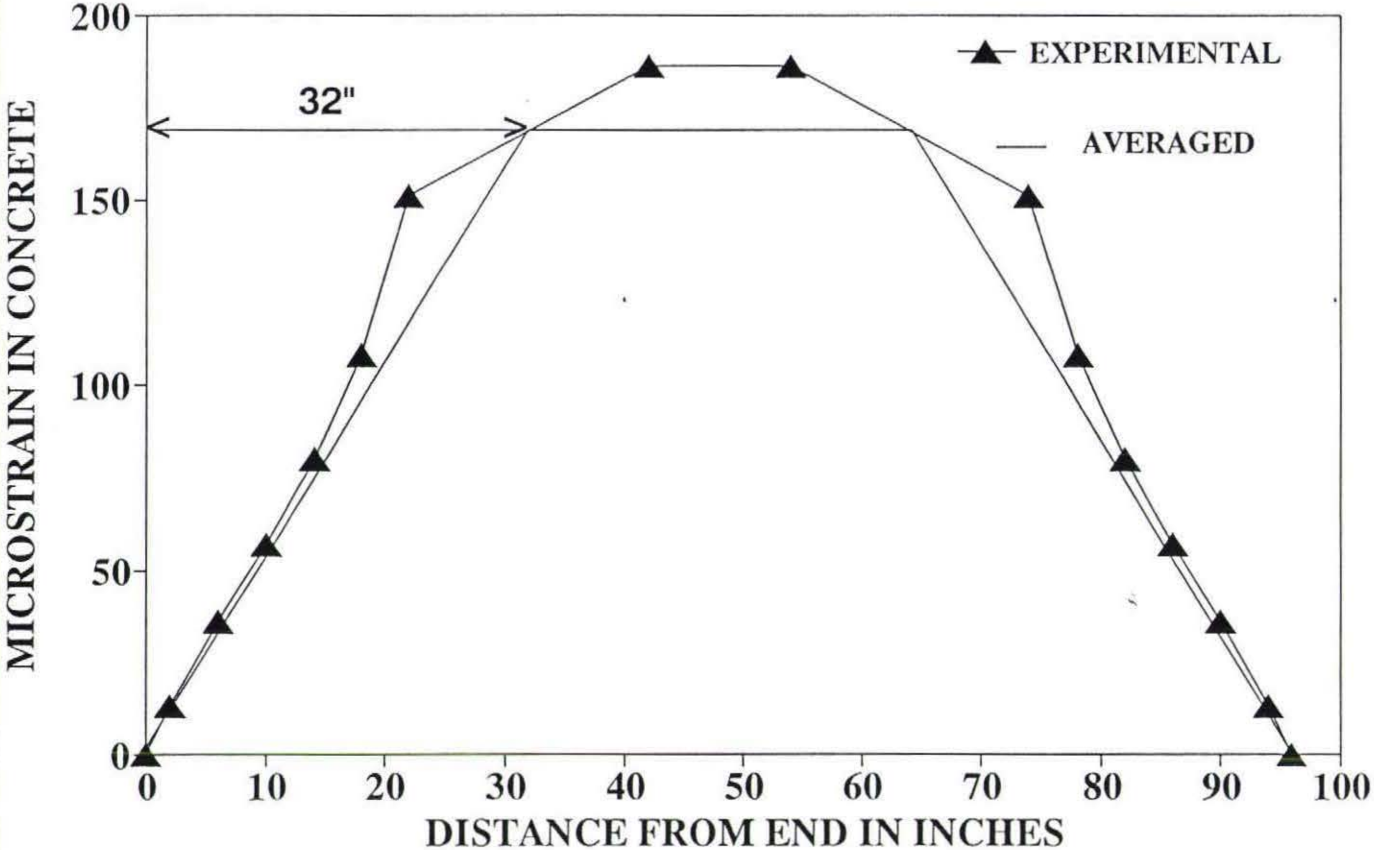


FIG-3.5.3 TRANSFER LENGTH OF GRAPHITE (UNSANDED) PRESTRESSED BEAM

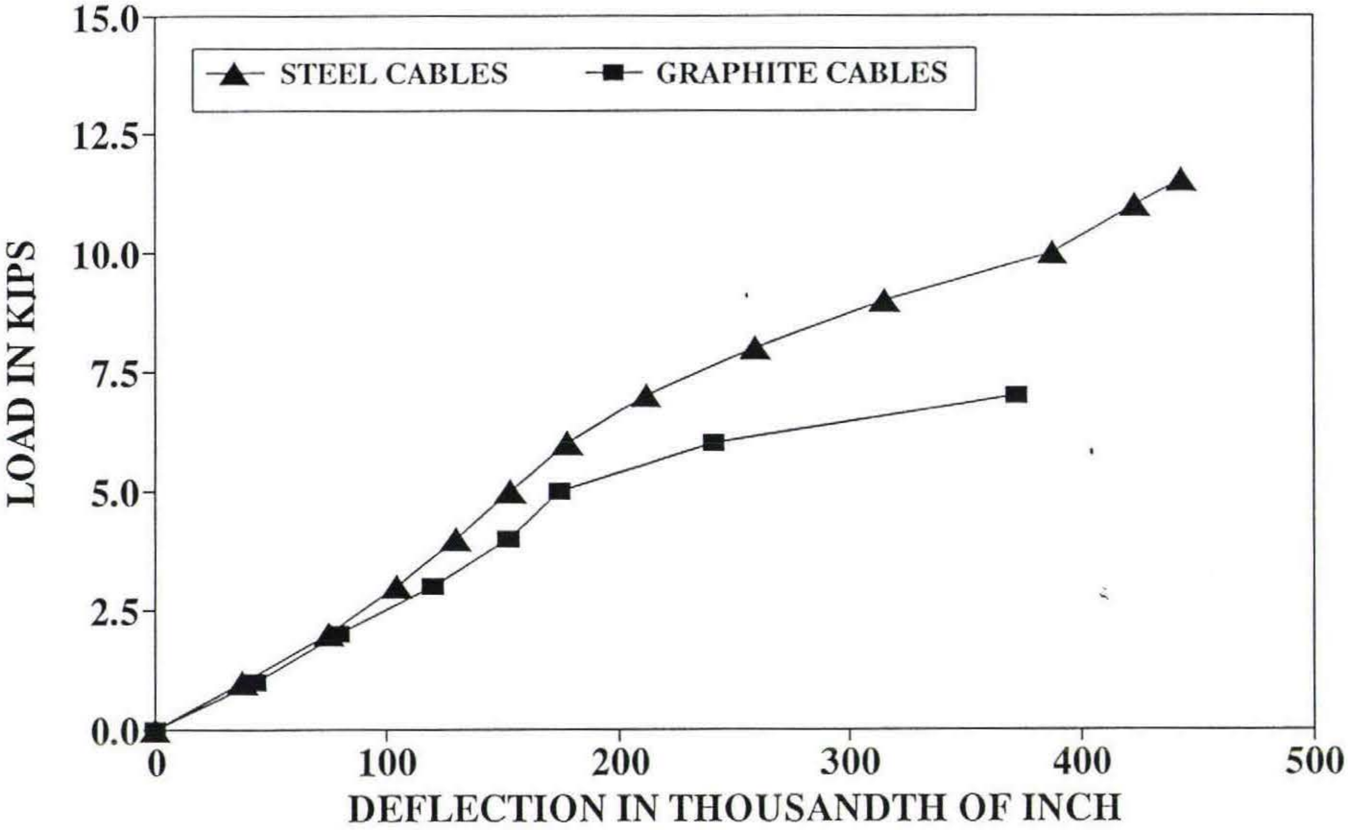


FIG-3.6.1.1 LOAD DEFLECTION DIAGRAMS FOR DIFFERENT BEAMS

SUBJECTED TO STATIC FLEXURAL LOAD

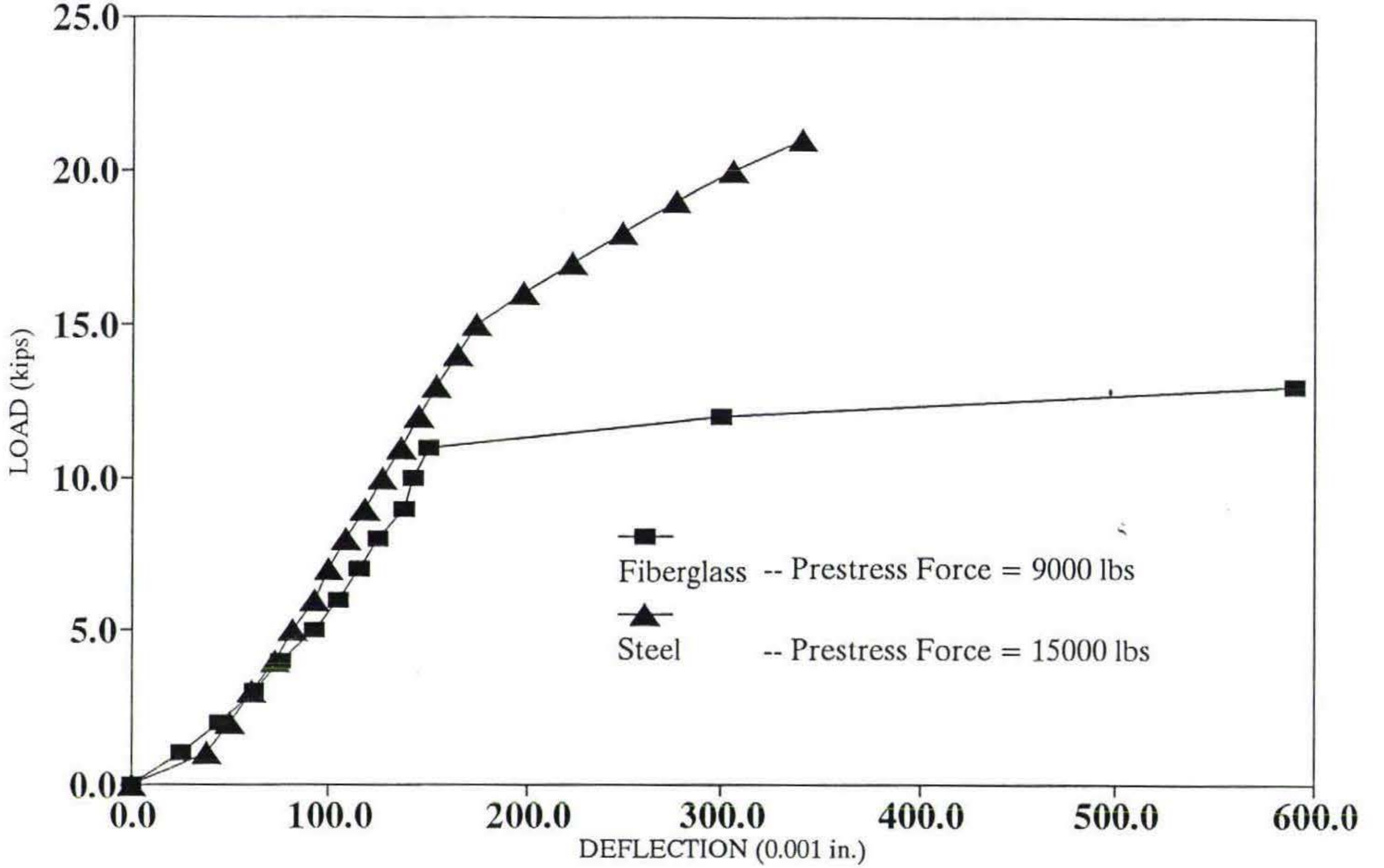


Figure 3.6.1.2 Load Deflection Diagram for Steel & Fiberglass Prestressed Beam Subjected to Flexural Loading

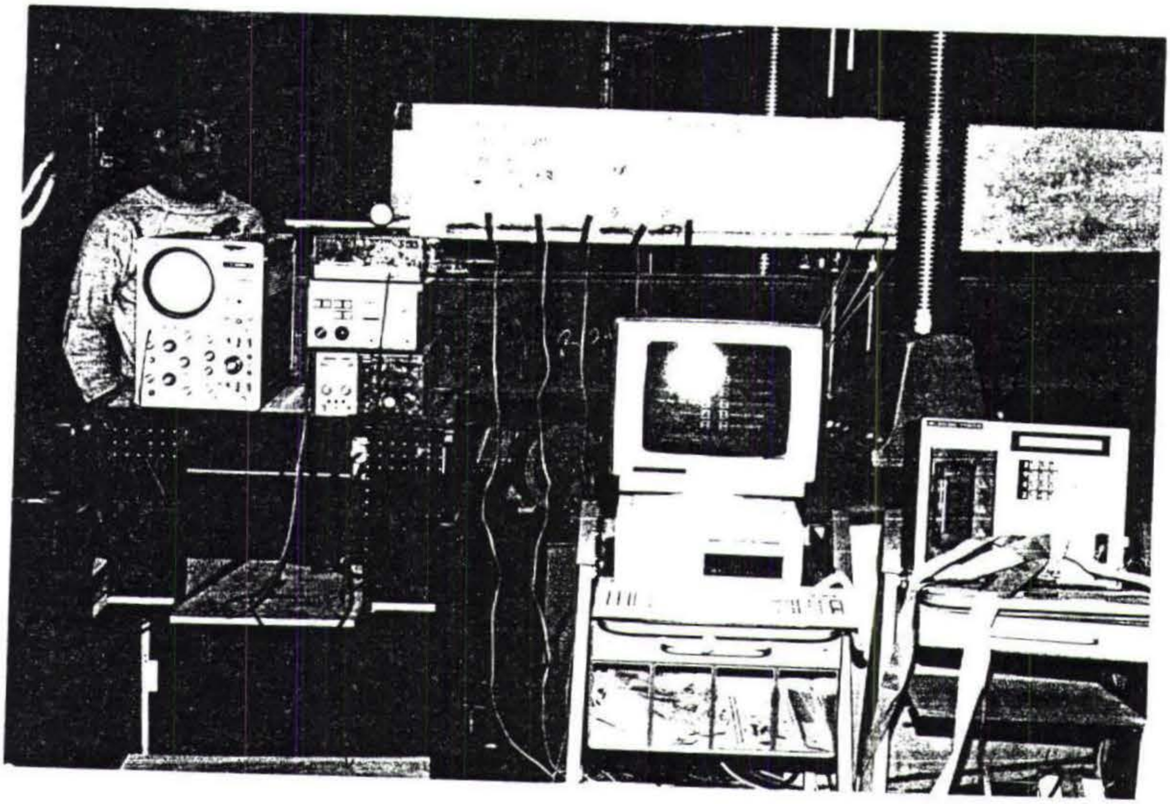


Fig. 3.6.2.1 CYCLIC FLEXURAL TEST SETUP - MTS CLOSED LOOP MACHINE AND DATA AQUISITION SYSTEMS

TABLE 2.1.1.1

DERAKANE VINYL ESTER RESINS PROPERTIES*

Physical Properties	8084 (Resin)
Viscosity, cps at 77° F	350
Specific Gravity	1.02
Tensile Strength, psi.	10-11,000
Tensile Modulus, 10^5 psi.	4.6
Elongation, in percentage	10-12
Flexural Strength, psi.	16-18,000
Flexural Modulus, 10^5 psi.	4.4
Heat Distortion Temp. degree F	170-180

* Data Supplied by Dow Chemicals (Ref. 18)

TABLE 2.1.1.2

FIBER AND RESIN DETAILS USED TO MAKE COMPOSITE RODS

FIBER			RESINS		
TYPE	SUPPLIER	PERCENTAGE BY VOLUME	TYPE	SUPPLIER	PERCENTAGE BY VOLUME
FIBER GLASS (S-2 GLASS)	OWENS-CORNING	65	VINYL ESTER 8084	DOW CHEMICALS	35
GRAPHITE AS4	HERCULES	65	VINYL ESTER 8084	DOW CHEMICALS	35
GRAPHITE AS2	HERCULES	65	VINYL ESTER 8084	DOW CHEMICALS	35

TABLE 2.1.1.3

PROPERTIES* OF S-2 GLASS FIBERS

Physical Properties+	Units	Value
Specific Gravity - Fibers Density	gms/cc lbs per in.^{3}	2.49 0.09
Mechanical Properties+		
Virgin Tensile Strength(70^0 F) Modulus of Elasticity 72^0 F 72^0 F 1000^0 F(after heat compaction) Elongation at 72^0 F	psix10^3 psix10^6 psix10^6 psix10^6 percentage	665 12.6 13.5 12.9 5.4
Thermal properties++		
Coefficient of Expansion Specific Heat at 75^0 F	in/in/^{0}Fx10^6 ---	1.3 0.176

+Properties were determined on glass fibers.
++Properties were determined on bulk glass.

* Data Supplied by Owens-Corning

TABLE 2.1.1.3 A

PROPERTIES* OF MAGNAMITE GRAPHITE FIBERS

Physical Properties	Units	AS2	AS4
Carbon Content Density	percentage lbs per in.^{3}	94 0.065	94 0.065
Mechanical Properties+			
Tensile Strength Tensile Modulus Minimum Elongation	ksi. psix10^6 percentage	400 33 1.3	550 34 1.53

+Properties were calulated from composite laminate test data.

* Product Data Supplied by Hercules.

TABLE 2.1.1.4

PROPERTIES OF LOW RELAXATION PRESTRESSING STEEL CABLE
Diameter of Cable = 0.375 in. (with seven wires)

Properties	Values
Nominal Area, in.^{2}	0.085
Nominal Weight, lbs/1000 ft.	290
Minimum Tensile Strength, ksi.	270
Minimum Yield Strength, ksi.	245
Minimum Elongation, percentage at Gage Length - 24 inches.	3.5

TABLE 2.1.2.1

TENSION TEST RESULTS ON PULTRUDED RODS

MATERIAL	AREA OF CROSS SECTION(in.^{2})	ULTIMATE STRESS (ksi)
AS2- GRAPHITE	0.0123	321.14
AS2- GRAPHITE	0.0123	300.81
AS2- GRAPHITE	0.0123	300.81
AS2- GRAPHITE	0.0123	294.72
AS4- GRAPHITE	0.0123	300.81
AS4- GRAPHITE	0.0123	315.04
AS4- GRAPHITE	0.0123	325.20
S2- GLASS	0.0100	286.30
S2- GLASS	0.0100	274.20
S2- GLASS	0.0100	259.20
S2- GLASS	0.0123	266.67
S2- GLASS	0.0123	243.90
S2- GLASS	0.0123	237.40

Note: 1. Aluminum grips were used for all tests as per ASTM
2. Rod failed in all the tests near the mid hight

TABLE 2.1.3.1

CONCRETE MIX DESIGN & DETAILS
(Design strength: 5000 psi)

For 1 cubic yard mix

1. Cement - Type III .... 752 lbs
2. Water .... 308 lbs
3. Coarse Aggregates .... 1797 lbs (1" max. size limestone aggregtes)
4. Fine Aggregates .... 1139 lbs
5. Air .... 6% +-1

Fresh Concrete Typical Properties

Slump .... $2^{1}/_{4}$ in. Room temperature 65^{o}F
Air .... 6.5% Room relative humidity=52%
Concrete Temperature .. 61 ^{o}F

TABLE 2.2.1.1

TENSION TEST RESULTS ON CABLES

MATERIAL	NOMINAL AREA(in.^{2})	EFFECTIVE AREA(in.^{2})	YOUNGS MODULUS (10^6 psi)	ULTIMATE EFFECTIVE STRESS(ksi)
AS2-Graphite	0.0859	0.0859	-	287.54
AS2-Graphite	0.0859	0.0859	24.1	274.45
AS2-Graphite	0.0859	0.0859	-	279.40
AS2-Graphite	0.0859	0.0859	-	288.13
AS2-Graphite	0.0859	0.0859	22.6	279.40
AS2-Graphite	0.0859	0.0859	23.8	293.36
AS2-Graphite	0.0859	0.0859	21.5	289.87
AS2-Graphite	0.0859	0.0859	-	285.22
AS2-Graphite	0.0859	0.0859	21.0	280.85
AS4-Graphite	0.0859	0.0859	-	305.60
AS2-Graphite	0.0859	0.0859	23.3	325.96
AS2-Graphite	0.0859	0.0859	23.6	314.32
AS2-Graphite	0.0859	0.0859	22.6	304.13
AS2-Graphite	0.0859	0.0859	21.2	305.33
AS2-Graphite	0.0859	0.0859	23.1	323.05
S2-Glass	0.0702	0.0702	8.71	304.13
S2-Glass	0.0702	0.0702	9.90	289.89
S2-Glass	0.0702	0.0702	8.70	236.82
S2-Glass	0.0702	0.0702	-	270.30
S2-Glass	0.0859	0.0702	9.20	304.50
S2-Glass	0.0859	0.0702	9.50	288.50
S2-Glass	0.0859	0.0702	9.80	279.60
S2-Glass	0.0859	0.0702	9.52	301.99
S2-Glass	0.0859	0.0702	9.70	281.34
S2-Glass	0.0859	0.0702	-	290.25
S2-Glass	0.0859	0.0702	9.67	294.87
S2-Glass	0.0859	0.0702	9.90	320.15
S2-Glass	0.0859	0.0702	-	324.07
S2-Glass	0.0859	0.0702	9.60	286.70
S2-Glass	0.0859	0.0702	-	281.34
S2-Glass	0.0859	0.0702	-	313.03
Steel	0.153	0.153	28.90	278.43
Steel	0.0859	0.0859	28.10	273.50
Steel	0.0859	0.0859	29.40	264.71
Steel	0.0859	0.0859	30.89	258.82
Steel	0.0859	0.0859	30.37	258.82

Note: 1. Graphite & fiberglass cables failed close to the middle of the cable
Steel cables failed closed to the chuck

TABLE 2.2.1.2

SUMMARY OF THE MECHANICAL PROPERTIES OF CABLES

Material	Effective Area (sq.in.)	Average Ultimate stress (ksi.)	Average Young's Modulus (million psi.)
AS2-GRAPHITE	0.0859	283.59	22.60
AS4-GRAPHITE	0.0859	314.56	22.76
S2-GLASS	0.0702	282.36	9.20
S2-GLASS	0.0859	243.00	9.70
STEEL	0.0859	266.86	29.53

Poisson's ratio provided by the suppliers:

Graphite = 0.3 (reference 16)
S2-Glass = 0.26 to 0.28 (reference 15)
Steel = 0.30 (reference 17)

TABLE 2.2.2.1

SUMMARY OF STATIC, SHORT TERM SUSTAINED, CYCLIC (TENSION-TENSION) AND STATIC TENSION TESTS ON CABLES

ID#	MATERIAL	AREA OF C/S sq.in.	Max. Stress (ksi) $	TYPE OF TEST	REMARKS
G3	AS4-GRAPHITE & VINYL	0.0859	186.3	Tension-sustained load-cyclic load-tension test	R= 0.90; 7Hz. 2 million cycles & tension test Failed at 314.3 ksi
S2	STEEL	0.0859	188.2*	Tension-sustained load-cyclic test	R= 0.89 & 7 Hz. Failed at 392,480 cycles.
S3	S2-GLASS & VINYL	0.0702	142+	Tension-sustained load-cyclic load-tension test	R= 0.90 & 7Hz. 2 million cycles & tension test. Failed at 313.4 ksi.

* corresponding to 16000 lbs. load

\+ corresponding to 10,000 lbs. load

$ Maximum stress for cyclic and sustained load test.

TABLE 2.2.2.2

STATIC TENSION TEST AS4-GRAPHITE VINYL ESTER(8084)

CABLE BEFORE SUSTAINED AND CYCLIC LOADING

(CABLE NO: G3)

DATE OF CASTING : 10/07/90.
DATE OF TESTING : 11/05/90.
GAGE LENGTH = 32 inches.
ROD DIAMETER = 0.125 inch.
EFFECTIVE AREA OF CABLE = 0.0859 sq. inches.

LOAD (lbs)	STRAIN GAGE READINGS (micro inch per inch)			STRESS (psi)
	1	2	Average	
0	0	0	0	11641
1000	525	551	538	23516
2020	1068	1141	1105	35460
3046	1606	1717	1662	46845
4024	2119	2262	2191	58650
5038	2636	2831	2734	70082
6020	3135	3374	3255	81537
7004	3632	3919	3775	93376
8021	4141	4476	4309	105029
9022	4634	5032	4833	116659
10021	5130	5584	5357	126659
10984	5599	6120	5860	127870
11984	6086	6681	6383	139511
12988	6572	7257	6915	151199
14021	7018	7830	7424	163225
15023	7322	8394	7858	174889
16001	7755	8946	8351	186275

TABLE 2.2.2.3

SUSTAINED TENSION TEST ON AS4-GRAPHITE

VINYL ESTER(8084) CABLE

(CABLE NO: G3)

DATE OF CASTING : 10/07/90.
DATE OF TESTING : 11/05/90.
GAGE LENGTH = 32 inches.
DIAMETER OF ROD = 0..125 inch.
EFFECTIVE AREA OF CABLE = 0.0859 sq. inches.

LOAD (lbs)	STRAIN GAGE READINGS (micro inch per inch)			EFFECTIVE STRESS (psi)	TIME (hrs)
	1	2	Average		
16127	7513	9050	8282	187742	0
16065	7447	9012	8230	187020	4
16180	7438	9021	8230	187194	8
16088	7429	9026	8228	187288	12
16104	7426	9036	8231	187474	16
16117	7423	9038	8231	187625	20
16112	7416	9037	8227	187567	24
16113	7414	9041	8228	187579	28
16127	7417	9051	8234	187742	32
16125	7415	9054	8235	187718	36
16128	7405	9046	8226	187753	40
16135	7408	9052	8230	187835	44
16135	7414	9061	8238	187835	48
16139	7420	9069	8245	187881	52
16133	7410	9061	8236	187811	56
16131	7407	9058	8233	187788	60
16134	7403	9054	8229	187823	64
16118	7340	9052	8196	187637	68
16115	7394	9047	8282	187624	72
16117	7392	9046	8219	187625	76
16116	7391	9047	8219	187614	80

TABLE 2.2.2.4

CYCLIC TENSION TEST ON AS4-GRAPHITE VINYL ESTER(8084) CABLE NUMBER G3

DATE OF CASTING : 10/07/90. DATE OF TESTING : 11/09/90.
GAGE LENGTH = 32 inches. EFFECTIVE AREA OF CABLE = 0.0859 sq. inches.
NUMBER OF CYCLES = 7 Hertz. R VALUE = 0.90. R = Minimum Load/Maximum Load.

LOAD (lbs)			STRAIN (micro inch per inch)			NUMBER OF CYCLES
MINIMUM	MAXIMUM	MEAN	MINIMUM	MAXIMUM	MEAN	
14503	16056	15249	7159	7720	7559	95400
14516	16031	15241	7365	8072	7707	142500
14509	16034	15239	7365	8067	7703	243300
14528	16022	15248	7368	8068	7707	344100
14519	16038	15246	7370	8069	7706	444900
14534	16025	15261	7375	8075	7716	545700
14541	16031	15270	7375	8072	7714	646500
14522	16028	15253	7360	8061	7698	747300
14531	16013	15247	7361	8061	7696	848100
14525	16019	15243	7362	8061	7696	948900
16016	16175	16101	8125	8126	8127	1 million
14456	16025	15242	7342	8045	7679	1196000
14509	16059	15250	7349	8053	7687	1296800
14503	16050	15251	7345	8050	7687	1396700
14528	16051	15261	7363	8068	7704	1498400
14535	16053	15268	7339	8046	7681	1599200
14456	16025	15266	7335	8043	7678	1700000
14528	16034	15261	7346	8052	7685	1800800
14534	16056	15260	7325	8034	7667	1901600
*16006	16163	16088	8126	8130	8128	2 million

*Static load after 2 million cycles

TABLE 2.2.2.5

STATIC TENSION TEST ON AS4-GRAPHITE VINYL ESTER (8084) CABLE AFTER TWO MILLION CYCLES OF CYCLIC LOADING

(CABLE NO: G3)

DATE OF CASTING : 10/07/90.
DATE OF TESTING : 11/13/90.
GAGE LENGTH = 32 inches.
DIAMETER OF ROD = 0.125 inch.
EFFECTIVE AREA OF CABLE = 0.0859 sq. inches.

LOAD (lbs)	STRAIN GAGE READINGS (micro inch per inch)			STRESS (psi)
	1	2	Average	
0	0	0	0	0
2000	849	1129	989	23283
4000	1560	2073	1817	46566
6000	2486	3159	2823	69849
8000	3226	4203	3715	93132
10000	3928	5207	4568	116414
12000	4710	6217	5464	139697
14000	5478	7235	6357	162980
16000	6260	8275	7268	186263
18000	6919	9258	8089	209546
20000	7625	10240	8933	232829
22000	8307	11230	9769	256112
23000	8641	11730	10186	267753
24000	8990	12260	10625	279395
25000	9285	12740	11013	291036
26000	9558	13270	11414	302678

NOTE: Cable failed at stress level 314.32 ksi. away from the anchorage system.

TABLE 2.2.2.6

STATIC TENSION & SUSTAINED TENSION TEST ON STEEL CABLE

(CABLE NO: S2)

DATE OF TESTING : 11/19/90.
GAGE LENGTH = 30 inches.
NOMINAL DIAMETER OF CABLE = 0.375 inch.
NOMINAL AREA OF CABLE = 0.085 sq. inches.

LOAD (lbs)	STRAIN, (10^{-6} inch/ inch)	STRESS (psi)	TIME (hrs)
0	0	0	
2000	733	23529	
4000	1503	47059	
6000	2268	70588	
8000	3033	94118	
10000	3805	117647	
12000	4591	141177	
14000	5388	164706	
16000	6220	188235	
SUTAINED TENSION TEST			
16000	6220	188235	0
16060	6075	188941	4
16128	6116	189741	8
16148	6104	189977	12
16101	6073	189423	16
16056	6047	188894	20
16052	6040	188847	24
16064	6038	188988	28
16075	6032	189118	32
16046	6021	188777	36
16047	6012	188788	40
16043	6006	188741	45

TABLE 2.2.2.7

CYCLIC TENSION TEST ON STEEL CABLE OF 0.375 INCH NOMINAL DIAMETER
(CABLE # S2)

Date of testing : 11-19-90.
Nominal area : 0.085 sq. in.
R value : 0.89

Gage length = 30 inches.
Number of cycles = 7 Hertz.
R = Min. load / Max. load.

Load (lbs)			Strain (micro in./in.)			Number of cycles
Minimum	Maximum	Mean	Minimum	Maximum	Mean	
15963	16138	16043	6009	6013	6011	0
14244	16316	15267	4846	5653	5241	7700
14256	16338	15272	5028	5835	5426	108500
14241	16334	15265	5026	5834	5422	209300
14247	16338	15276	5025	5833	5423	310100

Note: Cable failed at 392,480 cycles close to the anchorage.

TABLE-2.2.2.8

STATIC AND SUSTAINED TENSION TESTS ON S-2 GLASS CABLES

LOAD kips	STRAIN GAGES (microinch/inch)			STRESS (psi)
	#1	#2	AVG.	
0	6	7	6.5	0
1	1531	1053	1292	14245
2	2828	2326	2577	28490
3	4231	3674	3952	42735
4	5525	4961	5243	56980
5	7000	6429	6714	71225
6	8476	7879	8177	85470
7	9913	9269	9591	99715
8	11440	10680	11060	113960
9	12900	12210	12555	128205
10	14340	13630	13985	142450
10	14500	13680	14090	142450

The cable was subjected to sustained load of 10000 lbs. for a period of 50 hours.

After the sustained tension test, the cable was subjected to two million cycles with a maximum load of 10000 lbs. and a minimum load of 9000 lbs. (R=0.9) and at the end the maximum strain was 13915 microinch and minimum strain was 12400 microinch.

TABLE 2.2.2.9

STATIC TENSION TEST ON S-2 GLASS CABLE AFTER 2 MILLION CYCLES

LOAD kips	STRAIN GAGES (microinch/inch)			STRESS (psi)
	#1	#2	AVG.	
0	0	0	0	0
1	1175	1173	1174	14245
2	2478	2478	2478	28290
3	3794	3792	3793	42375
4	5131	5128	5129.	56980
5	6398	6402	6400	71225
6	7773	7778	7775	85470
7	9149	9149	9149	99715
8	10550	10550	10550	113960
9	11980	11970	11975	128205
10	13350	13360	13355	142450
11	14870	14870	14870	156695
12	16310	16310	16310	170940
13	17780	17780	17780	185185
14	19250	19240	19245	199430
15	20020	20200	20200	213675
16	20900	20890	20895	227920
17	22130	22120	22125	292165
18	23240	23360	23300	256410
19	24690	24700	24695	270655
20	26100	26100	26100	284900
21	27120	27130	27125	299145
22	27790	27790	27790	313390

TABLE 2.2.3.1

STRESS LEVEL IN EACH CABLE IN CREEP TEST

MATERIAL	CABLE	EFFECTIVE AREA OF CROSS SECTION (in.^{2})	STRESS (ksi)
Fiberglass	1	0.0702	140
Fiberglass	2	0.0702	121
Fiberglass	3	0.0702	94
Graphite	1	0.0859	142
Graphite	2	0.0859	143
Graphite	3	0.0859	167

TABLE 3.3.1

PULL OUT TEST SPECIMEN DETAILS

TYPE OF CABLE	NUMBER OF SPECIMEN	SIZE OF SPECIMEN	STORED IN	
			SALT	AIR
Fiberglass	48	6" dia.12" ht.	24	24
Steel	36	6" dia.12" ht.	12	24
Sanded Graphite	3	3"x3"x12"	---	3
Unsanded Graphite	3	3"x3"x12"	---	3

TABLE 3.3.2

DETAILS OF BEAMS WITH FIBERGLASS AND STEEL CABLES FOR SODIUM CHLORIDE SOLUTION TEST

TYPE OF CABLE	NO. OF CABLES	BEAM DIMENSIONS in inches	NO. OF BEAMS		REMARKS
			SALT	AIR	
Fiberglass	2	6x4x72	12	6	Cable consists of 7 rods of .113 in diameter
Steel	1	6x4x72	6	6	0.5 in. dia. cable consists of 7 wires of .165 in. diameter

TABLE 3.3.3

DETAILS OF PRESTRESSED CONCRETE TEST BEAMS

Beam Identi-ication	Type of Cable	No. of Cab.	Beam Section (in.xin.)	Length (ft)	Stirrup Holders	Stirrup spacing (c/c) in.	Type of Flexure Test
4ST 5-1	Steel	4	6x8.5	5	2-steel	6	Static
4ST 8-2	Steel	4	6x8.5	8	2-steel	6	Static
3ST 5-3	Steel	3	6x8.5	5	2-steel	6	Static
4UG 5-4	Graphite	4	6x8.5	5	2-graph.	6	Static
4UG 8-5	Graphite	4	6x8.5	8	2-graph.	6	Static
3UG 5-6	Graphite	3	6x8.5	5	2-graph.	6	Static
2SG 8-7	Sanded Graphite	2	6x8.5	8	2-graph.	6	Static
2SG 5-8	Sanded Graphite	2	6x8.5	5	2-graph.	6	Static
2SG 5-9	Sanded Graphite	2	6x8.5	5	2-graph.	6	Cyclic
2UG8-10	UnSand. Graphite	2	6x8.5	8	2-graph.	6	Static
2UG5-11	UnSand. Graphite	2	6x8.5	5	2-graph.	6	Static
2UG5-12	UnSand. Graphite	2	6x8.5	5	2-graph.	6	Cyclic
4FG8-13	Fiber glass	4	8.5x12.5	8	2-Fiber glass	9	Static
4FG5-14	Fiber glass	4	8.5x12.5	5	2-Fiber glass	9	Static
3FG8-15	Fiber glass	3	8.5x12.5	8	2-Fiber glass	9	Static
3FG5-16	Fiber glass	3	8.5x12.5	5	2-Fiber glass	9	Static
4FG5-17	Fiber glass	4	8.5x12.5	5	2-Fiber glass	9	Cyclic
3FG5-18	Fiber glass	3	8.5x12.5	5	2-Fiber glass	9	Cyclic
2ST8-19	Steel	2	8.5x12.5	8	2-Steel	9	Cyclic
2FG8-20	Fiber glass	2	8.5x12.5	8	2-Fiber glass	9	Cyclic

Note: #2 plain steel was used for the stirrups.

TABLE 3.3.4

DETAILS OF PRESTRESSED SLIP CRITICAL BEAMS SUBJECTED TO SODIUM CHLORIDE SOLUTION

BEAM DIMENSION: 8.5"X12.5"; SPACING OF STIRRUPS: 9" C/C

TYPE OF CABLE	NUMBER OF CABLES	STIRRUP HOLDER	STIRRUPS	CNDITIONING	TYPE OF FLEXURE TEST
Steel	2	Two steel rods	#2 steel	Air	Sustained
Steel	2	" "	" "	Salt	Sustained
Fiberglass	2	Two fiberglass cables	" "	Air	Sustained
Fiberglass	2	" "	" "	Salt	Sustained
Fiberglass	2	Two fiberglass cables	Fiberglass	Air	Static
Fiberglass	2	" "	" "	Salt(60 days)	Static
Fiberglass	2	" "	" "	Salt(120 days)	Static
Fiberglass	2	" "	" "	Salt(150 days)	-
Steel	2	Two steel rods	#2 steel	Air	Static
Steel	2	" "	" "	Salt(60 days)	Static
Steel	2	" "	" "	Salt(120 days)	Static
Steel	2	" "	" "	Salt(150 days)	-

(-) indicates test in progress

<u>**TABLE 3.4.1.1**</u>

SUMMARY OF PULL OUT TEST RESULTS ON CONCRETE CYLINDERS SUBJECTED TO SODIUM CHLORIDE SOLUTION

Specimen ID	Date of Testing	Max. Load - Pull Out Test				Remarks
		Fiberglass		Steel		
		Salt	Air	Salt	Air	
I. Series	12-09--89		12,700*		18,650	*Average of three. Salt cycle started on Dec. 16, 1989
	1-17-90	13,500	13,750	15,125	19,550	
	1-17-90	13,000				
	1-17-90	12,500	18,000	15,600	18,150	
II. Series	3-12-90	7,750	7,875	9,000	10,625	
	4-16-90	10,625	7,775	11,000	10,750	
	5-31-90	9,500	5,250	---	---	
	6-30-90	7,500	8,825	9,200	6,700	
	8-18-90	6,125	11,000	11,500	9,500	
	9-29-90	8,425	9,000	9,875	11,250	
	12-28-90	7,900	4,000	10,000	8,250	
I. Series	3-10-91	14,975	15,675	23,250	29,500	
	3-14-91	16,325	15,175	24,600	14,500	
	4-26-91	12,275	15,250			
	4-26-91	16,250	10,500			
	4-26-91	14,875	13,250			
	5-7-91	13,625	13,500	25,250	14,750	
	5-7-91	12,700	16,500		17,800	
	5-7-91	12,525	8,125		14,500	
	5-7-91	13,500	10,675		19,250	
	5-7-91				16,250	
	5-7-91				13,250	
	5-7-91				15,950	
	5-20-91	14,500	16,500	13,750	17,500	
	5-20-91	12,750	11,500		17,625	
	5-20-91	10,250	10,500		24,250	

TABLE 3.4.1.1 (continued)

Specimen ID	Date of Testing	Max. Load - Pull Out Test				Remarks
		Fiberglass		Steel		
		Salt	Air	Salt	Air	
I. Series	5-20-91 5-20-91 5-20-91	15,000 12,500			15,250 17,250 14,750	

Note: I. Series 6" diameter - 12" height.
II. Series 6" diameter - 6" height.

TABLE 3.4.2.1

FLEXURAL STRENGTH TEST SUMMARY ON BEAMS (6" X 4" X 72") SUBJECTED TO ENVIRONMENTAL TEST SIMPLE SPAN - 70 INCHES CENTRAL CONCENTRATED LOAD.

*** Beams with one inch eccentricity**

Date	First crack / Max. load				Half cell	Remarks
	Fiber glass		Steel		readings volt in	
	Salt	Air	Salt	Air	steelbeam in salt	
12-16-89	---	1600/2050	---	---	---	Salt cycle started in Dec 16,89.
1-12-90	1500/2025	1500/1950	1500/2950	1500/2950	-0.500	
1-12-90	1550/2050	---	---	---	---	
3-03-90	1500/2200	1000/1350	1650/3375	1750/2300	-0.350	
4-16-90	2500/3425*	---	1500/2550	---	-0.4521	
5-31-90	---	---	---	---	---	
6-27-90	2250/3550*	---	1950/3750	---	-0.327	
8-18-90	1250/2225	---	1550/2975	---	---	
9-30-90	2250/2925*	1500/1875	---	1425/2500	---	
12-28-90	1950/1925*	2100/2850*	---	---	---	
3-07-91	1350/2900*	1450*/3250*	---	1450/2650	---	
5-6-91	2200/2550	---	---	1875/3050	---	
5-6-91	1625/1825	---	---	---	---	
5-21-91	1500/2175	---	1250/2180	---	---	

Note: 1. Steel beams were prepared on 10-14-89.
2. Fiber glass beams were prepared on 10-30-89 (no eccentricity) on 11-10-89 (with eccentricity of 1").

TABLE 3.4.3.1

FLEXURAL TEST RESULTS OF SLIP CRITICAL BEAMS SUBJECTED TO SODIUM CHLORIDE SOLUTION

DATE OF CASTING: 11-13-90
STARTING DATE OF SALT CYCLE: 12-18-90

TYPE OF CABLES	BEAM SECTION (in. x in.)	SPAN	NO. OF DAYS IN SALT CYC	LOAD AT FIRST CRACK (lbs)	LOAD AT SLIP (lbs)
Fiberglass	8.5x12.5	4'9"	0	16000	16000
Steel	8.5x12.5	4'9"	0	18000	16000
Fiberglass	8.5x12.5	4'9"	60	13500	13500
Steel	8.5x12.5	4'9"	60	17000	19000
Fiberglass	8.5x12.5	4'9"	120	15500	16000
Steel	8.5x12.5	4'9"	120	18900	20000
Fiberglass	8.5x12.5	4'9"	150	16750	17000
Steel	8.5x12.5	4'9"	150	18750	19000

- indicates that the test is in progress.

TABLE 3.4.4.1

Summary of Static Flexure Test Results
After Sustained Flexural Loading
Span : 4'-9" Concentrated Central Load

	Fiber Glass Beam [1] max. load (lbs)		Steel Beam [2] max. load (lbs)	
	Salt	Air	Salt	Air
First crack	19000	*	32000	18000
Slip	21000	12000	37000	10000
Failure	22500	19000	42000	28000

* First crack developed during sustained load.
1 Initial Prestressing force = 20000 lbs/beam
2 Initial Prestressing force = 32000 lbs/beam

TABLE-3.5.1

Transfer length of different cables

Type of cable	F_{se} (ksi)	ACI 318 Equation $(f_{se}/3)*d_b$ (in)	Measured Length (in)
Fiberglass	109	13.6	13.0
Fiberglass	116	14.5	14.0
Steel	144	18.0	17.0
Unsanded Graphite	142.5	17.8	32.0

TABLE 3.6.1.1

SUMMARY OF FLEXURE STRENGTH TESTS ON BEAMS (7'9" OR 4'9") WITH CONCENTRATED CENTRAL LOAD

BEAM ID	SPAN	FIRST CRACK		SLIP LOAD	FAILURE		MODE OF FAILURE	REMARKS
		LOAD	MOMENT		LOAD	MOMENT		
	ft.	kips	ft-k	kips	kips	ft-k		
4ST 5-1	4'9"	10.0	11.88	10.0	13.0	15.44	SLIP	
4ST 8-2	7'9"	9.00	15.19	-	11.5	19.45	COMPRESSION	
4UG 5-4	4'9"	7.00	8.31	9.50	9.50	11.28	SLIP	
4UG 8-5	7'9"	7.00	13.56	7.6	7.6	14.82	SLIP	
2SG 8-7	7'9"	7.00	13.56	-	12.50	24.22	TENSION CAB.	
2SG 5-8	4'9"	12.0	14.25	14.0	15.0	17.81	SLIP	
2SG 5-9	4'9"	10.0	11.88	16.0	18.0	21.38	SLIP	AFTER 2 MILLION CYCLES
2UG 8-10	7'9"	6.00	11.63	7.0	8.2	15.98	SLIP	
2UG 5-11	4'9"	7.50	8.90	8.0	8.5	10.1	SLIP	
2UG 5-12	4'9"	6.00	7.13	6.0	8.0	9.5	SLIP	AFTER 2 MILLION CYCLES
4FG 8-13	7'9"	8.00	15.4	13.0	14.0	27.5	SLIP	
4FG 5-14	4'9"	13.0	15.5	17.0	21.0	25.25	SLIP	
3FG 8-15	7'9"	4.00	7.75	7.0	7.50	14.53	SLIP	
3FG 5-16	4'9"	9.00	10.67	10.0	10.0	12.0	SLIP	
4FG 5-17	4'9"	-	-	14.0	16.0	19.0	SLIP	AFTER 4 MILLION CYCLES
3FG 5-18	4'9"	-	-	7.0	8.50	10.2	SLIP	AFTER 2 MILLION CYCLES
2ST 8-19	7'9"	16.0	31.0	19.0	25.0	48.40	SLIP	AFTER 2 MILLION CYCLES
2FG 8-20	7'9"	13.0	25.2	14.0	17.0	32.90	SLIP	AFTER 2 MILLION CYCLES

\- First crack developed during cyclic loading (see table-3.6.2.1)
Prestressing force for steel and graphite beams was same whereas for fiberglass beams it was lower than steel beams.

TABLE 3.6.2.1

SUMMARY OF CYCLIC FLEXURAL TESTS ON PRESTRESSED CONCRETE BEAMS

Number of cycles per second: 7; Sinusoidal variation: Central concentrated load

Beam ID	Span ft.	Max. load kips	Min. load kips	Slip during cyclic	Flexure test after 2 millon cylces				Remarks
					Load 1st crack	Load slip	Ultimate load	Failure mode	
2SG5-9	4'-9"	9	2	Yes	10.0	16.0	18.0	slip	Slipping started at 529,000 cycles
2UG5-12	4'-9"	5.5	2	Yes	6.0	6.0	9.5	slip	Slipping started at 408,000 cycles
4FG5-17	4'-9"	9	2	No	-	14.0	16.0	slip	
3FG5-18	4'-9"	5	2	No	-	7.0	8.5	slip	
2FG8-20	7'-9"	8	2	No	13.0	14.0	17.0	slip	
2ST8-19	7'-9"	10	2	No	16.0	19.0	25.0	slip	

TABLE-3.7.1

SUMMARY OF LOSSES IN PRESTRESSING

BEAM IDENTI-FICATION	TYPE OF CABLE	CROSS SECTION OF BEAM (inxin)	LOSSES IN PRESTRESSING	
			ANCHORAGE (%)	ELASTIC (%)
4FG 8-13	Fiberglass	8.5x12.5	5.8	2.4
4FG 5-14	Fiberglass	8.5x12.5	5.2	2.0
4FG 5-17	Fiberglass	8.5x12.5	7.1	2.3
3FG 5-18	Fiberglass	8.5x12.5	5.7	1.1
2FG 8-20	Fiberglass	8.5x12.5	7.4	1.1
-	Steel	8.5x12.5	6.4	2.6
-	Steel	8.5x12.5	5.9	4.5
2SG 8-7	Sanded Graphite	6.0x8.5	8.3	2.6

(-) indicates that the beams were used for the sustained load test.

Table 4.3.1

COMPARISON OF EXPERIMENTAL AND THEORETICAL DEVELOPEMENT LENGTHS

STEEL

BEAM ID.	fse	fps	EXPERIMENTAL DEVELOPMENT LENGTH	THEORETICAL DEVELOPMENT LENGTH
	(ksi)	(ksi)	(inches)	(inches)
4ST8	125	191	42	40.38
4ST5	106	140	24	26.25
3ST5	106	148	24	29

GRAPHITE

BEAM ID.	fse	fps	EXPERIMENTAL DEVELOPMENT LENGTH	THEORETICAL DEVELOPMENT LENGTH
	(ksi)	(ksi)	(inches)	(inches)
2SG8	175	303	48	69.9
2SG5	132	184	30	36.0
2SG5C	134	182	30	34.8
2UG8	101	109	48	15.63
2UG5	90	101	30	15.38
2UG5C	90	94	30	12.75

FIBERGLASS

BEAM ID.	fse	fps	EXPERIMENTAL DEVELOPMENT LENGTH	THEORETICAL DEVELOPMENT LENGTH
	(ksi)	(ksi)	(inches)	(inches)
3FG5-16	84	103	27	17.5
4FG5-14	107	129	27	21.6
3FG8-15	97	164	45	37.4
4FG8-13	106	175	45	39.2
2FG8-20	133	161	48	27.4

$l_d = [fps - 2/3\ fse]\ d_b$

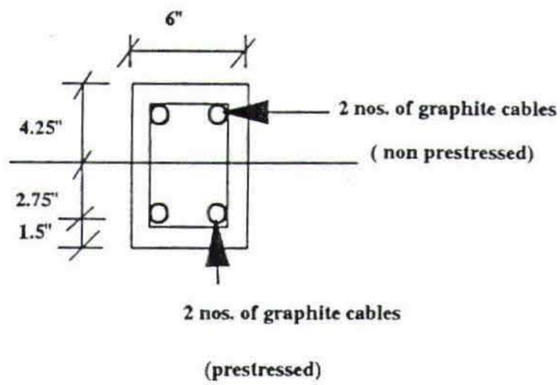
APPENDIX C

Design Calculations of Prestressed Beams

DESIGN OF BEAM WITH GRAPHITE CABLES

Fc'=5000 psi	Ec=4 million psi
fgf=325 ksi	Eg=24 million psi
fy=270 ksi	Es=29 million psi

Section of beam= 6" x 8.5"
I section= 307.06 in^4
A section= 51 in^2 r^2=I/A=307.06/51=6.02 in^2
Allowable tension= $7.5(fc')^{1/2}$= 530 psi
Allowable compression= 0.45(fc')= 2250 psi



Assuming tension on top is governing-

fct= P/A (1-e*y/$r^2$2)

530= P/51(1-2.75*4.25/6.02)

or P= 28711 lbs.

Let us use 2 nos. of graphite cables 3/8" diameter.

Force on every cable=28711/2= 14356 lbs.

Check for compression on bottom fiber-

fcb= P/A (1+e*y/r^2)

fcb= 28711/51*(1+2.75*4.25/6.02)

= 1656 psi<2250 psi O.K.
Now the stress in concrete at the level of graphite cables=

fcs= 28711/51(1+2.75/6.02)= 1270 psi

Loss due to elastic shortening = n*fcs

= $24*10^6/4*10^6$ (1270)

= 7620 psi

Loss in force/cable= 7620*0.0859= 655 lbs.

% loss= 4.56%

Final prestressing force/cable= 14356 = 655= 15010 lbs.

Stress on the cable= 1744738 psi

After the time dependent losses-

1.- Shrinkage loss = $3*10^{-4}*Eg$

$= 3*10^{-4}*24*10^{6}$

= 7200 psi

% loss= 4.6%

loss in force/cable = 7200*0.0859= 618 lbs.

2.- Creep loss = $0.33*10^{-6}*24*10^{6}*1270$

= 10058 psi

% loss= 6.0%

Loss in force/cable = 10058*0.0859= 864 lbs.

Total loss = 10.6% (Shrinkage and creep)

Therefore, the effective prestress after losses= Pe

Pe= (1-0.106)*2*14356= 25669 lbs.

Stress at top fiber = 25669/51*(1-2.75*4.25/6.02)

= 474 psi (tension)<530 psi, O.K.

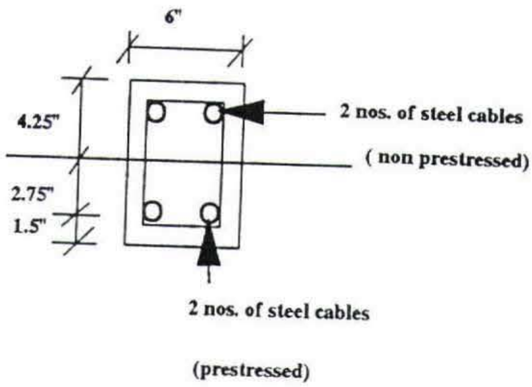
Stress at bottom fiber = 25669/51*(1+2.75*4.25/6.02)

= 1480 psi<2250 psi, O.K.

Design of Beam With Steel Cables

$f_c'=5000$ psi.
$f_{gf}=325$ ksi.
$E_c=4$ million psi

$E_s=29$ million psi
$E_{gf}=24$ million psi



I section = 307.06 in.^{4}
A = 51 in.^{2}
r^2 = I/A = 6.02 in.^{2}

Allowable tension while prestress transfer = 7.5 fc'
= 530 psi

Allowable compression = 2250 psi (0.45 fc')

Assuming tension on top is governing -

$$fct = \frac{P}{A}\left(1-\frac{ey}{r^2}\right)$$

$$530 = \frac{P}{6x8.5}\left(1-\frac{2.75 \times 4.25}{6.02}\right) \Rightarrow P = 28711 \text{ lbs}$$

Let us use 2 cables 3/8" diameter-force/cable = 14356 lbs
stress = 14356/0.0859 = 167125 psi

Check for compression on bottom fiber -

$$fcb = \frac{P}{A}\left(1+\frac{ey}{r^2}\right) = \frac{14356}{51}\left(1+\frac{2.75 \times 4.25}{6.02}\right) = 1656 \text{ psi} < 2250 \text{ psi ok}$$

∴ stress in concrete at level of steel =

$$fcs = \frac{P}{A}\left(1+\frac{2.75 \times 2.75}{6.02}\right) = \frac{28711}{51}\left(1+\frac{2.75 \times 2.75}{6.02}\right) = 1270 \text{ psi}$$

∴ Loss due to elastic shortening = nfcs

$$= \frac{Eg}{Ec} fcs$$

$$= \frac{29 \times 10^6}{4 \times 10^6} \times 1270 = 9208 \text{ psi}$$

∴ Loss in force/cable = 9208 x 0.0859 = 791 lbs
% loss in force = 5.5%

∴ Final prestressing force/cable = 14356 + 791 = 15147 lbs

After time dependent losses

1. Shrinkage loss = $3 \times 10^{-4} E_s$
$= 3 \times 10^{-4} \times 29 \times 10^{6}$ psi
$= 8700$ psi

$\therefore$ loss in force/cable = 8700 x 0.0859 = 747.33 lbs
% loss = 5.20%

2. Creep loss = $0.33 \times 10^{-6} E_s f_{cs}$
$= 0.33 \times 10^{-6} \times 29 \times 10^{6} \times 1270$
$= 12154$ psi

$\therefore$ loss in force/cable = 12154 x 0.0859 = 1044 lbs
% loss = 7.3%

Total loss = 12.5%

$\therefore$ effective prestress after these losses = (1-0.125) x 14356 x 2
= 25123 lbs

stresses at top fiber = $\frac{25123}{51}\left(1-\frac{2.75 \times 4.25}{6.02}\right)$
= 464 psi (tension) < 530 psi

stress at bottom fiber = $\frac{25123}{51}\left(1+\frac{2.75 \times 4.25}{6.02}\right)$
= 1449 psi < 2250 psi
ok

DESIGN OF BEAM WITH FIBERGLASS & STEEL CABLES

BEAM SECTION: 8.5" X 12.5"; A_c = 106 in^2; r^2 = 13.0 in.

f_c' = 5000 psi. E_c = 4 million psi.

f_{gf} = 300 ksi. E_{gf} = 10 million psi.

f_y = 270 ksi. E_s = 29 million psi.

Concrete fracture strength: $f_{cr} = 7.5(f_c')^{1/2}$ = 530 psi.

Concrete compressive strength: $f_c = 0.45f_c'$ = 2250 psi.

Tension at extreme concrete fiber at transfer:

$$f_{ct} = \frac{P_e}{A_c}\left(1 - \frac{e}{r^2}y\right)$$

Where, P_e = Effective prestressing force

For Max. P_e, $f_{ct} = f_{cr}$

$$-530 = \frac{P_e}{106}\left(1 - \frac{5.25}{13} \times 6.25\right)$$

P_e = 37,000 lbs. = 37 kips.

1. Design of Fiberglass Prestressing Cables

Design for P_e = 37 kips

Check compressive concrete stress:

$$f_{cb} = \frac{P_e}{A_c}\left(1 - \frac{e}{r^2}y\right) = 1226 \text{ psi} < 2250 \text{ psi. o.k.}$$

Try four fiberglass cables, A_{gf} = 4 x 0.702 = 0.281 in^2

Force on every cable = 37/4 = 9.25 kips.

Stress on every cable = 9.25/0.0702 = 131.8 ksi.(0.44 f_{gf})

Concrete stress at cable level:

$$f_{cs} = \frac{P_e}{A_c}\left(1 - \frac{e}{r^2} \times 5.25\right) = 1.09 \text{ ksi}$$

Elastic shortening loss on cable = $f_{cs}(E_f/E_c)$ = 1.09x10/4
= 2.7 ksi

Total initial prestressing force in cables:

P_i = 37 + 2.7(0.281)=37.76 lbs.

2. Design of Steel Prestressing Cables

Design for 37 kips

Try 3 steel cables, $A_s = 3(0.0859) = 0.258$

Force on every cable = 37/3 = 12.3 kips.
Stress on every cable = 37/0.258 = 143.6 ksi. (0.53 f_y)

Concrete stresss at cable level: $f_{cs} = 1.09$ ksi.

Elastic shortening loss on cables: $= f_{cs}(E_s/E_c) = 7.9$ ksi.

Total initial prestressing force on cables:

$P_i = 37.0 + 7.9(0.258) = 39.0$ kips