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16. Abstract

In assessing damage to a prestressed bridge girder, it is often necessary to determine the prestress remaining in the strands. A device was developed to estimate stress level in strands in damaged bridges. A lateral load is applied to a strand exposed by virtue of damagae to the concrete and the resulting displacement is measured. A series of tests were performed to calibrate the device and to determine its accuracy. Comparisons were made with techniques used in devices available commercially or developed by other researchers. The special features of the device developed in this project are its simplicity, portability, and versatility.

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METHOD TO EVALUATE REMAINING PRESTRESS IN DAMAGED PRESTRESSED BRIDGE GIRDERS

by

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RAMON L. CARRASQUILLO, AND DAVID W. FOWLER

Research Report No. 1370-2

Research Project 3-5-93/5-1370

"Repair of Impact Damaged Prestressed Concrete Girders"

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

OCTOBER 1995

IMPLEMENTATION

A device has been developed for determining remaining force levels in strands in damaged girders. The device is intended to be used in the field without the need for costly and complex instrumentation or extensive training of operators. It should not be possible to determine level of prestress in strands exposed by damage to concrete through impact or other catastrophic loading. The results of such field measurements will aid in the evaluation of remaining capacity, deformations, and durability of damaged girders and help the designer in determining the severity of damage and repair potential of impact-damaged girders.

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PURPOSES

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SUMMARY

In assessing damage to a prestressed bridge girder, it is often necessary to determine the prestress remaining in the strands. A device was developed to estimate stress level in strands in damaged bridges. A lateral load is applied to a strand exposed by virtue of damagae to the concrete and the resulting displacement is measured. A series of tests were performed to calibrate the device and to determine its accuracy. Comparisons were made with techniques used in devices available commercially or developed by other researchers. The special features of the device developed in this project are its simplicity, portability, and versatility.

CHAPTER 1

INTRODUCTION

Civil engineers collectively design and create new structures of all types. There are well-defined procedures for design and construction of new structures. However, there is often little consideration given to determining the course of action to take when structures are damaged. Engineers may often believe that a new, state-of-the-art structural system is inherently better than a repaired system that is old and may be damaged.

In the case of precast bridge girders there has been a tendency toward replacement of damaged girders. While the design and construction of new prestressed girders has not changed for many years, major technological advances have come in the form of repair materials and procedures. If the extent of damage can be determined, repairs to the girder can restore the original strength at a fraction of the cost and inconvenience of replacement.

The purpose of Project 1370 was to survey current practice for managing damaged prestressed girders in the United States and Canada. Various repair methods have been evaluated to determine their ability to adequately restore girder strength, appearance and durability.

This report focuses on the evaluation of damage and loss of prestress in strands in precast girders. While a visual inspection of exposed strands provides an indication of damage, a method for obtaining the stress remaining in the strand, for checking the stress in strands during preloading of a bridge for repair or for determining strand stresses during splicing of a severed strand would be useful to the designer responsible for evaluating or repairing a damaged girder. An instrument has been developed to perform this task, and tested to determine its accuracy and usefulness in the field.

CHAPTER 2

BACKGROUND INFORMATION

2.1 Girder Damage

2.1.1 Occurrence

Damage to prestressed concrete bridge members due to overheight loads appears to be increasing in recent years. In 1985 damage in the United States was reported as 162 occurrences per year (1). In 1993 the number of damaged girders due to overheight loads was found to be 250 occurrences per year, or 1249 over a five year period (3). The latter study noted that several states did not keep records of minor damage. Minor damage accounted for 72 percent of total incidences in the earlier report, while only 62 percent in the more recent study. It is unlikely that the occurence rate increase in the recent report can be attributed solely to an increase in moderate to severe incidences, coupled with a decrease in minor incidences. The fact that several states did not report minor damage in the latter report as well as slightly different criteria for assessing minor damage between the two reports would indicate that the increase in occurrence rates is actually even greater than indicated. The increase can be attributed to increased traffic flows, larger vehicles on the road, and most importantly, the greater number of prestressed concrete bridge members in use.

2.1.2 Classification of Damage

Damage is described as minor, moderate, severe, or critical.

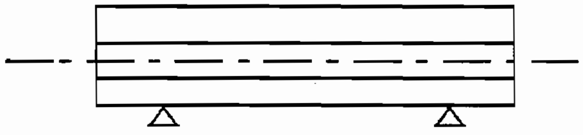
Minor damage is defined as surface damage which is limited to the concrete portion of a girder. No reinforcing bars or prestressing strands are exposed and concrete cracks are not more than three mils in width (1).

Moderate damage is also limited to the concrete portion of the girder, but extensive spalling and exposed reinforcing bars and/or prestressing strands may be seen but strands are not severed or seriously damaged. Cracks may exceed three mils, but they must close beneath the surface damage (1).

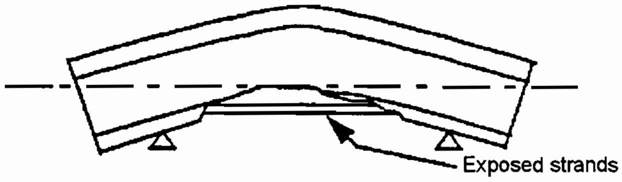
Severe and/or critical damage involves a significant loss of concrete cross section, damage or severing of prestressing strands, vertical misalignment along the girder, and horizontal misalignment of the bottom flange of the girder. A girder deemed irreparable involves critical damage and is generally related to the condition of the prestressing strands. If the strands have been stressed beyond the yield strength of the material, prestress is lost to such a degree that repairs cannot be made, large vertical misalignment has occurred, or concrete damaged is too extensive, repairs may be insufficient to restore the integrity and assure safety of the beam (1). Engineering judgement is critical in differentiating between severe and critical damage. If there is doubt as to the extent of damage to a girder, a conservative classification of critical is warranted. Therefore, methods to measure damage accurately would significantly aid classification.

2.1.3 Evaluation of Damage

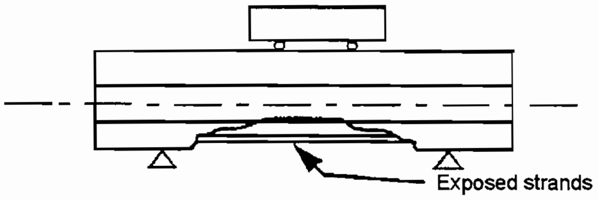
In evaluating the measures to be taken with a damaged girder the engineer must consider many issues, including: strength, durability, cost, time of repair, time of interruption to service, and esthetics. Of primary importance in these decisions is an understanding of the extent of damage sustained. Non-destructive testing (NDT) of the concrete is often performed when investigating severe damage, but damage to the prestressing strands is generally determined only through a visual inspection.



Undamaged Beam
(a)



Damaged Beam
(b)



Damaged Beam Preloaded for Repair
(c)

Figure 2- 1 Typical damaged beam

Of primary concern in this study are beams sustaining moderate to severe damage. Moderate damage may involve exposed prestressing strands with no apparent loss of prestress. Severe damage can consist of severed or obviously deformed prestressing strands. Visual inspections will reveal severe damage to exposed strands, such as nicks, severed wires, kinks, extensive yielding, and unraveling. It is generally assumed that if cracks around a strand do not close after impact, the strand has lost a significant portion of its prestress force. It is quite possible that a strand could exhibit none of these physical attributes and still be significantly damaged. With the typical spalling of large areas of concrete it is also quite possible that undamaged strands could have lost much of their pretensioning force through camber of the damaged girder. This action can be seen in Figure 2.1. It is precisely because of these concerns that many engineers are hesitant to repair girders with exposed strands or with extensive concrete damage.

There is clearly a need for a more accurate damage evaluation. It is the aim of this study to determine a method for assessing this damage more thoroughly by providing a means to estimate tension in strands.

2.2 Current Methods to Evaluate Strand Damage

As mentioned in the previous section, most evaluation of strand damage is done by visual inspection. It is possible for a strand to have lost prestress force without showing any signs of damage. It would therefore be useful to have a method of evaluation which supplements visual inspection with measurements to estimate tension remaining in the strand.

A literature review indicated that while extensive material is available pertaining to patching materials, limited information is available on repairing strands, and very little information is available for determining repair criteria. Almost no material was found pertaining to damage assessment of the prestressing strands. Information on assessing damage to strands was generally concerned only with finding damage to the physical structure of the strand through NDT procedures, such as electromagnetic fields (9,10,11,12). This method is used to find material irregularities and gives little information as to the overall performance of the existing strand. Some methods only measure changes in tension (7,8). It has also been reported that directly measuring strain on a strand wire does not necessarily relate well to the strain in the entire strand (4,7). Unfortunately both of these methods only measure changes in tension and therefore require a zero reading. In the cases of damaged girders, it is not possible to get this reading. Of special interest is the determination of stress in a given, loaded strand. A few instruments which use wave propagation through the strand to determine the tension in the strand are available commercially. Such equipment tends to be costly and not especially suited for field use, especially for tendons that are difficult to access. Information was also obtained for PROSEQ Wire Tension Meters, model numbers SM55 and SM150, and for the Kuhlman Bar (5).

2.2.1 PROSEQ Wire Tension Meter

The Swiss company PROSEQ manufactures two "wire tension meters", models SM55 and SM150. The SM55 is applicable for wire with diameters of 4,5,6,and 7 millimeters, and one quarter inch. The device is not applicable to use with strands. The dimensions of the instrument require a minimum exposed wire length of 13.78 inches to place the instrument. Wire tension in the range of 2.25 to 12.37 kips can be measured.

The SM150 requires 35.43 inches minimum exposed wire length for placement, and is applicable to wire diameters of 7 millimeters (round wire) as well as strands of three eighths and one half inch diameters. Wire tensions in the range of 6.75 to 33.70 kips can be measured. The SM150 model is appropriate for the strand sizes common in most prestressed girders in the United States.

2.2.1.1 Method

The wire tension meters work on a load-deflection principle. A hook fits around the wire and a crank develops a lateral force on the wire. From the catalog description, the wire bears against the ends of the instrument which appear to be free to rotate (roller supports). Output is in the form of a display of the axial strand force in Kilonewtons. A schematic of the instrument can be seen in Figure 2.2.

2.2.1.2 Accuracy

The PROSEQ instruments are reported to have an accuracy of plus or minus three percent. As the wires become shorter in length, however, an additional error is theoretically introduced. Table 2.1 includes the instrument's theoretical reading for a strand tension of approximately 29.5 kips for a range of strand lengths. It can be seen that the readings for a short length (one meter), can differ by approximately 3.7 percent from the reading at longer lengths. The difference is 2.7 percent from the calibration length of three meters.

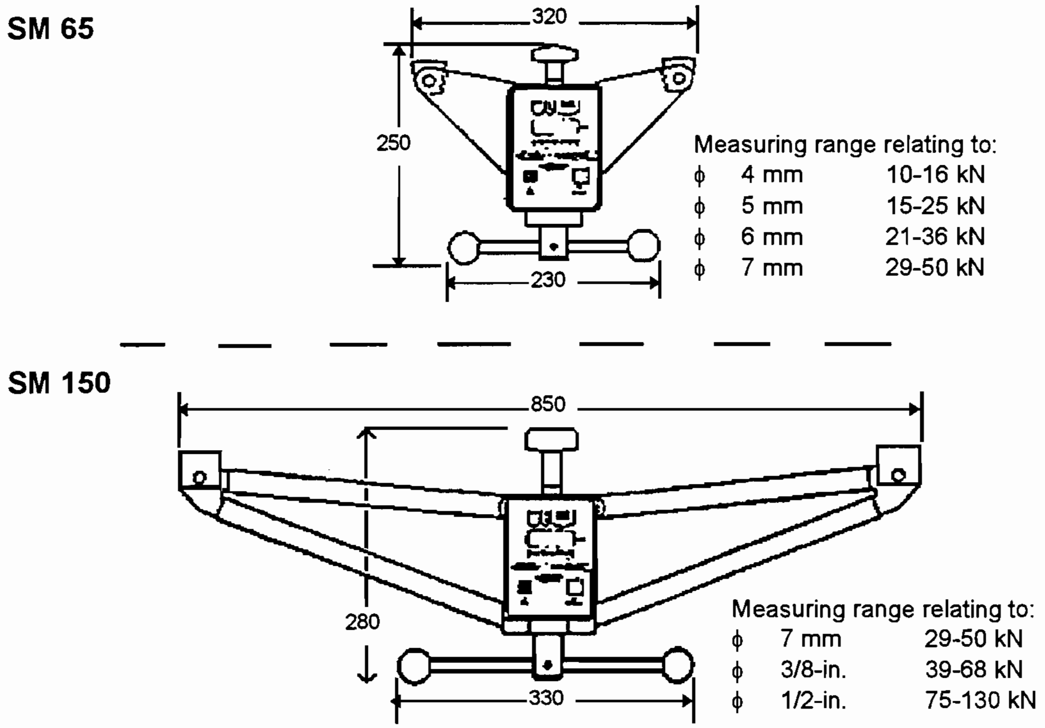


Figure 2- 2 PROSEQ model schematics (From ref. 13 - Reprinted with Permission)

The theoretical error, (chart difference between instrument readings and given effective force in the wire), is due to the increased strand length when the strand is slightly displaced across the instrument length. The change in length is small and of minimal influence in a long strand. When the strand length shortens, the increase in length during testing becomes more influential. The values in Table 2.1 are based on a deflection of ten millimeters which occurs for a strand tension of about 29.5 kips. This load is at the upper end of the maximum tension allowed in typical strands. It is noted that for lower forces in the strand, more deflection would occur for a given force applied by the instrument. The resulting length effects would therefore become more pronounced for lower strand tensions if the instrument is based on a standard load across the strand. Correlation between the theoretical numbers found in Table 2.1 and typical test results were not available.

2.2.1.3 Calibration

Using three meter samples of wire, an "individual correction curve" is obtained to calibrate the instrument to the specific wire. This is done by placing the wire in a testing machine and incrementally applying tension in the wire. Readings are taken at each increment. By comparing the instrument reading versus the actual load as defined by the loading machine display, a correction can

Table 2- 1 *PROSEQ Model SM150 length effects (From ref. 13 - Reprinted with permission)*

WIRE TENSION METER 8M 150
Theoretical incorrect readings on very short wires of strands

strand or wire type		1/2-inch	area = 100 mm2
effective force on the wi	F	130.000	kN
deflection	C	10.000	mm
length of the instrumen	Lm1	800.000	mm
basic tension	sigma 0	1300.000	N/mm2
	E modul	210000.000	N/mm2

Fixed wire length before the measuring Lo (mm)	deflected wire length within instrument Lm2 (mm)	tot. elongated wire length L end (mm)		add. elongation delta L (mm)	add. tension sigma add N/mm²	add. tension %	theoretical reading on the instrument F Instr. (kN)
1000.000	800.250	1000.250		0.250	52.492	4.038	135.249
1500.000	800.250	1500.250		0.250	34.995	2.692	133.499
2000.000	800.250	2000.250		0.250	26.246	2.019	132.625
2500.000	800.250	2500.250		0.250	20.997	1.615	132.100
3000.000	800.250	3000.250		0.250	17.497	1.346	131.760
3500.000	800.250	3500.250		0.250	14.998	1.154	131.500
4000.000	800.250	4000.250		0.250	13.123	1.009	131.312
4500.000	800.250	4500.250		0.250	11.660	0.897	131.166
5000.000	800.250	5000.250		0.250	10.498	0.808	131.050
5500.000	800.250	5500.250		0.250	9.544	0.734	130.854
6000.000	800.250	6000.250		0.250	8.749	0.673	130.875
6500.000	800.250	6500.250		0.250	8.076	0.621	130.808
7000.000	800.250	7000.250		0.250	7.499	0.577	130.750
7500.000	800.250	7500.250		0.250	6.999	0.538	130.700
8000.000	800.250	8000.250		0.250	6.661	0.505	130.656
8500.000	800.250	8500.250		0.250	6.176	0.475	130.618
9000.000	800.250	9000.250		0.250	5.832	0.449	130.683
9500.000	800.250	9500.250		0.250	5.525	0.425	130.553
10000.000	800.250	10000.250		0.250	5.249	0.404	130.525
10500.000	800.250	10500.250		0.250	4.999	0.385	130.500
11000.000	800.250	11000.250		0.250	4.772	0.367	130.477
11500.000	800.250	11500.250		0.250	4.565	0.351	130.456
12000.000	800.250	12000.250		0.250	4.374	0.336	130.437

be made to results. PROSEQ recommends that the instrument be applied at different locations on the wire for each measurement.

2.2.2 Kuhlman Bar

The Kuhlman bar was developed by the State of California Department of Transportation in the late 1960's (5). This device was designed for specific use with high strength prestressing strands. The instrument was developed for quality control use in a prestressing plant. Specifically, changes in tension along a strand were of concern. These could be due to friction losses across a harping point or guide, non-uniform tensions in strands all stressed simultaneously by a single jack, or creep effects. Typically, the strand tension forces were measured by the tensioning system at the ends of the strand during tensioning only. The Kuhlman bar was therefore designed to check individual strand forces in the stressing bed against design forces (5).

The Kuhlman bar was also reported to be used in the assessment of damage to prestressed girders in the mid 1980's, but the results did not prove consistent (1,2).

2.2.2.1 Method

The Kuhlman bar consists of a steel bar of known cross section and section properties with pins at each end. The prestressing strand rests against these pins. At the center of the bar, the bar and strand are pinched together. A picture of the instrument in use as well as a schematic of forces can be seen in Figures 2.3 and 2.4 respectively. By measuring the strains at a specific point on the bar when the bar and strand make contact, the strand tension can be estimated using relationships between the strand and bar properties.

The equations used in the analysis are based on the following assumptions: An approximate curvature formula neglecting second order terms is accurate due to the small deformations of beam and strand; small rotations occur at the ends and therefore only major components of forces need be considered; the frictional forces are neglected; and tensile force increase due to the strand deflection is neglected (5). This last assumption essentially ignores the change in length of strand which the PROSEQ theoretical values showed to be influential for short strand lengths, however, the length of strand in a stressing bed will be large.

Calibration curves are created for strands which relate beam strain directly to tensile force in the strand.

2.2.2.2 Accuracy

The Kuhlman bar is reported to estimate the tensile force in a prestressing strand within 0.4 kips. This is within "1.5 percent with 95 percent confidence limits" (5). The error was attributed primarily to variations in the strand moment of inertia. Calibration curves were shown to correlate very well with theoretical results. Strand lengths tested were thirteen and seventy-one feet. There was no measurable difference in results and so it was concluded that strand length does not affect the results (5). No measurable differences in results were noticed when the device was applied at any point along the strand to within one foot of the harping point (5).

When the Kuhlman Bar was used for inspection of damaged prestressed girders, the results were reported to be inconsistent (1,2). Apparently, it has not been used for damage assessment in recent years.

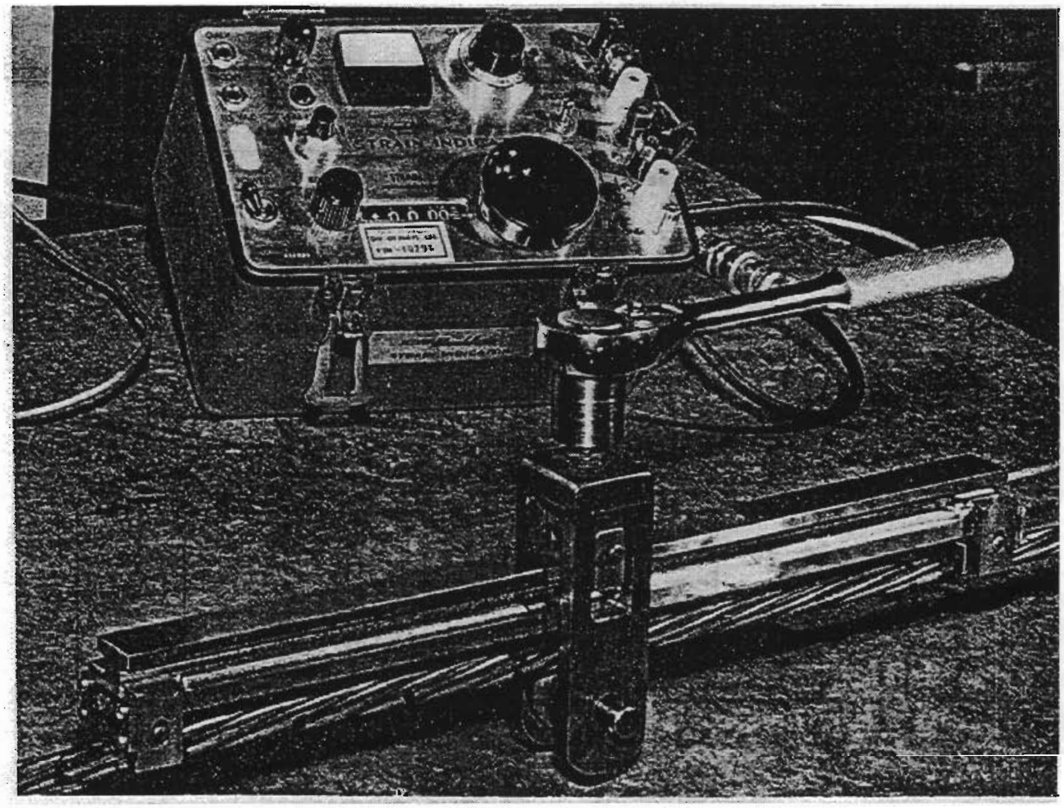


Figure 2- 3 Kuhlman Bar apparatus (From Ref. 5 - Reprinted with permission)

2.3 Purpose of Study

In order to accurately assess the amount of damage to a prestressed girder and to design a suitable repair scheme, it is essential to know the amount of prestress remaining in the exposed strands. While there are currently some methods of physically estimating this strand tension, these methods were not developed for application to damaged girders. Development of these methods was almost exclusively for use with long lengths of exposed strand with open access to the strands, such as in a prestressing bed or guy wire applications. Limiting the size of the instrument was not a design consideration. The device described above will be awkward for use with a damaged girder with a limited exposed strand length and accessibility, and their accuracy in this application may be reduced because only a short length of strand is exposed. The aim of this study was to develop a simple, inexpensive tool for use in the field during damage assessment of a bridge girder following an impact incident.

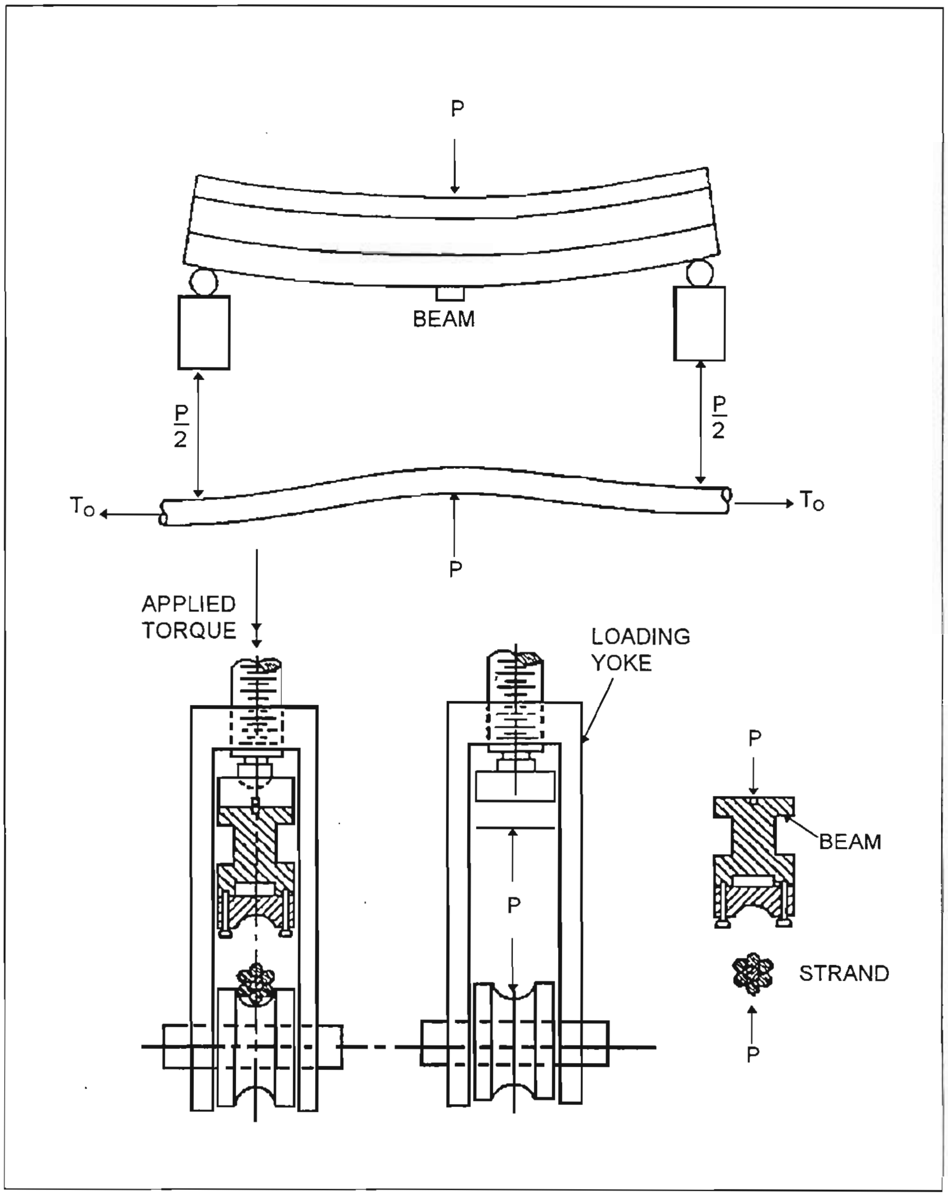


Figure 2- 4 *Kuhlman bar - forces on loading yoke, beam and strand (From Ref. 5 — Reprinted with permission)*

CHAPTER 3

DEVELOPMENT OF INSTRUMENT

Several methods were considered for estimating the actual stress in a strand in a damaged girder. The most practical method seemed to involve the incremental application of a force transverse to the strand and to measure the resulting deflection of the strand. The stress in the strand can then be related to the lateral force and deflection using basic principles of mechanics and material properties of the strand. The objective was to develop an instrument that was easily used and inexpensive to produce, and the simplicity of a "lateral force-deflection approach" was considered to be particularly attractive. Errors were expected to be minimized by limiting the number of variables introduced. For ease of use and evaluation of results, characteristic stress-strain plots could be developed for given strand stresses. By comparing the measured loads and deflections with calibration curves, the stress in a given strand could be determined.

3.1 Lateral Force - Deflection Approach

The lateral force - deflection approach, as its name implies, consists of incrementally applying a transverse load to a strand and measuring the resulting displacements. A schematic of loads is shown in Figure 3.1a. Figure 3.1b shows the layout of an instrument on a strand. It should be noted that, while the two figures appear the same, there are some critical differences.

In Figure 3.1a, the gage length is a known quantity L0. The length L1 is the length of strand L0 after it has been forced through a deformation, y. The associated strain increase in the strand is therefore (L1-L0)/L0. In Figure 3.1b the problem is not as straightforward. If the bearing pegs are frictionless, the final length L1 is no longer just the original strand L0 after it has undergone a certain strain. Rather, it consists of the original length L0 with the addition of a portion of the lengths L' which have slipped over the bearing pegs. The entire strand will undergo similar strains. Therefore, while the length L' does not change, the strand length between the bearing peg and end restraint is now L' plus L' times the strain undergone. This second term now extends beyond the bearing peg, within the gage length L0. The strain increase is the length L1 divided by this unknown original length L0 plus the length of strand slipping over the bearing peg from each side.

When friction is added to the bearing pegs the undeformed original length of L1 is even more complicated, because the movement of the strand at the support is dependant on the friction force at the peg. It is also inherent that as the strand deforms, it undergoes a strain, which infers an increase in stress. The tensile force in the strand is therefore not a constant throughout the test, but increases as the strand is deformed by the transverse load.

Calculations to estimate the relationship between lateral force applied and strand lateral displacement undergone can be found in Figure 3.2. Figure 3.2a shows a simplified model as a two bar truss. End rotations and deformations are assumed small, and bending of the strand as well as any tension increase in the strand are neglected. Note that the relationship between transverse force applied and the resulting deflection is linear. In Figure 3.2b the changing strand tension through the

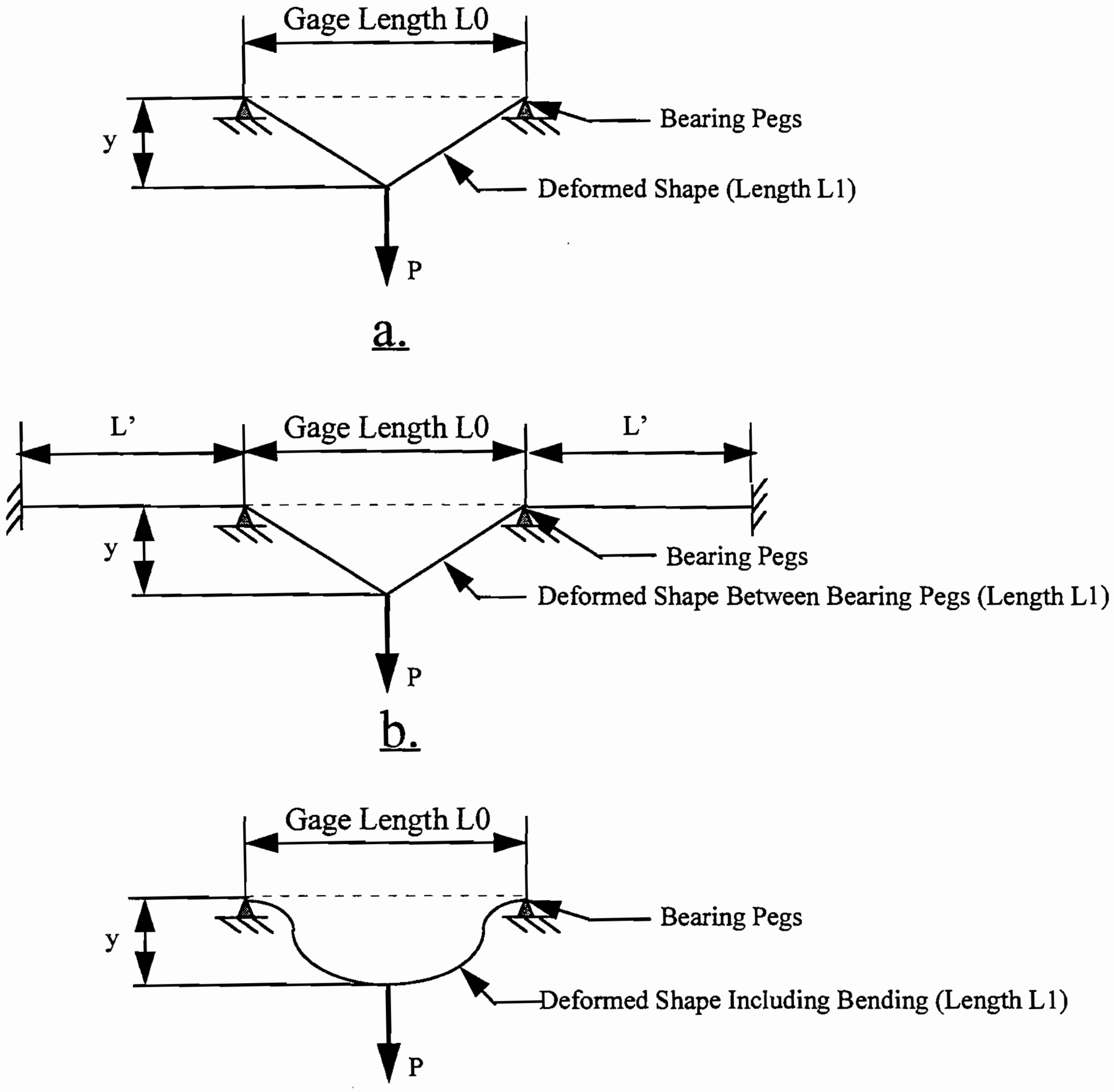
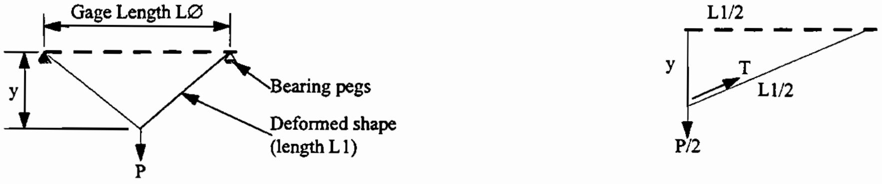


Figure 3- 1 Lateral force-deflection method schematic



$$L1 \bullet 2\sqrt{\left(\frac{L0}{2}\right)^2 + y^2}$$

$$d\ Strain = \frac{(L1 - L0)}{L0}$$

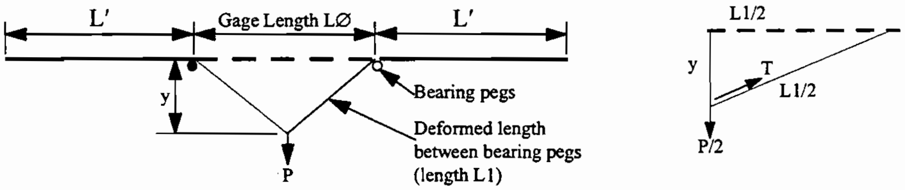
$$d\ Stress \quad + \quad (d\ Strain) = \quad E$$

$$\frac{P}{2} = \frac{y(2)}{L1}(T)$$

$$where \quad T + T0 + A = (d\ Stress)$$

$$y \quad = \quad \frac{PL1}{4T}$$

(a)



$$l1 \bullet 2\sqrt{\left(\frac{L0}{2}\right)^2 + y^2}$$

$$d\ Strain \quad = \quad \frac{(2L' + L1 - 2L' - L0)}{(2L' + L0)}$$

$$d\ Stress \quad = \quad (d\ Strain) = E$$

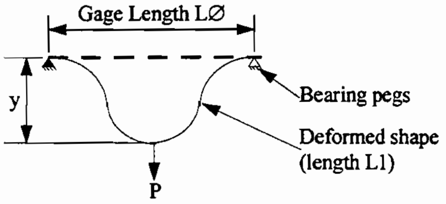
$$\frac{P}{2} = \frac{y(2)}{L1}(T)$$

$$where \quad T + T0 + A = (d\ Stress)$$

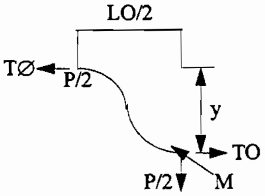
$$y \quad = \quad \frac{PL1}{4T}$$

(b)

Figure 3- 2 Calculation procedure



Assume small displacement and rotation $\therefore$ L1 $\approx$ L∅
Assume constant Tension T∅ in the strand



$$\Sigma M \qquad M + T\varnothing \bullet y = \frac{P}{2} * X$$

$$M \approx -EI\frac{d^2y}{dx^2}$$

$$\frac{d^2y}{dx^2} - \frac{TO*y}{EI} = -\frac{P*X}{2EI}$$

$$Let \quad K = \frac{T\varnothing}{EI} \qquad Let \quad A = k\frac{L\varnothing}{2}$$

$$\frac{d^2y}{dx^2} - k^2y = -\frac{k^2p}{2TO}X$$

$$So\ln. \quad w/ \quad initial \quad conditions \quad x=0, \quad y=0, \quad and \quad x=\frac{L\varnothing}{2}, \quad \frac{dy}{dx} =$$

$$y = \frac{P}{2TOk}\left(A - Tanh\,(A)\right)$$

(c)

Figure 3.2 (continued) Calculation procedure testing is considered. Figure 3.2c neglects the change in tension but accounts for the bending of the strand. When accounting for the bending of the strand, a question arises as to what value should be used for the moment of inertia of the strand. Using a gross moment of inertia of all of the components of the strand implies that the seven wires act rigidly together. Assuming that the strand moment of inertia is only the sum of the individual wire moments of inertia about their own centers would imply that the wires act independently. The actual condition is somewhere between these two bounds. The wires are not directly connected to each other, but friction between them and the pitch of the strand impose some continuity between the individual strand responses. Calculations were performed using both the upper and lower bounds on moments of inertia. A modulus of elasticity of 28,000,000 psi was used.

Results neglecting bending of the strand can be seen in Table 3.1, and typical plots are shown in Figure 3.3. Values are reported as the slope of the best fit line through the load-deflection plot, in inch/kips, for reasons which will be discussed later. It can be seen that the change in tension has much less influence when L0 is 24 inches. As the total exposed strand length increases the results

Table 3- 1 *Estimation of slope, including actual tension*

L0(inches)=	24.0
L'(inches)=	3.0
E (psi)	28000000
Tension(lbs)=	25000

Disp. (inch)	original length (inch)	deformed length (inch)	dstrain (in/in)	dstress (psi)	dTension (lbs)	Tension (lbs)	Transverse Force (lbs)
0.00	30.00	30.00000	0.00000	0.000	0.000	25000.000	0.000
0.05	30.00	30.00021	0.00001	194.444	29.750	25029.750	208.581
0.10	30.00	30.00083	0.00003	777.764	118.998	25118.998	418.650
0.15	30.00	30.00187	0.00006	1749.932	267.740	25267.740	631.693
0.20	30.00	30.00333	0.00011	3110.895	475.967	25475.967	849.199
0.25	30.00	30.00521	0.00017	4860.584	743.669	25743.669	1072.653
					Slope of Best Fit Line =====>		0.235004295

SUMMARY

Slope of Load Deflection Plot (inch/kips)

	Exposed Strand		Strand Tension (kips)				
L0=12"	Length (inches)	L'(inches)	30.00	25.00	20.00	15.00	10.00
	12	0.0	0.092	0.108	0.132	0.169	0.235
	18	3.0	0.094	0.112	0.138	0.179	0.254
	24	6.0	0.096	0.114	0.149	0.184	0.264
	30	9.0	0.097	0.115	0.142	0.187	0.271
	36	12.0	0.097	0.116	0.144	0.189	0.275
	45	16.5	0.098	0.117	0.145	0.191	0.280
g Tension Change==>			0.100	0.120	0.150	0.200	0.300

Slope of Load Deflection Plot (inch/kips)

	Exposed Strand		Strand Tension (kips)				
L0=24"	Length (inches)	L'(inches)	30.00	25.00	20.00	15.00	10.00
	12	0.0	0.196	0.234	0.290	0.383	0.562
	18	3.0	0.197	0.235	0.292	0.386	0.570
	24	6.0	0.197	0.236	0.293	0.389	0.574
	30	9.0	0.198	0.236	0.294	0.390	0.578
	36	12.0	0.198	0.237	0.295	0.391	0.581
	45	16.5	0.198	0.237	0.296	0.393	0.584
g Tension Change==>			0.200	0.240	0.300	0.400	0.600

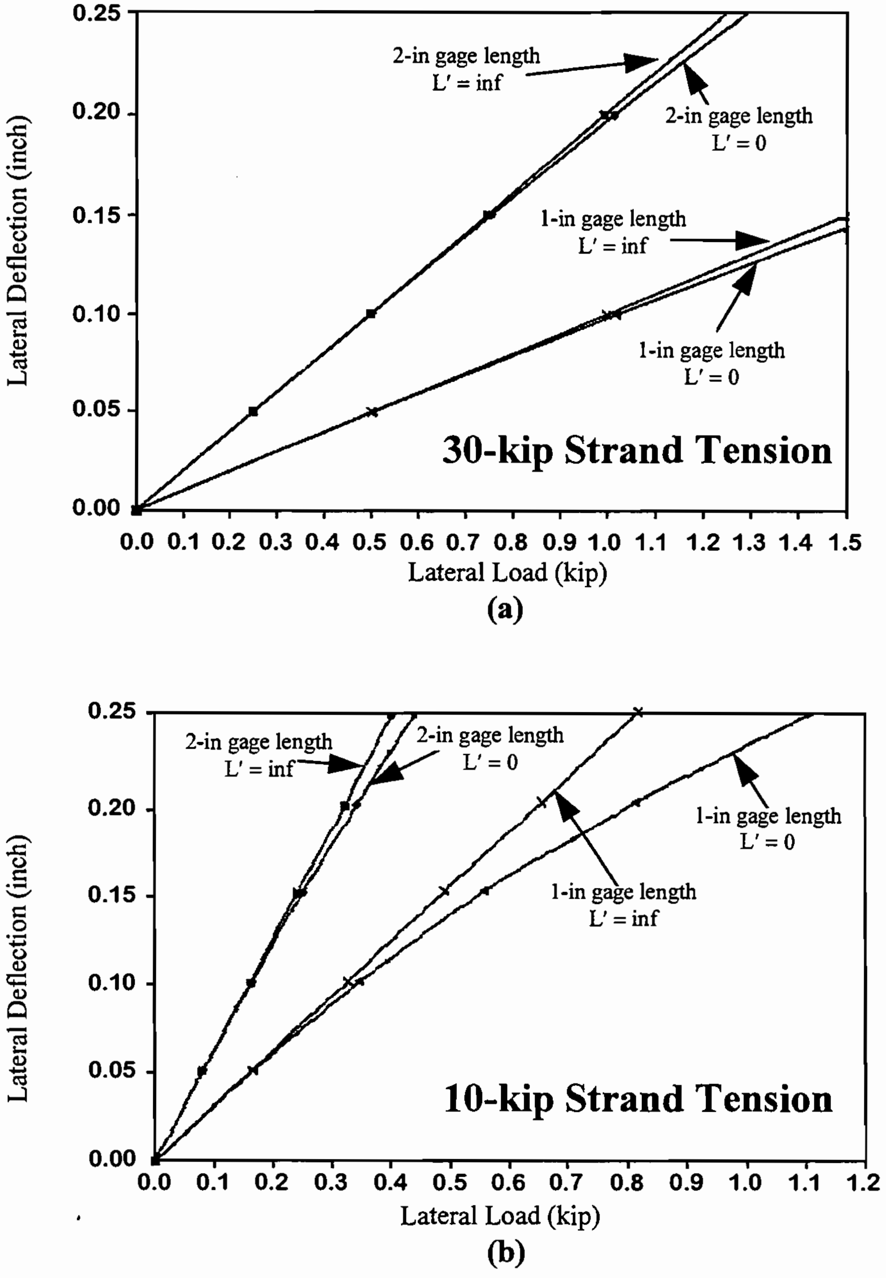


Figure 3- 3 *Theoretical results including changing strand tension*

approach the values obtained when the change in strand tension throughout the test is neglected. For a long strand length, the elongation of the strand is small compared to the total length, therefore the change in tension is also small. When the changing strand tension is considered, the relationship between lateral load and resulting displacement is no longer linear. More transverse force is required to produce the same deflection. It can be seen in Figure 3.3 that flattening of the load-deflection plot is small and a straight line can be fit to the calculations.

When the bending of the strand is accounted for the assumed moment of inertia of the strand plays a significant role, especially for the shorter one foot gage length. Results of this analysis are given in Table 3.2 and typical plots are shown in Figure 3.4. The relationship between lateral load and resulting deflection in these calculations is linear. The slopes calculated by this method can be directly compared to the calculations neglecting change in tension in Table 3.1 to see the effects of bending. The effects are larger for the lower strand tensions. The effects can be very significant if the individual wires act as a unit (strand moment of inertia equals 0.00207 in^4). Due to bending effects, the measured results from the prototype are expected to be lower than those calculated in Table 3.1.

3.2 Design Concerns

In the development of the device and measuring loads and displacements, there were several initial concerns. The method of measuring the force applied and the resultant displacements had to be as accurate as possible for a simple, sturdy device suitable for use in the field. With an applied maximum lateral force of one and a half kips, the resulting displacement was likely to be less than one eighth to one quarter of an inch. Therefore, displacements to one thousandth of an inch were needed. It was also necessary to take readings at one hundred pound increments. Accuracy within five percent of the actual load was desired. Errors in reading loads or displacements would directly influence the results.

The stability of the instrument itself could also affect the results. Deformation or warping of the base of the instrument might erroneously be attributed to deformations of the strand being studied. As discussed earlier, the effects of friction between the strand and the apparatus could be very important. It was necessary to determine how friction would affect the results and how to account for or minimize these effects.

For evaluating the behavior of a prestressed girder, it seems reasonable to determine strand tension within ten percent. A strand under full tension (about 33 kips for a half-inch strand) should have readings within plus or minus three kips. In addition, the apparatus should produce results that are repeatable under differing conditions and with different operators.

In a typical prestressed beam, the prestressing strands may be grouped in dense patterns with only a two inch spacing measured center to center on the strands (see Figure 3.5). While the exterior strands are most likely to be damaged, it is desirable to develop an instrument that could be used to evaluate the inner strands as well. Miniaturization of the device could be accomplished through higher strength materials which would allow the components to become smaller and by using small load cells and deformation measuring devices.

Table 3- 2 Estimation of slope including strand bending

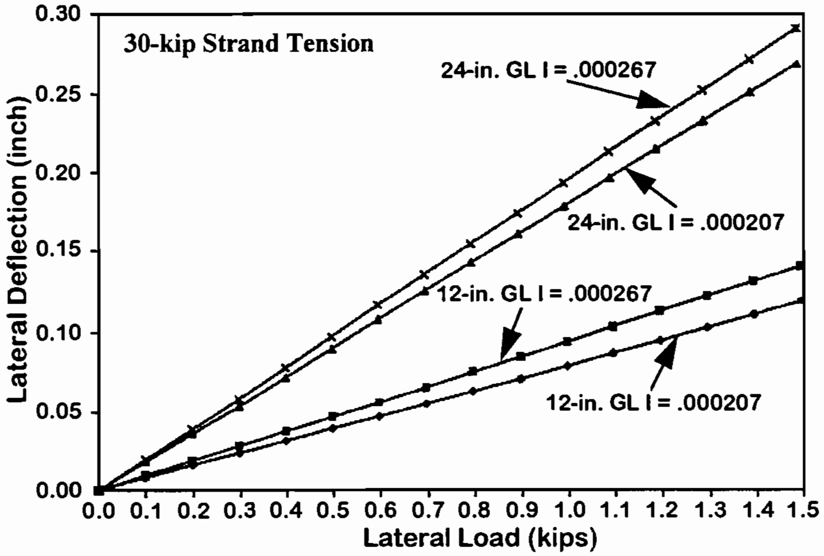
E (ksi)=	28000
I (in^4)=	0.00207
L (in)=	12.00

	Strand Tension (kips)	Strand Tension (kips)	Strand Tension (kips)	Strand Tension (kips)	Strand Tension (kips)	
	30.00	25.00	20.00	15.00	10.00	
	k	k	k	k	k	k=sqrt(T/(EI))
	0.7194	0.6568	0.5874	0.5087	0.4154	
	A	A	A	A	A	A=k*L/2
	4.3167	3.9406	3.5245	3.0523	2.4922	
Transverse Load (kips)	Displacement (inches)	Displacement (inches)	Displacement (inches)	Displacement (inches)	Displacement (inches)	disp=P/(2*T*k)*
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	(A-TANH(A))
0.1	0.0077	0.0090	0.0108	0.0135	0.0181	
0.2	0.0154	0.0179	0.0215	0.0270	0.0363	
0.3	0.0231	0.0269	0.0323	0.0404	0.0544	
0.4	0.0307	0.0358	0.0430	0.0539	0.0725	
0.5	0.0384	0.0448	0.0538	0.0674	0.0906	
0.6	0.0461	0.0537	0.0645	0.0809	0.1088	
0.7	0.0538	0.0627	0.0753	0.0943	0.1269	
0.8	0.0615	0.0717	0.0860	0.1078	0.1450	
0.9	0.0692	0.0806	0.0968	0.1213	0.1631	
1.0	0.0768	0.0896	0.1075	0.1348	0.1813	
1.1	0.0845	0.0985	0.1183	0.1482	0.1994	
1.2	0.0922	0.1075	0.1290	0.1617	0.2175	
1.3	0.0999	0.1164	0.1398	0.1752	0.2356	
1.4	0.1076	0.1254	0.1505	0.1887	0.2538	
1.5	0.1153	0.1344	0.1613	0.2022	0.2719	
Slope of Best Fit Line ==>	0.077	0.090	0.108	0.135	0.181	

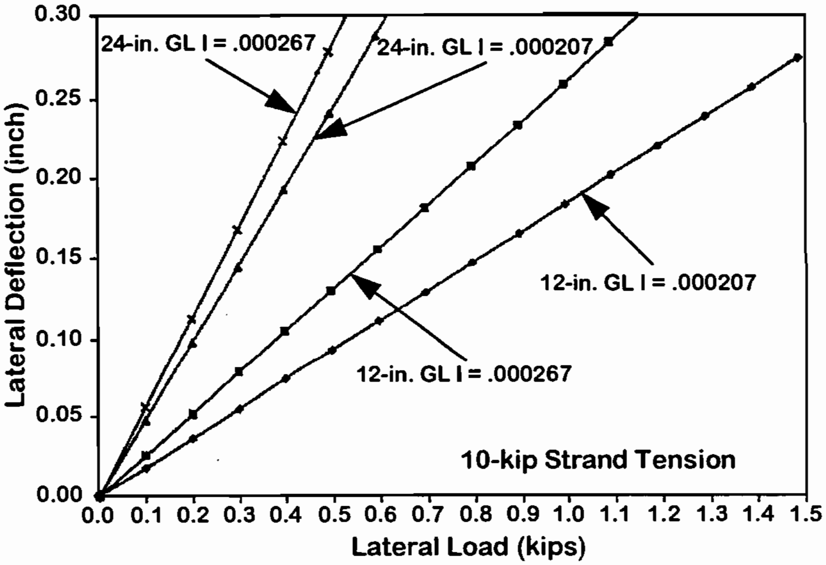
SUMMARY

Slope of Load-Deflection Plot

Gage Length (inch)	I(strand) (in^4)	Tension in Strand (kips)				
		30.00	25.00	20.00	15.00	10.00
12.00	0.002070	0.077	0.090	0.108	0.135	0.181
12.00	0.000267	0.092	0.109	0.135	0.176	0.257
24.00	0.002070	0.177	0.210	0.257	0.334	0.480
24.00	0.000267	0.192	0.229	0.285	0.376	0.557



(a)



(a)

Figure 3- 4 *Theoretical results including strand bending*

3.3 Apparatus

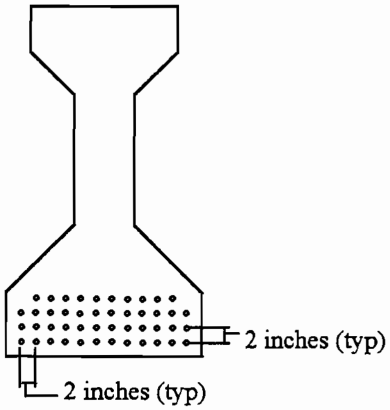


Figure 3- 5 Typical beam strand layout

Ideally, the apparatus should securely grip the strand at two points to allow the strand length to remain constant as well as to maintain the initial strand tension between the grips throughout the test. In such a device, the strand length would still change during testing due to the displacement at the center of the strand, but the length of the strand tested would be constant if the strand could not slip at the supports, a condition shown in Figure 3.1a. In designing the apparatus, it seemed unlikely that such boundary conditions could be realized. It would require very large clamping forces to prevent the strand from slipping through the grips. The grips themselves could move, and the strand could be damaged by the grips. Attachment of a gripping device to the strand seemed to complicate the design unnecessarily and eliminate the possibility of reaching interior strands in a typical strand pattern since extra space would be required for the grips. It was decided that gripping the strand introduced too many uncontrollable factors.

As a result, the design consisted of a simple peg or roller which the strand would bear against, and parameters such as friction and strand length would be addressed by calibration or adjustment factors, if necessary.

The mechanism for applying the load was a rod with a load cell in the load path. A load cell with a one inch diameter would be desirable, however due to budget constraints a larger available load cell was used. For stability of the apparatus, it was determined that the lateral load should be applied as a tension force. Ideally, displacements would be measured in line with the tension rod. In construction of the prototype it was necessary to add a small plate projecting perpendicular to the tension rod as close to the strand as possible and to measure deflection of this plate with a dial gauge (Figure 3.6). A digital depth gage was also considered, but costs were prohibitive.

Load was applied to the strand by means of a clevis with a removable peg (Figure 3.6). This simple design could be reduced in size later to allow use with interior strands.

Several methods of applying load to the rod were considered, including lever, miniature jack, and screw jack type systems. Due to the load required (up to two kips), the requirement that the load be stabilized at reading points, and the need for a device easy to use in the field, a simple in line screw type loading mechanism was used.

Two prototypes were constructed, one with a strand or gage length between bearing pegs of two feet and a second with a one foot gage length. It was assumed that the larger gage length would give more accurate results because under a given load, the longer strand length would allow for more lateral displacement at the center of the loaded strand. Errors in reading loads and deflections and those due to friction between the strand and the instrument are similar between the two gage lengths. Therefore, the error will be a smaller percentage of the larger deflection readings using the two foot gage length prototype. Although the results may not be as reliable, the one foot prototype seemed to be a more practical instrument since the exposed strand length in a damaged girder may be quite short. Figure 3.7 shows the two prototypes.

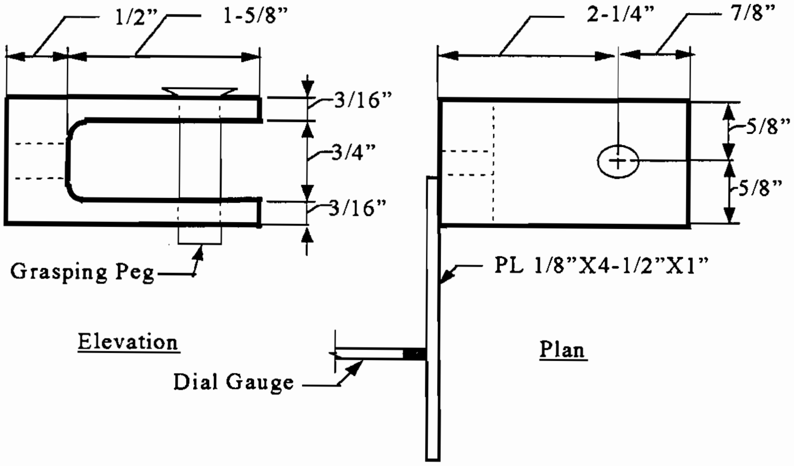


Figure 3- 6 Piece to grab strand and measure deflections

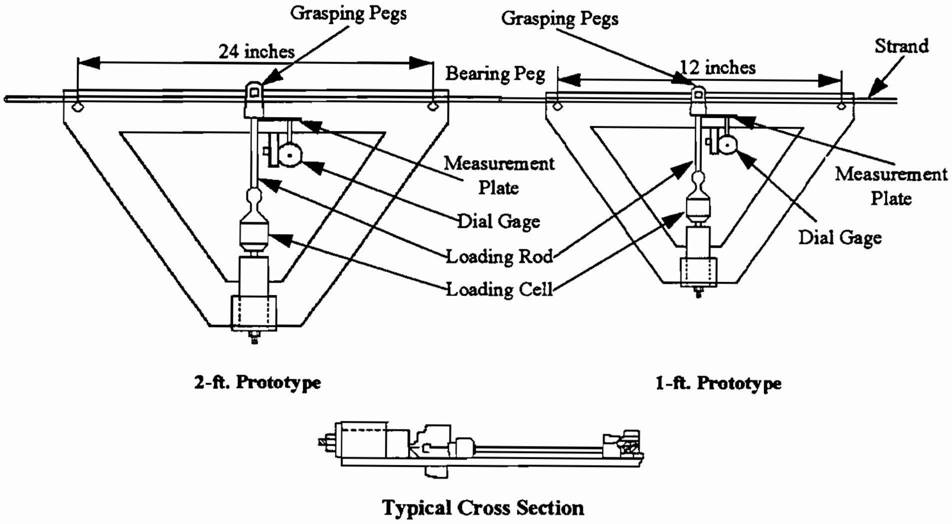


Figure 3- 7 Prototype schematics

3.4 Initial Tests

The tensile force in half inch diameter, seven wire strand was measured. The results are discussed for this size and type of strand, although the results should be indicative of the data that would be obtained for other strands. Prototypes of the measuring device developed are shown in Figures 3.8 and 3.9.

3.4.1 Setup of Initial Tests

Initial tests of the two foot gage length were carried out using a twenty foot length of strand loaded in a stressing bed. Tensile force levels of 11.9, 15.0, and 18.1 kips as measured with a pressure gage were applied. Data was also obtained for a 3'-9" strand length, the smallest length that could be anchored in a universal test machine. The strand tension forces applied in this test were 10.0, 11.9, 15.0, 18.1, 20.0, and 25.0 kips.

The prototype with a one-foot gage length was then constructed and tested using strands anchored in the test machine. Lengths of 3'-9", 3'-0", and 2'-8 ½" (the smallest length possible in the machine with a one-foot device gage length) were tested at strand tension force levels of 10.0, 15.0, 20.0, and 25.0 kips.

3.4.2 Results of Initial Tests

It was observed in plotting the applied transverse load versus deflection that the relationship is linear. There did not seem to be a reduction in slope at larger deflections as calculations for changing strand tension during testing indicated. Typical plots can be found in Figures 3.10 and 3.11. It was noticed that the plots often "stair step" around the best fit line, although some scatter was also observed. There did not appear to be a systematic pattern to the steps. It was assumed that the steps represent friction being overcome at the bearing pegs, allowing slippage of the strand. Due to these steps, it is felt that the defining characteristic of the plot is the slope of the best fit line through the data which appears to be fairly constant. For all comparisons and calibration in the remainder of the report, the slope of the best fit line through the data will be used.

3.4.2.1 Prototype with Two Foot Gage Length

Initial results for the prototype with a two foot gage length can be found in Table 3.3. As expected, the measured slopes are smaller than those determined analytically (Table 3.1). There is obviously some bending contribution of the strand, but a comparison with values in Table 3.2 shows that the strand is definitely not acting rigidly. Other factors such as friction between the strand and the bearing peg undoubtedly influence the results as well. It can be seen that the displacements, and therefore slopes of the load-deflection plot, for the twenty foot strand length were larger than the results for the 3"-9" strand length. If the 3'-9" results were used as a basis for standardization, estimations using the twenty foot strand would still be within about two kips of the actual strand tension. The results indicate that the length of strand is an influential factor, however it is still possible to differentiate between the results within the ten percent target value when this factor is ignored. The length effects, while detectable, may not be critical for reasonable exposed strand lengths for a result within ten percent.

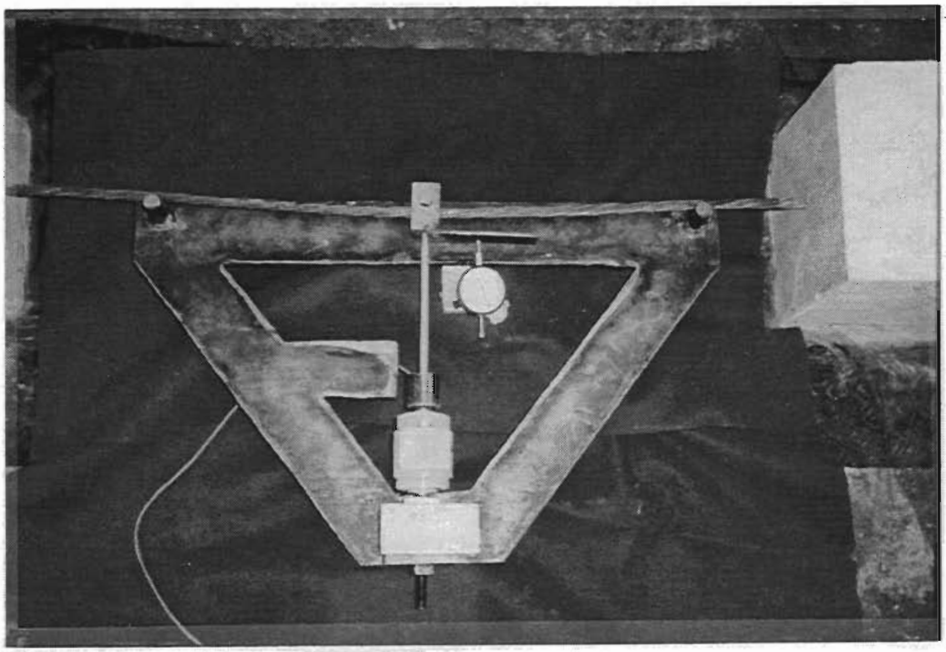


Figure 3- 8 Prototype with two-foot gage length photo

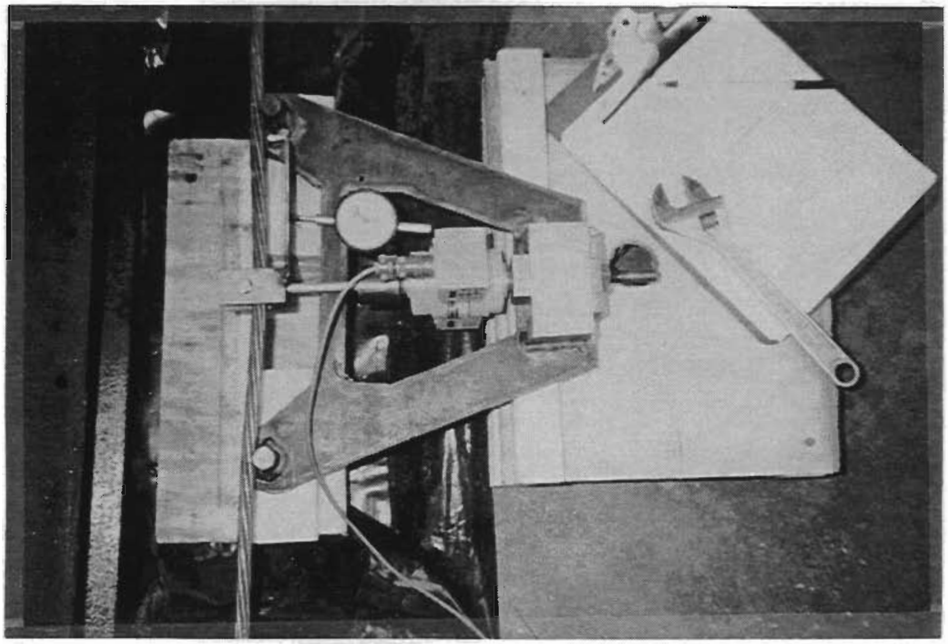
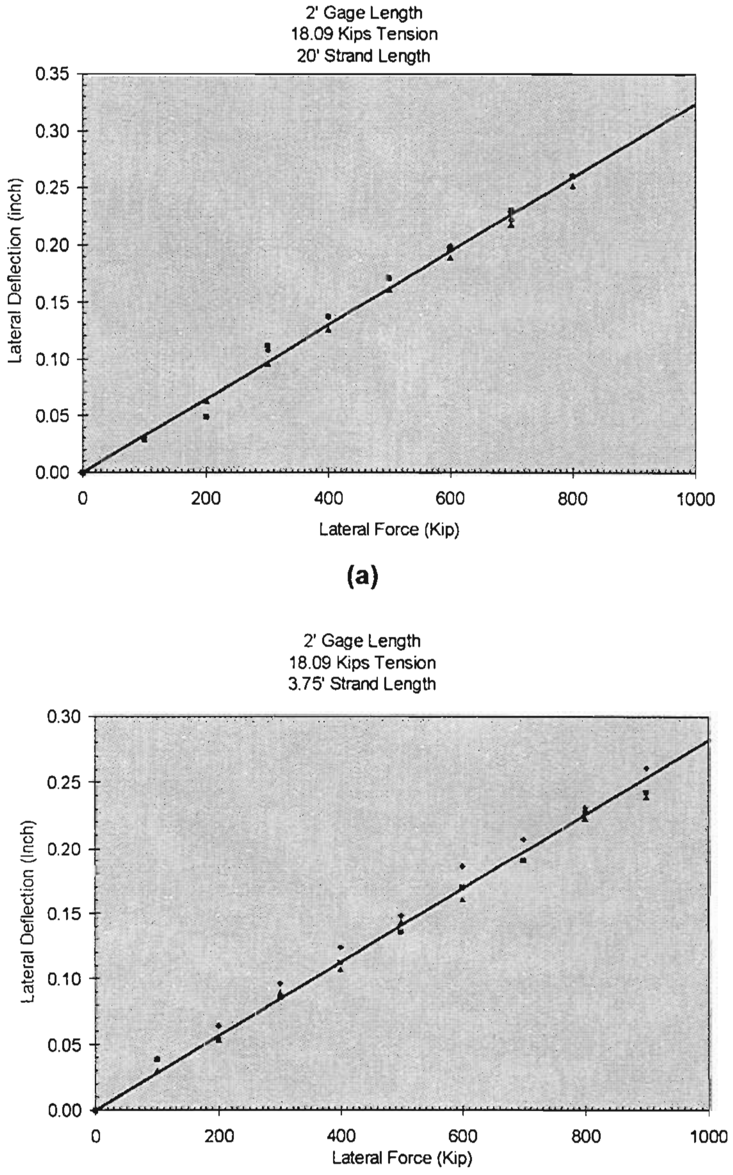


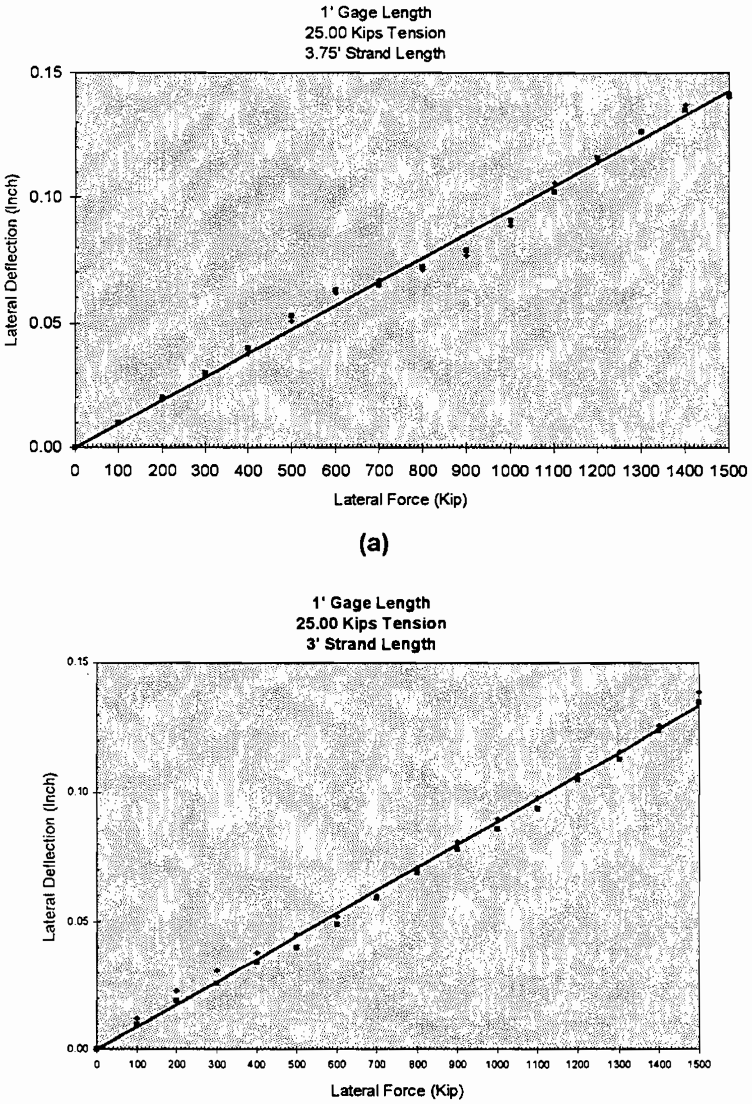
Figure 3- 9 Prototype with one-foot gage length photo



(a)

(b)

Figure 3- 10 Typical two-foot gage length plot



(a)

(b)

Figure 3- 11 *Typical one-foot gage length plot*

Table 3- 3 *Two-foot gage length initial results*

SLOPE OF LOAD DEFLECTION PLOT (INCH/KIP)

STRAND FORCE (KIPS)	STRAND LENGTH (FT)	
	3.75	20.00
10.0	0.492	
11.9	0.399	0.472
15.0	0.362	0.392
18.1	0.282	0.324
20.0	0.273	
25.0	0.203	

Table 3- 4 *One-foot gage length inital results*

SLOPE OF LOAD DEFLECTION PLOT (INCH/KIP)

STRAND FORCE (KIPS)	STRAND LENGTH (FT)		
	2.69	3.00	3.75
10.0	0.206	0.205	0.228
15.0	0.147	0.146	0.161
20.0	0.108	0.115	0.120
25.0	0.079	0.089	0.095

3.4.2.2 One Foot Gage Length Prototype

Results for the one foot gage length prototype are given in Table 3.4. Strand lengths of 2'-8.25", 3"-0", and 3'-9" were tested. Comparing these test results with the calculated slopes in Tables 3.1 and 3.2, bending of the strand seems to be playing a significant role. Other factors, such as friction between the strand and the bearing peg also play a role. It can be seen that, once again, the length of strand influenced the results. Longer strand lengths corresponded to larger displacements and therefore larger slopes. Since the strand lengths did not vary much, the resulting slopes were also close in value, but the trend is apparent. It is noted that despite the trend, all of the results for the 3'-9" lengths are clearly closer to the shorter strand length values at similar strand tensions than to those at the next higher load increment. This is not true for a strand force of twenty five kips, however. The results are fairly close for the twenty and twenty five kip strand tension forces for the shorter lengths. A two and a half kip discrepancy is still only ten percent of the twenty five kips being measured.

3.4.2.3 Results of Initial Tests

As expected, the two foot gage length gave results which more easily distinguish changes in strand force. The resulting displacements, and therefore the slopes of the load-deflection plot, for the one foot gage length prototype are only about one half of those for the prototype with a two foot gage length. Strand tensile force versus slope of the lateral load deflection plot are shown in Figures 3.12 and 3.13. As previously mentioned, the longer strand lengths tend to give a larger strand deflection for similar applied lateral loads.

It should be recognized that a consistent method for using the instrument was still being developed throughout these tests, as will be discussed in Chapter 5. The instrument was allowed to rotate about the strand, which was a common action at the twenty five kip strand load tests. This would give a lower deflection reading, as the instrument would not be "riding up" on the individual strands (see Figure 3.14). The instrument was also kept at the same location on the strand, the midpoint, for all readings. The preliminary tests merely serve as a reference to show general patterns of results. The general patterns are as follows:

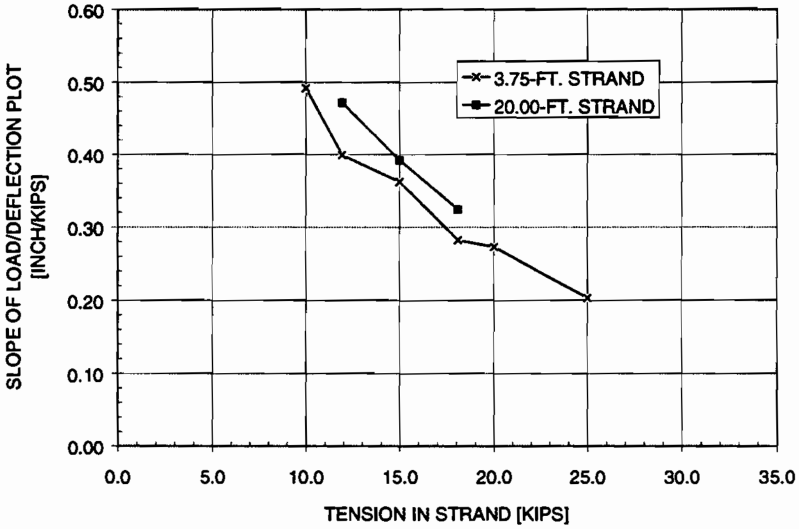


Figure 3- 12 Prototype with two-foot gage length. Slope vs. strand tension plot

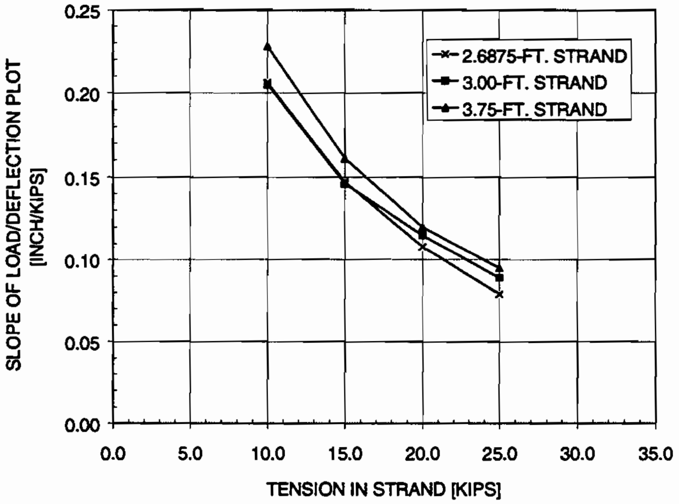


Figure 3- 13 Prototype with one-foot gage length. Slope vs. strand tension plot.

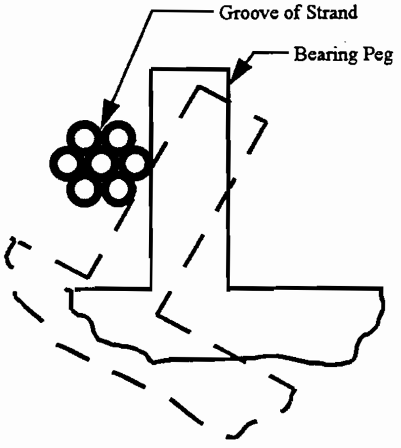


Figure 3- 14 *Bearing of strand on instrument*

1. For longer strand lengths with a given axial load, the strand will deflect more for a given transverse load.
2. A prototype with a larger gage length will result in a more precise load estimation.

3.5 Further Testing

Reasonable exposed tendon lengths in a damaged prestressed girder are believed to be approximately one to four feet. From the preliminary tests it is believed that the prototypes' designs can be improved to give more precise results. A one foot gage length is more suitable for the expected lengths of exposed tendons in the field, and the results appear to be within ten percent of the actual strand tension. For further testing, the one foot gage length was used exclusively. By standardizing testing procedures and improving design of the instrument, estimates of tension in a given strand can be consistently determined within ten percent of the strand force.

The goals of further development were two-fold. Of primary concern was the further improvement of the prototype and calibration of the instrument. The calibration procedure should take into account the length of exposed strand as well as the tensile force in the strand. The next phase of testing consisted of estimating the tension in a given strand using calibration curves.

CHAPTER 4

TEST SETUP

The tensile force in half inch diameter, seven wire strand was measured. The results are discussed for this size and type of strand, although the results should be indicative of the data that would be obtained for other strands.

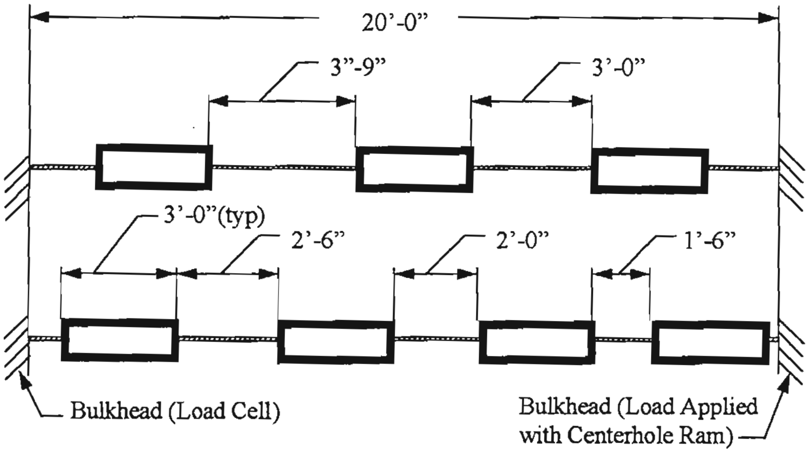


Figure 4- 1 *Schematic of test setup for length effects testing*

4.1 Evaluation of Effect of Strand Length

A test setup was constructed to evaluate the effect of strand length (See Figs. 4.1 and 4.2). Stressing beds for two strands were constructed, and several three foot long by nine inch square blocks were cast around the strands after they were stressed to about 28 kips. These blocks can be seen in Figs. 4.3 and 4.4. Some minimal transverse reinforcement was placed along the strand (#2 closed ties spaced at ten inches). Lengths of exposed strand between the blocks were 1'-6", 2'-0", 2'-6", 3'-0", and 3'-9". The concrete had a strength of about 4300 psi at 14 days before testing, and 5050 psi at 37 days at the end of testing. One block had a strength of only 1170 psi at 28 days due to introduction of several additives to the concrete which was delivered for another project. This block was at the end of the 3'-9" strand length only. Strand forces were measured by a load cell at the anchor end of the stressing bed and were checked by a pressure gage at the pump (Figs. 4.5 and 4.6). Care was taken to ensure that the blocks were free to slide on their bases by means of several double layers of thick plastic. Friction was minimized so that similar strand tensions would be developed in all exposed strands along the length of the setup. Once the desired load was applied to the strand a S6X12.5 steel section was bolted to the blocks on either side of the strand gap to be tested, (See Fig. 4.7). The blocks were fixed to minimize rotation of the blocks relative to one another in the plane of testing.

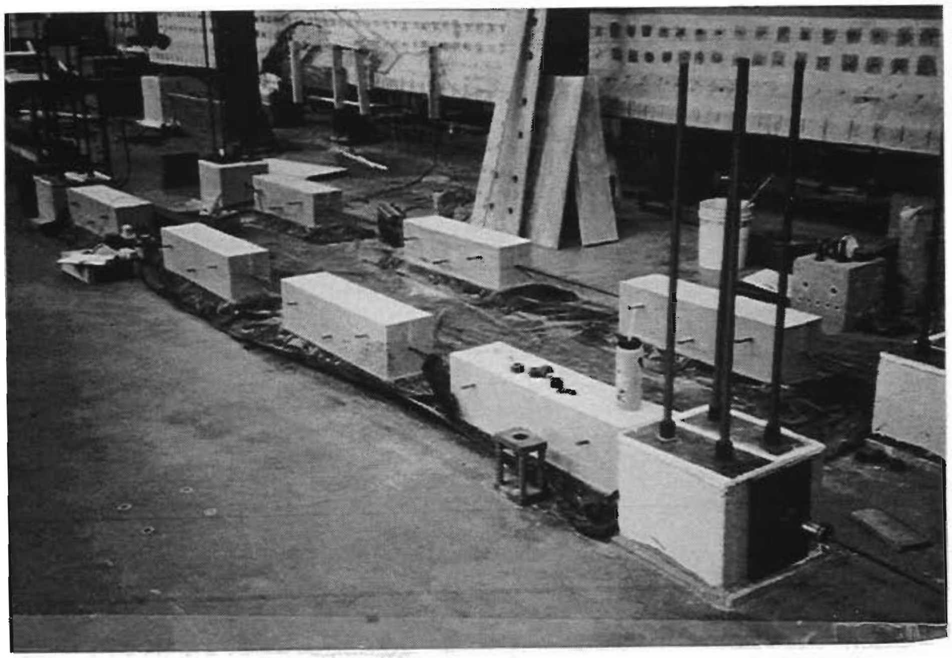


Figure 4- 2 Photo of test setup for length effects testing

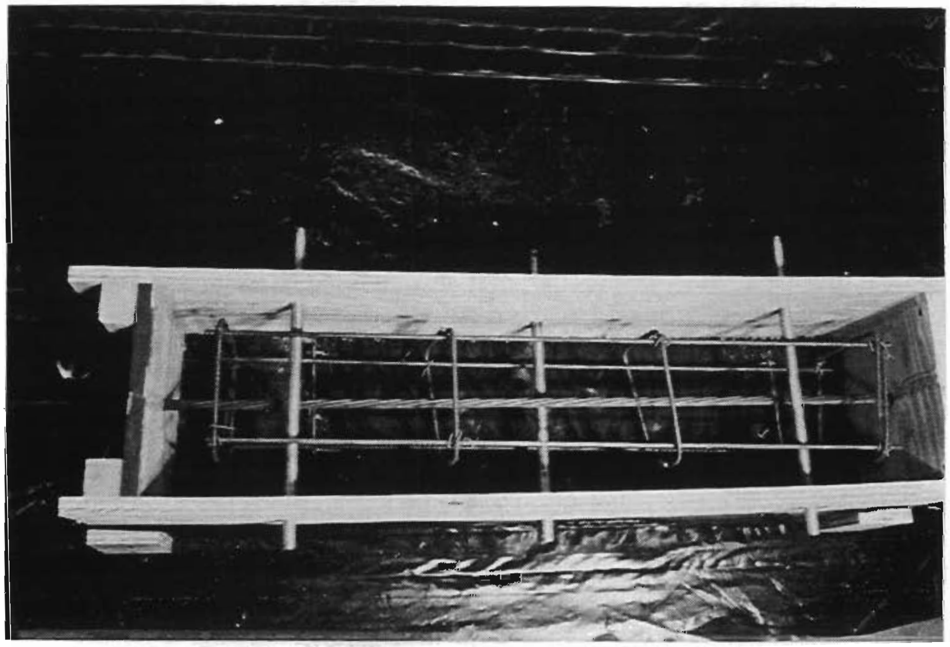


Figure 4- 3 Concrete blocks for providing end restraints - before casting

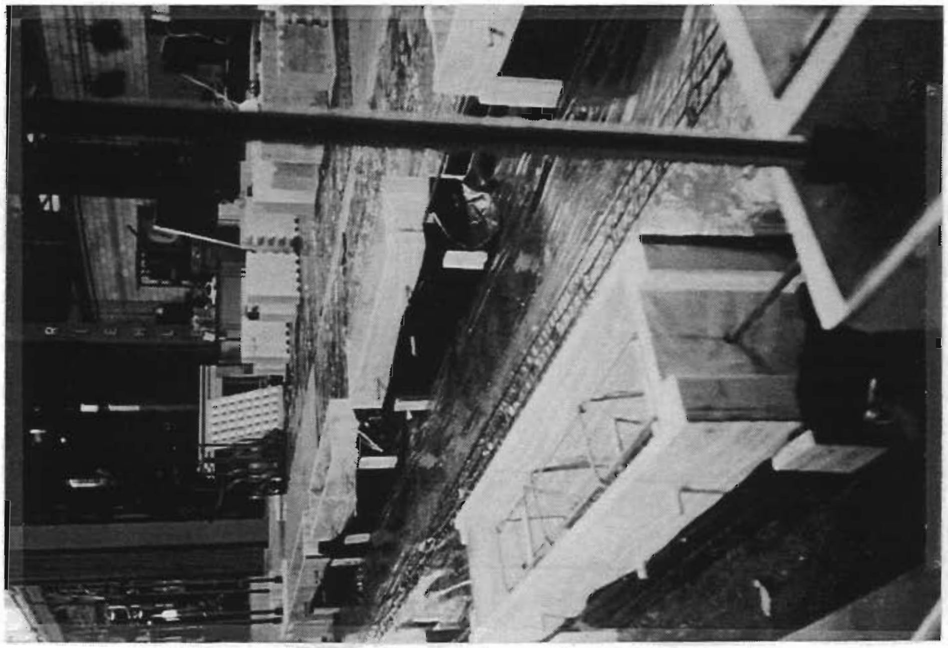


Figure 4- 4 Concrete blocks for providing end restraint - layout

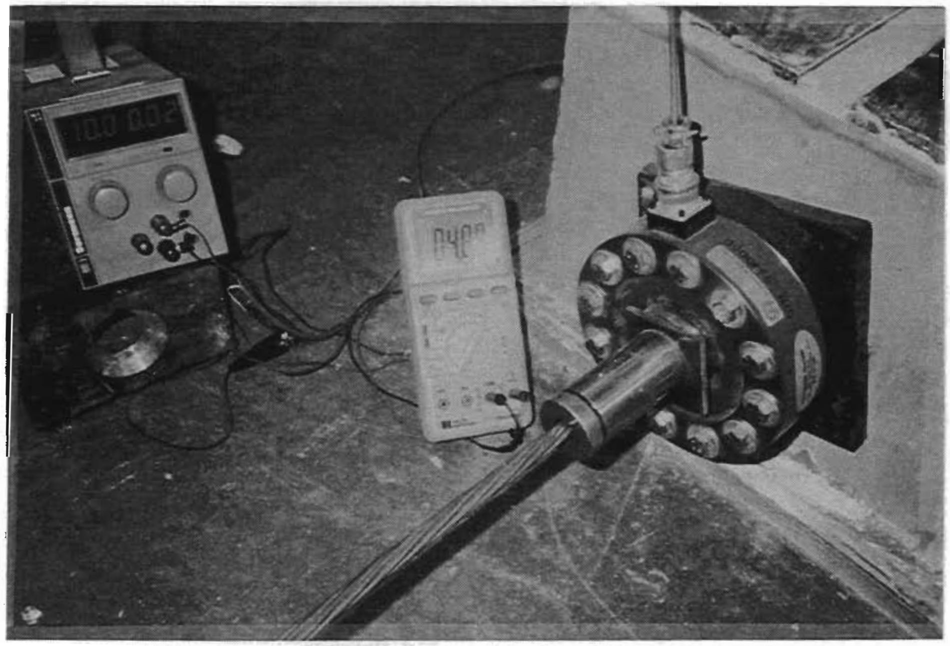


Figure 4- 5 Method for measuring load in strand

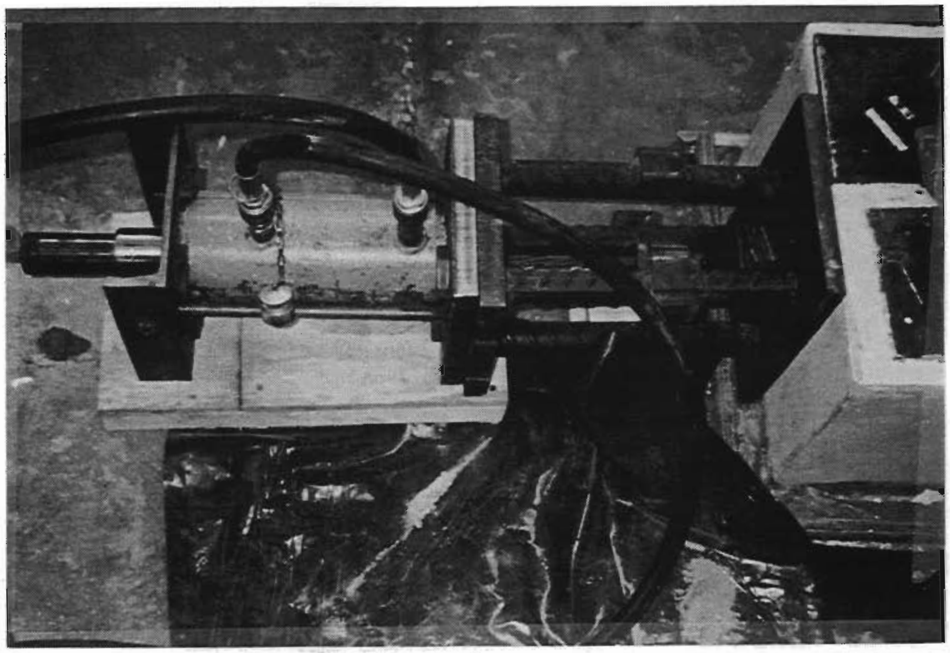


Figure 4- 6 Method for applying load in strand

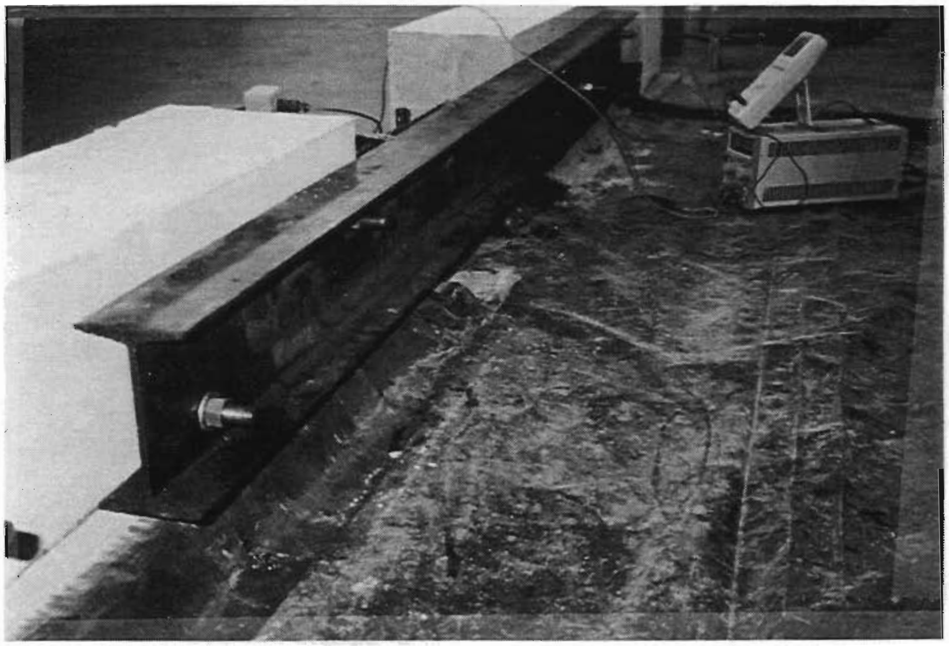


Figure 4- 7 Strongback between blocks

The steel section also maintained a constant spacing between the blocks throughout testing. The intent was to create a condition similar to a damaged girder in the field, where undamaged concrete would anchor the beam strand. The steel section was attached to the blocks by using threaded rods embedded in the blocks for this purpose. Tests were performed at strand tensile forces of 15.0, 20.0, 25.0, and 30.0 kips.

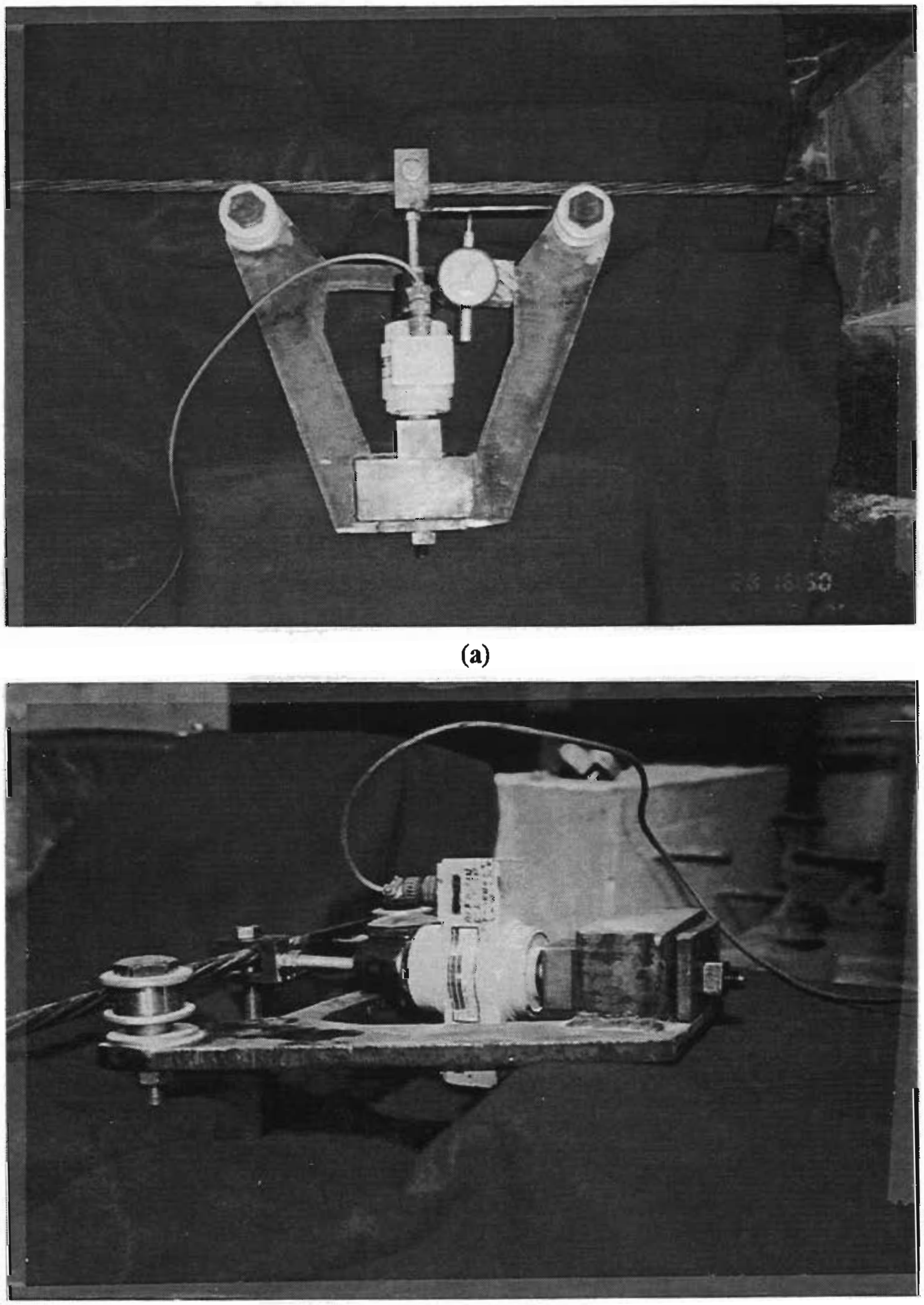
Tests were performed with the original (unmodified) prototype with a one foot gage length, with the same prototype but with grease on the bearing pegs to minimize friction, and with different supports to further minimize friction as a factor influencing measurements of tension in the strand. In addition to replacing the bearing pegs with rollers, the soft steel grasping peg was replaced with a high strength bolt, and some of the components along the loading rod were tightened using additional nuts. Photos of the revised prototype can be seen in Fig. 4.8.

Once these tests were completed, all of the load was removed from the strands to allow debonding of the strands and cracking in the blocks. After inspecting the blocks for cracks the strands were reloaded to 30.0 kips. The concrete was inspected again, and the revised prototype was used for comparison of the results to the fully bonded cases.

Finally, a twenty foot strand was placed in the stress bed and the revised prototype was tested at strand tensions of 15.0, 20.0, 25.0, and 30.0 kips.

4.2 Evaluation of Operator Influence on Test Results

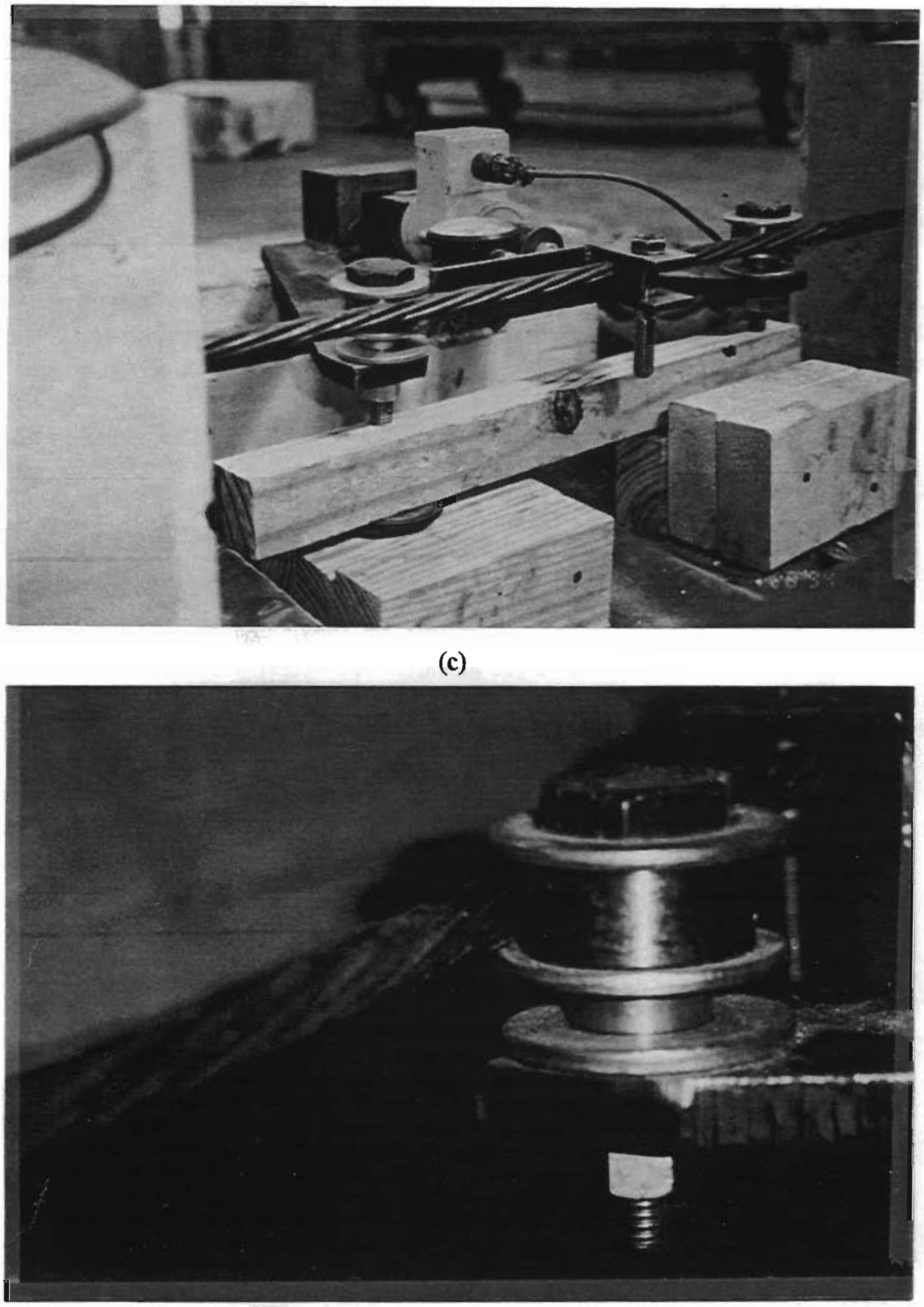
Of concern was the possibility that the operator could influence the results of the instrument. Several sources of error were minimized through improving the test method, as will be discussed in Chapter 5. To avoid some measurement errors, the operator needs to be sensitive to the sources of error. Many sources of error were limited by the operator checking that the displacement readings remained steady and that the prototype did not slip on the strand. In order to see if the results were operator dependent, a list of operating instructions were created (included in Appendix A) and a research assistant not familiar with the operation of the instrument conducted an independent series of tests. Strand tension forces of 15.0 and 25.0 kips were evaluated with a two foot strand length. The second operator was not informed of the tension in the strand.



(a)

(b)

Figure 4- 8 *Revised prototype*


(c)

(d)

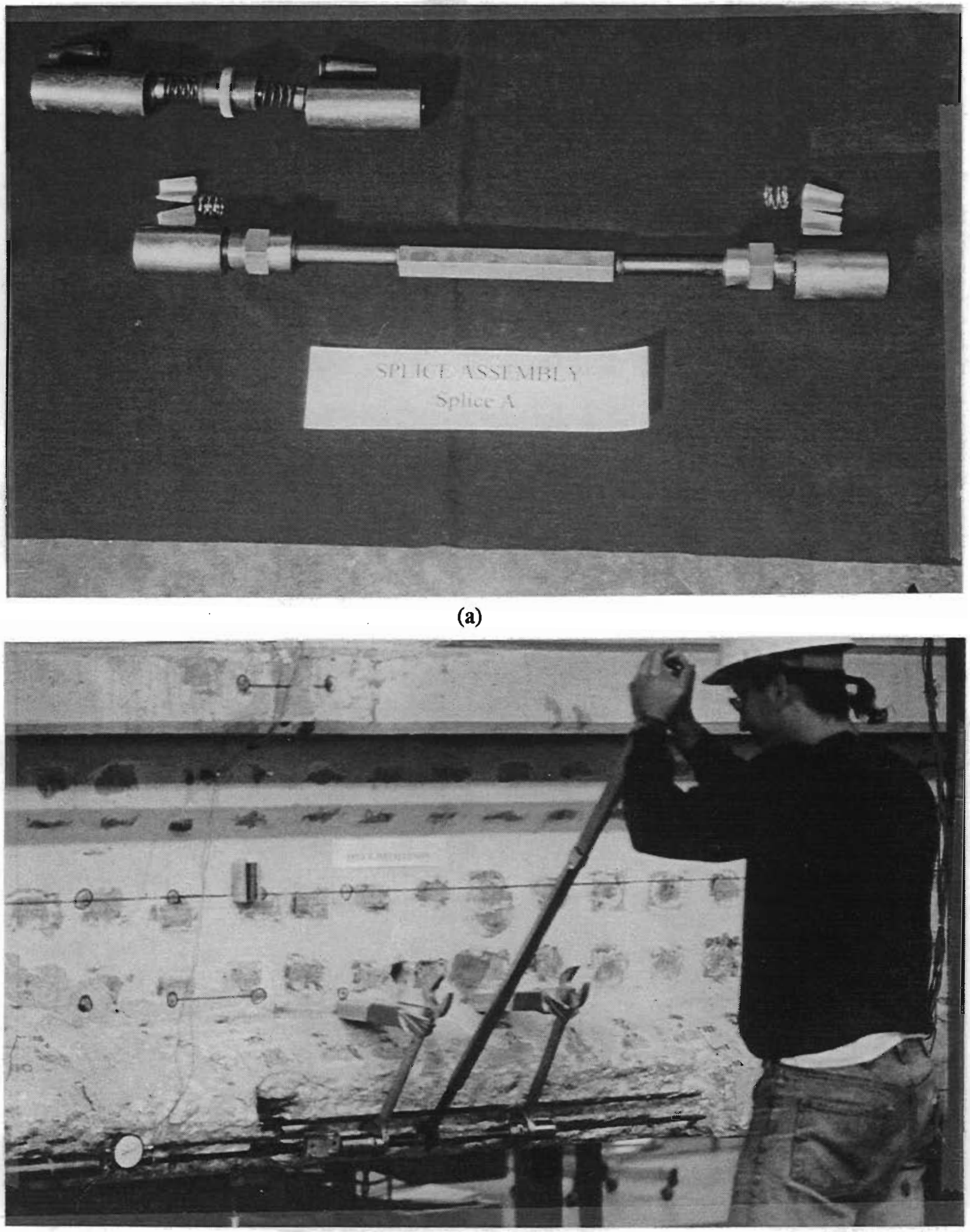
Figure 4.8 *Revised prototype (continued)*

4.3 Application of Instrument to Evaluate Strand Splice

In the repair of a damaged section there is often a need to splice severed strands. As part of this research project the performance of splices to restore the capacity of such damaged strands is being investigated. The strands must be retensioned to a known level to be effective, so a critical part of this research is the evaluation of the final strand tension.

In the laboratory it is possible to use several methods to evaluate the tension in the strand and compare the results. The splice studied is the Grab-it splice, supplied by Prestress Supply, Incorporated. The splice can be seen in Figure 4.9a. This particular splice consists of rods threaded in opposite directions so that when the center piece is rotated, the chucks are pulled toward or pushed away from the center piece simultaneously. This allows the strand to be tensioned or de-tensioned (Figure 4.9b). A calibrated torque can be applied to the splice unit to develop a desired axial tension in the strand. The manufacturer recommends that a torque of 250 foot-pounds be applied to produce a strand tension of approximately 25 kips.

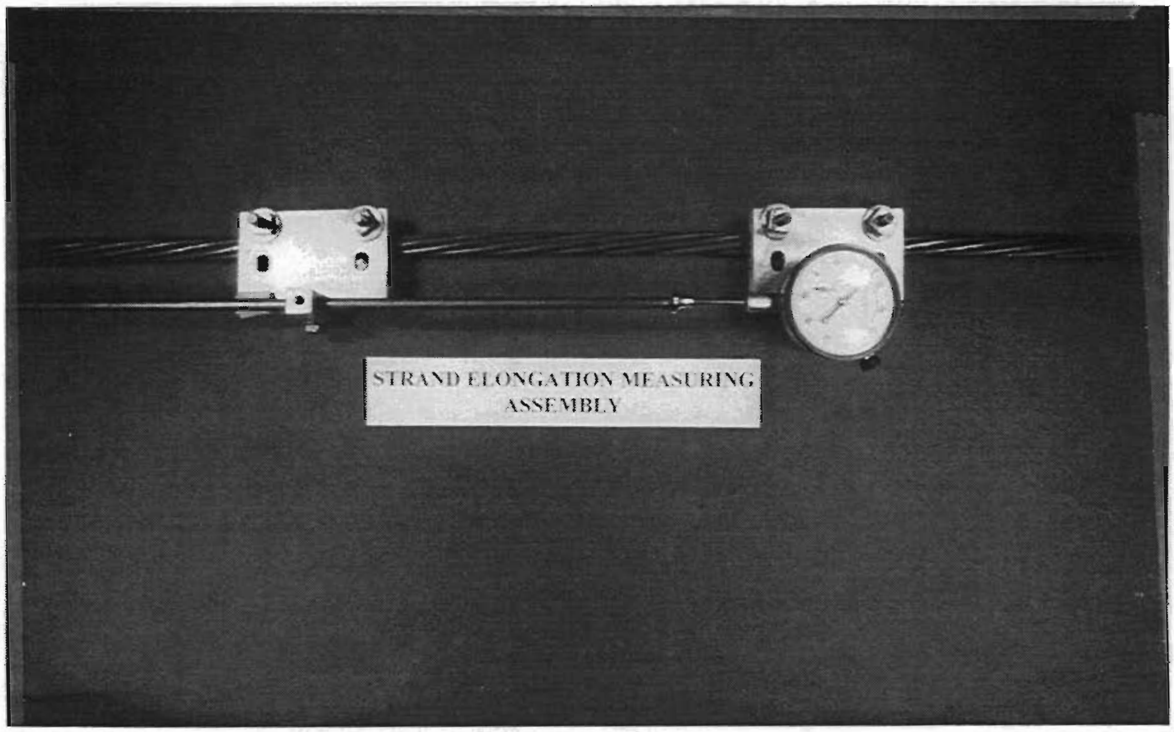
Testing was performed on a girder which was damaged by overheight loads and was being repaired as another part of this project. The strand was instrumented with strain gages to measure the longitudinal strains as the splice unit was installed and the tendon stressed. An extensometer was also attached to the strand to measure the elongation occurring over an eight inch gage length (Figure 4.9c). Finally, the instrument developed as part of this report was used to estimate the final strand tension (Figure 4.9d). The strand tensions estimated by each of these methods were compared for an applied torque reading of approximately 250 foot-pounds on a calibrated torque wrench.



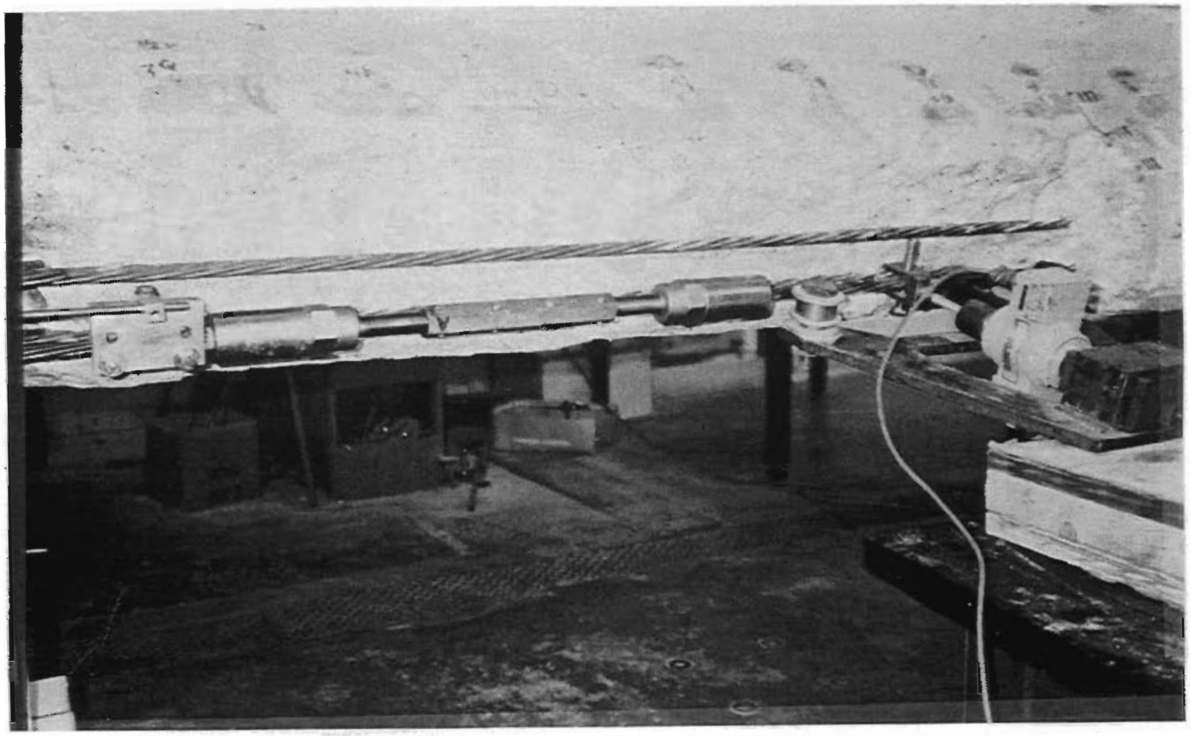
(a)

(b)

Figure 4- 9 Grab-it splice



(c)



(d)

Figure 4.9 *Grab-it splice (continued)*

CHAPTER 5

TEST OBSERVATIONS

5.1 Initial Tests

5.1.1 Unloading Data

While testing the initial prototype with a two foot gage length using a twenty foot exposed strand length, it was noted that the displacements for a given lateral load varied from those obtained while unloading. During unloading the system did not reach a condition of equilibrium immediately, and even when the readings stabilized, they were different than observed at the same lateral load level during loading. The difference was attributed to friction between the strand and the bearing pegs. Figure 5.1 shows typical plots of results during loading and unloading. It can be seen that the relationship between lateral loading and deflection is fairly linear, but erratic for unloading. When the lateral force was almost completely unloaded, the unloading curve would suddenly drop to match the loading curve. The data presented in Fig. 5.1 is better than most readings which were even more erratic and were therefore omitted. The displacements observed during loading were found to be repeatable, while those during unloading were not.

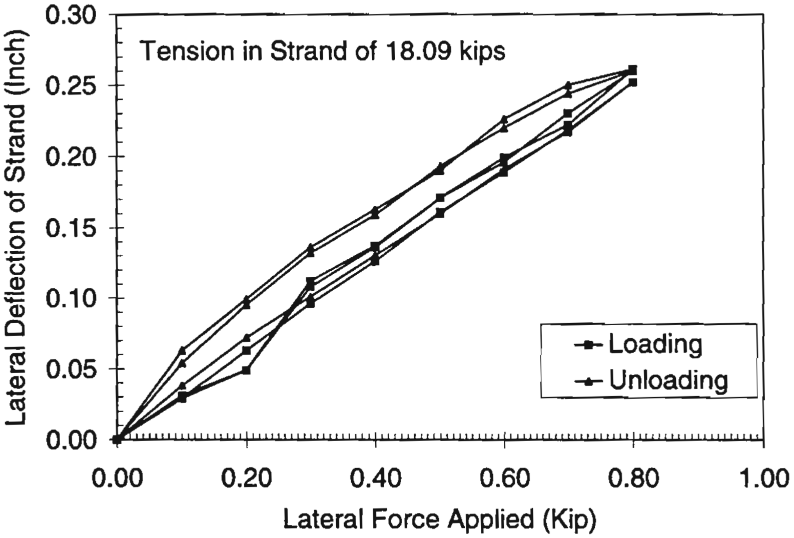
When the transverse load was returned to zero the displacements were approximately zero, but a deflection different from that at the start of the test (either positive or negative) was observed. This difference in deflection readings is termed the "residual zero reading".

Only loading data was subsequently considered, with the exception of the residual zero reading which was utilized in error correction as will be discussed in 5.1.3.

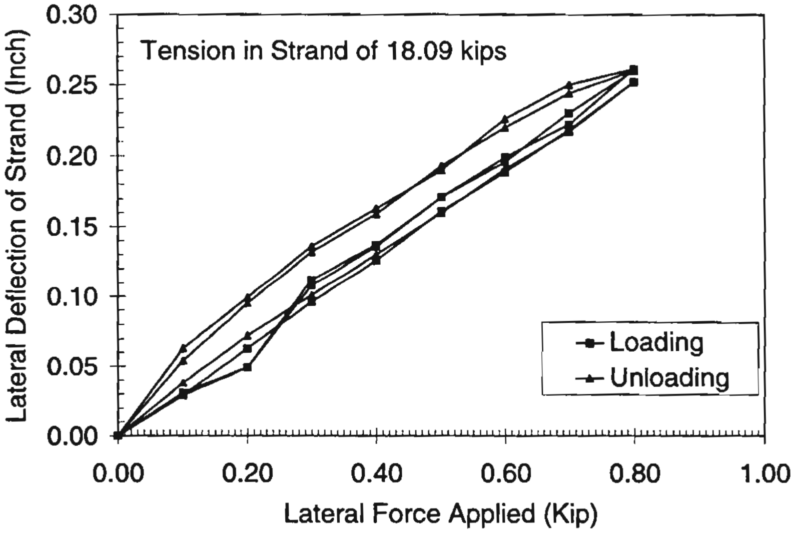
5.1.2 Tests in the Universal Test Machine

As loads were applied to the strand in the universal testing machine, it was also noted that the tension in the strand increased as shown by the testing machine readings. This was to be expected, as discussed earlier (Table 3.1). Tests were done both with a constant tension in the strand throughout the test as well as with the strand tension allowed to increase. In field applications of the prototype, the strand tension can not be changed, except through debonding with the concrete, slip in cable supports (both uncontrollable means), or external loading on the bridge. Therefore the strand tension will vary as the lateral load is applied since the boundary conditions can not be controlled. Constant tension readings were taken in the laboratory only for purposes of understanding the operation of the device.

While loading strands in the universal testing machine, the prototype was supported from the top of the machine. The displacements would sometimes increase steadily without any additional load being applied. It was discovered that this was caused by the prototype not being allowed to displace downward or rotate with the strand due to restraint from the cable supporting the prototype from the



(a)



(a)

Figure 5- 1 Typical loading and unloading plot

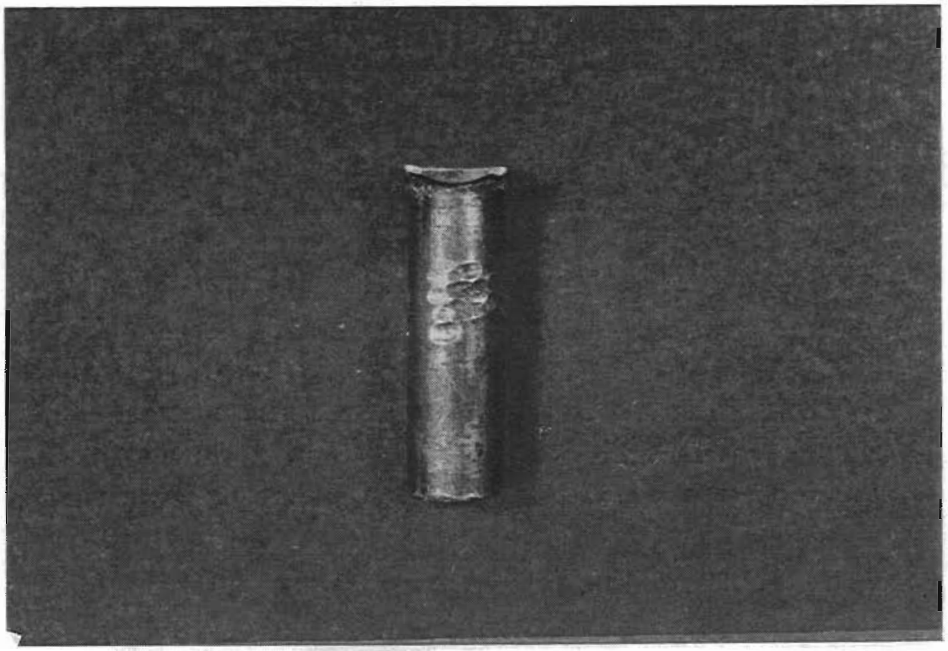


Figure 5- 2 *Grasping peg showing bearing deformations*

testing machine. The restraint caused the apparatus to twist slightly along the strand (about an axis perpendicular to the strand) and caused large differences in displacement readings, up to about 0.040 in. The instrument should therefore be allowed to translate along the length of the strand. It was also found that the deflection did not always return to a zero reading after load was released. It appeared that the residual zero reading was caused by rotation of the apparatus or slippage of the grasping peg along the strand. These problems were later addressed by supporting the prototype against rotation about the strand and by preloading to seat the grasping peg (see 5.2.3.2 and 5.2.3.1). As testing progressed, the grasping peg became indented where the strand was bearing against the grasping peg (see Fig. 5.2). As the transverse load became large enough to induce slippage, the strand would tend to seat in these indentations in addition to the slippage of the grasping peg along the length of strand. This was addressed in later tests by the use of a high strength grasping peg.

It was common for the prototype to rotate about the strand as the load was increased. Such rotation was allowed in the initial tests. It was observed that the main problem to address was that the plate which was used to measure displacements could easily rotate slightly with respect to the frame of the prototype, causing a change in the displacement reading due to the slight distortion of the plate (see Fig. 5.3). The realignment of the plate, compounded with slippage or seating of the grasping peg, could add up to a significant error in the deflection readings. Once these causes were identified, attention to positioning and restraint of the device reduced these errors.

5.1.3 Error Correction Method

Even with careful operation, some errors were still observed. Errors seemed to be linear or at best step functions at varying points in the loading, as was discussed in Chapter 3. Such errors appeared largely as the difference in the deflection readings at the start and end of each test, or the "residual zero" reading. The decision was made to handle these errors as a linear correction from zero at zero applied

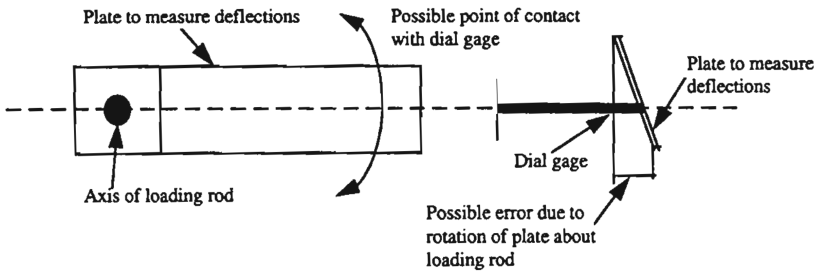


Figure 5- 3 Plate alignment error

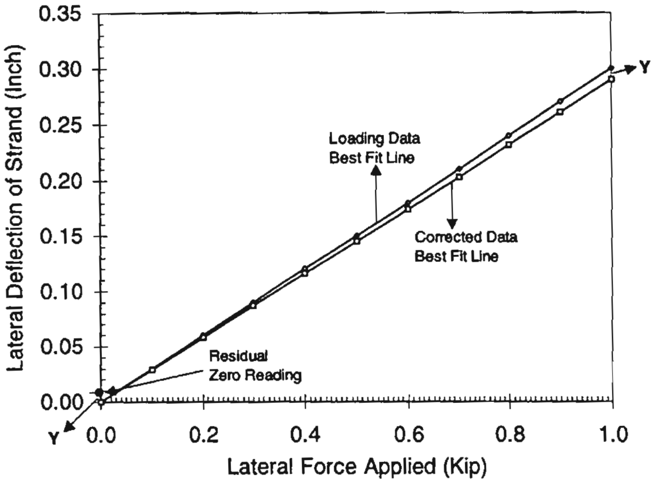


Figure 5- 4 Error correction method

transverse load to the residual zero reading at the final transverse load step (Fig. 5.4). This procedure is believed to be acceptable for correcting the remaining systematic errors and was followed for all subsequent testing. In later testing the residual zero value was also used as a benchmark for determining reliability, and tests with residual zero values greater than 0.015 inches were rejected. Errors in excess of 0.015 inches could significantly alter the test results, especially since large discrepancies tend to result from movement of the entire prototype along the strand which is usually sudden and therefore not a systematic error.

5.2 Length Effects Testing

Testing was performed to evaluate the influence of the exposed strand length on the results. Three versions of a prototype with a one foot gage length were used. These consisted of the prototype with the original bearing pegs, the same prototype with the bearing pegs greased, and a final revised prototype as was described in Chapter 4.

5.2.1 Original Prototype

While performing the tests for length effects with the original bearing pegs it was noticed that the grasping peg had become rather scarred (Fig. 5.2). This led to seating of the grasping peg on the strand during testing. Later testing overcame this problem through the use of a high strength steel grasping peg. Special care was required during unloading to make sure that the plate for measuring displacement did not rotate about the loading rod relative to the frame (see Fig. 5.3), and that no slip was experienced. These precautions were observed to prevent the sources of error found in the initial tests. A good practice was to rest one hand on the load cell, using pressure when required to resist the torque on the load cell. Some slip or movement was felt for nearly all rejected tests (residual zero reading greater than 0.015 inch), but movement was also experienced during some valid tests.

5.2.2 Prototype With Greased Pegs

When the prototype with greased bearing pegs was tested the same observations were noted. Some tests were also done with a high strength bolt replacing the grasping peg to verify the fact that it did not alter the tests. It was noticed that the bearing pegs tended to slide along the strand a little bit as transverse load was being applied. The instrument stabilized when the bearing pegs rested in the groove of the strand as shown in Fig. 3.14. It was noticed that the displacement readings were altered when this slip occurred and the tests were repeated. The grasping peg was similarly susceptible to slipping into a position of rest on the strand groove. Later tests preloaded the strand to induce this slip before tests began. For better results, the prototype was moved along the strand about one inch between each test. This was done to try to ensure that the average readings would be for various configurations of the strand bearing on the instrument. It was noted that results were almost identical if the prototype was not moved between tests, and could be fairly different when the prototype was moved along the strand. This did not seem to be dependent on the relative placement of the instrument along the exposed strand length, but rather on the position of the bearing peg surfaces against an individual wire or in the groove between them. The displacements obtained still seemed to be similar, but the non-linear steps in displacement readings seemed to occur at different levels of lateral loading. Since an average of several tests was used to obtain an estimate of tension in a strand, moving the apparatus frequently appeared to be a reasonable method to smooth out these non-linear steps and obtain a more representative curve. This should improve the reliability of the device and reduce variability of the curves.

The prototype was supported at the strand elevation throughout all of the length effects testing. It was noticed that occasionally the entire prototype would rotate about the strand and lift off of the supports. This allowed the bearing pegs to bear against the groove of the strand at the end of each test regardless of the original position, and altered the results. It is recommended that the prototype be supported to prevent rotation about the strand whenever possible.

5.2.3 Revised Prototype With Rollers

5.2.3.1 Changes in Behavior Due to Rollers

Adding the rollers tended to eliminate some problems but created others, such as allowing large slippage of the instrument along the strand. At first inability to prevent movement of the loading rod relative to the frame was frustrating, because many tests had to be rejected as they were being performed. Ultimately, the movement was utilized to improve accuracy. Before each test it is recommended to load the strand to a lateral load of at least one kip. Typically any large slips tended to occur just below this load. By inducing this slip beforehand, the test was always performed on the same part of the strand, i.e. with the bearing pegs lying in the groove of the strand.

High strength bolt grasping pegs were used, minimizing the indentations which were a cause of seating error. Tightening of the components along the loading rod also minimized error due to rotation of the displacement plate. The combination of these modifications improved consistency of results.

5.2.3.2 Overall Behavior

It was much easier to identify slip, rotation, and other causes of error during these tests because movements tended to occur much more suddenly. The likelihood of error could usually be foreseen by observing movement when resting a hand on the load cell, or seen by a sudden change in readings on the dial gage.

Results tended to be highly repeatable if the prototype was not repositioned on the strand between tests. Random errors were therefore assumed to be acceptably contained during testing. This repeatability does not, however, indicate that the readings are an accurate measure for the strand. As previously mentioned, repositioning the instrument between each test helped to smooth the averaged data curves by taking a more representative sample of data points. It therefore became standard practice to move the prototype along the strand and pre-load before each test to improve reliability of the data.

While a larger percentage of tests were required to be rejected due to excessive residual zero readings than in previous testing, the current errors were much more obvious in cause and effect. It was observed that there were very few negative residual zero readings compared to earlier tests, and later comparisons showed this to be the case. It is possible that this was because the grasping peg was less likely to seat or slide to the groove of the strand during testing, as both of these actions would cause a negative residual zero reading.

The equipment was also less sensitive to being tapped. In previous testing, especially without grease applied to the bearing pegs, a small tap to either the loading rod or the base could easily change the displacement reading. With the rollers added to the prototype the reading would waver, but quickly stabilize back to the displacement displayed before the instrument was tapped. With the original bearing pegs, the change in displacement reading was attributed to friction being overcome between the strand and bearing pegs when the instrument was tapped, but the friction then restrains the strand from returning to its original position. When the essentially frictionless rollers were added the strand was allowed to restabilize in the equilibrium position.

A few tests were done without supports beneath the prototype to test the requirement of restraining the prototype against rotation about the strand. It was found that the resulting displacements were lower than when the supports were included. It is assumed that the unsupported apparatus rotates slightly to follow the groove on the strand. When it is forced to rest on a support the rollers ride up on the individual wire a little, giving a slightly higher displacement (see Fig. 3.14). It is noted that the device was supported in the exposed strand length testing results throughout. It is felt that allowing the apparatus to rotate with the groove of the strand (no support) introduces the uncertainty of whether the prototype is subjected to unseen restraints to its rotation. While applying the apparatus to an interior strand it would be difficult at best to ensure that the device was free to rotate. Allowing the rotation of the device also tends to rotate the plate for measuring displacements relative to the base and therefore introduce error. Error could occur if both the bearing pegs and the grasping peg are not initially resting on the groove of the strand. By restraining the base (with supports), the base and loading rod will have less opportunity to rotate with respect to each other, and less space would be required to use the device. Restraining the instrument against rotation is believed to produce more accurate and reproducible results.

5.2.3.3 Twenty Foot Exposed Strand Length

When testing was performed on a twenty foot strand length, there is not as much of a tendency for the instrument to stabilize through slipping along the strand as was especially apparent during the preloading stage of testing. When slippage occurred it was at most a half inch whereas previously it was common to experience slippage of two inches or more. It appears as though the longer exposed length of strand allows the strand to rotate to keep the groove of the strand on the bearing pegs, whereas when the strand length was short the instrument needed to move to meet this condition. Restraining the prototype against rotation with supports no longer ensures a constant bearing surface between the strand and the bearing pegs. This implies that the calibrations done in this report apply only to the strand lengths studied and can not be directly extrapolated theoretically to longer lengths since the strand action differs. All calibrations should therefore specifically state the length of strand over which they are applicable.

5.3 Second Operator Test

A second independent operator was employed to see if a change would introduce new errors. He had several comments on the testing. It was felt that the zero reading was a difficult point to pinpoint. While it is possible to consistently assume a point to be the zero reading, it is not necessarily the zero reading that another operator would choose. The second operator was unsure of one of the tests due to the grasping peg "wobbling" on the strand during testing, resulting in highly variable displacement readings. This seemed to indicate that the instrument was not resting correctly on the strand. It was finally commented that while the first few readings were time consuming, the test became much easier with repetition.

5.4 Concluding Comments

The revised prototype with rollers appears to be the most reliable prototype, and this will be shown in Chapter 6. When this device is placed on the strand it should be free to slide along the strand length, but supported to prevent rotation about the strand. Before each test is performed the instrument should be relocated along the exposed strand and preloaded to one kip of transverse load. The high strength grasping rod should be replaced if it becomes indented. During testing, care must be taken to prevent the rotation of the displacement plate relative to the base of the device. Only loading data should be used, although a residual zero reading should be taken and an error correction performed as per 5.1.3. During calibration of the instrument the strand tension should be allowed to vary throughout the testing, and the strand lengths for which the data is applicable should be clearly stated. Operating instructions are included in Appendix A.

CHAPTER 6

RESULTS

Each number reported as a slope of the load deflection plot is actually an average of at least three individual tests. If a significant variance was noticed between results, additional tests were performed to obtain a more accurate average. The initial results showed the relationship between deflection and applied load to be linear. A best fit line was therefore applied to the data, and the slope of this line is considered to be the defining characteristic of the plot.

6.1 Length Effects Tests

Tests with different strand lengths were performed to account for the variation of exposed strand length which would occur in a damaged beam. The data from these tests was used to produce calibration curves from which the axial force in any exposed strand could be estimated. Testing operations were standardized as explained in Chapter 5. The final procedure is found in appendix A.

6.1.1 NUMERICAL VALUES

A summary of the slopes of the best fit line through the lateral load and deflection data can be seen in Tables 6.1 and 6.2. The numbers in the tables are the average value for all tests performed with the given exposed strand length and axial load on the strand. These are the slopes which would be used to estimate the tension in a given strand and are based on at least three individual tests. The two tables are differentiated by the best fit line being either forced through a zero y-intercept, or not. Theoretically, for a transverse load of zero, the resulting displacement would also be equal to zero. This would imply that a zero intercept would be applicable. It is, however, recognized that random errors occur throughout the testing. These errors can consist of rotation of the measurement plate, or friction between the strand and bearing pegs. Most of these errors are assumed to increase linearly or as a step function at unknown points, and so a linear error correction method was utilized as discussed in Chapter 5. It is realized that some error is non-linear, and usually occurs at the beginning of the testing. This error is caused by the seating of the strand onto the instrument. Although this type of error was minimized, it would be appropriate to allow a non-zero y-intercept wherever such error has occurred. It was of interest to investigate both cases to see if the accuracy of the testing was improved by allowing a non-zero y-intercept, which would indicate the occurrence of non-linear errors.

From the theoretical calculations discussed in Chapter 3, it would be expected that as the exposed strand length increases, the slope of the load-deflection plot would also increase. Comparing the results for individual exposed strand lengths in Tables 6.1 and 6.2, it was not apparent that there were any length effects in these tests. For any strand tension and prototype design at least one exposed strand length produced a slope which varied from the expected trend, and the variance between the minimum and maximum average slopes in Tables 6.1 and 6.2 were no more significant than individual test variances for a given exposed strand length. The assumption is made that length effects for a change in strand length from one to four feet is negligible given the precision of the instrument.

6.1.2 CALIBRATION CURVES

The slope of the load-deflection plots versus the tension in the strand can be seen plotted in Figs. 6.1 through 6.4. The slopes used are an average of the results from all five strand lengths as reported in Tables 6.1 and 6.2. Separate plots are obtained for the original prototype, the same instrument but with greased bearing pegs, the revised prototype with rollers, and this revised model tested again after full unloading of the strand had taken place. Data for both forced zero and non-forced zero y-intercepts are included in the plots. Figure 6.5 averages all results using the revised prototype with rollers into one data base, as there did not appear to be any difference in results between Fig. 6.3 and 6.4. Figure 6.5 is proposed for estimating half inch strand tension with the revised prototype.

It is interesting to note that the original prototype showed more of a discrepancy between the two plots (forced zero y-intercept or y-intercept), followed by the greased peg model (see Figs. 6.1 and 6.2). Once the prototype was revised, and rollers added, the two plots became virtually identical (see Fig. 6.3 and 6.4) and shows that non-linear errors were eliminated. It is still recommended that non-zero intercept results be used in actual use of the device to allow for the possibility of these errors.

It is also shown that at lower strand tensions the slope of the load-deflection plot is more sensitive to a change in strand tension. An estimate of tension in the strand is based on the slope of the load-deflection plot. For a given error in the test results the estimate will be closer to the actual value when measuring a low strand tension. This implies a greater accuracy in predicting the lower strand tensions. This may not be the case, as the theoretical calculations in Chapter 3 indicated a larger variance in load-deflection plot slopes at lower strand tensions due to bending of the strand and changing strand tension through the test (Tables 3.1 and 3.2).

Estimation of tension in the strand can be made by reading these graphs for a given load-deflection plot slope. This slope should be obtained from a series of at least three tests on the given strand to ensure that any faulty readings will be quite obvious. If there is a large variance between test results, more tests should be performed to get a more accurate average.

6.1.3 ACCURACY OF RESULTS

Tables 6.3 and 6.4 show the number of tests for which the strand tension was within ten or fifteen percent of the average for that group. The accuracy is shown both for individual tests and for the averaged tests which would actually be used for an estimation. It is noted that while many estimations from individual tests were not within ten percent of the actual loads, these tests were often recognized as not matching the other readings obtained during testing. More individual tests were then performed and the resulting estimation from the averages of all individual tests were therefore more accurate. For example, in Table 6.3 , for the revised prototype with rollers and a 20.0 kip strand tension, 26 of 32 individual tests were within ten percent when a zero intercept was enforced. When the results for each strand length were averaged to make an actual estimate, all strand tensions were estimated within ten percent. The single test values therefore represent the scatter of the tests, while the average tests involve the entire estimation procedure.

Table 6- 1 *Load-deflection plot slopes - forced zero intercept*

	1' Prototype, Original Design			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"		0.110	0.121	0.149
2'-0"		0.099	0.110	0.154
2'-6"		0.100	0.110	0.154
3'-0"		0.108	0.131	0.167
3'-9"		0.102	0.130	0.155
average		0.104	0.121	0.156

	1' Prototype, Greased Pegs			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"	0.091	0.092	0.116	0.145
2'-0"	0.089	0.106	0.121	0.153
2'-6"	0.091	0.102	0.120	0.151
3'-0"	0.098	0.098	0.120	0.158
3'-9"	0.098	0.099	0.120	0.156
average	0.093	0.100	0.119	0.153

	1' Prototype, Revised with Rollers			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"	0.085	0.103	0.119	0.157
2'-0"	0.087	0.108	0.123	0.154
2'-6"	0.085	0.101	0.123	0.158
3'-0"	0.103	0.110	0.132	0.164
3'-9"	0.093	0.110	0.129	0.155
average	0.091	0.106	0.125	0.158

	1' Prototype, Revised with Rollers Strand Tension Previously Released			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"	0.085	0.100	0.118	0.143
2'-0"	0.082	0.101	0.131	0.156
2'-6"	0.087	0.101	0.120	0.157
3'-0"	0.091	0.102	0.125	0.162
3'-9"	0.091	0.105	0.125	0.155
average	0.087	0.102	0.124	0.154

Table 6- 2 *Load-deflection plot slopes - non-zero intercept*

	1' Prototype, Original Design			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"		0.099	0.113	0.149
2'-0"		0.092	0.109	0.141
2'-6"		0.090	0.105	0.147
3'-0"		0.097	0.123	0.160
3'-9"		0.092	0.120	0.149
average		0.094	0.114	0.149

	1' Prototype, Greased Pegs			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"	0.076	0.086	0.113	0.134
2'-0"	0.080	0.099	0.119	0.149
2'-6"	0.079	0.098	0.122	0.142
3'-0"	0.089	0.089	0.112	0.150
3'-9"	0.085	0.089	0.117	0.142
average	0.082	0.092	0.117	0.144

	1' Prototype, Revised with Rollers			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"	0.082	0.105	0.125	0.157
2'-0"	0.089	0.107	0.126	0.158
2'-6"	0.090	0.105	0.125	0.158
3'-0"	0.098	0.105	0.131	0.161
3'-9"	0.093	0.108	0.128	0.155
average	0.090	0.106	0.127	0.158

	1' Prototype, Revised with Rollers Strand Tension Previously Released			
Strand	Tension in Strand			
Length	30 kips	25 kips	20 kips	15 kips
1'-6"	0.085	0.098	0.115	0.147
2'-0"	0.088	0.105	0.130	0.153
2'-6"	0.088	0.101	0.123	0.155
3'-0"	0.092	0.104	0.129	0.165
3'-9"	0.091	0.104	0.125	0.155
average	0.089	0.102	0.124	0.155

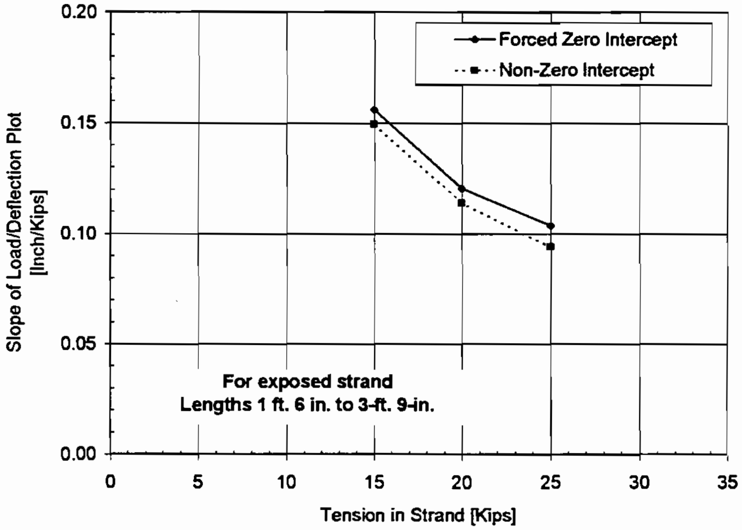


Figure 6- 1 *Calibration plot (original prototype)*

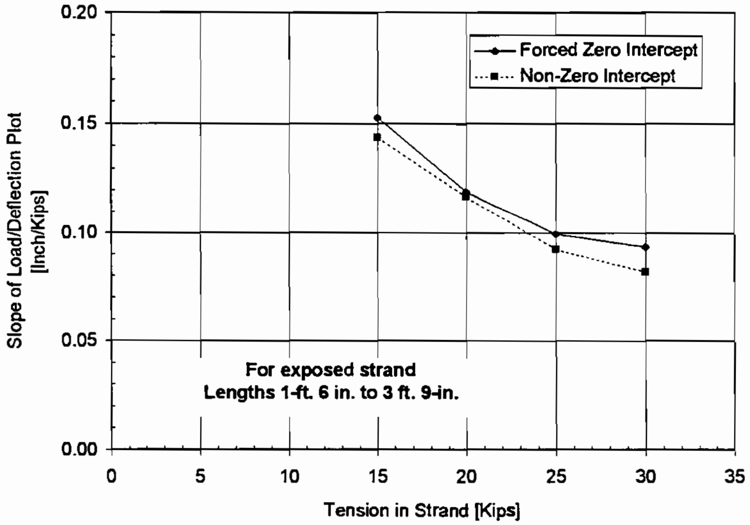


Figure 6- 2 *Calibration plot (prototype with greased pegs)*

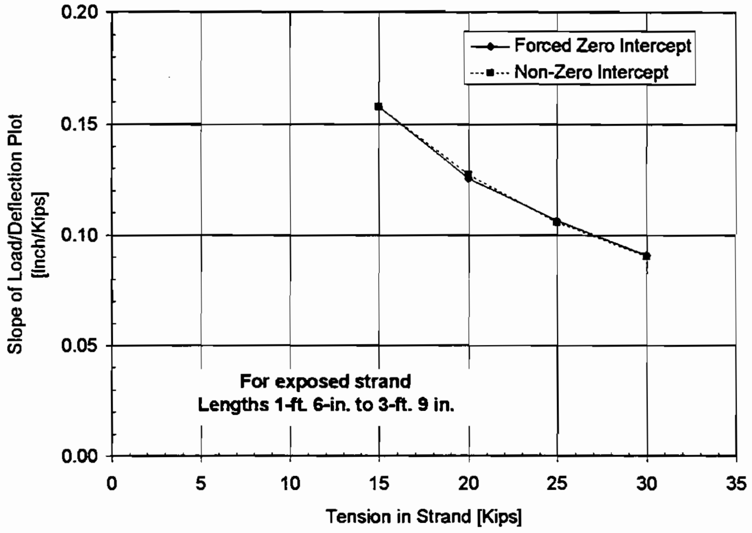


Figure 6- 3 *Calibration plot (revised prototype with rollers)*

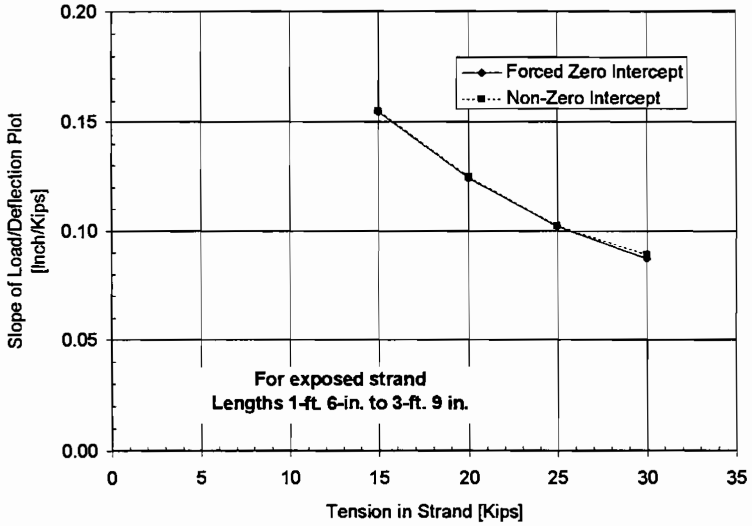


Figure 6- 4 *Calibration plot (revised prototype, strand tension previously released*

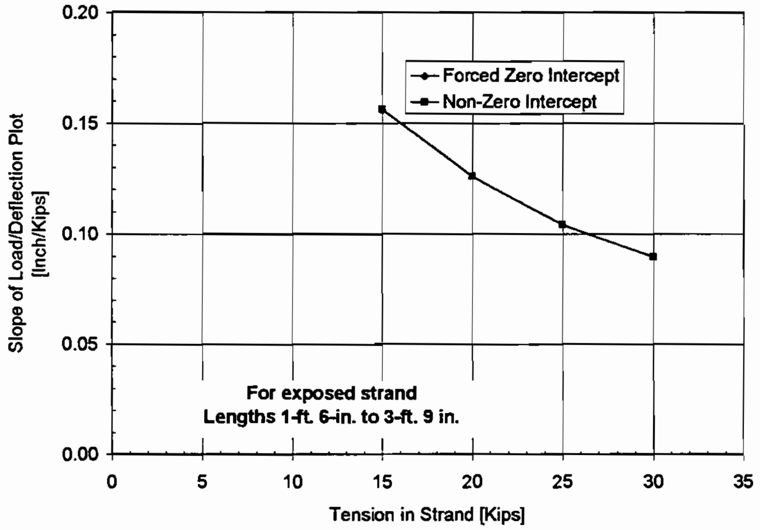


Figure 6- 5 *Final calibration plot (revised prototype, full data base)*

Table 6- 3 *Summary of tests meeting 10 percent criteria*

		TENSION IN STRAND [KIPS]							
		30		25		20		15	
PROTOTYPE	FORCED 0 INTERCEPT?	SINGLE TEST	AVG. TEST	SINGLE TEST	AVG. TEST	SINGLE TEST	AVG. TEST	SINGLE TEST	AVG. TEST
ORIGINAL	YES			11/15	5/5	10/16	3/5	16/16	5/5
	NO			11/15	5/5	13/16	4/5	14/16	5/5
GREASED	YES	11/26	4/5	8/16	4/5	15/15	5/5	19/19	5/5
	NO	13/26	3/5	10/16	4/5	15/15	5/5	16/19	4/5
ROLLERS	YES	22/30	9/10	27/30	10/10	26/32	10/10	24/30	9/10
	NO	26/30	10/10	29/30	10/10	29/32	9/10	28/30	10/10

Table 6- 4 *Summary of tests meeting 15 percent criteria*

		TENSION IN STRAND [KIPS]							
		30		25		20		15	
PROTOTYPE	FORCED 0 INTERCEPT?	SINGLE TEST	AVG. TEST	SINGLE TEST	AVG. TEST	SINGLE TEST	AVG. TEST	SINGLE TEST	AVG. TEST
ORIGINAL	YES			14/15	5/5	13/16	4/5	16/16	5/5
	NO			15/15	5/5	16/16	5/5	16/16	5/5
GREASED	YES	16/26	5/5	12/16	4/5	15/15	5/5	19/19	5/5
	NO	21/26	4/5	15/16	5/5	15/15	5/5	19/19	5/5
ROLLERS	YES	29/30	9/10	30/30	10/10	31/32	10/10	29/30	10/10
	NO	30/30	10/10	30/30	10/10	31/32	10/10	30/30	10/10

It can be seen that the accuracy of the instrument tended to improve with each additional attempt to reduce friction, especially at the higher loads where the displacements were smaller. The results also generally improved when the non-zero intercept was used. It is recommended that this method be used for fitting a line to the data.

It can be seen that instrument performed fairly well once revisions were made, estimating 39 of 40 strand tensions within ten percent, and all 40 within fifteen percent. It must be noted that this is a dubious statement since these calibration plots are based on the numbers that we are now estimating. While these comparisons address the scatter of the data, they do not necessarily indicate the accuracy of field estimates. The plots, and it is assumed the estimations, would benefit from a larger data base for the instrument calibration and must still be checked by actual field tests.

Table 6- 5 *Slope of load-deflection plot for 20-foot strand*

	Tension in Strand			
	30 kips	25 kips	20 kips	15 kips
zero intercept	0.096	0.120	0.130	0.164
non-zero intercept	0.094	0.110	0.128	0.156

6.1.4 *TWENTY FOOT EXPOSED STRAND LENGTH*

Table 6.5 shows the results for a twenty foot strand length. These results are compared to the average results from the previous tests in Fig. 6.6. Once again, the longer length strand gave higher slopes. This would result in a conservative (low) estimate of tension in the strand. The estimate It is also shown that the twenty foot strand exhibited some non-linear error. It is thought that this is due to the fact that in the shorter strands, the end fixity forced the instrument to physically move and stabilize at the grooved area of the strand, (see Fig. 3.14). In the twenty foot strand it was observed that these motions did not occur. It appears as though the strand is allowed to rotate to allow the groove of the strand to bear on the bearing pegs. It is assumed that this does not occur until a certain force is applied. When the strand rotates, the original deflection reading is no longer valid, and the following deflections will be larger than the strand deflection by the difference in height of the groove between the strands and the point on the strand where the instrument was originally resting. It is therefore

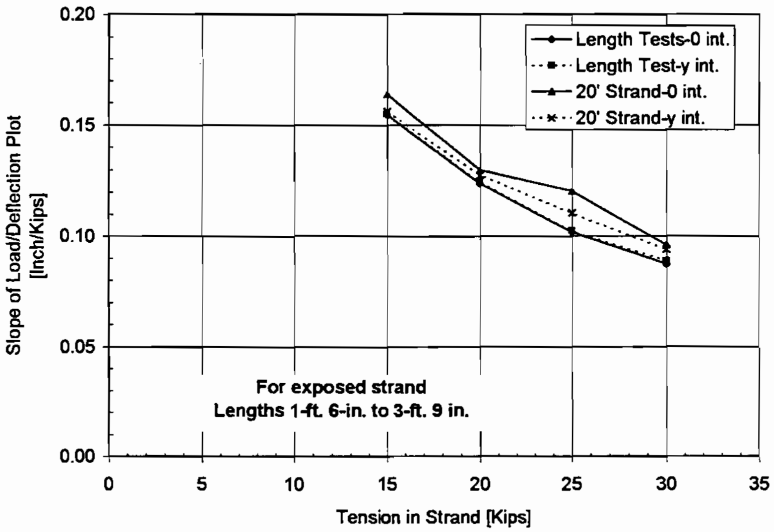


Figure 6- 6 *Calibration plot (with twenty-foot strand)*

once again recommended that the non-zero intercept be used in estimating the slope of the load-deflection plot.

6.2 Second Operator Test

Once the calibration of the instrument was completed including length effects, it was of interest to use the calibration plot to estimate an unknown strand tension. Tests were performed by an independent second operator.

6.2.1 ESTIMATION OF STRAND TENSION

Table 6.6 shows the results of the second operator tests. The estimated tension in the strand obtained from averaging three separate readings was 13.1 kips for the strand which actually had 15.0 kips. This is within thirteen percent. Throwing out the third reading which the second operator questioned due to difficulty keeping the readings constant the estimate is 14.0 kips. This brings the result within seven percent. The estimate was 24.4 kips for the strand with an actual load of 25.0 kips applied. This is within 2.5 percent. Individual readings were all within fifteen percent, except for the reading which was questioned which was within 28.0 percent of the actual value.

Table 6- 6 Second operator estimates

ACTUAL TENSION = 15 KIPS	
SLOPE OF PLOT [INCH/KIPS]	ESTIMATE OF TENSION [KIPS]
0.155	15.1
0.169	13.3
* 0.186	* 10.8
0.170	13.1
* 0.162 W/OUT 3RD	* 14.0 W/OUT 3RD
ACTUAL TENSION = 25 KIPS	
SLOPE OF PLOT [INCH/KIPS]	ESTIMATE OF TENSION [KIPS]
0.0995	26.9
0.1162	22.3
0.1080	24.2
0.1077	24.4
* SECOND OPERATOR QUESTIONED RESULTS	

6.2.2 COMMENTS

The second operator had several comments on the operation. First was that the zero reading was a difficult point to qualify. While the author agrees with this point, it is noted that the zero reading ends up having less impact than one would assume. Given the linear relationship between the transverse load and resulting deflection, the slope of the plot should remain constant regardless of the starting point (when a non-zero y-intercept is allowed). As long as individual operators are consistent with their own zero readings at the start and end of each test, the slope will be the same as the relationship is linear. It is therefore recommended that a each operator settle on a reasonable "zero" point which they feel that they can be consistent with.

It was also commented that one reading seemed faulty due to a "wobbling" of the instrument on the strand. The results showed this reading to be less accurate than the others. It is comforting to see that an operator unfamiliar with the apparatus could independently pick up on an inaccurate reading. As a general rule, if something seems to be unstable during testing, it is recommended that the results be disregarded and the test be redone.

The final comment was that the test became much easier with repetition. Indeed, the second operator spent nearly twenty five minutes for each of the first two readings, while the last few took closer to ten minutes each. The original operator spent a little over five minutes per test. The three readings required for an estimate could be taken in twenty minutes.

6.3 Splice Evaluation Tests

As a test of the effectiveness of the device in a "field" application, it was used as a comparison measure in the evaluation of the final strand tension in the splicing of a severed strand. Other methods used to estimate the tension in the strand were the recommended torque on the splice unit, an extensometer measurement of strain over a known gage length of eight inches, and the application of strain gages to the strand. A comparison of results for the four tests performed can be seen in Table 6.7.

In the evaluation of the tension in the strand in these preliminary splice studies it can be seen that the instrument developed in this report matched the results of the extensometer and strain gage measurements fairly well for all of the tests. Three of the values appear on the low side of the other measurements. This was to be expected as the exposed strand length exceeded the maximum recommended length of 3'-9" for the specific calibration chart developed earlier in this report. This chart was used to determine the tensile value shown in Table 6.7. This would result in a low

Table 6- 7 Estimation of final strand tension in splice test

Test #	Torque	Lateral-Delfection Instrument	Extensometer	Strain Gage
	(ft-lb)*	(kips)	(kips)	(kips)
1	250	22.4	25.9	23.9
2	260	27.9	24.1	25.2
3	250	22.8	22.6	23.5
4	250	18.7	20.4	19.6

***Torque of 250 ft-lb. is intended to produce a final strand tension of 25 kips according to manufacturers' recommendations**

discontinuity in the strand properties. It should be noted that the recommended torque often overestimated the tension in the strand. This is especially apparent in test number four. This was found to be caused by the torque being dependent on the condition of the threads in the splicing unit. A second check of strand tension is therefore recommended.

In a field application, strain gages would not be a cost effective alternative. The extensometer measurement requires a differential reading between the gage length with zero strand tension and the final gage length. It was susceptible to error depending on the point at which it was estimated that all of the slack was taken out of the strand. This error could be quite large. In the laboratory the strain gage readings were utilized to find this zero strand tension reading, but these would not be available in the field. Therefore, the instrument developed in this report is a useful tool for monitoring tension in splices on a severed strand.

In the evaluation of the tension remaining in a non-severed strand it must be noted that there is no zero reading that can be taken. Both the extensometer and the strain gages measure differential strains and are therefore reliant on a zero reading. The instrument developed in this report is the only alternative for this situation. The comparison of its estimation of strand tension to these other methods as part of the splicing study shows this instrument to provide reasonably accurate results.

CHAPTER 7

SUMMARY AND CONCLUSION

7.1 Devices to Measure Tension in a Strand

7.1.1 Development of Instrument

An instrument was produced to estimate the prestress remaining in an exposed strand of a damaged prestressed girder. This was done by applying a transverse load to the strand and measuring the resulting deflection. The slope of the best fit line through this data was used to define the results. A calibration curve was developed for half inch diameter strand with an exposed length of 1'-6" through 3'-9". Instructions for the use of the device are provided in Appendix A.

It is recommended that the prototype be improved by adding a deflection indicator which is directly in line with the load applied. A final working model would also have machined parts for extra stability and precision. Miniaturizing the instrument to allow testing of interior strands in a typical damaged beam would be valuable in some circumstances. It would be very handy if the instrument could output the corrected slope of the load-deflection plot. This would allow one to make an estimate of the strand tension on site, within a few minutes. More testing is recommended to provide a larger data base on which to base the standardized plots for estimating the strand loads.

With these improvements it is believed that the instrument would be accurate within ten percent in estimating the tension in any given strand. Tests were only conducted on half inch seven wire strand. Similar testing could be done to calibrate the instrument to any other particular type of strand.

The length of strand affects the results, however it is of negligible importance for the typical length of exposed strand in a damaged girder, generally one to four feet. If the exposed length exceeds four feet the accuracy may not be within ten percent. New calibrations could be made for any length, however it is noted that the results will always give a conservative estimation for longer lengths.

7.1.2 PROSEQ Instruments

The PROSEQ models SM55 and SM150 are similar products. Only the SM150 is capable of being used to test 7-wire strand. Since calibrations are done on three meter lengths of strand, the results will be unconservative when used to test shorter lengths of strand. The results would need to be recalibrated to these shorter lengths to meet the accuracy claimed by the manufacturer. Due to the requirement of a strand length of three feet just to place the instrument its application to damaged girders is limited.

7.1.3 The Kuhlman Bar

The Kuhlman bar, as developed by the California Department of Transportation, appears to be a fairly promising device. Initial test results showed the apparatus to be an effective tool for estimating tensions in long strands. The apparatus is small enough to be useful for testing most exposed strands.

indicated that length effects were negligible. While this is true for the lengths of strand that it was designed to test, for the shorter lengths presented by damaged girders new calibrations are required. The lack of calibration would explain the inconsistent results reported when it was applied to this specific use (1,2). The only apparent downfall of the application of this device to damaged girders is that the thickness of the apparatus prohibits its being applied to interior strands without major revisions.

7.2 Comparison of the Instruments

It is of some significance that three devices, the PROSEQ SM150, the Kuhlman Bar, and the instrument developed as part of this project all arrived at what is essentially the same design completely independently. This report's device is very similar to the SM150. The larger size gage length, as well as the in-line measurements, on the SM150 account for its greater accuracy. For the design to be optimized to the application for damaged prestressed girders it is recommended that the smaller size of a one foot gage length instrument be used. It would also be ideal for the device to be miniaturized such that it could be applied to interior strands.

The Kuhlman Bar is the most advanced design of the three for the purposes of this report. Additional testing is required to both calibrate the instrument to shorter strand lengths and to ensure the accuracy at these shorter lengths. Miniaturization of this instrument is likely to be very difficult, practically requiring a completely new design. It is therefore recommended that if measurement of tension in interior strands is desired, the instrument developed as part of this report would be preferable.

Critical elements to any further design include: rollers or other such parts to minimize effects of friction, sufficiently accurate load and deflection measurement devices, a rigid and stable frame unless frame deformations are considered as in the Kuhlman Bar, and application of a tension lateral load on the strand (pull the strand towards the apparatus) to ensure stability of the loading mechanism.

7.3 Length Effects

Length effects can be ignored for strand lengths from 1.5 to 4.0 feet and results of a completed design should still be well within ten percent error. At this point the accuracy of the instrument does not allow distinction of length effects in this range. If a final instrument allows a greater accuracy in readings, calibration could be done for strands at several increments in length to allow for increased accuracy. Damaged girders will rarely if ever have well defined strand lengths, however, and this detail in calibration is felt to be unwarranted. It should be clearly stated in the calibration charts the range of strand lengths to which the data is applicable. Estimations on strands longer than those calibrated will be conservative, while shorter strands can be quite unconservative. These effects will be more pronounced at larger strand tensions.

7.4 Conclusion

A working prototype was developed of an instrument to estimate the tension remaining in an exposed strand of a damaged prestressed girder. It was shown that length effects could be ignored over the range of strand lengths typically encountered. The instrument consistently gave estimations of strand tension within ten percent of the actual value. Suggestions were made to revise the instrument to increase its accuracy and applicability.

Comparisons were made to two other devices which could be modified to apply to damaged prestressed girders. It is recommended that further research be done with a revised working model of one of these three prototypes.

Comparisons were made to two other devices which could be modified to apply to damaged prestressed girders. It is recommended that further research be done with a revised working model of one of these three prototypes.

APPENDIX A

INSTRUCTIONS FOR THE USE OF THE STRAND TENSION INDICATOR

1. Preliminary Checks
    - a) Make sure that the strand is free of dirt and debris. Chip back to sound concrete without damaging the strand. A minimum of 1-1/2 feet of exposed strand is required.
    - b) Prepare the instrument. Check that rollers are free to rotate. Tighten and align all components along the tension loading rod. Orient the load cell vertically, with the displacement plate perpendicular to it.
    - c) Support the prototype to prevent twist. It is recommended to keep the instrument level if possible.
    - d) Connect the load cell to the volt source and voltmeter. Check the volt source output.
2. Attach to Strand
    - a) Place instrument near the center of the exposed strand.
    - b) Loosen loading rod. Place strand through the clevis piece and insert the grasping pin.
    - c) Check that the strand rests against the center of the pin and rollers, and is not bearing against any other piece of the apparatus.
    - d) Position the loading rod and grasping pin at about the midway point between the rollers. Finger tighten the loading nut, make sure that the back plate is secure.
    - e) Check that the load cell and displacement plate are not touching the base and are free to displace one quarter of an inch.
3. Set Instrument on Strand for Testing
    - a) Turn loading nut slowly, check that load readings are increasing.
    - b) Apply load slowly to a reading of one kip. If slip occurs, release load and reset instrument at new equilibrium position. Repeat process until no slip is detected when loading up to one kip.
4. Collect Data
    - a) Unload until the load and displacement readings do not change with further unloading. Apply load until the force and displacement are first seen to change and record the zero load voltmeter reading.
    - b) Zero the displacement dial gage.
    - c) Apply load at one hundred pound increments. Record the resulting displacements. If the desired load is exceeded, <u>do not</u> unload, simply record the load and displacement at this point.

d) When 1500 pounds of lateral force is reached, record the displacement and unload slowly to point at which the load is the same as when the test began. Some judgement is required here, as one must find the point at which no further displacement occurs before the strand loses contact with the grasping pin and slip may occur. This is a subjective combination of transverse load and displacement readings, proceed cautiously as this point is approached and loosen the nut by hand as the equilibrium point may be felt in the nut.

e) Record the residual zero displacement at the zero load point.

f) Shift the instrument a minimum of one inch along the strand and repeat the procedure to this point twice for a total of three test results.

g) Throughout the data collection, any noticeable slip or rotation of the apparatus voids the results. Twisting of the deflection plate can also affect results. It is recommended that one hand be placed on the load cell to resist torque in the loading rod. Any sudden increase in deflection without an increase in load, voids the results. Any residual zero deflection of greater than 0.015 inch voids the results.

5. Error Correction

a) Once three sets of valid data are obtained, distribute the residual displacement equally among the load steps. That is, correct the reading by zero at the zero reading incrementally up to the residual zero value at the final reading. Note that a positive residual value will be subtracted from the results, while a negative residual value will be added. Data with a residual value greater than 0.015 inch should be voided and retaken.

6. Estimating Load in Strand

a) The corrected data can now be averaged for each load point, alternatively the following can be performed for each set of data, and the results averaged at the end.

b) Obtain a best fit line through the data points. The line <u>should not</u> be forced to a zero y-intercept.

c) Compare the slope of the best fit line to the calibration plot values. Use judgement for values well between the plot values which are given for five kip increments, although these are shown as straight line steps, the actual plot is a curve.

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