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CIVIL ENGINEERING LABORATORY
Naval Consruction Battalion Center
Port Hueneme, California

Sponsored by
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EXPERIMENTAL STUDIES OF FATIGUE FAILURES OF DOWN LEAD CABLES

December 1976

An Investigation Conducted by

DEPARTMENT OF CIVIL ENGINEERING
CALIFORNIA STATE UNIVERSITY
Long Beach, California

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Eight hard drawn copper cables were tested to failure under static lateral axial load and either dynamic lateral load or torsional couple. Due to the large number of test parameters involved and the limited number of specimens tested, firm conclusions cannot be drawn about the fatigue life of copper cables under dynamic lateral or torsional loading combined with axial tension. With axial and lateral load, fatigue failure occurred at 4,000 cycles; with axial and torsional load failure occureed at about 10,000 cycles.

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EXPERIMENTAL STUDIES OF FATIGUE FAILURES OF DOWN LEAD CABLES

INTRODUCTION:

Down lead cables under the action of wind, ice and dead loads were observed to fail in a progressive pattern at the Naval Radio Station (T) (NAVRADSTA CTS), Cutler Maine. Under the action of these loads, the cable begins to basket and deform at the ends of the swages possibly due to stress discontinuities in the cable near swages. This weakens the cable action of downlead by separating the cable into its constituent strands and each of the strands begins to fail individually. The failure of the strands progresses to a point when the entire downlead cable breaks suddenly during strong wind and/or ice loads.

The objective of the experimental study reported herein is to determine the fatigue life of downlead cables under lateral and torsional loads.

EXPERIMENTAL STUDY

MATERIALS:

Downlead cables of hard drawn copper, having an outside diameter of .997 inch, consisting of 37 strands in three layers wrapped concentricly about a middle wire, with wire diameter of .1424 inch. The cable minimum breaking strength was specified as 33.4 kips. However, the actual breaking strength of cable was estimated at 35 kips.

TESTING APPARATUS:

The test frame is rectangular in shape made up of heavy W-sections with crossbeams added for structural stability. Three hydraulic rams are mounted on one side of this frame for application of static or dynamic loads or displacements. A schematic of frame is shown in Figure 1.

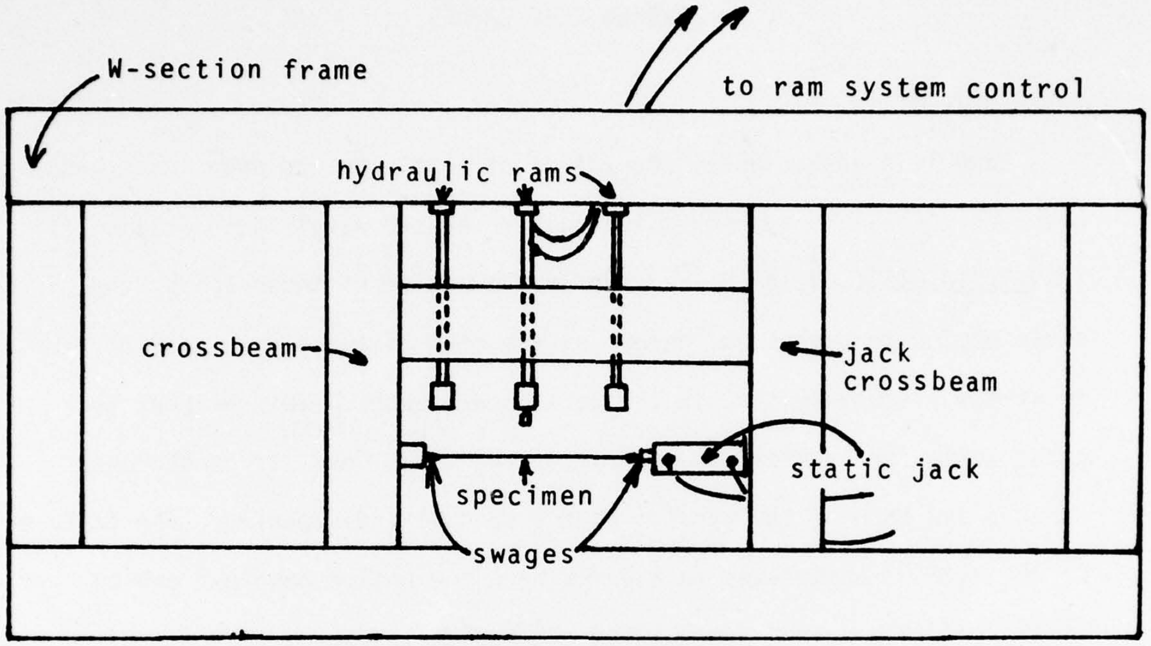


Figure 1. Schematic of Test Frame

Action of the hydraulic rams is set, monitored, and controlled electronically through a system console making adjustments in wave form, amplitude, and frequency in either stroke or load modes (Fig. 2). These rams were used to apply a dynamic lateral load or torsional couple to the test specimen.

The static tensile load was applied with a static hydraulic jack mounted to a test frame crossbeam. The tensile capacity of the static jack was 150 kilopounds tension and 300 kilopounds compression.

Figure 2 shows the loading frame modified for torsional fatigue test and system console.

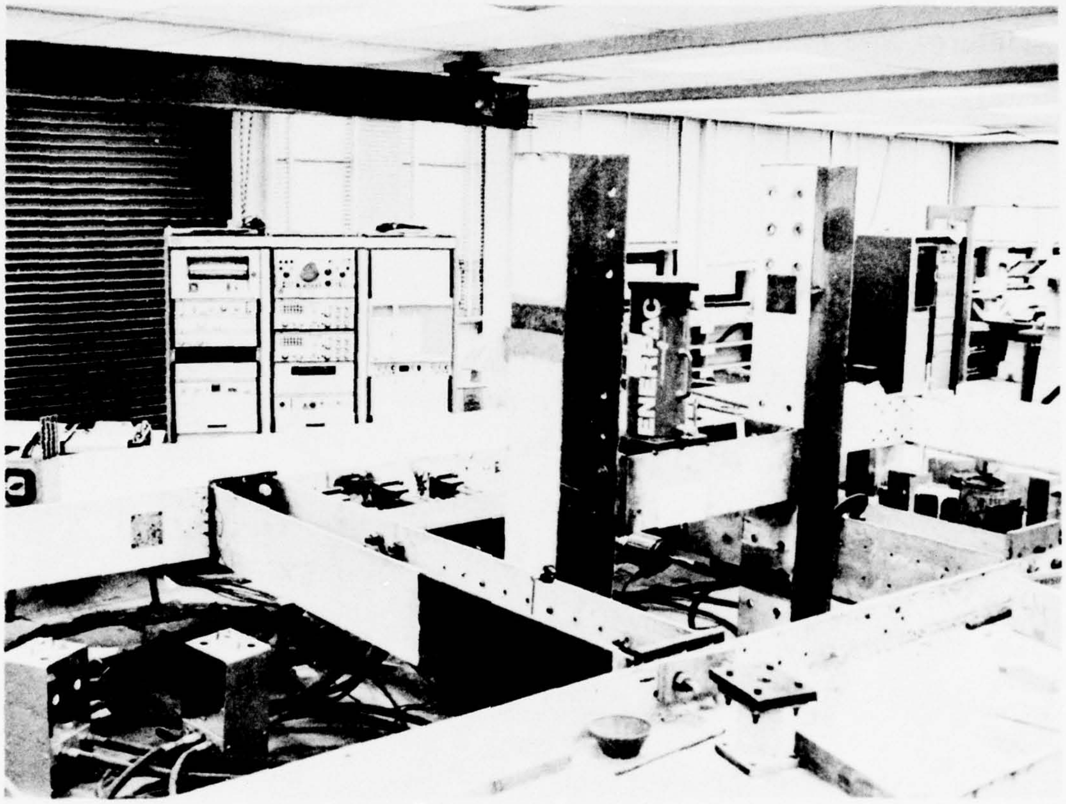


Figure 2. Loading Frame and Console

CONNECTORS:

Connectors for applying the axial static tensile load were steel cylindrical swages having an outside diameter of 1.75 inches and length of 5.25 inches with a minimum pullout strength of 30 kilopounds. Swage free ends were rounded to prevent cable abrasion or stress concentrations as the cable entered the swage.

The dynamic lateral load was applied from the middle hydraulic ram to the cable midspan as a point load by means of a snug (not tight) collar. The dynamic torsional couple was applied from the outer rams to the cable midspan through lever arms attached to this collar. Cloth insulation protected the copper test specimen from abrasion and insured more even distribution of lateral load or torsional couple (Fig. 3).

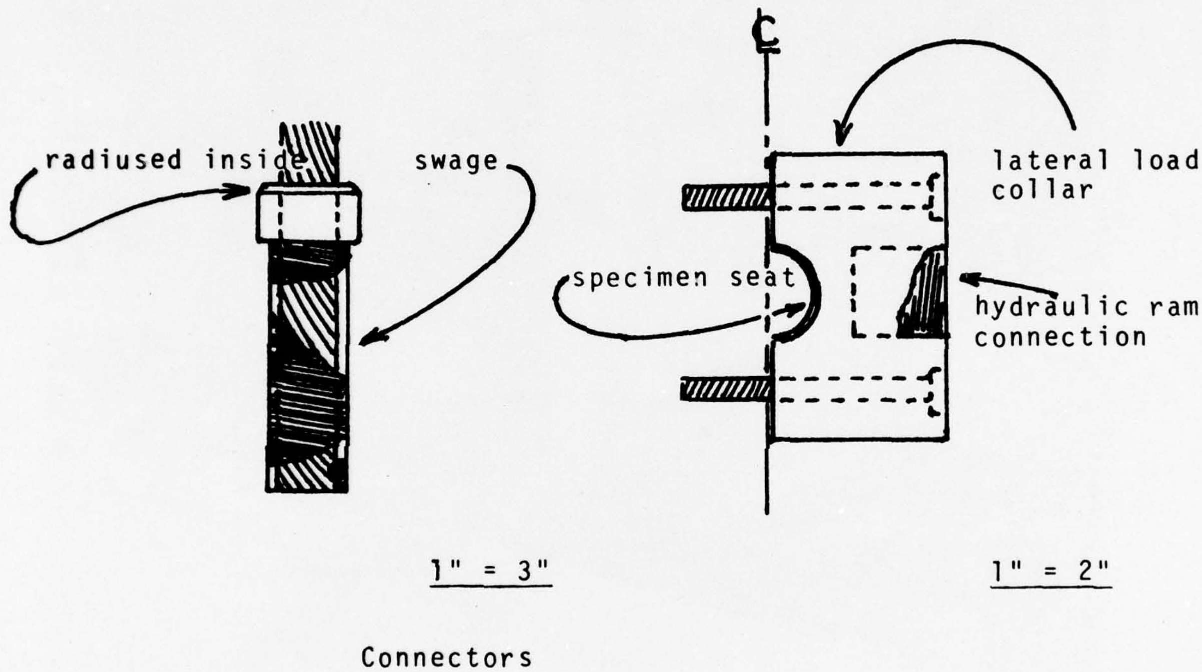


Figure 3. Swage Connectors and collar

PROCEDURE:

Specimens were made by cutting 32 inches of cable from the down lead stock and fitting them with 5.25 inch steel swages leaving an effective specimen length of 21.5 inches. Swage fixed ends were then threaded.

Dynamic Lateral Load Test: The specimen was placed in the frame, one end attached to the tension jack, the other attached to a test frame crossbeam. The cable midspan was aligned with the center hydraulic ram by adjusting the threaded swages (Fig. 4).

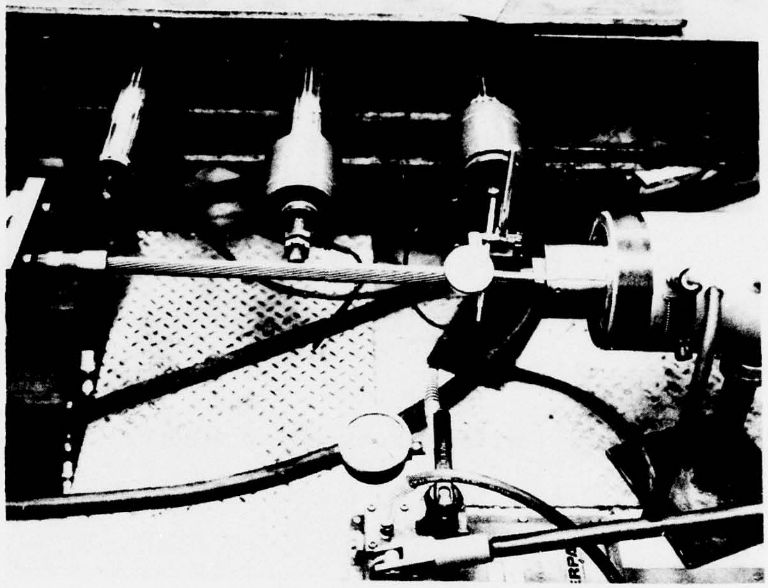


Figure 4. Dynamic Lateral Load Test Specimen in Place

At this point the specified axial tension load was applied in three increments and corresponding axial deflection was recorded. After full tensile load was applied the lateral load carrying collar, attached to the center ram, was secured to the cable midspan (Fig. 5).

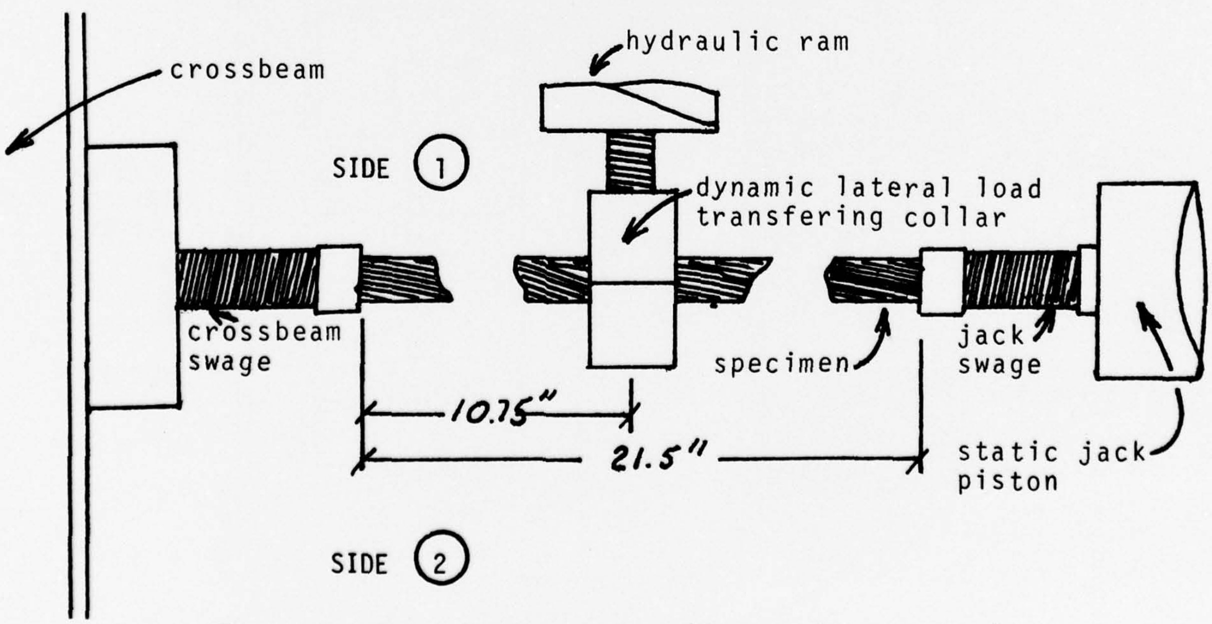


Figure 5. Test specimen set-up (dynamic lateral load)

Dynamic lateral load was applied as a sinusoidal waveform at a frequency of .5 hertz and at the specified amplitude. Lateral deflections were measured and recorded. After fatigue failure occurred, the number of cycles to failure was recorded and failure mode was documented. Based on this information, load magnitudes for subsequent tests were determined.

Dynamic Torsional Test: Test specimens were placed vertically in a modified test frame as shown in Figs. 6 and 7 with one end attached to

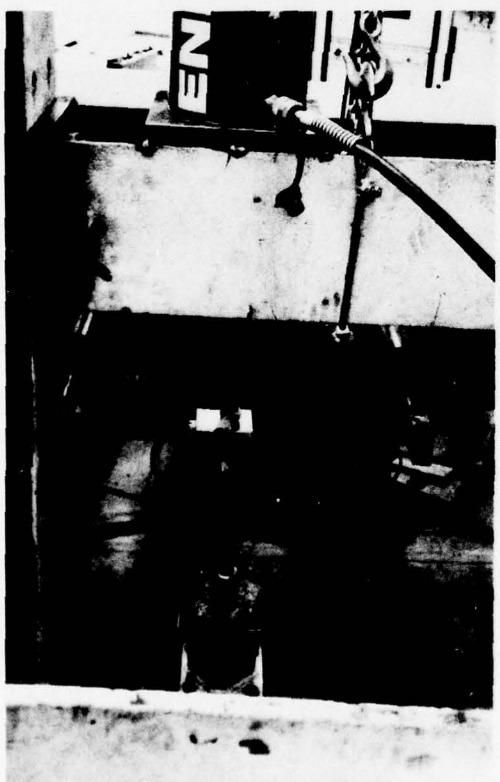


Figure 6. Test frame modified for torsion test

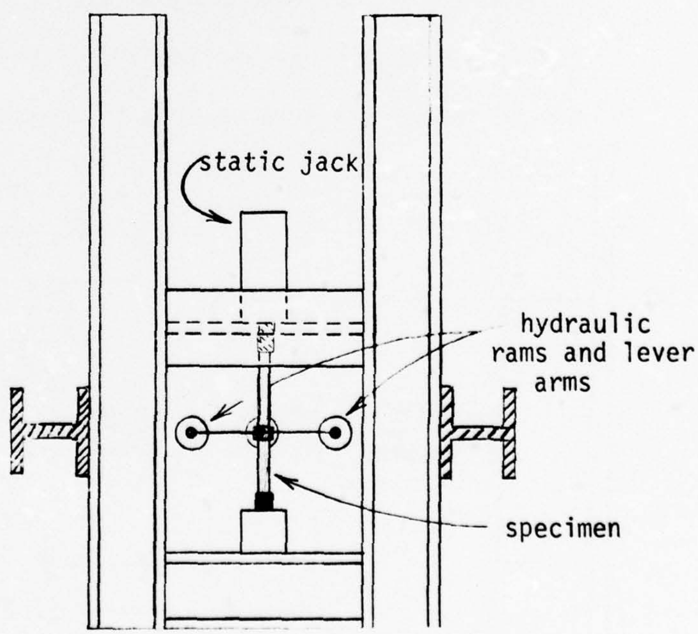


Figure 7. Schematic for torsion test

the tension jack and the other attached to a test frame crossbeam. The cable midspan was aligned with the center hydraulic ram by adjusting the threaded swages and the specified axial tension load was applied. A collar attached to the two outer rams was secured to the cable midspan to apply the dynamic torsional couple. Dynamic torsional load was applied as a sinusoidal waveform at a frequency of .1 hertz at the specified amplitude. Total torsional amplitude was measured from the positive maximum angle of cable rotation to the negative maximum angle of cable rotation. Rotation of the specimen during testing was measured and recorded. After failure occurred, the number of cycles to failure was recorded and failure mode was documented. A fatigue limit of 10,000 cycles was established. If, at this point failure had not occurred, static load or torsional moment were increased and testing resumed for *an additional 10,000 cycles.*

FAILURE DESCRIPTION:

Failure mode was described by number and location of failed wires, degree of strain of wires, and type of failure. Failure type was referred to as "shear" having a pronounced 45° failure plane with minor lateral strain, or as a "fatigue" failure having a cupped surface with excessive straining. These terms are only for descriptive purposes and may not exactly describe the failure mode. In addition, for each specimen a description and sketches are provided in Appendix A of this report. For orientation to specimen photographs, sketches are referenced with "side 1" corresponding to the side of test specimen nearest the hydraulic ram, and "side 2" corresponding to the test specimen side furthest from the hydraulic ram (Fig. 8).

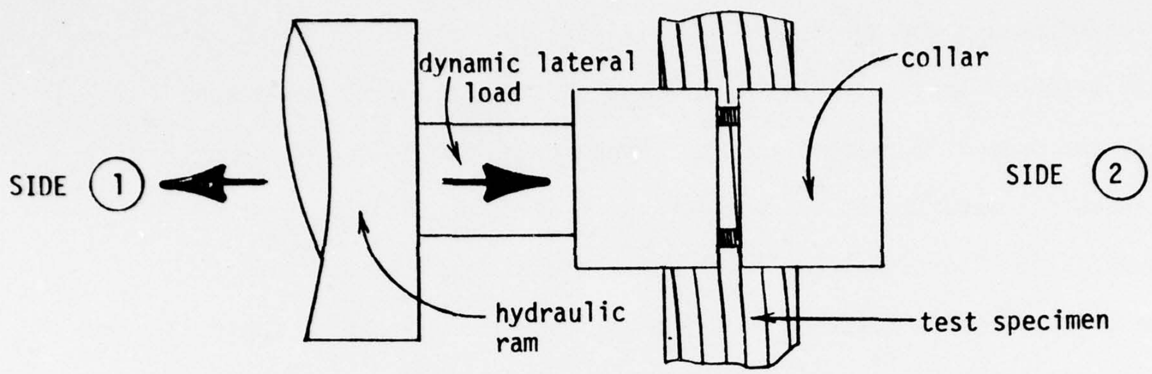


Figure 8. Convention for referencing failure sketches

A summary of results for dynamic lateral loading under static tension is given in Table 1 and a summary of results for dynamic torsional loading under static tension is given in Table 2.

Table 1. Summary of results for static axial load with dynamic lateral load

specimen	axial load, Kips	Fatigue under Lateral Load			nature of failure
		lateral load, Kips	midspan deflection	number of cycles	
1	30	4.8	----	-----	static failure in swages
2	10	4.0	1.5"	60	failure in swage
3	10	2.0	.6"	4310	fatigue type in swages
4	20	1.0	.15"	4970	fatigue type at collar

A detailed description of tests along with sketches are given in Appendix A.

Table 2. Summary of results for static axial load with torsional couple

specimen	axial load, Kips	Fatigue under Torsional Load			nature of failure
		torsion Kip-Ft	midspan rotation	number of cycles	
T5	10	.5 to 4	2.6 °	23	abrasive type at collar
T6	10-30	1.5 to 4.0	5.72°	30,000	cable pull-out at swage
T7	25-30	4.0	6.09°	20,431	fatigue type at 1/4 point
T8	30-33	4.0		10,013	shear type at swage

A detailed description of tests along with sketches are given in Appendix B.

CONCLUSION:

Due to the large number of test parameters involved and the limited number of specimens tested, firm conclusions can not be drawn about the fatigue life of copper cables under dynamic lateral or torsional loading combined with axial tension.

In general, for cable under static tension with lateral bending at the ultimate axial load of about 33 kips a static lateral load of about 5 kips may be applied at the center of the specimen before failure. With smaller axial loads (10 - 20 kips) and reduced lateral loads (1 - 2 kips) fatigue life is about 4,000 cycles.

For cable under static tension with torsional couple applied a fatigue life of 10,000 cycles is developed for a torque of 4 kip-feet at about ultimate axial load (33 kips). However, under such loading cable rotation in the 22 inch specimen tested was in excess of 6 degrees. It is unlikely that such large rotations can actually be developed in the field. Based on the large rotations necessary to develop torsional fatigue failure , it is probable that torsion is not a factor in actual cable failures.

Physical characteristics of individual strands in failed specimens indicate that sudden failures at high lateral or axial loads show reduced necking, reduced cupping, and a higher instance of 45 degree failure planes. Individual strands in cable failed after several thousand cycles of reduced loading show more surface abrasion, increased necking and deep cupping.

APPENDIX A

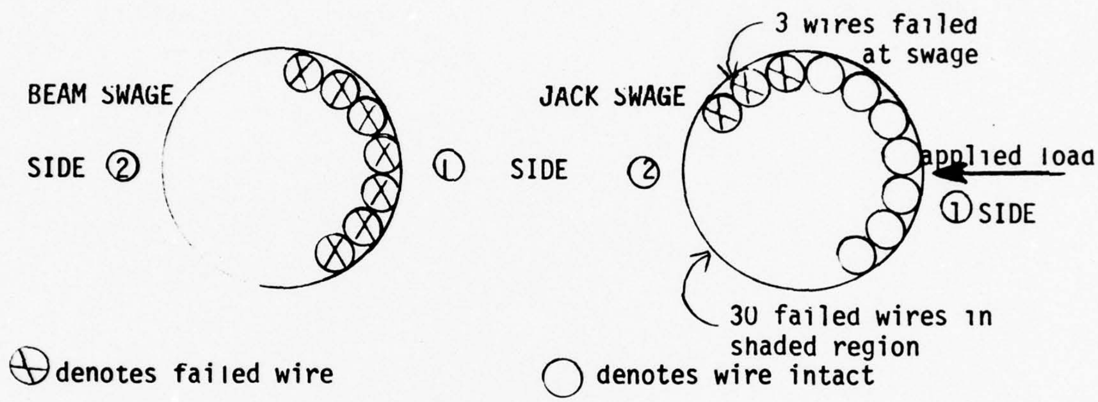
Test Results for Specimen Subjected to Static Axial Load and Varying Lateral Load

Specimen No. 1	7/15/76	length: 21.5"
30 kips axial See data	load set at 10 kips lateral for axial stress-strain	.10 cycles/sec

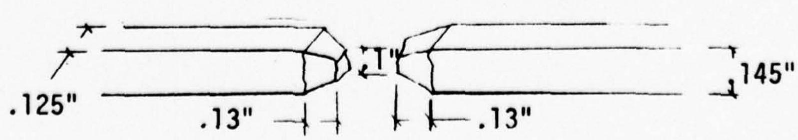
Specimen failed statically with axial load of 30 kips and lateral load of 4.8 kips. Lateral load was applied with slow rate of increase and failure is classed as static.

No. 1

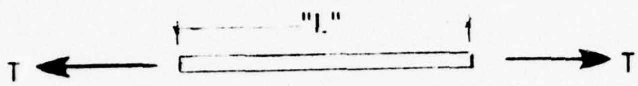
Cable failed at both ends inside swages. This test is considered static since a full cycle was never achieved. Location of failed wires is as noted



Most wires failed well within the swage. Average depth into swage to failure point is .645". The only visible copper wire deformation is at the point of collar contact and within swages. Within swages wire deformation is considerable. While at the collar contact, the deformation is not as significant. This deformation, coupled with large angle of rotation and subsequent high bending stress is probably responsible for failure in the swages. Figure shows deformation due to swaging and type of failure.



Static loads vs. longitudinal deflections
on the first specimen



Gage Length "L" : 21.5 in.

Log

1. Load: 0 (second time loads were released)
   Cable diameter: 1.005 in.
   Elongation: .032 in.

2. Load: 14,800 lbs. (fourth loading)
   Cable diameter: .995 in.
   Elongation: .154 in.

3. Load: 20,000 lbs.
   Cable diameter: .994
   Elongation: .21

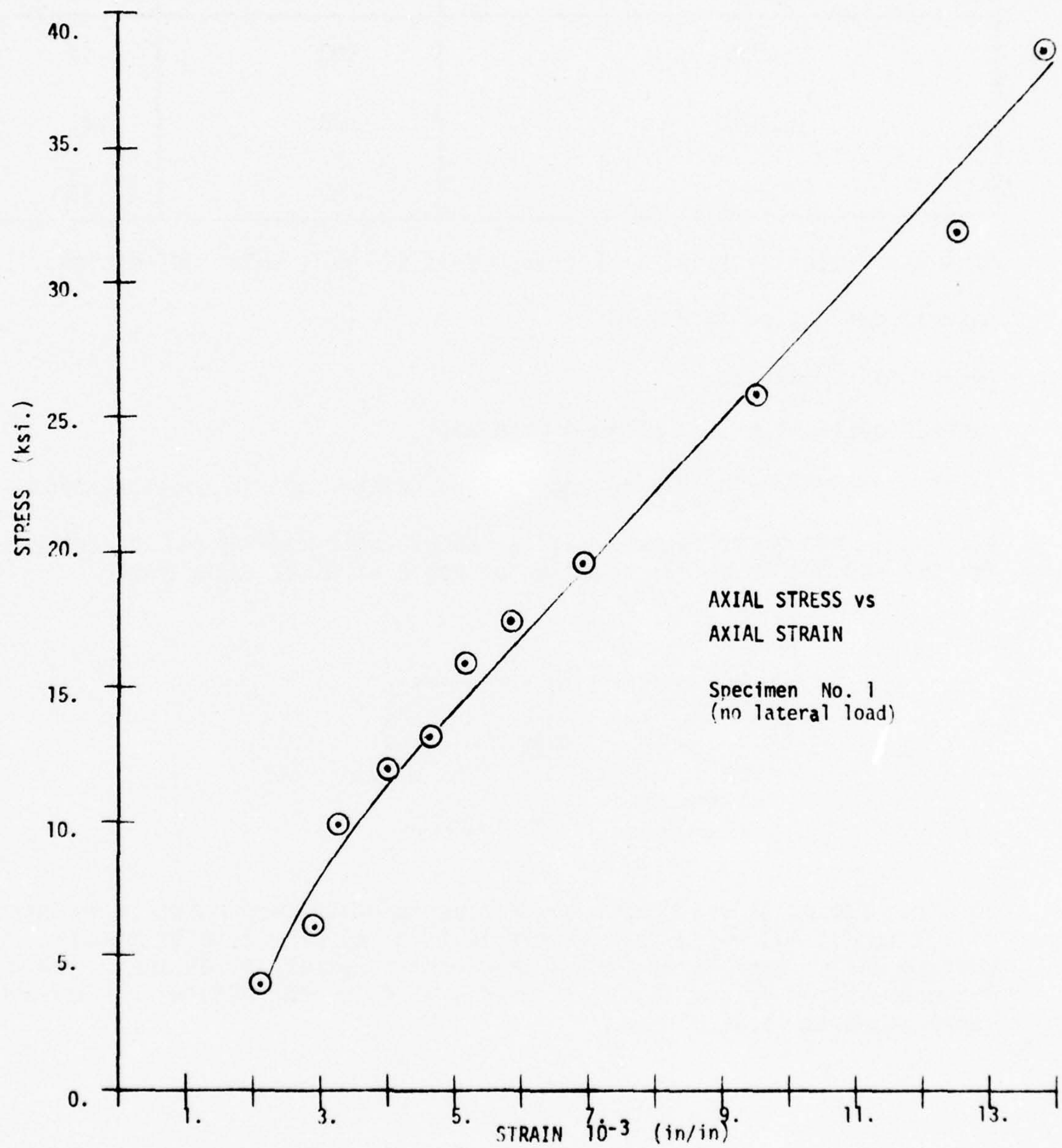
4. Release load to 0 lbs.
   Cable diameter: .995
   Permanent set after 1 load of 20,000 lbs: .058 in.

5. Load to: 25,000 lbs.
   Cable diameter: .995
   Elongation: .274

6. Load to 30,000 lbs.
   During loading, the apparatus readjusted itself
   Cable diameter: .254 in. (after slippage, the elongation at 30,000 lbs. was only .254 in. while the elongation at 25,000 lbs. was .274 in.

7. Release load to 0 lbs.
   Cable diameter: .995
   Permanent set: .098 in.

8. Reload to 30,000 lbs.
   Elongation: .299



AXIAL STRESS vs
AXIAL STRAIN
Specimen No. 1
(no lateral load)
STRESS (ksi.)
STRAIN 10-3 (in/in)
40.
35.
30.
25.
20.
15.
10.
5.
0.
1.
3.
5.
7.
9.
11.
13.

Specimen No. 2 8/3/76 Length: 21-5/8"

Axial Change in Length (in)	Gage pressure (psi)	Load (kips)
.056	300	4.44
.079	500	7.4
.111	700	10.36

At 4 kips lateral, axial jack pressure is 900 psi, axial deflection .112

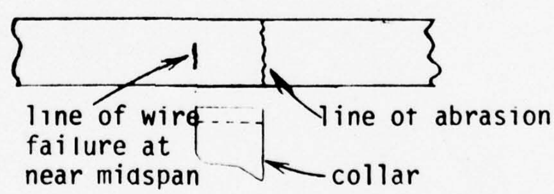
lateral deflection is ≃ 1.5"

Failure at 60 cycles

Lateral deflection 1.5" maximum both ways.

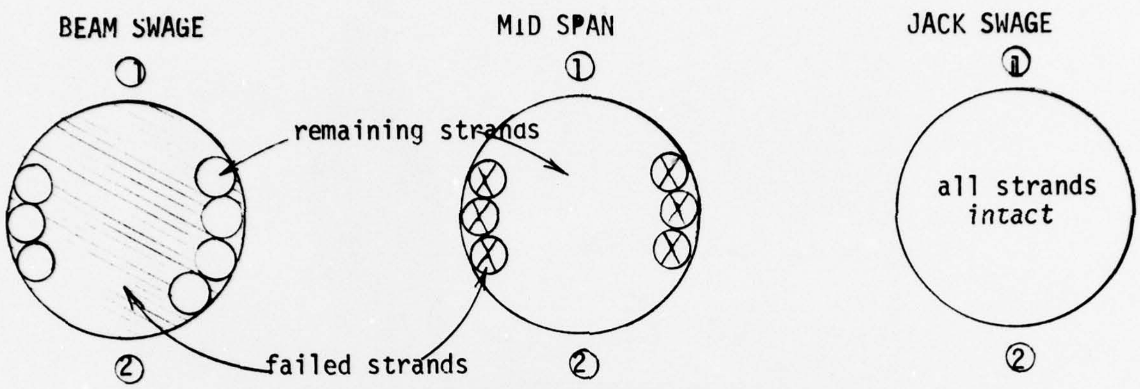
Axial deflection .06" during compression stroke .03" in tensile stroke

6 wires in the outer layer failed at about cable midspan. Apparently, failure was due to collar abrasion of cable wires at outer layer.



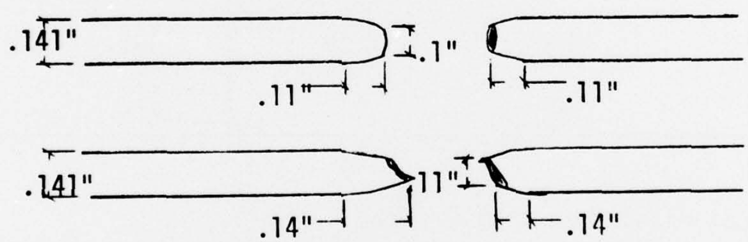
30 wires failed at swage with average depth of failure point in swage of .09 inch. All outer layer wires that failed here were at swage surface while inner wires failed at depths as great as .39 inch. Abrasion was moderate on second layer (12 wires) at swage and heaviest on second layer at about cable midspan.

Specimen No. 2

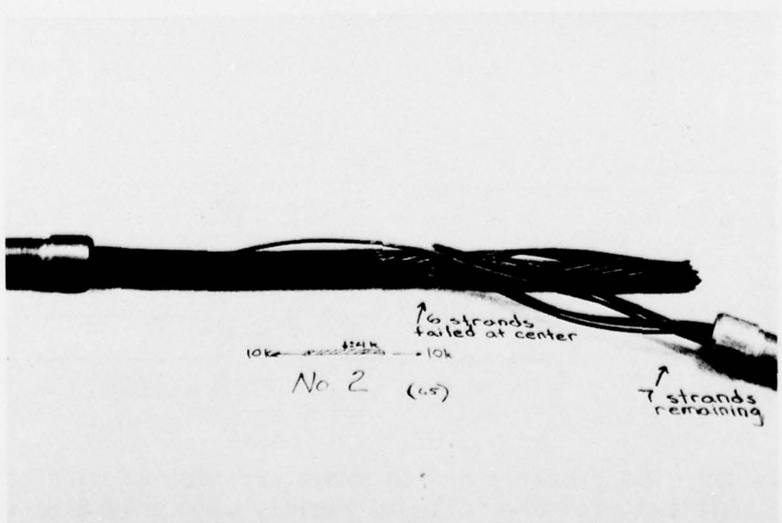


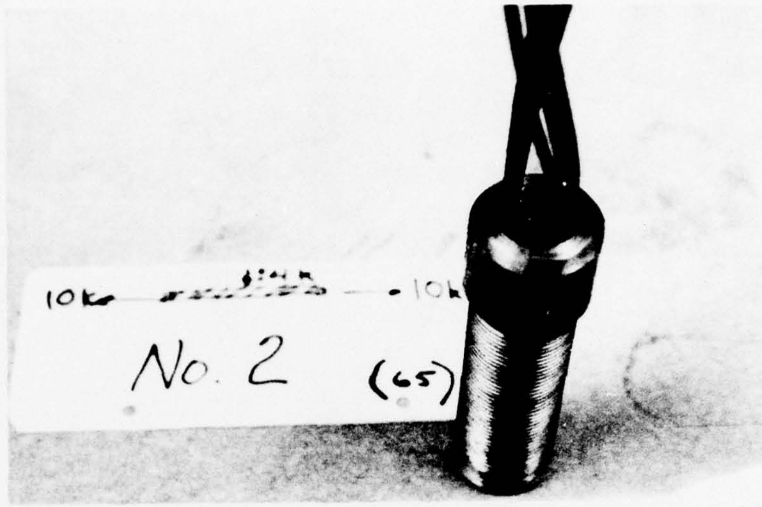
It is not known which wires failed first. However, it is likely that midspan failure occurred first due to high abrasion from collar and that swage failure followed due to excessive axial load on remaining strands and large lateral deflection of cable at midspan with ensuing high end moments.

It should be noted that lateral displacements were constantly high (1.5") relative to short specimen length (21.5"). Failures appeared as shown here.



Abrasion was highest at midspan on second layer (12 wires) decreasing slightly at swages. In general, degree of abrasion was moderately high.





Specimen No. 3 8/4/76 Length: 21-5/8"

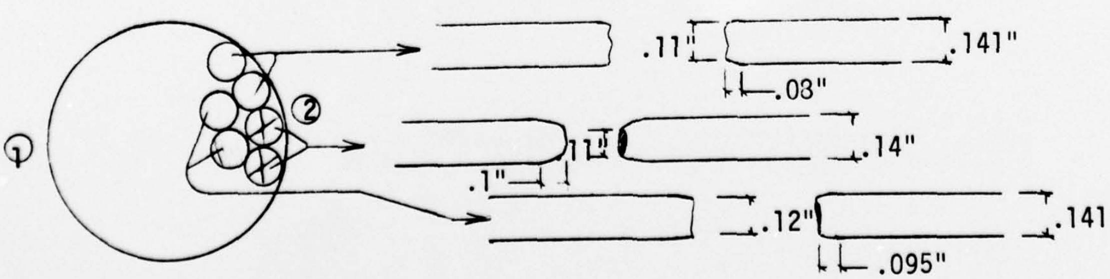
Axial Change in Length (in)	Gage Pressure (psi)	Load (kips)
.063	300	4.44
.091	500	7.4
.118	675	9.99

lateral displacement at 2 kips: .6"

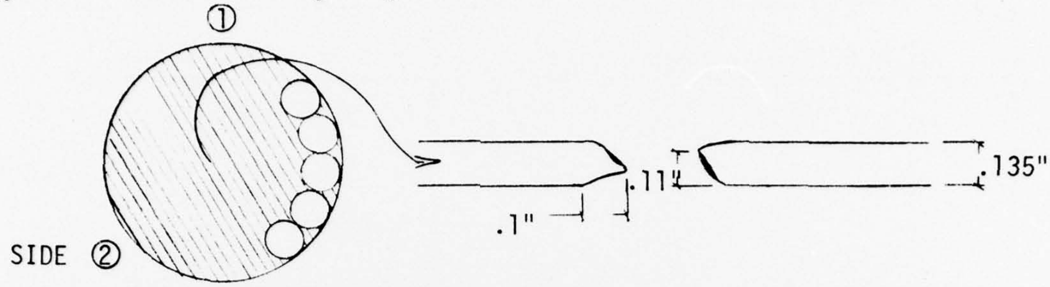
axial displacement at 2 kips: .015" (in addition to initial .118" displacement due to axial load)

Failure occurred at 4310 cycles.

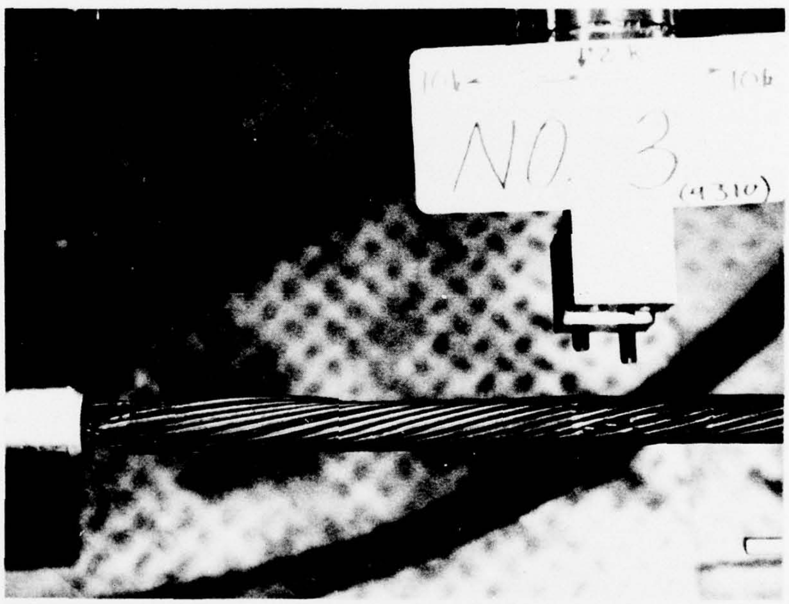
At 4300 cycles 2 wires in outer layer failed at jack swage, as noted below by X .



Failure here was probably due to swage abrasion of wires on specimen outer layer. Ultimate failure followed rapidly with only five strands remaining at crossbeam swage. Four additional strands broke at the jack swage as noted above. Failed wires at crossbeam swage showed signs of bending failure due to high lateral midspan deflection during the last few cycles. Crossbeam swage region cross-section is shown below.



Moderate straining occurred at the crossbeam swage indicating that this region was probably approaching failure at 4300 cycles. Abrasion was high on second layer (12 wires) at midspan and at both swages.



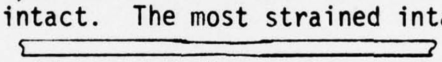
Specimen No. 4 8/4/76 Length: 21-5/8"

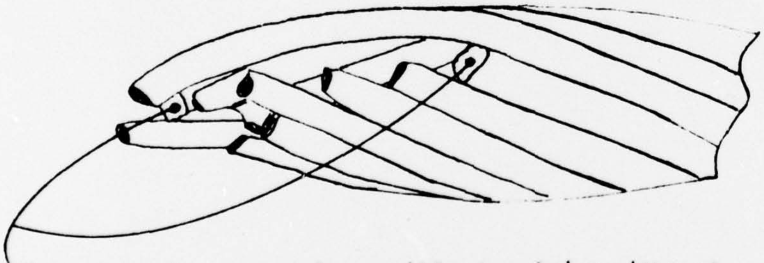
Axial Change in Length (in)	Gage Pressure (psi)	Load (kips)
.053	300	4.44
.104	700	10.36
.143	1000	14.8
.186	1350	19.98

Failure at 4970 cycles

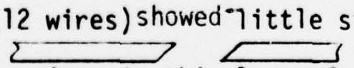
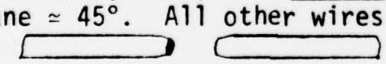
Deflection at midspan: .15"

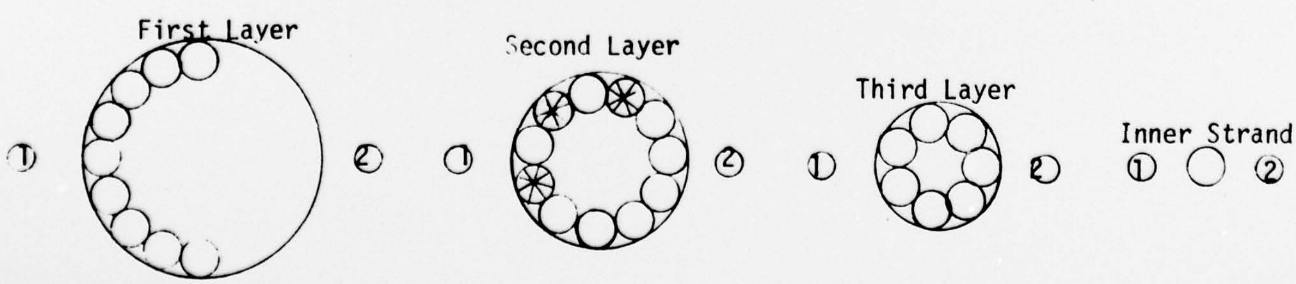
Axial deflection during loading ≃ .005"

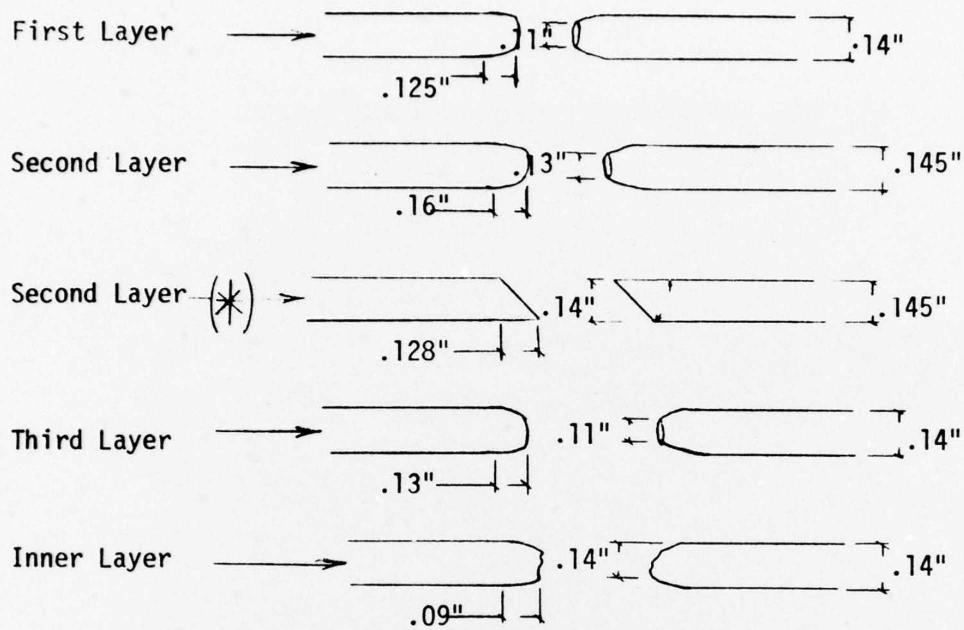
Failure occurred at midspan of cable on tension side. 9 outer layer wires failed leaving 9 wires intact. The most strained intact outer layer wire looked as follows: 
yielding at about cable midspan. Failure pattern of the inner wires is drastically different. The line of failure of successive wires in a given layer is along the same line as wire of successive inner and outer layers.



first inner layer (12 wires) with outer wires removed

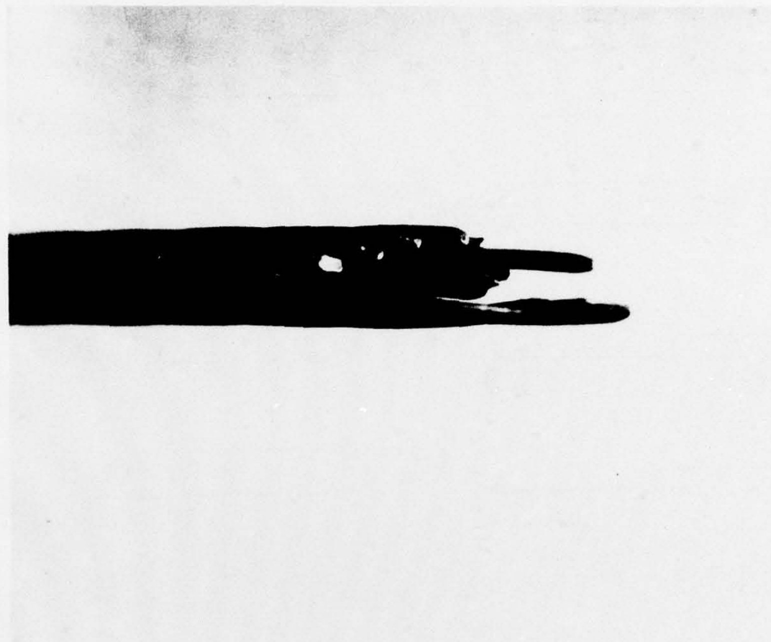
Two wires in second layer (12 wires) showed little strain, with a smooth failure surface, i.e., 
with plane ≃ 45°. All other wires in this layer failed with high strain, i.e., 





Abrasion on the outer layer of wire was visible but probably had negligible effect. Abrasion on the second and third cable layers was moderate and probably led to stress concentrations, reduced area, and eventual fatigue failure of these wires at points of bearing on wires of other layers. The inner layer (one wire) showed no sign of abrasion. Most abrasion occurred between the second and third cable layers. The failed end of the inner layer wire appears to have been initially a cupped shear failure subsequently further damaged by butting of the failed ends against each other. The degree of subsequent damage to the inner layer wire after initial failure indicates that this wire may have been among the first wires failed within this specimen. It should be noted that this test terminated 30 cycles after failure of the first wire at which time only nine strands (all in the outer layer) remained intact.

Wires in the region of the swages regardless of layer show no sign of failure. There is some abrasion due to wire contact stresses on the second and third layers but this abrasion is minor at the swages increasing along the wire length to its maximum at midspan.



Specimen No. 4 After Failure

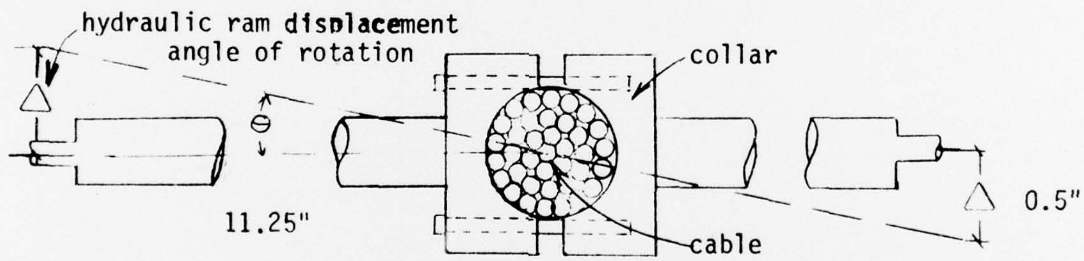
APPENDIX B

Test Results for Specimen Subjected to
Static Axial Load and Varying Torsional Couple

Specimen No. T5 | 9/27/76 | T5-1
10 kips Axial | 4 kp - in torque | .1 cyc/sec

Torque kp - in	Number of Cycles	Remarks
.5	3	
1.0	3	
1.5	3	
2.0	3	
2.5	3	
3.0	3	
3.5	3	deflection (max)
4.0	2	Δ = 1/2" * failure

Σ 23 cycles

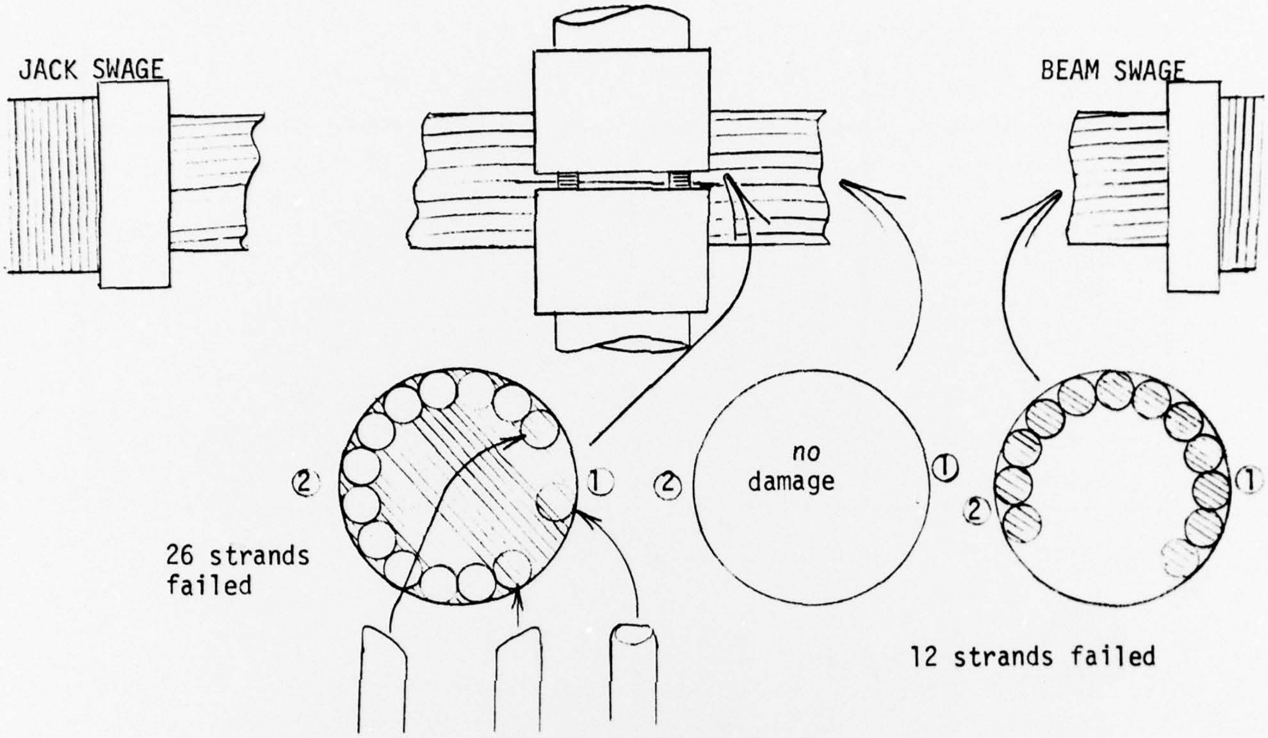


* Δ is deflection of torsion arm at free end in direction of applied load. Degree of cable rotation at midspan due to applied torsion is found as arctan Δ"/11".

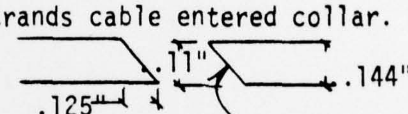
Maximum angle of rotation at time of failure:

$\tan^{-1}(.5/11) = 2.6$ degrees.

Specimen No. T5 9/27/76 T5-2
10 kips Axial 4 kp - in Torque .1 cyc/sec

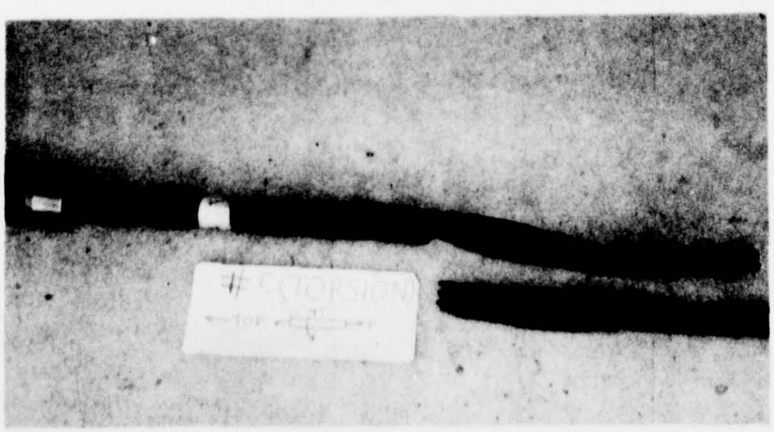


Primary failure occurred at point where 12 strands cable entered collar.
At this place, failed necking is slight.



Failure planes of individual wires indicate shear failure (no cup) during a twisting. Failure was due to excessive pressure from collar. Data from this specimen is questionable. 12 strands from outer layer failed at the base swage. Mode of failure was similar to that previously described. Excessive tightness of collar is indicated by extreme deformation of intact outer strands both entering and leaving the collar.

Abrasion between wire layers within the collar is extreme, but throughout the rest of cable there is no evidence of abrasion.



Specimen No. T6 T6-1

Axial Load: 10-30 kip Torque 1.5 - 4 Kp-in. .1 cyc/sec

Axial Load (kips)	Torque (kip in)	Cycles
10	1.5	9,750
10	2.5	9,800
20	4.0	10,000
30	4.0	failure

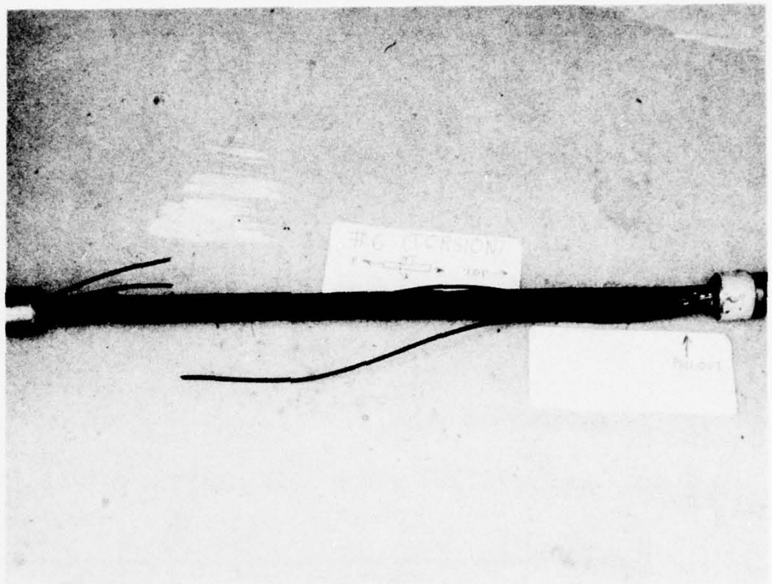
Cable rotation determined from

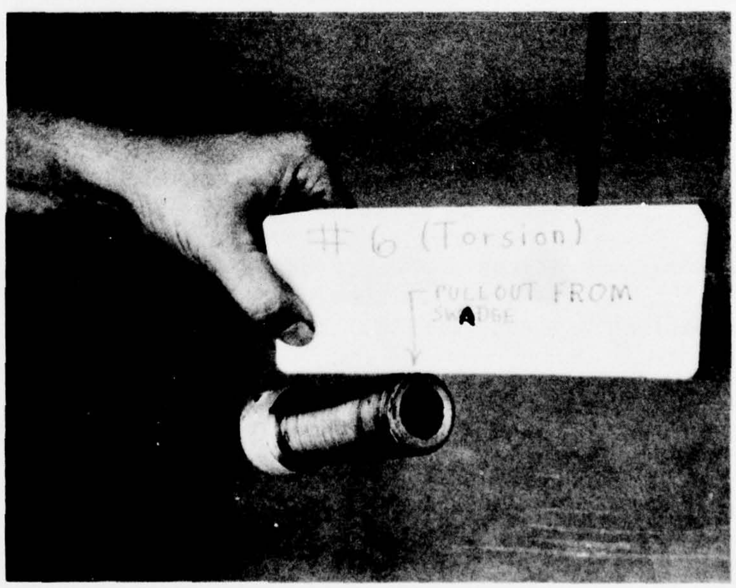
θ = arc tan $\Delta''/11.25''$ where Δ is maximum deflection of torsion arm at cable midspan.

Axial Load (kips)	Torque (kip in)	Rotation (degrees)
10	1.5	2.86
10	2.5	4.92
20	4.0	5.72
30	4.0	----

Failure occurred in static jack swage with complete cable pullout. Copper wires showed a high degree of abrasion between outer (18 wires) and first (12) layers. Abrasion occurred at contact points of wires from each layer. Abrasion was maximum at cable midspan decreasing toward swages. At swages little abrasion was visible. It should be noted that the cable itself did not fail. Failure was with the test apparatus (Swage).

Specimen No. T6 Torque 1.5 - 4 Kp-in. T6-1
Axial Load: 10-30 kp .1 cyc/sec



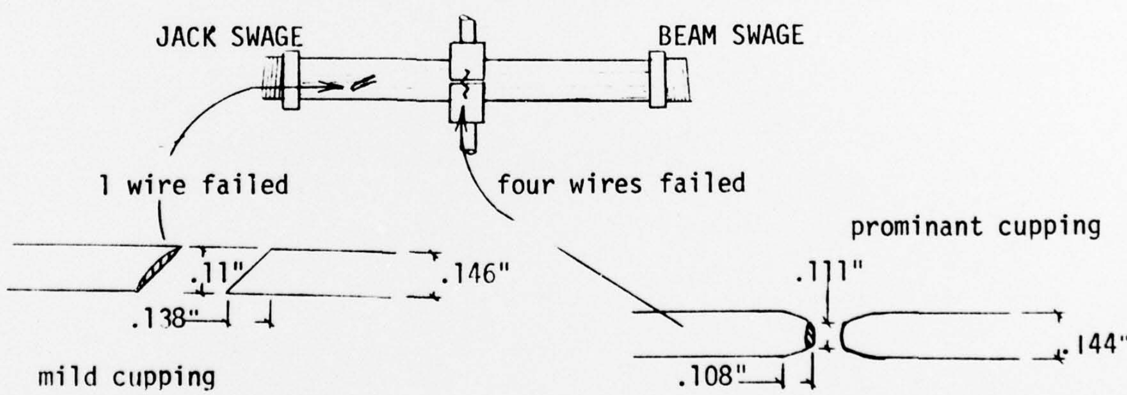


Specimen No.T7 10/18/76 T7-1
Axial Load: 25-30 kips Torque: 4 kp in .1 cyc/sec

Axial Load (kips)	Torque (kip in)	Cycles
25	4.0	10,000
30	4.0	10,000
33	4.0	431

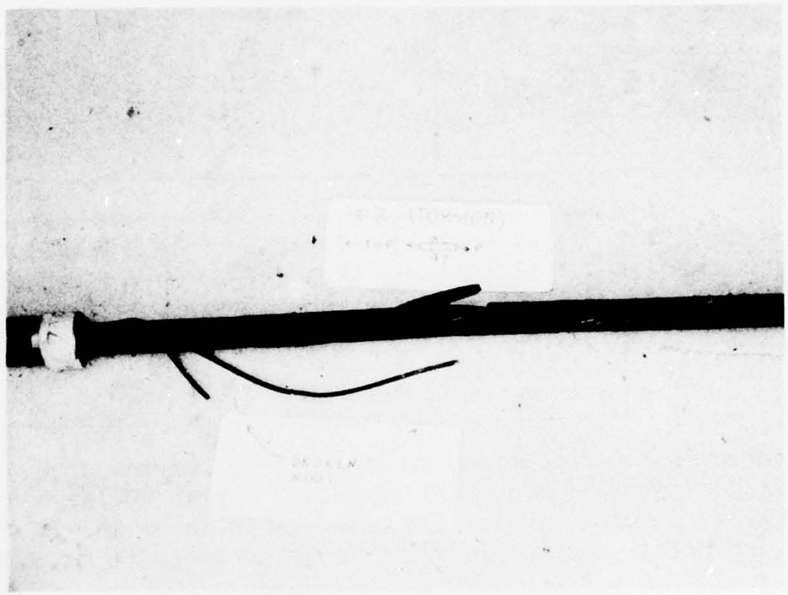
Axial Load (kips)	Torque (kip in)	Rotation (degrees)
25	4.0	5.724
30	4.0	6.09

Failure occurred in one strand at about cable quarter span. In addition, four strands failed at mid-point of cable, within collar. All failed strands were in outer layer. The outer cable layer showed strain in excess of that occurring in other layers. Additional strain was measured at .044".



Abrasion occured between outer (18 wire) and first (12 wire) layers. At cable midspan abrasion was high and decreased to low at swages.

Specimen No.T7	10/18/76	T7-1
Axial Load: 25-30 kips	Torque: 4 kip in	.1 cyc/sec

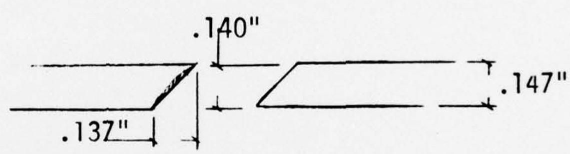


Specimen No. T7 After Failure

Specimen No. T8 | 10/20/76 | T8-1
Axial Load: 30-33 kp | Torque: 4.0 kp in | .1 cyc/sec

Axial load kips	Torque kp-in	Number of Cycles	Mid Point Deflection	Quarter Point Deflection	Rotation
30	4.0	10,000	---	---	---
33	4.0	13	Failure	---	---

Specimen was fatigued at 30 kips axial load and 4.0 kip inches torsional load for 10,000 cycles. At this point axial load was increased to 33 kips. Failure occurred after 13 additional cycles. Failure was of one strand in outer layer at base swage.



Failure plane was about 45° with very little local strain. However, entire outer layer of cable showed strain in excess of other layers of about .047".

Abrasion occurred between outer (18 wire) and first (12 wire) layers. Abrasion was moderate at midspan and decreasing to insignificant at swages.