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Te... Properties of Pleated ...tic Rope

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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
Structures Division
Gaithersburg, MD 20899

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TENSILE PROPERTIES OF PLEATED SYNTHETIC ROPE

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ABSTRACT

Pleated nylon ropes of two sizes and approximately the same length were tensioned to rupture in a universal testing machine. Several of the ropes were tested at room temperature. The others were subjected to specified high and low temperatures before testing. Deformation measurements of all the specimens were recorded while testing was in progress. The results were used to evaluate the breaking strength, ultimate elongation, and load-deformation properties, and to develop criteria for possible application in the recovery of mired vehicles.

Key words: breaking strength; load-deformation; nylon rope; pleated rope; pulse loads; specified strength; stiffness; synthesis; ultimate elongation.

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1. INTRODUCTION

Twenty pleated nylon ropes were tested in tension to determine breaking strength and load-deformation properties. The ropes were about 16-ft (5-m) long, center to center of eyes, and were of two nominal sizes. Some of the ropes were tested under a constant ambient temperature. Others were heated for a specified period then tested at ambient, or, were cooled and tested cold.

Synthetic fiber ropes are used in a variety of applications such as mooring, towing and lifting. The type of rope tested is intended for use by the U.S. Army to recover military tracked or untracked vehicles stranded in mire, a ditch, etc. The recovery is accomplished by transferring the kinetic energy of a moving vehicle (the recovery vehicle) through the rope to the mired vehicle as the moving vehicle is brought to a stop by the rope. Full recovery may require several trials. Starting from rest, with a specified slack in the rope, the recovery vehicle attains a certain velocity before the rope becomes taut and exerts a "shock" load upon the stranded vehicle. The process is repeated until the stranded vehicle is recovered.

The tensile tests conducted at the National Bureau of Standards (NBS) is part of a testing program undertaken by the U.S. Army to determine the suitability of eight-strand pleated nylon rope for kinetic energy recovery applications. Actual use under variable field conditions is predicated on the resolution of certain key questions such as, definition of safe working loads (to prevent premature rupture of the rope or its attachments), energy absorption capacity, progressive degradation due to repetitive use, and degradation as a result of extreme temperature and moisture conditions, or as a result of accumulation of field debris within the fibers.

The NBS tests provide data on the strength, stiffness and energy absorption capacity of previously-untensioned ropes under monotonic, quasi-static tensile loading to rupture. The information is needed to assist the U.S. Army in the design of selective field tests and subsequent upgrading of their product compliance requirements. The ropes were supplied by Marlow Ropes Ltd.[1]

2. DESCRIPTION OF TESTS

The tests were conducted using the NBS large scale testing facility [1]. The universal testing machine has a rated capacity

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[1] The manufacturer's or supplier's name is mentioned for product identification purposes only, and does not constitute endorsement of the product.

of 6000 kips (26,700 kN) in tension and twice as much in compression. It is equipped with a stationary (locked) tension crosshead at the top and a movable (sensitive) crosshead below that, as shown in figure 2.1. In tension tests the specimen is mounted between the two crossheads by means of clevises. Displacement-controlled loading is accomplished by lowering the sensitive head which can be actuated either hydraulically or mechanically.

The existing clevises were equipped with 16-in (406-mm) pins which were too large to accommodate the eyes of the ropes. To test the ropes, special fixtures were fabricated consisting of a 6-in (152-mm) diameter by 12-in (305-mm) long pin, a pair of 10-in (254-mm) O.D. by 2-in(51-mm) thick by 7-in (178-mm) long steel tubing, and a pair of 16-in (406-mm) O.D. by 3-in (76-mm) thick by 8-in (203-mm) long steel tubing for each clevis. The special fixtures were designed to keep bearing, shear and flexural stresses of the pin within the allowable limits under the maximum anticipated breaking load of the rope. A sketch of the attachments is shown in figure 2.2.

Except where noted otherwise, the tests were performed in accordance with Test Method 6015 of Federal Standard 191A [2]. The standard states that the pins shall be of sufficient size and held in a manner to assure breaking of the specimen in the free length. All specimens failed in the free length.

The Standard calls for a measuring device graduated in 1/8-in (3.21-mm) increments. During the tests the displacement of the gage marks were monitored at discrete load intervals by two theodolites. The resolution of the theodolites was within the specified tolerance by several orders of magnitude. The theodolites were aimed at two bull's eyes flanking the center of the rope and about 30-in (760-mm) apart as called for in the Standard. The initial gage length was recorded after loading the specimen to one percent of its specified breaking load in accordance with the Standard. The distance center-to-center of pins was measured at one percent of specified breaking load and at actual breaking load.

To examine extreme temperature effects the ropes were conditioned prior to testing as follows.

Four specimens of each size (64 and 80 mm; 2.52 and 3.15 in) were tested at 72°F (22°C), which was the constant ambient temperature of the laboratory. The Standard calls for triplicate tests of each size. The additional specimens of each size were initially tested as trial runs to validate the test setup. As both these tests turned out to be successful, their results were consolidated with the corresponding triplicate tests at ambient temperature.

Three specimens of each size were kept for five days in a thermostatically-controlled heating chamber at 165°F (74°C). They were then cooled to ambient temperature for one or two days before testing. The temperature of the specimens was monitored by thermocouples during the cooling process to assure that ambient temperature is attained before testing.

Three specimens of each size were cooled in a foam box packed with dry ice to temperatures ranging from -71°F to -97°F (-57°C to -72°C). While in the box, their temperature as well as the air temperature within the box were monitored by thermocouples. They were then removed from the box and installed in the test machine in about 10 to 20 minutes before the start of the actual testing. The temperature of two ropes were also monitored during the tests.

For low-temperature experiments, the Standard specifies that the specimens be cooled to a temperature of -65°F ± 5°F (-54°C ± 3°C) and tested cold. This provision is difficult to implement in a laboratory where the controlled environmental temperature is at 72°F (22°C). In consultation with the Sponsor, several schemes were considered, such as testing the specimen within an enclosure in which the air temperature would remain at -65°F (-45°C) during testing. None of the schemes turned out to be feasible because first, the explosive failure of nylon rope would shatter the containment device, and second, any confinement would prevent monitoring of gage deformations during testing. Two of the specimens were tested while wrapped in double aluminum foil. This scheme was abandoned after discovering that the foil was not very effective in keeping the temperature from rising during the time interval needed to mount the rope, and the breaking of the rope caused an excessive amount of aluminum debris.

The detachment of bull's eyes at low temperature was another difficulty encountered in the tests of cooled specimens. for the first cooled specimen (a 64-mm or 2.52-in rope), gage length deformation as well as pin-to-pin elongation were monitored during the test. The center-to-center of pin displacements were measured by sighting the scale of a retractable tape attached to the sensitive crosshead. The free end of the retracting tape was attached to a main column of the test machine such that during the course of testing, the downward moment of the crosshead could be monitored at discrete load intervals by sighting the uncoiling tape at the exit point of its casing. The method proved reliable and was adopted in the subsequent tests of the cooled specimens as an alternative to the measurement of gage elongation.

As noted earlier, the sensitive head can be actuated either hydraulically or mechanically. The hydraulic system has a maximum usable stroke of 5 ft (1.5 m) and a displacement rate of approximately 3 in/min (76 mm/min). The mechanical system operates at a displacement rate of approximately 12 in/min

(305mm/min). Its maximum available stroke depends on the initial length of the specimen. The maximum available distance center to center of clevis pins is 45 ft (13.7m). This is more than the 30-ft (9-m) estimated length of rope at breaking load.

The nylon ropes consist of eight strands, twisted clockwise and plaited in pairs. In the 80-mm rope each strand consists of 56 sets of yarns twisted counter-clockwise. Each set consists of three yarns twisted clockwise. Each yarn consists of nylon filaments. In the 64-mm rope, each strand consists of 44 sets of yarns twisted counter-clockwise. Each set consists of four yarns twisted clockwise. The number of filaments in a yarn is less than used to prepare the yarns for the 80-mm rope. Thus, to obtain a certain specified size of rope the number of yarns in a strand and the number of filaments in a yarn are altered.

Plaiting introduces a repetitive pattern or a "pitch" in the rope. Since plaiting does not introduce a constant twist, the orientation of the filaments with respect to the axis of the rope changes continuously within a pitch. The manufacturer's specified breaking strength is 72000 kilos (158.7 kips) for the 64-mm rope, and 110,000 kilos (242.5 kips) for the 80-mm rope.

In the initial tests (specimens 1 through 10), the ropes were loaded mechanically up to about 50 percent of breaking load. The machine was then switched to the slower hydraulic system for the remainder of the test. Specimens 11 through 20 were loaded mechanically throughout the entire loading range to examine any effects that might occur as a result of the faster loading rate. The hydraulic system could not be used exclusively because the total elongation at breaking load would have exceeded the available stroke.

3. TEST RESULTS

3.1 Strength and Elongation

Table 3.1 shows the breaking strength and the corresponding maximum elongation of the individual ropes. For specimens 1 through 15, the elongation of the gage length as well as the length center-to-center of the 6-in (152-mm) diameter clevis pins (pin-to-pin or PTP length, in brief) were measured. Actual gage lengths and PTP lengths under one percent specified breaking load are indicated in the table. Except as noted in the table, the percent elongations of gage and PTP lengths were calculated from the total elongation measured at breaking load. Where the last measurement was taken at a load less than the breaking strength, that load has been specified in a footnote to the table. For specimens 16 through 20 only PTP length elongations were measured. Where a measurement was lost due to any cause, attention is drawn by an appropriate footnote to the table.

Table 3.1

Breaking Strength and Maximum Elongation

T D.	ROPE NO.	size mm	Breaking strength	Gage Length (in.)			Pin-to-Pin Length (ft.)		
				1% ld.	brkg. ld.	% elong.	1% ld.	bkg. ld.	% elong.
UNTREATED	1	64	210.0[k]	31.30[a]	53.98	72.4	-	-	-
	3	64	205.0[k]	? [c]	34.51	? [c]	17.91	26.22	46.4
	4	64	184.5[k]	31,10[d]	? [d]	? [d]	18.38	26.63	44.9
	5	64	192.5[k]	30.62	50.27	64.2	17.88	26.58	48.7
	2	80	321.0	33.00	52.83[b]	60.1	18.73	28.08	49.9
	6	80	297.5	31.06	51.60	60.1	17.38	26.41	52.0
	7	80	295.5	29.88	49.62	66.1	19.28	29.13	51.1
	8	80	311.0	30.72	51.65	68.1	18.73	28.33	51.3
HEAT TREATED	9	64	210.0	30.22	50.70[b]	67.8	17.53	27.03	54.2
	10	64	217.0	30.00	51.78	72.6	17.50	26.63	52.2
	11	64	209.5	30.50	50.11[b]	64.3	17.90	26.91	50.3
	12	80	323.2	29.49	51.59	76.2	17.78	27.43	54.3
	13	80	319.0	30.33	51.41[b]	69.5	18.13	27.35	47.0
	14	80	320.0	30.03	52.62	75.2	17.81	27.48	54.3
COOLED	15	64	215.0	33.83	53.89[b]	62.7	18.57	27.22	46.6
	16	64	232.3	- [e]	-	-	18.60	27.35	47.0
	19	64	224.0	- [e]	-	-	18.35	26.93	46.8
	17	80	335.5	- [e]	-	-	18.70	28.05	49.7
	18	80	329.0	- [e]	-	-	18.27	27.43	50.1
	20	80	336.5	- [e]	-	-	19.16	28.05	46.2

ige Length and Pin-to-Pin Length at; 1600 lb, Rope 1; others, at 1600 lb
i4 mm) (2600 lb (80 mm).
ist measurement at: 330[k] (#2); 200[k] (#9); 200[k] (#11); 200[k] (#15).
ill's eye of top of gage became detached during test.
ie theodolite adjustment was destroyed.
ily Pin-to-pin elongations measured throughtout test.

Conversion Factors

1 kip = 4.45 kN
1 in. = 25.4 mm
1 ft. = 0.305 m

3.2 Load-Deformation Behavior

Load-deformation measurements were taken at discrete load intervals throughout the entire loading range. The deformations were gage length elongations for specimens 1 through 15, and PTP length elongations for specimens 16 through 20. This information is presented as load versus percent elongation plots of the individual ropes in figures 3.1 through 3.6. Replicate plots of a given size rope and specified temperature are shown on the same figure. The average curve of the replicate tests is shown as a solid line. The average percent elongation at 75 percent of specified breaking load is also shown. Other comments specific to these curves follow.

Among specimens 1,3,4,5 (64-mm ropes tested at ambient temperature) the load-deformation plots for specimens 1 and 5 are the only ones available (see footnotes table 3.1). These are in fairly close agreement as seen in figure 3.1. The information for specimen 4 was not meaningful because one of the theodolites went out of adjustment after sighting the initial gage length reading. In the case of specimen 3, the actual gage length is not known because one of the bull's eyes became detached after the initial gage length reading had been taken. After the bull's eye was lost, however, the theodolite kept tracking an identifiable target until rupture. The load-deformation curve for specimen 3 shown in figure 3.1 is developed by assuming an arbitrary initial gage length. It is seen that if the elongations of specimen 3 were reduced by the ratio of percent elongation of specimens 1 and 5 to percent elongation of specimen 3 at breaking load, the load-deformation curve of specimen 3 will not be appreciably different from those of specimens 1 and 5.

The load deformation curves for specimens 2,6,7,8 (80-mm ropes tested at ambient)are in good agreement, with specimen 2 showing slightly greater stiffness than the rest (figure 3.2). The heat-treated specimens of either size (specimens 9-11 and 12-14), also show close agreement in their load-deformation properties (figures 3.3 and 3.4).

Figure 3.6 shows load versus percent PTP length elongation of specimens 17,18,20 (80-mm ropes cooled and tested cold). The temperature of specimen 17 was -83°F (-64°C) at the time it was removed from the cooler. It was tested 40 minutes later. Specimen 18 registered a temperature of -88°F (-67°C) when it was removed from the cooler. At the start of testing 23 minutes later, a thermocouple embedded at the center of the rope registered a temperature of -43°F (-42°C). The temperature was monitored during testing which lasted 10 minutes. The last reading, taken at rupture was 16°F (8°C). The temperature of specimen 20 was -103°F (-75°C) when removed from the cooler. No other temperature readings are available for specimens 17 and 20 because the thermocouples detached during handling of these specimens. According to the diagrams shown in figure 3.6, these temperature differences did not have a significant effect on load-deformation properties.

Figure 3.5 shows the plots for specimens 15, 16, 19 (64-mm ropes tested cold). When first removed from the cooler, specimens 15, 16, and 19 registered temperatures of -70, -74 and -97° (-56, -59 and -72°C), respectively. The temperature of specimen 16 ranged from -5°F to 45°F (-21°C to 7°C) during testing. The temperatures of the other specimens were not monitored. The nearly identical curves for specimens 16 and 19 once again demonstrate the insensitivity of load-deformation properties to initial temperature differences between the replicate specimens. On the other hand, figure 3.5 indicates a major difference between PTP elongations (specimens 16 and 19) and gage elongations (Specimen 15). Most of the differences occurs at 10 percent breaking load at which point the elongation of the gage length is more than twice that of the PTP length. Beyond that load level, however, all the specimens exhibited similar stiffness properties until rupture.

3.3 Failure Modes

Figures 3.7-3.12 show the specimens after failure. Replicate specimens are shown in the same figure and are identified by their numbers. The top ends of the specimens (as installed in the test machine) are shown on the left side. Figure 3.13 is a general view of the testing facility with a specimen ready for testing. The movable work platform is at the center of the figure. Figures 3.14-3.17 show, respectively, specimen 17 being removed from the cooling box, being installed in the clevis, under load, and after rupture.

All the specimens broke suddenly and explosively, releasing fiber debris at the point of rupture. Popping of (intentionally-placed) black yarns within the ropes with increasing frequency provided an indication of approaching failure. In all cases rupture occurred in the rope. In some cases the point of rupture was away from the eyes (nos. 1,4,9,11,19). More frequently, rupture occurred close to or right beyond the eye splice. No ruptures occurred within the eye. Some of the specimens broke completely (nos. 1-4,6,7,9,11,19). In the others, a single or double-twisted strand remained unbroken.

All the specimens exhibited frictional heat damage to varying degrees, as evidenced by the coloring of the yarns from tan to dark brown and by their brittle texture. In specimen 1, smoke was detected near the point of rupture before it occurred. In most cases scorching was confined to the superficial yarns of the strands, which had maximum exposure to frictional heat. Upon rupture, the two segments of rope tended to compress axially towards the respective eyes and then solidify in that state. In some cases (specimens 10 and 15) the eye became tightly compressed around the pin and had to be sawed off to remove it. Several of the tests were videotaped or photographed on a time-lapse film.

4. INTERPRETATION

4.1 Breaking Strength

The specified breaking strengths of the 64- and 80-mm ropes are 158.7 and 242.5 kips, respectively. The actual average breaking strengths (table 3.1) were 198 and 306.2 kips (881 and 1363 kN), respectively, for the specimens tested at ambient temperature (the coefficient of variation was 0.10 for either size based on four tests each). The corresponding figures were 212.2 and 320.7 kips (944 and 1427 kN) for the heat-treated ropes, and 223.8 and 333.7 kips (996 and 1485 kN) for the cooled ropes.

The above information indicates that the specified temperature conditioning of the ropes had no detrimental effect on breaking strength. In fact, the cooled specimens developed around 10 percent greater strength than the untreated ropes. This may be attributed to the decrease of frictional heat degradation due to the lower temperature at the start of the test.

In the case of the heat-treated ropes, strength was exceeded by about 6 percent. The low strength of specimens 4 and 5 could have been caused by the abrasion of some of their yarns observed before testing. If this possibility is taken into consideration, strength differences between heat-treated and untreated ropes becomes statistically insignificant. According to the results in table 3.1, the proximity of the point of rupture to the eye splice (such failures are identified in section 3.3) had no effect on breaking strength.

As noted in section 2, two different loading rates were used in testing specimens 1 through 10. Attention is drawn to specimens 9 through 11 which are replicates. Specimens 9 and 10 were loaded hydraulically to 100 kips (445 kN), then mechanically to rupture. Specimen 11 was tested mechanically all the way. In this instance (table 3.1), the variation in the rate of loading does not show any discernible effect on strength (no unusual scatter compared to the other replicate tests).

In summary, heat treatment had no significant effect on breaking strength while low initial temperature caused the specimens to break at slightly higher load than those tested at ambient. There is some visual indication that superficial damage (such as caused by prior fictional contact with a rough surface), could have an adverse effect on breaking strength. Variation in the rate of loading in the range of 3 to 12 in/min (76 to 305 mm/min) had no significant effect on breaking strength.

4.2 Stiffness Properties

The load-gage length elongation curves shown in figures 3.1 through 3.5 exhibit a common trend. Initially, large deformations occurred under small loads. About two-thirds of the ultimate elongation occurred under 10 percent of the actual breaking load. Most of the stiffness gain occurred between 10 and 30 percent of the breaking load. Beyond that level, the stiffness remained fairly constant to rupture.

The low stiffness under small loads may be attributable to the slack in the "weave" of previously-untensioned plaited rope and possibly, to initial creep effects due to the slow displacement rate used. The consistency in replicate test results suggests that at a certain load level (about 30 percent, in this case) the rope becomes fully taut and develops a "characteristic" stiffness. Since the maximum rate of loading also occurs at this point and beyond, creep effects beyond the 30 percent load range may not be significant. This is reinforced by the absence of kinks in the load-deformation curves in cases where the loading was temporarily stopped to allow the theodolite readings to keep pace with the test.

For certain applications, manufacturers suggest that pleated rope be "stabilized" first by subjecting it to a specified number of load cycles at a given amplitude. This process minimizes hysteretic effects, stiffens the rope and renders its load-deformation response fairly linear. However, partial recovery of the resulting permanent elongation occurs with time.

In a kinetic energy recovery operation, the rope is subjected to three or four tugs. It is then stored, sometimes for months, before the next use. Between the tugs, the rope folds upon itself when the recovery vehicle backs up towards the mired vehicle before the next attempt. Perhaps because both these factors will tend to make a previously tensioned or stabilized rope slack, the present Standard [2] does not call for prior stabilization as a prerequisite for testing.

There is, however, another factor that needs to be considered. According to field tests conducted at the U.S. Army Aberdeen Proving Ground (APG), the duration of the initial pulse load of a tug is typically in the neighborhood of two seconds (one second rise time) [3]. This fast rate of loading is greater by several orders of magnitude than that achieved in the NBS universal testing machine.

In a recent field test of an 80-mm rope from the same source as the NBS specimens, but 70-ft (21-m) long, elongations produced by pulse loads of 120 and 165 kips (534 and 760 kN) were in the order of 10 and 18 percent, respectively. This indicates that the soft portion of the response curves obtained from the NBS tests may not materialize under a pulse-type load.

Because of its short period, it is possible that a pulse load will engage part of the fibers but will not allow full tautness to occur. The resulting stiffness would then be somewhat less than the characteristic stiffness of a fully taut rope obtained from quasi-static tests. If, for instance, a constant stiffness is assumed for the average response curve (figure 3.2) between the data points at 120^k and 240^k (530 and 1070 kN) (this portion of the curve is virtually linear), the corresponding elongations would be 8 and 17 percent, respectively. Therefore, on the basis of this limited information, it appears that the characteristic stiffness obtained from quasi-static load tests provides an upper bound estimate on the stiffness obtained from the pulse-type loads encountered in recovery operations.

The response curves of 64-mm untreated ropes (specimens 1 and 5, fig. 3.1) are not distinguishable from those which were heat-treated first (specimens 9,10 and 11, fig. 3.3). At breaking load, the gage length elongations were likewise in close agreement, while the PTP elongations of the heat-treated ropes were, on the average, 12 percent more than those of the untreated ropes. No specific reason can be given for this last difference, except to note that the gage length elongations for specimens 9 and 11 were obtained at a load slightly less than their breaking strength (footnote b to table 3.1), and also, elongations monitored on a longer portion of the rope (PTP length) tend to provide a better indication of the overall heat effect than those obtained from a much shorter segment of rope (the gage length).

Similar observations can be made on the responses of 80-mm untreated and heat-treated specimens. Differences in the response curves (figs. 3.2 vs fig. 3.4) as well as gage and PTP elongations at breaking load (table 3.1) are slight or insignificant. Note that heat treatment had almost no effect on the characteristic stiffness of either size rope (the slope of the response curve between approx. 30 and 90 percent of actual breaking load).

Because of a change in deformation measurements from gage to PTP length, no direct comparison can be made between the load-deformation responses of untreated and cooled specimens. The results for specimen 15 provide a possible link between the two. Attention is drawn to figure 3.5 where the response curves of the 64-mm cooled ropes are plotted. Beyond a load of about 40 kips (180 kN), the curves are virtually identical in slope. In other words, if the curve of specimen 15 were shifted to the left it would closely match these for specimens 16 and 19, which were developed from PTP elongations. The difference in the response curves below 40 kips (180 kN) suggests the presence of a greater degree of initial slackness in the gage length portion than in the rest of the rope. An indication of this trend is provided by the data in table 3.1 where the PTP elongations of specimens 1 through 14 at breaking load are consistently and significantly lower than the corresponding gage length elongations. Note that the gage length and PTP elongations of specimen 15 at breaking load is consistent with those for the 64-mm untreated ropes while its PTP elongation closely agrees with those of replicate specimens 16 and 19. These observations lend creditability to the test results of specimen 15.

Table 4.1 provides estimates of the stiffness properties in the near-linear range of the response curves. These were calculated by assuming a linear response between data points at 80 and 160 kips (356 and 712 kN) for the 64-mm ropes, and 120 and 240 kips (534 and 1070 kN) for the 80-mm ropes. The load-strain ratio is the slope of this linear portion divided by 100. The (characteristic) stiffness is the load-strain ratio divided by the appropriate gage or PTP length. The listed properties were calculated using average response curves of replicate tests.

The data in table 4.1 yields weighted average load-strain ratios of 956 kips (4254 kN) for the 64-mm ropes, and 1346 kips (5990 kN) for the 80-mm ropes. The changes in load-strain ratios due to heat-treating or cooling the specimens before testing are not significant, in light of the inherent scatter in the test results and the approximation introduced by the assumption of linear response. The trend in the characteristic stiffnesses is the same. Note that since stiffness is inversely proportional to length, a stiffness based on the PTP length will be less than that based on the gage length by the ratio of their lengths. This explains the low stiffness values of the cooled ropes (table 4.1) determined on the basis of the PTP length.

In summary, pleated nylon rope develops a characteristic stiffness within the range of approx. 30 to 90 percent of actual breaking load. This stiffness appears to be an upper bound estimate of the stiffness under a pulse-type load occurring in energy recovery applications. This observation is preliminary and needs further verification by selective field tests. Subjecting the rope to a specified high temperature for a specified length of time before testing at ambient temperature did not alter its mechanical properties under quasi-static tensile loading. Similarly, cooling the specimen to a specified temperature and testing it cold did not have a discernible effect on these properties.

4.3 Synthesis

Several factors will influence the choice of a rope suitable for kinetic energy recovery application. The right combination of

Table 4.1

Stiffness Properties of Pleated Rope in Tension

Size and Temperature Conditioning	Load-strain Ratio kips (kN)	Stiffness k/ft (kN/m)
64 mm Untreated (Specimens 1 and 5)	875 (3894)	341 (463)
64 mm Heat Treated (Specimens 9,10,11)	975 (4338)	387 (525)
64 mm Cooled (Specimen 15)	1126 (5011)	400 (543)
64 mm Cooled (Specimens 16 & 19)	1026 (4343)	56 (72)
80 mm Untreated (specimens 2,6,7,8)	1481 (6590)	571 (775)
80 mm Heat Treated (Specimens 12,13,14)	1319 (5870)	528 (716)
80 mm Cooled (Specimens 17,18,20)	1237 (5505)	66 (90)

size and length of rope will allow the required amount of energy transfer to recover the mired vehicle, while keeping the amplitude of the pulse load within a safe limit to avoid premature rupture of either the rope or its attachments and to inhibit frictional heat degradation.

According to the NBS tests, pleated nylon rope develops a characteristic stiffness in tension under a slow rate of loading. From the limited information available from field tests at APG, it appears that the characteristic stiffness provides an upper bound estimate of the stiffness occurring under a pulse-type loading in a kinetic energy recovery operation. If this observation could be further corroborated by additional field tests, the characteristic stiffness can be used as a criterion in the selection of an appropriate length for a given size rope.

Suppose, for example, the length L of a given size rope is desired. Assuming linear response, the stiffness k of the rope is given by

$$K = \frac{P}{\Delta} = \frac{L_o}{L} k_o \qquad (4.1)$$

where P is the tensile force and Δ is the corresponding elongation in length L. The notation L_o and k_o designate the length and stiffness of a specimen of the same size obtained from tensile tests (for instance, k_o = 571 kips/ft for the 80-mm untreated rope based on the average PTP length of 18.53 ft, tables 3.1 and 4.1).

The strain energy U_s under load P is then,

$$U_s = \frac{P\Delta}{2} = \frac{P^2}{2k} = \frac{P^2}{2k_o} \cdot \frac{L}{L_o} \qquad (4.2)$$

This yields an estimate of the desired length,

$$L = \frac{2k_oL_oU_s}{P^2} \qquad (4.3)$$

Assuming full energy transfer, the strain energy U_s will be equal to the kinetic energy of the recovery vehicle, $U_k = mv^2/2$, where m is the mass and v is the velocity of the vehicle just before it exerts a pulse load on the rope. Load P will be governed by considerations of maximum safe load to avoid failure in the rope or its connections during recovery, and to minimize frictional heat degradation in the material.

The compliance testing requirements of the present Standard can be upgraded in certain areas to reflect the findings of the NBS tests noted above. For instance, the requirement for recording elongations at 75 percent of the specified minimum breaking strength will not yield meaningful results because the large deformations occurring under low static loads in a previously-untensioned rope will distort the results significantly. Since there is partial evidence that such large deformations do not occur under pulse loads, it would be more meaningful to require, instead, deformation measurements to be taken at two distinct load levels, expressed as percentages of specified breaking strength. The selection of the two load levels should be made in such a manner as to yield reliable information on the characteristic stiffness of the rope. For the ropes used in the NBS tests, data points at 40 and 80 percent actual breaking load (or 50 and 100 percent specified breaking load) provided reasonably good estimates of the characteristic stiffness.

The definition of a safe working load depends on the strength of the rope, the strength of the connections and the load-capacity of the rope within which no permanent damage will occur. The NBS tests provide information on the first of these factors. The average breaking strength of the specimens exceeded the specified strength by 25 percent in the case of the untreated ropes of both sizes (section 4.1). The corresponding coefficient of variation was around 10 percent. Therefore, the specified strength appears to be reasonably conservative. In addition, the eyes of the test specimens had sufficient strength to develop the strength of the rope. However, it is not known whether this will also be true if a different pin size were used.

The Standard should stipulate that the connections should be strong enough to develop the strength of the rope. This will require verification through independent testing of the connections. The last factor, the maximum load that can be applied to the rope without causing material degradation, can be addressed by extending the scope of testing to include cyclic loading followed by loading to rupture. In such investigations the principal test variables would be the amplitude of the cycled load, the number of cycles, and possibly, the time interval at zero load between consecutive cycles.

5. SUMMARY AND CONCLUSIONS

Pleated nylon ropes of two sizes and approximately the same length were tested in tension to failure in a universal testing machine. Some of the ropes were tested at the ambient temperature of the laboratory. To study high and low temperature effects, the remaining specimens were subjected to a specified temperature for a specified number of days and tested at the ambient temperature, or, they were cooled to a specified temperature and tested cold.

The tests and pre-conditioning for temperature effects were carried out in accordance with the U.S. Army testing specifications for synthetic rope. The Army intends to use the ropes to recover mired military vehicles provided certain conditions are met. The NBS tests were part of a broader program, currently being implemented by the Army, to determine the suitability of pleated synthetic rope for recovery applications. This report documents and interprets the NBS test results in the light of this intended use. Included are data on breaking strength, corresponding elongations, and load-deformation properties. The following conclusions are drawn based on the observed behavior of the ropes in tension.

The mean breaking strength of the untreated specimens exceeded the specified strength by 25 percent. The coefficient of variation was 0.10 based on four replicate tests of each size.

The mean breaking strengths of heat-treated and cooled specimens were about 6 and 9 percent above the mean breaking strength of untreated rope, respectively. The coefficient of variation based on triplicate tests varied from 0.03 to 0.09, depending on size and type of treatment. The slightly higher strengths compared to untreated rope cannot be given much significance because of small sample size. However, it is reasonably safe to assume that the specified temperature treatment will have no detrimental effect on strength.

Similarly, the prescribed high and low temperature treatments had no significant effect on the load-deformation properties of the specimens. It is therefore concluded that simulated vehicle recovery tests in the field need not be concerned with ambient temperature fluctuations, specially since it is very unlikely that the extreme temperatures used in the tests will be encountered in the field.

All the specimens exhibited consistent load-deformation properties. In specimens where gage length elongations were measured, about two-thirds of the ultimate elongation occurred within 10 percent of breaking load. Between 10 and 30 percent of breaking load, the specimens developed full stiffness which remained nearly constant up to breaking load. In specimens where pin-to-pin (PTP) length elongations were measured, about one-third of the ultimate elongation occurred under 10 percent of breaking load. Otherwise, the response was nearly identical to those based on gage length elongations. The difference is attributed to differences in the initial slackness of the rope as a whole, versus that present in the gage portion of the rope.

According to the test results, a given size rope will develop a characteristic stiffness when tensioned at a low displacement rate (compared to the high flexibility of the specimen) typical of a universal testing machine. Good agreement between the characteristic stiffnesses obtained from gage and PTP elongation measurements of replicate specimens provides a degree of confidence that this is a dependable or "stable" property.

On the basis of limited field tests by the U.S. Army, there is some evidence that the characteristic stiffness provides an upper bound estimate on the stiffness that develops under a pulse-type load occurring in mired vehicle recovery operations. Subject to further verification through additional field tests, the characteristic stiffness could be used as a key parameter in the selection of an appropriate size and length of rope for use in recovery applications.

The tests show that elongation measurements at 75 percent of and at breaking load currently required by the Army specifications are distorted considerably due to the initial slack existing in a previously-untensioned rope. It would be more useful to take elongation measurements within the stable portion of load-elongation curves for the purpose of determining the characteristic stiffness. According to the test results, elongation measurements at 40 and 80 percent of actual breaking load (or 50 and 100 percent of specified breaking load) should yield reasonably accurate estimates of the characteristic stiffness.

6. RECOMMENDATIONS

The tensile tests of pleated nylon rope provided a ceratin amount of basic information on strength and stiffness properties which will be useful in upgrading current specifications and in developing the scope of supplementary tests. The following are suggested areas of research.

Selective field tests should be carried out to increase the data base on stiffness properties of rope under pulse-type loads. The results can be used to better correlate the stiffness obtained by static load tests with that expected to occur in recovery operations.

One question not addressed by this study is the maximum load the rope can be tensioned to without causing strength degradation. This can be achieved by cyclic tests followed by loading to rupture. The test variables would be the number of cycles and the amplitude of load. Another useful product of these tests would be the stabilization of the ropes as a result of cyclic loading. The stiffness of stabilized rope can then be compared and correlated with the characteristic stiffness obtained from static load test.

Frictional damage to surface fibers, debris penetration, and high moisture content are probable occurrences in the field. The effect of these factors on strength, stiffness and energy-absorption properties of pleated synthetic rope should be studied through controlled environment tests, or field tests, or preferably both. These investigations will provide information which can be used to develop criteria for rejection or replacement.

7. ACKNOWLEDGEMENTS

The assistance of the following persons or group is acknowledged. R. Sanders and K. North of the U.S. Army supplied information on the product and field test data, N. J. Carino developed the computer plots in this report, several CBT technicians provided assistance in conducting the tests.

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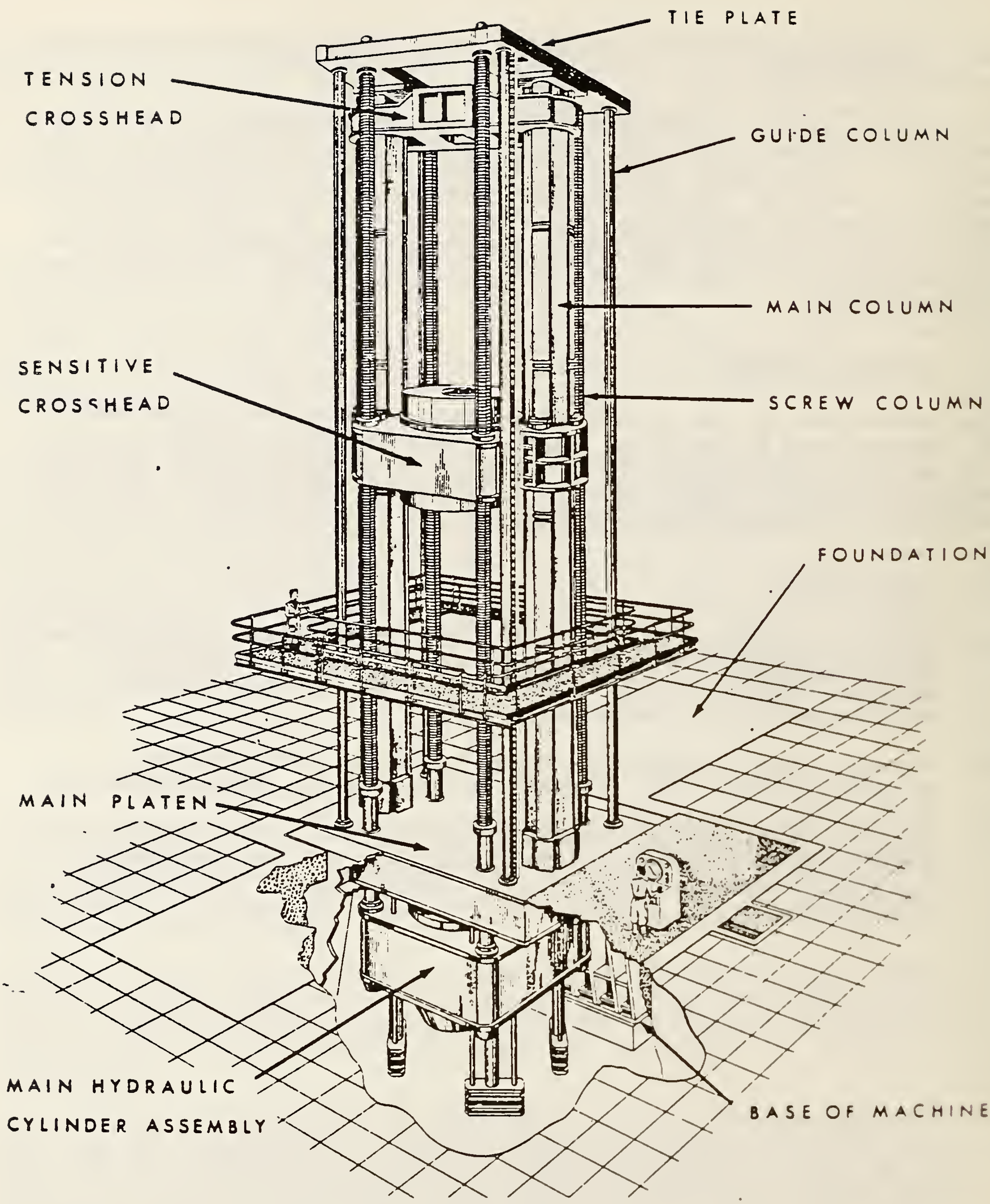

Figure 2.1 Drawing of 12,000,000 lbf capacity universal testing machine

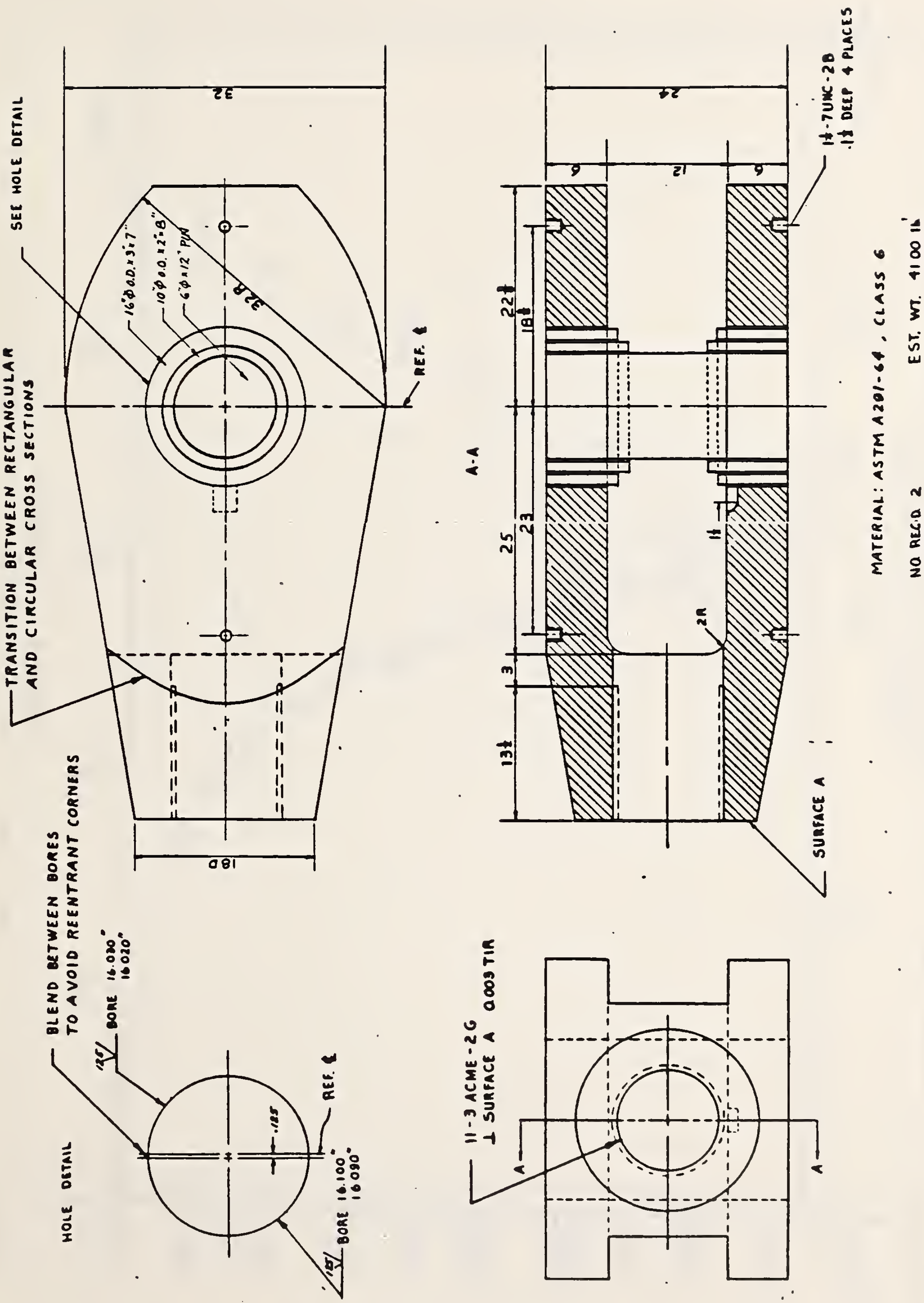

Figure 2.2 Special fixtures for attachment of rope to built-in clevises.

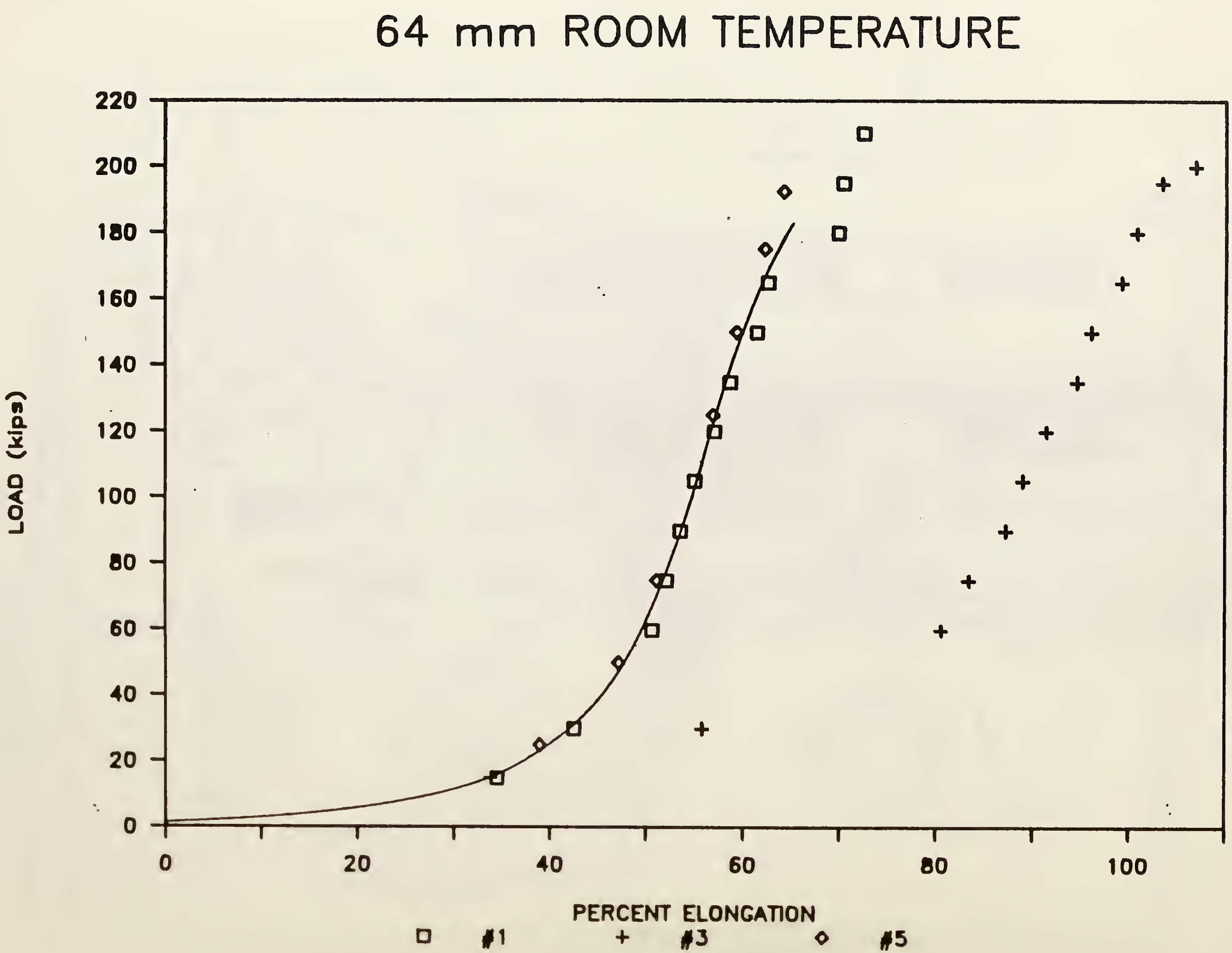

Figure 3.1 Load-deformation curves of specimens 1, 3, and 5.

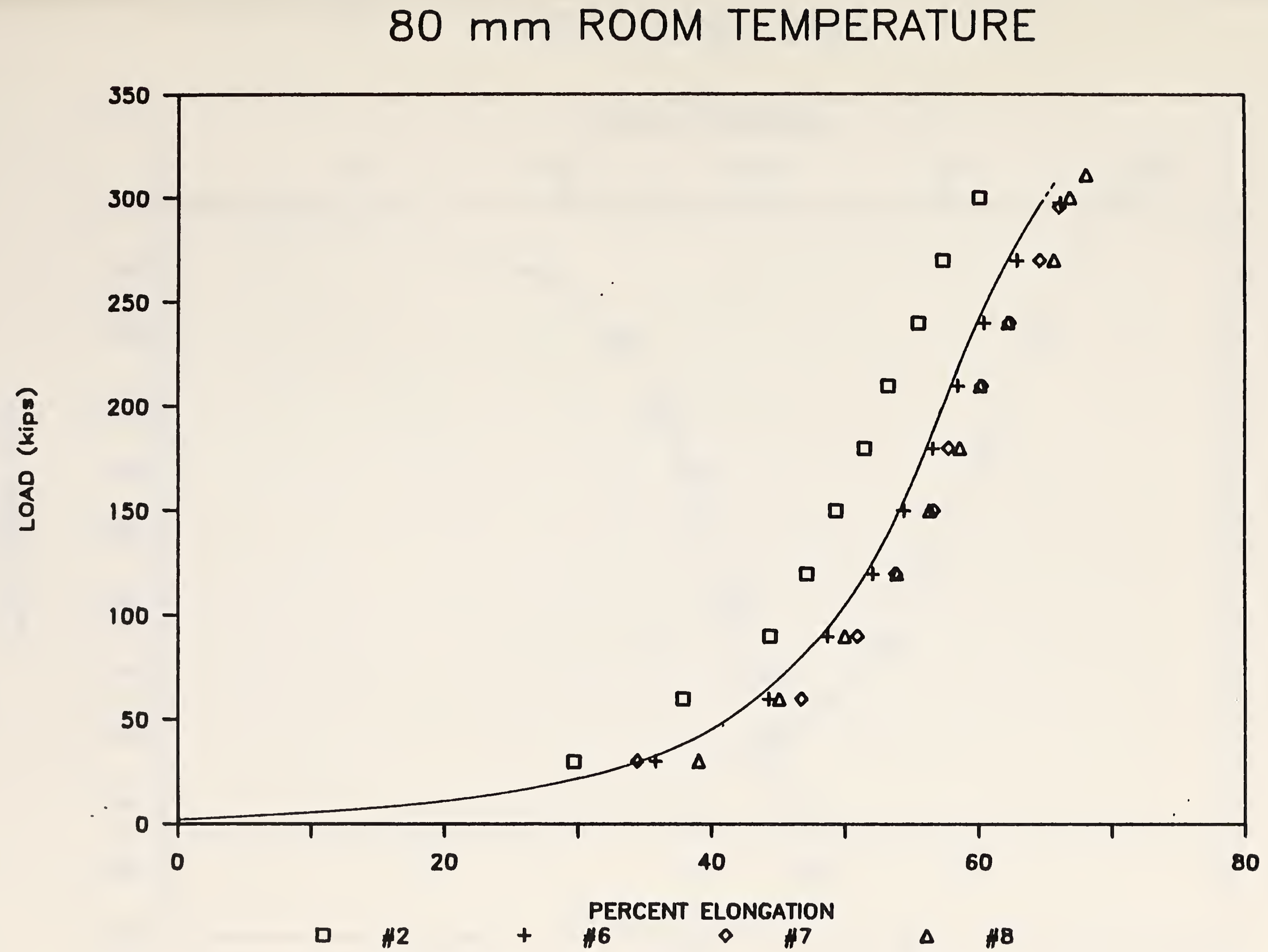

Figure 3.2 Load-deformation curves of specimens 2, 6, 7, and 8.

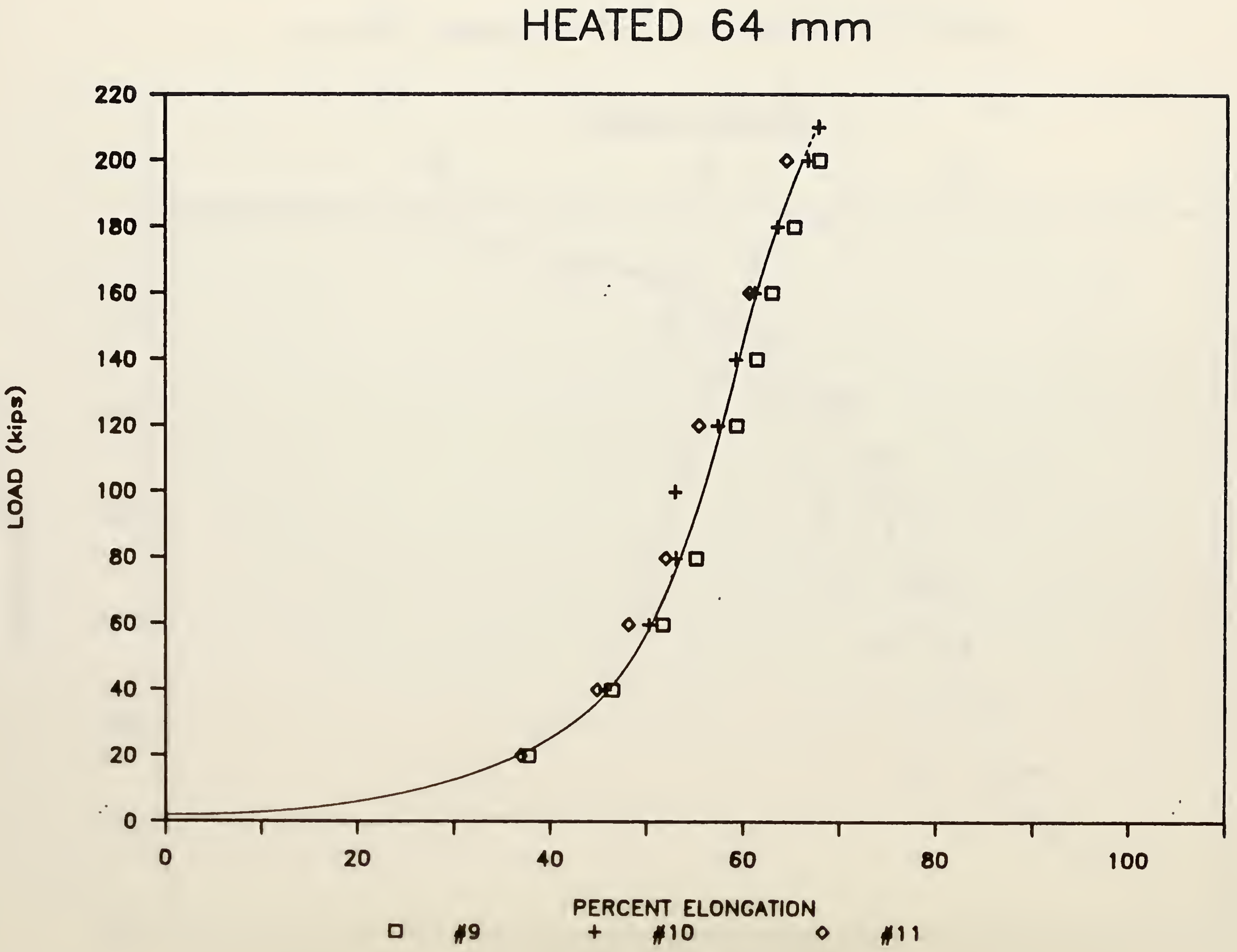

Figure 3.3 Load-deformation curves of specimens 9, 10, and 11.

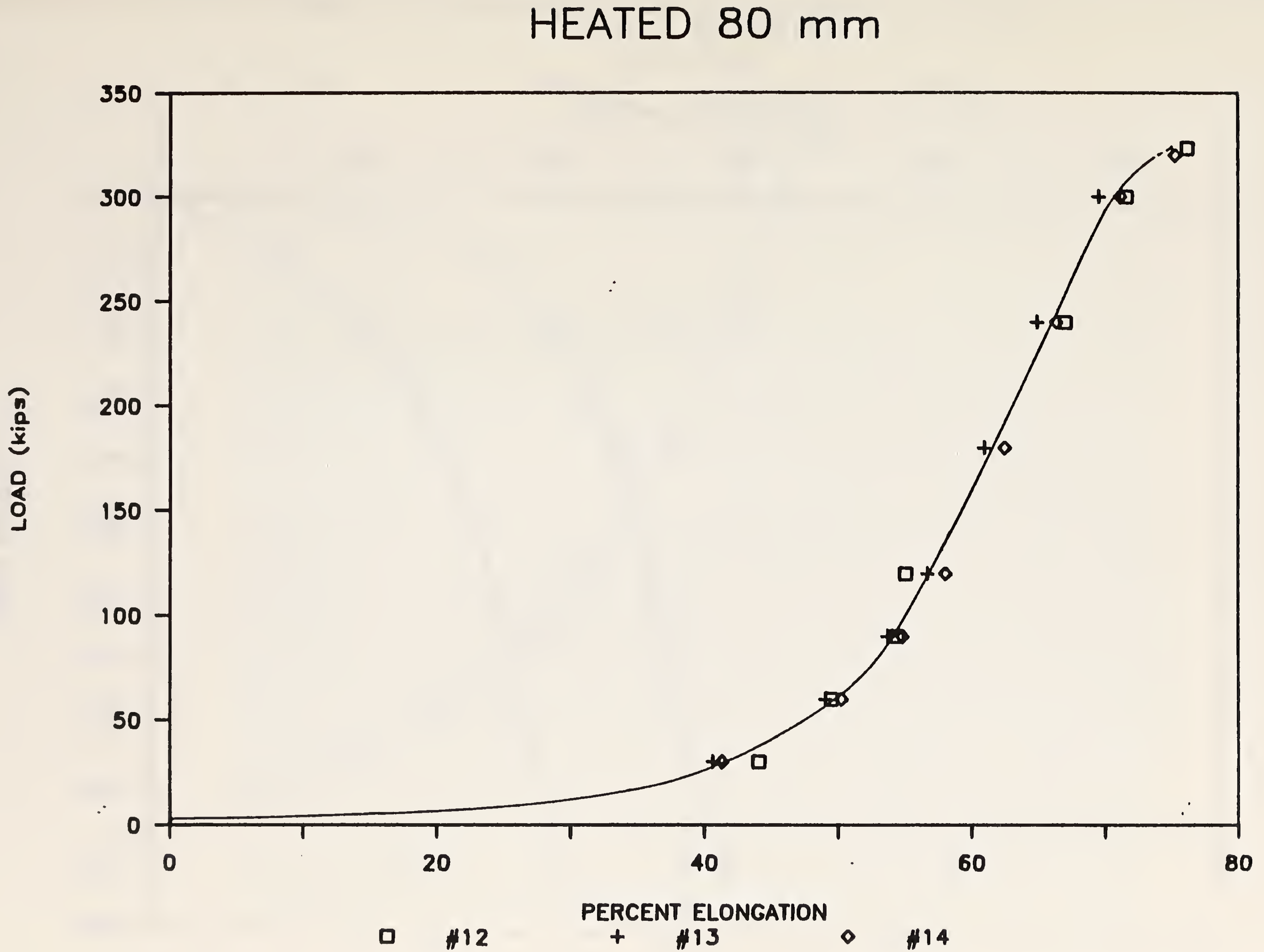

Figure 3.4 Load-deformation curves of specimens 12, 13, and 14.

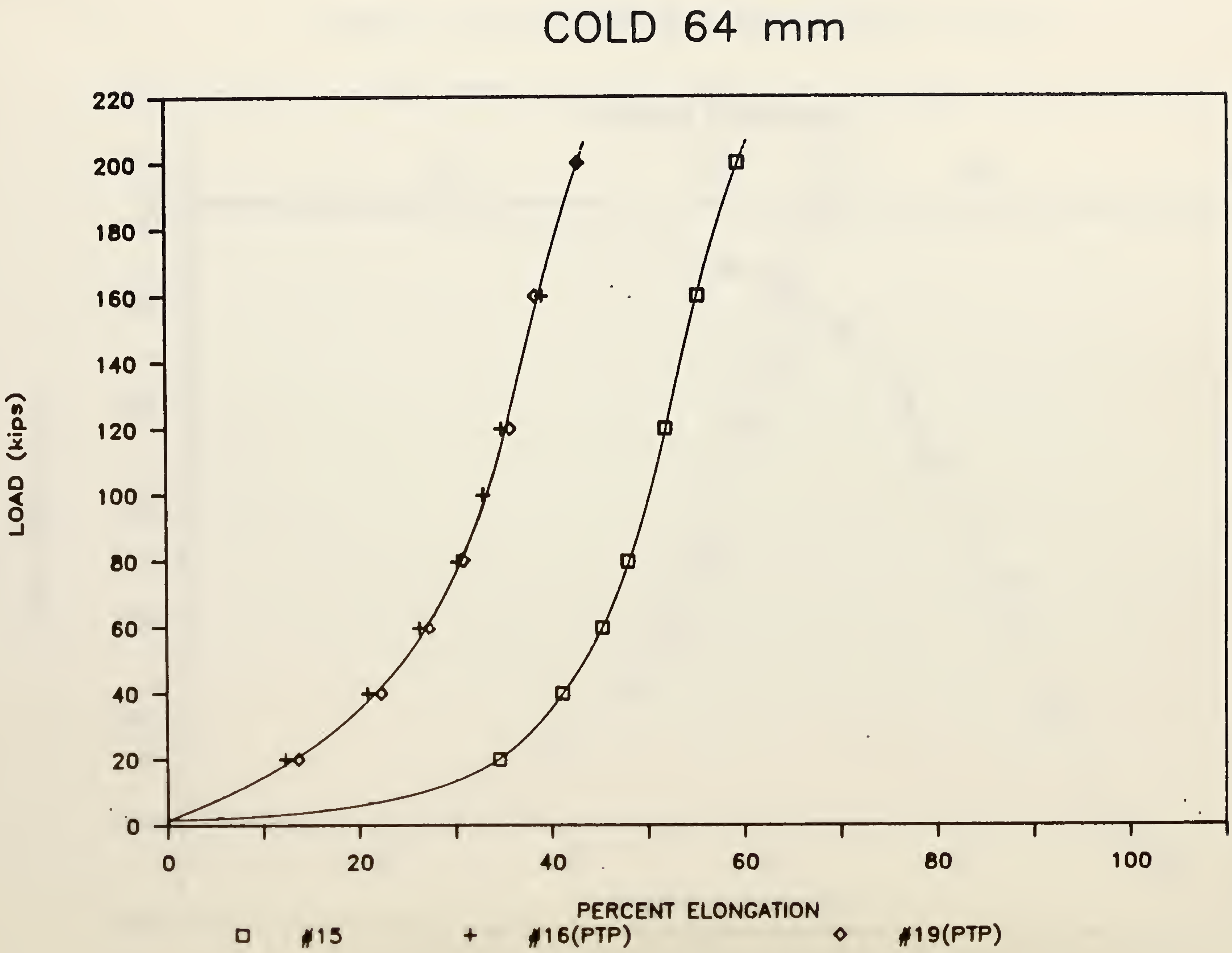

Figure 3.5 Load-deformation curves of specimens 15, 16, and 19.

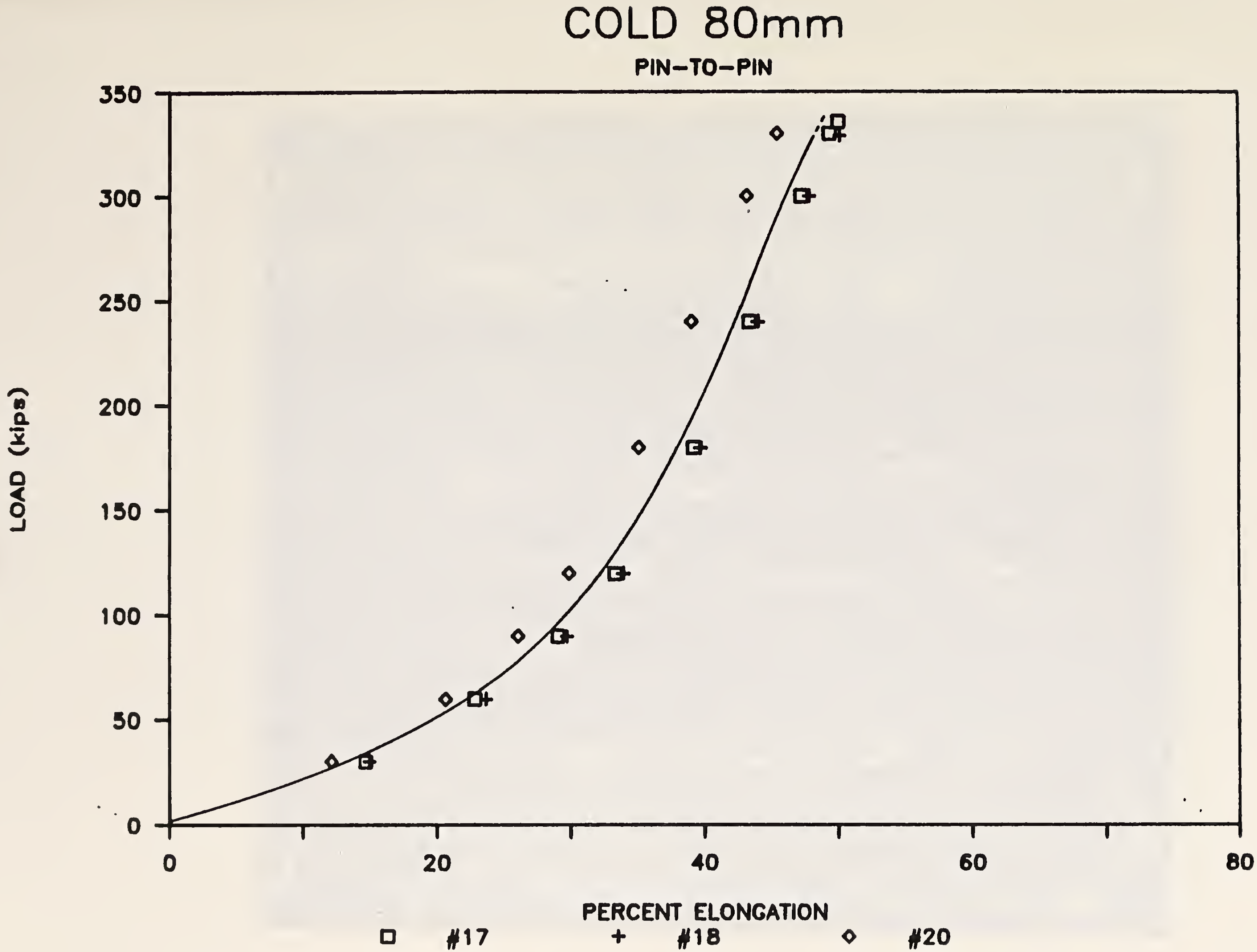

Figure 3.6 Load-deformation curves of specimens 17, 18, and 20.

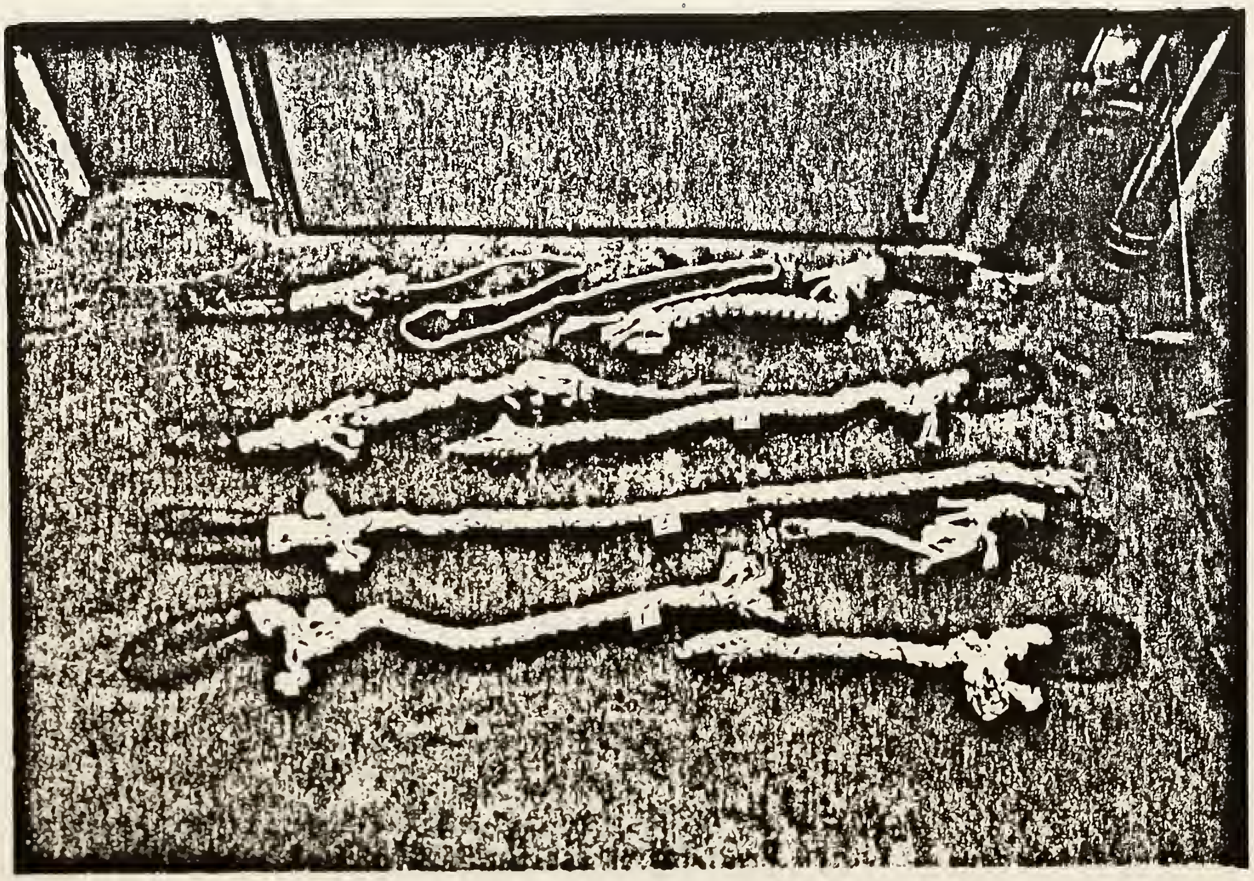

Figure 3.7 Failure of 64-mm untreated ropes.

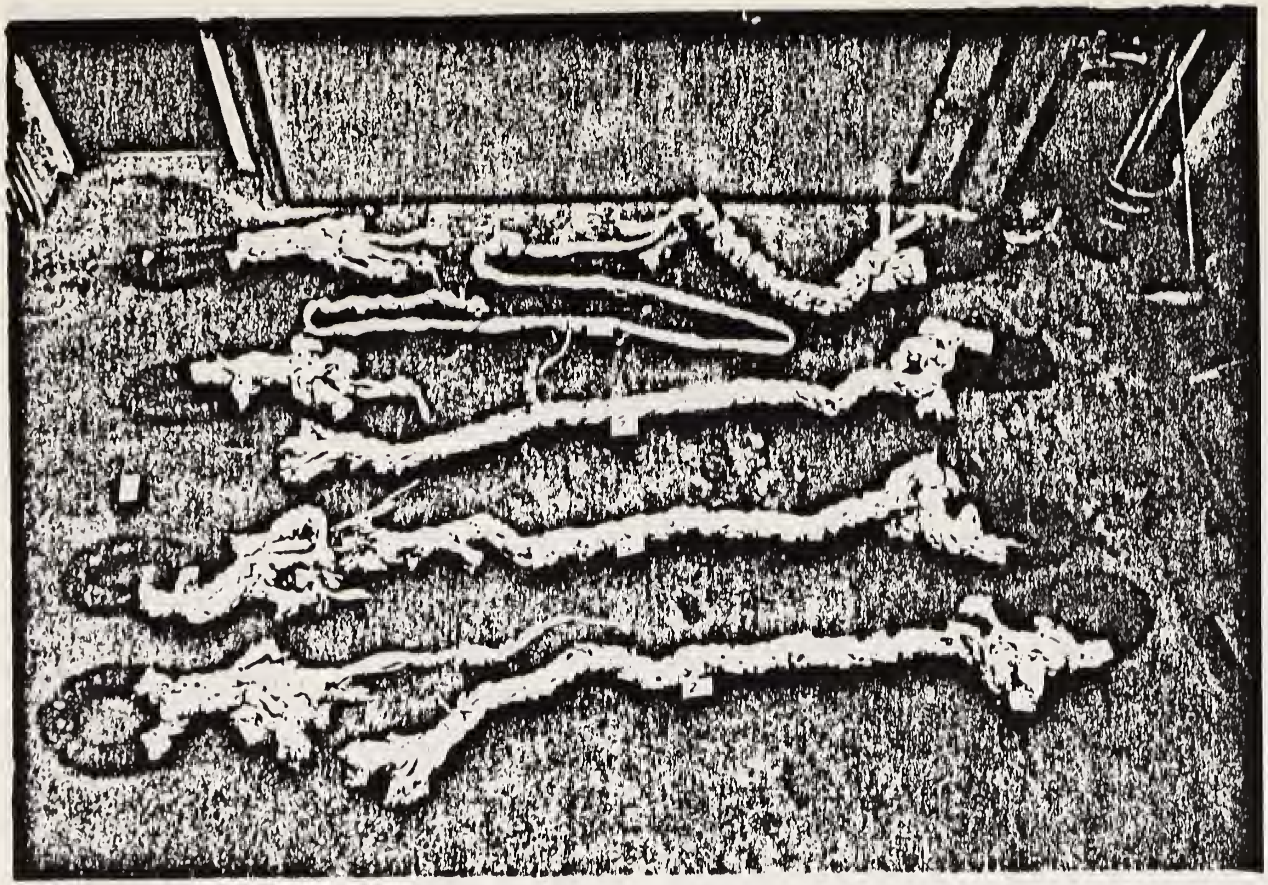

Figure 3.8 Failure of 80-mm untreated ropes.

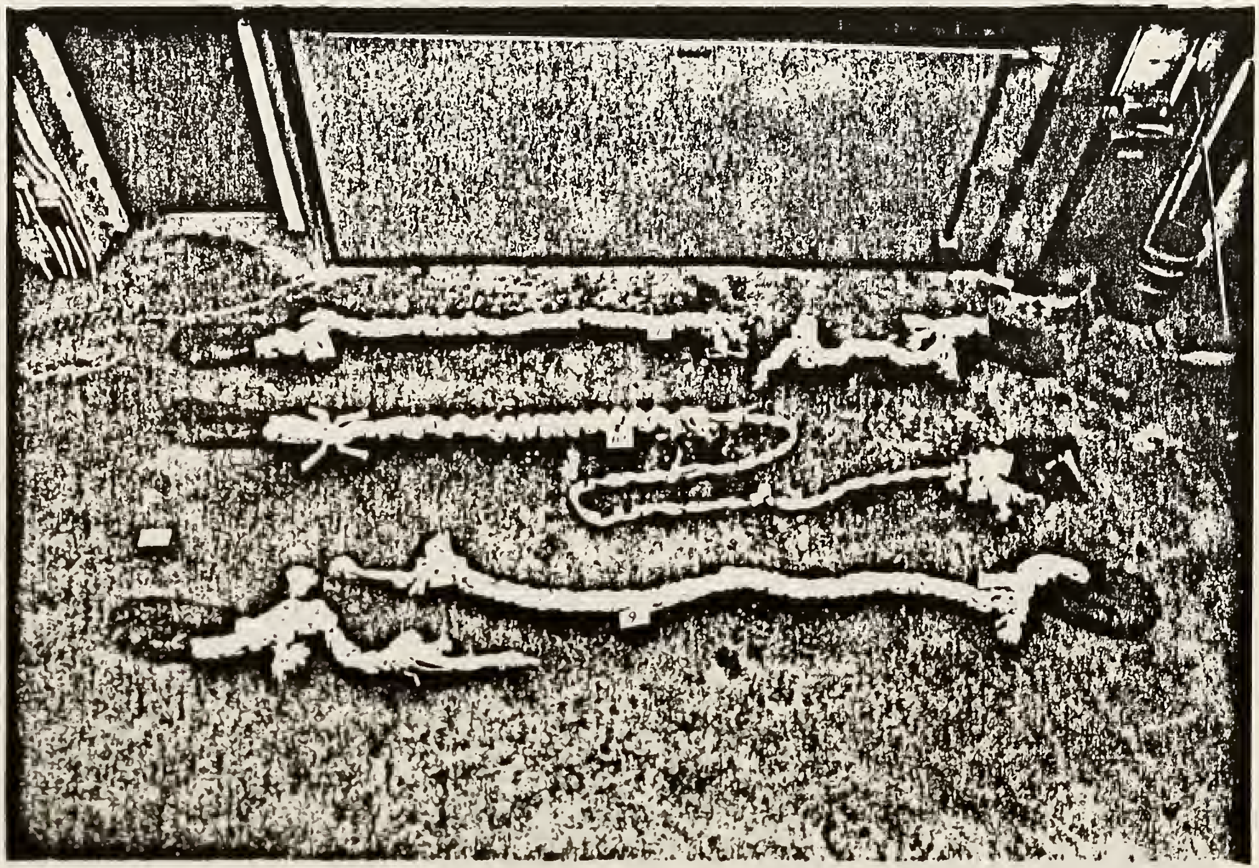

Figure 3.9 Failure of 64-mm heat-treated ropes.

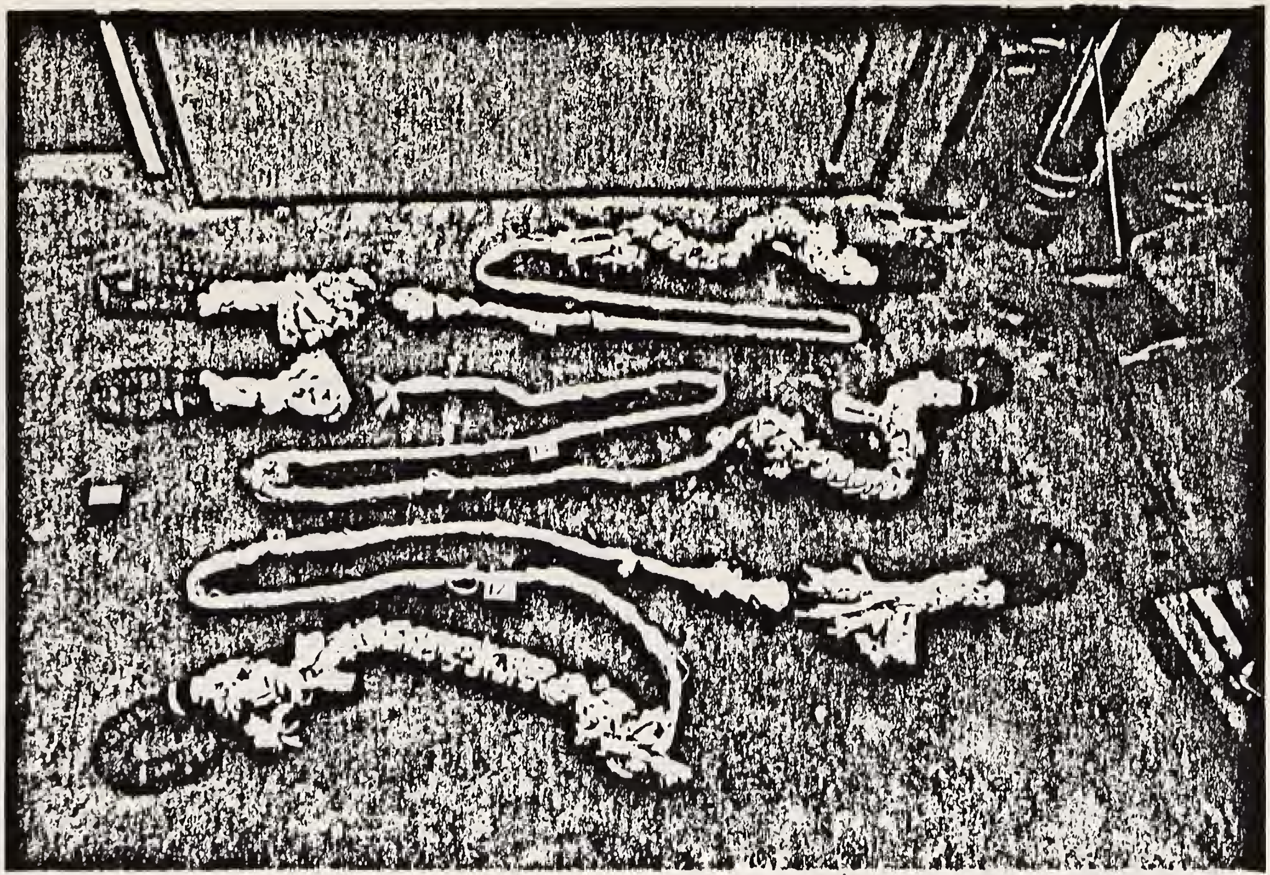

Figure 3.10 Failure of 80-mm heat-treated ropes.

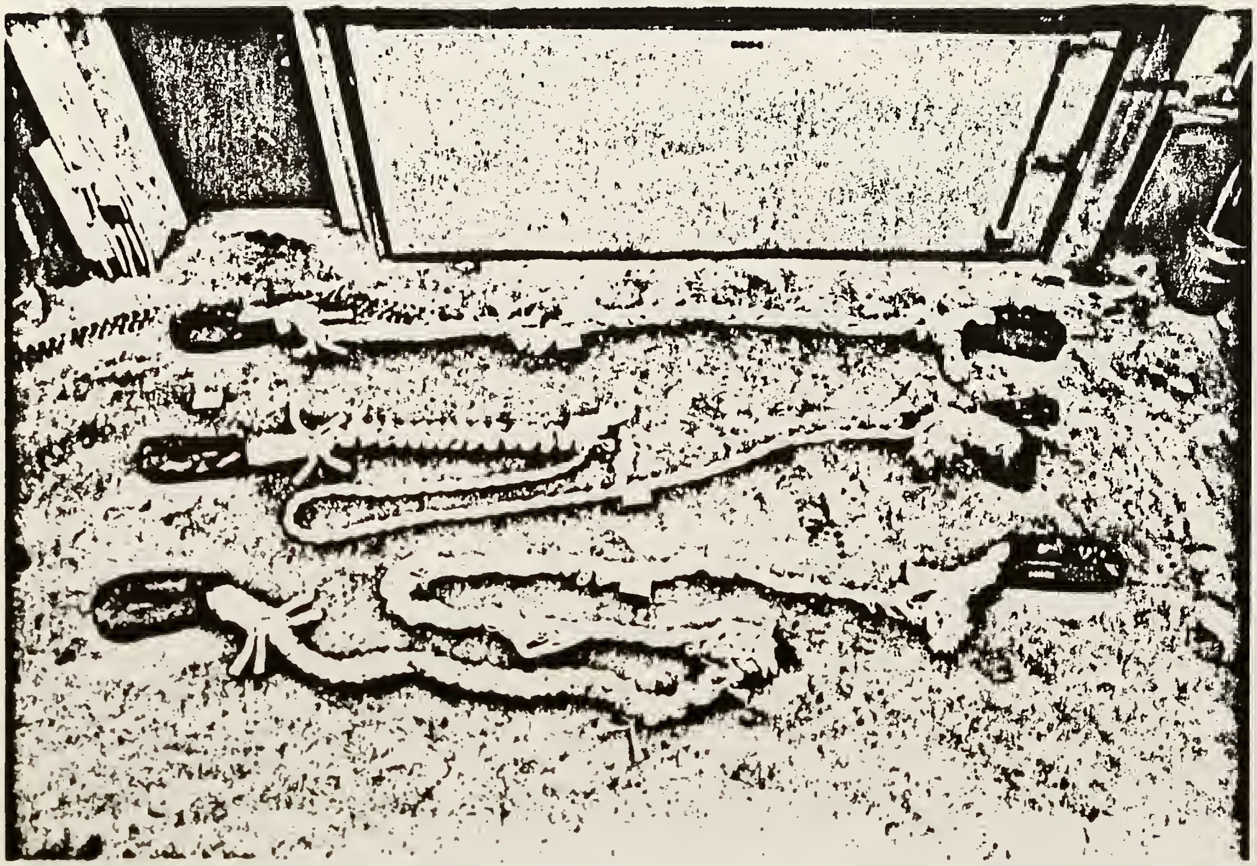

Figure 3.11 Failure of 64-mm cooled ropes.

Figure 3.12 Failure of 80-mm cooled ropes.

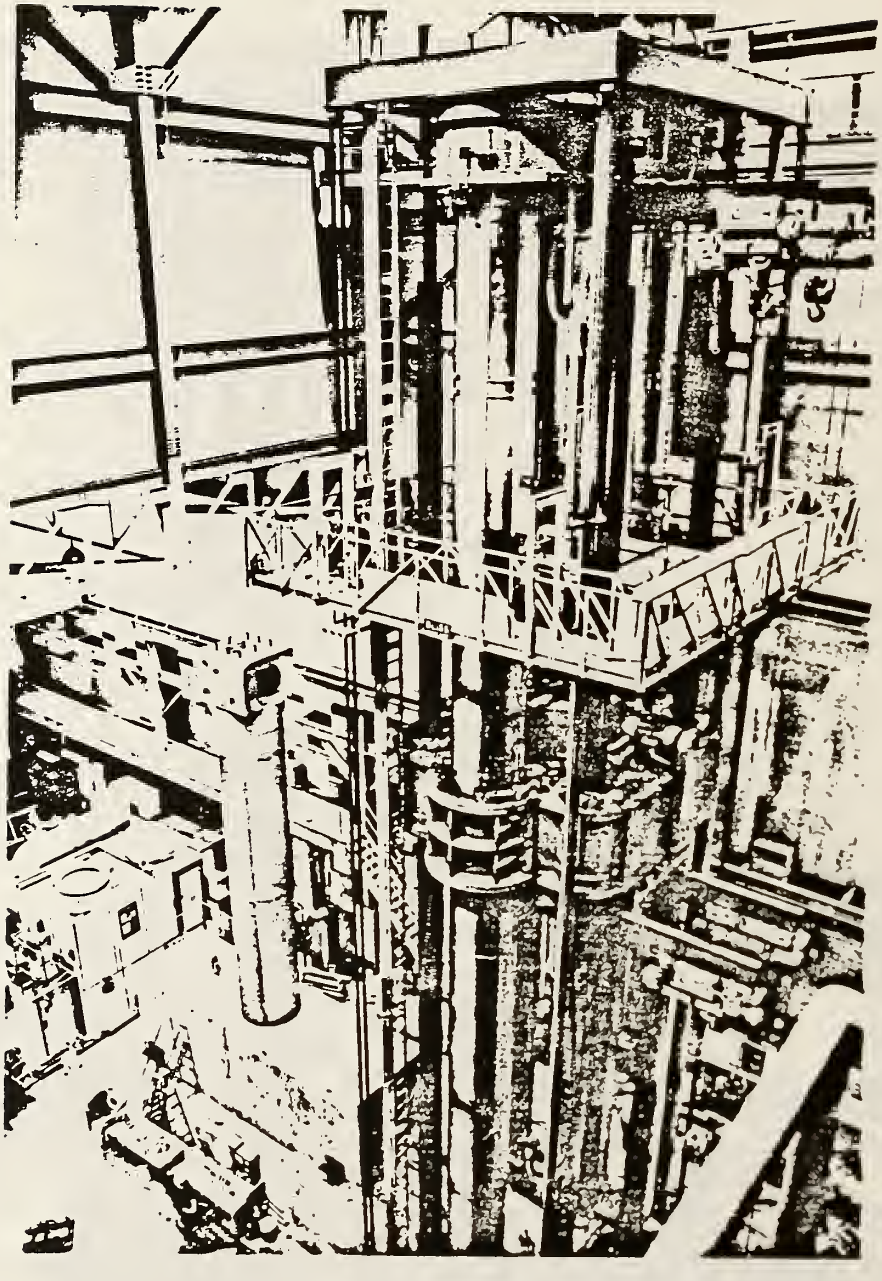

Figure 3.13 General view of 12M lbf universal testing facility.

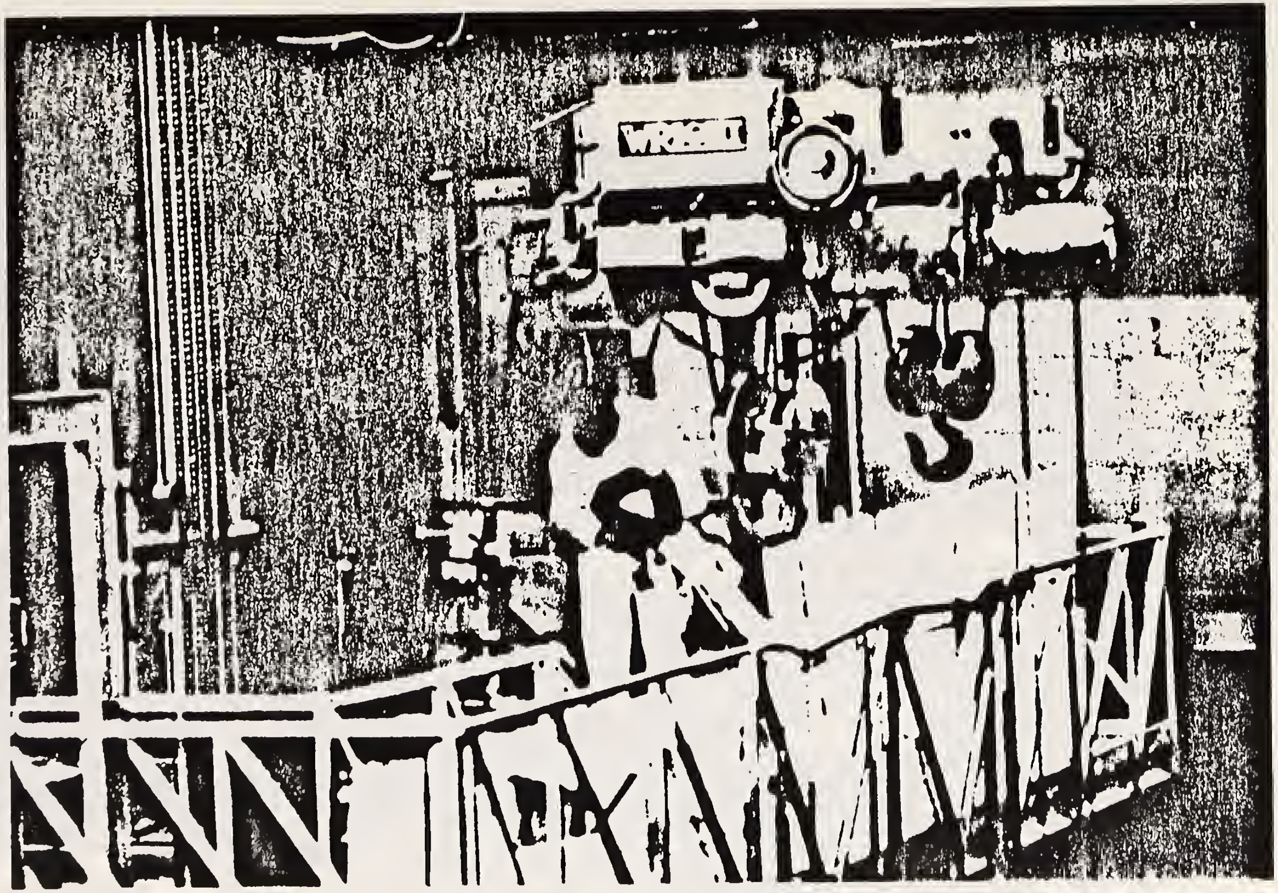

Figure 3.14 Specimen #17 being removed from cooling box.

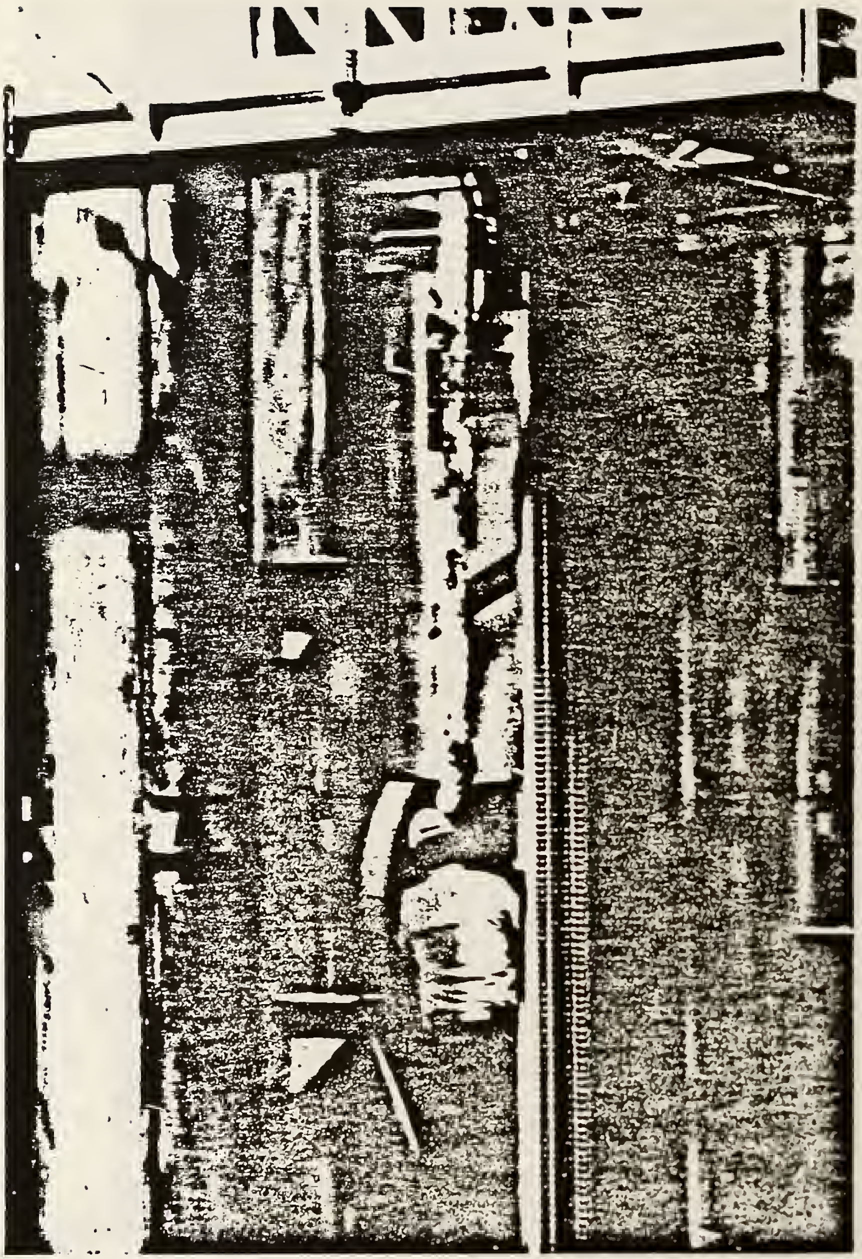

Figure 3.15 Specimen #17 being installed in the lower clevis.

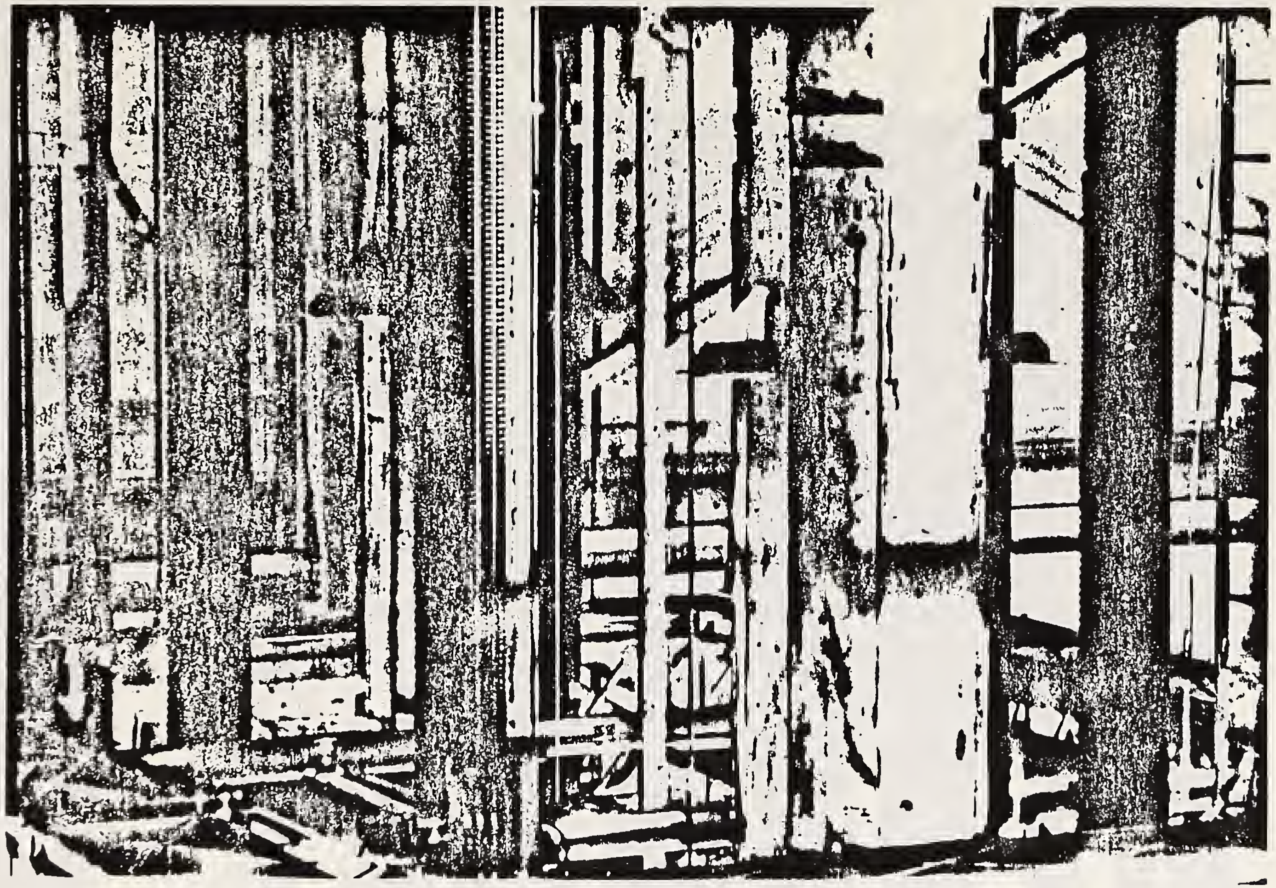

Figure 3.16 Specimen #17 under load.

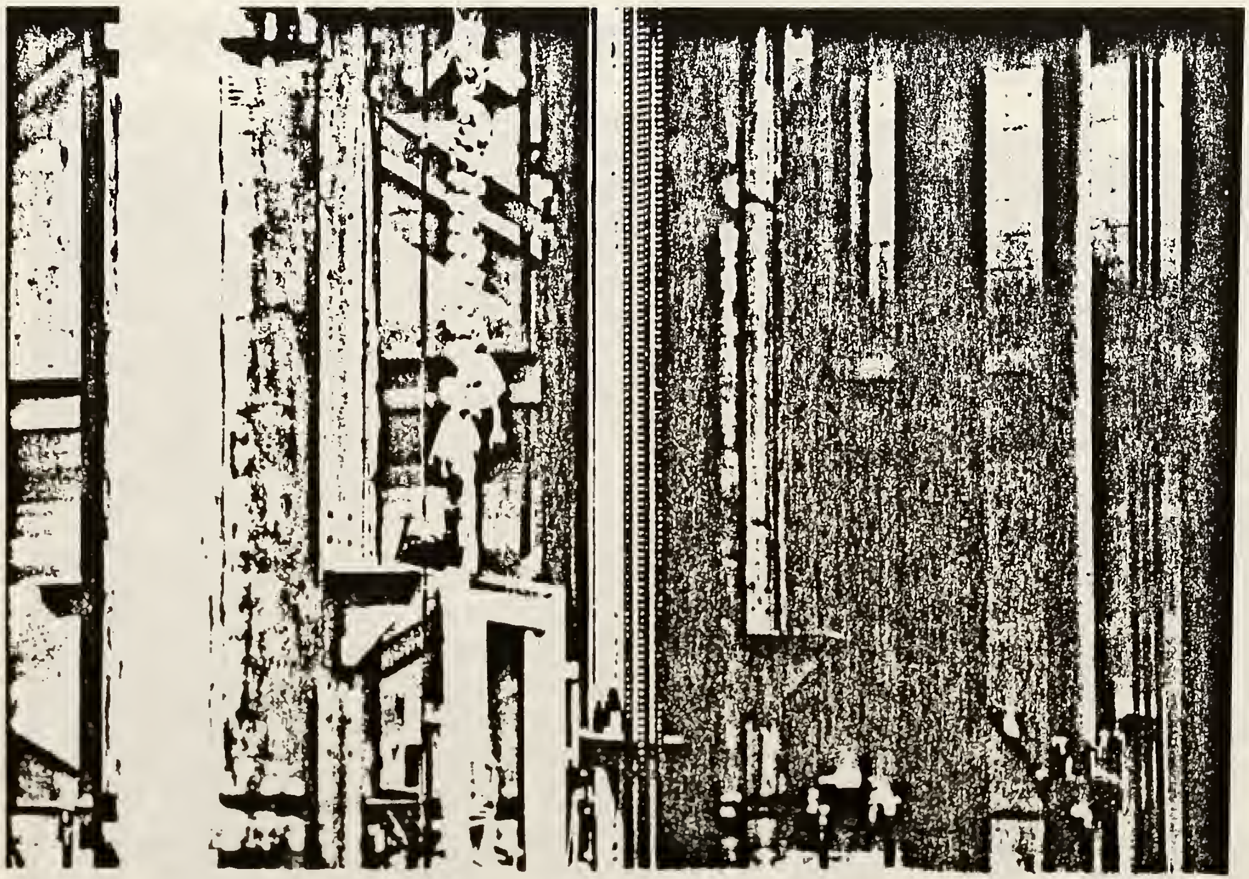

Figure 3.17 Specimen #17 after rupture.

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Pleated nylon ropes of two sizes and approximately the same length were tensioned to rupture in a universal testing machine. Several of the ropes were tested at room temperature. The others were subjected to specified high and low temperatures before testing. Deformation measurements of all the specimens were recorded while testing was in progress. The results were used to evaluate the breaking strength, ultimate elongation, and load-deformation properties, and to develop criteria for possible application in the recovery of mired vehicles.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

breaking strength; load-deformation; nylon rope; pleated rope; pulse loads; specified strength; stiffness; synthesis; ultimate elongation

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