THE EFFECT OF ROPE DAMAGE ON THE STRESS WAVE FACTOR

by

John Hainsworth

Submitted in Partial Fulfillment

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ABSTRACT

This study demonstrates that the stress wave factor (SWF) test can be used in some cases to nondestructively evaluate ropes that have been damaged in any one known characteristic way. Two phase dry 62 mm (1/4 in) diameter nylon rope was SWF tested under tensions ranging from 220 to 4400 N (2 to 40% of the rope tensile strength). Ropes were artificially damaged by cutting the cover or core, and the SWF of each type of damaged rope was compared to that of an undamaged rope at various tension levels. The SWF responded differently to different types of damage; in fact at some tension levels it increased in response to one type of rope damage and decreased in response to another. The SWF was correlated with each type of damage at at least one of the rope tension levels used, yet no tension level was found at which the SWF test was capable of distinguishing all types of rope damage considered.

Thesis Supervisor: Dr. James H. Williams, Jr.

Professor of Mechanical Engineering

ACKNOWLEDGEMENT

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I. INTRODUCTION

The breaking of a rope or cable is one of the most dangerous and unpredictable of mechanical failures. A rope or cable generally has a much lower elastic modulus than other mechanical parts, and thus stores much more elastic energy than other parts under a given operating load. Ropes generally may not show significant signs of damage, even when severely weakened. In particular, many environmental factors (water, salt, etc.) may significantly weaken most organic fiber ropes, yet these effects are often invisible to the naked eye. Ropes can also fatigue under cyclic loads, or degrade by tensile pullout (creep) even under steady loads. Again, this degradation is not readily apparent.

For these reasons there has been interest recently in studying rope failure in the hope of developing nondestructive tests for rope integrity. Destructive rope tests (the current state of the art) are relatively straightforward, but of limited usefulness. Specifically, the quality of one piece of rope does not guarantee the quality of a similar piece of rope, or even the quality of the next piece of rope on the spool: it only increases the probability that the other rope will be good. Determining the condition (and thus safety) of a piece of rope by probabilistic testing is clearly unacceptable.

The most promising nondestructive techniques for rope are the acoustic emission and ultrasonic techniques presently being used to test metals and composite materials. The feasibility of the acoustic emission technique for ropes has been is clearly demonstrated by Williams and Lee (Ref. [1]). Other work on acoustic emission in ropes is contained in References [2,3,4,5,6]. An ultrasonic test that appears to be applicable to ropes is the stress wave factor test (Ref. [7,8]). The stress wave factor (SWF) is a rough measure of the conductivity of a medium to stress waves. The strengths of metals and fiber-resin composites have been correlated using the SWF test (Ref. [7]). The purpose of this study is to demonstrate that the SWF test can be also be used to estimate the residual strength of ropes.

Metals and composite materials can be SWF tested easily in the field: a rope, however, must be put under axial tension before it will conduct waves to any significant extent. The SWF of a rope varies both with the condition of the rope and with the tension under which the rope is being tested.

II. STRESS WAVE FACTOR TESTING

A. Architecture of the AET 206 AU SWF Measurement Instrument

The AET 206-AU is a stress wave factor measurement system marketed by Acoustic Emission Technology, Inc. (AET). The primary instrument contains two independent modules: an electronic pulse generator and an acoustic emission (AE) receiver. The receiver automatically computes and digitally displays the stress wave factor. For actual testing the pulse generator is wired to a transducer which transmits a stress pulse into the sample, and a sensor receives the transmitted stress pulse and sends it through a 40 dB preamplifier to the AE signal processor module. Fig. 1 illustrates this system.

The pulse generator produces electronic pulses with durations of approximately 10 microseconds and magnitudes of 250, 150, or 50 volts, depending on the energy level setting.

The transmitting transducer (AET model FC-500) is a piezoelectric element enclosed in a steel case. The transducer has a tapered waveguide which decreases the contact area with the specimen.

The receiving transducer (AET model AC-375) is similar in design to the transmitter, but is slightly smaller and has a different connector. The receiving transducer is of a

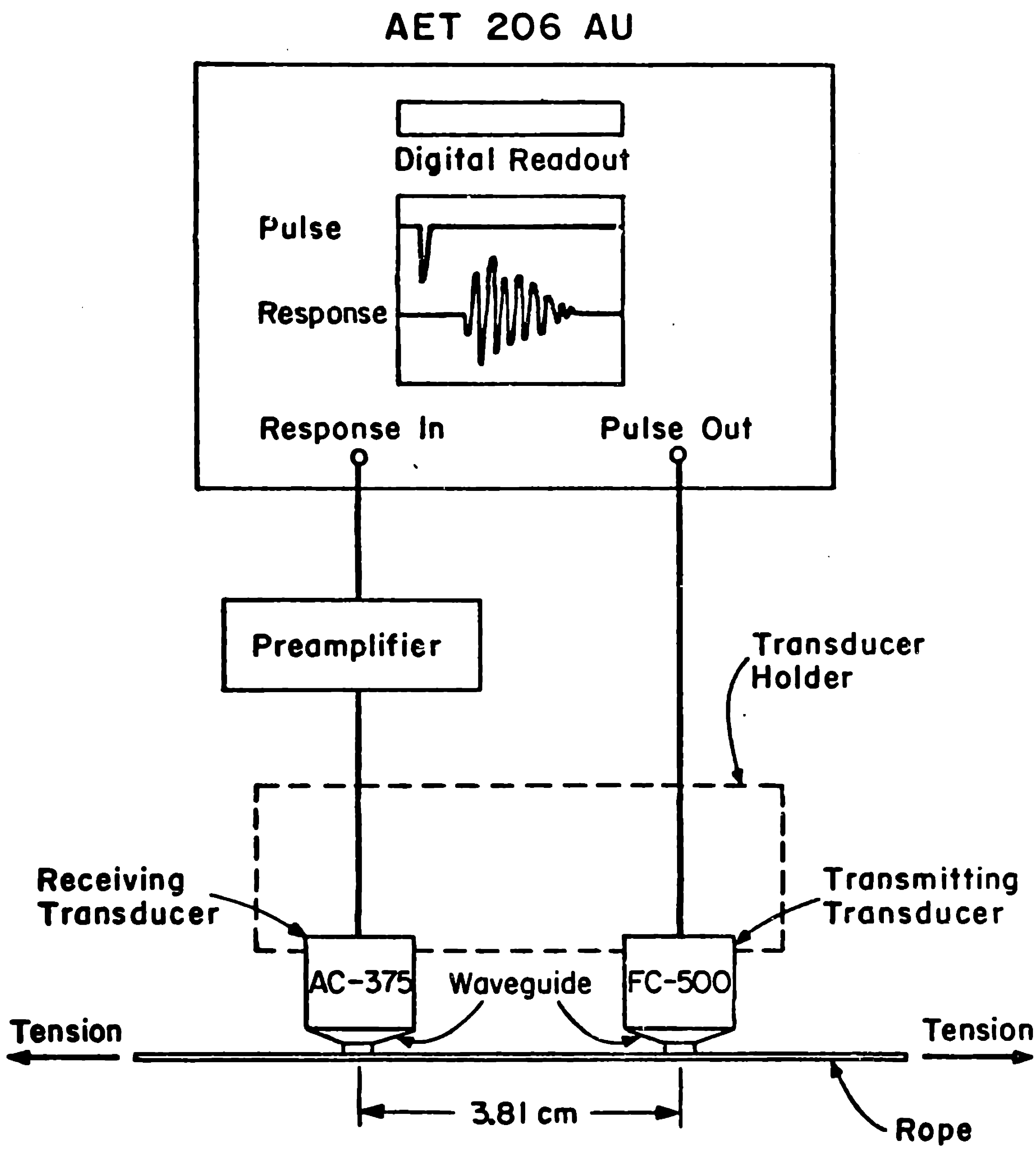


Fig. 1 AET 206 AU system for stress wave factor measurements.

resonant type: its impulse response is a slowly decaying sinusoid with an estimated damping ratio of 0.1 and natural frequency of 375 KHz.

The preamp amplifies the signal by 40 dB and the acoustic emission receiving unit amplifies the signal by an additional 0-60 dB and computes the SWF.

B. Computation of the Stress Wave Factor

The SWF is computed by counting the number of times (ringdown counts) that the received signal level crosses a certain threshold amplitude, and accumulating this count for a specified number of stress pulse inputs (events). In this study the SWF was accumulated over a period of one second for an input pulse train that excited the transmitter at 1000 pulses/sec. The threshold voltage level and the gate width (the duration of the period over which threshold crossings are counted) are adjustable on the AE receiving unit. The gate width is always left at its maximum setting. The threshold level is set to be just above the internal noise level of the instrument.

III. EXPERIMENTAL PROCEDURE

A. Special Fixtures and Facilities

In order to maintain a consistent and repeatable interface between the sample being tested and the transmitting and sensing transducers, AET has developed a fixture (model 206 FIX) for composite material testing that holds the transducers 3.81 cm apart and contains springs that press them into the rope. The springs exert approximately 25 N of force each when fully compressed. To insure consistent compression on these springs, and thus a consistent contact force on the rope, the author attached hose clamps to the fixture to act as adjustable rope positioners.

The rope can be held under tension in a standard tensile test machine, but the rope fixtures should be of a capstan jaw type: the rope must be wound around something before being clamped, or it will always break at the clamping point rather than at the test section. Fig. 2 shows a schematic of the 10.2 cm capstan jaw used for pulling rope samples in these experiments.

All of the tests in this study used the AET 206 AU SWF test instrument, described earlier in this report. The instrument control settings used in this study are listed in Table 1.

The viscous coupling fluids commonly used for SWF test-

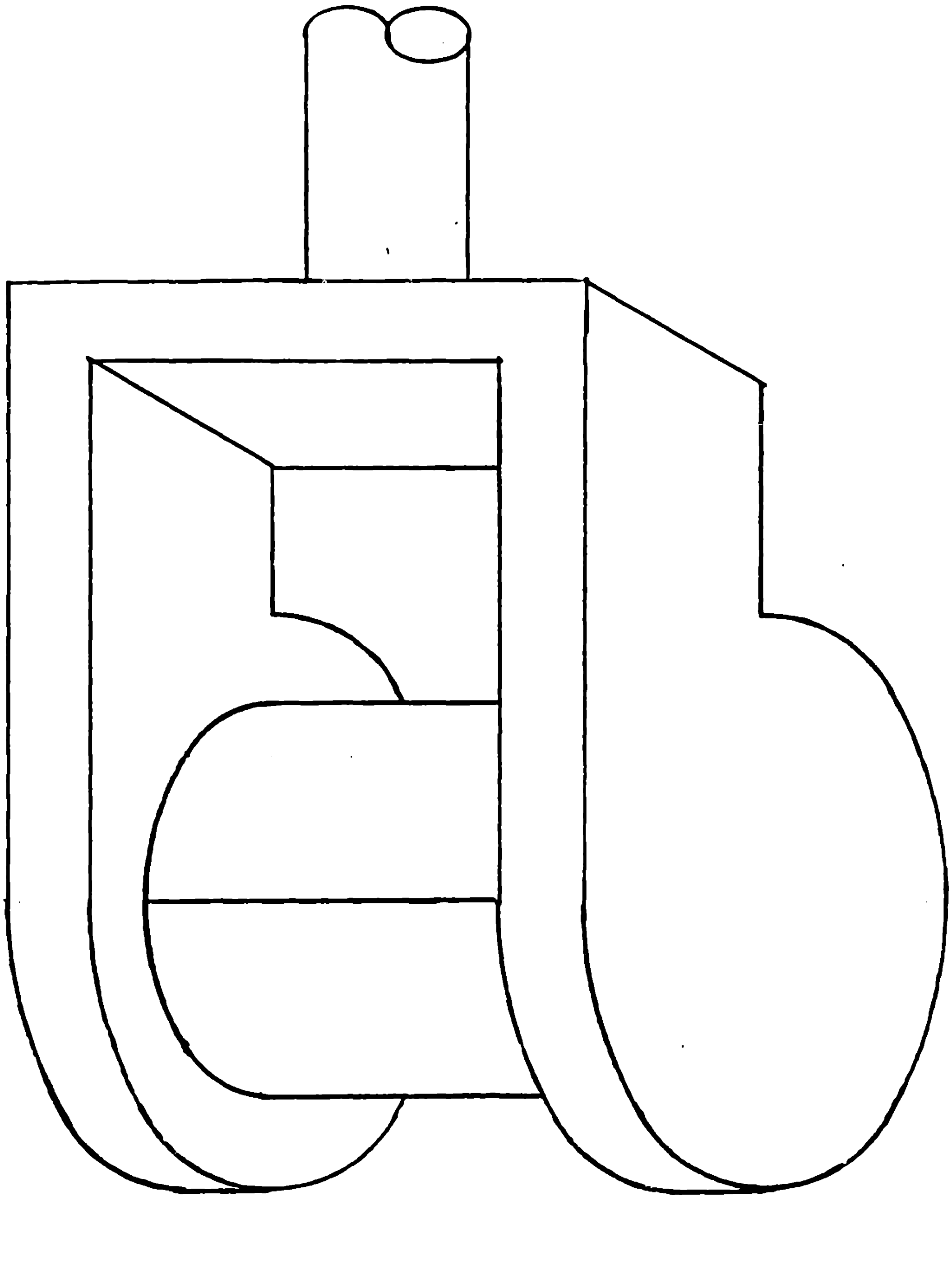


Fig. 2 A schematic of the 10.2 cm (4 in) capstan jaw used in pulling rope samples.

Table 1 Instrument control settings used in this study.

Threshold adjustment	1.0 V
Threshold type	FIXED
Gate width	maximum setting (clockwise)
Coarse gain adjustment	80 dB
Fine gain adjustment	0 dB
Totalizing period (RATE switch)	1 sec
Counts/events toggle	COUNTS
Energy level	3 (50 V)
Pulse generation rate	1000 pulses/sec
Generator mode	PULSE
Oscilloscope sweep rate	*
Burst Frequency	*
Burst duration	*
Volume	*
Tuning	*
Preamp gain	*

* The settings of these controls are unimportant, but these settings should be held constant throughout all tests.

ing on composite materials were not used in these experiments. These couplants wee found to increase the scatter among SWF readings on ropes, without significantly increasing the sensitivity of the test.

B. Experiments Conducted in this Study

All of the tests in this study were done on new dry Samson double-braided 2-in-1, 6.3 mm (1/4 in) diameter nylon rope. This rope has a nylon cover and a nylon core, each of which has a tensile strength of approximately 6200 N (1400 lb). The entire rope has a tensile strength of approximately 11000 N (2500 lb). The SWF was measured at tensions ranging from 220 N (50 lb) to 4400 N (1000 lb). Since many of the flawed ropes in this test failed in the vicinity of 6200 N (1400 lb), it would have been unsafe to test them at higher tensions.

Four different types of rope samples were tested in this way, and five identical ropes of each type were tested.

The first group of ropes tested was undamaged: each of these ropes was taken directly off the rope spool and tested. The other ropes were damaged in various ways:

In the second group each of the ropes had its core cut: in each of these rope sections the core was pulled through the cover, cut through, and replaced in the cover in the center of the test section. the cut core was left inside the rope with approximately a 63 mm (1/4 in) space between the cut ends, and the stress wave factor test was performed across this damaged section.

In the third group each of ropes had its core removed: the core was cut and replaced in the same way that it had been for the second group, except that the cut core sections were pulled back approximately 8 cm (3 in) from each other, and both transducers were placed on the section from which the core had been removed.

Each of the ropes in the fourth group had its cover cut: a section of the cover approximately 15 cm (6 in) long was cut away from the rest of the cover in the middle of the test section. The cut cover was left on the rope, and the testing transducers were placed on the cut cover section.

IV. DATA AND OBSERVATIONS

A. Data

Fig. 3 shows the data from five repetitions of the SWF test on undamaged ropes. Figs. 4, 5, and 6 show the data from tests on ropes with the cores cut, cores removed, and covers cut, respectively. Fig. 7 is a comparison of the average data from each of these tests. Fig. 8 shows the SWF data from Fig. 7 plotted against the percentage of the breaking strength of the type of damaged (or undamaged) type of rope being tested (the normalized load). The raw data and a set of normalized load plots for the individual tests are included in this report in Appendix A.

B. Observations

Two qualitative observations during the testing turned out to be significant in determining the mechanisms of stress wave propagation in the ropes.

In the case of the rope with the core cut, the core stretched as the rope did: the space between the cut sections only elongated approximately one centimeter during the test while the rope itself stretched approximately 1/2 meter. This means that the core was actually under tension at high loads, though not as much as it would have been in an undamaged rope.

The rope with the core removed did not collapse completely when placed under tension: even under relatively high tensions the rope still had a hollow space in the middle and was easily deformed by the test transducers.

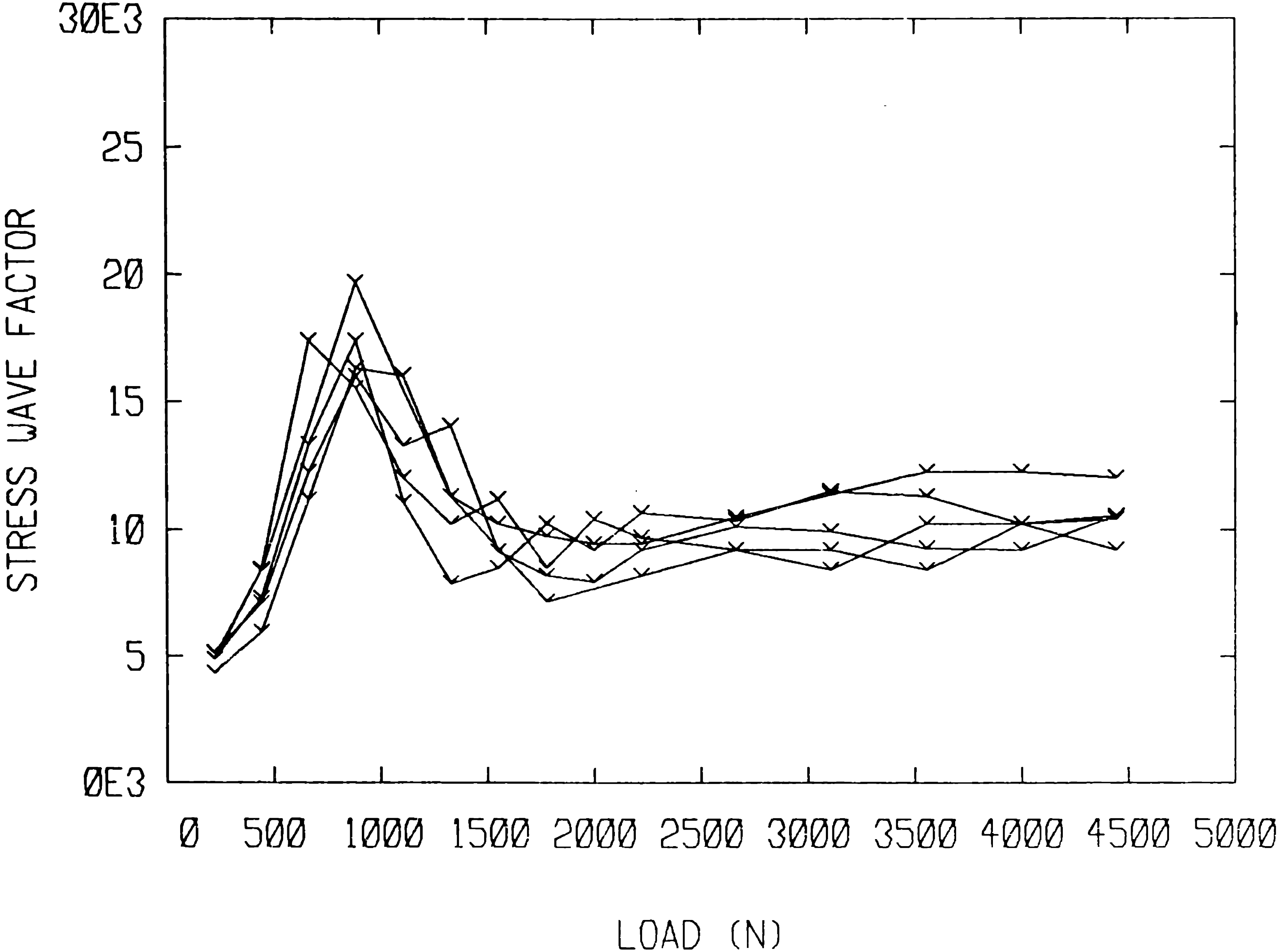


Fig. 3 SWF as a function of load for an undamaged rope.

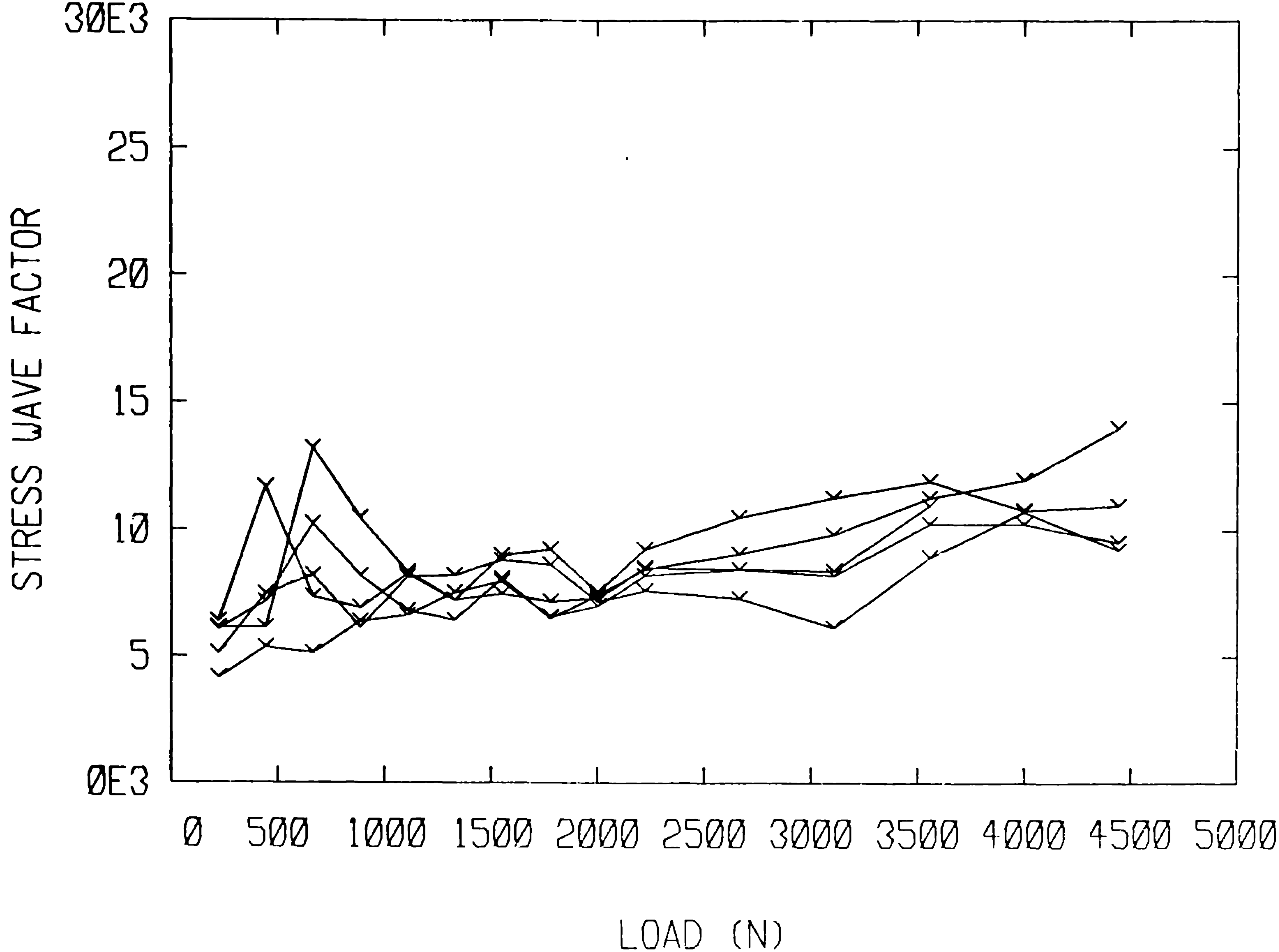


Fig. 4 SWF as a function of load for a rope with the core cut.

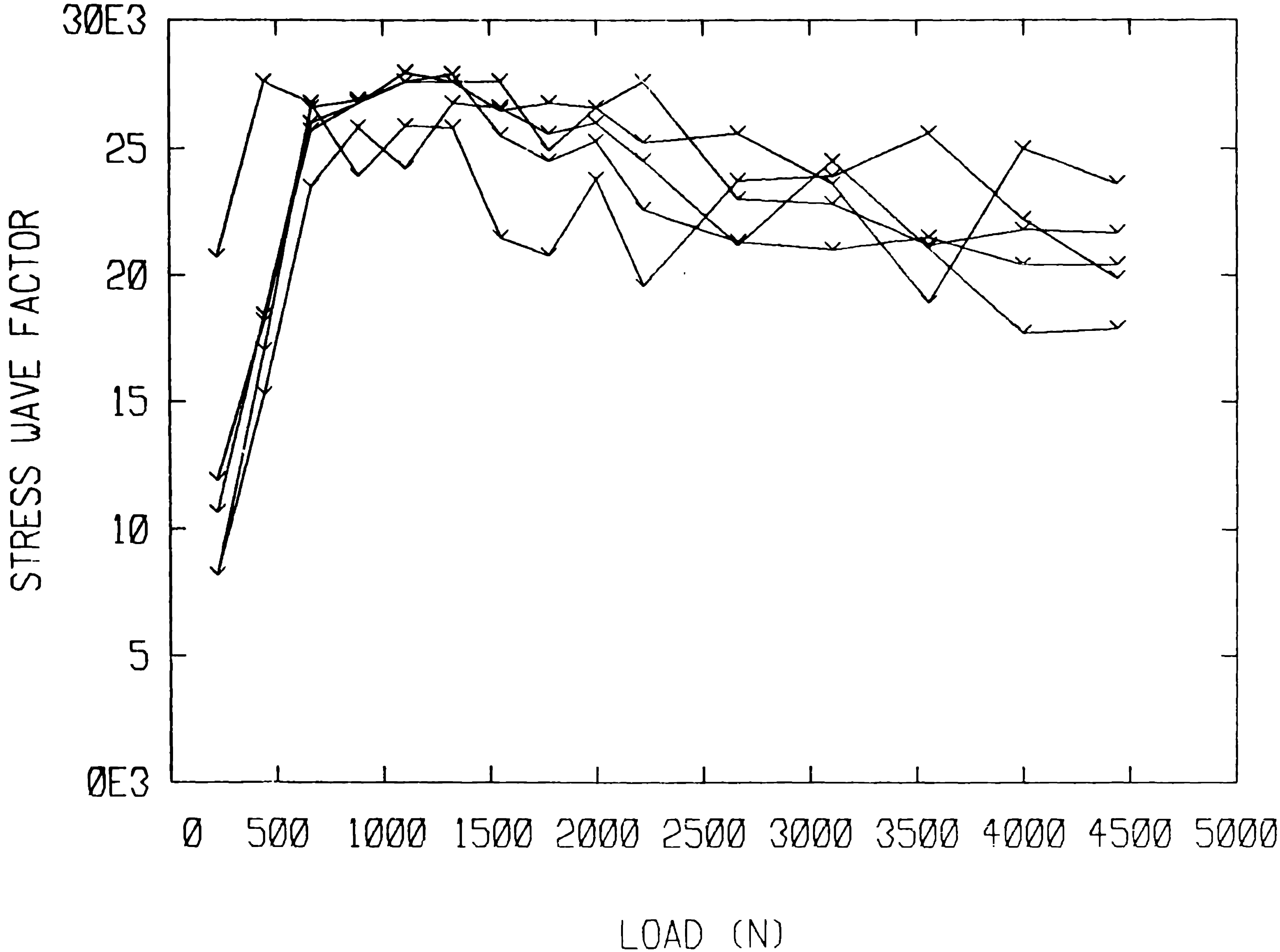


Fig. 5 SWF as a function of load for a rope with the core removed.

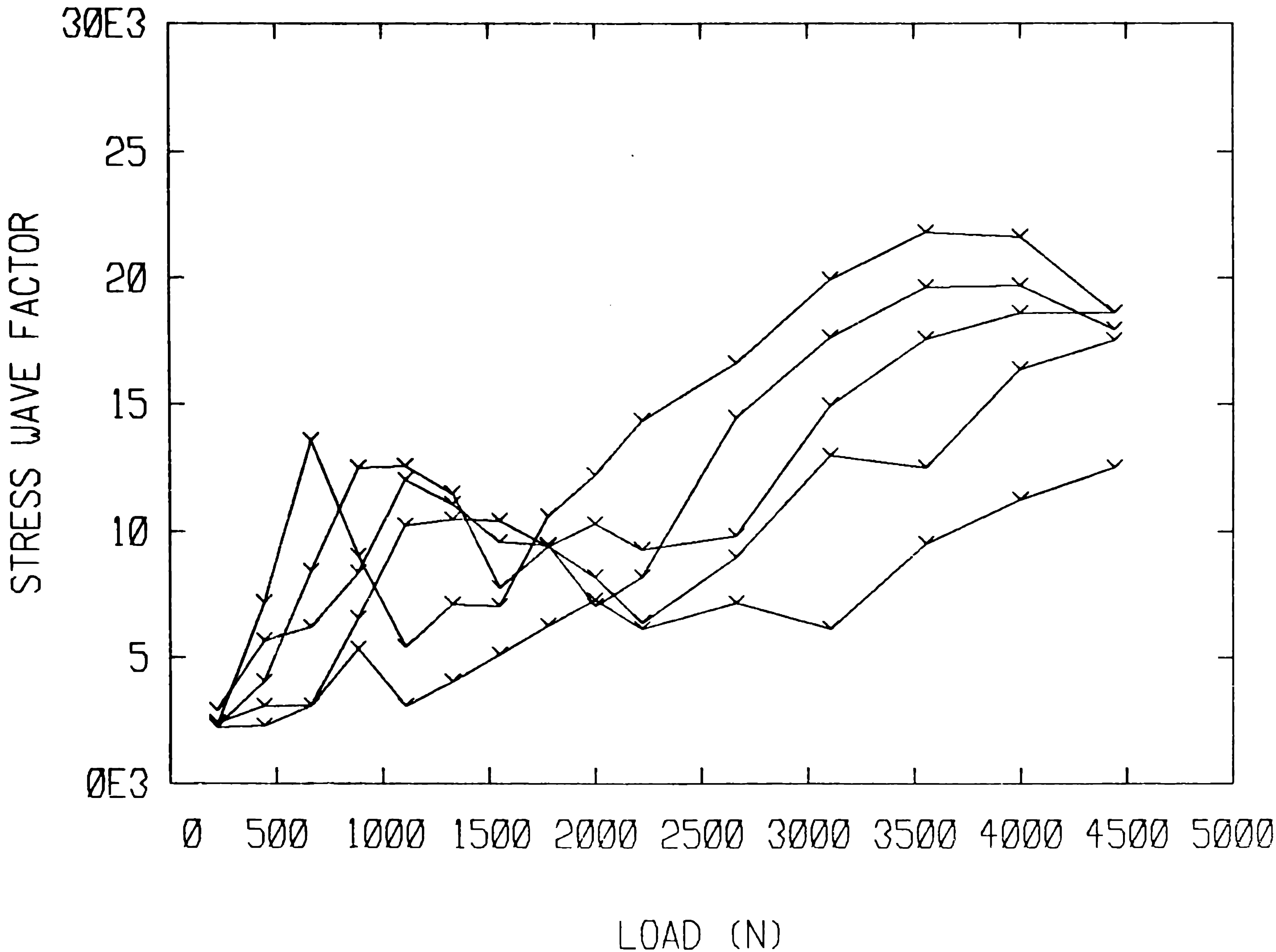


Fig. 6 SWF as a function of load for a rope with the cover cut.

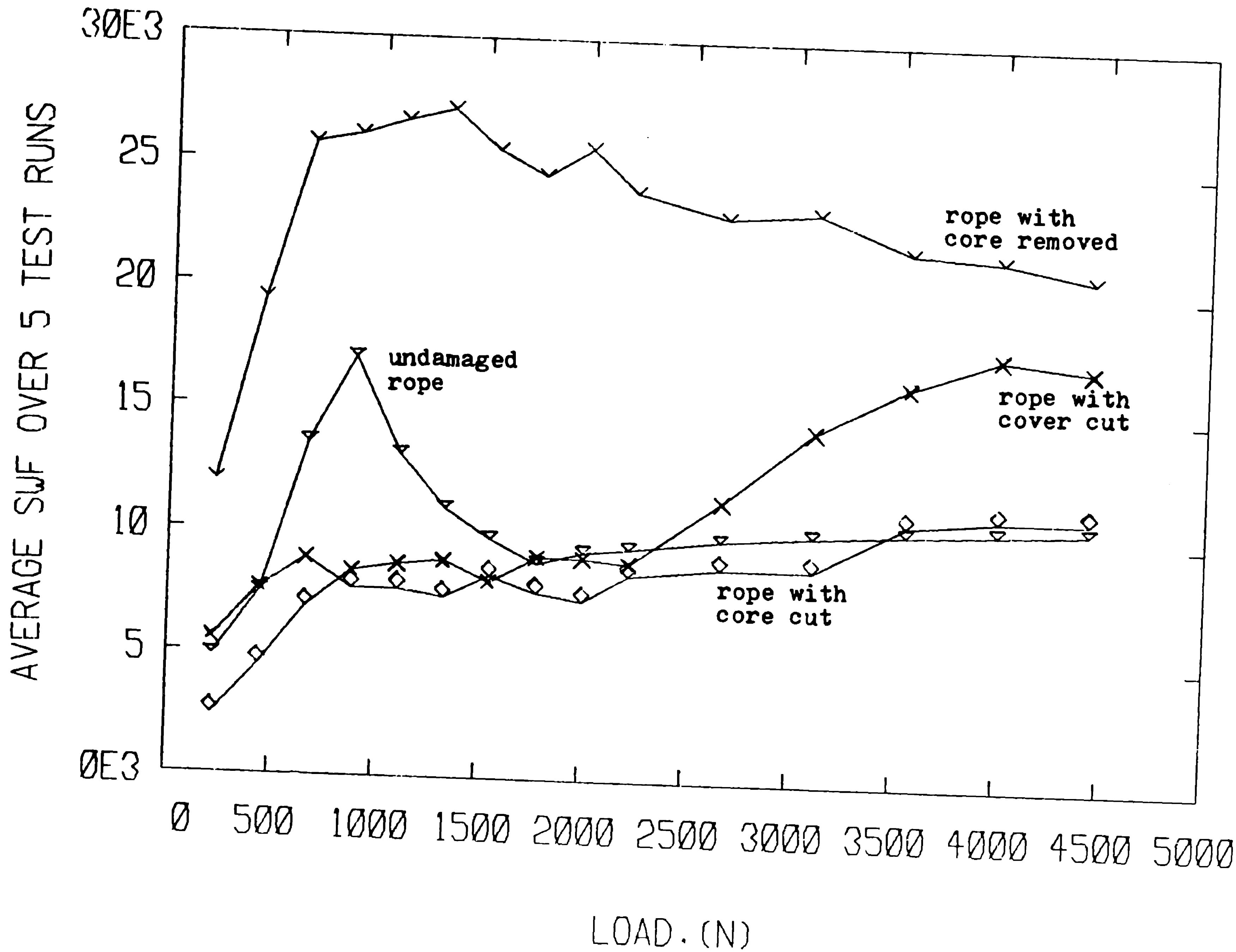


Fig. 7 Average SWF as a function of load for damaged and undamaged ropes.

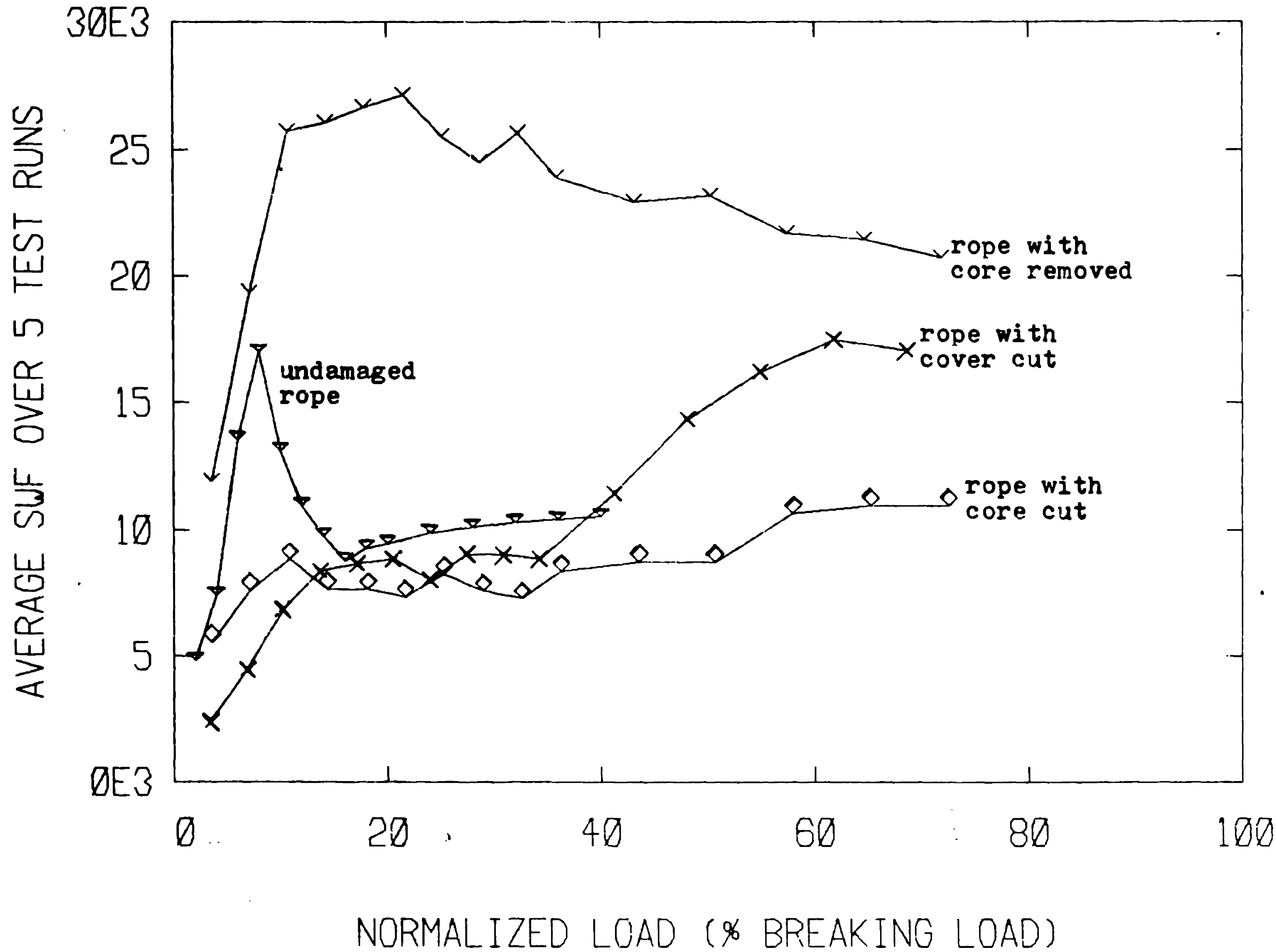


Fig. 8 Average SWF as a function of normalized load for damaged and undamaged ropes.

V. ANALYSIS

This section is divided into two parts. The first part presents theories to account for the shapes of the SWF-tension profiles corresponding to various types of rope damage. The second part outlines a method by which SWF testing can be used as a nondestructive evaluation technique on ropes.

A. Mechanisms of Stress Wave Conduction in Ropes

There appear to be two major competing effects that determine the conductivity of a rope at a given tension.

The first effect is a decrease in the contact area between each transducer and the rope as the tension increases. This effect arises from the use of constant-force transducers: the transducers press a smaller distance into the rope at higher tensions and thus are in direct contact with fewer fibers, resulting in a smaller conduction path. This effect causes the stress wave conductivity, and thus the SWF, of the rope to decrease as the tension on the rope is increased. This characterization shall be defined as Effect 1.

The second effect is an increase in the coupling within the rope itself as the rope tension increases. This effect results from the lateral compression of the filaments, yarns, and strands of the rope, which compacts the elements and thus increases the cross-conduction between them. This effect causes the stress wave conductivity of a rope to increase as the tension on the rope is increased. It should also be noted that a rope under no tension conducts no stress waves. Furthermore, at very low tensions (below 5% of the tensile strength of the rope) some of the fibers will be under no tension, and thus the SWF drops off as the rope tension is decreased in this region. This characterization shall be defined as Effect 2.

Figure 9 demonstrates how these two effects can combine to generate the SWF-tension profile observed for the undamaged rope. Since the contact area effect governs conductance through the transducer-rope interface and the compacting effect governs conductance through the rope, the resultant conductance between the two transducers is governed by the product of these effects.

The rope with the core cut (Fig. 10) did not have the high conductivity at low tensions that was observed in the undamaged rope, but behaved very similarly to the undamaged rope at higher tensions. Such behavior would be caused by a lessening of the first effect discussed above: that is, the area of the conduction path did not decrease significantly at high tensions in this rope. This would be expected in the case of a rope with the core cut: many of the fibers that would form the wider low-tension conduction path in an undamaged rope would be in the core, whereas in this test the core was unstretched at low tensions, and thus not able to conduct stress waves. The second effect discussed above (compacting of rope fibers) also acts to a lesser extent on a rope with the core cut than it would on an undamaged rope. The core of the rope, which is not stretched at low rope tensions, does not conduct stress waves. Thus a significant portion of the alternate wave paths to which the direct wave path will be coupled are nonconducting. At higher tensions the core does get put under some tension, so the variation in this effect from the undamaged rope case is less marked.

The rope with the core removed (Fig. 11) had less high tension attenuation due to the first effect than the undamaged rope: in this test the empty core remained collapsible enough throughout the test that the transducers could always press into it and assure a relatively larger direct conduction path. The collapsing of this rope also caused the coupling effect (the second effect outlined above) to occur to a greater extent: in an undamaged rope, both the core and the cover compacted under tension, but in the rope with the core removed the cover compacted much more under any given tension. Furthermore, the absence of the core decreased the path area through which the stress wave could propagate along the rope beyond the transducers (and thus not be sensed by the receiving transducer).

In the rope with the cover cut (Fig. 12), the contact area remained at a fairly constant size. This is because the stress wave was transmitted through a compliant cover, which conformed to the geometry of the transducers. This cover section, however, also dissipated some energy. At high tensions, however, the SWF was higher in this case than in the case of an undamaged rope. This finding suggests that the core alone conducts stress waves better than an undamaged rope at a given tension.

B. Suggested Method for Using the SWF Test on Ropes

Fig. 7 in the data section of this report shows that there exists no ideal tension level at which the SWF test will be able to both sense and distinguish between all three of these types of rope damage. At some tension levels the SWF test is completely incapable of sensing some types of rope damage. At other tension levels the SWF reading increases to indicate one type of rope damage and decreases to indicate another, meaning that there exists some combination of these two types of damage which this test will be totally incapable of sensing.

Fortunately, however, in most practical applications there is only one predominant mode of damage that ropes suffer: for example, a rope acting as a pulley drive will tend to fail due to wear on its surface, and an organic material rope in a marine application will probably fail due to degradation in fiber quality distributed throughout its cross section. To test a rope in either of these applications one needs to determine a tension level at which the SWF will respond to the type of damage that is characteristic of the given application.

This tension level can be determined by a procedure similar to that used in these experiments: if a large number of undamaged ropes and a large number of damaged ropes are SWF tested at various tensions, then the tension at which the average stress wave factors of the two ropes differ by the greatest margin is the most desirable testing tension. For example, Fig. 7 shows that the best tension at which to test 63 mm nylon rope for core damage is approximately 1000 N (200 lb). At this tension the difference between the average SWF values obtained for undamaged ropes and ropes with the cores cut was 9000, or approximately 50% of the undamaged rope value. If there is a choice in the matter, it is desirable to pick the smallest testing tension possible, as a rope test at too high a tension could damage the rope.

In these experiments the SWF test worked for at least one tension level for each type of damaged rope tested. The findings in this study indicate that the stress wave factor test will probably work in the majority of synthetic rope testing applications.

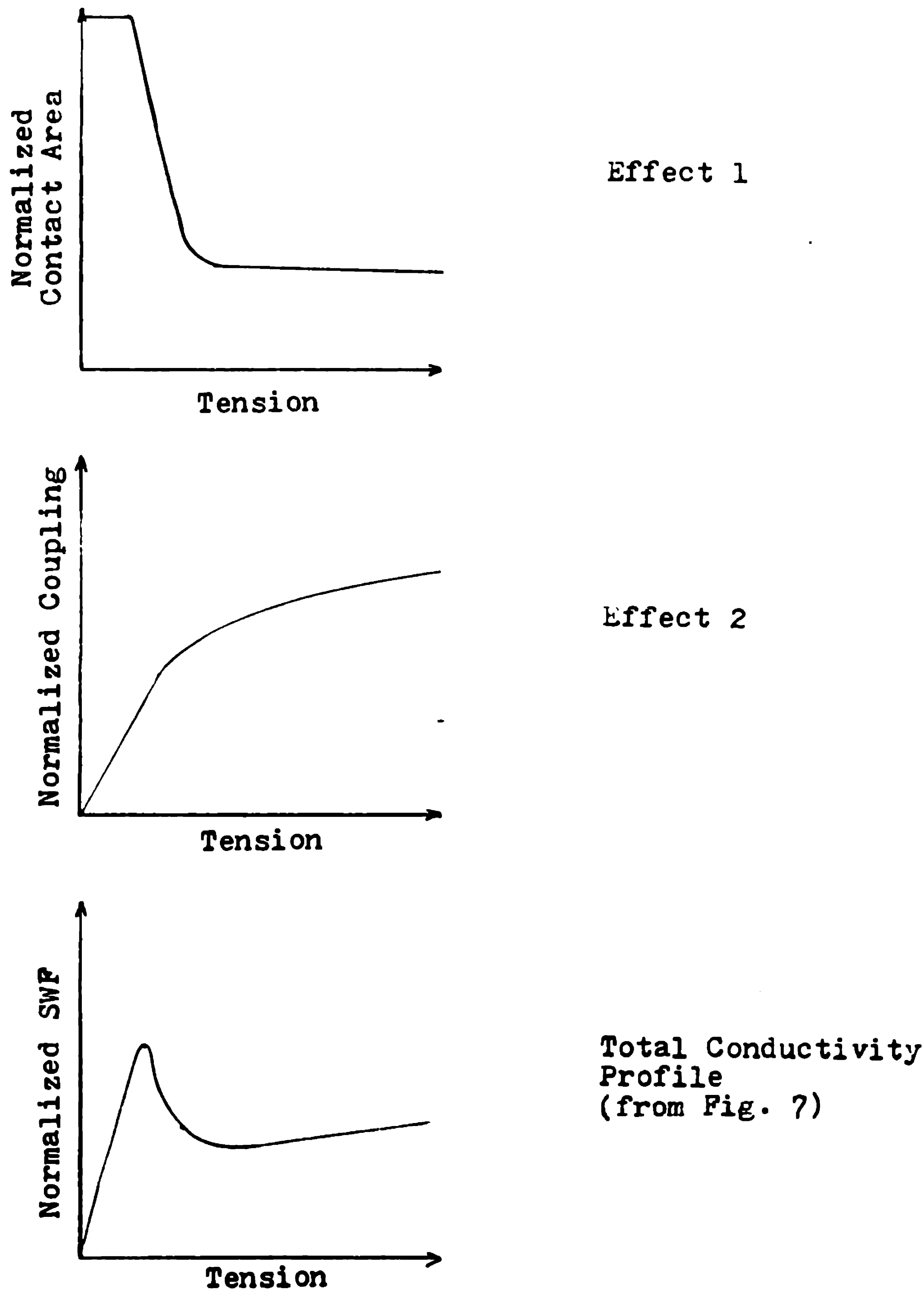


Fig. 9 Effects governing stress wave conduction in an undamaged rope.

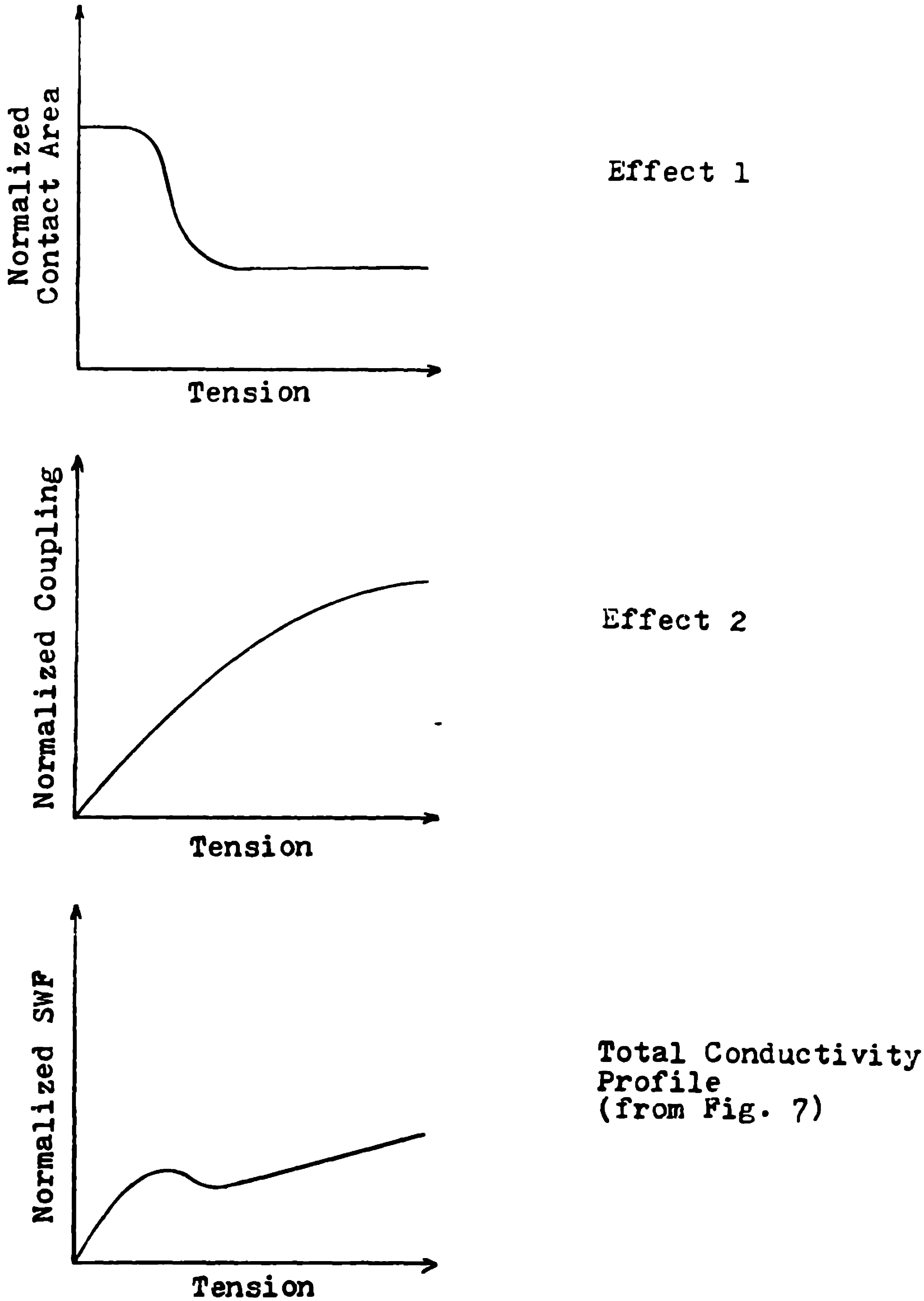
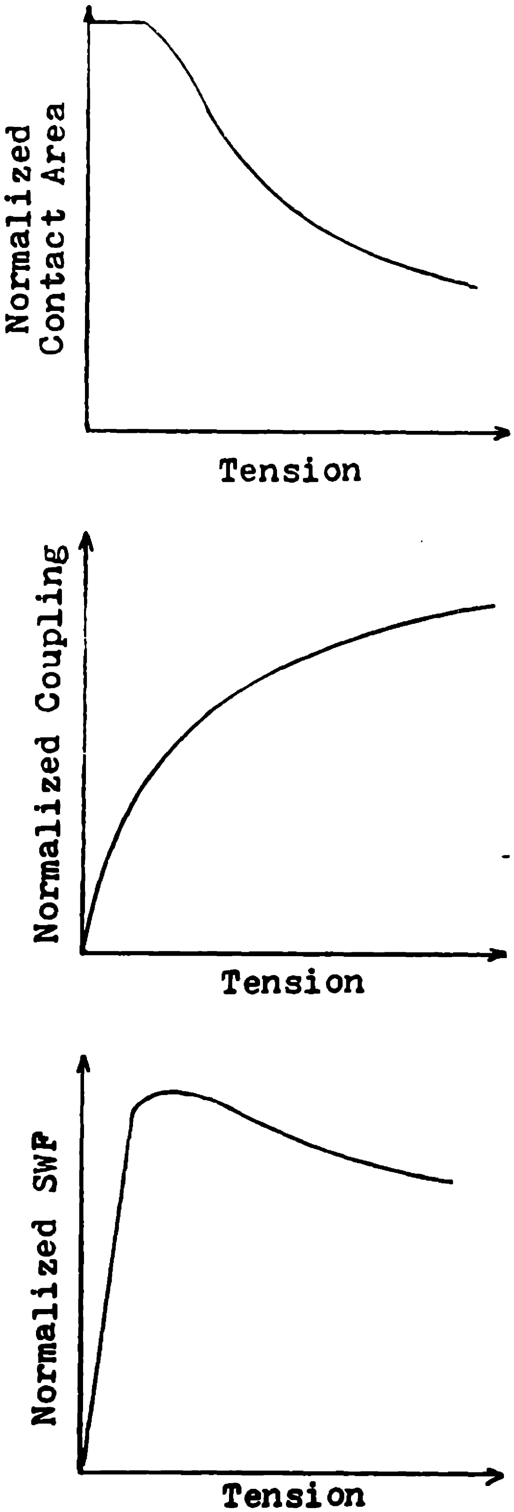


Fig. 10 Effects governing stress wave conduction in a rope with the core cut.

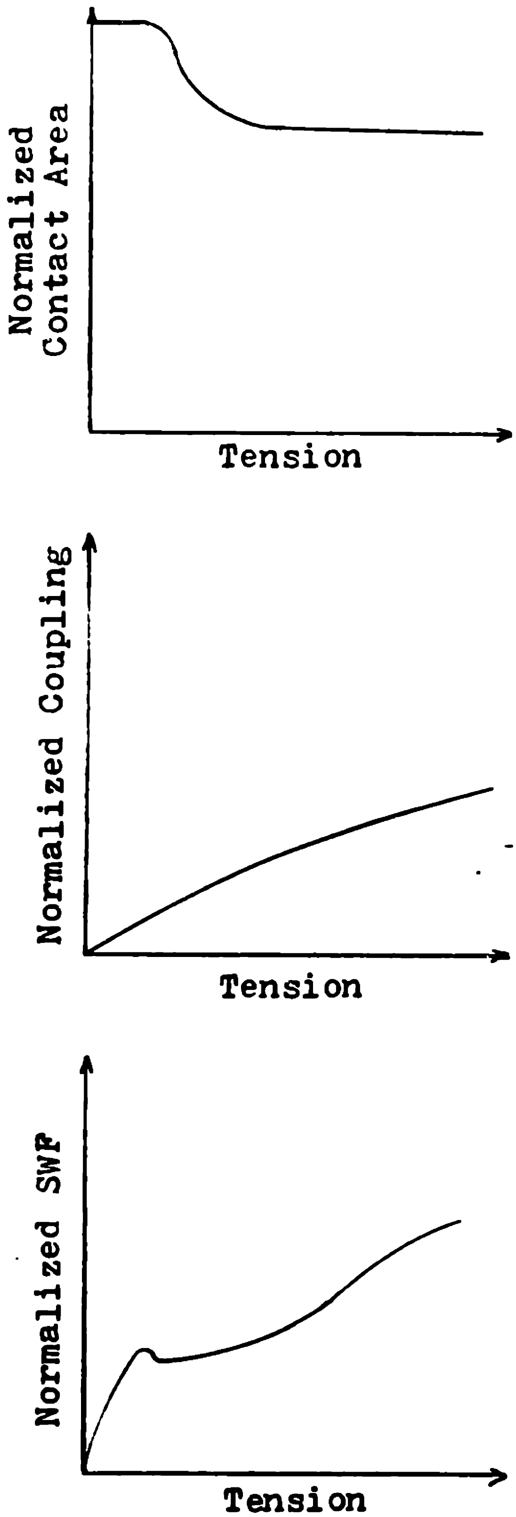


Effect 1

Effect 2

Total Conductivity Profile
(from Fig. 7)

Fig. 11 Effects governing stress wave conduction in a rope with the core removed.



Effect 1

Effect 2

Total Conductivity Profile (from Fig. 7)

Fig. 12 Effects governing stress wave conduction in a rope with the cover cut.

VI. CONCLUSIONS AND RECOMMENDATIONS

The stress wave factor test is by no means a "turnkey" (no preparation needed) nondestuctive evaluation technique for ropes. The SWF responds to different types of rope damage in different ways, and may increase in response to one type of damage and decrease in response to another type. The amount of change in the SWF in response to any given type of rope damage also varies with the tension exerted on the rope while the test is being performed. Thus the SWF can generally only be used to test for one type of rope damage in any given application, and preliminary tests must be done to determine a rope tension level at which the SWF is sensitive to this type of damage.

The SWF test can probably be developed as an effective nondestructive evaluation technique for ropes for many applications. In most cases there will probably exist at least one tension level below 50% of the rope breaking strength at which the stress wave factor test is sensitive to any given type of rope damage.

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APPENDIX A: DATA AND NORMALIZED LOAD GRAPHS

Tables A-1, A-2, A-3, and A-4 show the stress wave factors observed at various tensions during testing of undamaged ropes, ropes with the cores cut, ropes with the cores removed, and ropes with the covers cut, respectively. Figs. A-1, A-2, A-3, and A-4 show this stress wave factor data plotted as a function of normalized load: the load is expressed as a percentage of the breaking strength of the type of rope being tested.

Table A-1 Data from tests on undamaged ropes.

Load (N)	Test 1 SWF	Test 2 SWF	Test 3 SWF	Test 4 SWF	Test 5 SWF	Average
222	4350		5150	4900	4910	4828
445	5960	8350	7120	7310	8440	7436
667	11180		12280	13320	17400	13545
890	16360	19710	16050	17400	15560	17016
1112	16070		13300	11070	12040	13120
1334	11330	11290	14090	7900	10240	10970
1557	10250		9150	8460	11190	9763
1779	9720	7160	8190	10240	8490	8760
2002	9470		7950	9210	10430	9265
2224	9470	8190	9210	10650	9670	9438
2669	10490	9180	10120	10340	9220	9870
3114	11370	8440	9940	11470	9220	10088
3558	12280	10230	9270	11330	8420	10306
4003	12240	10240	9230	10240	10230	10436
4448	12020	10390	10500	10500	9210	10524
Breaking Load (N)	10987	11120	10987	11209	11253	11111

Table A-2 Raw data from tests on ropes with the cores cut.

Load (N)	Test 1 SWF	Test 2 SWF	Test 3 SWF	Test 4 SWF	Test 5 SWF	Average
222	4140	5100	6110	6390	6140	5576
445	5370	7470	7180	11660	6140	7564
667	5120	8190	10240	7320	13250	8824
890	6390	6170	8190	6940	10480	7634
1112	6630	8130	6810	8250	8300	7624
1334	7530	8200	6470	7220	7200	7324
1557	7920	8790	8070	7490	8980	8250
1779	6590	8580	6500	7160	9210	7608
2002	6970	7160	7430	7260	7530	7270
2224	8190	7570	8450	8460	9220	8378
2669	8450	7270	9030	8410	10440	8720
3114	8370	6140	9830	8210	11220	8754
3558	10940	8900	11230	10240	11890	10640
4003		10690	11980	10240	10790	10925
4448		9220	14010	9530	10920	10920
Breaking Load (N)	6294	6138	6383	5983	5827	6125

Table A-3 Raw data from tests on ropes with the cores removed.

Load (N)	Test 1 SWF	Test 2 SWF	Test 3 SWF	Test 4 SWF	Test 5 SWF	Average
222	10620	20700	8180	11930	8190	11924
445	18470	27600	15310	18180	17070	19326
667	26000	26800	23500	25700	26600	25720
890	26800	23900	25800	26800	26900	26040
1112	28000	25900	24200	27600	27600	26660
1334	27600	25800	26800	27900	27600	27140
1557	26500	21500	26600	25500	27600	25540
1779	26800	20800	25600	24500	24900	24520
2002	26600	23800	26000	25300	26600	25660
2224	25200	19600	24500	22600	27600	23900
2669	25600	23700	21200	21300	23000	22960
3114	23600	23900	24500	21000	22800	23160
3558	18900	25600	21100	21500	21200	21660
4003	25000	22200	17700	20400	21800	21420
4448	23600	19900	17900	20400	21700	20700
Breaking Load (N)	6361	5983	6316	5916	6338	6183

Table A-4 Raw data from tests on ropes with the covers cut.

Load (N)	Test 1 SWF	Test 2 SWF	Test 3 SWF	Test 4 SWF	Test 5 SWF	Average
222	2260	2300	2320	2930	2400	2442
445	2300	7190	4020	5660	3070	4448
667	3100	13560	8440	6220	3070	6878
890	6550	9020	12520	8390	5370	8370
1112	10240	5420	12560	12000	3070	8658
1334	10460	7110	11510	11080	4040	8840
1557	10430	7030	7770	9560	5120	7982
1779	9370	10570	9390	9430	6290	9010
2002	8180	12230	10300	7040	7310	9012
2224	6400	14370	9290	8180	6140	8876
2669	8950	16640	9830	14510	7160	11418
3114	13010	19950	14950	17670	6140	14344
3558	12510	21800	17580	19670	9510	16214
4003	16390	21600	18620	19710	11260	17516
4448	17550	18600	18620	17970	12490	17046
Breaking Load (N)	6338	6494	6539	6450	6494	6463

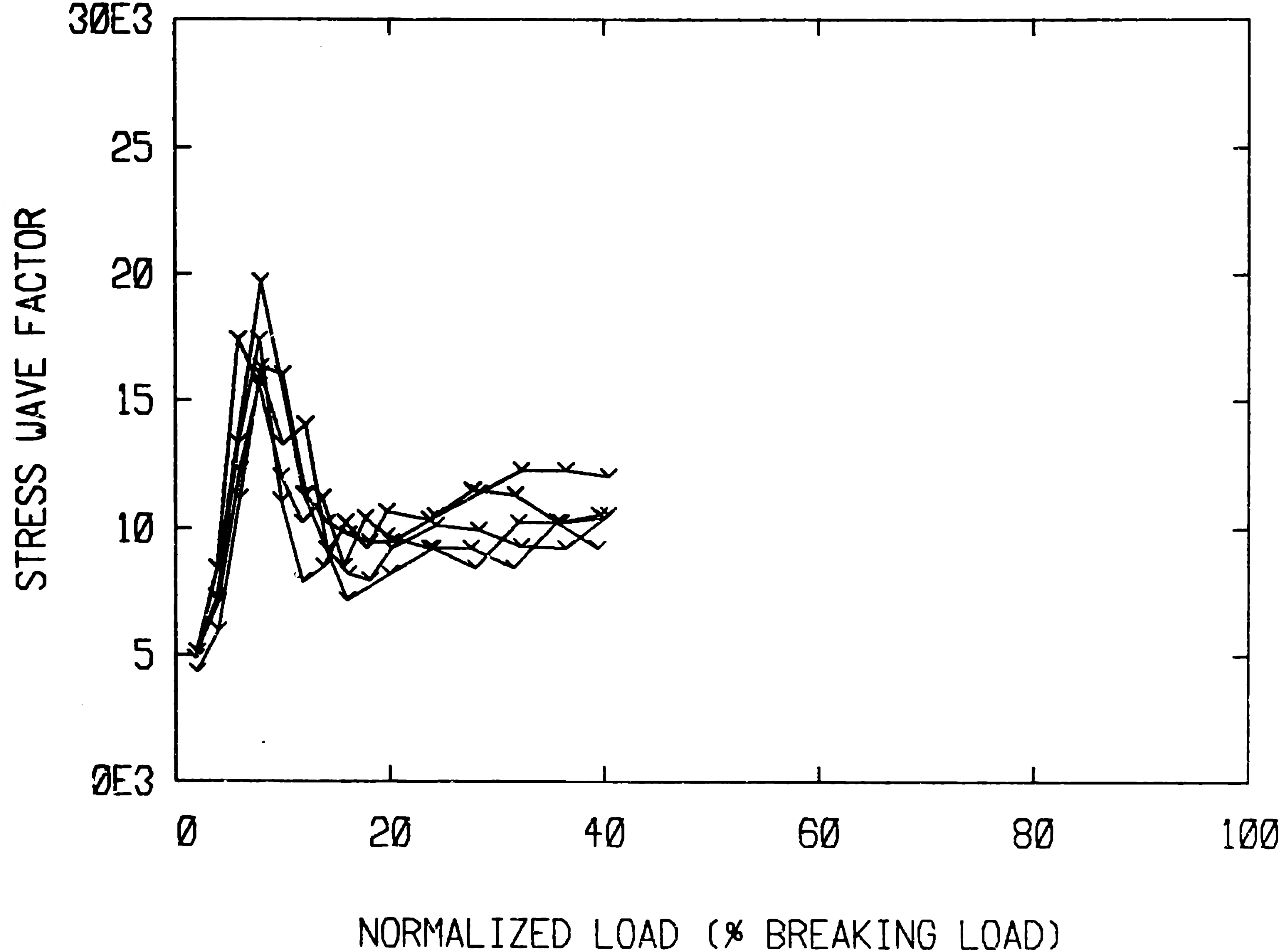

Fig. A-1 SWF as a function of normalized load for an undamaged rope.

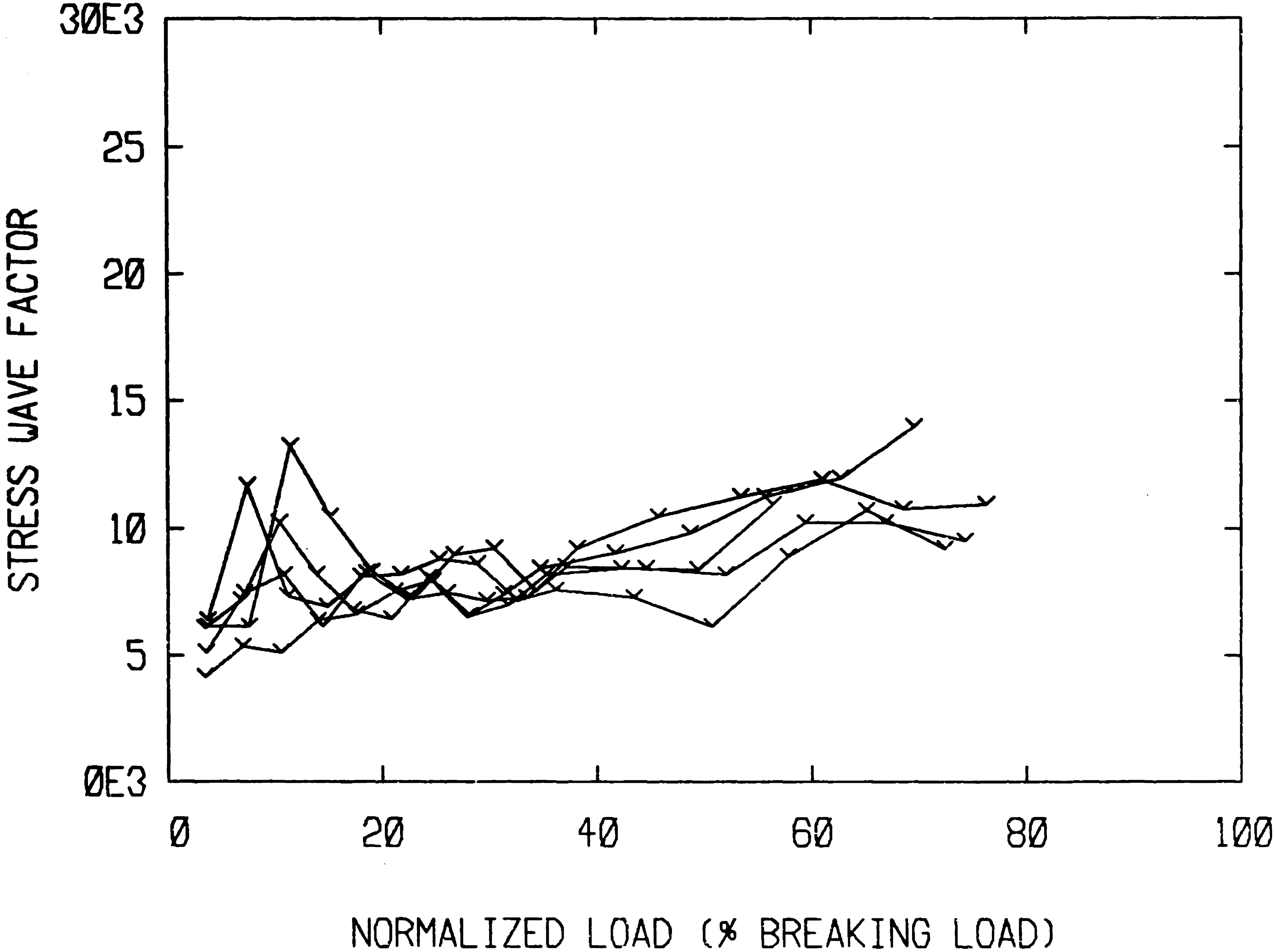

Fig. A-2 SWF as a function of normalized load for a rope with the core cut.

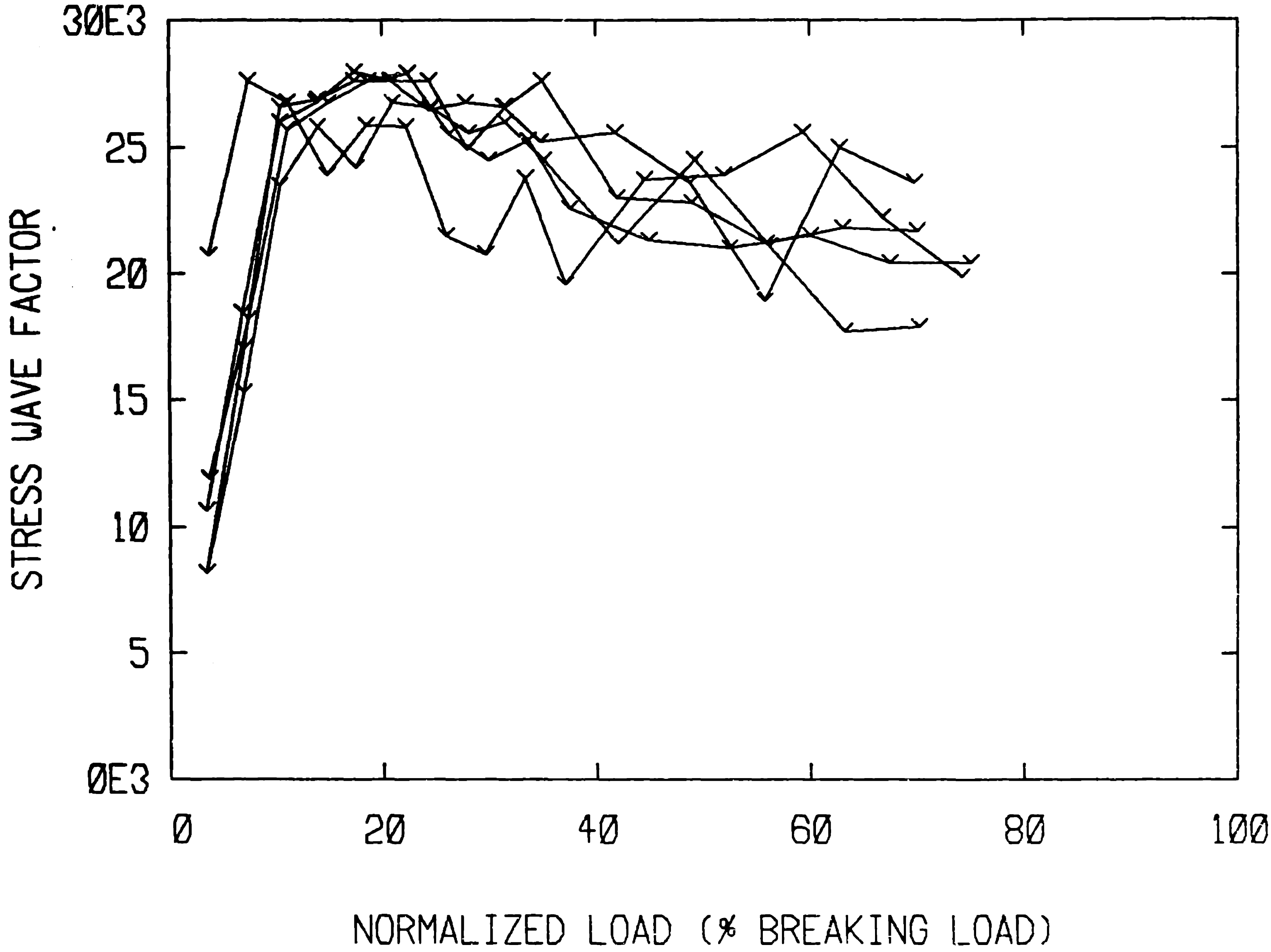

Fig. A-3 SWF as a function of normalized load for a rope with the core removed.

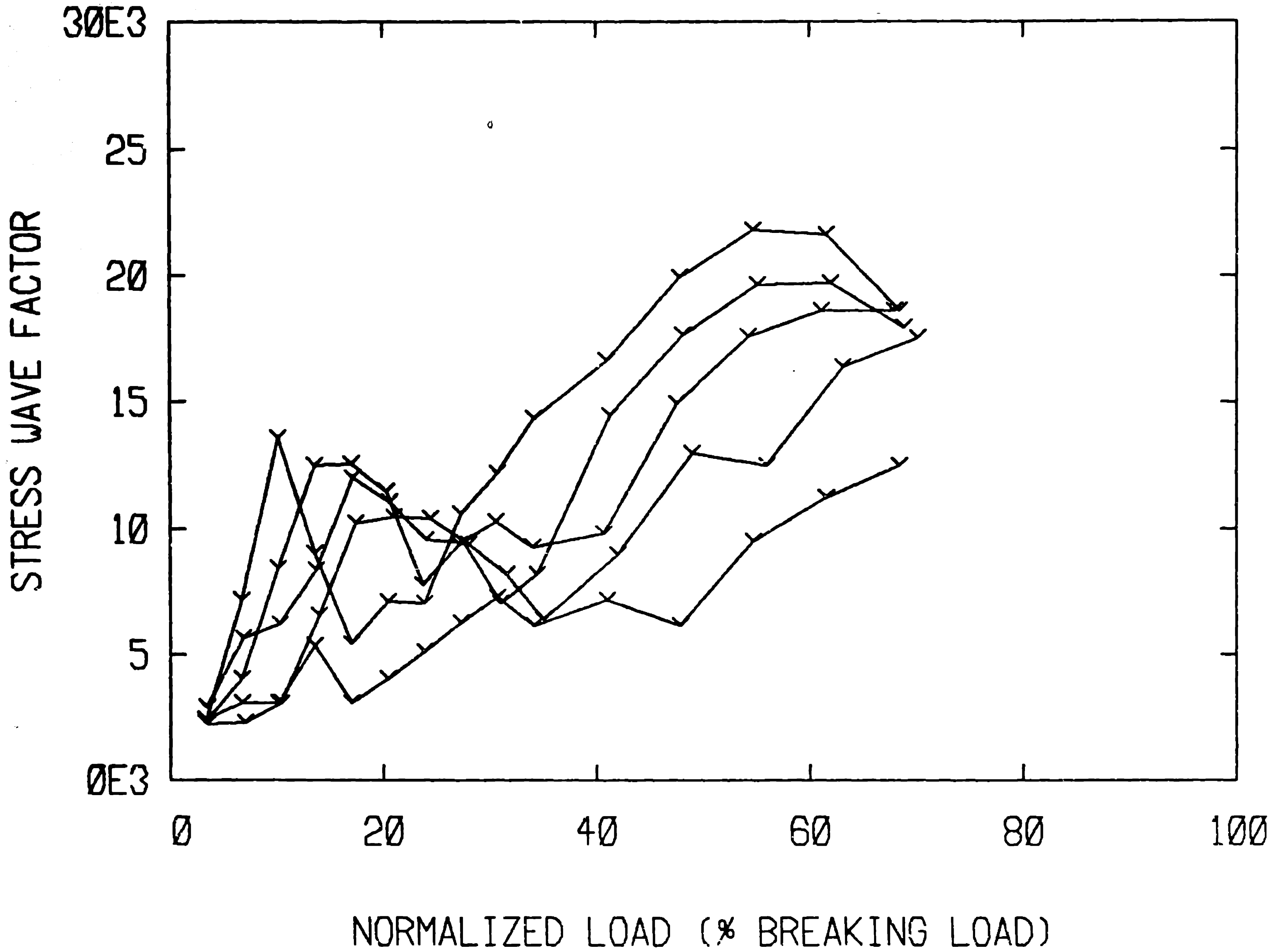

Fig. A-4 SWF as a function of normalized rope for a rope with the cover cut.

APPENDIX B: REPEATABILITY OF THE SWF TEST

All of the tests in this experiment were performed in the same manner, with the same instrument, and on the same day, yet the scatter in the SWF data between tests of identical ropes was generally 20% of the average SWF at all rope tensions. It is likely that these repeatability errors had three major causes: the rope interface, the instrument, and the precision of the SWF.

B-1. The Rope Interface

The interface between the transmitting and receiving transducers and the rope is by nature unrepeatable: each small area of the rope has a different random arrangement of fibers. The best way to minimize this variation is to develop large contact area transducers both for transmitting and for receiving the stress pulse. The development of large contact area transducers is an advance that would contribute greatly to making the SWF test a more practical technique for ropes.

B-2. The Instrument

The Acoustic Emission receiver and/or the wires to it often pick up significant amounts of atmospheric noise (including transmissions from radio stations). This problem could be partially alleviated by building the 40 dB preamplifier into (or at least nearer) the sensor unit, which would minimize the path in which the signal is sensitive to microvolt level electrical noise. This problem could also be remedied by using shielded cable, which is not available with the LEMO fittings used by AET.

The pulse generator does not appear to produce repeatable pulses. If the stress pulse inputs are periodic and identical then the SWF theoretically should be an integral multiple of 1000, yet on approximately ninety percent of the days on which the instrument was used the instrument did not give such readings. This condition is probably due to a variation in the magnitudes of the pulses from the pulse generator over the one second summation period. These pulses can easily vary because the instrument runs off of wall current and its power supply circuit can not reject noise significantly below 60 Hz in frequency. The instrument has a battery pack, but it does not hold a charge long enough to be useful. A better battery should be found for this instrument.

B-3. Precision Problems With the SWF

As mentioned above, in the total absence of noise the SWF would always be a multiple of 1000. This means that assuming perfect accuracy the resolution of the reading is at best only one part in 27 (27000 was the highest observed SWF) or approximately a 4% repeatability error. For high precision (or low sensitivity) measurements, it might be worth developing an instrument to compute the integrated intensity of the Acoustic Emission signal as a continuous rather than discrete stress conductivity indicator. This would be computed by rectifying the signal (i.e. taking its absolute value) and feeding this waveform into an integrator. this number is more sensitive to noise than the SWF (the SWF is not sensitive to noise with a zero mean value), but the noise is easier to measure and reject: one can turn off the pulse generator for one second and compute the "zero signal", and subtract this number off of the integrated intensity. The SWF has the advantage that it is computed by digital circuitry, which is easier and cheaper to build accurately than an integrator, but this alternative indicator may be worthwhile to develop for some special applications.