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CAIUS COLLEGE

20. 4. 84

FURTHER INVESTIGATION INTO MOUNTAINEERING ROPE FAILURE

SUMMARY

This report continues investigation into the mechanisms of mountaineering rope failure in a simulated fall, carrying on the work of T.A. Coombs in 1983. It attempts to provide a more quantitative evaluation, and some amendment to his theories.

The following conclusions were drawn:

(i) There are four phenomena which cause the failure of a mountaineering rope.

a) Tensile overload

b) Abrasion

c) Fatigue

d) Environmental degradation.

(ii) Final failure is always by tensile overload, but the forces generated in a fall are not high enough for this to be the sole cause of failure in a new rope.

(iii) a) and b) predominate in the new rope. It is deduced that all four forms of damage may occur after the rope has been used.

CONTENTS

INTRODUCTION

Ropes have been used in mountaineering since 1786. Initially they were for hauling tackle, but with the development of the sport, they became valuable climbing aids. Very little research on them was done until after the Second World War, when ropes specifically designed for climbing were produced. There has been steady development since, and recently, the increasing cost of equipment, and severity of routes climbed, has meant that from both a financial and safety point of view, "gut feeling" of when a rope becomes unserviceable is no longer adequate.

The rope's primary function is to arrest a climber's fall without injuring him. Current climbing practice is to have the rope payed out at the belay stance, and to pass it through Karabiners, attached to the rock at intervals as the climb proceeds (Fig 1). In other circumstances, it may be easier to use two "half-ropes" (Fig 2.).

11 mm diameter ropes are used for single rope ascent, and 9 mm diameter for the "half-rope" method. (Both diameters are investigated.)

In either case, when the leading climber falls, the rope becomes taut, and is bent around the Karabiners. This is why drop-tests are carried out over a radiused edge approximating to a Karabiner.

Moreover, although in the "half-rope" case two ropes support the mountaineer, these do not necessarily carry the load equally, and can, in an extreme case, carry the full load on just one rope.

Thus, it is the dynamic situation of a fall that we wish to investigate, the damage caused by it, and what previous damage, combined with it may cause failure.

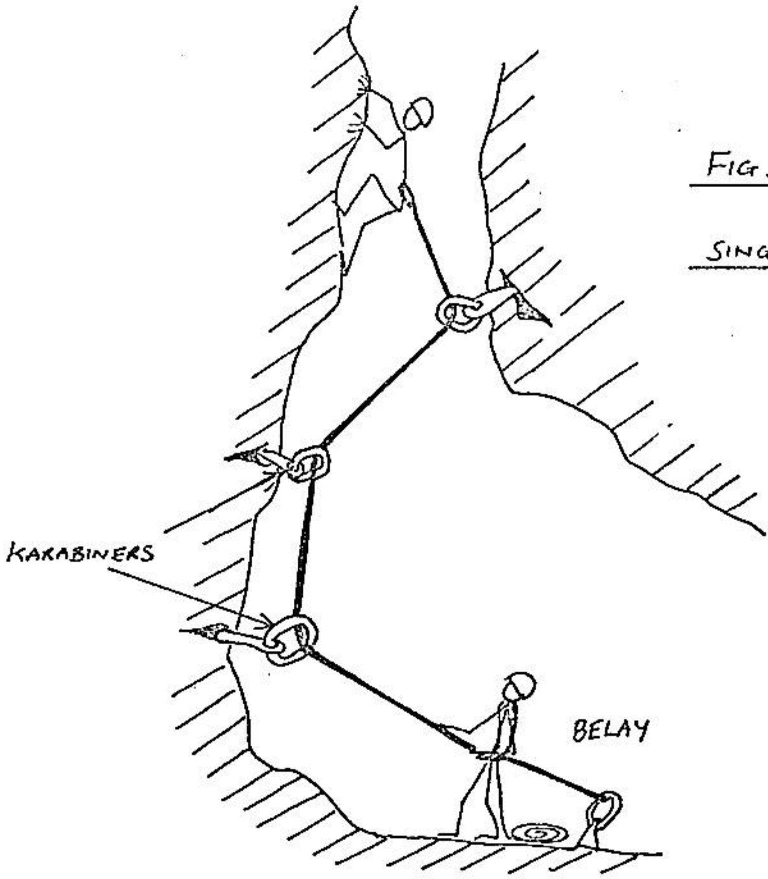


FIG. 1

SINGLE ROPE

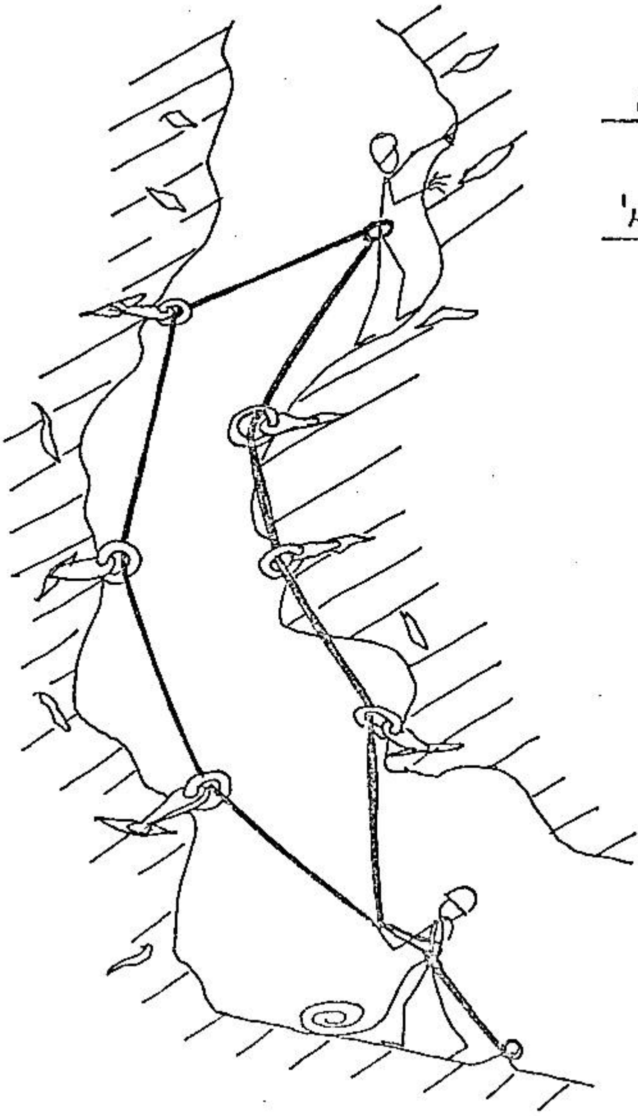


FIG. 2

'HALF' - ROPES

OBJECT.

By applying loads in both static and dynamic situations to different ropes and their constituent parts, to develop some theories about rope failure, its mechanisms and causes. Also, to separate the effects of these different forms of damage, and thus to rate them in importance. To see how well the developed theory agrees with results, and to present these results in such a way that they may be applied by a climber to his own rope, without the use of sophisticated equipment; thus to predict a rope's service life.

SYMBOLS AND DESCRIPTIVE TERMS

x – measure of strand length in determining cord strain (see p 29) or distance from mean position in simple harmonic motion.

l – measure of length. – may be given various subscripts (see p 25)

λ – rope spring constant in N/m.

e – rope stretch in metres under climbers weight mg.

S – the percentage e represents of l, the initial length of rope.

m – mass (of climber) in kg.

F – force in Newtons.

ε – strain

$\dot{\varepsilon}$ – strain rate

STAT – static (abbrev.)

DYN – dynamic (abbrev.)

pk – peak (abbrev.)

U.T.S. – ultimate tensile strength (abbrev.) in newtons.

η – the fall factor. $= \dfrac{\text{Length of fall}}{\text{Length of free rope holding the fall.}}$

(written F.F.).

This is a useful concept since the rope's capacity to dissipate the energy of a falling body (dependent on the height of the fall) depends on the length of rope holding the fall. It will be shown on p. 22 that by using this number, the peak force is independent of rope length, if rope self-weight is neglected.

Karabiner (Fig 3) - from here on abbreviated to Krab.

- a metal-link with one side which opens: (the "gate").

This may be opened by hand, but is normally held closed by a spring. Usual radius of edge is between 4 & 5 mm.

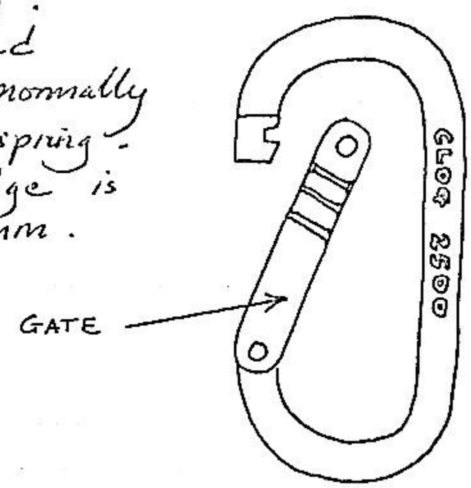
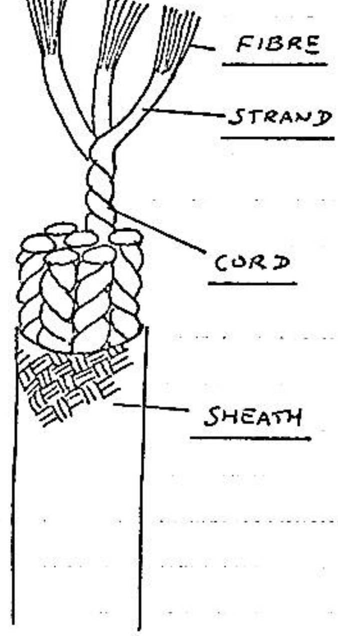


FIG. 3

KARABINER

THE ROPE. - FIG. 4.



Fibre

Over 50,000, of 25 μm diameter are contained in an 11 mm rope.

Strand

A bunch of several thousand fibres, Three are wound in a helix to form a cord.

Cord.

Equal numbers of each 'handed' helix are bundled together and held in by the sheath.

Sheath

Interwoven fibres to form a circular ring, protecting the core from abrasion.

This in known as 'Kernmantle' construction.

Apparatus

There were three major items of equipment used. These were a drop-test rig, an Instron tensile test machine, and a J.J. 22K tensile test machine.

(i) The Drop Tower (see Fig. 5)

This is built from two channel sections, placed vertically, and running from the floor of the laboratory, almost to the roof. These were suitably supported by bracing at their lower ends, and by fixing to the laboratory roof supports. The two channels enclose an 85 Kg weight which slides vertically between them, it being prevented from hitting protruding bolt-heads by the channels being lined with timber. The base of the tower is filled with sand, to absorb the impact of the weight if the rope fails.

Approximately half way up the tower is a plate, to which an eye-bolt is attached. This forms a tie-off point, and c. 25 cm further up may be fixed profiled plates of known radius which act as the "edge", over which the rope falls. For all tests, one edge of radius 4 mm was used, this being the radius of the smallest krab likely to be used in a real climb. The dimensions of the test rig are given in Fig 5. and may be compared with the standard U.I.A.A. drop test whose dimensions are given in Fig. 6.

The weight may be raised or lowered in the tower by a pulley-block, fastened in the roof, and attached to the weight via a shackle, and manually operated release mechanism. Its spring loaded jaws may be opened by the operator, when standing on the ground. The rope test-specimen is fastened to both weight and eye-bolt by krabs.

For safety's sake, the front of the tower is enclosed with wire-mesh to contain the broken rope ends, or in an extreme case, a broken krab.

Access to the edge-plate, eyebolt, or other parts of the tower is by a ladder, adjacent to the tower and laboratory wall.

By calculation, (p. 25) the position of the weight to produce any desired value of η could be determined. These points were marked on the channel section, as was a scale, showing distance below the highest possible position of the weight.

(ii) J.J. & INSTRON TENSILE-TEST MACHINES

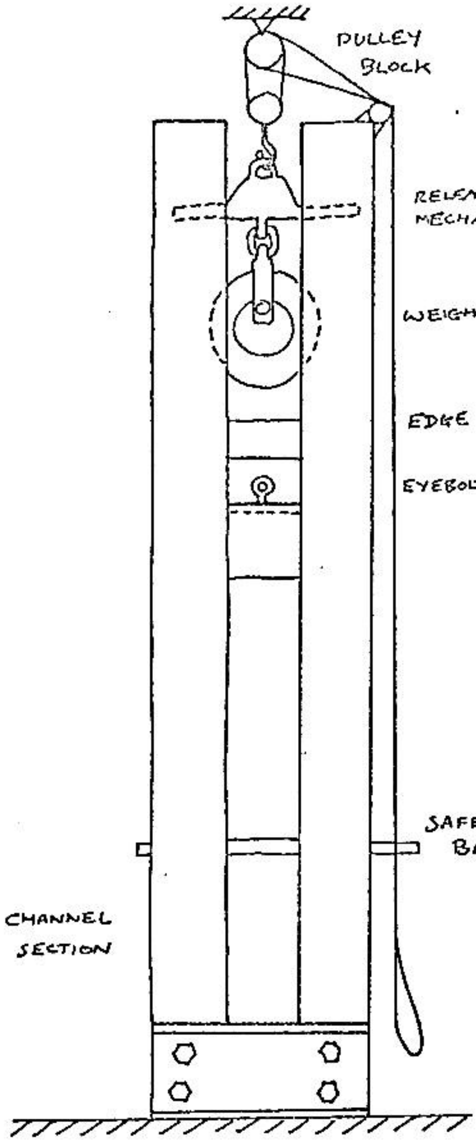
These perform the same function, but are of different capacities; the Instron being used for complete ropes, the J.J. for rope sub-elements.

Each machine consists of a screw-operated crosshead which may be moved at varying rates, and a load-cell, connected to an x-y plotter so as to produce graphs of force against crosshead displacement.

The test specimen is fixed between crosshead and machine frame and is stretched, the load cell registering the force in the specimen.

In an attempt to eliminate rope-slip, and reductions in strength due to knots, encountered in the previous project, some new rope-grips were designed. (see Fig 7) The idea being to take the load in friction around the bar. The grips for the J.J. were scaled down versions of the Instron grips.

FIG. 5. THE DROP TEST



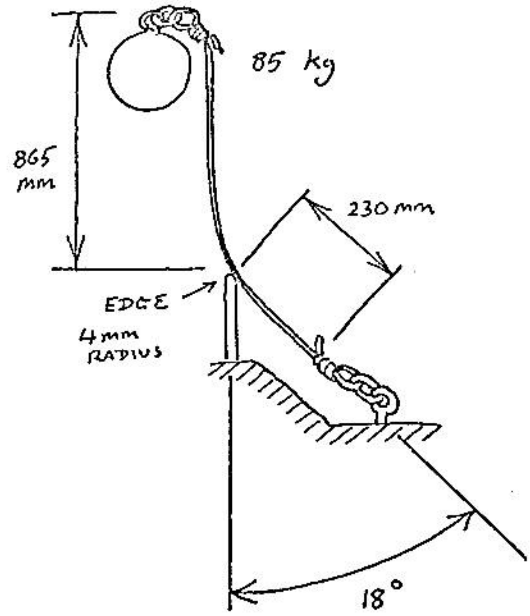


FIG. 6 THE U.I.A.A. TEST

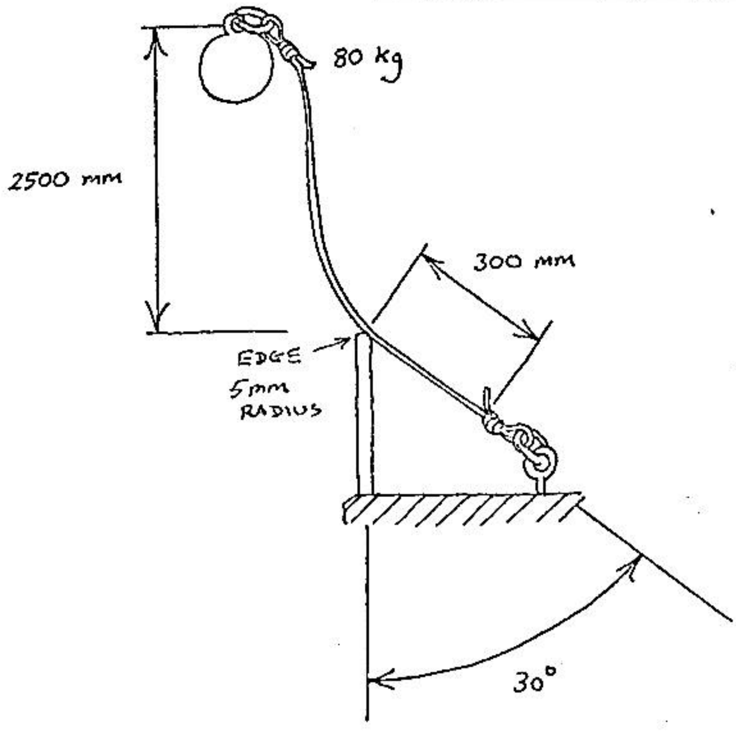
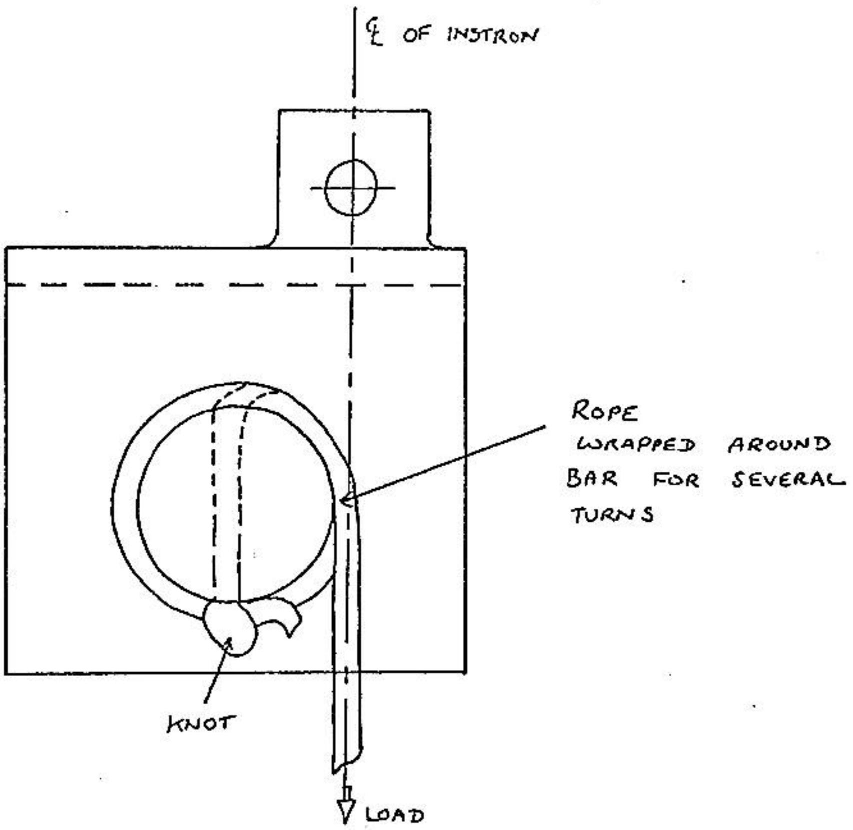


FIG. 7 ROPE GRIP



PROCEDURE

(This may have been amended as the project developed, and if so, will be covered in the section "OBSERVATIONS".)

The maximum possible fall (less than $\eta = 2$ due to space limitations) was calculated as 1.836 (see p 25) and the length of free-rope needed to produce this was established as 109.5 cm. Each end of the rope was knotted in a loop, and by tying various knots it was established that the bowline took least rope at 35 cm for the 9mm rope and 40 cm for the 11 mm rope. Thus the total lengths of each specimen were 179.5 cm and 189.5 cm respectively. These were cut with a hot knife, to seal the ends and prevent fraying. Into each end-loop was clipped a krab, and each rope end was wound with masking tape and marked with a number.

A major problem with the investigation was that we wished to observe effects on the rope core, since it was believed that this could well behave differently to the sheath, but the sheath blocked our view. Moreover, it would only be the sheath which, in normal circumstances a climber could inspect for damage. It was therefore decided to compare the effects of a drop on both sheathed and unsheathed specimens.

It was decided to measure the strain in the rope after the drop; not only total strain, but strain throughout the rope, and particularly at the edge.

Gauge-lengths were marked using the regularly repeating yellow-thread pattern for sheathed specimens (gauge-length = 2.75 cm under firm hand tension) and by sewing black cotton thread into the unsheathed specimen at gauge lengths of 5 cm near the edge and 10 cm further from it. (See Table 1 and Graph 1 for details)

Gauge-lengths were measured immediately after dropping, and also 24 hours later when the rope had had chance to relax.

The procedure for carrying out a drop-test was as follows :

The rope, marked with its number, and "short end" or "long end" at each end, its gauge lengths, and in some cases other points, such as the positions of the knots and the edge, had a krab clipped in each end, and the 'short' end fastened to the eyebolt. The weight was raised to the required position by the pulley-block, and the rope passed over the profiled edge and clipped to the weight. The safety bar was removed, and the weight released by pulling on a piece of string at ground level, which was fastened to the release mechanism.

If the rope fractured, it would be dismounted. If the rope did not fracture, any measurements required at that point (see Tables 1 to 4) would be taken, the pulley block would then be lowered, a second length of rope fastened between it and the weight, and the tension relieved in the test specimen which was then dismounted for further measurements.

Lowering of the weight onto the safety-bar allowed re-attachment of the release mechanism and the weight could be lifted again. If required, the rope could then be remounted in the normal way, or set aside for further tests.

In order to obtain information about the cumulative damage to the rope, it was decided to carry out tensile tests after differing numbers of falls at a given fall factor (η), rather than to tensile test after one fall at varying ηs.

The fall-factor was chosen by lowering η until it gave sufficient data points in a plot of (say) retained rope strength v. number of falls. Therefore, in order to save rope, one rope would be drop-tested to destruction. If it failed on the 5th drop, this would give us 5 data points (including the point produced by testing an undamaged specimen). This was felt to be sufficient.

If acceptable, this η would be chosen, and ropes would be dropped once, twice etc. before being Instron tested.

The procedure for carrying out an Instron tensile test was as follows :

The specimen was fastened in the grips (Fig 7) by winding around the central bar and tying off with a bowline. The cross-head was raised, until the grips could be mounted in the locations on crosshead and load-cell which was fastened to the frame. The plotter was then calibrated, and the crosshead moved by fine control until there was a tension of 25 lbf (111.25 N) applied to the rope. A gauge length of 100 mm was marked (since there will be some rope-slip in the grips, and the distance between grips varies) on the free part of the rope.

The test was started by switching on the plotter whose 'distance' axis was set to move at a constant 10 inches/min, and then the crosshead which was set to move at a constant 2.0 inches/min. At regular intervals, the gauge length was measured, and noted on the force-distance plot, and the specimen was stretched until failure occurred.

For some specimens it was felt to be valuable to look at them under a microscope and make sketches of what was observed. (This being done before they were tensile-tested.)

Results from the drop-tests were tabulated (see Tables 1, 2, and 3) and from the tensile-tests in graphical form. (see Graphs 2, 3 and 4).

In order to investigate events within the rope core, it was decided to individually test the rope sub-elements; cord, strand & sheath. (see P 7). Carried out on the JJ22k, the procedure is similar to the Instron, but on a smaller scale, the gauge length again being 100 mm.

Tests on undamaged cord, strand, and sheath were performed, and the results are on p 31. At a later stage cords which had suffered some drop-damage were tested, both from rope near the 'edge' and rope nearer the ends. These results are shown on p 31.

To provide some back-up evidence of any conclusions which may have been drawn from drop and tensile tests, it was decided to simulate, as far as possible in a static test, the conditions of repeated drops. This was done by calculating the dynamic strain encountered in a drop (see p 25) and then, cyclically loading the specimen to this strain, observing the change in area of hysteresis curve with cycle number. (see Graph 15)

Because of the provision of a large amount of used 11 mm rope with a well-documented history (see Appendix I), it was decided to do some comparative tests to determine the effects of usage and age.

Thus, the drop, tensile, and cyclic tests were repeated, using new rope of 11 mm diameter. (see pp 28,34). The used rope, referred to as "Old blue", was also drop-tested and then tensile tested, after observation under a microscope. The results are on p 30.

Some cyclic tests were carried out on individual cords (p 45)

(A history of the tests performed on each numbered rope is given in Appendix III)

Observations

9mm Drop-Test Specimens

When the sheathed, and unsheathed specimens were drop tested, it was found that the unsheathed specimen broke immediately on the first drop; so no useable data could be obtained in a tensile test. However, there still remained the problem of observing what went on in the core. It was felt that study of the rope sub-elements alone would not provide the answer, and so pieces of thread were sewn through both sheath and core of some specimens and afterwards, by stripping off the sheath, observed to see whether there had been any relative movement.

The results of these initial single drops and the later multiple drop threaded specimens are recorded in tables 1, 2, and 3. As may be seen, there is a noticeable strain in the rope, but particularly at the edge. There is also some recovery of length after 24 hours (not shown). The strain in sheath and core are not the same. Reference to Table 1 shows that for Rope 13, the core was displaced in a different manner than the sheath, or perhaps the sheath recovered more than the core, In any case there was relative movement.

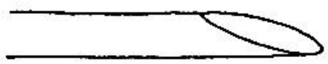
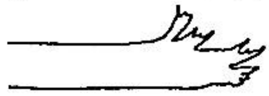
Back up evidence for non-uniform strain was obtained by measurements conducted on rope cords taken from Ropes 8 and 13. (see Table 6) This gave 'undamaged' sections an average value for $x = 5.9$ mm but at the edge $x = 6.3$ mm.

The first four ropes were dropped at $\eta = 1.836$ and all showed varying knot slippage of c. 5cm, referred to as 'pull-through', and where the rope had passed over the edge, it was warm to the touch. Specimen 1, which did not break, showed an area of sheath abrasion extending 12 cm before the sheath was torn. This tear lead to kinking, and a considerable decrease in rope stiffness at this point. The other ropes also showed the abrasion and at the break, there was evidence of fibres melting. The remaining rope ends were kinked, indicating different strains in the rope cords.

To obtain sufficient data points to draw any conclusions it was decided to reduce η to 1.2.

However, fracture occurred on the second drop and so η was further reduced to 0.8.

The opportunity was taken to microscopically inspect ropes which had been dropped so far. Damage areas showed considerable fibre melting and kinking. Typical breaks occurred as shown in a) below, with one or two as b)

a)  b) 

There was also evidence of inter-fibre contact, fusion, and separation again, resulting in fibre surface damage.

At $\eta = 0.8$, there were sufficient data points for a graph (Five). Due to the inaccuracies and inconsistency of both forms of strain measurement hitherto adopted, it was decided to measure dynamic and static strains in some of the specimens, by measuring the amount of scuffing and pull-through, and, knowing the fixed distance between edge and tie-off point, calculating the maximum strain in the tie-off section of the rope. (see Table 3 and p 28)

The general trend was to increased abrasion damage, and increased flexibility with increasing numbers of drops. Static strain tended to increase with number of drops, sharply at first, then more slowly. Dynamic strain could not be said to have any pattern of consistency however, but the results were averaged, and used to provide a strain-figure for the semi-static cyclic loading carried out in the Instron to produce a hysteresis loss curve for the rope. Visually it appeared that with increasing number of drops, the weight was arrested more violently; ie a decrease in "stretchiness".

General trends in the Instron tests (see p 30 and Graphs 10, 11, and 12) were unsurprising; allowing for the expected 'scatter' of results when just one specimen is used for each data point.

There was a decrease in the value of strain to failure from c. 35% to 23% with increasing number of drops, and a retention of the initial U.T.S. of c. 15.6 kN up to 3 drops. However, the four-fall rope showed a big drop in U.T.S. to 4.45 kN.

The Instron test specimens did not always break at the point that they had been over the edge. If they did not, they broke at the point where the knot had been in the original drop-test specimen.

Cyclic tests to a strain of 22.5% gave hysteresis curves of decreasing area with increasing number of cycles indicating lower energy absorbtion.

11 mm Drop-Test Specimens

Drop tests at $\eta = 1.836$ caused failure on the third drop, so again, to achieve sufficient data points η was decreased to 1.4. (In all cases where failure did take place, the rope broke at the edge rather than in a knot, including tensile tests.)

The 11mm specimens followed the same pattern of cumulative visual damage as did the 9 mm batch. Measured strains (Table 3) showed similar trends, but the dynamic strain increased with increasing number of falls. It may be seen that for Rope 3, the increment in dynamic strain decreased with increasing number of falls. I.E. the rope becomes stiffer. This is again confirmed visually, by more violent arrests of the weight's fall on those ropes which have been dropped more times.

The Instron tests give a gradual decrease in U.T.S. with increasing number of falls, and the trend of strain to failure is similar. (see Graphs 11 and 12)

Cyclic tests to a strain of 26% showed similar trends to the 9mm rope, with a greatly reduced hysteresis curve area after the first cycle.

Used 11 mm Rope

It was decided not to both drop and tensile test each specimen, but to carry out either a drop or tensile test.

A section which appeared to have suffered little damage was tested at $\eta = 1.4$. This failed on the second drop. A section of higher stiffness was also tested with the same result. Examination of the core section showed a completely different construction of plaited core-strands (not Kernmantle) and so it became apparent that no direct comparison with the new 11mm rope was possible.

Microscopic examination of the fibres showed many to have fused together, and also some to exhibit signs of fatigue (see Reference 3)

Tensile tests gave failure loads of about one quarter that of new 11mm Kernmantle-type rope, irrespective of apparent surface damage. There was also very little difference in failure strain, this being approximately 30%.

ROPE SUB-ELEMENT SAMPLES

UNDAMAGED CORDS

Failure load varied between 0.79 and 1.65 kN and failure strain was between 27 and 34.5%.

However, if one result is ignored, we get fairly consistent failure strain of approximately 34% and failure load of 1.35 to 1.65 kN. On average, permanent extension of 5.5 mm was found. It was noted that there was continual fibre damage throughout the specimens, not just at the point of break.

UNDAMAGED STRANDS

U.T.S. varied from 0.28 to 0.55 kN with failure strains of between 16.4 and 24.8%. - a much lower failure strain than the cords. There was permanent extension of 3 mm - less than the cords.

UNDAMAGED SHEATH

This failed at 3.5 kN and a strain of c. 36%.

BLACK THREAD

This was tested to satisfy any doubts about its significance. It failed at 0.1 kN and a strain of 8%. So by calculation (p 24) it can be seen that even the smallest fall will produce large enough strains to break this thread in the 9 mm rope, and only a slightly larger fall is required to break it in the 11 mm rope.

DAMAGED CORDS

Three tests on cords from the 'free' part of the rope (away from the edge) and three from the part going over the edge were tested in the JJ22K after two drops at $\eta = 0.8$.

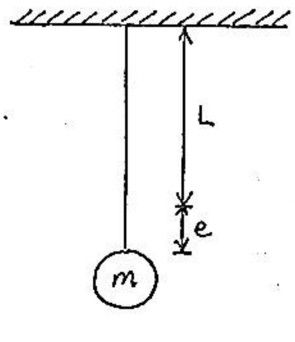
Those in the 'free' part of the rope had an average failure load of 1.33 kN and strain to failure of 27%. Those in the damaged 'edge' part of the rope had an average failure load of 1.53 kN and strain to failure of 24.8%.

CORD HYSTERESIS CURVES

Comparison of two adjacent cycles (in time) for an undamaged cord gives a greatly reduced area of the hysteresis curve (see p 46). However, a fall damaged rope ($3 \times \eta = 0.8$) has a larger hysteresis area curve (see Graph 14).

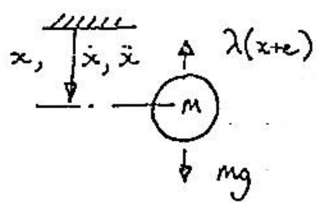
THEORY

PEAK LOAD CALCULATION



Consider a mass m, fixed by a rope, initial length L, to a rigid support such that the rope is extended by an amount e when the mass is at rest.
For small oscillations about this mean position, the mass will execute simple harmonic motion as demonstrated below.

Let the displacement from the datum be x, positive downwards, and the rope constant be λ N/m.



We have $-\lambda(x+e)+mg = m\ddot{x}$

but $\lambda e = mg$ so : $m\ddot{x} = mg - \lambda x - mg$

$$\ddot{x} = \frac{-\lambda}{m} x$$

which is the basic S.H.M. equation.

So we have

$$x = A \sin \omega t \quad (1)$$
$$\dot{x} = A\omega \cos \omega t \quad (2)$$
$$\ddot{x} = -A\omega^2 \sin \omega t = -\omega^2 x \quad (3)$$

where $\omega = \sqrt{\frac{\lambda}{m}}$.

Initial conditions : If we know the height of fall we may calculate the speed of travel of the mass at the moment the rope becomes taut.

$$V^2 = u^2 + 2as.$$

$V = \dot{x}$ at $x = -e$.
u = initial speed $= 0$.
$a = g$ = gravitational acceleration
s = distance fallen $= \eta L$
where η is the fall factor (p 6)

so $$V = \sqrt{2g\eta L}$$

$$-e = A \sin \omega t \Rightarrow e^2 = A^2 \sin^2 \omega t$$

$$V = \omega A \cos \omega t \Rightarrow \left(\frac{V}{\omega}\right)^2 = A^2 \cos^2 \omega t$$

so $e^2 + \left(\frac{V}{\omega}\right)^2 = A^2$

so $A^2 = e^2 + \dfrac{2mg\eta L}{\lambda}$

$mg = \lambda e$ so $A^2 = (e^2 + 2e\eta L)$

Let $s = e/L$ ie, the fractional static rope stretch in %.

$$A = L\sqrt{2s\eta + s^2}.$$

maximum stretch of the rope $= A + e$

$= L\left(s + \sqrt{2\eta s + s^2}\right)$ so the maximum force in the rope $= (A+e)\lambda$, $\lambda = \dfrac{mg}{e} = \dfrac{mg}{sL}$

so $F_{pk} = mg\left[1 + \sqrt{\dfrac{2\eta}{s} + 1}\right]$

ie it is independent of rope length.

(A table of maximum forces is included in Appendix II)

Peak Strain Rate

Strain rate $\dot{\varepsilon} = \dfrac{\text{rate of extension}}{\text{length at that moment}} = \dfrac{\dot{x}}{L+e+x}$

Peak strain rate occurs approximately at the datum level,

so $\dot{\varepsilon}_{max} = \dfrac{\dot{x}_{max}}{L+e} = \dfrac{A\omega}{L+e}$

So $\dot{\varepsilon}_{max} = \dfrac{L\sqrt{2s\eta + s^2}.\sqrt{g/sL}}{L+e} = \dfrac{\sqrt{gL(2\eta+s)}}{L+e}.$

(A table of strain rates is included in Appendix IV)

Both these analyses ignore damping:
For a linear, second order system, the exponential envelope of decay goes down as

$$e^{-c\omega_n t}$$

We are interested in $t = \frac{T}{4}$ (T = period) $T = \frac{2\pi}{\omega_n}$ so we have decay as $e^{-c\pi/2}$ between damped and undamped first peaks. (see calculations for value of c)

CALCULATIONS

PEAK LOAD

$$F_{pk} = mg\left[1 + \sqrt{\frac{2\eta}{s} + 1}\right].$$

For the 9mm new rope
$m = 85$ kg, $\eta = 0.8$, $s = 0.07$

so $F_{pk} = 4910$ N.

For the 11 mm new rope
$m = 85$ kg, $\eta = 1.4$, $s = 0.03$

So $F_{pk} = 8930$ N.

DAMPING.

The value of c to choose in the expression $e^{-c\omega_n t}$ would appear to be low, and in our case negligible. (Reference 2).

Compact S has a peak impact force of 10590 N at $\eta = 2$, $m = 80$ kg.

Assuming its static stretch fraction $s = 3\%$ as with our 11mm.

We get F_{pk} (no damping) $= 80 \times 9.81\left[1 + \sqrt{\frac{4}{0.03} + 1}\right]$

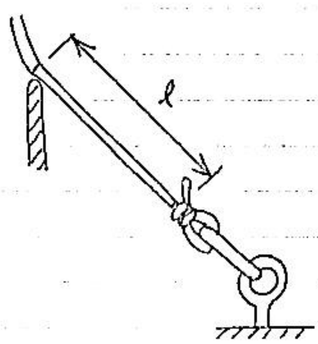
$= 9881$ N

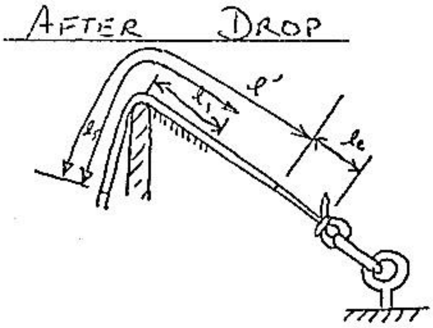
– ie less than the damped case!

STRAIN CALCULATION

l in cm

BEFORE DROP





$$\varepsilon_{STAT} = \frac{l' - l}{l}.$$

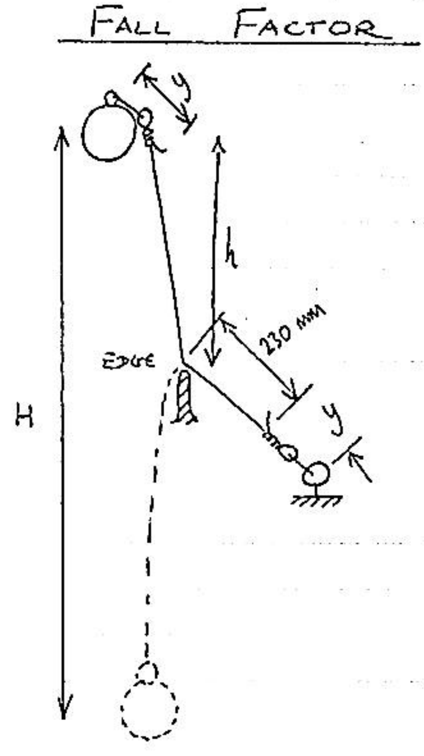
$$\varepsilon_{DYN} = \frac{l_1}{l' + l_e - l_s}$$

For example : 9mm rope, $\eta = 0.8$

1st fall :

$l = 24$ cm
$l' = 25$ cm
$l_1 = 4.5$ cm
$l_e = 5.0$ cm = pull through
$l_s = 10$ cm. = scuffed length.

so $\varepsilon_{STAT} = 0.0417$, $\varepsilon_{DYN} = 0.225$.



Total fall height = H
$= 2 \times (h + y)$
$y = 14$ cm (constant).

Total free length of the rope = $h + 23$

so $$\eta = \frac{2(h+y)}{h+23}$$

Max value of h attainable in the rig ≈ 86.5 cm.

so $$\eta_{max} = \frac{2(86.5 + 14)}{86.5 + 23}$$

$$= \underline{1.836}$$

conversely $$h = \frac{23\eta - 2y}{(2 - \eta)}$$

RESULTS

TABLE 1 — EXTENSION DISTRIBUTION THROUGHOUT THE ROPE

DATE	ROPE NUMBER	FALL FACTOR	NUMBER OF FALLS	NOTES
27.1.84	1	1.836	1	ALL LENGTHS IN CM REFER ALSO TO GRAPH 1
GAUGE LENGTHS (FROM SHORT END)		2.75 THROUGHOUT LENGTH.		

FINAL GAUGE LENGTH	2.85	2.75	2.75	3.3	3.0	2.85	2.95	2.9	2.9	→ TO THE END.
GAUGE LENGTH EXTENSION	0.1	0	0	1.05	0.25	0.1	0.2	0.15	0.15	→ TO THE END.

ROPE NUMBERS 2, 3, 4 ALL FAILED ON THE 1ST. DROP.

DATE	ROPE NUMBER	FALL FACTOR	NUMBER OF FALLS
1.3.84	13	0.8	3

INITIAL GAUGE LENGTHS (SHEATH & CORE)	5	5	5	5	5	5	5	5	10	10	10	10	10	10	10
GAUGE LENGTH AFTER DROP — SHEATH	5.3	5.1	6.2	5.2	5.3	5.5	5.3	5.5	10.6	11.0	10.9	10.8	11.0	11.0	11.0
GAUGE LENGTH AFTER DROP — CORE	5.4	5.5	6.0	5.5	5.6	5.2	5.2	5.5	← 'AS SHEATH →						
EXT^N. SHEATH	0.3	0.1	1.2	0.2	0.3	0.5	0.3	0.5	0.6	1.0	0.9	0.8	1.0	1.0	1.0
EXT^N. CORE	0.4	0.5	1.0	0.5	0.6	0.2	0.2	0.5	0.6	1.0	0.9	0.8	1.0	1.0	1.0

DATE	ROPE NUMBER	FALL FACTOR	NUMBER OF FALLS
27.3.84	8	0.8	3

RELAXED GAUGE LENGTHS — SHEATH	5.0	5.1	5.5	5.3	5.5	5.4	5.3	5.2	10.6	10.8	10.9	10.9	10.4	10.8	10.8
RELAXED GAUGE LENGTHS — CORE	5.0	← NO CONCLUSIVE RESULTS DUE TO BROKEN COTTON →													
EXT^N. SHEATH	0	0.1	0.5	0.3	0.5	0.4	0.5	0.2	0.6	0.8	0.9	0.9	0.4	0.8	0.8
EXT^N. CORE	0	← NO CONCLUSIVE RESULTS DUE TO BROKEN COTTON →													

TABLE 2		MISCELLANEOUS DROP - TEST DATA					
DATE	ROPE NUMBER (DIAMETER MM)	η	NUMBER OF DROPS	INITIAL LENGTH (CM)	FINAL LENGTH (CM)	RELAXED LENGTH (CM)	PULL THROUGH (CM)
22.2.84	5 (9)	1.2	1		NO DATA		
22.2.84	6 (9)	1.2	2 (FAILED)		NO DATA		
29.2.84	7 (9)	0.8	4	109.5	119	115.7	4
29.2.84	9 (9)	0.8	3	109.5	113	112.3	4
29.2.84	10 (9)	0.8	2	111.0	120	117	6.5
1.3.84	11 (9)	0.8	1	109.5	115	112	4

TABLE 3			DROP TEST STRAIN DATA								
DATE	ROPE Nº (DIAMETER) (MM)	η	Nº OF DROPS	l (CM)	l' (CM)	l_1 (CM)	l_e (CM)	l_s (CM)	ε_{STAT}	ε_{STAT} RELAX	ε_{DYN}
2.3.84	8 (9)	0.8	1	23	24.3	3.5	5.0	11	0.06	0.04	0.19
2.3.84	8 (9)	0.8	2	23	24.7	4.0	5.5	13	0.07	0.04	0.23
2.3.84	8 (9)	0.8	3	23	25.0	4.0	6.3	13.5	0.09	0.04	0.22
2.3.84	13 (9)	0.8	1	24	25.0	4.5	5.0	10	0.04	0.01	0.23
2.3.84	13 (9)	0.8	2	24	25.4	4.0	8.0	14	0.05	0.02	0.21
2.3.84	13 (9)	0.8	3	24	25.5	4.0	8.0	15.5	0.06	0.05	0.22
5.3.84	1 (11)	1.836	1	22	23.5	4.8	7.0	14	0.07	–	0.29
5.3.84	1 (11)	1.836	2	22	25.0	5.0	8.0	16	0.14	–	0.29
6.3.84	2 (11)	1.4	1	22.5	–	–	–	–	ROPE WRAPPED AROUND BAR		
6.3.84	2 (11)	1.4	2	22.5	25.5	4.5	6.0	13.5	0.13	–	0.25
6.3.84	2 (11)	1.4	3	22.5	25.5	4.0	7.0	14	0.13	–	0.22
6.3.84	2 (11)	1.4	4	22.5	25.5	4.5	7.3	15	0.13	–	0.25
7.3.84	3 (11)	1.4	1	22	24.3	4.0	4.8	12.3	0.11	–	0.24
7.3.84	3 (11)	1.4	2	22	24.5	4.5	6.0	14	0.11	–	0.27
7.3.84	3 (11)	1.4	3	22	24.8	4.8	6.5	15.1	0.13	–	0.30
7.3.84	4 (11)	1.4	1	23	25.3	4.0	4.8	12.5	0.10	–	0.23
7.3.84	4 (11)	1.4	2	23	25.6	5.5	5.3	14.7	0.11	–	0.34
7.3.84	5 (11)	1.4	1	23	25.5	4.0	4.5	13	0.11	–	0.24
7.3.84	5 (11)	1.4	2	23	25.3	4.8	5.5	14.6	0.12	–	0.29
7.3.84	6 (11)	1.4	1	24	25.8	4.3	5.0	12.6	0.08	–	0.24

See also Graph 10

TABLE 4	DAMAGED ROPE STRAND ELONGATION				
DATE	ROPE Nº (DIAMETER) (MM)	POSITION	x (mm)	$X_{average}$ (mm)	No. of drops
9.3.84	8 (9)	FREE	5.5, 6.5, 6.5, 5.9 6, 5, 5, 6	5.8	3
9.3.84	8 (9)	EDGE	7, 6.5, 5.5, 7 6.5, 5.6, 6.4, 6.2	6.3	3
9.3.84	13 (9)	FREE	5.5, 5, 6.5, 6.5 6, 6, 5, 6.5	5.9	3
9.3.84	13 (9)	EDGE	6, 6.5, 6, 6.5 6, 7, 6, 6.3	6.3	3
9.3.84	15 (9)	FREE	6.5, 6.5, 6, 6.5 6.5, 6.5, 6.5, 6	6.4	2
9.3.84	15 (9)	EDGE	7.5, 6, 5.5, 6.5 6, 6, 6.5, 6.5	6.3	2

All ropes were dropped at $\eta = 0.8$

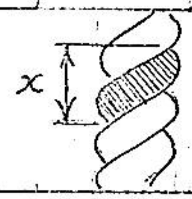


TABLE 5		INSTRON TENSILE TEST DATA			
DATE	ROPE Nº (DIAMETER) (mm)	η	Nº OF DROPS	U.T.S (kN)	FAILURE EXTN (mm).
2.3.84	7 (9)	0.8	4	4.45	20
2.3.84	9 (9)	0.8	3	15.22	32
2.3.84	10 (9)	0.8	2	9.57	28
2.3.84	11 (9)	0.8	1	15.31	37
2.3.84	12 (9)	0.8	0	14.69	35
13.3.84	16 (9)	0.8	3	14.56	33
13.3.84	2 (11)	1.4	5	11.61	24
13.3.84	4 (11)	1.4	3	15.00	21
13.3.84	5 (11)	1.4	2	19.85	27
13.3.84	6 (11)	1.4	1	20.03	34
13.3.84	7 (11)	1.4	0	43.28	34
14.3.84	B4 (11)	–	0	9.35	29
14.3.84	B5 (11)	–	0	9.79	32
14.3.84	B6 (11)	–	0	7.57	29
14.3.84	B7 (11)	–	0	9.57	33
14.3.84	B8 (11)	–	0	10.01	31

See also Graphs 2, 3, and 4

TABLE 6 : TENSILE TESTS ON DAMAGED ROPE CORDS (9.3.84)			
CORD Nº	SECTION POSITION	U.T.S (KN)	FAILURE EXT^N (MM)
15 F 1	FREE	1.55	27
15 F 2	FREE	1.05	23
15 F 3	FREE	1.39	28
	AVERAGE	1.33	26
15 E 1	EDGE	1.51	29
15 E 2	EDGE	1.40	23
15 E 3	EDGE	1.69	23
	AVERAGE	1.53	25

Cords from Rope 15 (3 falls at $\eta = 0.8$).
All gauge lengths = 100 mm.
(See also Graphs 8 & 9)

TABLE 7 : TENSILE TESTS ON UNDAMAGED CORDS					
DATE	CORD NUMBER	U.T.S. (KN)	FAILURE EXT^N (mm)	AVERAGE UTS (KN)	AVERAGE FAILURE EXT^N (mm)
10.2.84	1	0.79	27	IGNORED	IN AVERAGE
15.2.84	2	1.35	34		
15.2.84	3	1.65	34	1.54	34
15.2.84	4	1.63	34		
24.2.84	SHEATH	3.48	32	—	—

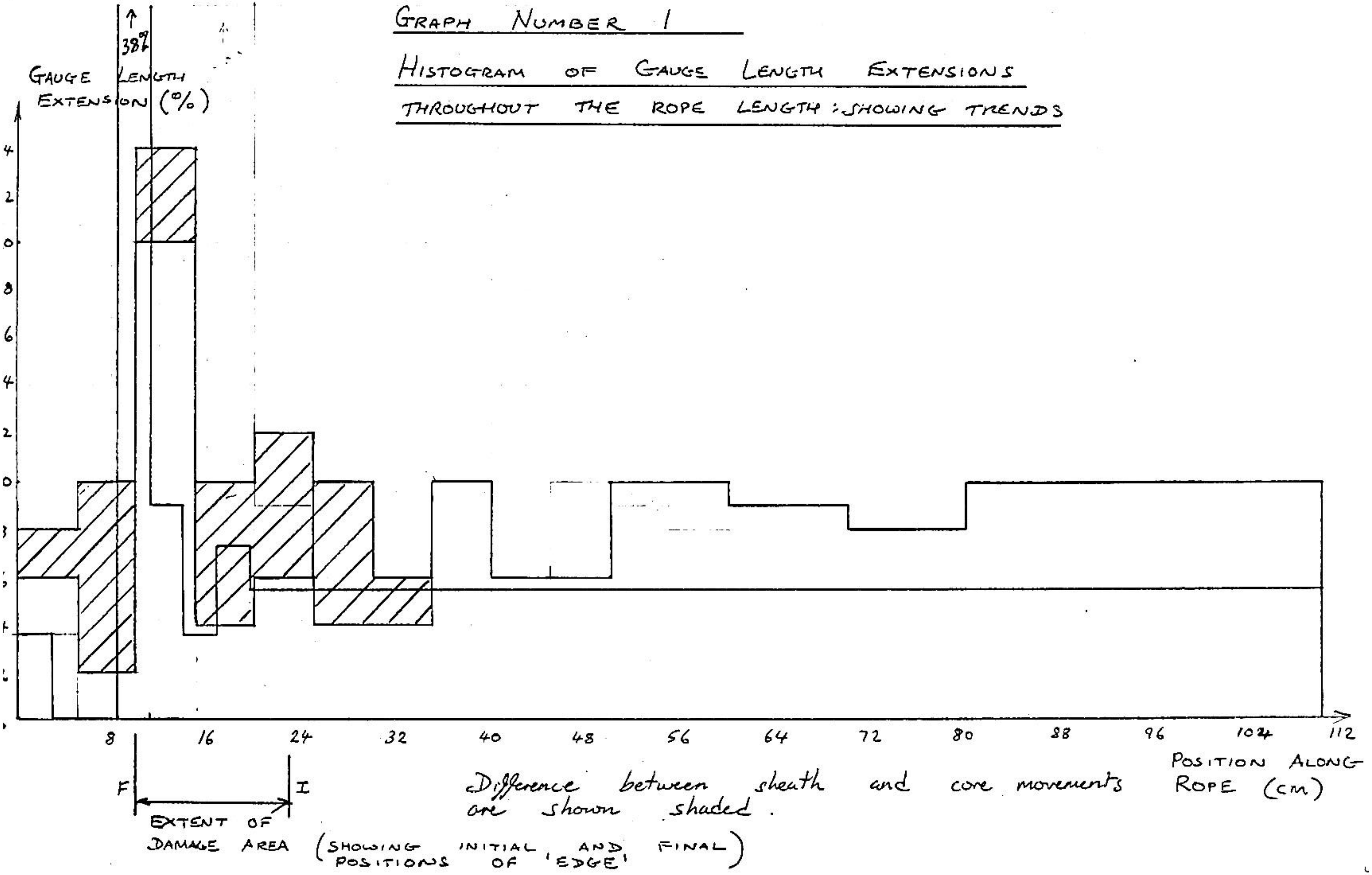
Gauge length = 100 mm. (See also Graphs 7, 8 and 9)

TABLE 8 : TENSILE TESTS ON UNDAMAGED STRANDS					
DATE	STRAND Nº	U.T.S (KN)	FAILURE EXT^N (mm)	AVERAGE UTS (KN)	AVERAGE FAILURE EXT^N (mm)
15.2.84	1	0.30	17		
15.2.84	2	0.27	16	0.37	19
15.2.84	3	0.55	25		
15.2.84	BLACK THREAD	0.11	8		

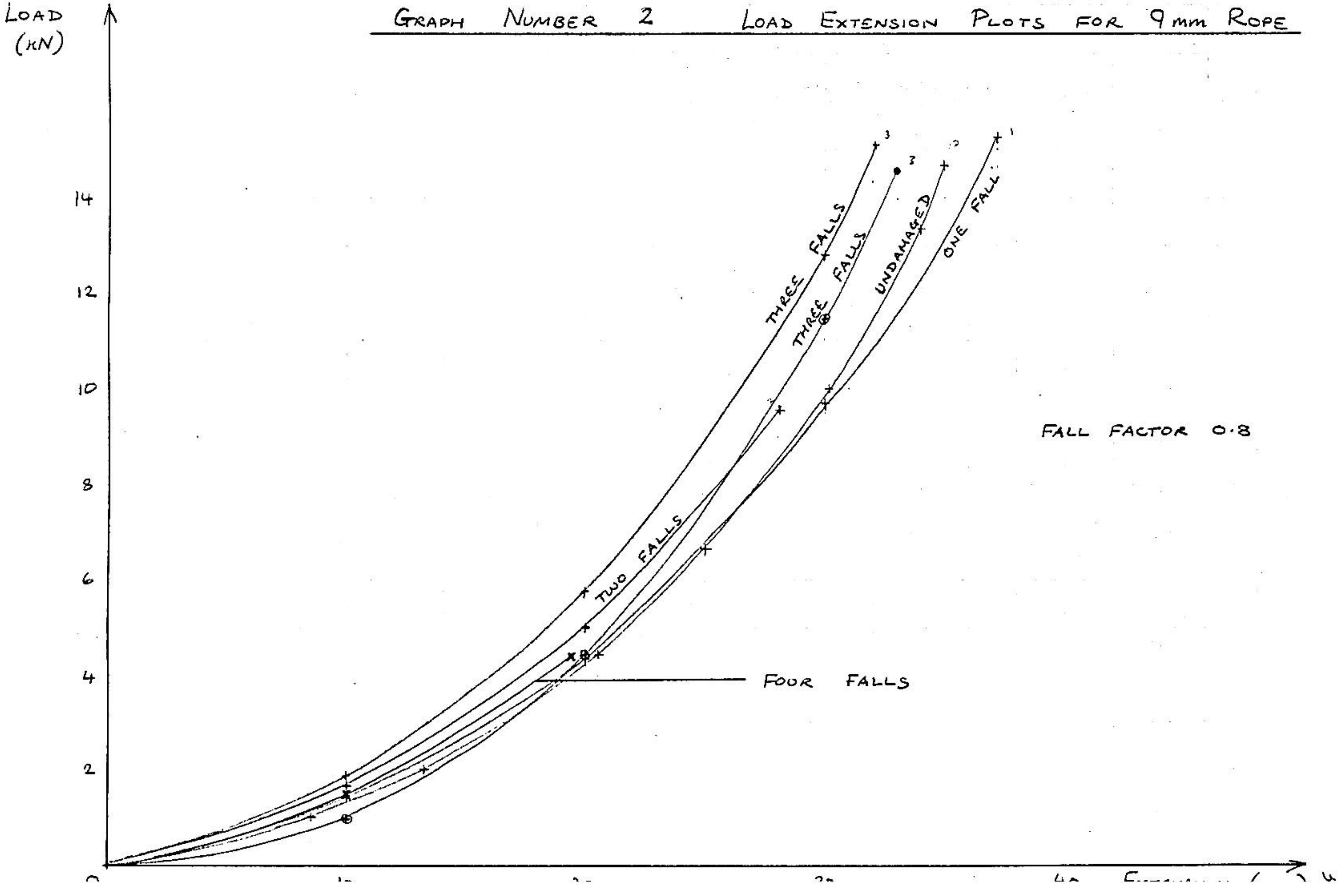
Gauge length = 100 mm (See also Graph 6)

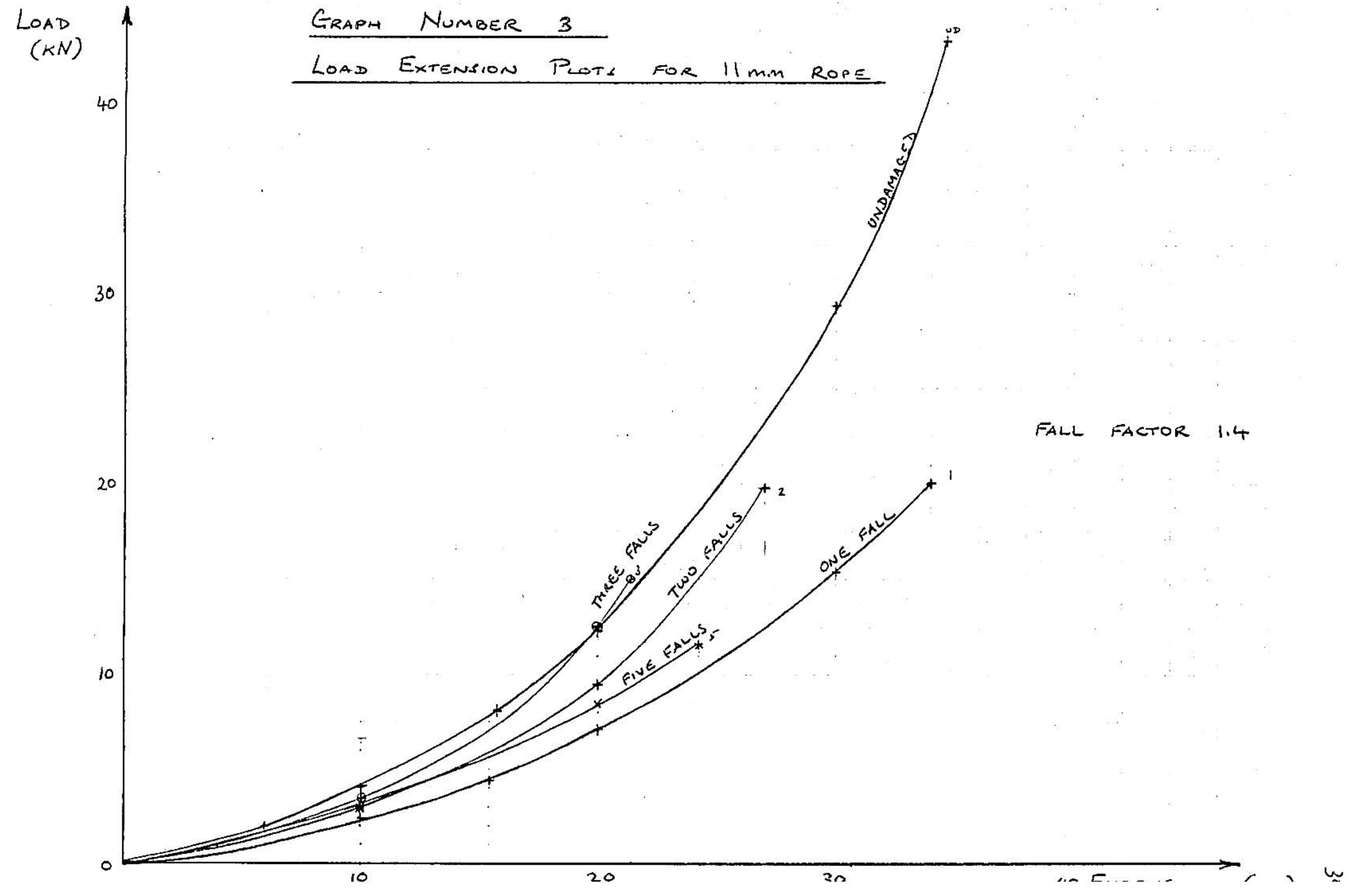
Graph Number 1

Histogram of Gauge Length Extensions throughout the Rope Length: Showing Trends



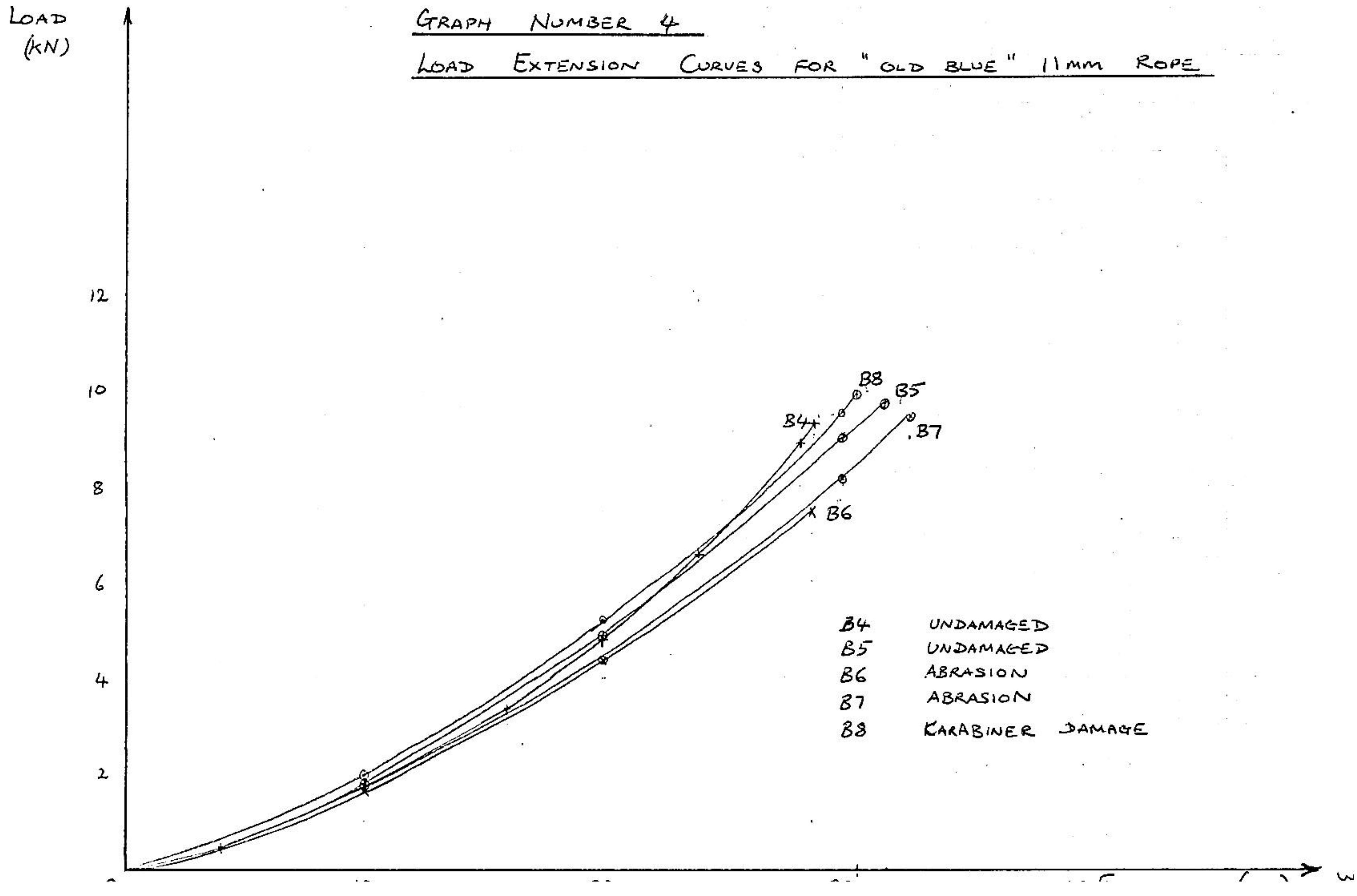
Graph Number 2 Load Extension Plots for 9 mm Rope




GRAPH NUMBER 3
LOAD EXTENSION PLOTS FOR 11mm ROPE
LOAD (kN)
40
30
20
10
0
10
20
30
UNDAMAGED
UD
THREE FALLS
TWO FALLS
FIVE FALLS
ONE FALL
FALL FACTOR 1.4

Graph Number 4

Load Extension Curves for "Old Blue" 11mm Rope

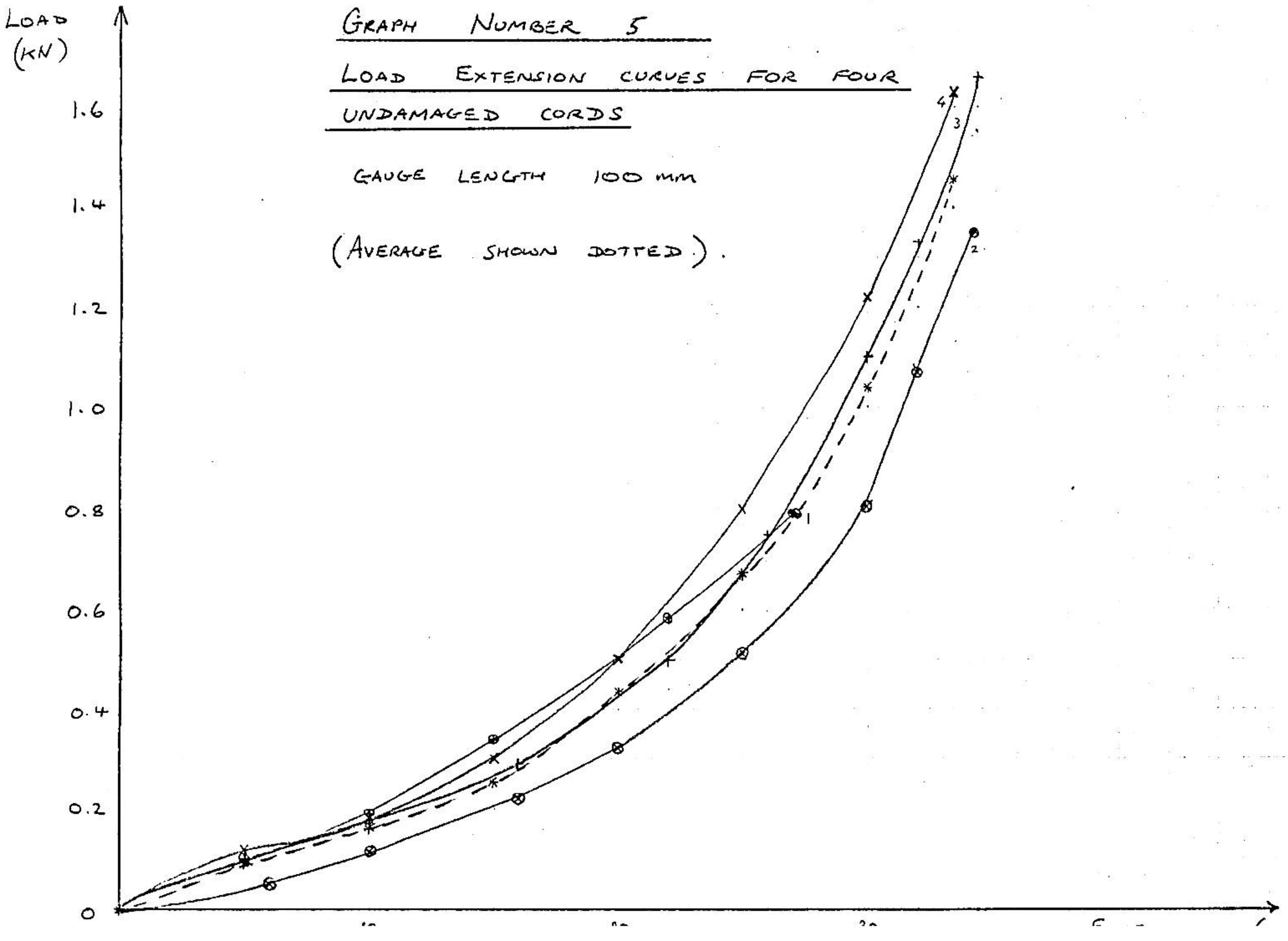


GRAPH NUMBER 5

LOAD EXTENSION CURVES FOR FOUR UNDAMAGED CORDS

GAUGE LENGTH 100 mm

(AVERAGE SHOWN DOTTED).

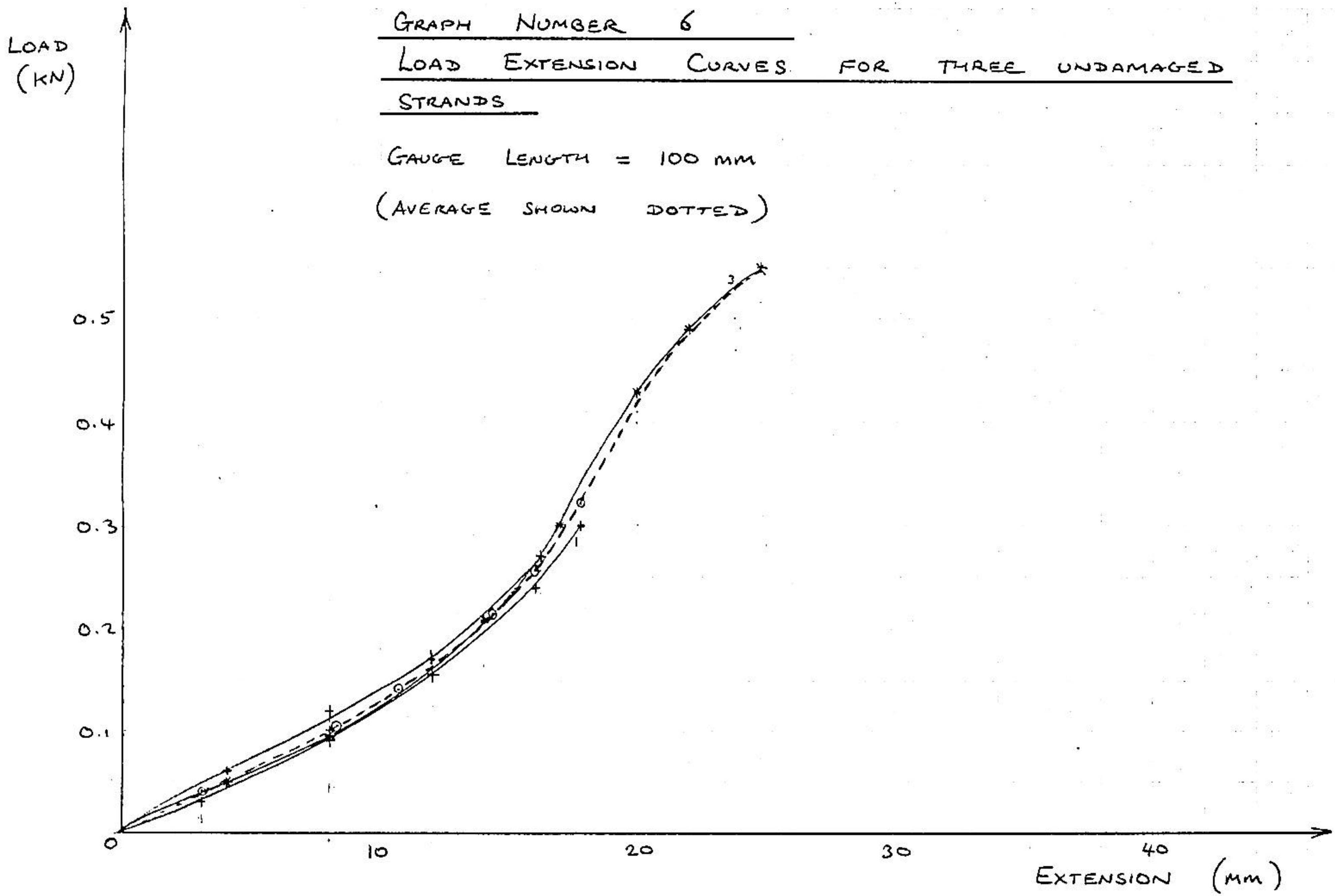


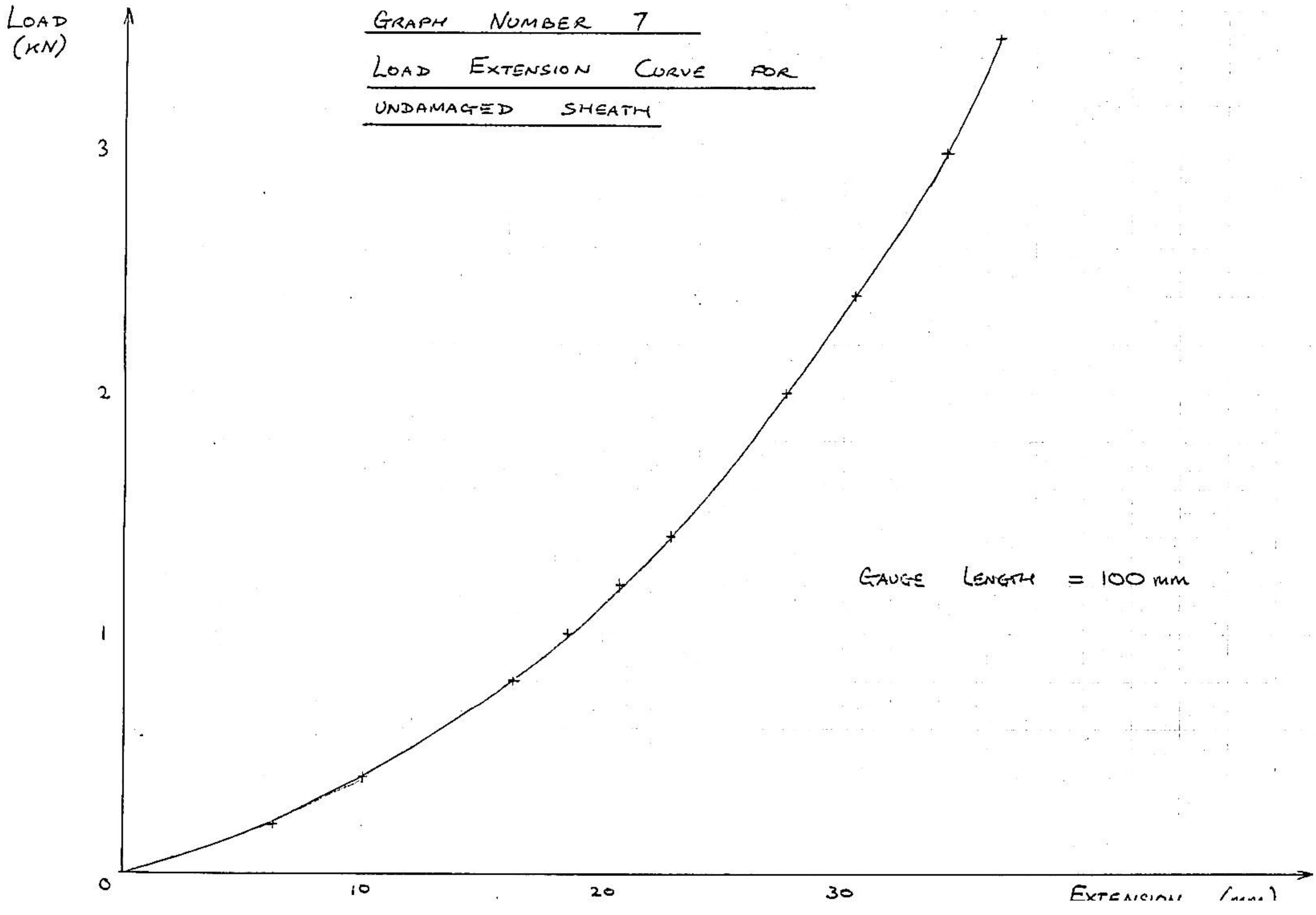
GRAPH NUMBER 6

LOAD EXTENSION CURVES FOR THREE UNDAMAGED STRANDS

GAUGE LENGTH = 100 MM

(AVERAGE SHOWN DOTTED)

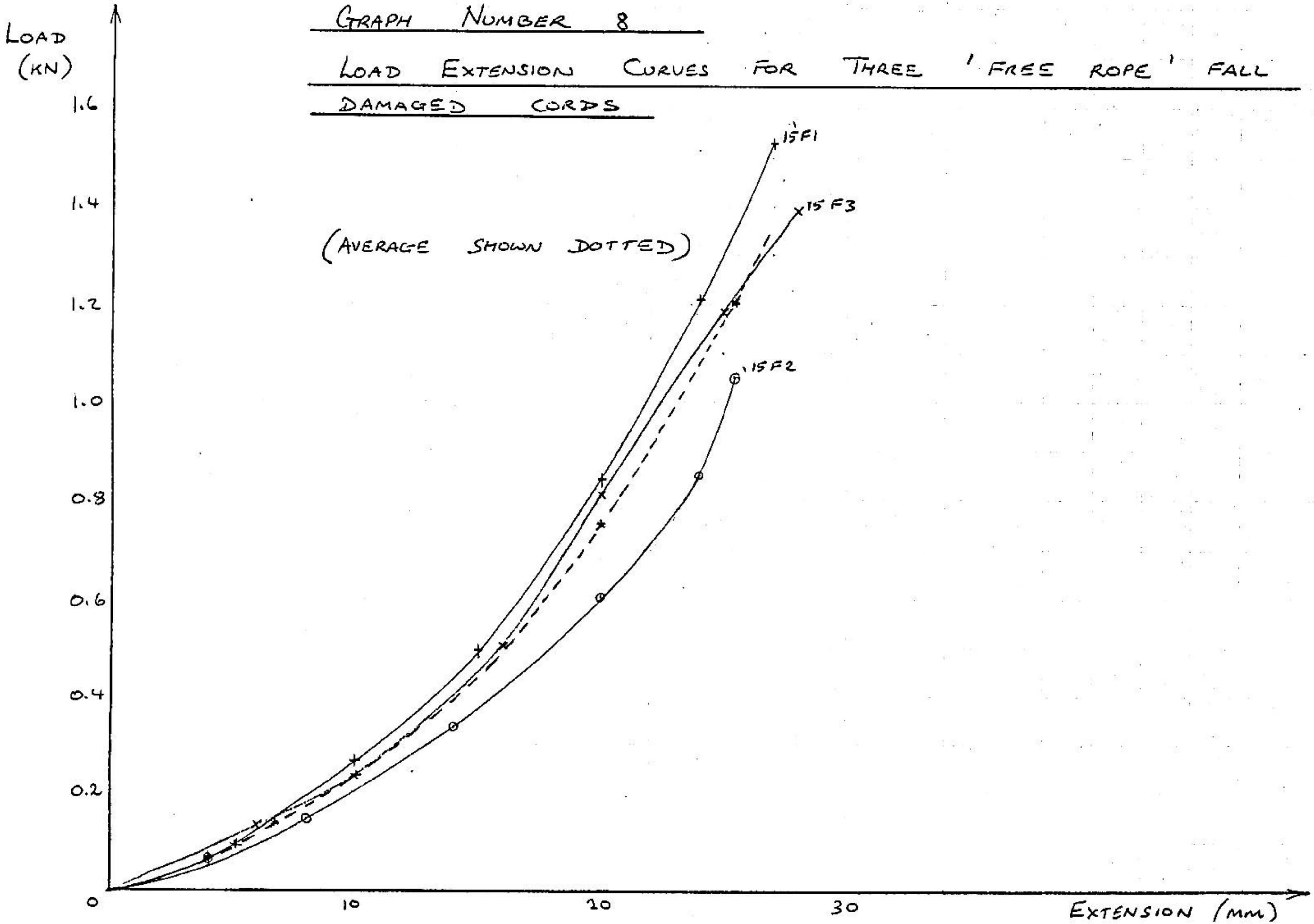


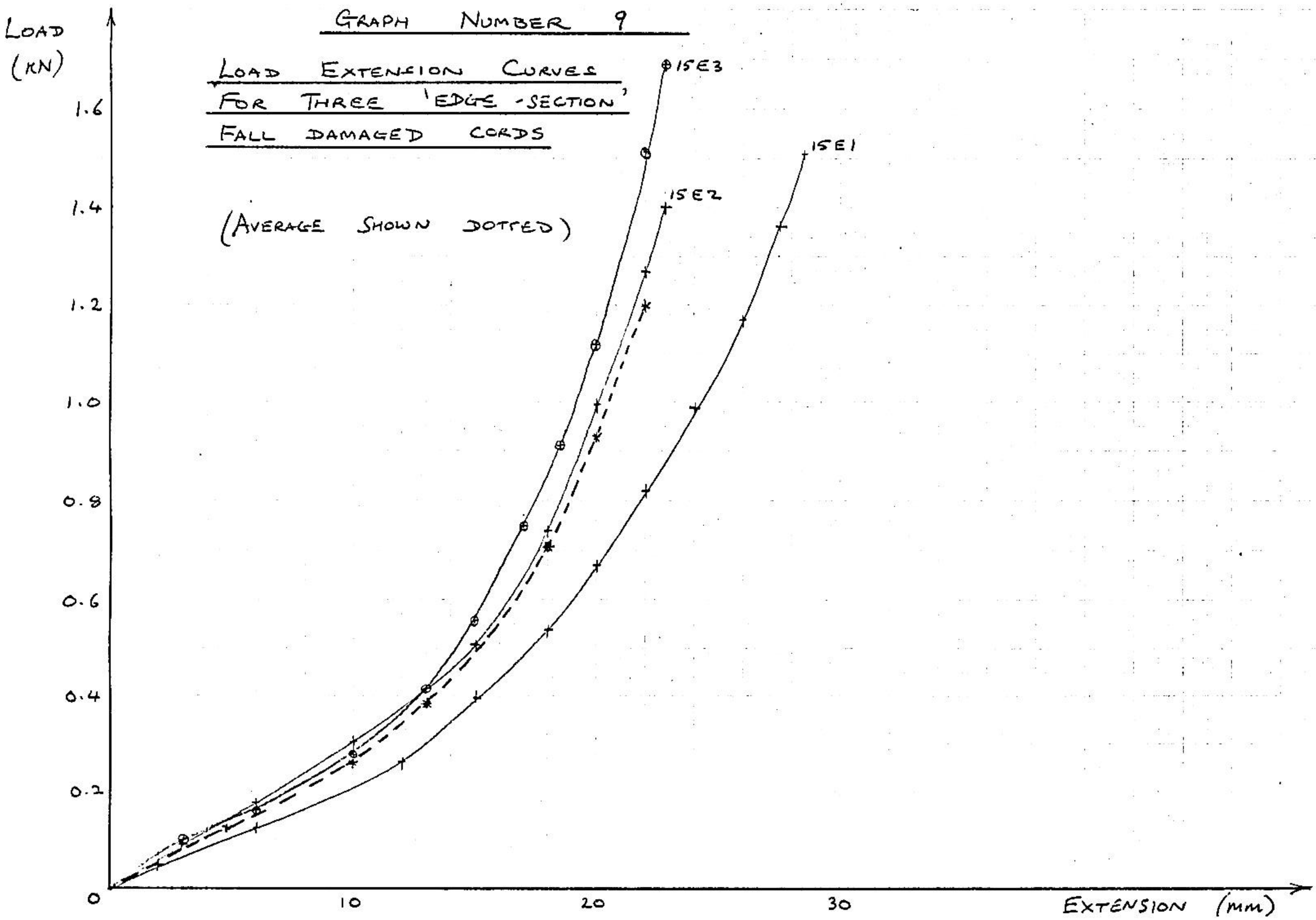

GRAPH NUMBER 7
LOAD EXTENSION CURVE FOR
UNDAMAGED SHEATH
LOAD (KN)
3
2
1
0
10
20
30
GAUGE LENGTH = 100 mm

GRAPH NUMBER 8

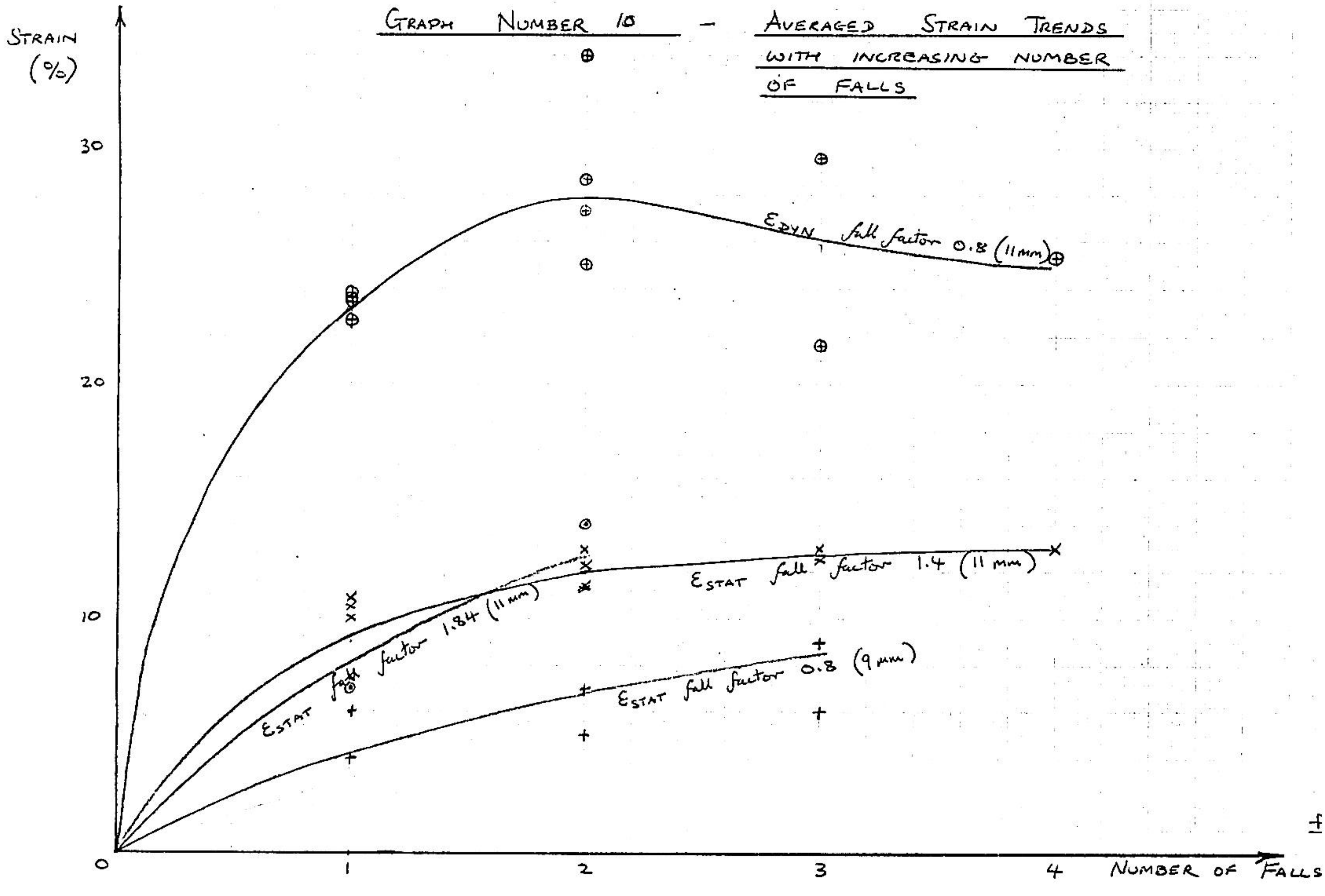
LOAD EXTENSION CURVES FOR THREE 'FREE ROPE' FALL DAMAGED CORDS

(AVERAGE SHOWN DOTTED)



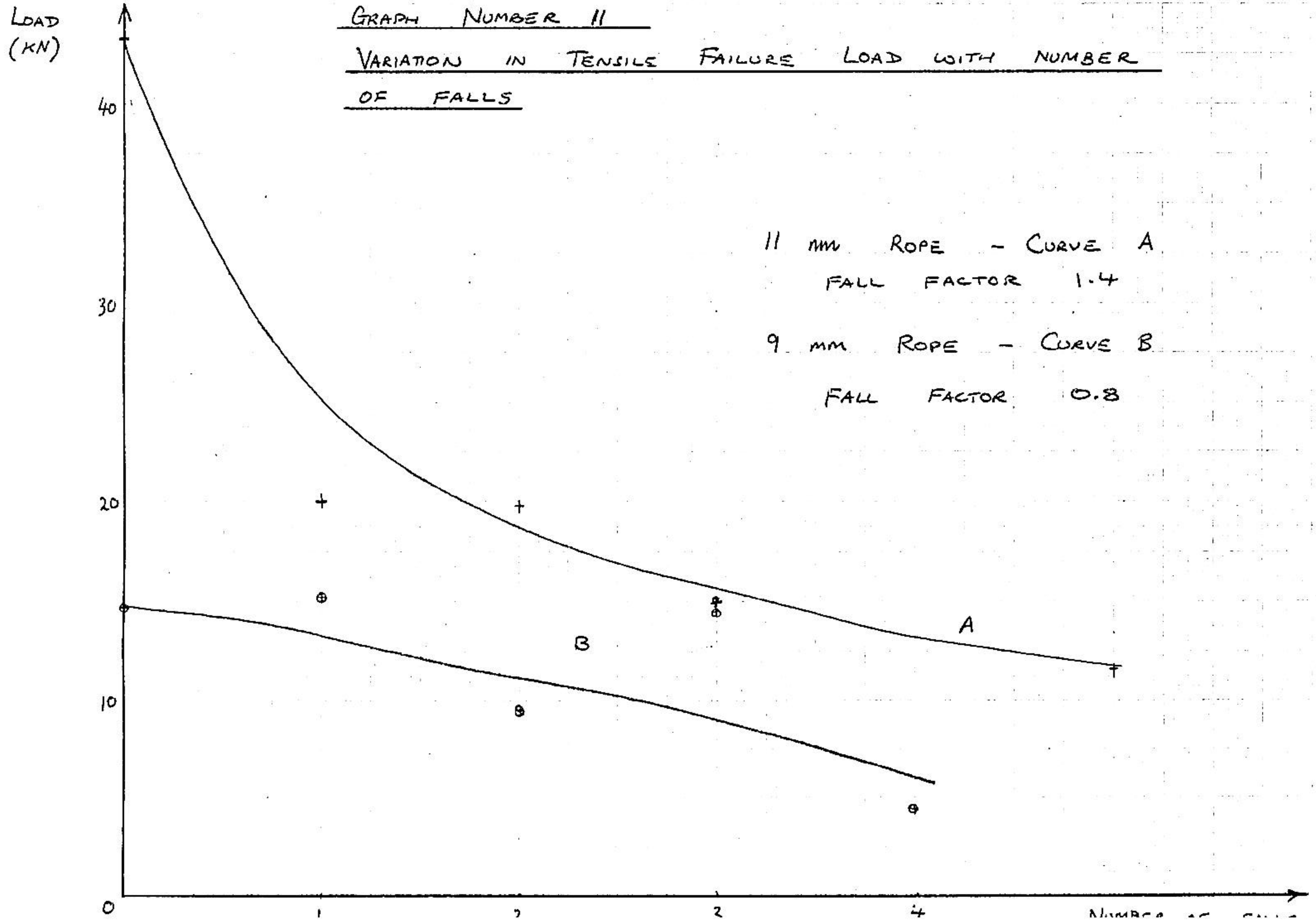

GRAPH NUMBER 9
LOAD EXTENSION CURVES
FOR THREE 'EDGE-SECTION'
FALL DAMAGED CORDS
(AVERAGE SHOWN DOTTED)
LOAD (KN)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
10
20
30
EXTENSION (MM)
15E3
15E1
15E2

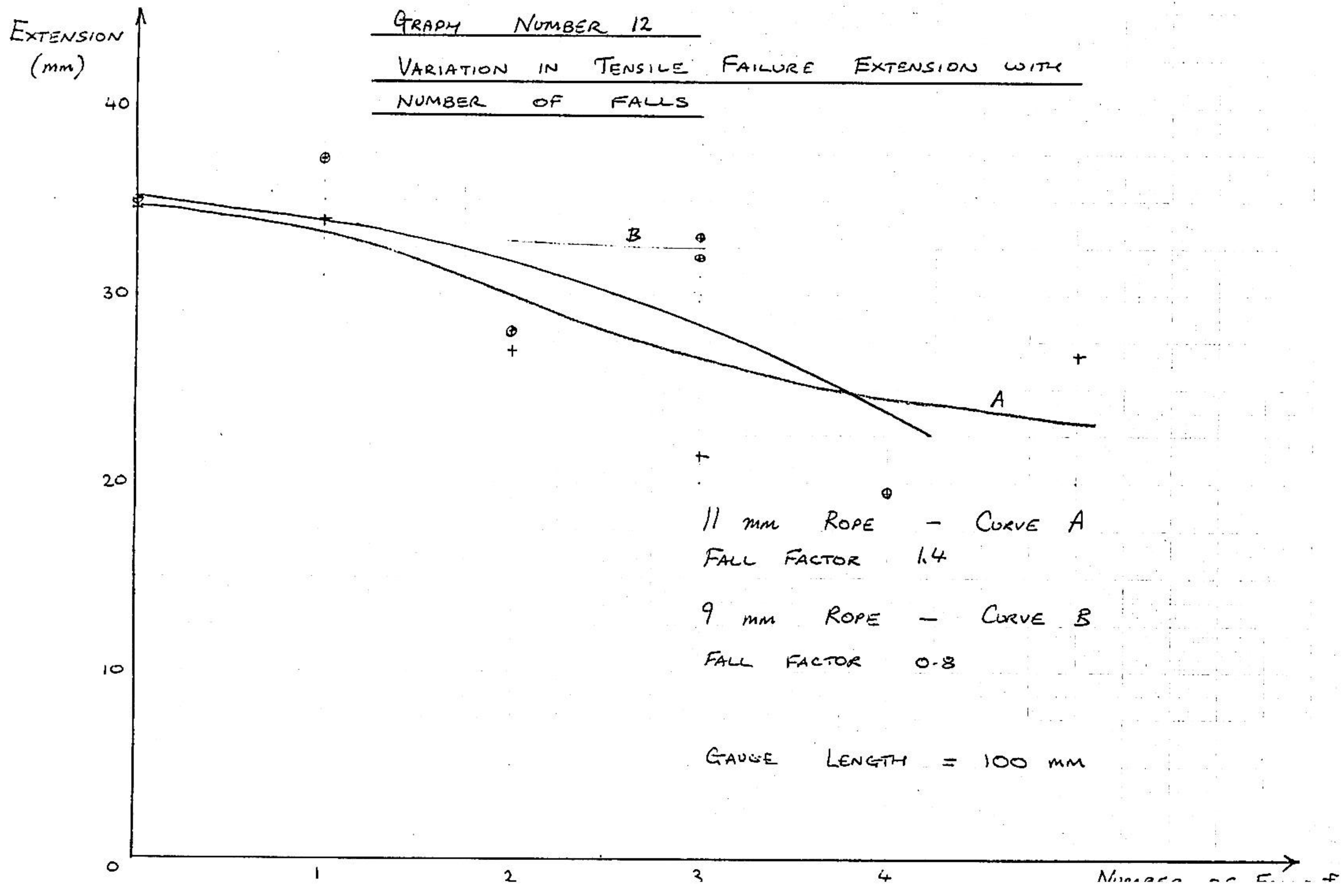
Graph Number 10 – Averaged Strain Trends with increasing number of falls



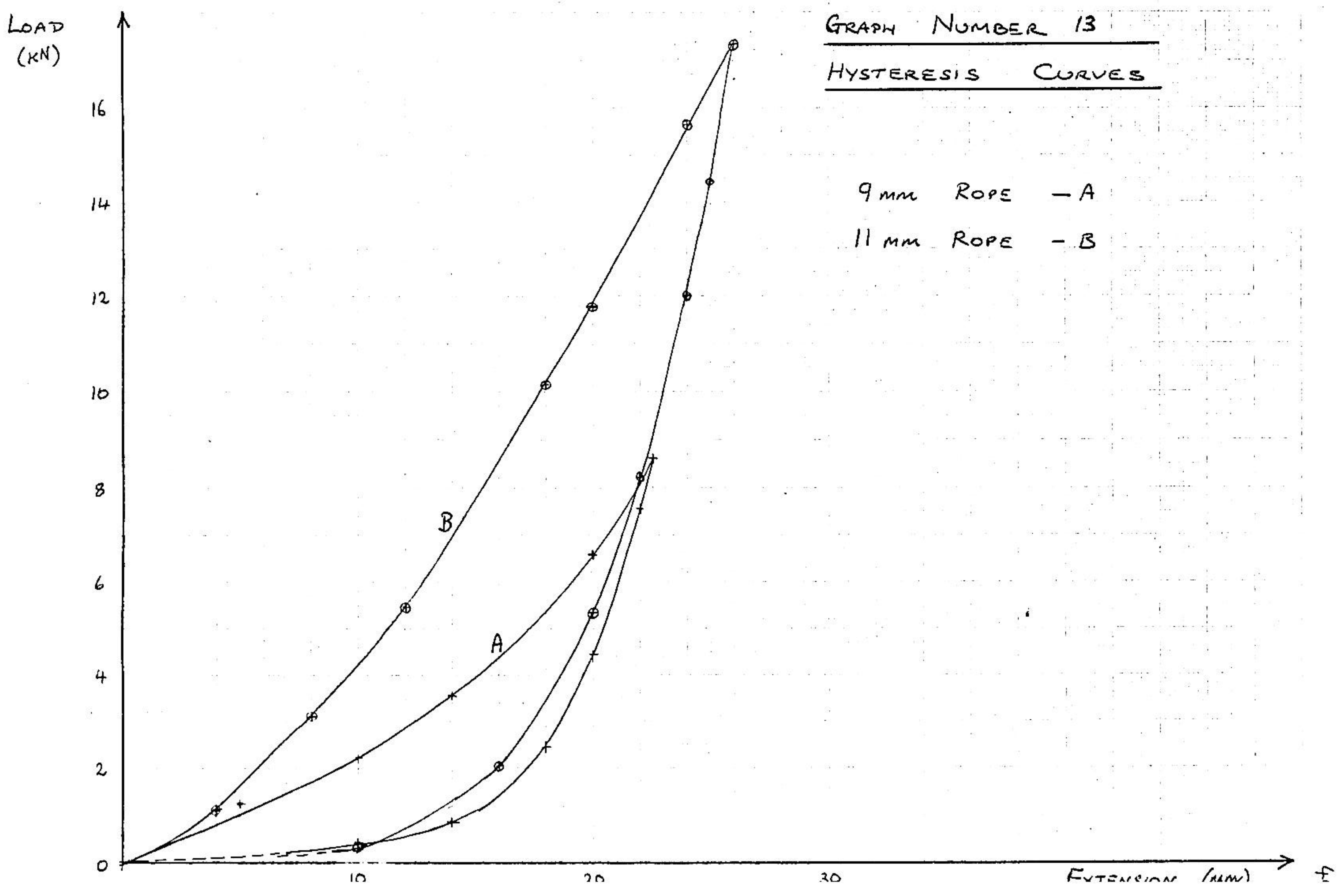
Graph Number 11

Variation in Tensile Failure Load with Number of Falls





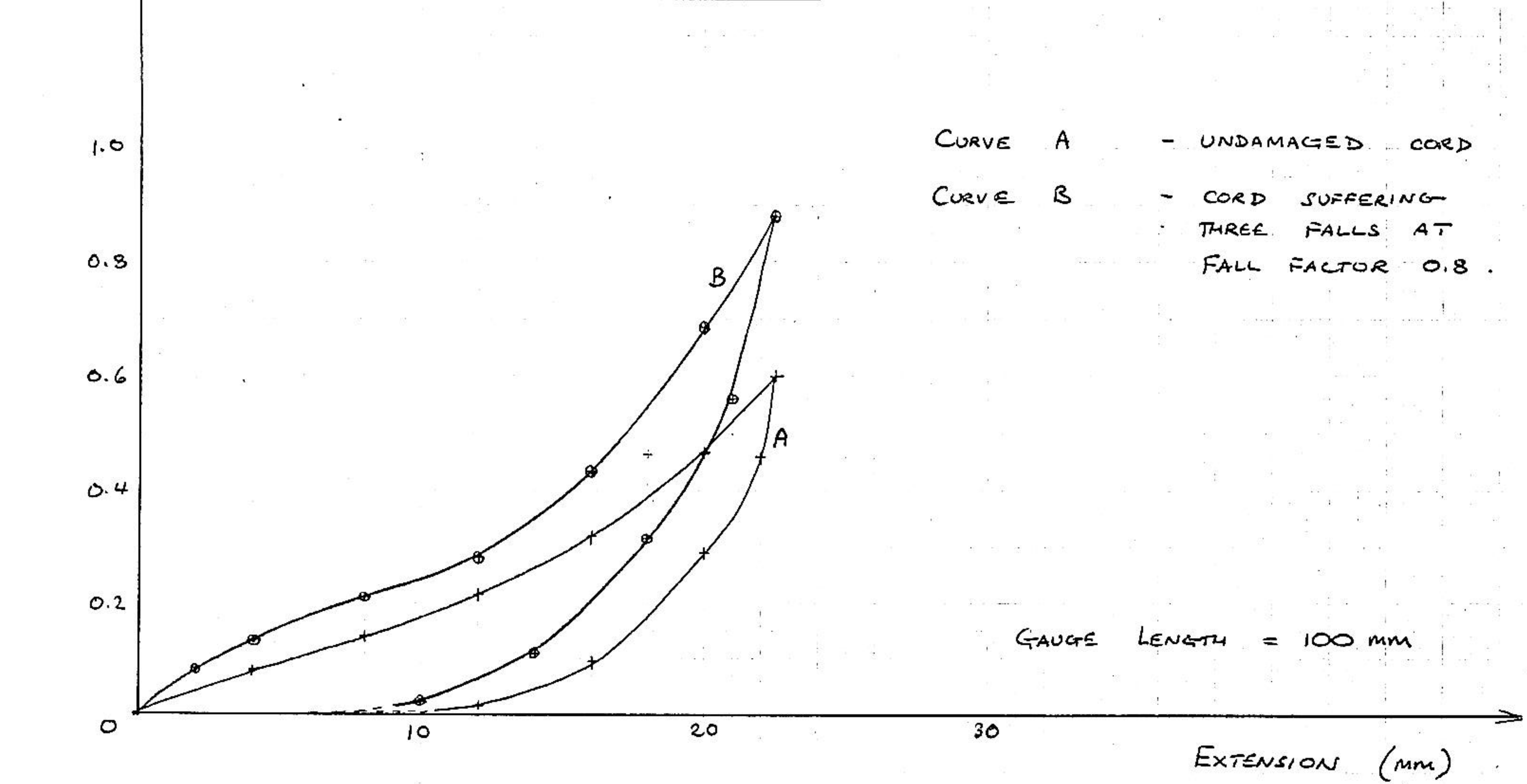
GRAPH NUMBER 12
VARIATION IN TENSILE FAILURE EXTENSION WITH NUMBER OF FALLS
EXTENSION (mm)
40
30
20
10
0
1
2
3
4
A
B
11 mm ROPE – CURVE A
FALL FACTOR 1.4
9 mm ROPE – CURVE B
FALL FACTOR 0-8
GAUGE LENGTH = 100 mm

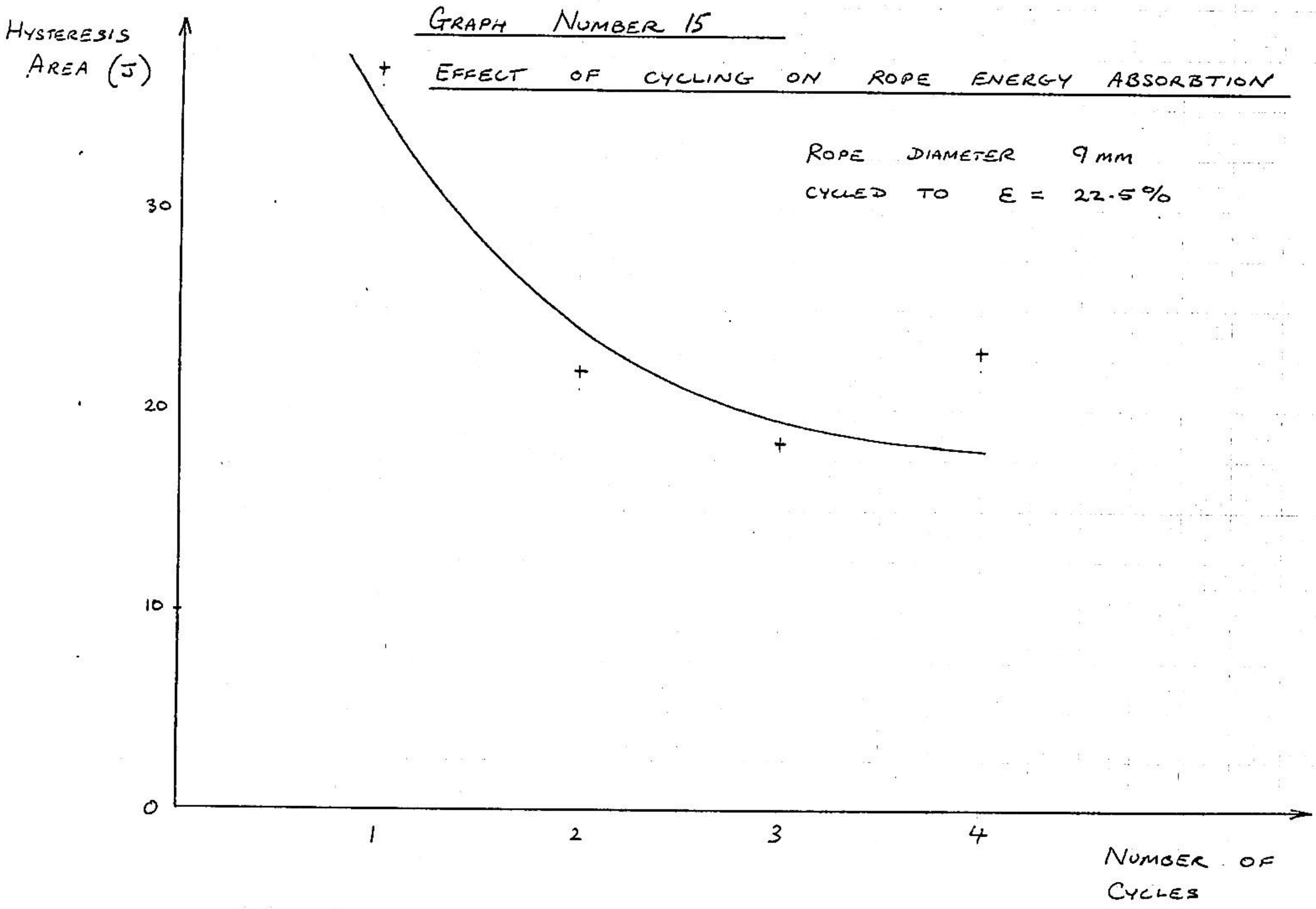


GRAPH NUMBER 13
HYSTERESIS CURVES
9 mm ROPE - A
11 mm ROPE - B
LOAD (kN)
16
14
12
10
8
6
4
2
0
10
20
30
EXTENSION (mm)
A
B

Graph Number 14

Hysteresis Curves comparing Damaged and Undamaged Cord Specimens





GRAPH NUMBER 15
EFFECT OF CYCLING ON ROPE ENERGY ABSORBTION
ROPE DIAMETER 9 MM
CYCLED TO ε = 22.5%
HYSTERESIS AREA (J)
30
20
10
0
1
2
3
4
NUMBER OF CYCLES

Discussion

Factors which influence whether a rope will fail during a fall may be broadly catagorised as fall severity and condition of rope. Fall severity depends on the geometry of the fall (see Fig 5). In the lab. test rig it was possible to alter either fall factor or edge radius. The condition of the rope depends on its previous history - ie what environmental degradation it may have suffered and the number and severity of the falls it has previously exprienced. Since Coombs has, in previous work investigated the way in which rope life is affected by fall severity (see Reference 7), giving the results that increased fall factor and decreased edge radius lead to a lower number of falls to failure, it was decided to concentrate on rope condition.

Since new rope was nearly always being used, environmental degradation effects were mostly unobtainable, therefore, variations in retained rope properties with increasing number of falls were investigated.

Comparison of the laboratory test rig with the standard U.I.A.A. test rig (p 10) shows the former to be a more severe test in almost every way (except for maximum fall factor). This explains why U.I.A.A rated ropes (5 falls $\eta = 2$) were failing at (say) four falls, $\eta = 1.4$. However, the question should be posed; "Is the U.I.A.A. test severe enough, considering that rock-edges & flakes over which a rope may pass can have radii of less than 1mm?"

This report endeavours to determine the factors causing rope failure, It is therefore important to know

(i) How a rope absorbs a fall?

(ii) What factors affect this ability?

(i) When a climber falls on the rope, the fall energy is absorbed by friction caused by relative movement of the rope sub-elements. The strands, wound in groups of three into cords rub against each other as the cords stretch. The cord also rubs against the sheath.

Evidence for this is shown in Graph 1, where relative movement between sheath & core is shown shaded. Microscopic examination of Ropes 1 and 2 showed fibres to have suffered surface abrasion and fusion to each other, indicating relative movement, and reference to Graphs 5 and 6 give a much lower extension to failure for the single strand than a cord, indicating that the difference is due to unwinding, during which there must be relative movement.

During a fall, the rope bounces, and two semi-static hysteresis cycles are shown in Graph 13. The area under the 11 mm curve is 98 J. However, during a fall, energy of the order of $85 \times 9.81 \times 1.8 = 1.5$ kJ must be absorbed!

Reference 1 shows that dynamic working capacity over an edge is greater than the static equivalent, but the difference is not as great as an order of magnitude! It must therefore be concluded that either the semi-static situation is a poor model for dynamic purposes, or that there are other means of energy absorbtion. These are most likely to be friction over the edge and pull-through of the rope knots. (see Reference 5) In a real fall, the muscles of the climber, and his harness will absorb energy. (see Reference 5). There may also be some plastic deformation of the rope (see below).

Thus it may be seen that it is not so much Ultimate Tensile Strength (although this must be adequate) that determines whether a rope will fail, but its energy absorbtion ability. If this latter is inadequate, the peak forces produced within the rope will exceed the U.T.S. and lead to catastrophic failure.

(ii) Microscopic examination of the damaged ropes showed the broken fibres to be inconsistent with those exhibiting fatigue damage (Reference 3) and the rope was not sufficiently old, or well used to have been degraded by the environment. However, the microscope did show a considerable number of melted fibre ends. This is consistent with the fact that all the fall energy must eventually be converted into heat, and that the 'edge', knots, and internal friction cause the rope to be warm to the touch, immediately after a fall.

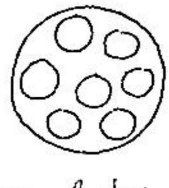
Reference to p 24, Appendix II, and References 1, 2, 4 and 5 show that the peak load generated in a fall exceeds by many times the climber's weight. As shown on p 24 damping is very small. Stiffer ropes (i.e. smaller s) cause greater peak forces. It is the writer's conclusion that the longitudinal stiffness of a rope increases with increasing number of falls. This is because the strands unwind, but do not fully recover elastically, ie there is some plastic deformation. Graphs 10, 11, 12, 14 and 15 may be used to back up this assertion.

Graphs 11 and 12 show that both extension and load to failure decrease with increasing number of falls, affecting energy absorbtion ability adversely. This was also shown up in the semi-static hysteresis tests (Graph 15)

Graph 14 shows two hysteresis curves, one for an undamaged cord, and one for a damaged cord. Although the damaged specimen has apparently greater energy absorbtion ability, it must be remembered that the gauge length was marked after the damage (stretching) occurred. Therefore, to achieve the same gauge length extension higher peak loads were required for B, because of the rope's higher modulus (lower s)

Finally Graph 10 shows that both ε_{DYN} and ε_{STAT} do not increase uniformly with number of falls. The increase gets smaller indicating increasing modulus.

Visually, the idea is confirmed by the mass being brought to rest more violently as the number of falls increases. The rope also increases in flexibility. This is because the central cords, in pulling become thinner (conservation of volume) leading to gaps in the previously well packed sheath space. Thus the cords may move more freely. In his previous report Coombs states that flexibility bears no correlation to damage. These results show that



he is mistaken, and that the rope becomes stiffer longitudinally but more flexible laterally with increasing number of falls.

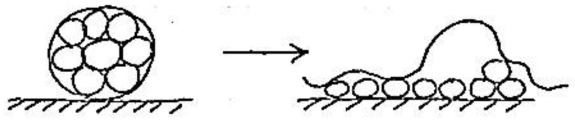
For the 11mm rope, Graph 3 and p 24 give for $S = 1.8\%$, $m = 85$ kg, $\eta = 1.4$

$$F_{pk} = 11.27 \text{ kN}.$$

This is approaching the tensile failure load of a rope which has been fallen on two or three times (Graph 4) and has had arduous use.

Damage always occurs at the edge in the rope. Reference to Graph 1 shows the strain to be large and localised in that region. Also, Tables 1 and 4 show the cords to be stretched more in the edge region. Thus the entire length of the rope does not share energy absorbtion equally. Moreover, at the bend around the edge, cords on the outermost edge are more highly stressed, and thus more liable to failure; leading to progressive failure as the other cords have to bear more load. This is shown by kinking of damaged specimens indicating different strains (and thus stresses) in the different cords.

The rope does not fail at the krab, because, although it is as severely bent, there is no movement of the rope, and consequently no abrasion. The sheath, which will protect the core as long as it remains intact, will, on rupture, peel back allowing



the central cords to displace as shown, so that they are all immediately vulnerable to abrasion damage. The subsequent loss of strength and increase of peak load on the next fall leads to failure.

Reference to Graph 10 shows there to be some permanent strain accumulated in a fall. Therefore, plastic extension of the fibres does take place. Further reference to Graphs 5 and 6 show that at failure, the difference in extension between cords and strands (ie. unwinding) was $\approx 10\%$. Therefore plastic strain to failure was $\approx 24\%$.

Little firm evidence is available on which to base a discussion of rope-ageing, since the one sample of used rope available had a different core construction to that of the new 11mm rope which was a 'Kernmantle' type. Microscopic investigation showed more fibres to have failed by fatigue than in the new specimens. Reference to Graph 4 shows that there is little difference in the behaviour of abraded and unabraded rope sections in a tensile test. Some other factor, which could possibly be fatigue is dominating the failure of this older rope. However, because of the rope's age and arduous use, it is not possible to say any more than this.

What is certain is that the rope should be retired. Calculation with $s = 0.05$, $m = 80$, $\eta = 2$ gives $F_{pre} = 7850\ N$; greater than the U.T.S. of section B6.

Conclusions

There are four forms of failure which have made themselves apparent during this investigation.

a) **Fatigue.**

This is not discernable in new ropes as may be expected, since climbing ropes are usually expected to sustain large infrequent loads, rather than higher frequency small loads. However, these latter may be caused by rope kinking and movement during an average climb. Thus, a contribution from this form of damage could well be expected in a well used rope.

b) **Environmental Degradation**

As in a), this cannot be expected to manifest itself in new rope. Both a) and b) depend to a large extent on the care with which a mountaineer treats his rope. Contact with water in particular causes hydrolysis in any sort of nylon, and exposure to sunlight results in ultra-violet deterioration.

c) **Tensile Overload**

This is always the ultimate form of failure but may be aggravated by causes a) b) and d). Final failure is caused by the raising of the peak load in the rope due to increase in longitudinal stiffness, until it exceeds the ultimate Tensile strength of the specimen.

d) **Abrasion**

This occurs at rock edges and karabiners, and is again dependent on good rope care. Increased abrasion causes a gradual lowering of the ultimate tensile strength, until tensile overload causes failure.

In the cases studied in most detail it was apparent that abrasion at the edge led to a reduction in rope strength, and that increased numbers of drops led to a higher peak load until failure occurred.

The tested situation represents the worst possible case, since it is extremely unlikely that the abrasion resulting from several falls would occur in the same place twice or more in normal circumstances.

A test which the mountaineer could easily perform himself would be to hang on the rope and measure its stretch, s. Measure his own weight, and then calculate the maximum possible impact force from page 24. Then, knowing the history of his rope, he may make a reasoned guess at its U.T.S., or indeed test a section and see whether the rope is safe.

RECOMMENDATIONS FOR FURTHER WORK.

1) If possible, the drop-test rig should be altered to make the dimensions and weight the same as the U.I.A.A. fall test.

2) It was not possible, due to lack of time, to investigate the effects of actual mountaineering use and environmental degradation.

It is suggested therefore, that suitable tests are devised for rope with a well documented history. Also, the effects of water and sunlight on a new rope could be examined.

3) Reference to Appendix IV shows the strain rates in the rope to be very high compared to normal tensile tests. A useful investigation to see what effects this has on the tensile strength of nylon could be performed.

References

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Appendix I

"OLD BLUE"

An 11mm diameter Mammut mountaineering rope of kernmantel construction was purchased in a California climbing shop in 1971. The rope is distinguished by a predominately blue mantel, a generally 'tatty' appearance and an obvious break in the mantel about five meters from one end.- hence the name "Old Blue". This rope served faithfully as a principal climbing rope for over five active seasons in the Sierra Nevada mountains of California. She never let me down.

The rope was ordinarily used 50-70 days per year with perhaps six pitches of 100 feet each as a typical climbing day. During most of the early use, I was a cautious beginner slowly increasing my standard of climbing and "Old Blue" was rarely called upon to hold a modest fall. Short falls of 2-3 meters that began near the topmost point of protection occurred every few climbing days but these mostly involved rope stretch. When there is 25 meters of rope between the climber and belayer the rope can easily stretch and stretches enough to cause a 2 m fall. The first serious fall occurred after 2½ years of use.

A fall of 30 m lasts for seconds and there is plenty of time to be scared. I'ld climbed an easy crack for 20 m straight up from a narrow belay ledge, placing chocks for protection as I climbed. From the top, an easy traverse across a pockmarked face led upward toward another crack - but stopped a few meters short. There had been no cracks across the face in which one could place protection so when I slipped from a wet move, the fall was about 30 m - ending not far above the belayer. This fall was almost free on a steep face and involved some penduluming. As I hung on the end, the rope was only supported at the top krab. After the fall a 2 cm segment of rope that was at the krab felt more soft and pliable than adjacent sections although the sheath was not damaged. Nevertheless, I continued to use the rope as my sole lifeline while leading climbs.

About 1974 I became a more serious climber; that is, I was one of the better climbers in an active area and continually tried to ascend more difficult rock. Consequently, short falls became common as I searched for and pushed my personal limitations. These falls caused no apparent damage to the rope. My next damaging fall occurred in 1975.

This fall was only about 15 m but it was serious because there was only about 2 m of rope between the topmost protection that remained in place and the belay. The climber was about 7 m above this protection before falling and essentially fell free without touching the overhanging face. The belay was by a Sticht plate tied to the anchor so no human body intervened; this doubtless provided a stiffer anchor than the usual body belay. The rope near the top krab was distorted - after the fall it felt smaller in diameter and had smaller bending stiffness than adjacent sections.

After this fall, "Old Blue" was no longer used as a climbing rope but was relegated to the ignominious role of hauling 40kg sacks of gear up big walls during multiday climbs. This is a wearing role as the rope is often drawn up over edges while under tension. This rope survived almost 2km of such usage before being retired.

Bill Stronge
1984

APPENDIX II

Table of factors by which the climbers weight is multiplied to obtain peak fall force.

ROPE STRETCH S

FALL FACTOR η — OVERLOAD	1%	2%	5%	10%	50%	100%
2	21.0	15.2	10.0	7.4	4.0	3.2
1	15.1	11.0	7.4	5.6	3.2	2.7
0.5	11.0	7.4	5.6	4.3	2.7	2.4
0.2	7.4	5.6	4.0	3.2	2.3	2.1
0.1	5.6	4.3	3.2	2.7	2.2	2.1
0	2.0	2.0	2.0	2.0	2.0	2.0

APPENDIX III

Individual rope histories.

9mm ROPES

1). One fall, F.F. 1.836, no failure, no tensile test.

2) One fall, F.F. 1.836, failed on 1st. fall. (no sheath)

3) } One fall, F.F. 1.836, failed on 1st fall.
4) }

5) One fall, F.F. 1.2, no failure, no tensile test.

6) Two falls, F.F. 1.2, failed on 2nd fall.

7) Four falls, F.F. 0.8, no failure, tensile tested

8) Three falls, F.F. 0.8, no failure, measured for strain.

9) Three falls, F.F. 0.8, no failure, tensile tested.

10) Two falls, F.F. 0.8, no failure, tensile tested

11) One fall, F.F. 0.8, no failure, tensile tested.

12) No falls, tensile tested.

13) Three falls, F.F. 0.8, no failure, measured for strain.

14) Cyclically tested for a hysteresis curve.

15) Two falls, F.F. 0.8, no failure, cords tensile tested.

16) Three falls, F.F. 0.8, no failure, tensile tested as a check on (9).

APPENDIX III contd.

Individual rope histories.

11 mm ROPES

1) Two falls, F.F. 1.836, failure on third fall foreseen, no tensile test.

2) Five falls, F.F. 1.4, no failure, tensile tested and measured for strain.

3) Four falls, F.F. 1.4, failed on 4th fall.

4) Three falls, F.F. 1.4, no failure, tensile tested and measured for strain.

5) Two falls, F.F. 1.4, no failure, tensile tested and measured for strain.

6) One fall, F.F. 1.4, no failure, tensile tested and measured for strain.

7) No falls, tensile tested.

8) Cyclically tested for a hysteresis curve.

'Old Blue' 11 mm ROPES

B1) Two falls, F.F. 1.4, failed on 2nd fall.

B2) Two falls, F.F. 1.4, failed on 2nd fall.

B3) Rope sub-elements untested; due to construction.

B4)
B5) No falls, tensile tested.

B6)
B7) Evidence of abrasive damage; tensile tested.

B8) Evidence of karabiner damage; tensile tested.

APPENDIX IV

Strain rates in s^{-1} for various rope lengths and fall factors.

For $s = 3\%$.

η	STRAIN RATE				
	ROPE LENGTH (M).				
	1	5	10	50	100
2	6.1	2.7	1.9	0.9	0.6
1	4.3	1.9	1.4	0.6	0.4
0	0.5	0.29	0.2	0.1	0.1