Safety in Mines Research Advisory Committee

Final Report

Discard criteria for mine winder ropes

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Executive summary

Various SIMRAC projects have been carried out over the past seven years to verify and refine the discard criteria of SABS0293: The South African Bureau of Standards Code of Practice for the Condition Assessment of Steel Wire Ropes on Mine Winders.

The objectives of the investigation described in this report (GAP502) were the same as those of the previous SIMRAC projects, i.e. to verify, and possibly refine, the discard criteria of SABS0293. For this investigation special emphasis had to be placed on non-spin ropes, because the discard criteria for non-spin ropes were not yet well defined in SABS0293, and the possible use of non-spin ropes in future deep shaft operations required the situation to be addressed. The majority of (drum) winder ropes are discarded because of broken wires. The discard criteria for broken wires were therefore the focus of this investigation.

The samples collected and tested from discarded ropes included samples with broken wires, corrosion, substantial plastic deformation, and ropes that had sustained abnormal damage. However, the most important finding of this report ensued from a thorough analysis of "cut-wire" tests.

Very few rope samples from discarded non-spin ropes were, or could be, obtained for the establishment and verification of the discard criteria for non-spin ropes. The effects of broken wires in non-spin ropes were therefore simulated by testing laboratory prepared specimens with selected wires cut in the outer and inner strands. These tests were a continuation of work carried in two previous SIMRAC projects: GAP324 and GAP439. Although not part of the scope of GAP502 (this investigation), the author of this report decided that all cut-wire tests on non-spin ropes of the previous investigations had to be evaluated together with those of GAP502 to be able to establish and propose proper discard criteria for broken wires in non-spin ropes.

The discard criteria for broken wires in SABS0293 were based on a 10% reduction in strength of a rope. An expectation was therefore created that by complying with these discard criteria, a rope would not fail as long as the rope loads did not exceed 90% of the new rope breaking strength.

However, it is shown in this report that rope strands with "allowable" broken wires could fail at loads considerably lower than 90% of new rope breaking strengths. An example: A rope sample from a discarded fishback rope that operated on a drum winder had four broken wires in one outer rope strand. Although the broken wires only made up 1,5% of the total cross-sectional steel area of the rope, that rope strand failed at a load that was 16% lower than the new rope strength, while the remainder of the rope broke at more than 95% of the new rope strength. A thorough analysis of the results of the cut-wire tests of GAP439 further substantiated that weakened rope strands fail at rope loads far lower than originally anticipated.

A theoretical failure analysis of stranded ropes was then performed to explain how and why weakened strands could fail at relatively low rope loads. The failure analysis was not part of the scope of GAP502 but was considered essential, otherwise the apparent anomalies in the results of cut-wire tests would have remained unexplained.

The failure analysis further showed that the load at which a weakened strand in a rope specimen would fail depended on the length of the rope specimen tested. It was also shown that the length of a strand affected by broken or cut wires was the most probable reason for relatively large scatter in breaking strengths observed in the past for identical specimens.

Friction between a weakened outer strand of a non-spin rope and the rest of the rope was not sufficient to prevent the weakened strand from failing. Although inner rope strands of non-spin ropes would probably be assisted to some extent by inter strand friction, there is very little reason why the strands of triangular strand ropes would not behave the same as the outer strands of non-spin ropes.

Therefore, if the cut-wire and discarded rope tests of triangular strand ropes were carried out on longer specimen lengths, previous researchers would have obtained different results, and would have established different discard criteria.

It was concluded that the concept of a rope having lost 10% of its original strength was only valid for broken wires, damage or corrosion distributed absolutely evenly throughout all the strands of a rope, and then also only valid for ropes of which all strands were identical. It is therefore not possible to establish a general relationship between the reduction in steel area in a stranded rope from broken and cut wires, and the loss in rope strength.

The premise of a rope having lost 10% of its original strength, used previously for establishing discard criteria for broken wires in ropes, does not exist if different lengths of rope are considered. It is therefore required that the basis for establishing discard criteria be reconsidered, especially for broken wires, and therefore what is to be expected if such discard criteria are applied.

It is further recommended that tests be carried out on laboratory prepared specimens to verify the suggested failure behaviour of stranded ropes (fishback, ribbon strand and triangular strand ropes).

Irrespective of how the conclusions and findings in this report are interpreted, winder ropes still have to be inspected and discarded according to the current specifications of SABS0293. The discard criterion that the number of broken wires in a single strand may not exceed 40% of the number of wires in the strand will, at least for the near future, ensure that non-spin ropes with outer strand damage do not remain in service too long.

A major part of this report was done at the cost of the research agency. The findings in this report could not have been anticipated beforehand. Without the additional effort, the larger part of the results obtained from the investigation would have been meaningless.

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Terminology

New rope strength: The strength of a rope when new, and as determined by a tensile test.

Front end: The section of rope at and near the conveyance end of the rope.

Back end: The section of rope at and near the drum of the winder when the conveyance is at its lowest point in the shaft.

Non-spin rope: A rope consisting of multiple layers of strands in which the strand layers are laid in opposite directions to achieve opposing torques under load.

1 Introduction

Regulation 16.33 of the Mine Health and Safety Act required a winding rope to be discarded when it had lost 10% of its breaking strength. When the new regulations were published in November 1999, Regulation 16.33 was changed to read:

> "The condition of a winding rope or balance rope must be assessed in accordance with the South African Bureau of Standards Code of Practice for the Condition Assessment of Steel Wire Ropes on Mine Winders, SABS 0293, as amended and the rope may not be used if the condition thus assessed at that point in the rope has reached the discard criteria."

The reasons for the change were:

- The 10% loss in strength, used as the basis for the discard criteria, was only a general norm. Scatter in the breaking strengths obtained from rope specimens with the identical broken wires meant that an assessed loss in rope strength can only be approximate.

- Although the general discard criteria of SABS0293 were based on a 10% loss in rope strength, a number of the discard criteria in the code required a rope to be discarded, not because it had lost an estimated 10% of its strength, but because it had sustained damage of a nature such that the rate of subsequent deterioration would be far greater than normal to the extent that the rope would have to be discarded before the next inspection.

The majority of winder ropes are discarded because of broken wires. The discard criteria for broken wires are therefore considered as the principal part of the discard criteria.

The discard criteria for broken wires in triangular and round strand ropes were originally based on the results of tensile tests carried out in 1953 by Haggie and reported to Hartebeestfontein GM and further tests for Gold Fields in 1959 which were reported by Harvey and Kruger (1959).[1] They simulated broken wires in triangular strand ropes by cutting selected wires on the rope samples before carrying out a tensile test. A relationship between the steel area loss of the cut wires and loss in rope strength was then obtained. Subsequently, the cut-wire investigations for triangular strand ropes were expanded by Borello and Kuun (1994),[2] and then by Hecker and Kuun (1996).[3] Both investigations formed part of the SIMRAC project GAP054, and were reported in Volume 4 of GAP054 (1996).

Appendix A gives more information on the variability of breaking strengths of triangular strand ropes and the selection of discard criteria to minimise the probability of breaking strength losses of greater than 10%.

Samples from discarded winder ropes were also collected and tested to verify the discard criteria proposed for SABS0293, and secondly to establish the ability of magnetic rope testing instruments to locate the broken wires and other anomalies in winding ropes. The tensile test results of samples collected from discarded ropes were presented in Volume 4 of the GAP054 report (1996) and also in Volume 1 of the GAP324 report (1997).

The apparent success in establishing broken wire discard criteria for triangular strand ropes prompted researchers to perform similar investigations for non-spin ropes. The discard criteria for non-spin ropes had not been satisfactorily defined in SABS0293, and the possible use of non-spin ropes in future deep shaft operations required that the situation be addressed.

The drum winders that generally use non-spin ropes are kibble winders on shaft sinking operations and permanent drum winders operating in shafts with guide ropes. Non-spin ropes are also used on Koepe winders (friction winders). Compared to triangular strand ropes, non-spin ropes are used on a small percentage of winders in this country. It was therefore known that not very many samples of discarded non-spin ropes would become available. Therefore the tests on rope samples with cut wires would constitute the greater part of this investigation.

Cut-wire tests on non-spin ropes were done as part of SIMRAC project GAP324, and continued in GAP439. The report on GAP439 (1998) recommended that more tests were required before discard criteria could be proposed.

1.1 Methodology

The objective of this investigation was to verify, and possibly refine, the discard criteria of SABS0293. Special emphasis was to be placed on obtaining samples of non-spin ropes. As the investigation progressed, it became clear that very few non-spin rope samples would be obtained. Permission was then obtained to perform more cut-wire tests on non-spin ropes. The cut-wire selections were done as recommended in GAP439.

The discard criteria that were investigated were broken wires in triangular strand ropes and non-spin ropes, corrosion, rope damage, and rope diameter reductions on triangular strand ropes. Two samples from two relatively old ropes were also tested for the sake of interest.

The following is a list of the different rope samples tested for this investigation (69 in total). The number of samples in each category includes control samples:

Triangular strand ropes with broken wires:	10
Non-spin rope with broken wires:	3
Corroded ropes:	2
Damaged ropes:	3
Very old ropes:	2
Triangular strand ropes with diameter reductions:	12
Cut-wire tests on non-spin ropes:	37

In addition, the records of tensile tests on front end sections of inclined winders were analysed in an attempt to obtain information on strength losses due to diameter reductions from abrasive wear.

Although not part of the scope of GAP502 (this investigation), it was decided by the author of this report that all cut-wire tests on non-spin ropes of previous investigations (GAP324 and GAP439) had to be evaluated together with those of GAP502 to be able to recommend proper discard criteria for broken wires on non-spin ropes.

1.2 Additional studies

When the data of the cut-wire tests on non-spin ropes were analysed, it was found that the correlation between the reduction in rope steel area from the cut wires and loss in rope breaking strength was quite poor. It was then postulated that the results of all tests on rope samples with broken and cut wires (including triangular strand ropes) were only valid for the selected length of the samples. If the tests had been performed on longer sample lengths, the results would have been different. A section to examine the postulation was therefore included in this report.

2 Ropes discarded because of broken wires

2.1 Non-spin ropes

During the time of this investigation, only one set of non-spin ropes was discarded from a drum winder. Non-spin ropes were used on this winder because the shaft had guide ropes.

The ropes were 18 strand fishback construction, 46 mm diameter, 1 800 MPa tensile grade and galvanised. Detailed construction was as follows:

12x10(8/2)/6x29(11/12/6 Δ)/WMC

The one rope reached discard because it had four outer wires of one outer strand broken. Four outer wires constituted 39% of the cross-sectional steel area of an outer strand. The discard criteria of SABS0293 requires a rope to be discarded when the broken wires in one strand reaches 40% of the cross-sectional steel area of the strand. Four outer strand wires only makes up 1,5% of the total steel area of the rope.

The new rope strength was determined at Haggie as 1 693 kN. The six-monthly statutory tests, carried out at Haggie on samples from the rope front end, showed a gradual increase in rope strength. The last front end test returned a strength of 1 731 kN.

Three samples were obtained from the discarded rope: The section with the broken wires, a control sample from the front end of the rope, and a section from the dead turns on the drum. These samples were subjected to a standard tensile test. The results of the tests are given in Table 2.1 below.

Table 2.1: Tensile tests on samples of an 18 strand fishback rope discarded from a drum winder.

Specimen designation	Breaking load
Front end Dead turns Broken wires	1 733 kN 1 734 kN 1 651 kN

The two control samples had strengths 2,4% greater than the new rope strength, which were practically the same as that of the last front end test.

The strength of the sample with broken wires was 2,5% less than the new rope strength, and 4,7% less than the values obtained from the control samples. A strength reduction of more than 10% was not expected for the reason-for-discard specimen, because the rope was discarded for having 40% broken wire area in one strand.

2.2 Triangular strand ropes

2.2.1 Ropes with acceptable degrees of strength loss

Three triangular strand rope samples with broken wires were received together with some control samples. The rope strengths from the tensile tests carried out on these samples are given in Table 2.2.1 below, together with other relevant rope information.

Table 2.2.1: Tensile tests on triangular strand rope samples with broken wires.

Specimen	New rope strength	Rope strength	Strength loss	Broken wire area
B1	1 882 kN	1 647 kN	12,5%	3,6%

B2	2 347 kN	2 167 kN	7,7%	1,9%
B3c	2 347 kN	2 172 kN	7,5%	0%
B4c	2 338 kN	2 330 kN	0,3%	0%
B5	1 280 kN	1 156 kN	9,7%	2,1%
B6c	1 280 kN	1 225 kN	4,3%	0%

Sample B1 had a total of 5 broken wires in two adjacent strands (i.e. an asymmetric broken wire distribution). It also had a localised diameter reduction of 1 mm (2%). The combined discard factor (calculated in accordance with SABS0293) was 1,12. A strength reduction of more than 10% was therefore not unexpected. The reason for the localised diameter reduction was not given. The tensile test report noted brittle fractures on nine outer wires, and abrasive wear on the outer wires. It was therefore possible that the section of rope tested had been subjected to abnormal conditions while in service. The "plastic fraction of elongation" obtained from the tensile test was also relatively small (0,3%), which is, in the absence of significant corrosion, a further indication of possible abnormal degradation.

Sample B2 (an underlay rope) had a total of three broken wires in one strand, and very little was "wrong" otherwise. The discard factor for the broken wires was 0,48. The breaking strength loss of 7,7% was more than expected, but then the "plastic fraction of elongation" was only 0,5%. Only two of the six strands failed at maximum load. Sample B3c was a control sample for B2, presumably cut from the rope adjacent to B2. Apart from not having broken wires, the tensile test on this control sample returned much the same values as sample B2. Only two strands failed, and the "plastic fraction of elongation" was also only 0,5%. The reason for the strength of this sample to be 7,5% down was not apparent. Sample B4c was cut from the overlay rope of the same winder. The sample was marked as "interesting", but nothing abnormal was noticeable from the specimen or from the tensile test results.

Samples B5 (two broken wires in one strand) and B6c (a control sample with no broken wires) were cut from the same rope. The discard factor for the broken wires was 0,52. "Abrasive wear" on the outer wires of the ropes was noted for both samples. The tensile tests of both samples returned relatively small "plastic fractions of elongation" (0,4%), which go hand in hand with the greater-than-expected losses in breaking strength. The reason for the "abrasive wear" was not given in the discard report.

As was found during previous investigations, none of the rope specimens with discard factors less than one had breaking strength losses of more than 10%.

2.2.2 Ropes with unacceptable degrees of strength loss

Two rope samples that were tested produced unexpected large losses in strength. The two cases are discussed separately. Detailed rope and winder parameters are secondary to the large degrees of breaking strength losses, and are therefore not given.

Drum flange contact

Magnetic testing of a triangular strand rope on a drum winder uncovered a section of the rope with 11 broken outer strand wires. This was at the 2nd to 3rd rope layer cross-over on the drum.

One strand had a single broken wire, the adjacent strand had seven broken wires over a length of 300 mm, and the strand after the next one had three broken wires at the same location. The cross-sectional area of the 11 broken wires constituted 8,9% of the total rope steel area. This was greater than the 7% allowed by the code of practice for broken wires in more than two adjacent strands, and the rope was discarded. An examination of the rope sample before the test confirmed that the rope was in a poor condition and it was expected that the rope would have a reduction in strength between 15 % and 25 %.

Three sections of the discarded rope were tensile tested:

- The "reason for discard" section,
- a section of rope from the 1st to 2nd drum layer cross-over, and
- a control sample near the front end of the rope.

The control sample had a strength 1,2% greater than the new rope strength. The strength of the 1st to 2nd cross-over section was 1,7% greater than new. The rope section with the 11 broken wires (8,9% rope area reduction) returned the following:

- A breaking strength of 29% lower than new;
- a plastic fraction of elongation of only 0,05% (only 1,3 mm of plastic elongation on a 2 750 mm long rope specimen), and
- the inspection after the tensile test showed brittle failures on 18 outer strand wires.

Brittle failure of a wire (not already broken before the tensile test) is usually an indication that the wire was already cracked before the tensile test.

An investigation commissioned by the mine revealed that the rope made contact with the drum flange at the 2nd to 3rd layer drum cross-over because of severe catenary dynamics. The damage to this point on the rope was caused by the high speed contact and high speed abrasive wear.

The problem here was that the rope deterioration was only discovered after the serious rope condition had developed. The rope condition assessment procedures and/or intervals employed for the winder may have been inappropriate.

Therefore: Abnormal deterioration of a winder rope should be treated with the utmost caution, because the rope strength loss could be much greater than apparent, and could be a reason for immediate discard of the rope.

For interest: The problem was eventually solved by fitting coiling sleeves on the previously smooth winder drum.

Drum turn cross-over damage

The magnetic test of a triangular strand rope on a drum winder showed anomalies (on the local area trace) at drum turn cross-over points. At one of the drum turn cross-over points, five broken wires were found in one location in one strand plus one more broken wire in the same strand 240 mm away.

The six broken wires in one strand and in one laylength of the rope constituted 4,8% of the total cross-sectional steel area of the rope, which was more than the 4% allowed by the code of practice for broken wires in one strand (i.e. a discard factor greater than one). The rope was therefore discarded and the reason-for-discard section of rope was submitted for tensile testing. The tensile test on the rope section gave:

- A breaking strength of 37% lower than new;
- a plastic fraction of elongation of only 0,09% (only 2,5 mm of plastic elongation on a 2 750

mm long rope specimen), and
- the inspection after the tensile test showed brittle failures on "numerous" outer strand wires.

It was reported that rope back-ends were not pulled in regularly (or this was not done for some time) on this particular winder. Visible layer cross-over points on a magnetic trace of a rope should therefore be a cause for alarm. Such instances should also be "classified" as abnormal rope deterioration or abnormal rope damage.

Therefore: Any indication of turn and layer crossovers from magnetic testing of a rope should require immediate pulling-in of the back-end of the rope. Very visible drum layer cross-over points and drum turn cross-over points may require immediate discard of the rope.

3 Reduction in rope diameter

The outer wires of a rope operating on a drum winder (especially a rock winder) in a vertical shaft undergo significant plastic deformation. The plastic deformation is always more significant towards the back end of the rope. The ropes generally also exhibit some wear (removal of material). Both plastic deformation and wear contribute towards a reduction in the rope diameter. On rock winders the contribution of plastic deformation is much more significant than wear.

A rope operating on an inclined winder (shallow angle) is generally subjected to a large amount of abrasive wear, because the rope makes contact with (is dragged over) rollers and other objects in the shaft. The wear, which reduces the rope diameter, is generally more significant towards the front end of the rope.

Rope diameter reductions, caused by abrasive wear only, will be more detrimental to rope strength than the same diameter reduction caused by plastic deformation, because abrasive wear causes material to be lost.

The code of practice (SABS0293) includes the following discard criteria for triangular strand and round strand ropes as percentage loss in rope diameter. According to the code, the allowable loss is calculated as a percentage of the nominal rope diameter. Actual rope diameter losses are calculated on the as-installed rope diameters.

Abrasive wear only:	Uniform wear:	7%
	Non-uniform wear:	5%
Plastic deformation and wear:	Uniform wear:	9%
	Non-uniform wear:	7%

The origin (technical motivation) for the above values could not be traced.

3.1 Diameter reductions due to plastic deformation

Sections of a set of ropes discarded from a drum winder after 5 years and 8 months in service were obtained. The winder was a rock winder with a shaft depth of 1 800 m. Because the ropes remained in service for a relatively long time, they had quite severe plastic deformation at the back ends.

Rope diameter measurements at installation and at discard were available for these ropes, which provided an opportunity to study the effect of rope diameter reductions due to plastic deformation on the breaking strength of a rope.

For the sake of interest: The two ropes from which the sections were obtained were the ropes on which the report "Triangular strand ropes for deep shaft operations" (SIMRAC project GAP324) was based. The underlay rope on the winder accidentally lost a large amount of spin (turns) 15 months after installation, which resulted in longer-than-normal rope laylengths at the back end of that rope.

The ropes were 39 mm nominal diameter of 6x29 triangular strand rope construction, and 1 900 MPa tensile grade. Both the overlay (O/L) and underlay (U/L) ropes had new rope breaking strengths of 1 233 kN.

The physical appearance of the ropes after four years in service is shown in Fig. 3.1. Severe plastic deformation is noticeable on the image of the back end of the underlay rope. This image shows that the small valleys between the wires in a strand were already nearly "filled" at that time. Visually, the ropes did not deteriorate much more during the last 1½years in service. The plastic deformation was evenly spread around the circumference of the rope.

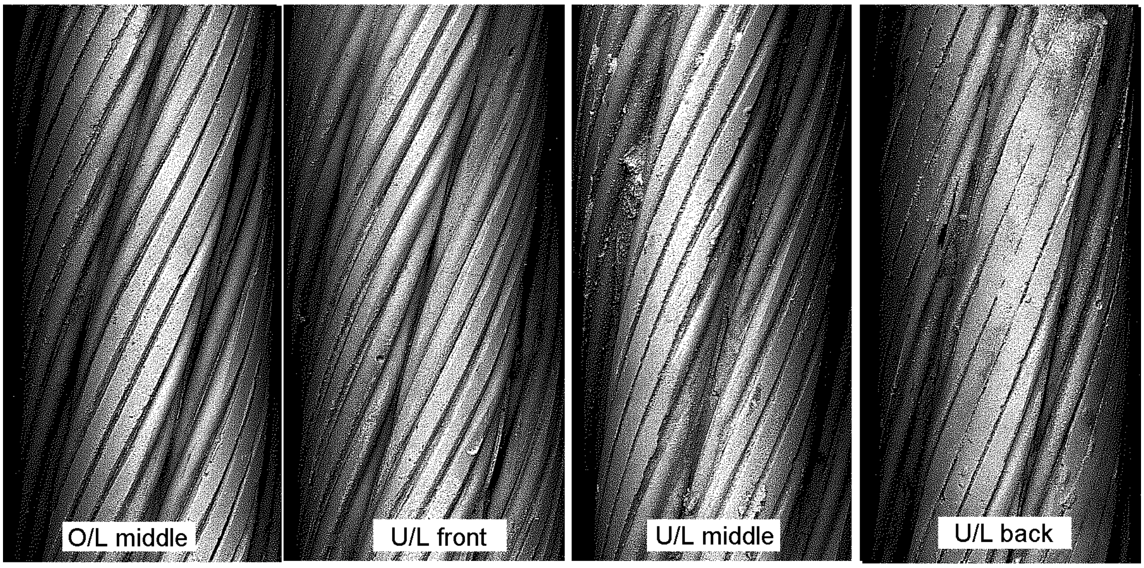

Figure 3.1: Physical appearance of the ropes used for diameter reduction tests

For each of the overlay and underlay ropes, specimens were cut from rope sections of the front end of the rope, from around midshaft, and from the back end.

The 12 specimens were subjected to standard tensile tests. The results of the tests, together with other relevant data, are given in Table 3.1. The rope diameters at installation and at discard were average values obtained from measurements taken by the mine during the monthly rope inspections. The "diameter reduction" in the table is for the "discard diameter" compared to the "installed diameter".

The "least wire diameter" in Table 3.1 is the smallest outer wire dimension measured during the inspection of a test specimen after the tensile test. The nominal outer wire diameter when new was 3,05 mm. A negative "loss in strength" in the table means that the breaking strength was greater than the new rope breaking strength.

For information: Changes in the laylength of a triangular strand rope do not necessarily cause diameter changes. If the core of a rope is of sufficient size, an increase in laylength alone will not cause a decrease in the rope diameter. An increase in laylength, increases the space between strands. Applying tensile load to a rope on which the laylength was increased, will decrease the rope diameter depending on the stiffness or compressibility of the rope core. In the case of the underlay rope discussed here, no significant variation in rope diameters were recorded anywhere along the length of the rope when it lost the mentioned large amount of spin (which resulted in a significant increase in laylength). After installation of a rope in a shaft, the back end will have the smallest diameter.

Table 3.1: Tensile tests on rope specimens with rope diameter reductions due to plastic deformation. New rope breaking strength = 1 233 kN

Specimen	Breaking load	Installed diameter	Diameter at discard	Least wire dimension	Diameter reduction	Loss in strength
O/L front	1 231 kN	39,8 mm	38,2 mm	2,63 mm	4,0%	0,2%
O/L front	1 224 kN	39,8 mm	38,2 mm	2,71 mm	4,0%	0,7%
O/L mid	1 211 kN	39,0 mm	37,2 mm	2,58 mm	4,6%	1,8%
O/L mid	1 210 kN	39,0 mm	37,2 mm	2,55 mm	4,6%	1,9%
O/L back	1 171 kN	38,8 mm	36,2 mm	2,07 mm	6,7%	5,0%
O/L back	1 158 kN	38,8 mm	36,2 mm	2,13 mm	6,7%	6,1%
U/L front	1 212 kN	39,8 mm	38,1 mm	2,68 mm	4,3%	-0,7%
U/L front	1 247 kN	39,8 mm	38,1 mm	2,67 mm	4,3%	-1,1%
U/L mid	1 235 kN	39,2 mm	37,4 mm	2,53 mm	4,6%	-0,2%
U/L mid	1 223 kN	39,2 mm	37,4 mm	2,62 mm	4,6%	1,2%
U/L back	1 168 kN	38,8 mm	36,5 mm	2,24 mm	5,9%	5,7%
U/L back	1 174 kN	38,8 mm	36,5 mm	2,32 mm	5,9%	5,2%

The following was noted from the results of the tensile tests:

- The flattening of the outer wires of the rope, reducing the wire diameters from 3,05 mm to the least wire dimension in the table above, did not account for the full reduction in rope diameter. The remaining reduction of the rope diameters were between 2% and 2,5%. This additional reduction in rope diameter is probably caused by the rope being compressed with extensive usage.
- Diameter reductions of 4%, compared to the as-installed diameter, did not change the rope strength significantly.
- The plastic deformation at the back ends of the two ropes tested was already so extensive that it is unlikely that diameters of the back ends could have been reduced further through plastic deformation. It could therefore be that, depending on the rope construction, rope diameters can only be reduced by a maximum of 7% below the initial installed measured diameter due to plastic deformation of the outer wires. The accompanying rope strength reduction should then not be more than 7% and definitely not more than 10%.

3.2 Diameter reductions due to abrasive wear

Because the front ends of inclined winder ropes could undergo significant diameter reductions due to abrasive wear, and because six monthly statutory test were carried out on the front ends of ropes, it was considered that sufficient information on rope strength loss due to abrasive wear could be obtained from statutory test records.

Over 1 300 records of front end tests of inclined winder ropes were obtained from the CSIR rope data base. The parameters extracted from the data base included:

Winder permit number, angle of the incline, rope coil number, nominal rope diameter, measured diameter of new rope, measured diameter of the tested specimen, new rope strength, strength of the tested specimen, least outer wire dimension, date rope was cut, and date of rope test.

Information on the strength loss as a function of reduction in rope diameter could not be extracted from the data with confidence, because of the following problems:

- All measured rope diameters in the data base were not available for all the ropes, and some values were obviously incorrect.
- Rope diameter measurements at the time of installation were not available.
- The rope strength is influenced by factors such as corrosion.
- Significant increases in rope strength (as much as 10%) with time (usage) for a large percentage of the ropes made it virtually impossible to isolate the influence of rope diameter reductions.

As an example: The "least wire diameter" measurement after a test on a 36 mm diameter rope gave a wire diameter reduction of 0,5 mm on a 3 mm wire. The rope diameter was down by 1,2 mm, but the tensile test did not show any significant loss in breaking strength.

Therefore: It does not seem likely that proper information on the effects of abrasive wear will be obtained from the front end tests of inclined winder ropes.

Proper data on the effect of diameter reduction due to abrasive wear could be obtained through the testing of laboratory prepared specimens. However, preparation of such test specimens may not be an easy matter.

4 Ropes with excessive corrosion

A length of a 36 mm non-spin rope, which had a localised section with excessive corrosion, was located by Anglo American Technical Services. A rope strength loss of 40% was estimated by the AATS rope test technicians from the indications obtained from the RAU magnetic rope testing instrument.

Two test specimens, both with gauge lengths of 4,8 m, were cut from the length of rope: One specimen contained the localised corrosion, and the second specimen served as a control.

The control sample returned a strength 1,5% less than the new rope strength. The maximum load carried by the sample with the corroded section was 48% lower than the new rope strength.

The load-elongation graph of the tensile test of the corroded section showed that a first strand failure most likely already occurred at 45% of the new rope strength, but the specimen still reached a maximum load of 52% of the new rope strength.

Although a rope with a degree of corrosion and strength loss as the one described above should not have remained in service for so long, the exercise showed the ability of the magnetic testing instrument to identify excessive corrosion successfully, even in a non-spin rope. However, previous investigations (GAP054, GAP324) have shown that the instruments can identify corrosion where the breaking strength (due to corrosion alone) has only reduced by the statutory 10%.

Greater detail of the performance of the RAU instrument and various other instruments on this particular length of rope with its localised corrosion is given in the SIMRAC report GAP503 and GAP535 (1999).

5 Damaged ropes

Visual damage on the rope (bird-caging, corkscrews, mechanical damage and other rope distortions) requires the rope to be discarded. The general reason being that subsequent rope deterioration will be greater than normal and unpredictable, i.e. the rope would have reached a dangerous condition before the next rope examination.

A tensile test on a damaged rope does not really contribute towards the discard criteria, but it does give information on the remaining strength of the rope, i.e. was there ever a possibility of a disaster (total rope failure) between the time of the incident that caused the damage to the rope, and the time that the section of rope (or complete rope) was removed from the winder.

One triangular strand rope with a severe distortion and one stage rope (a non-spin rope), which "popped" a core, were located and test samples were obtained.

5.1 An extruded rope

A section of a dead turn of a triangular strand rope on a winder drum was severely deformed when this section of rope was extruded between two rope turns of the next rope layer. The reason (which is not of direct concern) was most probably that the dead turns were not properly tensioned. The extent of the rope distortion is shown in Fig. 5.1.

A standard test specimen was cut from the 1 800 MPa rope. Although the rope was severely deformed, there were no broken wires visible. As the load increased during the tensile test, the distorted part of the rope "closed" again into its original shape. The breaking strength of the rope was only 2,6% down from the new rope strength, but the plastic fraction of elongation was down to 0,8%. Although a rope with damage as shown will be discarded, it is encouraging that an 1 800 MPa triangular strand rope could retain a very large portion of its tensile strength after being severely deformed. However, should winding operations have continued after the damage occurred, rope deterioration would have been extremely rapid.

Figure 5.1: An extruded drum dead turn.

5.2 A kinked non-spin stage rope

When one of the two ropes on a stage winder slipped on the winder during raising of the stage, the excess rope accumulated at the termination of the rope on the stage, and "corkscrewed". The triangular strand inner-rope "popped" out in two places over a five metre length of rope. The rope was tensioned again, and after the stage was brought to the bank, the damaged rope section was removed. The damaged length of rope remained corkscrewed after it was removed.

The rope was a 42 mm diameter, 15 strand fishback construction and of 1900 MPa tensile grade. Two test specimens (gauge lengths of 1,6 m and 2,4 m) were cut from the damaged length of rope. Numerous broken wires were visible on both test specimens.

The tensile tests returned breaking strength losses (compared to the new rope strength of 1 434 kN) of 56% and 65%, which were very severe. This specific non-spin rope did not take too kindly to being corkscrewed.

6 Very old ropes

Two rope samples (from rope coil Nos 914797 and 914798) were tested before the origin of the samples and reason for submitting the samples for testing could be determined. Subsequent efforts to locate the origin of the samples were also not successful.

The two ropes were 43 mm diameter, 18 strand fishback ropes of 1 800 MPa tensile grade, and galvanised. The particular diameter, construction and galvanising indicated that the ropes were stage ropes or Koepe winder head-ropes.

Nevertheless, the two rope samples were of interest because they were both 22 years old at the time of the tensile test. Although slight pitting and corrosion were visible on the outside of both ropes, the breaking strength losses were only 1,7% and 4,0%.

7 Cut-wire tests on non-spin ropes

Two non-spin rope constructions were studied: 18 strand fishback ropes and 15 strand ribbon strand ropes. Earlier cut-wire tests on fishback ropes were described in SIMRAC report GAP324 (1997) Volume 1. More cut-wire tests on fishback ropes were carried out as part of GAP502 (this investigation). Cut-wire tests on ribbon strand ropes were described in SIMRAC report GAP439 (1998), and were continued as part of GAP502.

The objective of the cut-wire tests on the fishback and ribbon strand non-spin ropes was to determine allowable reductions in steel area for broken wires in these constructions so that the probability of a strength loss of greater than 10% would be small. The ability of non-destructive rope testing instruments to detect external and internal broken wires in a non-spin rope is beyond the scope of this report, and was therefore not considered.

At the time that the cut-wire tests of this investigation were carried out, the "recipe" for cut wire tests was well established (and accepted). The cut wire tests were done according to the procedures inherited from the earlier investigations[1,2,3] and the previous SIMRAC investigations. In these investigations, selected wires were cut in a standard rope tensile test specimen, and the breaking strength of the specimen was determined. Relationships and scatter (deviation) were then determined between the loss in breaking strengths and the area reductions from the cut wires. Allowable area losses for broken wires were then determined, taking the scatter in the results into account.

In none of the earlier reports was the scatter in the breaking strength results for a given amount of area reduction ever questioned or addressed. It was simply accepted that scatter in the results was to be expected.

The cut-wire tests of this investigation were carried out as per the recommendations of the GAP439 report, and in the same way as all previous cut-wire tests. In order to recommend discard criteria for broken wires on non-spin ropes, it was decided that all cut-wire tests on non-spin ropes of previous investigations (GAP324 and GAP439) had to be evaluated together with those of GAP502. The results of all the cut-wire tests on non-spin ropes are given and discussed in detail in Appendix B. Greater details on the earlier tests than that given in the GAP324 and GAP439 reports are included in Appendix B.

It was only when all of the cut-wire results were analysed together, and greater details obtained for the tests of earlier investigations, that possible problems regarding the cut-wire test and analysis procedures were identified (i.e. details that were not considered or mentioned in previous reports). The findings, problems and possible irregularities identified in Appendix B were the following.

New rope breaking strengths

Relatively large new rope strength differences were encountered for the non-spin ropes compared to triangular strand ropes. Differences of as much as 5% were encountered between new rope tests carried out at Haggie and the CSIR, while the greatest difference of new rope tests carried out at the CSIR on the same rope coil was 2%. Reasons for the differences could have been:

- Calibration differences between the Haggie and the CSIR rope testing machines.
- Unsatisfactory rope specimen preparation procedures (fishback and ribbon strand ropes are prone to relative movement between outer strands and the inner rope if not properly "seized" before cutting).

The calculation of the "loss in breaking strength" for a specimen depends directly on the new rope strength selected for the calculation. Incorrect or non-representative new rope breaking strengths will skew "loss in breaking strength" results, especially if rope strength losses of 10% and less are considered.

Specimen preparation

All the non-spin rope specimens were subjected to 500 load cycles **after** wires were cut. When cut-wire tests were carried out on triangular strand ropes,[2,3] the specimens were subjected to 500 load cycles **before** wires were cut. During one of the triangular strand rope investigations[3] (by Hecker and Kuun) two specimens were cycled after the wires were cut. The following was included in that report:

> "The effect of cycling is not yet fully understood. The only effect of cycling that can be observed from the current tests seems to be: The largest difference between the results from identical tests is obtained if the specimens are not cycled at all and the smallest difference is obtained when the wires are cut before the specimens are cycled."

The loads at failure of rope strands with cut wires and the breaking strengths of rope specimens could therefore be influenced by load cycling before the tensile test.

Inner rope wires cut

The inner ropes of 18 strand fishback ropes and 15 strand ribbon strand ropes are triangular strand ropes. For the rope diameters tested, the fishback and ribbon strand ropes had identical 6x29 triangular strand inner ropes. Similar behaviour could therefore be expected for cut-wires of the inner triangular strand rope part of both rope constructions.

Generally the breaking strength losses were of the same percentage as the area reductions from the cut wires (see Fig. 7.1). Asymmetrical distributions of broken wires in the inner rope part did not make as much difference as was the case for the tests on triangular strand ropes.

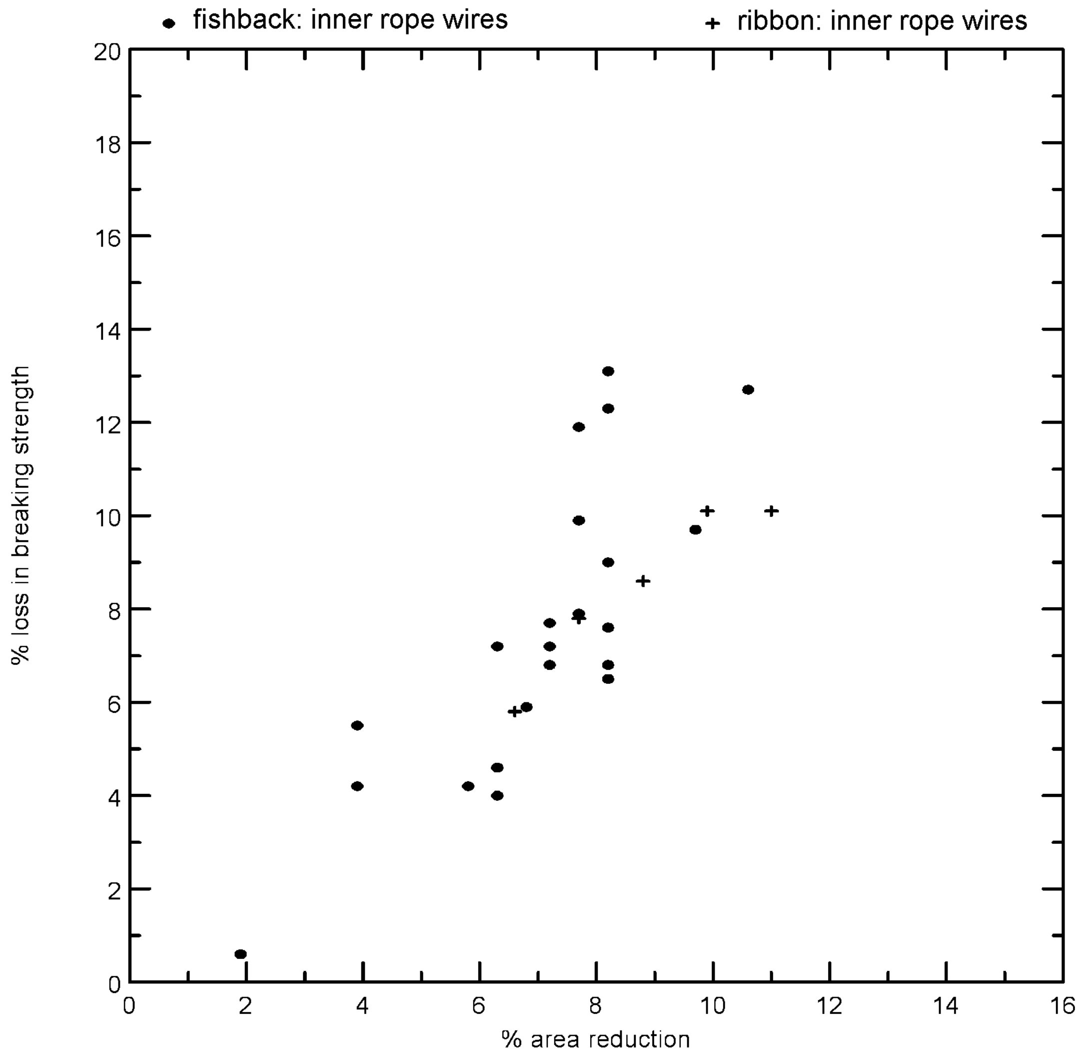

Figure 7.1: ***All non-spin ropes tested: Loss in breaking strength vs. total area reduction from cut inner rope wires.***

For area reductions of 7,7% to 8,2% for inner rope wires cut, strength losses varied between 6,5% and 13,1%. Although it can be reasoned that such a variation is of the same order as that observed for tests on pure triangular strand ropes,[2] the following observations still need to be explained:

- For a number of the specimens (only inner rope wires cut), only outer strands failed during the test.

- For a number of specimens the losses in breaking strength were noticeably less than the reductions in steel area.

Outer strand wires cut

All but three of the cut-wire tests on outer rope strands were carried out on the ribbon strand construction.

A major finding of this report was that all previous tests, including the tests of this investigation, were continued after strands had failed. In many of the cases, the rope specimens had remaining strengths greater than the loads at which strands with cut wires failed. In such cases, the maximum loads carried during such tensile tests did not reflect the load at which the "weakened" strand or strands failed.

At the CSIR, tensile tests on rope specimens are carried out under a protective cover for safety reasons. Unfortunately this prevented witnessing of "early" strand failures. Only after the data of all the tests were analysed thoroughly, it was realised that early strand failures did occur.

The loads at which the first (weakened) outer strands failed were visible on the load-elongation graphs generated during the tensile tests. These loads could therefore be obtained, together with the specimen elongation at failure of the weakened strand, for the tests of GAP439 and of this investigation. The failure of a strand is considered failure of the rope, or at least it will be a reason for discarding the rope. The loss in breaking strengths for the first strand failures were much greater than the anticipated breaking strength losses.

The breaking strength losses obtained for outer strand wires cut are shown in Fig. 7.2 against the total cut-wire area reductions. The area reductions included all the wires that were cut, even that of strands cut completely.

In some cases the same number of wires were cut in more than one strand. The "first strand failures" in these cases were mostly the failure of only one strand, the other weakened strands failing at slightly greater elongations (but not always at greater loads; see Appendix B for details). Cut wires in a strand other than the one that failed first should not influence the behaviour of the rope specimen much other than slightly reducing the stiffness of the specimen. If the "first strand failure loads" of Fig. 7.2 were plotted against the area reduction of only the cut wires in the strand that failed first, the failure loads for a given area reduction would even have been greater.

The situation seems to be much more complicated than had been experienced with tests on triangular strand ropes. Furthermore, Fig. 7.2 shows that a total area reduction of 2% could already give a strength loss of 10%.

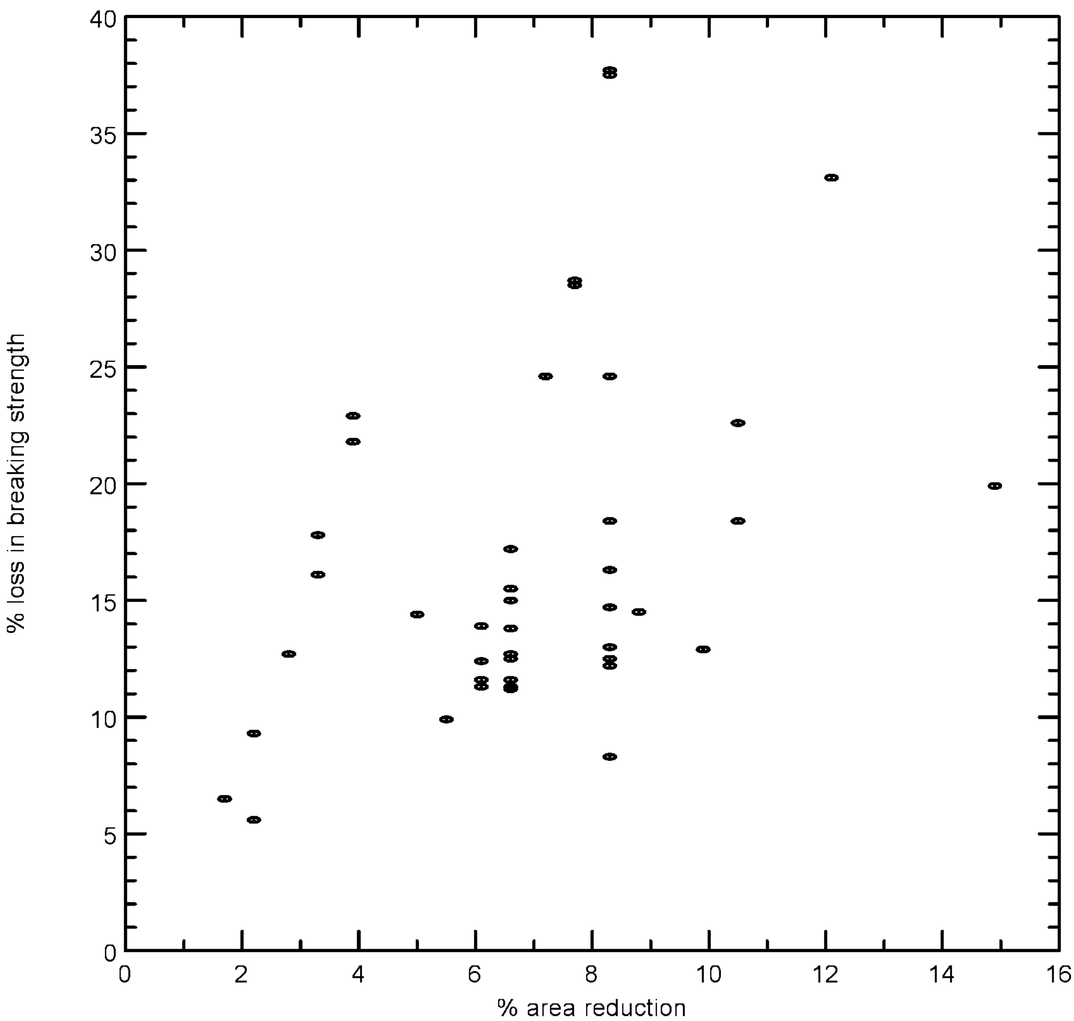

Figure 7.2: First strand failures of the ribbon strand rope: Loss in breaking strength vs. total area reduction from cut outer strand wires.

Generally the breaking strength losses were greater for the specimens with the larger number of cut wires in an outer strand. The larger breaking strength losses were also experienced (as should be the case) for the shorter elongations to failure. The elongation to failure of a strand with cut wires decreased as the number of cut wires increased. For wires cut in one and two strands, the weakened strands all failed at loads less than the remaining strength of the specimens.

The questions and irregularities raised by the analysis of all cut wire tests on non-spin ropes indicated to the author of this report that simply comparing the breaking strength losses with steel area reductions from cut (or broken) wires, as was done for all investigations to date, may not have been the correct way to investigate the effect of broken wires on the strength of winding ropes. Section 9 of this report introduces another approach.

Combinations of cut wires on inner and outer strands on the non-spin ropes were not investigated in either GAP324, GAP439 or this investigation (GAP502). Such combinations would most probably only have resulted in further questions.

8 Revisiting the discarded rope tests

In section 2.1 a test on a fishback rope specimen, obtained from a rope discarded from a drum winder, was discussed. The rope specimen had four broken wires in one outer strand, which amounted to a steel area reduction of 39% of the area of the strand, and 1,5% of the steel area of the rope. The loss in breaking strength, determined in the standard way, was 2,5% less than the new rope strength, and 4,7% less than the values of control samples cut from the discarded rope. The load-elongation graph produced during the tensile test is shown in Fig. 8.

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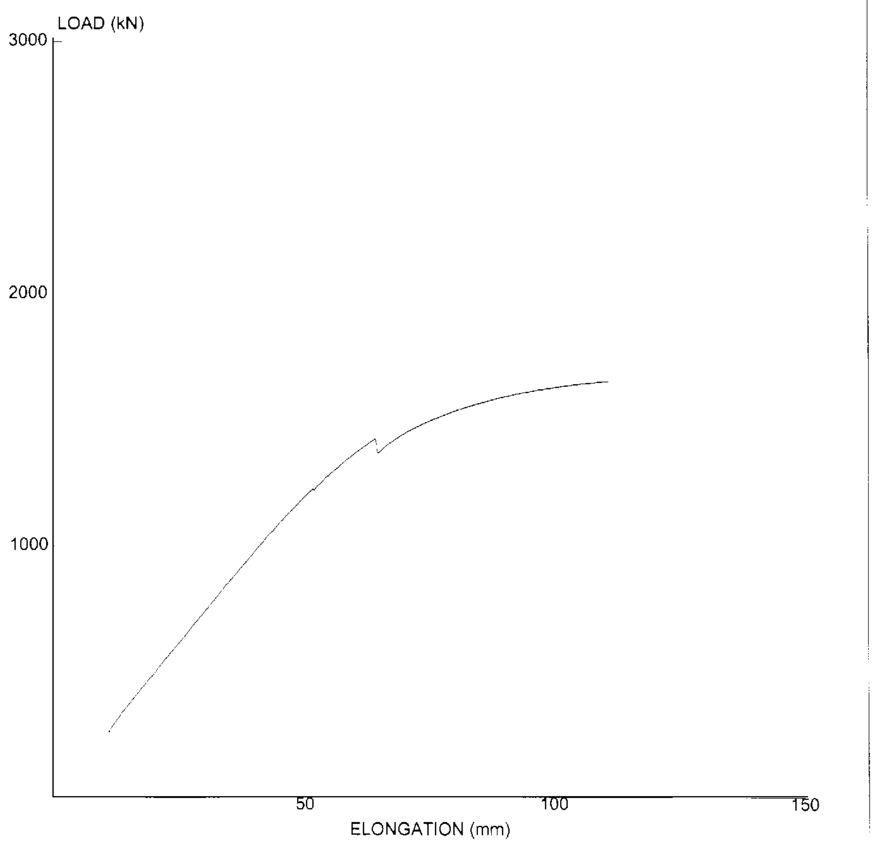
Strain energy to failure	122,3 kN.m	Certificate Number	216353
Plastic fraction of energy	65,9 kN.m	Date of test	98-05-15
Plastic fraction of elongation	43,2 mm (1,6%)	Specimen coil number	137114002
Slope	24,3 kN/mm	Diameter (mm)	46,0
Maximum load carried	1651 kN	Applicant:	
Gauge length	2750 mm	E.R.P.M (MIKE VAN ZYL).	



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Engineer:

Figure 8: Load-elongation graph of a fishback rope specimen with 40% of the wires of a single outer strand broken.

The outcome of the in-depth evaluation of the cut-wire tests on non-spin ropes (section 7) prompted this re-evaluation of the result obtained from the tensile test. With hindsight it can now be seen quite clearly that the weakened strand failed at a load of 1 420 kN and at a specimen elongation of approximately 60 mm. This comprises a loss in breaking strength of 16% for an area reduction of only 1,5% and reinforces the notion that weakened strands could fail at relatively low rope loads. During the tensile test, which was carried out under a protective cover, the failure of the strand was incorrectly noted as a "first wire failure".

9 A rope failure analysis

The failure of stranded ropes are analysed in this section to explain apparent anomalies and irregularities that ensued from the execution and analysis of cut wire tests on non-spin ropes.

For stranded ropes, wires are first twisted together into the individual rope strands. In a secondary process the strands are closed together into the wire rope. The rope strands are the distinguishable elements of a stranded rope. On the other hand ropes that are referred to as "single strands" are made up of successive layers of wires, generally with the wire lay direction changing from one layer to the next. Half-locked and full-locked coil ropes are single strands.

During operation of stranded ropes on drum winders and friction winders, broken wires can occur in the strands of the rope. Ropes are generally discarded before strand failures occur.

However, four separate cases have been reported where failure of an outer strand on a 15 strand ribbon strand rope was the reason for discarding the rope. This happened recently on two shaft sinking kibble winders. On both winders, the maximum (dynamic) rope loads that could be generated during normal winding were only around 30% of the (new) breaking strength of the kibble ropes. It was known that the strands that failed had some broken wires at the failure locations before the complete in-service failures of the strands. The remaining wires of these strand therefore failed at rope loads not greater than 30% of the new rope breaking strengths. The strength losses of the weakened strands of these kibble ropes therefore had to have been even greater than those determined for the cut-wire tests on 2,75 m long rope specimens described in Appendix B.

9.1 Load distribution in a weakened strand

In order to visualise the effect of broken wires in a strand, consider only one ribbon strand of a 15 strand ribbon strand rope. The strand consists of eight wires of the same diameter, twisted into the flat shape of the strand. Now consider a three metre length of the ribbon strand, with three adjacent wires cut or broken at one location, and the strand subjected to a tensile load.

It is common knowledge that a broken wire in a strand of a rope can "recover" in a relatively short distance from the break, i.e. some distance from the break all the strand wires will carry (approximately) equal loads. Closer to the break, the loads in the five uncut wires will start to increase, and the loads in the three cut wires will start to decrease. In the vicinity of the wire breaks, the loads in the cut wires will be zero, while the full strand load will be carried by the five remaining uncut wires. If the tensile load on the strand is increased, the strand will fail at (approximately) five-eights of the failure load of an undamaged strand.

Thus, for any type of strand with a broken wire or a cluster of broken wires, there will be the lengths of strand not affected by the broken wires, transition lengths on each side of the broken wire section in which the wire stresses vary, and a length of strand that consists only of the remaining wires of the strand. Very little information is available on the length of a strand affected by broken wires. Therefore, the section of a strand with broken wires will be approximated as a finite (but not yet quantified) length of strand of reduced cross-sectional area. The rest of the strand will be considered as undamaged.

For the analysis and the net result of this section, the exact strand length affected by broken wires does not have to be known other than that it is finite.

Nevertheless, and for the sake of interest: Visual assessment of the construction of ribbon strands, fishback strands and triangular strands indicate that ribbon strands should have a relatively short "affected length", longer for fishback strands, and longest for triangular strands because of the radii of curvature and the variation of the radii of curvature of outer strand wires. Another factor that will increase the "affected length" is creeping of the ends of broken wires (observed for triangular strand ropes operating on drum winders).

The non-spin rope specimens with cut wires, described in section 7, were subjected to 500 loading cycles after wires were cut and before the tensile tests were carried out. Unfortunately, no data was collected on whether the gaps between the ends of cut wires were larger after the loading cycles. This would have given an indication of whether and at what rate wires crept during pure tension-tension loading. Running a rope over sheaves and winding a rope onto a drum may increase the rate of creep of broken wires.

If broken wires in a strand cause unequal loading of the remaining wires in the strand, a "stress concentration" would have been formed effectively, i.e. the stress in one or some of the remaining wires in the strand will be greater than the average stress of the remainder of the strand. The remainder of a strand will then be even weaker.

9.2 A weakened strand in a rope

In tensile tests on stranded ropes, strands fail completely. It not uncommon to get only one strand of a new triangular strand rope and only three outer strands of a new non-spin rope failing at maximum load carried during a test. It will be most unusual if a half-failed strand is discovered after a tensile test. It is also uncommon for a stranded rope specimen to fail completely (all strands) during a tensile test. Because rope strands can fail individually, they will be considered as the individual elements of a rope.

For the ductile failure of a strand, the wires "neck" before failure. To accommodate the additional elongation for necking, relative (lengthwise) movement between that strand and the rest of the rope is required. For the remainder of a weakened strand to fail, relative movement between the strand and the rest of the rope is also required. The cut wire tests on non-spin ropes have shown that such relative movement does take place during a tensile test, otherwise individual strands would not fail, or strands would not be able to fail one at a time.

Any relative movement between a strand and the rest of a rope will be impeded by static friction between strands. The amount of friction depends on the type of strand, and the position of the strand in a rope, i.e. the type of rope construction.

For triangular strand ropes and fishback and ribbon strand non-spin ropes, the least amount of static friction will be experienced by the outer strands of the non-spin ropes. The fact that small gaps exist between the outer strands means that there will be no "clamping" or wedging of an outer strand between other strands. The inner rope strands and wire main core of non-spin ropes will therefore experience greater static friction than the outer strands.

The contact loads that will generate the friction between strands in a triangular strand rope are less certain. The contact loads will depend on whether there were gaps between strands at manufacture, the size and lateral stiffness of the fibre core, and the difference between the in-service laylength of the rope and the as-manufactured laylength. A somewhat extreme example is that with a very stiff and oversized core, unlaying a triangular strand rope will lead to no contact between the strands.

The action of bending a rope over sheaves and coiling it onto a drum induces relative movement between strands. Forced relative movement between strands will overcome static friction between strands. In a rope with a weakened strand, varying the rope loads could also overcome static friction between strands, especially for the outer strands of non-spin ropes, and probably for the strands of triangular strand ropes.

If an outer strand of a non-spin rope or a strand of a triangular strand rope is completely cut off for a rope that is operating on a winder, the cut strand will be "lost" for the entire length of the rope. Inter strand friction will not keep such a strand in place. Cutting an inner rope strand will be much like a broken wire in a strand; the ends of the cut strand will creep back with usage of the rope.

The point of all the above arguments is simply that friction between strands cannot be totally relied upon to maintain the rope integrity when the rope contains a weakened strand. Weakened outer strands of non-spin ropes have failed at relatively low loads; a weakened strand of a triangular strand rope could behave in the same way; while inner rope strands will most probably be assisted by inter strand friction.

The behaviour of braided ropes (like a rope slice at the termination of a rope) will, of course, be totally different, but braided ropes and splices are not considered in this analysis.

9.3 Strand and rope failures

In order to be able to understand how a weakened strand or strands in a rope could behave, it will be assumed that inter strand friction will not be large enough to prevent relative strand movement. Inter strand friction will therefore not be taken into account in the analysis of this section.

A rope will be considered as being made up of individual and separate elements: The strands. Only tensile loads on a rope are considered in this section. Therefore, strands are regarded as solid members, i.e. the sum total of their individual wires. A broken wire or a cluster of broken wires in a strand will cause a local weakening of the strand as described in section 9.1. At that point or section in the strand, the strand will have less cross-sectional steel area, less strength and less stiffness.

With the above representation of a stranded rope, the analysis of rope failures were carried out as shown in Appendix C. The main findings are:

> The rope load at which a weakened strand will fail depends on both the effective length of the weakened section in the strand and the length of the rope specimen tested. If a weakened strand has, say, 70% of its steel area or strength remaining, it will fail at around 70% of the new rope strength, provided the rope specimen is long enough.
>
> When a weakened strand fails at a relatively low rope load, the remaining strength of the rope will be greater than the strand failure load.
>
> If all cut-wire tests (including those on triangular strand rope specimens) were carried out on longer rope specimens, different results would have been obtained.
>
> The premise that a rope has lost a given amount of strength is only valid for a rope construction in which all strands are identical and then the damage (broken or cut wires, wear, plastic deformation and corrosion) has to be the same for each strand.

The analysis of Appendix C further shows:

For triangular strand ropes (rope construction with all strands identical) it is not possible to get a loss in rope strength less than the reduction in steel area, for any length of specimen. However, such an occurrence is possible for a non-spin rope construction

The remaining strength of a rope, after one or more strands have been removed completely, is consistent and predictable.

The variation is strength obtained for actual rope tests on identical specimens (scatter) was most probably caused by the differences in the affected length of the weakened sections of the strands.

The analysis of Appendix C has therefore explained all apparent anomalies encountered during the cut-wire test of rope specimens.

Appendix C also shows that it is not possible to establish a relationship between breaking strength loss and area reduction in an assembly consisting of solid steel bars instead of strands. It will therefore also not be possible to establish such a relationship for stranded ropes, as has been attempted in the past. It will, however, be possible to calculate a minimum rope load at which a damaged strand or damaged strands of a stranded strand rope will fail.

The relatively good correlation for triangular strand ropes obtained in the past between cut-wire specimens and samples from discarded winder ropes was only because both the cut-wire test specimens and the discarded rope specimens had the same length.

10 Conclusions

The discard criteria for broken wires in SABS0293 were based on a 10% reduction in strength of a rope. An expectation was therefore created that by complying with these discard criteria, a rope would not fail as long as the rope loads did not exceed 90% of the new rope breaking strength.

However, it is shown in this report that rope strands with broken wires could fail at loads considerably lower than 90% of new rope breaking strengths. The cut-wire tests on non-spin ropes have shown this to be true for the outer strands of non-spin rope constructions, i.e. friction between the damaged strand and the rest of the rope is not sufficient to maintain the integrity of the rope. Inner rope strands of non-spin ropes will probably be assisted to some extent by inter strand friction, but the strands of triangular strand ropes will probably behave much like the outer strands of non-spin ropes.

If the cut-wire and discarded rope tests of triangular strand ropes were carried out on longer specimen lengths, previous researchers would have obtained different results, and would have established different discard criteria.

A relationship between the reduction in steel area in a stranded rope from broken and cut wires and the loss in rope strength can only be established for a rope of which all the strands are identical, and then only if the broken wires are identical in each strand.

The premise of a rope having lost 10% of its original strength, used previously for establishing discard criteria for broken wires in ropes, does not exist if different lengths of rope are considered. The basis for establishing discard criteria, and therefore what is to be expected if such discard criteria are applied, needs to be reconsidered.

Most winder ropes are discarded because of broken wires. The discard criteria for broken wires will remain the most important part of SABS0293. Irrespective of what is found in future or what the discard criteria will mean, the discard criteria for broken wires will in the end still be an allowable percentage of the area reduction of a strand or a rope, i.e. uncomplicated.

Regardless of the conclusions above, the other tests in this report showed that:

The results from tests carried out on rope specimens with broken wires, discarded from mine winders, were not different from what were obtained before, and were therefore as expected. However, only considering the maximum load carried during a tensile test without giving proper attention to what actually happened during the test could lead to incorrect conclusions.

The tests carried out on triangular strand rope specimens that had relatively large amounts of diameter reductions due to plastic deformation of the outer strand wires showed that the relevant discard criteria could be too onerous. Taking the findings of this report on rope failures into account, it will not be as easy as before to readily add together the "discard factors" for broken wires and diameter reductions.

The attempt to obtain suitable data for diameter reductions for pure wear from the data of statutory front end tests on inclined winder ropes was not successful. Specific rope specimens will have to be collected or laboratory prepared specimens will have to be tested.

The unacceptable degrees of strength loss for ropes that sustained abnormal damage remain disconcerting. Appropriate measures have to be included in SABS0293 that will ensure that such ropes are discarded immediately.

Differences between the breaking strengths of new rope tests carried out at Haggie and those carried out at the CSIR are of concern, especially if collected rope samples are tested at the CSIR and compared with the new rope strengths determined at Haggie.

Irrespective of how the conclusions and findings in this report are interpreted, winder ropes still have to be inspected and discarded according to the current specifications of SABS0293. The discard criterion that the number of broken wires in a single strand may not exceed 40% of the number of wires in the strand will, at least for the near future, ensure that non-spin ropes with outer strand damage do not remain in service too long.

11 Recommendations

Tensile tests on longer specimens with weakened strands have to be carried out to determine the effect of inter strand friction in fishback, ribbon strand and triangular strand ropes.

The mechanism or reason for scatter in earlier cut-wire tests on triangular strand rope specimens can be confirmed by testing standard length tensile specimens with weakened strands in which the affected length of the weakened sections are varied.

The relative stiffnesses of the different rope layers of non-spin ropes have to be determined to be able to predict at what rope loads weakened outer strands will fail.

The effect on rope strength of rope diameter reductions due to pure wear needs to be verified.

A new basis for the discard criteria of winder ropes has to be established:

> To this extent, the maximum rope loads that could be generated by different winders, the modes of failure of different rope constructions, and the consequences of rope failures or failures of rope strands have to be taken into account. The rate of deterioration subsequent to any rope damage or deterioration also has to be considered.
>
> It may be necessary to review the concept of rope safety for different winder types (e.g. drum, Koepe, stage) before a new basis for discard criteria is established. It may further be required that different discard criteria have to be established for each combination of rope construction and winder type, e.g. different criteria for fishback ropes operating as kibble ropes, stage ropes, and Koepe headropes.
>
> For the situations and types of rope deterioration where it is physically possible to get a loss in rope strength that is not dependent on rope length, the 10% loss in breaking strength should be retained as basis for the discard criteria. Examples of such conditions are: Corrosion, and symmetrical wear on triangular strand ropes.
>
> The combination of different modes of rope deterioration (e.g. broken wires, diameter reductions) has to be determined.

Whenever "premature" failure of any part of a rope can be expected during a tensile test, the rope specimen should not be tested under a protective cover so that the course of the test can be observed.

12 References

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4. Verbal communication: GFK Hecker, 1999.

Appendix A: Allowing for scatter in rope breaking strengths

A1 New rope strength

Tests on adjacent sections of a triangular strand rope, conducted at the CSIR laboratory, have shown a scatter in breaking strength of less than 1%.[4] This scatter included the inaccuracy of the rope testing machine.

The wire drawing process and the fact that a rope consists of the order of 100 individual wires averages out material property and wire size differences, resulting in consistent strengths for samples from the same rope.

A2 Ropes with broken wires

Tensile tests on triangular strand rope specimens with identical cut wires[2,3] have shown scatter in breaking strengths of as much as ±2%, and a scatter of ±3% for the specimens with the same number of broken wires (but slightly different distributions).

Previous researchers[1,2,3] assumed that the scatter in the results for a given percentage of steel area reduction due to broken wires was normal, and made no attempt to explain it. To take the scatter into account and to minimise the probability for a rope breaking strength to be greater than 10%, they:

- Assumed that the scatter in breaking strength for a given configuration and number of broken wires (area reduction) would have a "normal distribution".

- Selected a maximum allowable reduction in steel area from broken wires such that the average loss in breaking strength (for the selected steel area) plus either one standard deviation or two standard deviations would be 10%. For a rope sample with the number of broken wires equal to the selected amount of area reduction, the probability that the breaking strength of the rope sample will be greater than 10% would then be 15% (one standard deviation) or 2% (two standard deviations).

Figure A2 illustrates the above graphically.

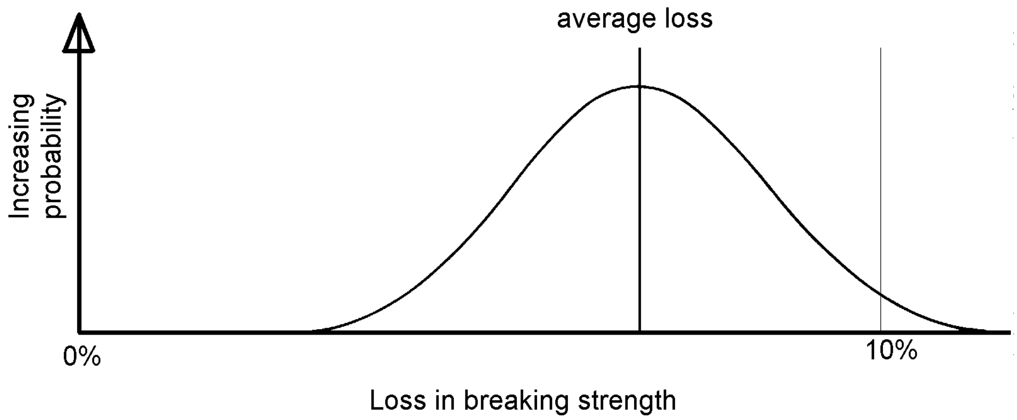

Figure A2: Assumed breaking strength loss distribution for a selected allowable reduction in rope steel area from broken wires.

There is some uncertainty whether the original intentions were to select the average loss in breaking strength such that the 10% strength loss would be one or two standard deviations greater, because it was never written up in the records of either SIMRAC or the earlier COMRO Steering Committee on Factors of Safety of Winder Ropes.

Nevertheless, the point was that the discard criteria would be chosen such that the probability of exceeding a 10% loss in breaking strength would be small. The following illustrates the point:

Borello and Kuun[2] reported the following after their tests on triangular strand ropes:

- For a selected loss in steel area of 4% of the rope area in a single strand of a triangular strand rope:

  Average loss in rope breaking strength = 6,8%
  Probability of a strength loss of greater than 10% = 0,4%

- For a selected loss in steel area of 4% of the rope area for asymmetrically distributed broken wires in a triangular strand rope:

  Average loss in rope breaking strength = 6,2%
  Probability of a strength loss of greater than 10% = 3,1%

- For a selected loss in steel area of 7% of the rope area for symmetrically distributed broken wires in a triangular strand rope:

  Average loss in rope breaking strength = 8,3%
  Probability of a strength loss of greater than 10% = 0,6%

After further tests were carried out by Hecker and Kuun[3] on triangular strand ropes with asymmetrical distributed broken (cut) wires, the following was concluded:

> "Based on the 1994 48 mm and the present 41 and 62 mm specimen test results, the probability of a loss in strength greater than 10% is 0,1%, 0,2% and 0,4% respectively for a reduction in area of 4%."
>
> (The mentioned report actually quoted wrong probabilities of 0,4%, 0,2% and 0,4% from a table. The probabilities should have been as mentioned.)

AppendixB: Cut wire tests on non-spin ropes

B1 Fishback ropes

B1.1 Cut-wire tests of GAP324

The cut-wire tests of GAP324 were performed on a 44 mm diameter, 1800 MPa, 18 strand fishback rope. The rope had the following construction:

12x10(8/2)/6x29(11/12/6 Δ)/WMC

12 fishback outer strands of 8 outer wires over 2 core wires.
A 6x29 triangular strand rope as the inner strands; each triangular strand had 11 outer strand wires.
The rope had a wire main core, i.e. the main core of the triangular strand inner rope.

Only the effect of cut outer wires of the inner triangular strand rope part was investigated. The total cross-sectional steel area of the rope was 968 mm². Each outer wire of a triangular strand had a diameter of 2,44 mm and an area of 4,68 mm². All the tests were carried out on standard tensile test specimens with gauge lengths of 2,75 m.

The "new rope test" for determining the initial strength of the rope was carried out at Haggie, and returned a strength of 1 497 kN.

Preparation of the cut-wire specimens

After preparation of a tensile test specimen, the one end of the specimen was twisted through one full rotation in order to unlay the outer strands and to give access to the triangular strand inner rope for cutting of the wires. After the wires were cut with an angle grinder, the rope was "closed" again, and then subjected to 500 load cycles between 5% and 25% of the new breaking strength to "settle" the rope before the tensile test was performed.

Subjecting a specimen to 500 load cycles was inherited from the earlier cut-wire tests performed on triangular strand ropes. For reasons of uniformity, this process was maintained.

Actual rope strength

For the tests of GAP324, a number of rope specimens without any broken wires were tested to obtain a "comparative" new rope strength. The following samples were tested:

- It was reported that the length of rope obtained from Haggie had some external corrosion. Two rope samples without any corrosion and one rope sample with corrosion were tested. These are designated "new1", "new2" and "corr".
- Two specimens that were twisted open (as described earlier) and then closed again without cutting any wires (and without subjecting the specimens to any load cycles) were tested. These two specimens are designated "twist1" and "twist2". According to GAP324, these specimens were tested to determine whether the action of twisting a rope open, and closing it again, had any influence on the rope strength.
- Two more "new" samples were tested at the time that the cut-wire tests were carried out. The reasons for testing these samples were not given in GAP324. These two are designated "new3" and "new4"

The results obtained from the seven "new" rope tests of GAP324 are given in Table B1.1.1

below, together with the new rope strength determined by Haggie. The number of strands broken during the tensile tests are also given.

Table B1.1.1: ***New rope tests on 18 strand fishback rope (GAP324). Standard tensile test specimens of 2,75 m long.***

Designation	Breaking load	Strands broken 12 o, 6 i, WMC
Haggie	1 497 kN	no information
new1	1 544 kN	5 o
new2	1 542 kN	3 o
new3	1 546 kN	5 o
new4	1 552 kN	6 o
corr	1 532 kN	6 o
twist1	1 522 kN	5 o
twist2	1 533 kN	5 o

Note that in all cases only outer (fishback) strands broke, which is considered normal for a new fishback rope.

The average strength of the specimens designated as "new" in Table B1.1.1 above is 1 546 kN ±0,4%. The lowest strength of the "twisted" specimens is 1,5% lower than the average "new" strength. The Haggie strength is 3,2% lower than the average "new" strength. It is unlikely that large strength variations are possible for a new (unused) fishback rope. Tests on adjacent sections of a triangular strand rope have shown a scatter in breaking strength of less than 1% (see section A1). The same can be expected of non-spin ropes.

The significantly lower new rope strength of the Haggie test was either the result of a calibration difference between the Haggie and CSIR testing machines, or a result of the rope specimen not being properly prepared. Observations of samples cut from fishback and ribbon strand ropes have shown that the outer strands tend to "lengthen" if not properly "seized" before cutting. In such cases, the outer strands would reach their failure strain earlier during a tensile test than would be the case for a properly prepared specimen.

For the comparison of the strengths obtained from the cut-wire tests, GAP324 used the average between "new3" and "new4" (1 549 kN), i.e. the value used for the calculation of strength losses.

The results of the cut-wire tests

The GAP324 report did not expand much on the actual results apart from tabling the cut-wire area and the reduction in strength. Greater details on the tests could fortunately still be obtained and are included in Table B1.1.2 below.

The outer wires of the 6x29 triangular strand inner part of the fishback rope are located such that a maximum of five wires could be cut in one location on the outside of a strand. It was assumed that the cut-wire distribution would have strived for the maximum asymmetry possible, i.e. a minimum of five wires cut per triangular strand.

Table B1.1.2 also gives the number of strands broken during a tensile test. No information was available on the failure or no failure of the wire main core. Load-elongation graphs for the tests were not available.

Table B1.1.2: Cut-wire tests on 18 strand fishback rope (GAP324). Standard tensile test specimens 2,75 m long. Inner strand wires cut (outer wires of the triangular strand inner rope). New rope strength = 1 549 kN

No.	Number of inner rope wires cut	Area reduct.	Load at failure	Strength loss	Strands broken 12 out., 6 in.
18-1	8	3,9%	1 464 kN	5,5%	2 o
18-2	8	3,9%	1 484 kN	4,2%	3 o
18-3	13	6,3%	1 438 kN	7,2%	8 o, 3 i
18-4	13	6,3%	1 478 kN	4,6%	8 o, 4 i
18-5	13	6,3%	1 487 kN	4,0%	9 o, 3 i
18-6	15	7,2%	1 444 kN	6,8%	8 o, 3 i
18-7	15	7,2%	1 438 kN	7,2%	8 o, 3 i
18-8	15	7,2%	1 430 kN	7,7%	9 o, 3 i
18-9	16	7,7%	1 396 kN	9,9%	1 o
18-10	16	7,7%	1 427 kN	7,9%	10 o, 4 i
18-11	16	7,7%	1 365 kN	11,9%	10 o, 3 i
18-12	17	8,2%	1 410 kN	9,0%	6 o
18-13	17	8,2%	1 346 kN	13,1%	8 o, 4 i
18-14	17	8,2%	1 359 kN	12,3%	7 o, 5 i
18-15	17 *	8,2%	1 443 kN	6,8%	8 o, 5 i
18-16	17 (symm) **	8,2%	1 449 kN	6,5%	12 o, 4 i

* This result was not included in the GAP324 report. No reason for the exclusion of this result in GAP324 could be found.

** The cut wires were distributed symmetrically (as close as possible) in all six strands. This result was also not included in GAP324.

Table B1.1.2 shows five cases where the losses in breaking strength were lower than the reductions in cross-sectional steel area from the wires that were cut.

For specimen nos 18-1, 18-2, 18-9 and 18-12, only outer strands failed, although only inner strand wires were cut.

Specimen nos 18-13 and 18-15: The strength losses were 13,1% to 6,8% for an identical 8,2% reduction in steel area.

The calculated strength loss of a specimen depends, of course, on the new rope strength selected for the calculation of the strength loss. If the action of twisting the rope open to cut the wires actually influences the strength of a specimen, the strength losses in Table B1.1.1 would be less (by approximately a further 1,5 percentage points).

B1.2 Additional tests on fishback ropes

Further tests on fishback ropes were carried out as part of this project (GAP502). In addition to more tests on specimens with cut inner rope wires, three test were also carried out for cut outer strands and cut outer strand wires.

The tests were performed on samples of rope from sections cut off when new ropes were installed on a Koepe winder. The 44 mm rope had a diameter and rope construction identical to the rope used for the cut-wire tests of GAP324. It also had the same tensile grade of 1 800 MPa.

The total cross-sectional steel area of the rope and wire diameters were therefore the same as for the tests of GAP324. The area of one outer wire of an outer strand was 3,66 mm², and the area of one complete outer strand was 37,8 mm² (3,9% of the total area). All the tests were carried out on standard tensile test specimens with gauge lengths of 2,75 m.

The preparation of the tensile test specimens was the same as that of GAP324, except that cutting of outer strands and outer strand wires did not require a test specimen to be twisted open. As before, all specimens were subjected to 500 load cycles between 5% and 25% of the new breaking strength, after wires were cut.

Two rope samples with no cut wires were prepared to determine the "new rope" breaking strength. "New1" was tested as prepared, and "new2" was first subjected to 500 loading cycles as for the cut-wire test specimens. The new rope breaking strengths are given in Table B1.2.1 below, together with the new rope breaking strength determined by Haggie.

Table B1.2.1: New rope tests on 18 strand fishback rope (GAP324). Standard tensile test specimens 2,75 m long (coil no. 140193/004)

Designation	Breaking load	Strands broken 12 o, 6 i, WMC
Haggie	1 528 kN	no information
new1	1 602 kN	5 o
new2	1 607 kN	4 o

As before, only outer (fishback) strands broke during the tensile tests. A new rope strength of 1 600 kN was assumed, which is 4,7% greater than the strength determined by the Haggie test. The reasons for the difference could be one of those given earlier.

Six specimens with wires cut on the inner strands were tested. The meaning of the description of the number of wires cut is:

14 (5x2sti 4x1sti): 14 wires cut: 5 outer wires on each of two inner (triangular) strands, plus 4 outer wires on one other inner strand.

Three specimens with outer strand wires cut were tested: One specimen with two wires cut in each of two opposing outer strands; one specimen with one outer strand cut completely; and one specimen with two outer strands cut completely.

The results of the tests are given in Table B1.2.2. The number of strands broken during a tensile test is also given in the table. This number of broken strands does **not** include the (outer) strands cut completely before a test. No information was available on the failure or no failure of the wire main core.

Table B1.2.2: Cut-wire tests on 18 strand fishback rope. Standard tensile test specimens 2,75 m long. New rope strength = 1 600 kN

No.	Description number of cut wires	Area reduct.	Load at failure	Strength loss	Strands broken 12 out., 6 in.

18-17	4 (4x1sti)	1,9%	1 590 kN	0,6%	6 o, 1 i
18-18	12 (4x3sti)	5,8%	1 533 kN	4,2%	12 o, 3 i
18-19	14 (5x2sti 4x1sti)	6,8%	1 506 kN	5,9%	9 o, 4 i
18-20	17 (5x1sti 4x3sti)	8,2%	1 478 kN	7,6%	7 o, 4 i
18-21	20 (5x4sti)	9,7%	1 445 kN	9,7%	6 o, 4 i
18-22	22 (5x4sti 2x1sti)	10,6%	1 397 kN	12,7%	7 o, 4 i
		1,5%			
18-23	4 (2x2sto)	3,9%	1 530 kN	4,4%	2 o
18-24	10 (one outer strand)	7,8%	1 545 kN	3,4%	1 o
18-25	20 (two outer strands)		1 479 kN	7,6%	3 o

The following was observed:

- For cut wires on the inner strands, the loss in breaking strength was much the same as the reduction in steel area for values up to 10%. However, only one sample was tested for a given number of cut wires; therefore, no scatter in the results.
- In four cases the losses in breaking strength were lower than the reductions in cross-sectional steel area from the wires that were cut.
- The results are not much different to that of GAP324 (Table B1.1.2).
- Cutting one or two outer strands of the rope show the remaining strength of the rope after one and two strands "failed". Removing two outer strands still leaves the rope with more than 90% of its original strength.

B1.3 Summary of the results of the tests on fishback ropes

Figure B1.3 shows the results of Tables B1.1.2 and B1.2.2 as a graph of strength loss against area reduction.

Too few (only one) test was done for outer strand wires cut to come to any conclusions on the effect of cut or broken wires in the outer strands of fishback ropes. Cutting complete outer strands does not really contribute to the discard criteria, because a rope with a failed outer strand will be discarded, irrespective of the loss in strength.

For area reductions of 7,7% to 8,2% for inner rope wires cut, strength losses varied between 6,5% and 13,1%. Although this variation is of the same order as determined for triangular strand ropes,[2] the following peculiarities have to be explained before an allowable steel area reduction is selected for broken wires in the inner rope of a fishback rope:

- For a number of specimens with only inner rope wires cut, only outer strands failed during the test.

- For a number of specimens the losses in breaking strength were noticeably less than the reductions in steel area.

The above is explained later in this report.

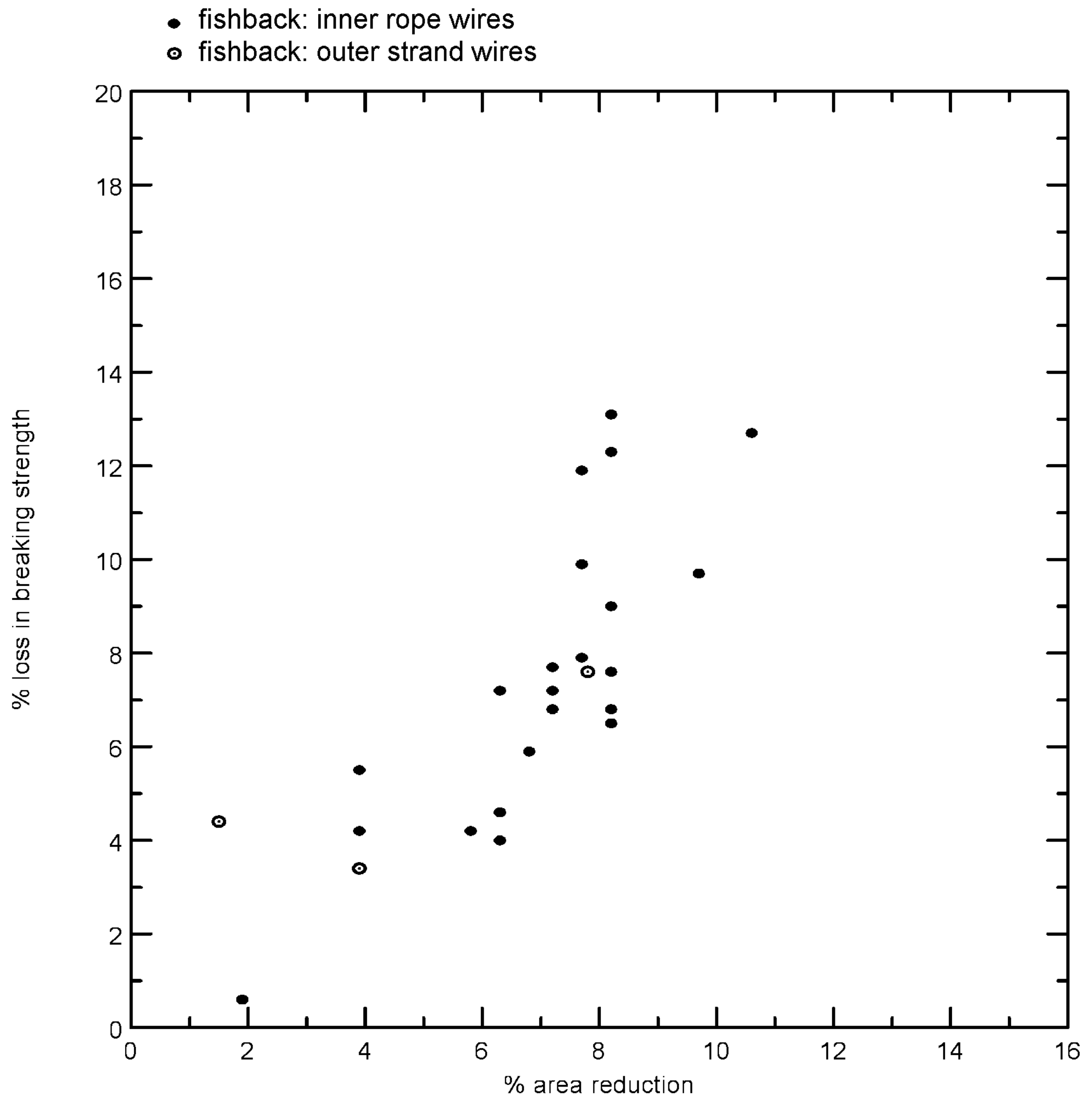

Figure B1.3: Results of cut wire tests on fishback ropes.

B2 Cut-wire tests on ribbon strand ropes

B2.1 Cut-wire tests of GAP439

B2.1.1 The results as obtained

For GAP324 cut-wire tests were only carried out on fishback ropes. That report concluded that recommended discard criteria would only be valid for fishback rope constructions. For GAP439, cut-wire tests on ribbon strand ropes were therefore carried out.

The cut-wire tests of GAP439 were carried out on samples cut from an unused length of a 46 mm diameter, 1 900 MPa, 15 strand ribbon construction non-spin rope. Only complete outer strands and wires of outer strands were cut. The rope details were:

9x8/6x29(11/12/6 △)/WMC i.e.	9 outer ribbon strands over 6 triangular strands over a wire main core

Rope cross-sectional steel area = 1 077 mm²
Outer strand wire diameter = 2,75 mm
One outer strand cross-sectional area = 47,5 mm² (4,4% of the rope)

All the cut-wire tests were carried out on standard tensile test specimens with gauge lengths of 2,75 m. The preparation of the tensile test specimens was the same as that of GAP324, except that cutting of outer strand wires did not require a test specimen to be twisted open. After wires were cut, all specimens were subjected to 500 load cycles between 5% and 25% of the new rope breaking strength.

Three rope samples with no cut wires were prepared to determine the "new" rope breaking strength. Only sample "new1" of the three samples, designated "new1" to "new3", was subjected to 500 loading cycles before the tensile test. The new rope breaking strengths, including the one determined by Haggie, are given in Table B2.1.1.1.

Table B2.1.1.1: New rope tests on 15 strand ribbon strand rope (GAP439). Standard tensile test specimens 2,75 m long (coil no. 139177/001)

Designation	Breaking load	Strands broken 9 o, 6 i, WMC	Specimen elongation at failure
Haggie	1 764 kN	no information	no information
new1 (cycled)	1 791 kN	3 o	125 mm
new2	1 788 kN	4 o	135 mm
new3	1 747 kN	6 o, 6 i	100 mm

Samples "new1" and "new2" had the same breaking strength for all practical purposes. The "new3" specimen failed only 100 mm from the endcap, which explains the lower breaking strength, the greater number of strands that failed, and also the relatively low elongation at failure. "New3" was therefore not representative of the new rope breaking strength.

The calculated loss in breaking strength of the samples with cut wires will differ depending on which new rope strength was selected. The GAP439 report did not mention the variation in the new rope breaking strength, and also did not indicate which one was selected. Inspection of the graphs of breaking strength loss against area loss in GAP439 showed that the Haggie determined new rope strength of 1 764 kN was used in that report.

The GAP439 report only gave a graph of breaking strength loss against area loss for the specimens tested, and then proceeded with a statistical analysis of the data, which included the fitting of curves and the calculation of the variation of the data.

The results of the GAP439 tests are given in Table B2.1.1.2. The number of strands broken during a tensile test is also given in the table. The number of strands broken does not include the strands that were cut off completely. No information was available on the failure or no failure of the wire main core. For uniformity, the same new rope strength of 1 764 kN was selected for the calculation of the strength losses.

29 specimens with wires cut on the outer strands were tested. The meaning of the description of the number of wires cut is:

22 (8+8+6): 22 wires cut: 8 in one outer strand, 8 wires in an adjacent strand, and 6 wires in the strand adjacent to the previous one. 8 wires cut in one outer strand requires the strand to be cut completely.

Table B2.1.1.2: Cut-wire tests on 15 strand ribbon strand rope (GAP439). Standard

tensile test specimens 2,75 m long. New rope strength = 1 764 kN

No.	Description number of cut wires	Area reduct.	Load at failure	Strength loss	Strands broken 12 out., 6 in.
15-1	3	1,7%	1 723 kN	2,3%	2 o
15-2	4	2,2%	1 695 kN	3,9%	2 o
15-3	4	2,2%	1 733 kN	1,8%	1 o
15-4	5	2,8%	1 715 kN	2,8%	2 o
15-5	6	3,3%	1 720 kN	2,5%	3 o
15-6	6	3,3%	1 717 kN	2,7%	1 o
15-7	7	3,9%	1 721 kN	2,4%	1 o
15-8	7	3,9%	1 687 kN	4,4%	5 o, 6i *
15-9	8	4,4%	1 719 kN	2,6%	1 o
15-10	9 (8+1)	5,0%	1 682 kN	4,6%	1 o
15-11	10 (8+2)	5,5%	1 628 kN	7,7%	1 o
15-12	11 (8+3) **	6,1%	1 565 kN	11,3%	1 o
15-13	11 (8+3) **	6,1%	1 518 kN	13,9%	1 o
15-14	11 (8+3)	6,1%	1 634 kN	7,4%	2 o
15-15	11 (8+3)	6,1%	1 647 kN	6,6%	1 o
15-16	12 (8+4)	6,6%	1 639 kN	7,1%	2 o
15-17	12 (8+4)	6,6%	1 635 kN	7,3%	2 o
15-18	13 (8+5)	7,2%	1 629 kN	7,7%	2 o
15-19	14 (8+6)	7,7%	1 640 kN	7,0%	1 o
15-20	14 (8+6)	7,7%	1 635 kN	7,3%	1 o
15-21	15 (8+7)	8,3%	1 642 kN	6,9%	1 o
15-22	15 (8+7)	8,3%	1 637 kN	7,2%	1 o
15-23	16 (8+8)	8,8%	1 634 kN	7,4%	1 o
15-24	16 (8+8)	8,8%	1 620 kN	8,2%	1 o
15-25	16 (8+8)	8,8%	1 640 kN	7,0%	1 o
15-26	16 (4+4+4+4) **	8,8%	1 508 kN	14,5%	4 o
15-27	19 (8+8+3)	10,5%	1 559 kN	11,6%	1 o
15-28	19 (8+8+3)	10,5%	1 561 kN	11,5%	1 o
15-29	22 (8+8+6)	12,1%	1 536 kN	12,9%	1 o

* This specimen failed at one of the end caps. It was not recorded whether the "weakened" strand failed at the location of the cut wires.

** These results were not included in the GAP439 report.

Before the results of the test are analysed thoroughly, the following should be noted:

- Table B2.1.1.2 shows quite a number of results where the loss in breaking strength was less than the reduction in steel area. As mentioned, the calculation of the breaking strength loss depends on the selected new rope strength. In the case of specimen 15-9, the loss in strength would still have been less than the reduction in steel area, even if the highest new rope breaking strength in Table B2.1.1.1 (1 791 kN) was selected.

- A winder will never continue to operate when a strand is broken on the winder rope. A broken strand will always be a reason to discard the rope. Therefore, the results of all specimens with more than one strand cut completely will not contribute to the development of discard criteria in the way it was done in the past. However, removing one or more complete outer strands gives the remaining strength of the rope for such occurrences. Removing two outer strands of the 15 strand rope still leaves the rope with more than 90% of it original strength.

- During a tensile test, the specimen is covered with a protective shield for safety. Unfortunately this prevented witnessing and recording of events such as: In which strand the first wire failure occur, and, was the first wire failure not the failure of the weakened strand.

- The number of strands recorded as broken after a test seemed to be incorrect in some cases. For specimens 15-14 and 15-15 one and two broken strands were recorded respectively. If this was correct, then did only the weakened strand fail in the one case, and one other strand as well in the second case. Both specimens had much the same breaking strength.

- Four specimens of the "8+3" combination were tested. For a 6,1% reduction in area, the breaking strength losses varied from 6,6% to 13,9%.

In order to explain these apparent irregularities, the load-elongation graphs generated during the tensile tests of Table B2.1.1.2 were obtained for the analyses that follow.

B2.1.2 Wires cut in one outer strand

Specimen 15-1: Three wires cut in one outer strand

Figure 2.1.2.1 shows the load-elongation graph of specimen 15-1. Three wires of an outer rope strand were cut. The note on the graph was added by the author of this report. The test certificate reported the following:

First wire failure at 1610 kN, breaking strength of 1723 kN, and that two outer strands failed.

Actually the events were the following:

When the load reached 1650 kN (at an elongation of approximately 75 mm) the weakened outer strand failed. At that point the load on the specimen dropped by approximately 50 kN. The tensile test was continued until another (uncut) outer strand failed (at 1 723 kN).

Each outer strand wire of 2,75 mm diameter has a strength of approximately 10 kN. The weakened outer strand had five wires remaining, therefore the load on the rope had to drop by approximately 50 kN when the weakened strand failed. The actual drop in load will depend on the relative load sharing between the different rope strands and the characteristics of the testing machine.

The "breaking strength" of 1723 kN was therefore the same as the strength of a specimen with one outer strand cut completely.

The "first wire failure" recorded at 1610 kN was, of course, after the strand failed, and was simply a visual observation of the load displayed.

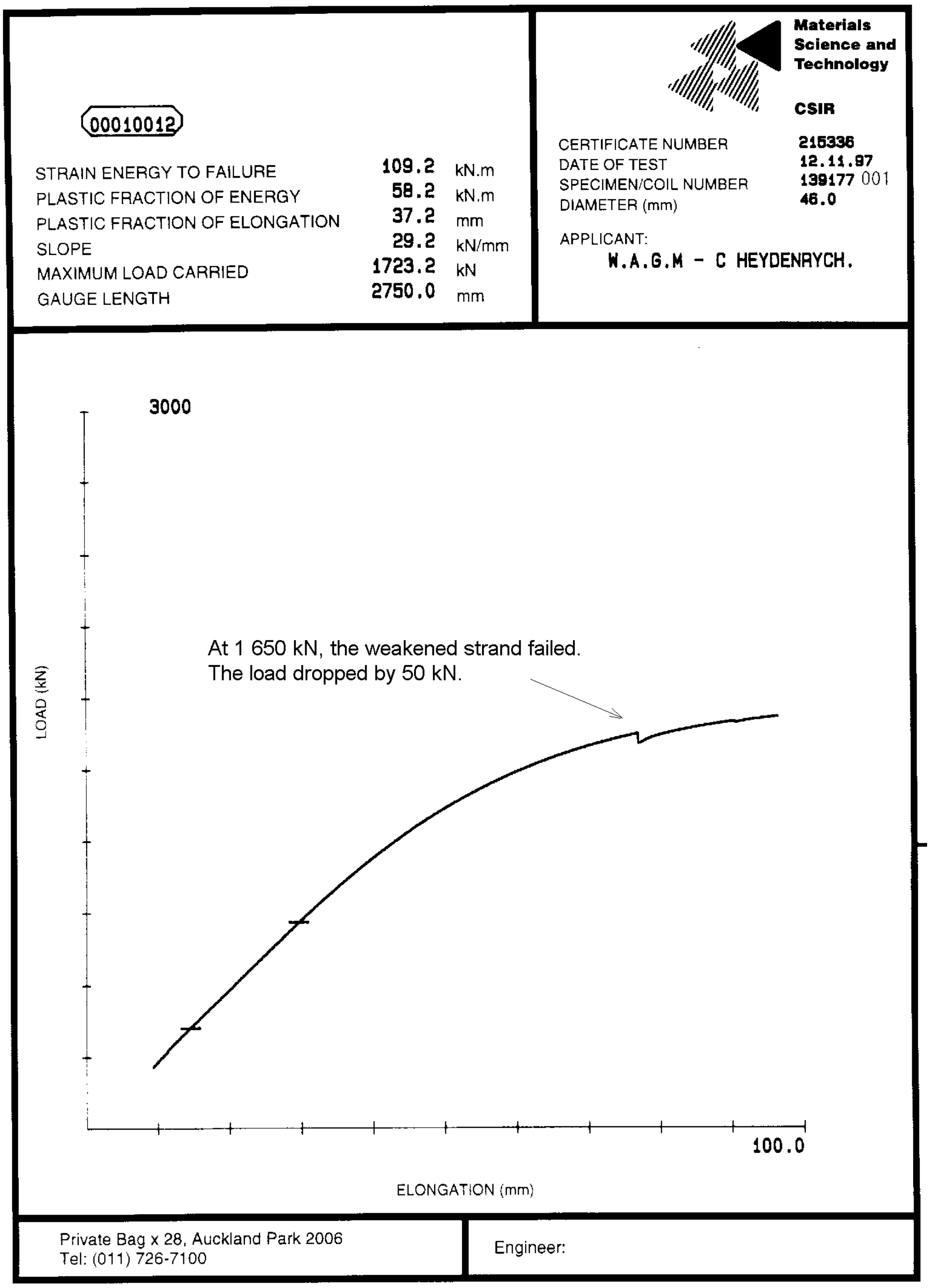

Figure B2.1.2.1: ***Load-elongation graph of specimen 15-1. Three wires cut in one outer strand.***

Specimen 15-2: Four wires cut in one outer strand

The test certificate recorded: First wire failure at 1 500 kN, breaking strength of 1 695 kN, and that two outer strands failed.

The load-elongation graph looked similar to that of specimen 15-1 (Fig. B2.1.2.1) and showed that the weakened strand failed at a load of 1665 kN (and at an elongation of approximately 70 mm). The drop in load at failure of the weakened strand was of the order of 100 kN (measured on the graph). The test was continued until another outer strand failed. The "breaking strength" of 1 695 kN was therefore the same as the strength of a specimen with one outer strand cut completely.
The "first wire failure" was probably incorrectly recorded as 1 500 kN instead of 1 600 kN.

Specimen 15-3: Four wires cut in one outer strand

The test certificate recorded: First wire failure at 1 590 kN, breaking strength of 1 733 kN, and that only one outer strand failed.

The load-elongation graph looked similar to that of specimen 15-1. The weakened strand failed at a load of 1 600 kN (and at an elongation of approximately 60 mm). The drop in load at failure of the weakened strand was of the order of 80 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 733 kN was therefore the same as the strength of a specimen with one outer strand cut completely.

From the graph it is very evident that the weakened and one other strand failed. The recording on the test certificate of "one outer strand failed" is therefore wrong. In the cases where one outer strand was cut completely, the rope testing personnel did not record that strand as having failed during the test. The tests were not carried out in the listed order of Table B2.1.1.2, and the error was most probably due to slight confusion.

Specimen 15-4: Five wires cut in one outer strand

The test certificate recorded: First wire failure at 1 490 kN, breaking strength of 1 715 kN, and that two outer strands failed.

The load-elongation graph looked similar to that of specimen 15-1. The weakened strand failed at a load of 1 540 kN (and at an elongation of approximately 60 mm). The drop in load at failure of the weakened strand was of the order of 70 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 715 kN was therefore the same as the strength of a specimen with one outer strand cut completely.

Specimen 15-5: Six wires cut in one outer strand

The test certificate recorded: First wire failure at 1 490 kN, breaking strength of 1 720 kN, and that three outer strands failed.

The load-elongation graph looked similar to that of specimen 15-1. The weakened strand failed at a load of 1 480 kN (and at an elongation of approximately 50 mm). The drop in load at failure of the weakened strand was of the order of 50 kN. The test was continued until another two outer strands failed (simultaneously at maximum load). The "breaking strength" of 1 720 kN was therefore the same as the strength of a specimen with one outer strand cut completely.

Specimen 15-6: Six wires cut in one outer strand

The test certificate recorded: First wire failure at 1 450 kN, breaking strength of 1 717 kN, and that only one outer strand failed (should have been two strands; probably for the same reason as given for specimen 15-3).

The load-elongation graph looked similar to that of specimen 15-1. The weakened strand failed at a load of 1 450 kN (and at an elongation of approximately 60 mm). The drop in load at failure of the weakened strand was of the order of 40 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 717 kN was therefore the same as the strength of a specimen with one outer strand cut completely.

Specimen 15-7: Seven (of a total of eight) wires cut in one outer strand

The test certificate recorded: First wire failure at 1 410 kN, breaking strength of 1 721 kN, and that only one outer strand failed (should have been two strands; probably for the same reason as given for specimen 15-3).

The load-elongation graph looked similar to that of specimen 15-1. The weakened strand failed at a load of 1 380 kN (and at an elongation of approximately 50 mm). The drop in load at failure of the weakened strand was of the order of 10 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 721 kN was therefore the same as the strength of a specimen with one outer strand cut completely.

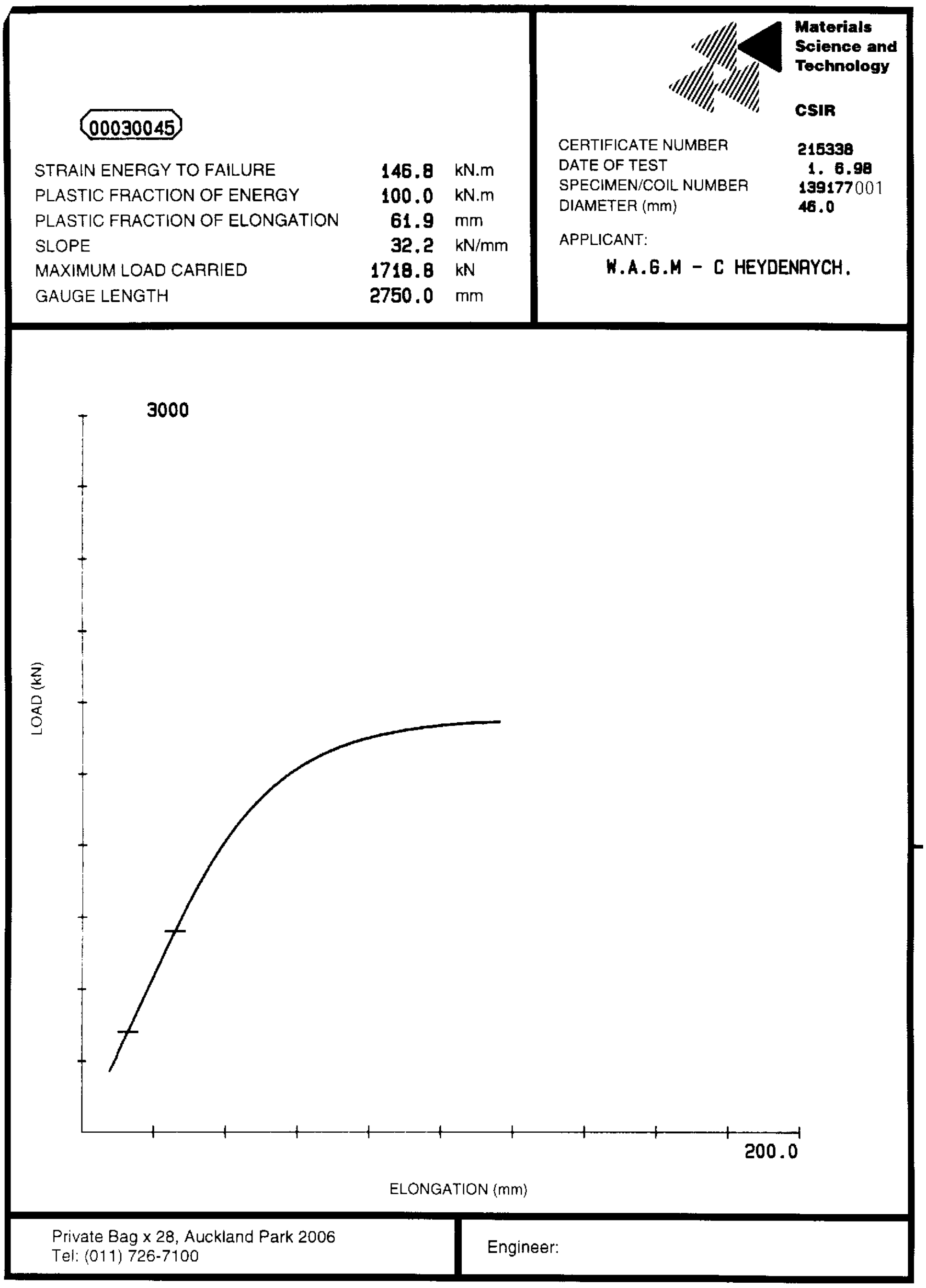

Figure B2.1.2.2: Load-elongation graph of specimen 15-9. One complete outer strand cut.

Specimen 15-8: Seven (of a total of eight) wires cut in one outer strand

The test certificate recorded: First wire failure at 1 360 kN, breaking strength of 1 687 kN, that all except four outer strands broke, and that the "position of fracture" was at the metal endcap.

A failure "at the metal endcap" is a failure at one of the terminations of the rope specimen. It is generally accepted that a metal endcap failure does not reflect the true strength of a rope specimen.

The load-elongation graph looked similar to that of specimen 15-1, except that the "end" of the graph showed evidence of the metal endcap failure. The weakened strand failed at a load of 1 360 kN (and at an elongation of approximately 50 mm). The drop in load at failure of the weakened strand was of the order of 10 kN. The test was continued until the endcap failure occurred. The "breaking strength" of 1 687 kN was therefore not a true reflection of the strength of a specimen with one outer strand cut completely.

Specimen 15-9: One complete outer strand cut

The test certificate recorded: First wire failure at 1 650 kN, breaking strength of 1 719 kN, and that only one outer strand failed (that is disregarding the one strand that was cut completely).

The load-elongation graph is shown in Fig. B2.1.2.2. The graph is absolutely smooth and the reported "first wire failure" cannot be seen on the graph. The elongation at failure was approximately 120 mm. The elongation at failure (maximum load carried) of specimens 15-1 to 15-7 was of the same order. The elongation at failure (maximum load) of specimen 15-8 (metal endcap failure) was 90 mm (what was to be expected). The "breaking strength" of 1 719 kN was, as intended, the strength of a specimen with one outer strand cut completely.

A summary of the results of wires cut in one outer strand, obtained from the analysis of the load-elongation graphs, is given in Table B2.1.2.

Table B2.1.2: ***Cut-wire tests on 15 strand ribbon strand rope (GAP439). Standard tensile test specimens 2,75 m long. New rope strength = 1 764 kN***
Proper reflection of the results of wires cut in one strand.

No.	Wires Cut in one outer strand	Area Reduct.	Weak. strand failure load	Weak. strand elong. at failure	Weak. strand loss in strength	Failure load one strand cut	Strength loss one strand cut
15-1	3	1,7%	1 650 kN	75 mm	6,5%	1 723 kN	2,3%
15-2	4	2,2%	1 665 kN	70 mm	5,6%	1 695 kN	3,9%
15-3	4	2,2%	1 600 kN	60 mm	9,3%	1 733 kN	1,8%
15-4	5	2,8%	1 540 kN	60 mm	12,7%	1 715 kN	2,8%
15-5	6	3,3%	1 480 kN	50 mm	16,1%	1 720 kN	2,5%
15-6	6	3,3%	1 450 kN	60 mm	17,8%	1 717 kN	2,7%
15-7	7	3,9%	1 380 kN	50 mm	21,8%	1 721 kN	2,4%
15-8	7	3,9%	1 360 kN	50 mm	22,9%		
15-9	8	4,4%				1 719 kN	2,6%

As should be expected, the strength losses for one strand completely cut is consistent. It should be noted that, although one outer strand makes up 4,4% of the total steel area of the rope, the strength losses were less. The weakened strands failed at loads far lower than originally anticipated. Both these apparent anomalies are explained later in this report.

B2.1.3 One outer strand cut completely plus wires cut in an adjacent outer strand

A typical load-elongation graph of specimens with one outer strand cut completely and wires cut in an adjacent strand (that of specimen 15-14) is shown in Fig. B2.1.3. Although it has been mentioned that a winder will not continue to operate when a strand is broken on the winder rope, the results are analysed to establish the failure behaviour of ropes.

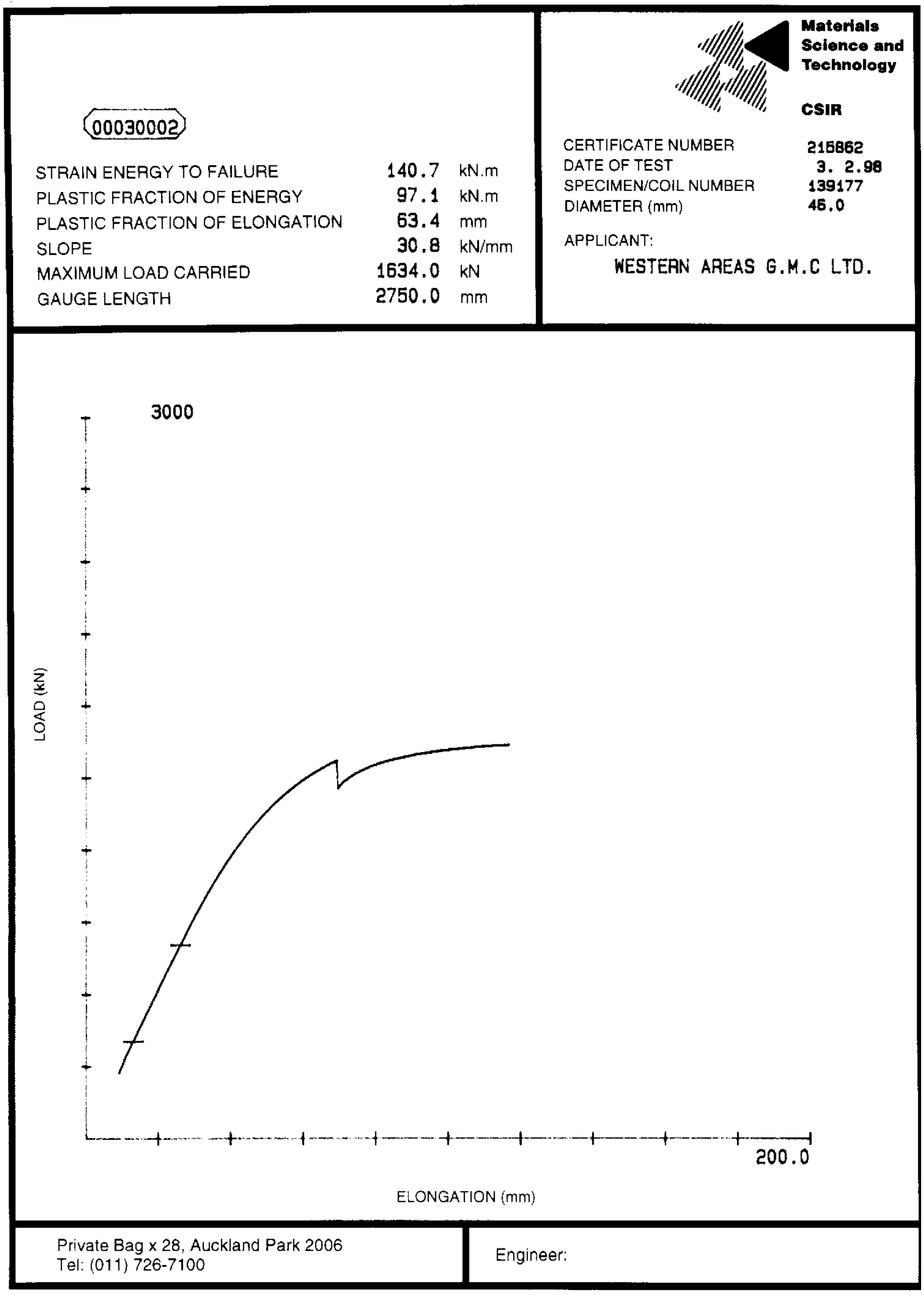

Figure B2.1.3: Load-elongation graph of specimen 15-14. One outer strand cut completely plus three wires in an adjacent strand.

Specimen 15-10: One outer strand cut plus one wire in an adjacent strand

The test certificate recorded: First wire failure at 1 530 kN, breaking strength of 1 682 kN, and that only one outer strand failed; that is disregarding the one strand that was cut completely. Judging from the load-elongation graph, the number of strands failed should actually have been two: The weakened strand plus one more.

The load-elongation graph looked similar to that of specimen 15-14 (Fig. B2.1.3). The weakened strand failed at a load of 1510 kN (and at an elongation of approximately 65 mm). The drop in load at failure of the weakened strand was only just noticeable on the graph, and was in the order of 5 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 682 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-11: One outer strand cut plus two wires in an adjacent strand

The test certificate recorded: First wire failure at 1 600 kN, breaking strength of 1 628 kN, and that only one outer strand failed (actually it should have been two outer strands failed).

The load-elongation graph looked similar to that of specimen 15-14 (Fig. B2.1.3). The weakened strand failed at a load of 1590 kN (and at an elongation of approximately 75 mm). The drop in load at failure of the weakened strand was in the order of 100 kN. The test was continued until another outer strand failed. The "breaking strength" of 1628 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-12: One outer strand cut plus three wires in an adjacent strand

The test certificate recorded: First wire failure at 1 500 kN, breaking strength of 1 565 kN, and that only one outer strand failed. No sign of the first wire failure was noticeable on the load elongation graph.

The load-elongation graph showed that the test was terminated when the weakened strand failed at a load of 1 565 kN (and at an elongation of approximately 65 mm). The "breaking strength" of 1 565 kN was therefore not a reflection of the strength of a specimen with two outer strands cut completely.

Specimen 15-13: One outer strand cut plus three wires in an adjacent strand

The test certificate recorded: Breaking strength of 1 518 kN, and that only one outer strand failed.

The load-elongation graph showed that the test was terminated when the weakened strand failed at a load of 1 518 kN (and at an elongation of approximately 65 mm). The "breaking strength" of 1 518 kN was therefore not a reflection of the strength of a specimen with two outer strands cut completely.

Specimen 15-14: One outer strand cut plus three wires in an adjacent strand

The test certificate recorded: First wire failure at 1 470 kN, breaking strength of 1 634 kN, and that two outer strands failed.

The load-elongation graph is the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 560 kN (and at an elongation of approximately 70 mm). The drop in load at failure of the weakened strand was in the order of 100 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 634 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-15: One outer strand cut plus three wires in an adjacent strand

The test certificate recorded: First wire failure at 1 590 kN, breaking strength of 1 647 kN, and that one outer strand failed.

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 545 kN (and at an elongation of approximately 70 mm). The drop in load at failure of the weakened strand was in the order of 100 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 647 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

The rope testing personnel got it wrong in two out of the three reported numbers. Apart from the one strand that was cut completely, one other outer strand failed. They "missed" the failure of the weakened strand. The "first wire failure" was that of the second (uncut) strand that failed.

Specimen 15-16: One outer strand cut plus four wires in an adjacent strand

The test certificate recorded: First wire failure at 1 500 kN, breaking strength of 1 639 kN, and that two outer strands failed.

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 520 kN (and at an elongation of approximately 65 mm). The drop in load at failure of the weakened strand was in the order of 60 kN. The test was continued until another outer strand failed. The "breaking strength" of 1639 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-17: One outer strand cut plus four wires in an adjacent strand

The test certificate recorded: First wire failure at 1 450 kN, breaking strength of 1 635 kN, and that two outer strands failed.

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 500 kN (and at an elongation of approximately 65 mm). The drop in load at failure of the weakened strand was in the order of 90 kN. The test was continued until another outer strand failed. The "breaking strength" of 1635 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-18: One outer strand cut plus five wires in an adjacent strand

The test certificate recorded: First wire failure at 1 290 kN, breaking strength of 1 639 kN, and that two outer strands failed.

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 330 kN (and at an elongation of approximately 50 mm). The drop in load at failure of the weakened strand was in the order of 70 kN. The test was continued until another outer strand failed. The "breaking strength" of 1639 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-19: One outer strand cut plus six wires in an adjacent strand

The test certificate recorded: First wire failure at 1 220 kN, breaking strength of 1 640 kN, and that one outer strand failed (should have been recorded as two).

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 260 kN (and at an elongation of approximately 45 mm). The drop in load at failure of the weakened strand was in the order of 50 kN. The test was continued until another outer strand failed. The "breaking strength" of 1640 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-20: One outer strand cut plus six wires in an adjacent strand

The test certificate recorded: First wire failure at 1 260 kN, breaking strength of 1 635 kN, and that one outer strand failed (should have been recorded as two).

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 260 kN (and at an elongation of approximately 45 mm). The drop in load at failure of the weakened strand was in the order of 40 kN. The test was continued until another outer strand failed. The "breaking strength" of 1635 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-21: One outer strand cut plus seven (of eight) wires in an adjacent strand

The test certificate recorded: First wire failure at 1 050 kN, breaking strength of 1 642 kN, and that one outer strand failed (should have been recorded as two).

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 100 kN (and at an elongation of approximately 40 mm). The drop in load at failure of the weakened strand was in the order of 10 kN. The test was continued until another outer strand failed. The "breaking strength" of 1642 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-22: One outer strand cut plus seven (of eight) wires in an adjacent strand

The test certificate recorded: First wire failure at 1 080 kN, breaking strength of 1 637 kN, and that one outer strand failed (should have been recorded as two).

The load-elongation graph looked similar to the one shown in Fig. B2.1.3. The weakened strand failed at a load of 1 100 kN (and at an elongation of approximately 40 mm). The drop in load at failure of the weakened strand was in the order of 10 kN. The test was continued until another outer strand failed. The "breaking strength" of 1642 kN was therefore the same as the strength of a specimen with two outer strands cut completely.

Specimen 15-23: Two outer strands cut completely

The test certificate recorded: First wire failure at 1 560 kN, breaking strength of 1 634 kN, and that one outer strand failed (i.e. disregarding the two that were cut completely).

The load-elongation graph looked similar to the one shown in Fig. B2.1.2.2 (smooth with no evidence of "premature" strand failures). The "breaking strength" of 1634 kN was, as intended, the strength of a specimen with two outer strands cut completely.

Specimen 15-24: Two outer strands cut completely

The test certificate recorded: First wire failure at 1 558 kN, breaking strength of 1 620 kN, and that one outer strand failed.

The load-elongation graph looked similar to the one shown in Fig. B2.1.2.2. The "breaking strength" of 1 620 kN was the strength of a specimen with two outer strands cut completely.

Specimen 15-25: Two outer strands cut completely

The test certificate recorded: First wire failure at 1 630 kN, breaking strength of 1 640 kN, and that one outer strand failed.

The load-elongation graph looked similar to the one shown in Fig. B2.1.2.2. The "breaking strength" of 1 640 kN was the strength of a specimen with two outer strands cut completely.

A summary of the results of wires cut in one outer strand plus another strand cut off completely, obtained from the analysis of the load-elongation graphs, is given in Table B2.1.3.

Table B2.1.3: Cut-wire tests on 15 strand ribbon strand rope (GAP439). Standard tensile test specimens 2,75 m long. New rope strength = 1 764 kN Proper reflection of the results of one strand cut completely plus wires cut in an adjacent strand.

No.	Wires cut in outer strands	Area reduct.	Weak. strand failure load	Weak. strand elong. at failure	Weak. strand loss in strength	Failure Load two Strands cut	Strength loss two strands cut
15-10	8+1	5,0%	1 510 kN	65 mm	14,4%	1 682 kN	4,6%
15-11	8+2	5,5%	1 590 kN	75 mm	9,9%	1 628 kN	7,7%
15-12	8+3	6,1%	1 565 kN	65 mm	11,3%		
15-13	8+3	6,1%	1 518 kN	65 mm	13,9%		
15-14	8+3	6,1%	1 560 kN	70 mm	11,6%	1 634 kN	7,4%
15-15	8+3	6,1%	1 545 kN	70 mm	12,4%	1 647 kN	6,6%
15-16	8+4	6,6%	1 520 kN	65 mm	13,8%	1 639 kN	7,1%
15-17	8+4	6,6%	1 500 kN	65 mm	15,0%	1 635 kN	7,3%
15-18	8+5	7,2%	1 330 kN	50 mm	24,6%	1 629 kN	7,7%
15-19	8+6	7,7%	1 260 kN	45 mm	28,6%	1 640 kN	7,0%
15-20	8+6	7,7%	1 260 kN	45 mm	28,6%	1 635 kN	7,3%
15-21	8+7	8,3%	1 100 kN	40 mm	37,6%	1 642 kN	6,9%
15-22	8+7	8,3%	1 100 kN	40 mm	37,6%	1 637 kN	7,2%
15-23	8+8	8,8%				1 634 kN	7,4%
15-24	8+8	8,8%				1 620 kN	8,2%
15-25	8+8	8,8%				1 640 kN	7,0%

As should be expected, the strength losses for two strands completely cut are consistent. It should be noted that, although two outer strands make up 8,8% of the total steel area of the rope, the strength losses were less. The weakened strands failed at loads far lower than originally anticipated. Both these apparent anomalies are explained later in this report.

B2.1.4 Two outer strands cut completely plus wires cut in an adjacent outer strand

Specimen 15-27: Two outer strands cut plus three wires in an adjacent strand

The test certificate recorded: First wire failure at 1 400 kN, breaking strength of 1 559 kN, and that only one outer strand failed; should have been two strands for reasons given earlier (the weakened strand and one more strand) and that is disregarding the two strands that were cut completely.

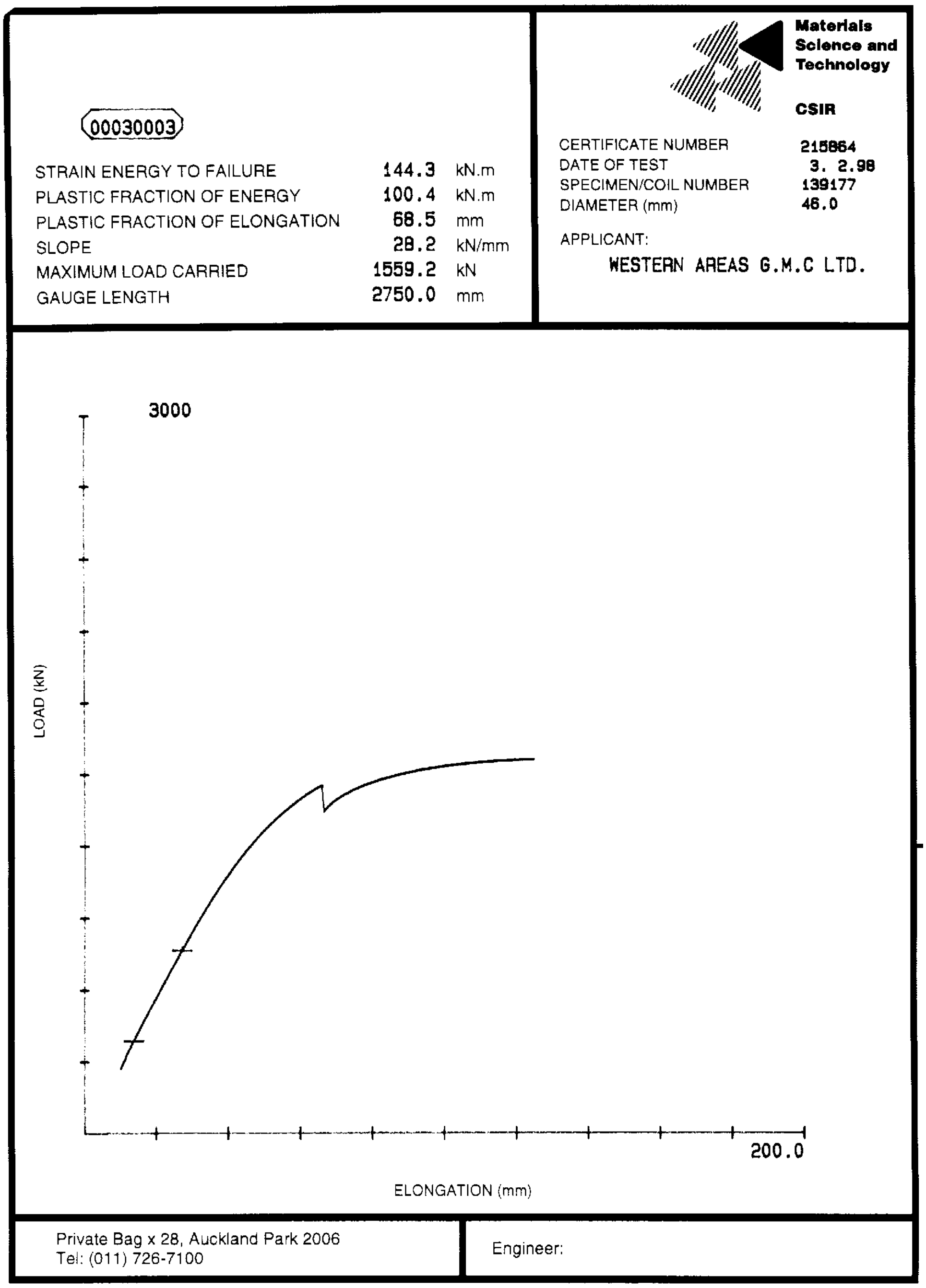

Figure B2.1.4: Load-elongation graph of specimen 15-27. Two outer strands cut completely plus three wires in an adjacent strand.

The load-elongation graph of this specimen is shown in Fig. B2.1.4. The weakened strand failed at a load of 1 440 kN (and at an elongation of approximately 70 mm). The drop in load at failure of the weakened strand was in the order of 100 kN. The test was continued until another outer strand failed. The "breaking strength" of 1 559 kN was therefore the same as the strength of a specimen with three outer strands cut completely.

Specimen 15-28: Two outer strands cut plus three wires in an adjacent strand

The test certificate recorded: First wire failure at 1 370 kN, breaking strength of 1 561 kN, and that only one outer strand failed (questionable, see what follows).

The load-elongation graph looked similar to that of specimen 15-27 (Fig. B2.1.4), but with the exception that the graph displayed two "saw-teeth" parts. The first saw-tooth occurred at 1 365 kN with a drop in load of the order of 50 kN and at an elongation of approximately 55 mm. The second saw-tooth occurred at 1 540 kN with a drop in load of the order of 100 kN and at an elongation of approximately 85 mm. The test was terminated at a load of 1 561 kN, presumably after another strand failed.

The actual sequence of events are not known, because the specimen was tested under a protective shield. The results will therefore only be interpreted as that the weakened strand failed at a load of 1 365 kN (and at an elongation of approximately 55 mm).

Specimen 15-29: Two outer strands cut plus six wires in an adjacent strand

The test certificate recorded: First wire failure at 1150 kN and a breaking strength of 1 536 kN. The number of strands that failed was not recorded on the test certificate.

The load-elongation graph of this specimen is similar to that shown in Fig. B2.1.4. The weakened strand failed at a load of 1180 kN (and at an elongation of approximately 50 mm). The drop in load at failure of the weakened strand was in the order of 45 kN. The test was continued until another outer strand failed. The "breaking strength" of 1536 kN was therefore the same as the strength of a specimen with three outer strands cut completely.

A summary of the results of wires cut in one outer strand plus two other strands cut off completely, obtained from the analysis of the load-elongation graphs, is given in Table B2.1.4.

Table B2.1.4: Cut-wire tests on 15 strand ribbon strand rope (GAP439). Standard tensile test specimens 2,75 m long. New rope strength = 1 764 kN Proper reflection of the results of two strands cut completely plus wires cut in an adjacent strand.

No.	Wires cut in outer strands	Area reduct.	Weak. strand failure load	Weak. strand elong. at failure	Weak. strand loss in strength	Failure load three strands cut	Strength loss three strands cut
15-10	8+8+3	10,5%	1 440 kN	70 mm	18,4%	1 559 kN	11,6%
15-11	8+8+3	10,5%	1 365 kN	55 mm	22,6%		
15-12	8+8+6	12,1%	1 180 kN	50 mm	33,1%	1 536 kN	12,9%

As should be expected, the strength losses for three strands completely cut are consistent. It should be noted that, although three outer strands make up 13,2% of the total steel area of the rope, the strength losses were less. The weakened strands failed at loads far lower than originally anticipated. Both these apparent anomalies are explained later in this report.

B2.1.5 Wires cut in four adjacent outer strands

Specimen 15-26: Four wires cut in each of four outer strands

The test certificate recorded: Breaking strength of 1 508 kN and that four outer strands failed.

The load-elongation graph of this specimen is shown in Fig. B2.1.5.

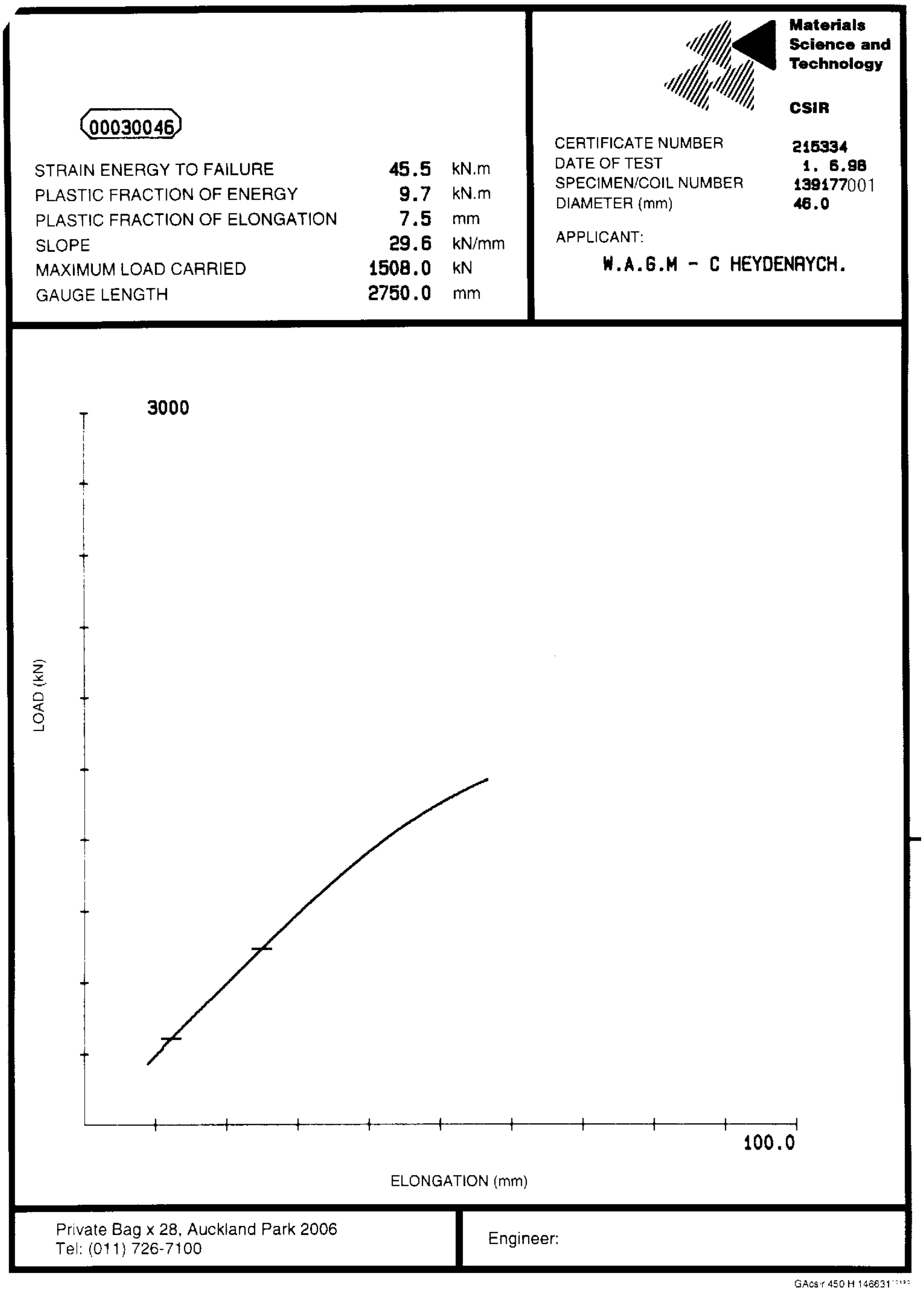

Figure B2.1.5: Load-elongation graph of specimen 15-26. Four wires cut in each of four outer strands.

The four strands that failed were presumably the weakened strands. They failed simultaneously at a load of 1 508 kN (and at an elongation of approximately 55 mm). The test was terminated when the four strands failed.

Judging from the results of specimens with one and two outer strands lost, the remaining strength of the specimen would have been of the same order as the failure load of the weakened strands. Previously, strands with four wires cut failed at specimen elongations of 60 mm to 70 mm. More information is required on tests such as this one before any further comment can be made on the actual behaviour of the rope specimen.

Table B2.1.5: Cut-wire tests on 15 strand ribbon strand rope (GAP439). Standard

tensile test specimens 2,75 m long. New rope strength = 1 764 kN
Proper reflection of the results of four wires cut in each of four strands.

No.	Wires cut in each of four outer strands	Area reduction	Weakened strands failure load	Weakened strands elongation at failure	Weakened strands loss in strength
15-26	4+4+4+4	8,8%	1 508 kN	55 mm	14,5%

B2.1.6 Summary of the GAP439 results

With hindsight, simply comparing the failure load of a rope specimen (actually the maximum load carried up to the time that a test was terminated) with the area reduction from broken or cut wires was definitely not the correct way to analyse the results, especially for cut wires on the outer strands of a ribbon strand rope.

The elongation to failure of a strand with cut wires decreased as the number of cut wires increased. For wires cut in one and two strands, the weakened strands all failed at loads less than the remaining strength of the specimens. Weakened strands failed at loads far lower than anticipated.

The loss in strength of specimens with one, two and three outer strands "lost" were less than the steel area reduction from the strands lost.

B2.2 Additional tests on ribbon strand ropes

An additional 26 tensile tests were carried out on ribbon strand rope specimens as part of the current project (GAP502) and as per the recommendations of GAP439. The planning and execution of the tests for this investigation would have been different, of course, if the results of the additional analysis of the GAP439 results were available at that time. But then it was only after the results of GAP502 were obtained that enough data were available to suggest the possibility of a different approach.

The tests for GAP502 were performed on samples of the same section of 46 mm diameter ribbon strand rope used for the tests of GAP439. The preparation of the tensile test specimens was the same as before, including the 500 load cycles after wires were cut.

To obtain a "new" rope breaking strength, two rope samples with no cut wires (and not cycled) were tensile tested. These samples returned breaking strengths of 1 804 kN and 1 806 kN. Only outer strands (four and five respectively) failed during the tensile tests. The results of previous tensile test on samples with no cut wires are listed in Table B2.1.1. The breaking strengths of the two samples tested for this investigation were slightly higher than the highest value of Table B2.1.1.

For consistency, the same new breaking strength of 1 764 kN will be used here for the calculation of the breaking strength losses of the cut-wire specimens. Using a new breaking strength of 1 806 kN when comparing the results from the specimens with cut wires will give breaking strength losses of the order of 2% more than when a new breaking strength of 1 764 kN is used.

B2.2.1 The results as obtained

Nineteen tests were carried out on samples with outer strand wires cut, and five tests were carried out on samples with wires cut on the inner rope triangular strands. For all these tests, no rope strands were completely cut on a specimen. A maximum of five wires per strand were cut. The meaning of the description of the number of wires cut is:

15 (323232000): 15 wires cut in outer strands: 3 in one strand, 2 wires in an adjacent strand, 3 wires in the strand adjacent to the previous one, and so forth. 3 strands had no cut wires.

i 14 (554000): 14 outer wires of the inner triangular strands cut: 5 in one strand, 5 wires in an adjacent strand, 4 wires in the next strand. 3 strands had no cut wires.

The results of the tests are given in Table B2.2.1. The number of strands broken during a tensile test is also given in the table. No information was available on the failure or no failure of the wire main core.

Notes of interest:

- Two identical specimens (15-44 and 15-45), with the same number of outer strand wires cut, returned breaking strength losses of 7,4% and 13,9%.

- The number of outer strands with cut wires did not all always fail during a test. That is according to the test certificates, which could have been wrong judging from the results of the GAP439 tests.

- Four specimens with wires cut in outer strands had inner strands fail as well. The tests of GAP439 reported no such cases. The reason for inner strands failing is that the tests of this investigation were continued longer after outer strands failed.

- The specimen strength losses from cutting inner strand wires were less than cutting wires on outer strands.

Table B2.2.1: Cut-wire tests on 15 strand ribbon strand rope. Standard tensile test specimens 2,75 m long. New rope strength = 1 764 kN

No.	Description number of cut wires	Area reduct.	Load at failure	Strength reduct.	Strands broken 12 out., 6 in.
15-30	12 (400400400)	6,6%	1 573 kN	10,8%	7 o, 4 i
15-31	12 (400400400)	6,6%	1 555 kN	11,8%	4 o
15-32	12 (444000000)	6,6%	1 567 kN	11,2%	7 o, 6 i
15-33	12 (444000000)	6,6%	1 538 kN	12,8%	4 o
15-34	12 (303030300)	6,6%	1 589 kN	9,9%	4 o
15-34	12 (303030300)	6,6%	1 576 kN	10,7%	7 o
15-36	12 (333300000)	6,6%	1 560 kN	11,6%	4 o
15-37	12 (222222000)	6,6%	1 565 kN	11,3%	6 o

15-38	15 (555000000)	8,3%	1 564 kN	11,3%	7 o, 4 i
15-39	15 (443400000)	8,3%	1 497 kN	15,1%	4 o
15-40	15 (443400000)	8,3%	1 502 kN	14,9%	7 o, 5 i
15-41	15 (303030303)	8,3%	1 544 kN	12,5%	5 o
15-42	15 (303030303)	8,3%	1 548 kN	12,2%	6 o
15-43	15 (323232000)	8,3%	1 535 kN	13,0%	5 o
15-44	15 (122122122)	8,3%	1 618 kN	8,3%	8 o
15-45	15 (122122122)	8,3%	1 504 kN	14,7%	9 o
15-46	15 (122122122)	8,3%	1 548 kN	12,2%	9 o
15-47	18 (222222222)	9,9%	1 536 kN	12,9%	8 o
15-48	27 (333333333)	14,9%	1 428 kN	19,0%	6 o
15-49	i 12 (444000)	6,6%	1 661 kN	5,8%	6 o, 3 i
15-50	i 14 (554000)	7,7%	1 627 kN	7,8%	6 o, 3 i
15-51	i 16 (444400)	8,8%	1 612 kN	8,6%	4 o, 4 i
15-52	i 18 (554400)	9,9%	1 586 kN	10,1%	6 o, 4 i
15-53	i 20 (555500)	11,0%	1 585 kN	10,1%	5 o, 6 i

At the time that the tests described in this section were carried out, the "recipe" for cut wire tests was well established. The intentions of the tests, carried out as per the recommendations of GAP439, were to compare losses in breaking strengths of specimens with the area reductions from the cut wires. After the more thorough analysis of the GAP439 results, the results of Table B2.2.1 were revisited. What follows were then found.

B2.2.2 Wires cut in outer rope strands

Specimen 15-30: Cut wire pattern: 400400400

The test certificate recorded: First wire failure at 1 540 kN, a breaking strength of 1 573 kN, and that all strands failed except two inner and two outer strands.

The load-elongation graph of this specimen is shown in Fig. B2.2.2.1. The first of the weakened strands failed at a load of 1543 kN (and at an elongation of approximately 60 mm). A second strand failed at a load of 1 563 kN (elongation of 65 mm). The maximum load was reached when a third strand failed (at 1 573 kN, elongation 75 mm). As mentioned before, the specimens were tested under a protective cover, and therefore it cannot be deducted from the graph what happened after maximum load was reached.

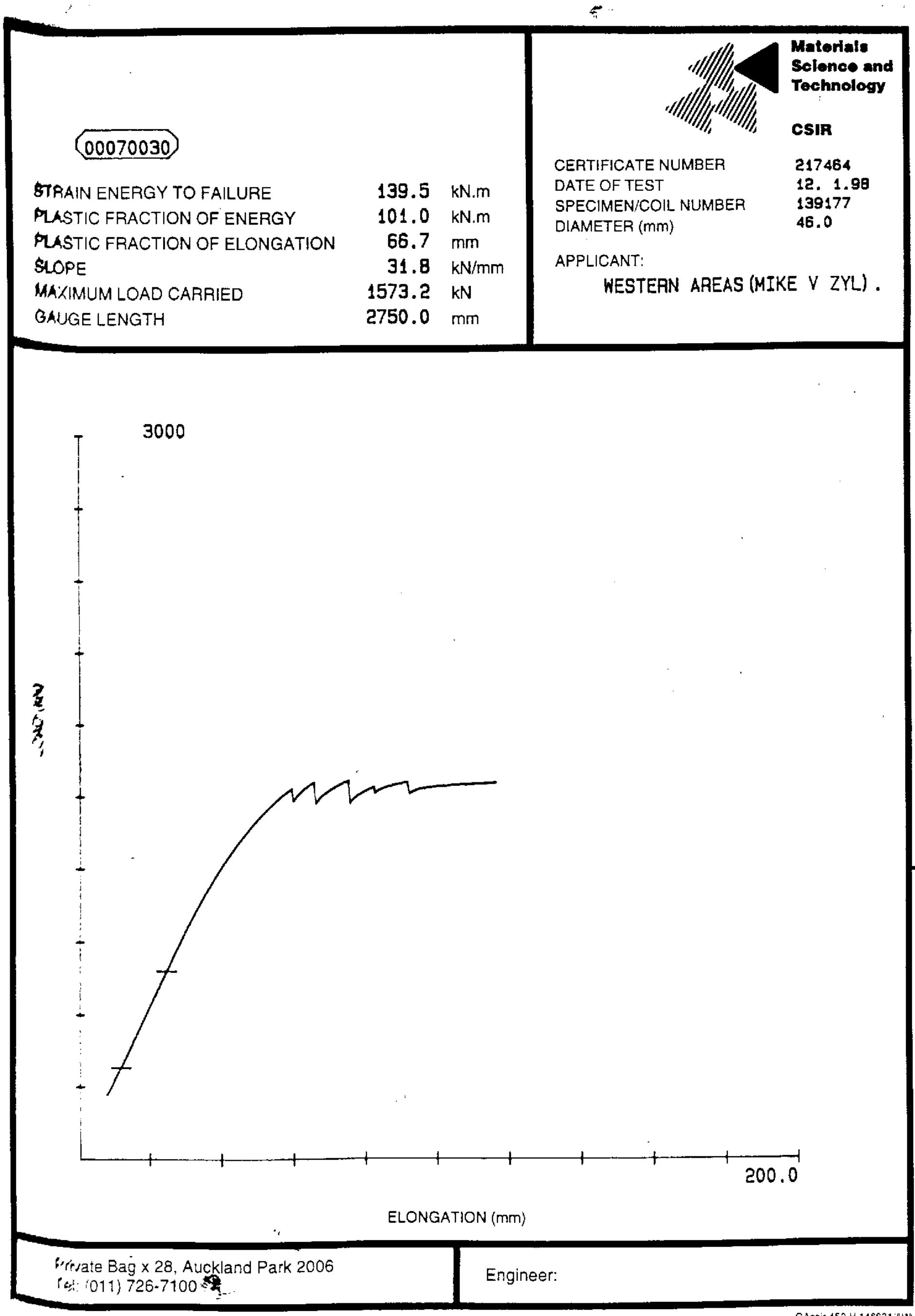

Figure B2.2.2.1: ***Load-elongation graph of specimen 15-30. Four wires cut in each of three outer strands.***

For each of the tensile tests listed in Table B2.2.1 the load and elongation of the first strand failure could be determined from the load-elongation graphs.

In nearly all cases, only one strand failed at a time. For specimens with the same number of wires cut per outer strand it was even possible to obtain a measure of the scatter in strain to failure of a weakened strand. However, for the analysis of this report, only the load and elongation of the first strand failure was obtained from the load-elongation graphs. The results obtained are given in Table B2.2.2 together with the results of the two uncut (new rope) specimens.

Table B2.2.2: ***Cut-wire tests on 15 strand ribbon strand rope. Standard tensile test specimens 2,75 m long. New rope strength = 1 764 kN***

First strand failure loads and elongations for outer strand wires cut.

No.	Description number of cut wires	Area reduct.	Load at first strand failure	Elongation at first strand failure	Strength loss at first strand failure
	0	0%	1 804 kN	130 mm	0%
	0	0%	1 806 kN	130 mm	0%
15-30	12 (400400400)	6,6%	1 543 kN	60 mm	12,5%
15-31	12 (400400400)	6,6%	1 490 kN	55 mm	15,5%
15-32	12 (444000000)	6,6%	1 540 kN	60 mm	12,7%
15-33	12 (444000000)	6,6%	1 461 kN	55 mm	17,2%
15-34	12 (303030300)	6,6%	1 567 kN	60 mm	11,2%
15-35	12 (303030300)	6,6%	1 560 kN	65 mm	11,6%
15-36	12 (333300000)	6,6%	1 540 kN	60 mm	12,7%
15-37	12 (222222000)	6,6%	1 565 kN	65 mm	11,3%
15-38	15 (555000000)	8,3%	1 330 kN	50 mm	24,6%
15-39	15 (443400000)	8,3%	1 477 kN	55 mm	16,3%
15-40	15 (443400000)	8,3%	1 440 kN	55 mm	18,4%
15-41	15 (303030303)	8,3%	1 544 kN	65 mm	12,5%
15-42	15 (303030303)	8,3%	1 548 kN	65 mm	12,2%
15-43	15 (323232000)	8,3%	1 535 kN	60 mm	13,0%
15-44	15 (122122122)	8,3%	1 618 kN	70 mm	8,3%
15-45	15 (122122122)	8,3%	1 504 kN	65 mm	14,7%
15-46	15 (122122122)	8,3%	1 548 kN	70 mm	12,2%
15-47	18 (222222222)	9,9%	1 536 kN	60 mm	12,9%
15-48	27 (333333333)	14,9%	1 428 kN	50 mm	19,9%

Generally the breaking strength losses were greater for the specimens with the larger number of cut wires in an outer strand. The larger breaking strength losses were also experienced (as should be the case) for the shorter elongations to failure.

One further detail not experienced in earlier tests (GAP439) is shown in Fig B2.2.2.2, the load-elongation graph of specimen 15-43. Small load drops occurred at an elongation of 50 mm and just before the first strand failed at an elongation of 60 mm. The slopes of the load drops suggest that these drops may not be wire failures but that the cut wires at the "damaged" outer strand sections may have been slipping back (creating larger gaps between the cut ends). The actual events can, however, only be determined if a specimen is tested without a protective shield.

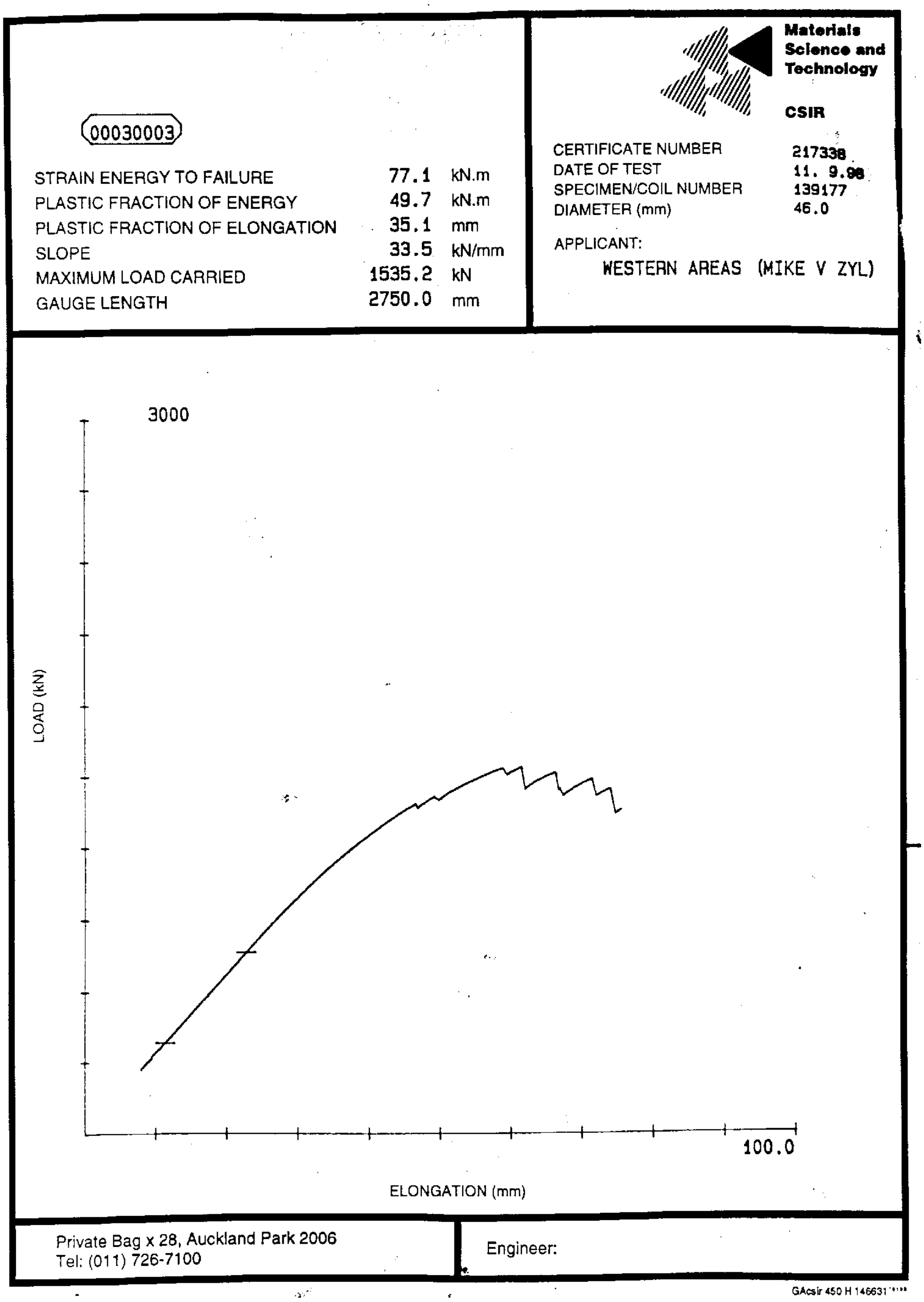

Figure B2.2.2.2: ***Load-elongation graph of specimen 15-43. Four wires cut in each of three outer strands.***

B2.2.3 Cut inner rope wires

Only five specimens with inner rope cut wires were tested, and only one specimen of each cut-wire configuration. The loss in strength of these specimens were much the same as the reduction in steel area. In all cases the strands that failed all failed simultaneously and at the maximum load carried.

B3 Summary of the cut-wire tests

Combinations of cut wires on inner and outer strands on the non-spin ropes were not investigated in either GAP324, GAP439 or this investigation (GAP502).

B3.1 Inner rope wires

Figure B3.1 shows the loss in breaking strength for the area reductions from cutting wires on the inner triangular strand rope part of both the 18 strand fishback rope specimens and the 15 strand ribbon strand rope specimens.

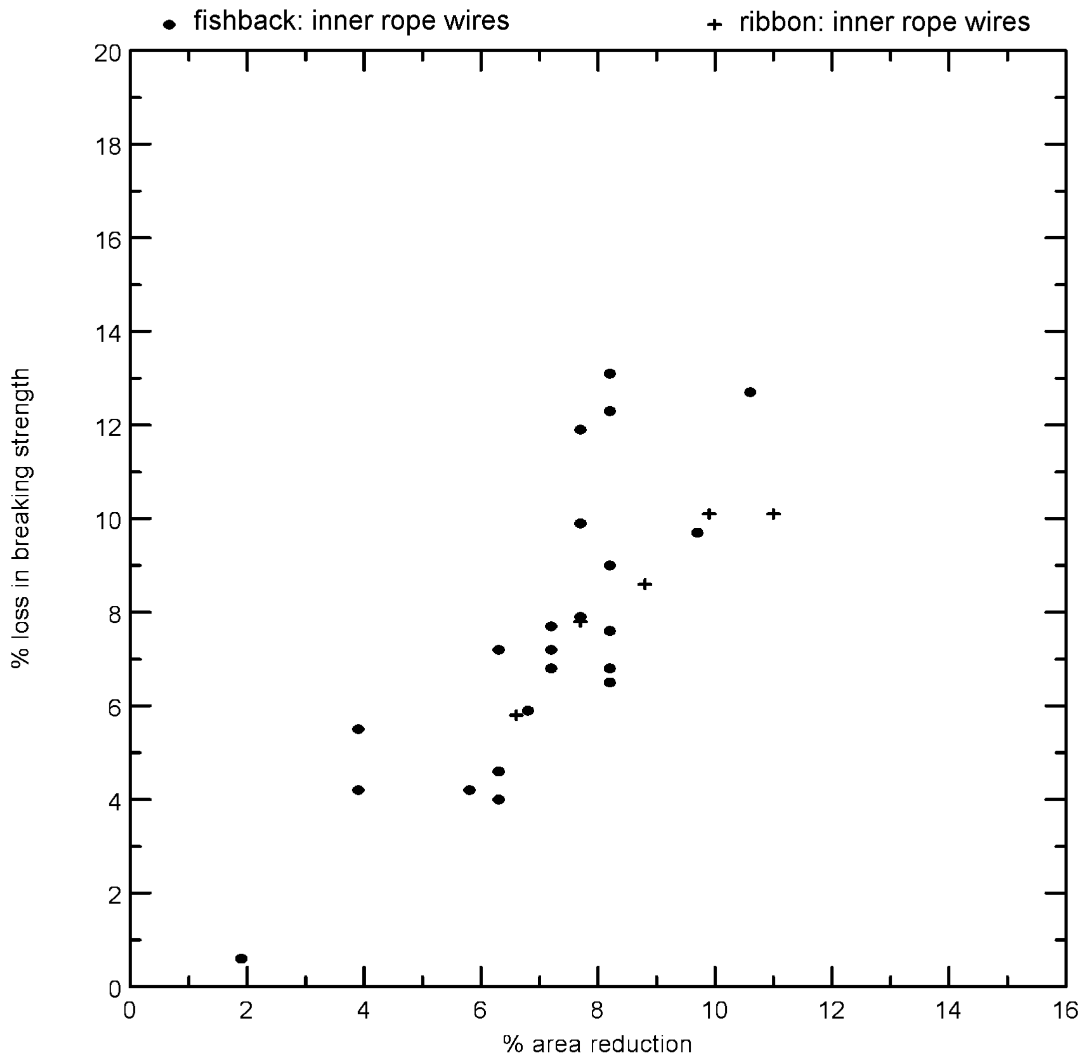

Figure B3.1: All non-spin ropes tested: Loss in breaking strength vs. total area reduction from cut inner rope wires.

The inner triangular strand rope of the 18 strand fishback rope was identical to the inner rope of the 15 strand ribbon strand rope. Similar behaviour could therefore be expected for cut-wires in the inner ropes of both rope constructions. Although only a few ribbon strand specimens were tested, and only one specimen of a specific cut-wire configuration, the results of the ribbon strand rope specimens fit well into the results of the fishback rope specimens (for which more than one specimen of a specific cut-wire configuration was tested).

Although the breaking strength losses are, on average, the same as the area reductions, the following needs to be explained or shown to be possible before the data can be analysed further.

- For a number of specimens the losses in breaking strength were noticeably less than the reductions in steel area.
- For area reductions of 7,7% to 8,2% for inner rope wires cut, strength losses varied between 6,5% and 13,1%.
- For a number of the specimens (with only inner rope wires cut), only outer strands failed during the test.

At the end of this report these apparent irregularities will have been explained.

B3.2 Outer strand wires

The major result of the cut-wire test on outer strands of the 15 strand ribbon strand rope was that the strength losses at failure of weakened strands were much greater than anticipated.

Generally the breaking strength losses were greater for the specimens with the larger number of cut wires in an outer strand. The larger breaking strength losses were also experienced (as should be the case) for the shorter elongations to failure. The elongation to failure of a strand with cut wires decreased as the number of cut wires increased. For wires cut in one and two strands, the weakened strands all failed at loads less than the remaining strength of the specimens.

Therefore, simply comparing the (maximum) failure load of a rope specimen with the area reduction from broken or cut wires was not the correct way to analyse the results, especially for cut wires on the outer strands of a ribbon strand rope.

For the sake of interest, the breaking strength losses at first strand failures were plotted against the total area reductions of the specimens. The graph is shown in Fig. B3.2 and include the results from Tables B2.1.2, B2.1.3, B2.1.4, B2.1.5 and B2.2.2.

If the results in Fig. B3.2 were to be used (as was done in the past) to determine an allowable area reduction for a 10% strength loss, then most of the results should be considered superfluous because of the excessive strength losses. Only the three or four results in the bottom left hand corner of Fig. B3.2 should be considered valid, which are too few for a statistical analysis. A conclusion that can be made from Fig. B3.2 is that an area reduction of 2% could already give a strength loss of 10%.

The larger-than-anticipated strength losses for weakened outer strands are explained later in this report. It is also shown that the failure load of a weakened outer strand is influenced by the length of the tensile test specimen.

Being able to see and record the actual sequence of failure events on rope specimens will be of great value for any future tests.

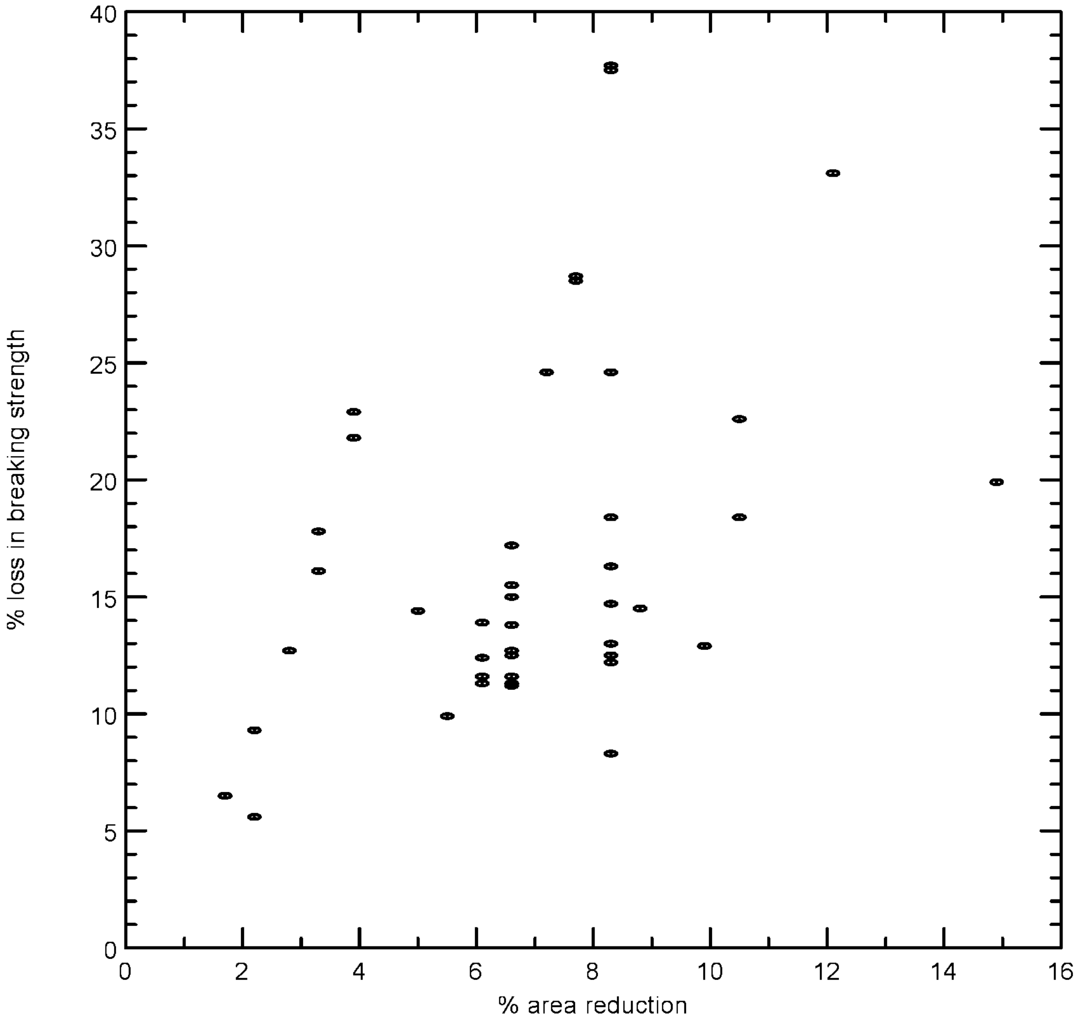

Figure B3.2: First strand failures of the ribbon strand rope: Loss in breaking strength vs. total area reduction from cut outer strand wires.

Appendix C: Failure of assemblies

The failure of a steel wire rope, is analysed in this section. A wire rope is approximated as being made up of individual solid strands. The effect of friction between strands are neglected.

C1 Basic failure principles

The concept of failure of an assembly, consisting of two steel bars subjected to the same elongation, has to be understood before the behaviour of more complex assemblies can be appreciated.

Consider a one metre long steel bar with a cross-sectional area of 20 mm². Assume that this steel bar has stress-strain curve as given in Fig. C1.

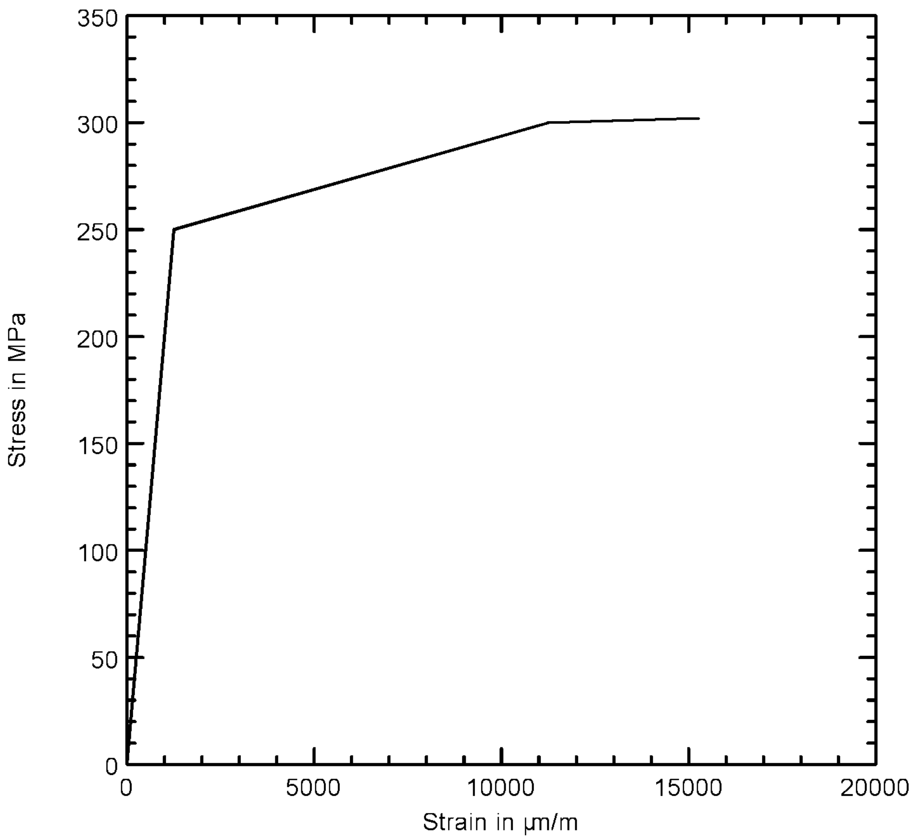

Figure C1: Assumed stress-strain relationship for a steel bar

The assumed stress-strain curve shown in Fig. C1 includes an approximation of the plastic behaviour of the steel. The steel is elastic (at 200 GPa) up to 250 MPa after which it becomes plastic and eventually fails at a stress of 302 MPa and a strain of 15,25 mm/m. The assumed plastic behaviour of the steel is approximated by two linear functions (5 GPa from 250 MPa to 300 MPa, and 0,5 GPa from 300 MPa to 302 MPa). Although the linear approximation of the plastic behaviour may be somewhat crude, it made the calculations easier to execute and to understand. The assumed stress-strain behaviours in the section of the report is for demonstrative purposes only and do not necessarily approximate the behaviour of any given steel.

If the 1 m long 20 mm² bar is subjected to a tensile load, it will fail at a load of 6,04 kN and at an elongation of 15,25 mm.

Reducing the cross-sectional steel area of the bar over its entire length to 16 mm² (80% of 20 mm²) will reduce the breaking strength to 80% of the original bar (4,83 kN), but the elongation at failure would still be 15,25 mm.

This means that if the 20 mm² bar and the 16 mm² bar are loaded together and the ends subjected to the same elongation (the ends of the parallel bars connected as in the end fitting of rope specimen), the two bars will fail simultaneously at an elongation of 15,25 mm. The breaking load of the assembly will be 10,87 kN (6,04 kN plus 4,83 kN), which is, as expected, 90% of the breaking load of two 20 mm² bars. The steel area of the assembly was reduced by 10% compared to two 20 mm² bars.

Now consider a bar on which the 20% area reduction is not over the complete one metre length of the bar, but only over a section, 200 mm in length. Stress concentrations between the "normal" part of the bar and the reduced area section are ignored for the purposes of the calculations that follow. If this bar is subjected to a tensile test, the load at failure will still be 4,83 kN (as before). This bar fails when the stress in the reduced area section reaches 302 MPa. At failure, the normal part of the bar will be subjected to a stress of 242 MPa, which is still in the elastic part of the stress-strain relationship given above. Therefore, at failure, the reduced area section would have yielded and deformed plastically, but the normal part of the bar would only have deformed elastically. At failure the total elongation of the bar with the reduced area section will only be 4,02 mm, as opposed to 15,25 mm for a bar with an area reduction over its full length.

An assembly, consisting of a two one-metre long bars of 20 mm², but one having a reduced area section of 16 mm² over 200 mm as described in the preceding paragraph, will fail when the bar with the reduced area part reached its elongation at failure, i.e. 4,02 mm. At this point the other bar would be just past yield (and will of course not fail). Failure of the assembly is defined as failure of any element of the assembly. At failure, the load on the assembly will be 10,11 kN, which is 84% of an assembly consisting of two 20 mm² bars. The reduced area is still only 10% of the total.

Table C1 below gives a summary of the elongation and (maximum) load at failure of the one metre long assemblies discussed above, as well as a number of other variations of the two-bar combination.

The "descriptions" have the following meaning:

20 + 16: One bar with a area of 20 mm², plus one with an area of 16 mm². i.e. a 4 mm² area reduction over the complete one metre length.

20/(16 for 0,2)): A 20 mm² bar with a reduced area section of 16 mm² and 0,2 m long, i.e. 4 mm² area reduction over 0,2 m.

The "area reduction" in Table C1 below, is a percentage of the total area of the assembly.

Table C1: Assemblies consisting of two steel bars, one metre in length.

No.	Description (1 m length)	Area reduction	Load at failure	Load reduction	Elongation at failure
2-1	2 x 20	0%	12,08 kN	0%	15,25 mm
2-2	20 + 16	10%	10,87 kN	10%	15,25 mm
2-3	2 x (20/(18 for 0,2))	10%	10,87 kN	10%	7,54 mm
2-4	20 + 20/(16 for 0,2)	10%	10,11 kN	16%	4,02 mm
2-5	20 + 20/(16 for 0,05)	10%	9,90 kN	18%	1,91 mm

The reduced area section of example 2-5 in Table C1 above is only 50 mm long, compared to 200 mm for example 2-4. The load at failure for example 2-5 above is lower than that of 2-4, because failure occurs at a shorter elongation of the assembly.

Six strand ropes and multi-layer stranded ropes will be approximated by substituting a straight steel bar for each strand in the rope. Different load-elongation properties can be assigned to each strand layer by varying stiffnesses and the elastic-plastic transition stresses.

C2 A six strand rope

A six (triangular) strand rope is approximated by six steel bars of the same cross-sectional area (150 mm² each) in parallel, and all six having the stress-strain characteristics as shown in Fig. C1. A "gauge length" of 3 m was selected for the assembly of six bars.

The breaking strengths of different combinations and area reductions are given on Table C2.1. The description of an assembly is the same as before.

Table C2.1: Assemblies consisting of six steel bars, 3 m in length.

No.	Description (3 m length)	Area reduct	Load at failure	Load reduct	Elongation at failure
6-1	6 x 150	0%	271,8 kN	0%	45,75 mm
6-2	5 x 150 + 1 x 60	10%	244,6 kN	10%	45,75 mm
6-3	6 x 150/(135 for 1,0)	10%	244,6 kN	10%	26,47 mm
6-4	1 x 150 + 5(150/(132 for 1,0))	10%	241,9 kN	11%	24,05 mm
6-5	2 x 150 + 4(150/(127,5 for 1,0))	10%	237,4 kN	13%	20,43 mm
6-6	3 x 150 + 3(150/(120 for 1,0))	10%	231,7 kN	15%	17,67 mm
6-7	4 x 150 + 2(150/(105 for 1,0))	10%	227,0 kN	16%	17,34 mm
6-8	5 x 150 + 1(150/(60 for 1,0))	10%	221,5 kN	19%	16,46 mm

The results in Table C2.1 show that if the reduction in area is evenly spread (absolutely symmetrical as for example 6-3), or if the total area reduction is in one strand and over the entire length of the assembly (example 6-2), the reduction in breaking strength is the same as the total reduction in cross-sectional area.

As the reduction in cross-sectional area is concentrated into fewer "strands", the loss in breaking strength increases compared to the reduction in cross-sectional area. This trend, observed on actual cut-wire test specimens, most probably led previous researchers to believe that an asymmetrical distribution of broken wires was more severe than a symmetrical distribution. This is, however, not so: It should make no difference if the area reduction of example 6-7 was in two adjacent "strands" (asymmetrical) or in two opposing "strands" (symmetrical).

For the sake of interest: The remaining strength of assembly 6-8 is greater than the load at which the weakest "strand" failed.

The results in Table C2.1 are typical of results obtained from cut-wire tests. Although the results seem to be interpretable (asymmetric vs, symmetric), it will now be shown that the results of Table C2.1 are only valid for 3 m long assemblies with their one metre long reduced area sections.

For the results in Table C2.1 above, it was assumed that the affected length of the "broken wires" in a "rope strand" (the length of the reduced area section) was one metre in the 3 m long assemblies. The effect of shortening the length of the reduced area sections to 100 mm in the 3 m long assemblies is shown in Table C2.2 below.

Table C2.2: Assemblies consisting of six steel bars, 3 m in length; 100 mm lengths for the reduced area sections.

No.	Description (3 m length)	Area reduct	Load at failure	Load reduct	Elongation at failure
6-41	1 x 150 + 5(150/(132 for 0,1))	10%	239,5 kN	12%	14,29 mm
6-51	2 x 150 + 4(150/(127,5 for 0,1))	10%	231,7 kN	15%	9,04 mm
6-61	3 x 150 + 3(150/(120 for 0,1))	10%	222,2 kN	18%	5,03 mm
6-71	4 x 150 + 2(150/(105 for 0,1))	10%	214,3 kN	21%	4,59 mm
6-81	5 x 150 + 1(150/(60 for 0,1))	10%	182,0 kN	23%	3,28 mm

If the reduced area sections remained one metre in length, but the specimen length was increased to 30 m, the same results as those given in Table C2.2 would be obtained. The only difference would be that the elongation at failure would be 10 times greater than that given in Table C2.2. Shorter reduced area sections and longer specimens both lead to greater strength reductions.

In very deep mine shafts the rope loads do not vary much over any 100 m length of rope. Therefore, the playoff between the specimen length and the length of the reduced area section can be continued until it is shown that if the steel area of a single strand (bar) is reduced to 60% of the area of the strand (6,7% of the assembly) failure of that strand will occur when the load on the assembly reaches (just more than) 60% of the original strength. If the steel area of two strands are each reduced to 60% of the strand area, failure of these two strands will still occur at just more than 60% of the original assembly strength.

If the effect of a broken wire is such that it is "removed" from the entire length of the test specimen, the assembly will only lose strength equal to the strength of that wire.

C3 Different elastic moduli

Before multi-layered strand ropes are discussed, the effect of different stiffnesses between the elements of an assembly will be shown. An assembly, one metre long, consisting of three steel bars and three aluminium bars was selected for this illustration. All six bars have cross-sectional areas of 20 mm². The assumed stress-strain relationships for the bars are shown in Fig. C3.

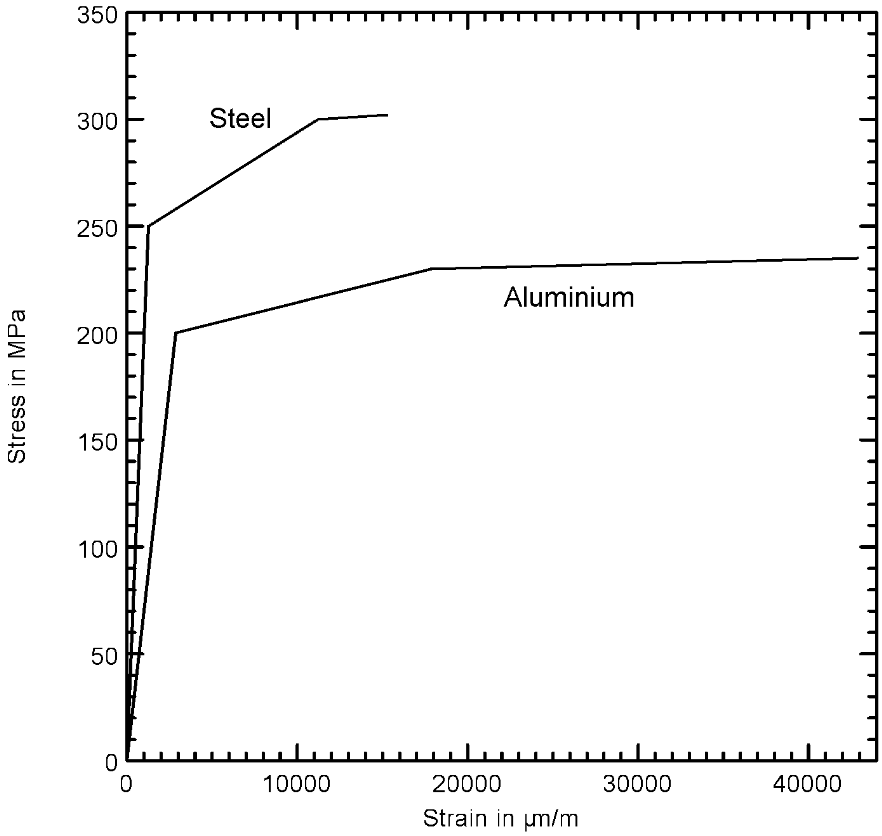

Figure C3: Assumed stress-strain relationship for steel and aluminium.

One steel bar will have a breaking strength of 6,04 kN, and one aluminium bar will have a breaking strength of 4,70 kN. Theoretically an assembly of three bars of each will have a strength of 32,22 kN, but if the six bars are loaded together, the steel will fail before the aluminium has reached maximum strain and stress. The breaking strength of the assembly is 31,61 kN (98% of theoretical) and will have an elongation at failure of 15,25 mm.

The breaking strengths of various combinations of reduced area sections ("broken wires") are given in Table C3. The area reduction is simply the total steel and aluminium areas removed, expressed as a percentage of the total assembly area of 120 mm².

The assembly descriptions in Table C3 are:

"S" refers to steel bars and "A" to aluminium bars.

3S + 2A + A(18 for 0,2) 3 steel bars of 20 mm², plus one aluminium bar of 20 mm², and one aluminium bar of 20 mm² with a 200 mm section reduced to 18 mm².

Table C3: Assemblies consisting of three steel bars and three aluminium bars, one metre in length.

No.	Description (1 m length, 20 mm² each)	Area reduct	Load at failure	Strength reduct	Elongation at failure
33-1	3S + 3A	0%	31,61 kN	0%	15,25 mm

33-2	2S + S(10 for 0,2) + 3A	8,3%	25,60 kN	19%	3,65 mm
33-3	2S + S(10 for 0,1) + 3A	8,3%	22,47 kN	29%	2,20 mm
33-4	3S + 2A + A(10 for 0,2)	8,3%	28,51 kN	10%	9,91 mm
33-5	3S + 2A + A(10 for 0,1)	8,3%	26,95 kN	15%	5,80 mm
33-6	3S + 2A + A(18 for 0,2)	1,7%	31,34 kN	* 1%	15,25 mm
33-7	3S + 2A + A(14 for 0,4)	5,0%	30,38 kN	* 4%	15,25 mm
33-8	3S + 2A + A(10 for 0,4)	8,3%	29,45 kN	* 7%	15,25 mm
33-9	2S + S(15 for 0,2) + 2A + A(15 for 0,2)	8,3%	26,39 kN	* 17%	3,96 mm

* In all these cases (33-6 to 33-9) the steel failed and not the weakened section of the aluminium bar. The strength losses were also less than the area reductions.

The results of Table C3 show that the behaviour of an assembly with elements of different stress-strain properties are even more unpredictable than for a six "strand" assembly in which all the elements have the same stress-strain properties.

The results also show that reducing the cross-sectional area of the less stiff elements (in this case also the weaker elements) does not affect the assembly in the same detrimental way as when the area of a stiffer (and stronger) element is reduced.

The above exercise was done to illustrate how different stiffnesses of elements affect the behaviour of an assembly. In the section that follows, this principle is expanded to approximate a non-spin (multi-layered) rope.

C4 Non-spin ropes

A 15 strand non-spin rope (ribbon strand) is approximated by the following combination of bars:

Wire main core:	64 mm² each
6 triangular (inner) strands:	90 mm² each
9 ribbon (outer) strands:	44 mm² each

The total cross-sectional area of the assembly will then be equal to 1 000 mm².

No information on the relative stiffnesses of the different strands in a non-spin rope is generally available. The following reasoning was followed to assign rational stiffnesses to the three groups of strands:

The wire main core (WMC) of a non-spin rope should be relatively stiff because it is the straightest of all the strands in a rope. Generally the grade of the wires in a wire main core is chosen such that the elongation to failure is greater than that of the rest of the rope so that the core will not fail prematurely during a tensile test.

The ribbon strands of a non-spin rope usually consist of eight wires in the form of a flattened strand without a core. From the geometry of a ribbon strand, one could envisage a relatively stiff element.

It was assumed that a triangular (inner) strand would have a stiffness less than that of the ribbon strands.

Stress-strain behaviours, as shown in Fig. C4, were assigned to the three different steel bars (strands). In this case "strain" reflects the behaviour of a "strand" as part of the rope.

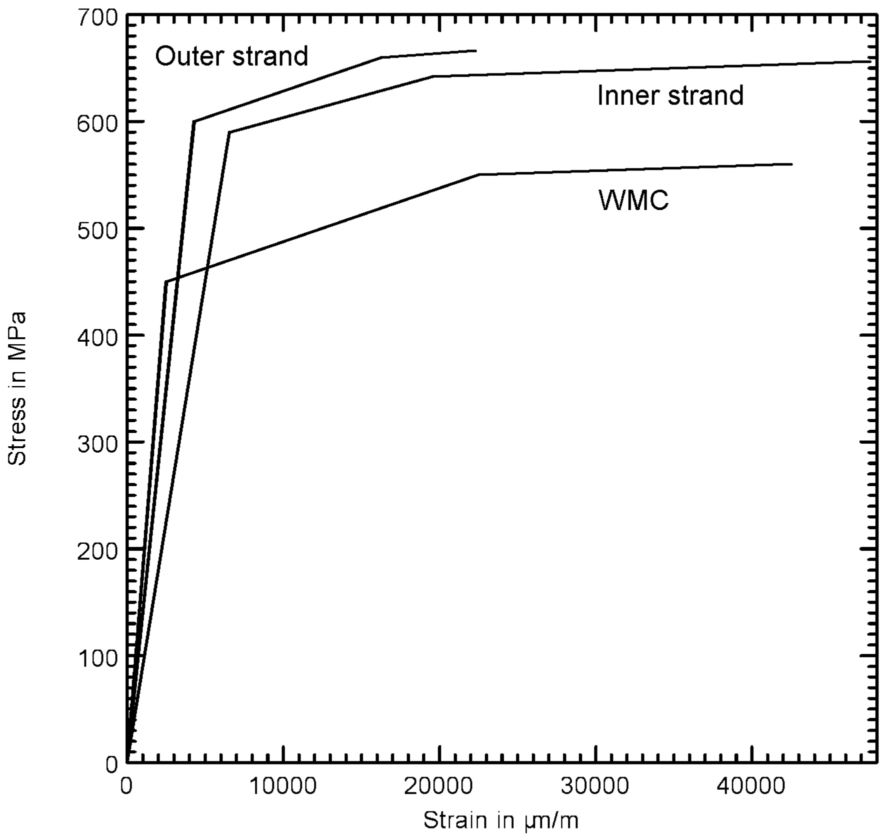

Figure C4: Assumed stress-strain relationships for the three strand types in a non-spin rope

With the stress-strain relationships of Fig. C4, a 3 m long bar will fail at:

wire main core:	35,8 kN at an elongation of 127,5 mm
triangle:	59,0 kN at an elongation of 142,7 mm
ribbon:	29,3 kN at an elongation of 66,9 mm

C4.1 Cutting strands completely

Table C4.1 below gives results of completely cutting a number of ribbon (outer) or triangular (inner) strands. The following descriptions were used:

new: no area reductions
-2t: 2 triangulars (inner strands) cut completely
-2r: 2 ribbons (outer strands) cut completely

Table C4.1: Assemblies approximating a 15 strand ribbon strand non-spin rope. The length of the assembly is 3 m. Complete strands removed.

No.	Description (3 m length 1 000 mm² total)	Area reduct	Load at failure	Strength reduct	Elongation at failure
15-1	new	0%	646,3 kN	0%	66,9 mm
15-2	-1r	4,4%	617,0 kN	4,5%	66,9 mm
15-3	-2r	8,8%	587,7 kN	9,1%	66,9 mm
15-4	-3r	13,2%	558,4 kN	13,6%	66,9 mm
15-5	-1t	9,0%	588,4 kN	9,0%	66,9 mm
15-6	-2t	18,0%	530,5 kN	17,9%	66,9 mm

Cutting a complete strand (removing a bar from the assembly) gives a very good correlation between area reduction and strength reduction, even though the bars have different stiffnesses.

C4.2 Reducing the area of a strand

The effect of broken or cut wires was simulated by reducing the area of a "strand" over a given length of the assembly. In the preceding parts it was always assumed that all the "strands" had exactly the same strength. To make the model more realistic, one of the ribbon strand was made very slightly weaker than the others, for some of the examples that will be shown. Table C4.2.1 below gives results for various combinations of reduced areas. In all cases, the reduced area length was selected as one metre of the 3 m specimen length. The descriptions of Table C4.2.1 have the following meanings:

3t(-3% for 1,0): Three triangular strands, each with area reduction of 3% of the total area (i.e. 3% of 1 000 mm = 30 mm²) over a length of 1,0 m.

+ wr One ribbon strand slightly weakened by reducing the area of the ribbon strand by 1 mm² over a length of 1,0 m. This reduction is 2,3% of the strand area, and 0,1% of the total area of the assembly (rope).

2r(-2% for 1,0): Two ribbon strands, each with an area reduction of 2% of the total rope area (i.e. 20 mm²) over a length of 1,5 m.

Note: An area reduction of 4% of the total rope (40 mm²) in one ribbon strand leaves only 4 mm² (9% of the strand area).

From practical considerations, the area reduction of a triangular strand (by "cutting wires") was limited to 25 mm², i.e. 28% of the triangular strand and 2,5% of the total rope area.

Table C4.2.1: Assemblies approximating a 15 strand ribbon strand rope. The length of the assembly is 3 m. Reduced area sections. Initial strength = 646,3 kN

No.	Description (3 m, 1 000 mm² total)	Area reduct	Load at failure	Strength reduct	Elongation at failure
15-7	1r(-1% for 1,0)	1,0%	600,6 kN	! 7,1%	29,6 mm
15-8	1r(-2% for 1,0)	2,0%	590,9 kN	! 8,6%	27,5 mm
15-9	1r(-3% for 1,0)	3,0%	581,2 kN	! 10,1%	25,3 mm
15-10	1r(-4% for 1,0)	4,0%	571,5 kN	! 11,6%	23,2 mm
15-11	2r(-2% for 1,0)	4,0%	579,4 kN	! 10,4%	27,5 mm
15-12	3r(-2% for 1,0)	6,0%	567,9 kN	12,1%	27,5 mm

15-13	2r(-4% for 1,0)	8,0%	547,0 kN	! 15,4%	23,2 mm
15-14	3r(-4% for 1,0)	12,0%	522,5 kN	! 19,2%	23,2 mm
15-15	1t(-1% for 1,0)	1,0%	638,9 kN	1,1%	60,5 mm
15-16	2t(-1% for 1,0)	2,0%	633,5 kN	2,0%	60,5 mm
15-17	1t(-2% for 1,0)	2,0%	631,8 kN	2,2%	58,9 mm
15-18	2t(-2% for 1,0)	4,0%	619,9 kN	4,1%	58,9 mm
15-19	2t(-2,5% for 1,0)	5,0%	612,9 kN	5,2%	58,1 mm
15-20	2t(-2,5% for 1,0) + wr	5,1%	607,1 kN	* 6,1%	51,2 mm
15-21	3t(-2,5% for 1,0)	7,5%	597,8 kN	7,5%	58,1 mm
15-22	4t(-2% for 1,0)	8,0%	596,2 kN	7,8%	58,9 mm
15-23	4t(-2% for 1,0) + wr	8,1%	591,1 kN	* 8,5%	51,2 mm
15-24	5t(-2% for 1,0)	10,0%	584,4 kN	9,6%	58,9 mm
15-25	4t(-2,5% for 1,0)	10,0%	582,8 kN	9,8%	58,1 mm
15-26	6t(-2% for 1,0)	12,0%	572,5 kN	11,4%	58,9 mm
15-27	6t(-2% for 1,0) + wr	12,1%	568,6 kN	* 12,0%	51,2 mm

! In all these cases the remaining strength of the assembly is greater than the load at which the "weakened" parts failed.

* In all these cases the slightly weakened ribbon failed and not the weakened sections of the triangular "strands".

The results in Table C4.2.1 could make one believe that a one-to-one relationship exists between area reductions on the triangular parts and loss in strength, and that the area reductions on the ribbons have double the effect on the strength. However, the behaviour of the assembly is merely a coincidence of the selected length of the assembly, the length of the reduced area part, and the selected stress-strain relationships of the various parts of the "rope".

The results of Table C4.2.1 appear very similar to those obtained from actual cut-wire tests on ribbon strand ropes (see Tables B2.1.2 and B2.2).

As mentioned: Information on the strand length affected by area reductions in the strand is not available. The specific construction of a ribbon strand could make it difficult for a broken wire to creep. It is not inconceivable that the strand length affected by broken wires in ribbon strands could be significantly smaller than the one metre selected.

In Table C4.2.2 the "experiment" of Table C4.2.1 was repeated, but with the assembly (specimen) lengths increased to 30 m.

Table C4.2.2: Assemblies approximating a 15 strand ribbon strand rope. The length of the assembly is 30 m. Initial strength = 646,3 kN

No.	Description (30 m, 1 000 mm² total)	Area reduct	Load at failure	Strength reduct	Elongation at failure
15-28	1r(-1% for 1,0)	1%	472,0 kN	! 27%	129 mm
15-29	1r(-2% for 1,0)	2%	363,2 kN	! 44%	98 mm
15-30	1r(-3% for 1,0)	3%	250,7 kN	! 61%	66 mm
15-31	1r(-4% for 1,0)	4%	129,7 kN	! 80%	35 mm
15-32	2r(-2% for 1,0)	4%	359,2 kN	! 44%	98 mm
15-33	3r(-2% for 1,0)	6%	355,2 kN	! 45%	98 mm
15-34	4r(-2% for 1,0)	8%	351,1 kN	! 46%	98 mm

15-35	2r(-4% for 1,0)	8%	125,2 kN	! 80%	35 mm
15-36	3r(-4% for 1,0)	12%	120,7 kN	! 81%	35 mm
15-37	1t(-1% for 1,0)	1%	595,5 kN	8%	235 mm
15-38	2t(-1% for 1,0)	2%	594,4 kN	8%	235 mm
15-38	1t(-2% for 1,0)	2%	585,7 kN	9%	212 mm
15-39	2t(-2% for 1,0)	4%	578,3 kN	11%	212 mm
15-40	4t(-2% for 1,0)	8%	563,6 kN	13%	212 mm
15-41	4t(-2% for 1,0) + wr	8,1%	563,6 kN	13%	212 mm
15-42	4t(-2,5% for 1,0)	10%	549,3 kN	15%	200 mm
15-43	6t(-2% for 1,0)	12%	548,9 kN	15%	212 mm

! In all these cases the remaining strength of the assembly is greater than the load at which the "weakened" parts failed.

The weakened strand of example 15-31 failed at 20% of the original strength, but the remainder of the assembly still having a strength of 95% of the original (one ribbon removed completely). In this case the weakened strand only had 9% of its original strand area.

For the selected assembly length and the selected reduced area length, it did not matter much whether one or four ribbon strands were cut, although the remaining strength of the rope would drop by 4,5% for every affected strand.

For the selected element strengths, cutting the triangular (inner) strands did not have the same severe effect on the failure strength as cutting the ribbon strands.

The shorter the strand length affected by the area reduction, the smaller the load at which the strand would break (up to a point). Longer assembly lengths would give the same effect. The effect of assembly length and reduced area length is further shown in the Table C4.2.3.

A reduced area of 50% of the specific strand area was selected for the demonstration of Table C4.2.3.

Table C4.2.3: Assemblies approximating a 15 strand ribbon strand rope. Different assembly lengths and reduced area lengths. Initial strength = 646,3 kN

No.	Description (1 000 mm² total)	Area reduct	Load at failure	Strength reduct	Elongation at failure
15-44	1r(-2,2% for 1,0): 3 m	2,2%	589,0 kN	! 9%	27 mm
15-45	1r(-2,2% for 1,0): 30 m	2,2%	341,4 kN	! 47%	91 mm
15-46	1r(-2,2% for 0,1): 30 m	2,2%	282,1 kN	! 56%	73 mm
15-47	1r(-2,2% for 0,1): 300 m	2,2%	275,6 kN	! 57%	716 mm
15-48	1t(-4,5% for 1,0): 3 m	4,5%	612,1 kN	5%	55 mm
15-49	1t(-4,5% for 1,0): 30 m	4,5%	505,3 kN	! 22%	153 mm
15-50	1t(-4,5% for 0,1): 30 m	4,5%	422,4 kN	! 35%	114 mm

15-51	1t(-4,5% for 0,1): 300 m	4,5%	409,7 kN	! 37%	1 098 mm

! In all these cases the remaining strength of the assembly is greater than the load at which the "weakened" part failed.

In a long rope, as will be the case of a rope suspended in a shaft, a weakened strand will fail at a relatively low load. For a six strand rope it was found that if the strength of one strand is reduced by 50%, that strand would fail if the rope load was just greater than 50% of the original rope strength. For the "non-spin" rope the effect on the (outer) ribbon strands are even greater: example 15-47: An area reduction of 50% of the strand, and a failure of the strand at 43% of the new rope strength.

However, as a general rule, it can be presumed that if a strand has, say, 70% of its area or strength left, it will fail at around 70% of the original rope strength.

Although the selection of different stress-strain relationships for the approximation of the non-spin rope (multi-layered) would have given different results, the example calculations produced much of the same effects as observed during the actual cut-wire tests.