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THE PERFORMANCE OF AIRCRAFT CONTROL CABLES UNDER SERVICE CONDITIONS

by

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SUMMARY

After examination of aircraft control cables broken or worn in service together with mechanical tests and theoretical analysis the following factors were found to contribute to failure:

(a) *Abrasion of the cables on pulleys or fairleads causing a much more serious loss of strength than is apparent from surface wear.*

(b) *"Brinelling" of the individual wires in the strands due to fluctuating cable tension inducing high contact stresses between helically wound wires. This causes strain-hardening followed by brittleness in the hard-drawn wires leading to the formation of surface cracks.*

(c) *Fatigue of wires due to flexing around pulleys and fairleads.*

(d) *Unobserved failure of the core strand due to the combined effects of (b) and (c).*

Subsequent to the investigations a review was made of the published work on aircraft control cables and covers the development of standards and air-worthiness requirements. A bibliography, which includes wire ropes in general engineering has also been added.

CONTENTS

1. INTRODUCTION

Following the occurrence of service failures in rudder cables of Auster aircraft an investigation was undertaken at the request of D.C.A. as reported in Reference 1. As a result of this work the problem of progressive deterioration of aircraft control cables in service was considered to be of sufficient importance to warrant extending the A.R.L. investigations.

Examination of worn control cables from small civil and military aircraft and gliders indicated that a substantial reduction in strength could occur with little or no visible evidence of deterioration. An experimental programme, including some theoretical analysis, was therefore planned to investigate the factors contributing to the reduction of ultimate strength of control cables in service.

The following three types of cables were considered:

(i) 7 x 7 aircraft cable (i.e. 7 strands of 7 wires) minimum breaking load 10 cwt., (4.98kN) made to an Auster specification (Ref. 2)

(ii) 7 x 14 aircraft cable (i.e. 7 strands of 14 wires) minimum breaking load 10 cwt., (4.98 kN) made to British Standard Specification W9. (Ref. 3).

(iii) 7 x 19 aircraft cable (i.e. 7 strands of 19 wires) minimum breaking load 1760lbf (7.83 kN) made to American Military Specification MIL-C-5424. (Ref. 4).

The layout of the wires in the cables is illustrated in Figs. 1 and 2.

Fatigue tests were also carried out on samples of galvanised steel cable (5 cwt. (2.49kN) minimum breaking load, 7 x 7 construction to B.S. W.9) specially prepared with a nylon covering to resist abrasion.

It should be noted that this report is based on work which was carried out in the early 1960's and was the subject of two internal A.R.L. reports. Because of delays in vetting etc. due to higher priority tasks, it has only now been consolidated into one report with the addition of later developments.

The investigation's, experimental work and results are as presented in the earlier reports but in the Discussion allusions are made to the influences of advances in cable design, current technology and standards. An up-to-date bibliography is included at the end of the report.

2. INVESTIGATION OF SERVICE CONDITIONS AND CABLE DAMAGE

In order to determine the factors that caused deterioration of control cables a number of cables damaged in service were examined and the control cable installation was inspected in a number of Auster aircraft.

2.1 Examination of Cables Damaged in service

A number of cables worn or broken in service was examined by microscope. The rudder cable failures from the Auster aircraft (reported in Ref. 1) are included. The aircraft have been given an arbitrary designation for the purposes of this report, i.e. VHA, VHB, VHC, VHE.

In the Auster rudder cables most of the worn and distorted sections of cable occurred at 254-305mm (10 - 12 inches) from the rudder pedal eye attachment and 356mm (14 inches) from the horn turnbuckle attachment (Fig. 3). The wear for the former condition was at a change of direction pulley and the latter where the cable rubbed on the fabric fairlead or emerged from the rear fuselage. It was at this latter location where some of the cables were corroded and the position where VHC had severe internal corrosion which was not detected by external visual inspection.

The wires of the 7 x 14 cable from VHA were heavily abraded, the abrasion marks being clearly visible and laying approximately at right angles to the cable. This abrasion had occurred on one side of the cable only (approximately half the circumference) and extended about 57 mm ($2\frac{1}{4}$ inches) each side of the failure. The individual wires were each examined at the point of fracture by microscope and this revealed no clear evidence of fatigue failure but showed that most of the wires had failed by static-tensile load. A photograph of the failure showing the extent of abrasion is shown in Fig. 4.

In the 7 x 7 cable VHB the wires showed no marked external abrasion but were heavily damaged consistent with high pressure between wires. There was considerable deformation and in some strands the core wire had assumed a hexagonal cross-section under pressure, which was probably combined with rubbing, from the surrounding wires. Fig. 5 shows a photo of the failure in which the damage to the wires can be clearly seen.

The difficulty of detecting internal wire damage was emphasised when the operator of VHE removed both 7 x 14 rudder cables two flying hours after a Certificate of Airworthiness because of a broken wire found in one of the cables. These cables were examined in the laboratory and one was found to have a completely broken core strand, each side of the fracture was corroded a distance of about 12.7 mm (½ inch) and indications were that failure had existed for some time prior to the inspection.

The 7 x 7 cable from VHC had worn approximately 0.051 mm (0.002 inch) where it had rubbed on the fabric but had no other abnormal change in appearance. However, extremely close inspection revealed a slight discolouration at the point of the strands. Cutting of the cable and subsequent inspection with a microscope showed that a considerable area of the strand in contact with the core strand had corroded and brinelling of the wires of adjacent strands had also occurred. This damage was attributed to the continual hammering and rubbing between the wires of the cable under fluctuating tension arising from cable vibration due to rudder buffetting from the propeller slipstream. However, the same state of corrosion and brinelling was found in a 7 x 14 cable removed from a glider where vibration could occur due to self excitation or running over uneven ground surfaces. It was interesting to note that this glider cable, while showing outer wear of approx. 0.051 mm (0.002 inch) had several core strand wires failed as shown in Fig. 7. In another glider cable wires in several strands had failed in fatigue at various locations but little or no wear was externally evident (Fig. 8). It was only after several inspections of the cable that these wires were observed because the fractures were of such a nature that the "cloth method" of detection (Ref. 6) did not indicate any failed wires.

2.2 Inspection of control cable installations

There are four factors in control cable installations which can be recognized as contributing to cable damage. These are.

(i) Cable vibration against pulleys and fairleads. This is particularly important in rudder cables on small propeller driven aircraft due to the effects of slipstream on the rudder.

(ii) Cable bending stresses due to flexing of the cable around pulleys.

(iii) Damage to unprotected cables.

(iv) Corrosion, due to removal of protective coatings by rubbing of wires against each other.

The control circuit of the Auster is described in some detail as it is typical of small propeller driven aircraft and illustrates some of the adverse conditions in which cables operate.

In some of the Auster aircraft examined the cables were slack in the unloaded condition while in others they were tensioned to 2.27 kg (5 lb.) by bungee cord. The cable was linked directly to the rudder pedal, the load from which is subject to a lever ratio of 1.5 : 1. The cable is deflected through approx. 18° by a 31.8 mm (1.25 in.) diameter pulley situated at the forward lower corner of the cabin entry door. This is the only pulley on the port side, while on the starboard side there are two pulleys one of 31.8 mm (1.25 in.) diameter and one of 57.2 mm (2.25 in.) diameter, the larger pulley appearing to be provided to accommodate a larger angular deflection.

In the J.1. series aircraft the cable runs are unprotected throughout the cockpit area, while in the J.5 series shrouding is provided aft of the pulleys. However the pulleys are in all cases vulnerable to damage from personnel entering or leaving the cockpit and to contamination. From the pulley the cable runs aft via two block and two ring fairleads down the fuselage and emerges through a reinforced hole in the fabric in the side of the fuselage, the final 610 mm (24 in.) of the cable to the rudder being exposed. The cable was subject to about 3° deflection at the aft fairlead and the exit hole from the fuselage; at the former the fairlead was worn to about 30% of the cable diameter and slight wear and corrosion was evident at the exit hole. The adjustment and stop limiting rudder movement were located in the rudder horn.

2.3 Measurement of cable loads in service

The majority of cables examined were from Auster J5 aircraft and to investigate the reasons for cable failures in service typical cable generating loads were measured.

A type J5G Auster was modified to enable the insertion of an A.R.L. loop transducer of 2.23 kN (500 lbf.) capacity. The aircraft was flown under various conditions, and the loads at the transducer were recorded automatically by a S.F.I.M. recorder. A series of ground manoeuvre loads were also recorded using this equipment. These conditions and results (shown in Tables I and II) where the manoeuvre of full "left" and "right" rudder at 80 knots straight and level produced a measured load of 0.98 kN (220 lbf*), while a maximum load of 1.95 kN (440 lbf) was recorded for a ground manoeuvre when the instructor applied opposite rudder control to over-ride that being applied by the pupil (Ref. 5 relates to a cable failure during dual instruction).

The ultimate design load requirements for the various types of Auster aircraft are set out in Table III to give an indication of typical control forces that can be expected in small aircraft of this type.

3. INVESTIGATION OF THE FACTORS AFFECTING CABLE STRENGTH

A number of investigations were carried out to determine the causes of cable damage observed in Para. 2.

3.1 Determination of the mechanical properties of cables

As previously stated some cables removed from service were found to have a broken core strand while the outer strands appeared intact. Tensile tests were therefore made on cables, core strands from the cable and wires from the core strand.

The specification and test data for the three types of cable are shown in Table IV. Tensile properties and dimensions of single wires from the cable are shown in Table V. Curves of direct tensile stress versus extension are shown in Fig. 9. for the centre wire and outer wire of the core strand of a 7 x 7 cable. Since the wires were preformed it was not possible to express the extension in terms of strain since a large part of the extension for an outer wire occurs in straightening of the helical twist. Slight crimping of the core wire may also be present due to the effect of the contact forces of the outer wires.

However, these graphs give the average tensile stress and an indication of the plastic elongation at failure. It is interesting to note that both the ultimate stress and the plastic deformation of the outer wire appear to be significantly less than the centre wire. It is possible that this effect is due to the superimposed bending stresses applied in straightening the preformed outer wire. In such very hard drawn wires these stresses are likely to be quite significant.

3.2 Effect of cable wear on ultimate strength

To investigate the effect of wear in service, the minimum diameter of the worn cables taken from service was measured and the failing load determined in a tension test. New cables were also abraded using fine emery cloth and rubbing the cable by hand in a longitudinal direction over a length of three inches and around one third of the circumference. This corresponded to the extent of the worn area observed on cables from service. The failing load of the cable was then determined in a testing machine, the overall length of the cable being 610 mm (24 inches).

By microscopical examination of each cable tested the area of the failed section of each wire was measured to within an estimated 5%. This enabled the failing load to be plotted against percentage reduction of area in Fig. 10. and against reduction of cable diameter in Fig. 11. There is a considerable variation in results but curves have been drawn through average values. The percentage reduction of area was estimated by the microscopic examination of abraded cables that had failed in service and an estimate of the expected failing load could be obtained from Fig. 10.

3.3 Evaluation of nylon covered cable

Wear and abrasion had been cited as one of the principle causes of cable failure, Ref. 1. Therefore, in conjunction with D.C.A. it was decided to carry out fatigue tests to evaluate the performance of nylon jacketed cable in comparison with standard cable.

Standard 5 cwt. (2.49kN) 7 x 7 cable to B.S.S. W9 covered with nylon was available in only limited quantity so only four test specimens were available. Two specimens of nylon covered cable

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*As the max. speed for this type of aircraft is 120 knots it was estimated that flight loads may exceed 1.11kN (250 lbf) for a similar manoeuvre.

and two specimens of standard cable were tested on hardened steel and 'Micarta' pulleys (at a temperature of 53° C (120° F.) Although, as expected, the nylon jacketed cable on the steel pulley was far superior to the standard cable the results using a Micarta Pulley were inconclusive. The results of these tests are summarised in Table VI.

4. ANALYSIS OF CABLE STRESSES

Some of the wires of the core strand under contact from the wires of the outer strands showed evidence of plastic deformation. Evidence of fretting was also present. In the tests to failure on new cables described in Para. 3.1 there was also evidence of the wires in the core strand having been indented by wires from the outer strands. In a cable the outer strands are arranged in a helix around the core strand. When tension is applied to the cable the outer strands close on the core strand resulting in pressure between adjacent strands in the rope. In a similar way contact forces occur between wires within the core strand. Forces at contact between strands also arise due to the cable passing around a pulley, the most heavily loaded strand being the inner strand bearing against the pulley.

A theoretical analysis of the contact forces between wires of a 7 x 7 cable was therefore carried out by applying the theory of Ref. 7.

The following equations for this case are derived in Appendix I.

In a 7 wire strand the load in the strand is given by:

$$T = T_c\,(1 + 6\cos^3\beta_s) \qquad \ldots (1)$$

Where T_c is the tensile load in the core wire and β_s is the helix angle.

Similarly for the cable the axial load is given by:

$$P = P_c\,(1 + 6\cos^3\beta_c) \qquad \ldots (2)$$

Where P_c is the load in the core strand and β_c is the lay angle.

Considering now the radial force where the outer strands contact the core strand we have:

$$F_p = \frac{\pi T \cos^2\beta \sin^2\beta}{9(1 + 6\cos^2\beta)}$$

Applying the general equations in Ref. 8 for elastic contact stresses between two cylinders, an expression for contact stresses between the wires of adjoining strands has been obtained in Appendix I. The contact stresses as a function of cable load have been calculated and the results are presented in Table VI.

Considering the core strand the radial loading on the core wire exerted by an outer wire is:

$$F_p = \frac{2\,T_o \sin^2\beta_s}{d} \text{ in the strand}$$

where d is the wire diameter and T_o the load in the outer wire

and $$F_p = \frac{2\,P_o \sin^2\beta_c}{D} \text{ in the cable}$$

where D is the strand diameter and P_o is the load in the outer strand with the assumptions of Appendix I.

This leads to an expression for the contact stresses on the core wire of:

$$\sigma_c = \left(\frac{2\,F_p}{\pi\,\Delta}\right)^{1/2}$$

where Δ is a function of the wire diameter and contact angle and may be obtained graphically from Ref. 8.

The experimentally determined failing loads of a 7 wire strand have been compared with those predicted from the strength of a single wire using equation (1) which assumes that all wires behave elastically up to failure. In the same way the ultimate strength of each of two cables has been predicted from the measured failing load for a single strand. All these results are presented in Table VIIIa which shows that there is reasonable agreement between predicted and measured values of ultimate strength.

Tests were also conducted on cables in which the core strand had been cut. The predicted failing load in this case is:

$$P = 6\ P_a \cos \beta_s,$$

assuming that all the outer strands carry equal tensile loads. The test results are compared with the predicted values in Table VIIIb.

5. DISCUSSION

5.1 Historical

With the limited documentation available an attempt has been made to piece together the history of the Auster rudder control circuit.

The Auster was the product of Taylorcraft Aeroplanes (England) Ltd. a company formed about 1940 to manufacture the American Taylorcraft light cabin monoplane under licence. The aircraft was used during the war as a light utility and observation aeroplane. The company later became Auster Aircraft Ltd. It is presumed that the rudder control circuit was originally designed with an American cable to MIL-C-1511, probably a 2.38 mm (3/32 in.) diameter cable of 7 x 7 construction and an ultimate breaking strength of 4.09kN (920 lbf). (This was the cable the Belgian authorities used as a replacement for the British cable in 1949 and reported no further defects in 1961). The nearest British cable would have been the 10 cwt. (4.98kN) 7 x 14 cable of 3.05 (0.120 in.) diameter to B.S.S. W2 (not preformed: W9 did not appear till 1946).

In 1945 due to failure of cables then in use (presumably the 7 x 14 British cable) British Ropes carried out a series of tests using an oscillator to reproduce the hammering and consequent abrasion and fraying of the cable on pulleys. The hammering was due to the slipstream over the rudder. (para 2.2). The conclusions reached in these tests was that a 7 x 7 cable was more resistant to abrasion than the 7 x 14 due to the larger diameter of the wire. 7 x 7 cables were therefore adopted. In 1952 another "crop of troubles" was experienced resulting in a further series of tests by British Ropes, in this case comparative fatigue tests. The existing 7 x 7 cable was compared with "a comparable American cable" and a 7 x 7 cable "manufactured to a new technique", (probably preformed as in W9). The new 7 x 7 cable had a life 2½ times the American cable and 5 times the existing 7 x 7 cable. This new 7 x 7 cable subsequently became Auster Standard JB 264 and was adopted for all Austers and is one of the cables which is the subject of this investigation.

One of the other cables investigated was of 7 x 14 construction and this would appear to be the result of D.C.A. Air Navigation Order which requested replacement of all 7 x 7 cables with 7 x 14 or 7 x 19 construction. (Ref. 9).

5.2 Cables

Cable of 7 x 14 construction is more flexible than 7 x 7 cable and hence has higher resistance to fatigue. It follows that the cable of 7 x 19 construction is superior to both the 7 x 14 and the 7 x 7 given similar conditions and materials. The 7 x 19 cable to MIL-C5425 is 50% stronger (static tensile strength) for the same diameter as the 7 x 7 and 7 x 14 and is superior in fatigue to the cable made to British Standards (See Refs. 10 and 11).

The investigation revealed that the cable of 7 x 14 construction was an inherently unstable configuration prone to internal abrasion and a tendency to ovality. Difficulty was experienced in service in checking the uniform diameter of the cable with a micrometer because of ovality of up to 0.15 mm (0.006 in.). The tendency to instability is well illustrated in Fig. 2, where a length of 7 x 14 cable has been set in Araldite and the ends of the cable polished to show the wire layout in the strands. The mobile four wire core is adequately illustrated leading to a variety of other than circular strand shapes. The comparatively orderly arrangement of 7 x 7 and 7 x 19 construction is shown in the sketches in Fig. 1.

It may be of interest to note that the daughtsman who prepared these sketches was unable to find any illustration of 7 x 14 cable despite a thorough search of references and the literature on aircraft and commercial cables. There was also no mention of 7 x 14 cable except in the British Standards related to aircraft cables.

The comparative fatigue tests on standard and nylon covered cable (5 cwt. (2.49kN) capacity 7 x 7 construction) on steel pulleys demonstrated the superiority of the covered cable, 2.7 times the endurance of the standard cable. However, the results using an aircraft pulley (Micarta material) were inconclusive due to the limited number of specimens available at that time. It was noted that the nylon jacket tended to interlock the broken strands of the cable and thus prevent total failure unless the failure was entirely at one cross section. One serious disadvantage of the nylon covered cable is the difficulty in detecting broken wires, an important aspect of maintenance inspection in service.

Other characteristics noted were the tendency to local bending of the cable at the site of cracks in the nylon cover and the increased resistance to bending caused by the nylon cover on small diameter cable.

5.3 Pulleys

The existing "sheave ratio" (Pulley diameter/cable diameter) for the Auster rudder circuit is 11.8 for the 31.75 mm (1.25 in.) diameter pulley and the 7 x 7 cable. If this pulley was the same diameter in the American design then the sheave ratio using the MIL-C-1511 cable of 2.38 mm (3/32 in.) diameter would have been 13.3. For a satisfactory fatigue performance for 7 x 19 galvanised cable loaded to 20% of its breaking strength Ref. 12 recommends a minimum sheave ratio of 16, and states "less than 16 rope diameters falls within a critical region in which cable life is relatively low". Reference 13 recommends a sheave ratio of 18 for 7 x 19 galvanised and stainless cables and a ratio of 28 for 7 x 7 cables.

In Ref. 14 F.T. Hill states "A minimum pulley diameter is suggested by the British Airworthiness Authorities as not less than 20 times the diameter of the cable".

It would seem that sufficient information was available at that time to enable reasonable sheave ratios to be specified, although the figure of 11.8 could possibly have been condoned on the basis of the small wrap angle of 18°. Again, in the elevator circuit a 57.15mm (2.25 in.) diameter pulley is fitted apparently to accommodate a larger wrap angle. There seems to be little justification for this as Ref. 15 finds there is no significant variation in fatigue life above a wrap angle of 20°.

5.4 Cable Standards

The relevant British Standards for aircraft cables at the time were:-

6W2 (Sept. 1946) Steel wire rope and straining cords (not preformed)
W9 (Sept. 1946) Preformed steel wire rope.
W10 Non corrodible steel wire rope (not preformed)
W11 (1946) Preformed non corrodible steel wire rope.

The American standards were:-

MIL-C-1511 (Nov. (1949) Cable; steel (carbon) flexible, preformed.
MIL-C-5424 (Aug. 1948) Cable; steel (corrosion resisting) flexible preformed for aeronautical use).

The specification drawn up by Auster Aircraft for 10 cwt. (4.98 kN) cable called for wire in accordance with BSS W9.

In assessing the relative merits of the various cables it is difficult to make a direct comparison because of the differences of so-called equivalent cables. The British method of designation of the cable is by ultimate breaking load whereas the American system is by cable diameter. If the American and British cables happen to have the same breaking load then the construction may be different. For example Reference 10 finds that the cable to MIL-C-5424 is superior to the British cable but this finding is qualified by the fact that the tests were carried out over the same diameter pulleys for cables for cables of different diameters, viz.:- 3.18 mm (0.125 in.) and 3.64 mm (0.143 in.) and 15 cwt. (7.47 kN) capacity. Generally, the only obvious differences between the American and British specifications are:

(i) The American specification calls for an endurance test.
(ii) The American specification calls for lubrication of the cable during manufacture.

The Auster specification, incidentally, called for an endurance test of 2,400 cycles with the cable loaded to 1/3 of the breaking load and a sheave ratio of over 20.

If we now examine the Standards for cables in the Auster category we find the following comparison:

Construction	Diameter mm (inches)	Min. Breaking Load kN (lb)	Specifications
7 x 7	2.38 (0.094)	4.09 (920)	(MIL-C-1511 (MIL-C-5424
7 x 7	2.69 (0.106)	4.98 (1,120)	Auster JB 264
*7 x 14	3.05 (0.120)	4.98 (1,120)	(BS W9 (BS W11
7 x 19	3.18 (0.125)	7.83 (1,760)	MIL-C-5424 (1957)
7 x 19	(0.125)	8.90 (2,000)	MIL-C-1511 (1948)
*7 x 19	3.81 (0.150)	7.48 (1,680)	B.S.W9 - W11

*Also available not preformed BS W2 and W10.

6. CONCLUSIONS

6.1 Cables

The performance of the 3.18 mm (1/8 in.) diameter cable of 7 x 19 construction to MIL-C-1511 or MIL-C-5424 is superior to cables of 7 x 7 or 7 x 14 construction.

6.2 Nylon covered cables

No conclusion is possible on the performance of the nylon covered cable due to the limited number of specimens available. However, inspection for broken wires is likely to be a major problem for this type of cable.

6.3 Pulleys

Pulley diameters should be as large as practicable and at least 20 times the cable diameters.

6.4 Rudder control circuit

6.4.1 Rudder limit stop

The rudder limit stop should be situated at the pedal rather than at the rudder horn. Many aircraft later than the Auster feature stops at the pedal as well as on the control surface itself.

6.4.2 Circuit tensioning

The rudder control circuit needs to be "closed" and tensioned. (Ref. 16)

6.4.3 Fairleads

More direct routing of the cable (particularly at the fuselage exit) is required to avoid abrasion due to fairleads. Protective covering over exposed cables in the cockpit area are desirable.

7. REVIEW OF STANDARDS AND RELATED INVESTIGATIONS

With the passage of time some of the findings and recommendations from this investigation have been overtaken by the updating of standards in the light of experience, increasing severity of operating conditions and improvements in manufacturing techniques. For example the International Organisation for Standardisation (ISO) has played an increasingly important role in the formulation of standards through Committee ISO/TC 20 (Aircraft and Space Vehicles).

In 1957 ISO/TC 20 had asked the Italian Member Body to draw up a proposal on the international standardization of pulleys for flight controls. This proposal was based on a revision of the American standards for pulleys at that time, AN 219, AN 220 and AN 221 (now MS 20219, MS 20220 and MS 20221) where it was permitted to use several cable diameters for a given pulley diameter and vice versa e.g. M.S. 20220 (Ref. 17) for cable diameters of 3.18 mm (1/8 in.), 3.97 mm (5/32 in.) and 4.76 mm (3/16 in.) permits the use of pulley diameters 31.88 mm (1.255 in), 63.63

mm (2.505 in.), 95.38 mm (3.755 in.) and 127.13mm (5.005 in.). The design parameters are the pulley maximum operating loads and the cable maximum operating loads and no reference is made to the minimum sheave ratio. Thus it is possible to specify a pulley/cable combination with a sheave ratio of less than 10.

Meanwhile, in 1966, British Civil Airworthiness Requirements (Ref. 18) laid down rules for control system installations and gave recommendations for pulley sizes. This was presented in graphical form with the number of wires in the cable as abscissa and the sheave ratio as the ordinate and a family of curves with the sheave ratio increasing for a given cable according to the load (expressed as a percentage of the breaking strength) in the cable. Within practical limits this standard has set a sheave ratio of 20 or above.

In Reference 19 (1971) the U.K., commenting on the Italian proposals and other international investigations, pointed out that the U.S. were still discussing pulley standardisation and planned to conduct additional tests. The U.K. recommended that one cable should be used for two pulley sizes, one with a minimum sheave ratio of 25 to be used where space was limited and the other with an ideal sheave ratio of 40 for use wherever possible. The Italian Member Body was again invited to recommence a study of aeronautical pulleys and so far as can be ascertained no ISO standard has yet been agreed upon.

7.1 Cable Standards

Of the British Standards issued in 1946, viz. 6W2, W9, W10, and W11, 6WE and W10 were rendered obsolescent in 1964 because the S.B.A.C. indicated a preference for preformed cables. W9 was replaced by 2W9 in 1965 and 2W11 superseded W11 in 1967. These two specifications recognised that "there has been a marked increase in the severity of conditions under which flexible wire ropes operate in aircraft flying control systems", and introduced corresponding improvements. Lubrication during manufacture was introduced (U.S. practice), the wire from which the rope was made was more fully specified, dimensional tolerances and ranges of tensile strength were specified. The issue of British Standard W12 in 1968 showed the effects of I.S.O. with the introduction of the specification of the cable by diameter (U.S. practice) instead of by breaking strength. The cable of 7 x 14 construction was discontinued.

W12 was followed by W13 in 1973 specifying the corrosion resisting equivalent of W12. The situation can be well summarised by quoting from the Foreword to W13 viz.:

"This British Standard specifies the requirements for preformed corrosion-resisting steel wire rope to comply with ISO Recommendation R 564 'Designations, diameters and breaking strengths of preformed stranded steel cables for aircraft controls' and International Standard ISO 2020 'Technical Specification for flexible steel wire rope for aircraft controls'.

ISO/R 564 specifies the diameter, construction and minimum breaking strength of the rope, all of which are in accordance with Recommendation No. 3310 of l'Association Internationale des Constructeurs de Materiel Aerospatiale (A.I.C.M.A.) and with the United States Military Specification MIL-C-5424A. Sizes of rope, larger than 6.4 mm (¼ in.) diameter, though included in MIL-C-5424A, are seldom used in modern aircraft, and have been omitted from this standard".

Recapitulating, it is interesting to note that in 1965 in 2W9 a sentence in the Foreword stated "An endurance test is being formulated and will be added to the specification by amendment as soon as possible". In 1973, eight years later, the same statement appears in the Foreword of W13. Evidently, some difficulty was being experienced in the formulation of an endurance test. Moreover, in 1969, at the ISO meeting, the U.K. and French delegates were charged with the responsibility of producing recommendations for an endurance test. Investigations on this matter had been in progress for some time and a test programme designed to compare the scatter of results between a proposed U.K. method and the U.S. MIL-Spec. method showed a considerable scatter between three nominally identical machines built to the MIL-Spec (Ref. 20).

The issue of the ISO Technical Specification for flexible steel wire ropes for aircraft controls ISO 2020 shows that the problem of the endurance test has still not been resolved. A footnote to the specification states:

"While awaiting the publication of an ISO test procedure — an endurance test can be carried out in accordance with a relevant national specification". The United States, incidentally, has expressed its disapproval of ISO 2020.

If we now turn to the American scene we find that the U.S. Military Specifications MIL-C-

1511 (1949 and MIL-C-5424 (1949) have continued through to 1973 with a few minor amendments such as specification of the chemical composition of the steel, wire tolerances and tensile strengths. In 1973 MIL-W-83420 was issued superseding MIL-C-1511 and 5424 and combining in one specification carbon steel and corrosion resisting steel cables and their nylon jacketed equivalents. This specification is now entitled "wire rope", flexible instead of "cable" — flexible.

7.1.1 Nylon covered cables

Because of reports of excessive wear on control cables in F-5 and T-38 aircraft extensive tests on nylon covered cables were carried out by Wright Patterson Air Force Base in 1967-68. The nylon cover, or jacketing, is extruded over the cable to completely enclose the cable with a protective coating. The cables tested were nylon covered stainless steel cables to MIL-C-5424 and tests were made at normal temperature and at −40° C (−40° F). (Ref. 21). The results of these tests showed that the life of the cables was significantly increased by the wear protection afforded by the nylon covering and in addition assisted in vibration damping, protection against sand, grit, fluids and other harmful elements. However Ref. 22, commenting on the tests, again emphasised the serious problem of cable wear detection on this nylon covered cable and states that, to date, no satisfactory solutions have been found to solve this problem. Reference 22 also indicates that in the U.S. carbon steel cables are being replaced by stainless steel cables. Results of endurance tests at low temperature show that the stainless steel cables are far superior to the carbon steel product. (Ref. 23).

7.2 Pulleys

During the course of the ISO sponsored investigations already mentioned in Paras 7 and 7.1 other significant factors in cable wear have been discovered. (Ref. 23). One of these is the considerable wear sustained by a cable where it passes over a pulley, at a small wrap angle.* (This is relevant to the Auster see paras. 2.2 and 5.3). There was a marked difference in the wire wear and failure at pulleys in which the angle of wrap was only 15° compared with those of a wrap angle of over 90°. It appears that the rope with the small wrap angle, due to the lack of support from the pulley groove, has a transverse scrubbing action imposed upon the wires in contact with the pulley which leads to abrasion and early fatigue failure. However these findings do not appear to agree with the investigations in Italy (Lab. Centre FIAT. Ref. 24) where it was found that cable life decreases with increase of wrap angle from 0° to 45°.

7.2.1 Pulley groove profile

In 1971 the United Kingdom ISO Document (Ref. 19) still indicates some disagreement with ISO proposals on groove profiles and favours a groove to give maximum support to a cable and to provide for regular proportional increases in pulley groove dimensions as the cable size increases. Some U.S. investigations in this area are described in Ref. 26.

In conclusion it seems there is still much work to be done to arrive at agreement on standards and international acceptance of design criteria to ensure the satisfactory performance of aircraft control systems and cables.

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*The angle subtended, at the pulley centre, by the arc of contact of the cable.

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APPENDIX I

by

Patricia Diamond & Sue Vanderborght

(i) Notation

β_s	Angle of lay of the axis of an outer wire of a strand to the core wire.
β_c	Angle of lay of the axis of an outer strand of a cable to the core strand.
ν	Angle between the line of contact of outer wire and axis of core wire
D, d	Diameter of strand and wire respectively, inches
T_o, P_o	Load in outer wire and outer strand respectively, lb.
T_c, P_c	Load in core wire and core strand respectively, lb.
T, P	Load in strand and cable respectively, lb.
F_p	Radial loading between wires at parallel wire critical region lb/in.
F_c	Radial force between wires at crossed wire critical region, lb.
b.	Semi minor axis of ellipse of contact.
x	Axial co-ordinate, inches.
y	Tangential co-ordinate, inches
z	Co-ordinate radially inward from cylindrical surface, inches.
A, B	Terms dependent in geometry of contacting bodies.
Δ	Term dependent on material and geometry of contacting bodies.
E	Modulus of elasticity, p.s.i.
μ	Poisson's ratio.
σ_c	Normal stress in axial direction in core wire of strand, p.s.i.
σ_o	Normal stress in axial direction in outer wire of strand, p.s.i.
σ_{cr}	Critical normal stress, p.s.i.

(ii) Analysis of stresses in a 7 x 7 cable

Consider six wires wound round a centre wire at helix angle β_s to form a strand and six strands wound round a core strand at a lay angle of β_c.

The load T in a strand is given by:

$$T = T_c + 6\,T_o \cos\beta_s \qquad \ldots (1)$$

where T_c and T_o are tensile loads in core and outer wires respectively.
If wires are elastic, compatibility of strain gives:

$$T_c = \frac{T_o}{\cos^2\beta_s} \qquad \ldots (2)$$

$$\therefore \quad T_o = \frac{T\cos^2\beta_s}{1 + 6\cos^3\beta_s} \qquad \ldots (3)$$

and $$T = T_c\,(1 + 6\cos^3\beta_s) \qquad \ldots (4)$$

Similarly the load in the outer strands of the cable is given by:

$$P_o = \frac{P\cos^2\beta_c}{1 + 6\cos^3\beta_c} \qquad \ldots (5)$$

and $$P = P_c\,(1 + 6\cos^3\beta_c)$$

where P_c and P_o are loads in the core strand and outer strands respectively and P is the load in the cable.

There are two important critical regions of contact stress in a cable subjected to a tensile force. The first of these, called the parallel wire critical region is located at the line of contact between the wires of the strand. Whether the region is between an outer wire and core wire of a strand or between two outer wires is dependent on the diameter of the core wire. The critical stresses are higher when the contact is between the outer wire and core wire of a strand (Fig. 13 (a)). The second critical region, called the crossed wire critical region, is located between the wires of adjacent strands.

(a) Parallel wire critical region

The most serious case of an outer wire wrapped round the core wire results in a radial loading F_p

$$F_p = 2\,T_o \sin^2 \beta \qquad \ldots (7)$$

where $\beta_s = \beta = \beta_c$ (Fig. 13 (b))

However the outer wire makes contact with the core wire at an angle ν where $\tan \nu = \frac{1}{2} \tan \beta$ (Fig. 13 (c))

Hence the contact loading per inch is given by:

$$F_p = 2\,T_o \sin^2 \beta \cos (\beta - \nu) \qquad \ldots (8)$$

$$\therefore F_p = \frac{2T \cos^2 \beta \sin^2 \beta \cos (\beta - \nu)}{d\,(1 + 6 \cos^3 \beta)} \qquad \ldots (9)$$

where $\nu = \text{artan}\,(\frac{1}{2} \tan \beta)$

Contact Stresses

From Ref. 8

$$\sigma_x = -2\mu \left\{ \left[1 + \left(\frac{z}{b}\right)^2 \right]^{1/2} - \frac{z}{b} \right\} \frac{b}{\Delta} \qquad \ldots (10)$$

$$\sigma_y = -\left[\frac{\left\{ \left[1 + \left(\frac{z}{b}\right)^2 \right]^{1/2} - \frac{z}{b} \right\}}{\left[1 + \left(\frac{z}{b}\right)^2 \right]^{1/2}} \right] \frac{b}{\Delta} \qquad \ldots (11)$$

$$\sigma_z = -\frac{\frac{b}{\Delta}}{\left[1 + \left(\frac{z}{b}\right)^2 \right]^{1/2}} \qquad \ldots (12)$$

where b is one half the width of the rectangle area of contact and Δ is a function of the geometry of the contact region.

$$b = \sqrt{2 F_p \Delta / \pi} \qquad \ldots (13)$$

$$\text{and } \Delta = \frac{d\,(1 - \mu^2)}{E} \qquad \ldots (14)$$

The principal stresses σ_x, σ_y, σ_z, have their maximum values at $z = 0$, that is, at the surface of contact.

Critical Stresses

The critical normal stress, σ_o, is given by substituting equations (9), (13) and (14) into equation (12).

$$\sigma_o = -\frac{b}{\Delta} + = \left[\frac{4TE \cos^2 \beta \sin^2 \beta \cos (\beta - \nu)}{\pi d^2\,(1 + 6 \cos^3 \beta)\,(1 - \mu^2)} \right]^{1/2} \qquad \ldots (15)$$

(b) Crossed Wire Critical Region

The radial force, F_c, between two wires of adjacent strands is given by:

$$F_c = \frac{F_p\,d}{3 \tan \beta} = \frac{\pi\,To \sin^2 \beta}{9 \tan \beta} \qquad \ldots (16)$$

Critical Stresses

The critical normal stress in the crossed wire critical region is given by:

$$\sigma_{cr} = - c_{\sigma} \quad (b / \Delta) \qquad \ldots (17)$$

where $$b = c_b \quad (F / \Delta)^{1/3} \quad \text{(Ref. 7)} \qquad \ldots (18)$$

where c_b and c_σ are functions of the angle β and are presented graphically on pages 356 and 357 of Ref. 8. plotted against a quantity B/A where

$$B/A = \frac{\left(1 + \frac{\sin^2 \beta}{3}\right) + \left(1 - \frac{\sin^2 \beta}{3}\right) \cos 2\beta}{\left(1 + \frac{\sin^2 \beta}{3}\right) - \left(1 - \frac{\sin^2 \beta}{3}\right) \cos 2\beta} \qquad \ldots (19)$$

TABLE I

CABLE LOADS RESULTING FROM FLIGHT MANOEUVRES

Manoeuvre	Speed - Knots	Cable Load kN (lb.)	Pedal Force kN (lb.)
Straight & Level			
Full L. & R.	50	0.712 (160)	0.472 (106)
Rudder	60	0.890 (200)	0.592 (133)
Rudder	70	0.935 (210)	0.623 (140)
Rudder	80	0.979 (220)	0.654 (147)
Estimated	120	1.1[illegible] (250)*	0.743 (167)
Steep Turns L. & R.	—	0.312 (70)	0.209 (47)
Side Slip R	—	0.579 (130)	0.383 (86)
L	—	0.668 (150)	0.445 (100)
Level Medium Turns	—	0.312 (70)	0.209 (47)
Taxying with application of brake	—	0.445 (100)	0.298 (67)

***The load for the manoeuvre at the maximum design cruising speed of 120 knots was obtained by extrapolation.**

TABLE II

CABLE LOADS RESULTING FROM STATIC GROUND MANOEUVRES

Manoeuvre	"A" kN (lb.)	"B" kN (lb.)	Average	Average Pedal Force kN (lb.f)
* Instructor applying opposite rudder to pupil	1.56 (350)	1.96 (440)	1.70 (385)	1.099 (247)
Applying parking brake	0.445 (100)	0.623 (140)	0.534 (120)	0.356 (80)
Releasing parking brake	0.579 (130)	0.623 (140)	0.600 (135)	0.401 (90)
Shifting position in seat	—	0.890 (200)	—	0.592 (133)
Full rudder to limit stop against horn	—	1.56 (350)	—	1.037 233

"A" and "B" were different combinations of "Instructor and Pupil"

*For safety reasons this test was not made during flight.

TABLE III

AUSTER RUDDER CABLE DESIGN PROOF LOADS

Type	Pilot Effort kN (lb.)	Cable Load kN (lbf.)	Reserve factor
J5F	1.335 (300)	1.962 (441)	1.9
J5K			
J5L			
All others Incl. J5A J5R	1.780 (400)	2.621 (589)	1.43

The above information was obtained from the Auster Type Record and assumes an ultimate load for the cable of 840 lb. based on a splice efficiency of 75% for the 10 cwt. cable.

TABLE IV

CABLE DETAILS

Cable Specification	Construction	Max. Lead kN (lbf.)	Specified Min. load kN (lbf.)	Measured Cable	
				Spec. Max. dia.	Ovality
B.S.S. -W9 -5P	7 x 14	6.23 (1400)	4.98 (1120)	3.05mm (0.120 in.) 2.90mm (0.114 in.)	0.15 mm (0.006 in.)
Auster Spec AJB 264 (Wire to BSS W9)	7 x 7	5.96 (1340)	4.98 (1120)	2.59 mm (0.102 in.)	0.05 mm (0.002 in.)
MIL-C5424	7 x 19	8.23 (1850)	7.83 (1760	3.53 mm (0.139 in.) 3.35 mm (0.132 in.)	0.08 mm (0.003 in.)

TABLE V

TENSILE PROPERTIES AND DIMENSIONS OF SINGLE WIRES

Cable	Wire Location in strand	Meas. Dia. mm (inch)	Max. Load kN (lbf)	Approx. 0.2% P.S kPa (p.s.i.)	Max. Stress kPa (p.s.i.)	Spec. Wire Dia.
	Core of Centre	0.325 (0.0128)	0.167	1,722,560	2,039,440	0.33 (0.013)
	Core of outer	0.300 (0.0118)	(37.5)	(250,000)	(296,000)	0.305 (0.012)
7 x 7	Outer of centre	0.305 (0.012)	0.125	1,894,750	2,032,550	0.305 (0.12)
	Outer of outer	0.279 (0.011)	(28.0'	(275,000)	(295,000)	0.285 (0.0112)
	Core of centre	0.216 (0.0085)	0.076	1,722,500	2,067,000	0.203
	Core of outer	0.216 (0.0085)	(17.0)	(250,000)	(300,000)	(0.008)
7 x 14	Outer of centre	0.203 (0.008)	0.065	1,825,850	1,998,100	0.229
	Outer of outer	0.203 (0.008)	(14.5)	(265,000)	(290,000)	(0.[illegible]9)
	Core of centre	0.295 (0.0116)	0.142	1,791,400	2,067,000	
	Core of outer	0.229 (0.009)	(32.0)	(260,000)	(300,000)	
7 x 19	2nd row of centre	0.229 (0.009)				Not
	2nd row of outer	0.216 (0.0085)				Specified
	Outer of centre	0.216 (0.0085)	0.076	2,135,900	2,342,600	
	Outer of outer	0.203 (0.0085)	(17.0)	(310,000)	(340,000)	

TABLE VI
ENDURANCE TEST RESULTS

Specimen No.	Test Conditions	Cycles to first detected wire failure	Cycles to cable failure	Mean cycles to failure	Site of failure	$\frac{(3)}{(4)}$	Wear at fairlead mm (in.)	Period of wear, cycles	Wear per 10,000 cycles mm (in.)	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1A	Standard cable Steel pulley	6,000	7,309	7,981	Pulley	82%	0	6,000	0	Initial wire failure took place on the inside of the bend where wires had been polished by contact with the pulley
1B		6,000	8,653		Pulley	69%	0.0102 (0.0004 in.)	6,000	0.0178 (0.0007)	
2A	Nylon covered cable, steel pulley	20,000	20,514	21,650	Pulley	97%	0.0152 (0.0006 in.)	20,000	0.0076 (0.0003)	Some nylon cracks existed but did not develop. Due to greater stiffness and low tension the cable did not follow the radius of the pulley completely.
2B		18,000	22,787		Pulley	79%	0	18,000	0	
3A	Standard cable, micarta pulley	12,000	21,976	23,425	Pulley	55%	0.0279 (0.0011)	10,000	0.0279 (0.0011)	No polishing, but wire failure on inside of bend Fan inoperative at 15,000 cycles. Failure @ 76° F.
3B		18,000	24,865		Pulley	72%	0.0025 (0.0001)	20,000	0	Oil was extruded during the test until 14,000 cycles. Removed periodically.
4A	Nylon covered cable Micarta pulley		12,670	23,445	Pulley	100%	0	12,000	0	Failure occurred at 2 cracks in the nylon which were undeveloped at 8000 cycles.
4B		22,000	34,220		Pulley	64%	0	24,250	0	Stiffness noted in specimens

TABLE VII

LOADS AND STRESSES
(a) PARALLEL WIRE CRITICAL REGION

σ cr Pascal (psi)	T N. (lb)	P N (lb)
-6.59×10^{3} (-9.57×10^{5})	962.0 (216.09)	6008 (1350)
-1.52×10^{3} (-2.2×10^{5})	8.18 (1.8385)	51.1 (11.486)
-1.65×10^{3} (-2.4×10^{5})	8.55 (1.9203)	53.4 (11.997)

(b) CROSSED WIRE CRITICAL REGION

σ cr Pascal (psi)	T N (lb)	P N (lb)
-1.79×10^{4} (-2.6×10^{6})	8793 (197.6)	6008 (1350)
-1.52×10^{3} (-2.2×10^{5})	0.549 0.1233	3.748 (0.8423)
-1.65×10^{3} (-2.4×10^{5})	0.713 0.1602	4.870 (1.0943)

TABLE VIII

COMPARISON OF PREDICTED AND MEASURED FAILING LOADS

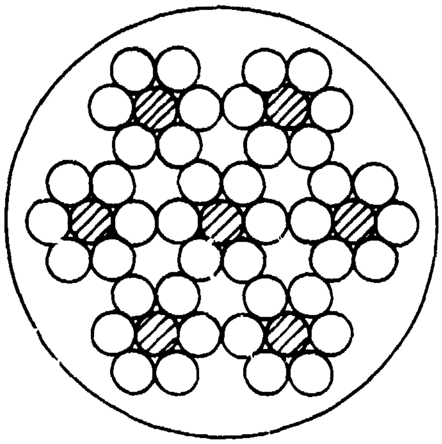
(a) CABLE LOADS

Cable Type (1)	Measured Load kN (lbf) (2)	Strand Load kN (lbf) (3) P_c	Cable Lay (4)	$(1 + 6\cos^3\alpha)$ (5)	Predicted Load $P_c(1 + 6\cos^3\alpha)$ (6) kN (lbf)
7 x 7	5.69 (1280)	1.0 (225)	16°	6.30	6.27 (1410)
	5.96 (1340)	1.06 (240)			6.72 (1510)
7 x 14	5.78 (1300)	1.02 (230)	16°	6.30	6.45 (1450)
	6.23 (1400)	1.06 (240)			6.72 (1510)

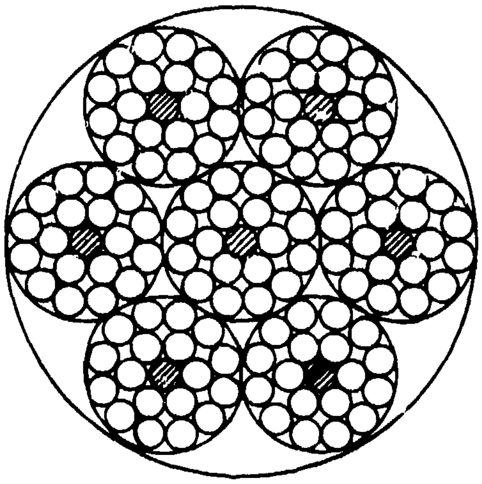
col (6) = col (3) x col (5)

(b) STRAND LOADS

Strand Type (1)	Measured Load kN (lbf) (2)	Wire Ult. Load kN (lbf) (3) T_c	Strand Lay α (4)	$1 + 6\cos^3\alpha$ (5)	Predicted Load $T_c(1 + 6\cos^3\alpha)$ (6)
7 wire	1.024 - 1.068 (230-240)	0.167 (37.5)	16	6.30	1.055 kN (237 lbf)

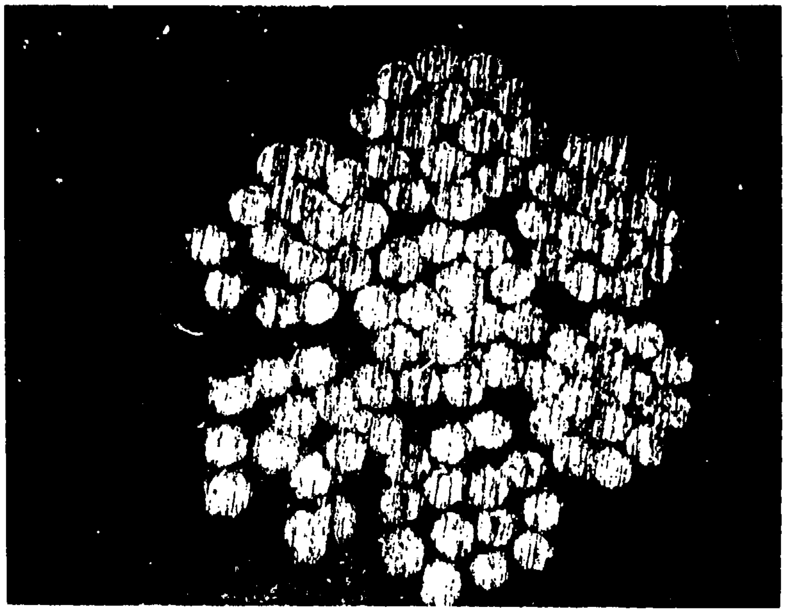


7 x 7

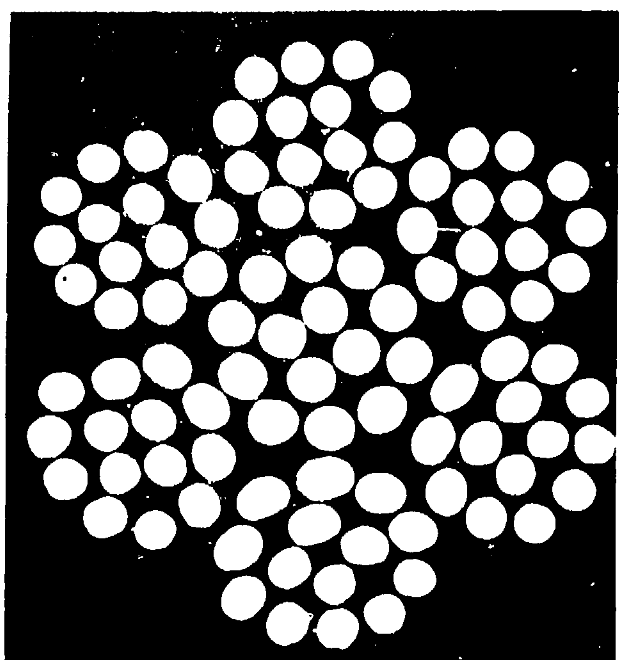


7 x 19

ARRANGEMENT OF WIRES IN 7 X 7 CABLE AND 7 X 19 CABLE



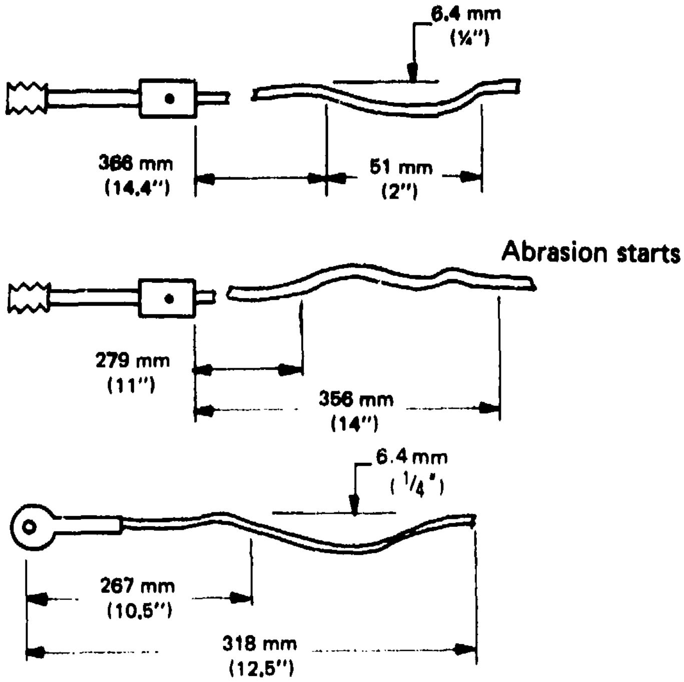
(a) As cut at one end



(b) Polished at the other end

ARRANGEMENT OF WIRES IN A 4.98 kN (10 CWT) 7 x 14 CABLE TO BSW 9
(Set in araldite)

Cable deformations

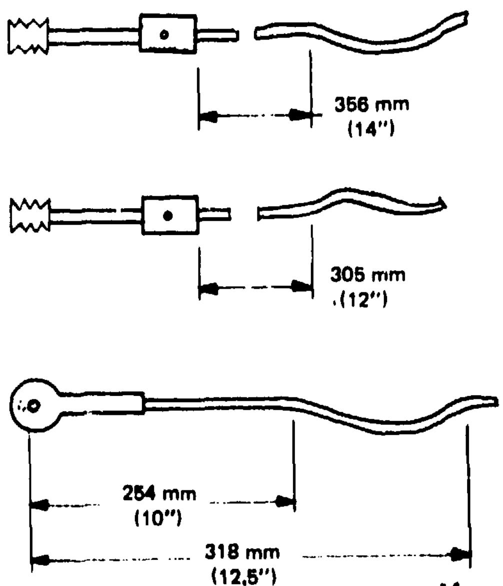


Stbd cable
Horn. attachment end

Cable JA 2393X
Port cable
Horn. attachment end

Port cable
Rudder pedal attachment end

CABLES ON VHD



Corrosion 38 mm (1.5") long.
Cable JA 2393X

Corrosion 25.4 mm (1.0") long
Cable JA 2394X

Max. abrasion measured 0.05 mm (0.002") on dia.

CABLES FROM VHC.

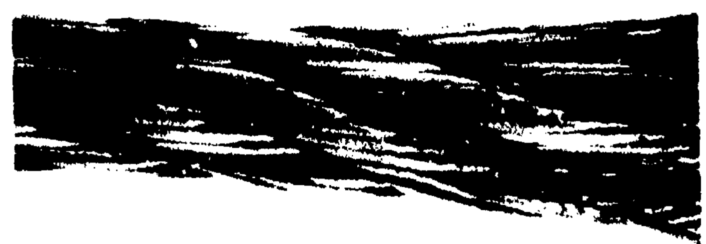
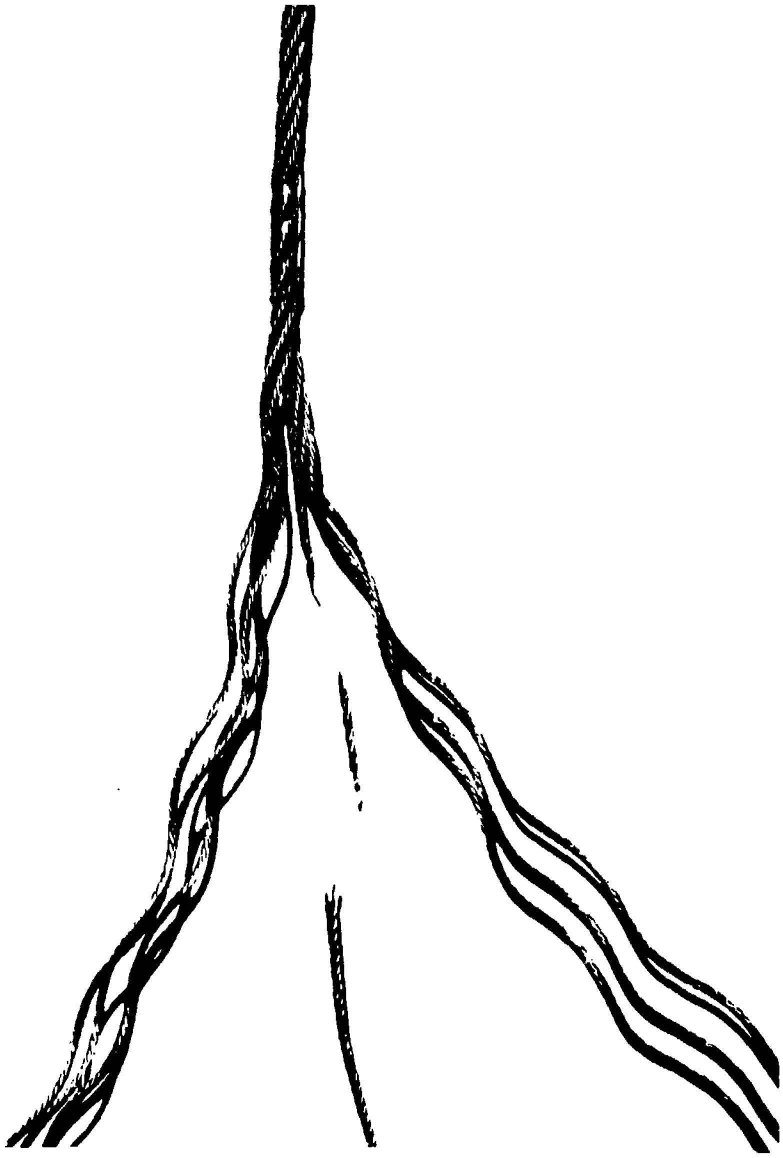


FIG. 4 CABLE FAILURE IN VHA SHOWING ABRASION OF STRANDS.

FIG. 5 STRAND FAILURE IN VHB SHOWING DAMAGE BETWEEN WIRES.



Neg. no. 5409

INTERNAL WIRE DAMAGE IN CORE STRAND VHE

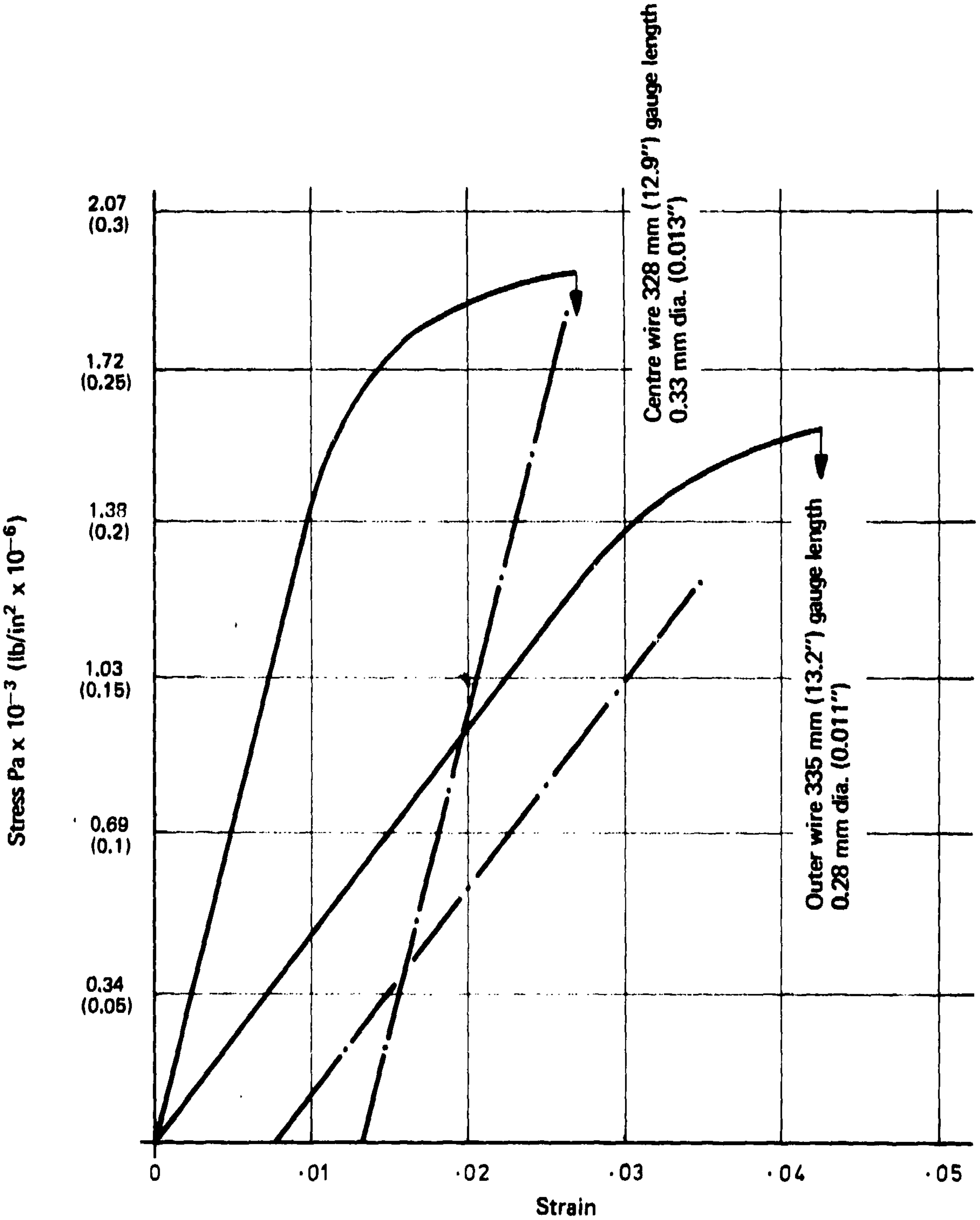
FIG. 7 FAILURE OF CORE STRAND WIRES.

(a)

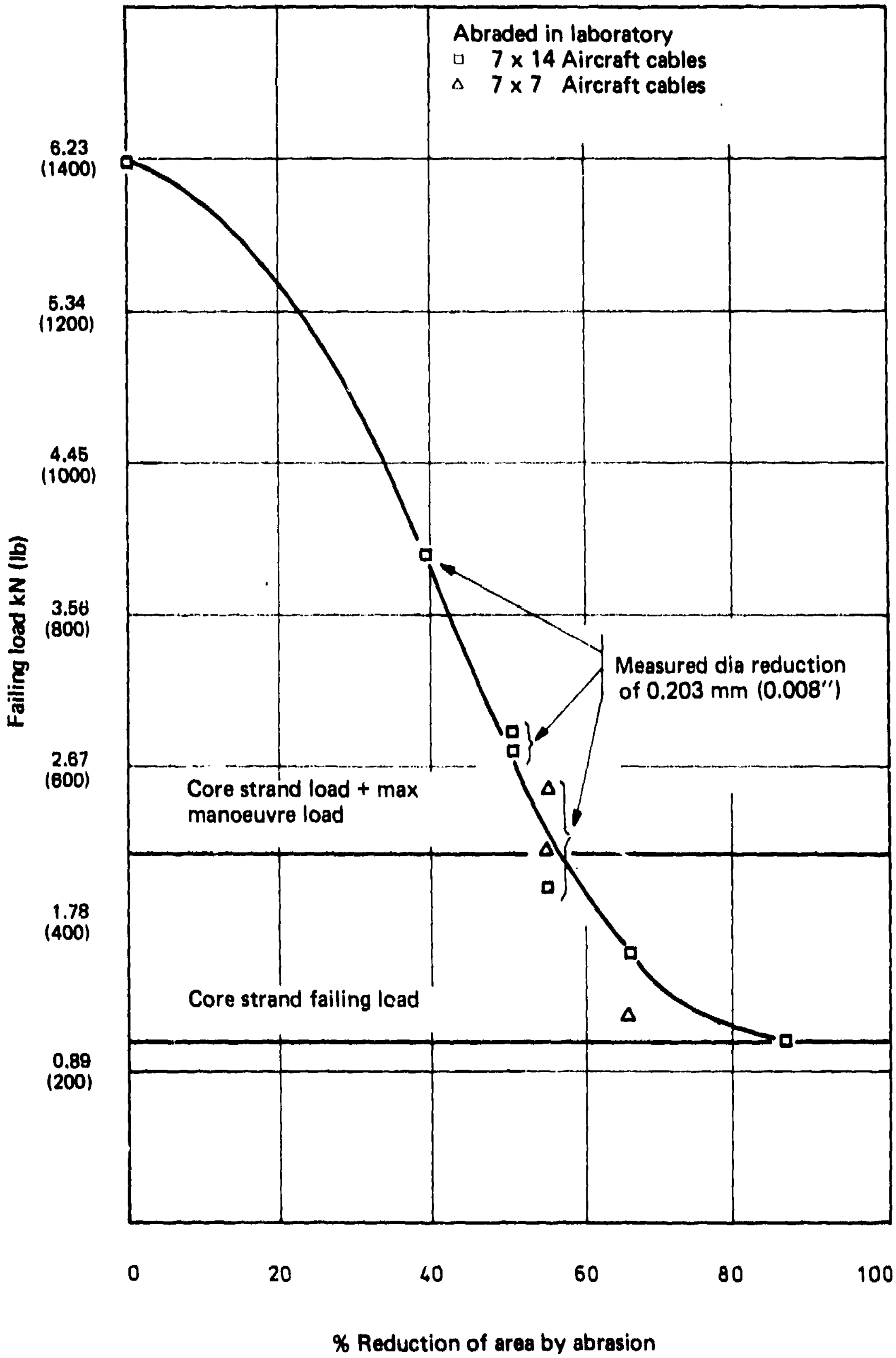
(b)

Worn and fretted cable 7 x 14
removed two flying hours after a C. of A. inspection

FIG. 8 (VISIBLE DAMAGED WIRES PRIOR TO UNRAVELLING)

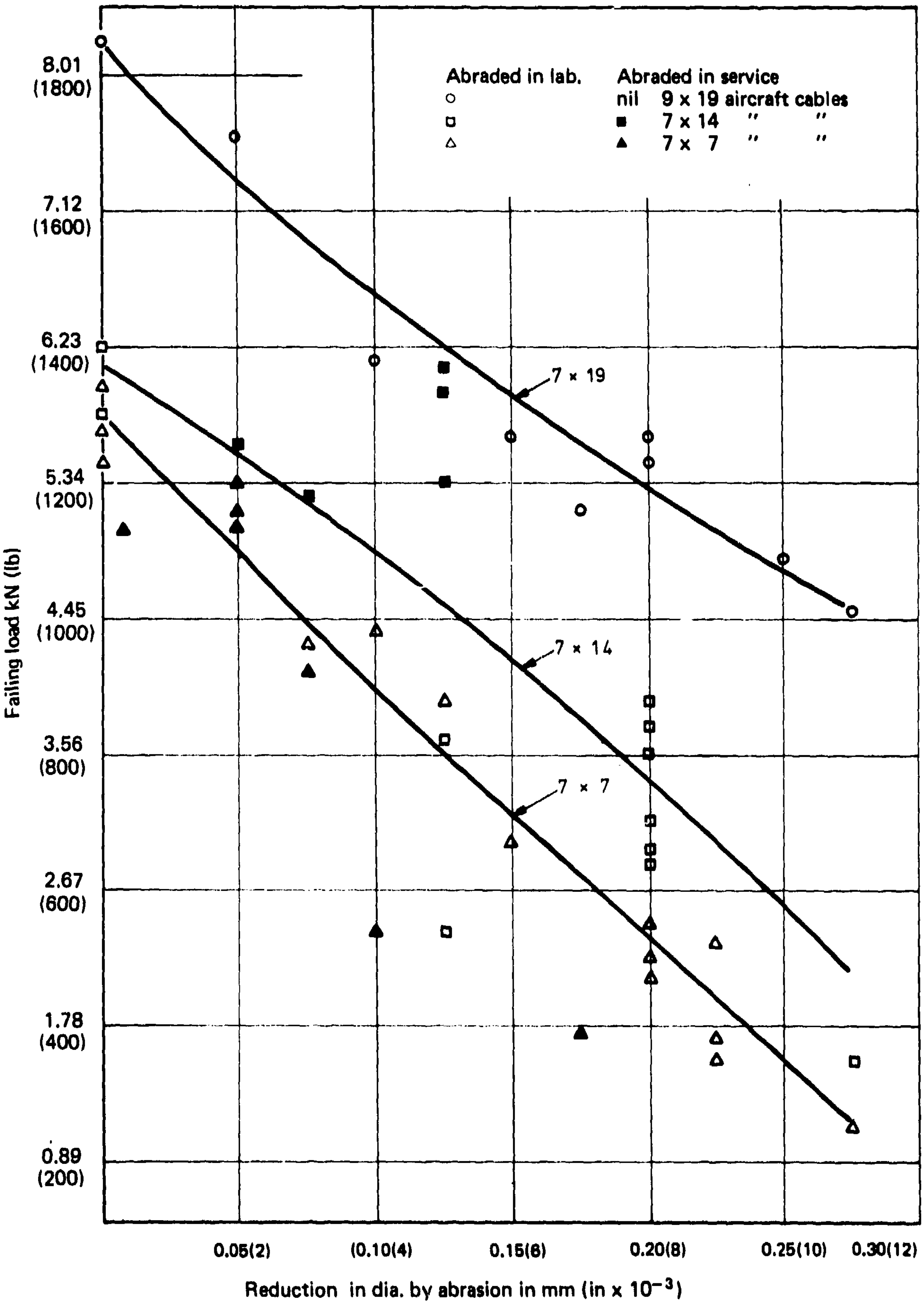


STRESS-STRAIN CURVES FOR TWO WIRES OF A 10 CWT (4.98 kN)
7 X 7 GALVANIZED CABLE.

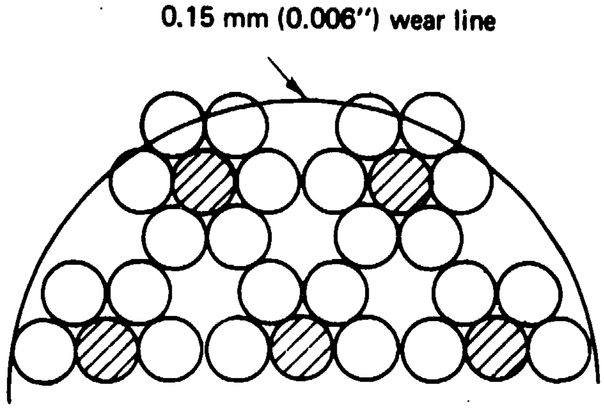


VARIATION OF FAILING LOAD WITH REDUCTION IN AREA OF CABLE.

(Extracted from ref. 1)

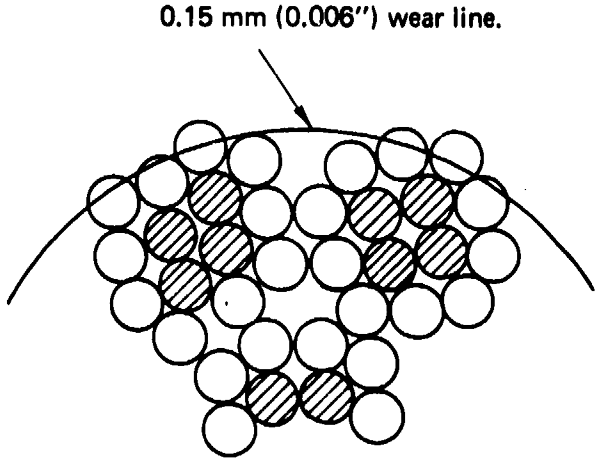


FAILING LOAD OF ABRAIDED CABLES (Extracted from ref. 1.)



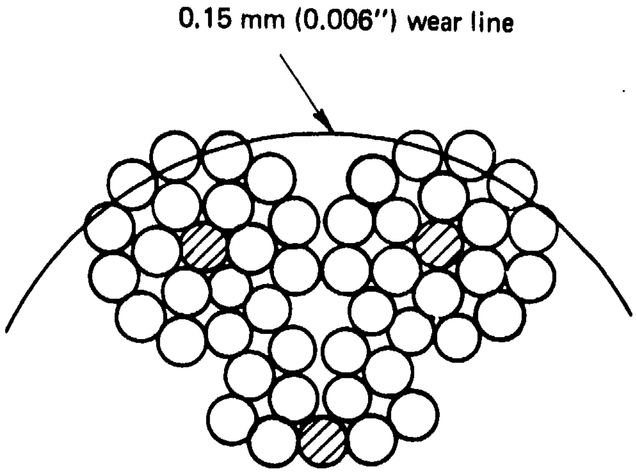
7 x 7

wire dia. 0.28 mm (0.011")
cable dia. 2.59 mm (0.102")



7 x 14

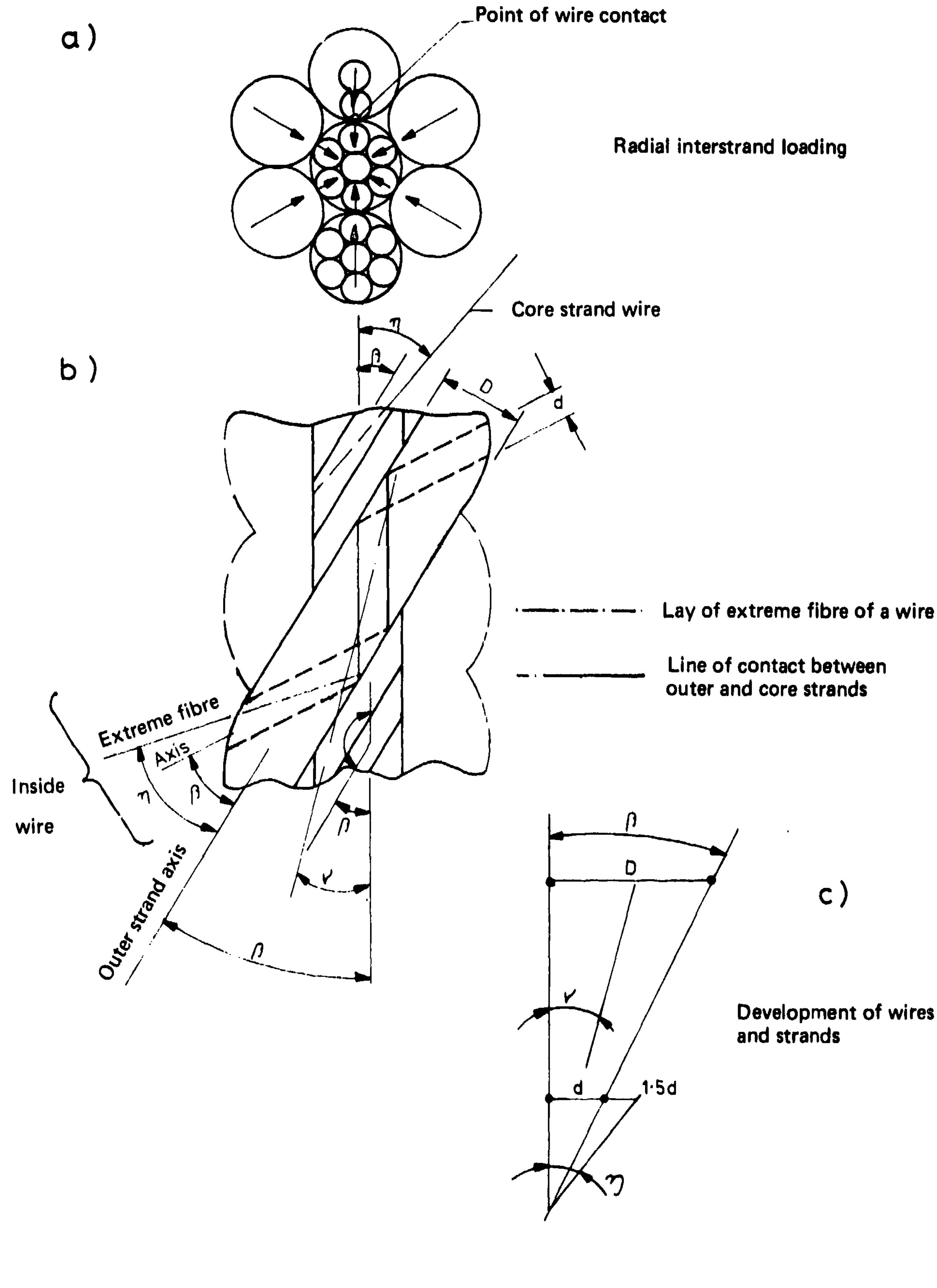
wire dia. 0.23 mm (0.009")
cable dia. 2.90 mm (0.114")



7 x 19

wire dia. 0.20 mm (0.008")
cable dia. 3.35 mm (0.132")

WEAR ON INDIVIDUAL WIRES OF VARIOUS CABLES.



GEOMETRY OF 7 X 7 CABLE.

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