# DEVELOPMENT OF WIRE ROPE FOR CATAPULT AND FLIGHT DECK USE

by

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The Carrier Equipment Division at the Royal Aircraft Establishment, Farnborough, has been charged with the development of Catapults and Arresting Gear for installation in Aircraft Carriers. All types at present in service, or to go into service in ships now building, are dependent on wire rope to convey the load between the aircraft and the hydraulic energy absorbing system in arresting gear or the power system in catapults. It is therefore true to say that the wire rope is the heart of the design and also its most heavily loaded member.

## The Importance of Inertia

In flight deck machinery it is necessary to deal with large accelerations of the order of 3–4g, which entail very high dynamic loads in the members and also make inertia of paramount importance. In both catapults and arresting gear it is essential to accelerate large masses of operating machinery as well as the aircraft, the equivalent weight of the catapult moving parts in the B.H.5 design being, for instance, approximately the same as the average large naval aircraft. " Equivalent weight " is a convenient method of expressing inertia. It is clear that any reduction in this equivalent weight of the gear will be most valuable, since not only is the work expended on accelerating it wasted, but it has to be stopped again when the launch is over in the case of the catapult, or accelerated violently to the speed of the aircraft during an arrestment. Of the moving parts of typical catapults and arresting gear, approximately 53% of the equivalent weight is that of the wire rope and 42% that of the various pulleys around which the ropes run. Thus at least 90% of the inertia in the gear itself is directly attributable to the wire rope and its pulleys. In catapult design it is the bringing of the mass to rest which sets the limit of performance, since, in order to conserve flight deck space, without increasing the acceleration or the accelerating stroke, the retardation stroke must be kept to a minimum. Alternatively, for a given total length of catapult track, the less the retardation stroke the greater the acceleration stroke and the less the acceleration.

In arresting gear design it is the inertia of the moving parts which imparts a large part of the initial deceleration forces felt by the aircraft.

When the B.H.5 catapult and its equivalent arresting gear, the Mark 10, are operating at their maximum designed speed of 75 knots, the mean value of the trolley retardation in the former is approximately equal to the maximum acceleration imparted to the rope system of the latter, viz., 22g. As designed, the equivalent weight of the catapult was about 15,000 lb and of the arresting gear 2,800 lb.

In both catapults and arresting gear, a reduction in the equivalent weight of the moving parts brings about a corresponding increase in operating speed which varies inversely as the square root of the ratio of $\frac{\text{old mass}}{\text{new mass.}}$

## Ropes and Sizes used previously

It was found that for an equivalent task, the size and type of rope used by the Engineer-in-Chief for catapults, the Director of Naval Construction for arresting gear and the United States Navy varied considerably. A preliminary investigation of the design methods employed by E.-in-C. and D.N.C. to arrive at the rope size for a particular job showed considerable variation. Two things, however, were common, namely, the construction of the rope used and the size of the sheaves over which it was led. Both departments, being originally advised by the wire rope makers, specified that the ropes should be of 6/37 construction, ordinary lay, and made from wire having a U.T.S. in the range 115 to 125 ton/in.² and that the ratio $\frac{\text{effective pulley diam.}}{\text{rope diam.}}$ should not be less than 22 for this construction of rope.

In E.-in-C.'s Department the practice was to use the following factor of safety :—

$$\text{F. of S.} = \frac{(\text{breaking stress of the rope}) \times 0.8}{(\text{stress due to bending}) + (\text{stress due to tension})}$$

D.N.C. used :—

$$\text{F. of S.} = \frac{(\text{breaking stress}) \times 0.8 - (\text{bending stress})}{(\text{tension stress})}$$

*Note.*—Constant 0.8 appearing in both D.N.C. and E.-in-C. formulae is called the " age factor " and is designed to cater for the loss in strength of a rope due to exposure to atmospheric conditions at sea.

As an example, for the ropes fitted in the B.H.5 catapult
the F. of S. according to E.-in-C. is 1.99, whereas
the F. of S. according to D.N.C. is 2.44.

At the same time, information arrived which showed an even larger divergence of opinion between catapult and arresting gear designers in Britain and America in the method of assessing the tension in a wire due to bending. It should be noted that the effects of bending a wire rope round a pulley are usually expressed in terms of an equivalent tensile load.

In Britain this tension due to bending was assumed to be

$$S = E_r \frac{d}{D}$$

where

$S$ = Stress due to bending.
$E_r$ = Modulus of elasticity of the whole rope (which for a 6/37 construction rope was usually assumed to be $12 \times 16^6$ lb/in.²).
$d$ = Diameter of individual wires forming rope.
D = Effective pulley diameter.

In America, according to Technical Bulletin No. 5, the tension due to bending is given as

$$S = \frac{2K_t}{D + d_r}$$

where

$D + d_r$ = Effective pulley diameter.
$K_t$ = Is a parameter obtained from a graph.

Comparing the bending stress given by the English and American formulae for the case of the B.H.5 catapult—

By the English formula = S = 10.4 tons/in.²
By the American formula = S = 1.465 tons/in.²

Since by the British method of design the bending stress comes out 7 times that by the American formula, in the latter case much more of the total strength of the rope is available to do useful work, or conversely a smaller size of rope is used for the same job.

It is interesting to note that, as far as enquiries were possible, there was no known case of a rope failing under overload in British or American catapults or arresting gears.

**Terms, Expressions and Definitions used in Wire Rope Work**

Before proceeding to describe the research into the properties of wire ropes which has been carried out, the terms and expressions used will be briefly described.

*Construction.* The construction of a rope is the way in which the individual wires from which it is made are made up.

*Lay.* The direction of the helix formed by the wires and by the strands.

*Ordinary lay.* In ordinary lay the strands are made up by twisting together wires in a left-hand lay and then making up the rope by twisting the strands in a right-hand lay, so that the outer wires appear to run more or less axially along the rope. Occasionally ropes are made where the strands are made up right-handed and the rope left-handed, but this is unusual and is done to special order only.

*Langs lay.* In langs lay ropes the wires in the strand and the strands in the rope are made up with the same lay, so that the outer wires appear to run nearly normally to the axis of the rope.

*Scale construction.* Where the wires that make up the strand are all wound in the same direction and at the same pitch, so that they lie on top of each other without crossing. This means that the outer layers have wires of larger diameter than the inner to cater for the increased mean diameter of the layer.

*Flattened strand.* Where the core of the strand is made in delta formation, either by having a single triangular wire or three small wires twisted up together. The outer wires are wound on this and the finished strand has three more or less flat surfaces, instead of being circular.

*Cross laid.* Where the wires in the strand are made up with alternate layers to make a non-rotating rope such as is used in cranes, etc.

*Locked coil.* A rope where the outer layer is made up of profiled strips which interlock to give a smooth exterior ; the rope is made up as one strand, so that it looks like a rod.

*Numerical designation.* Ropes are normally designated numerically, *e.g.*, 6/37, or, more precisely, $6/18 \times 12 \times 6 \times 1$. In every case the first figure refers to the number of strands which make up the complete rope, and the second figure to the number of individual wires forming the strand or, in its extended form, gives the number in each layer of the strand. Whilst many different combinations are made, for naval flight deck use nearly all ropes have six strands. Occasionally an odd number of strands will be specified, *e.g.*, seven, which means that the rope has a strand acting as wire core instead of the usual hemp.

*Independent wire rope core.* Apart from the fibre core which is found in most ropes, some have wire cores. If the construction of the wire core is identical with that of the main strands, then the rope is referred to as, for instance, 7/37 instead of 6/37. If on the other hand, as is often the case, the core has a different construction to the main strands, then it is known as an " independent wire rope core ". As an example, Fig. 1 (2) and (6) have independent wire rope cores of 7/7 construction, but Fig. 1 (5) is a 7/19 rope.

*Pre-formed rope.* Where the wires are given a twist into the double helix they will occupy in the complete rope as they are laid up into the strand. The rope is then without locked up stresses and is "dead", so that when cut it does

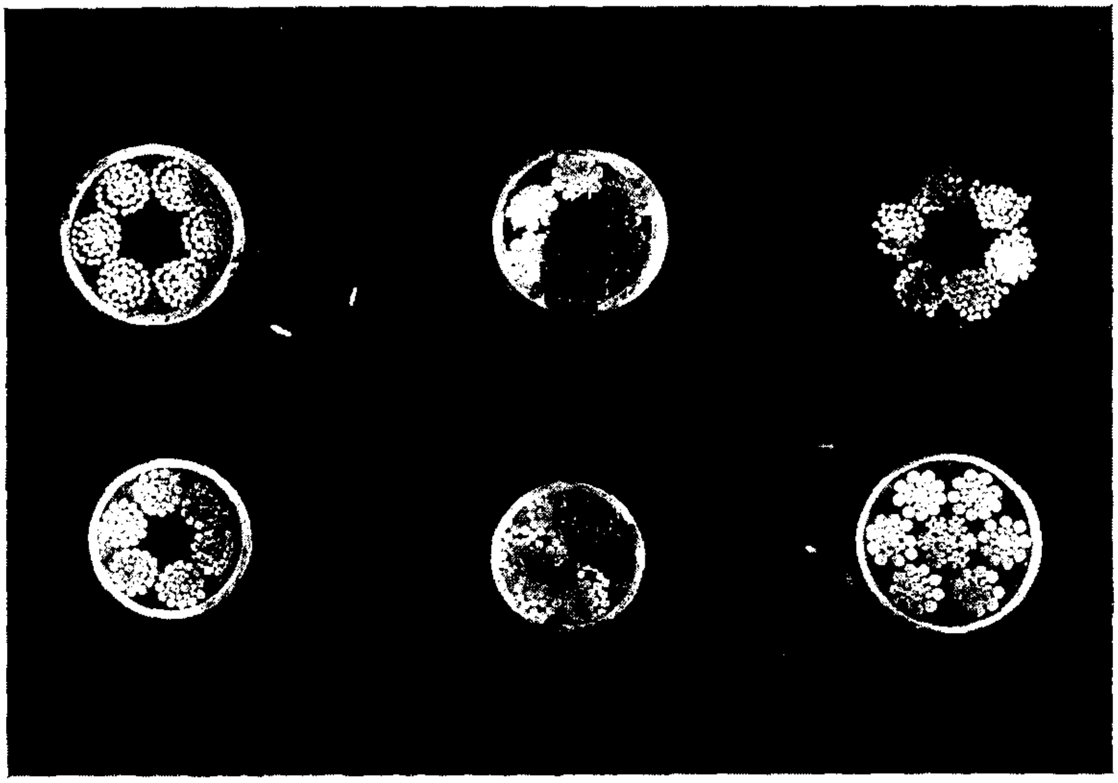


FIG. 1.—SHOWING CROSS SECTION OF 6 TYPES OF ROPE

LEGEND

1. 6/37 ORDINARY LAY
2. 6/19 SCALE ORDINARY LAY WITH INDEPENDENT WIRE ROPE MAIN CORE
3. 6/37 ORDINARY LAY PREFORMED
4. 6/19 SCALE ROUND STRAND LANG'S LAY WITH INDEPENDENT WIRE ROPE MAIN CORE
5. 7/19 ORDINARY LAY
6. 6/25 LANG'S LAY (TRIANGLE OF THREE WIRES)

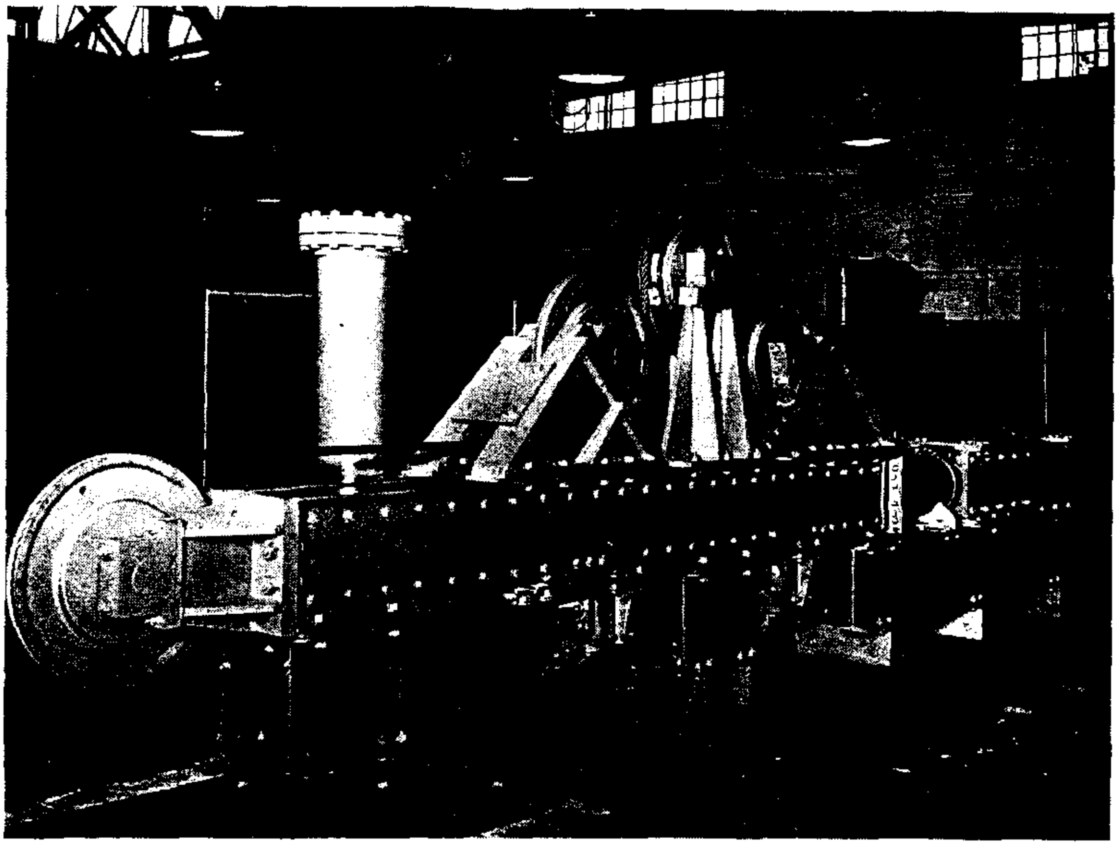


Fig. 2.—Wire Rope Test Rig

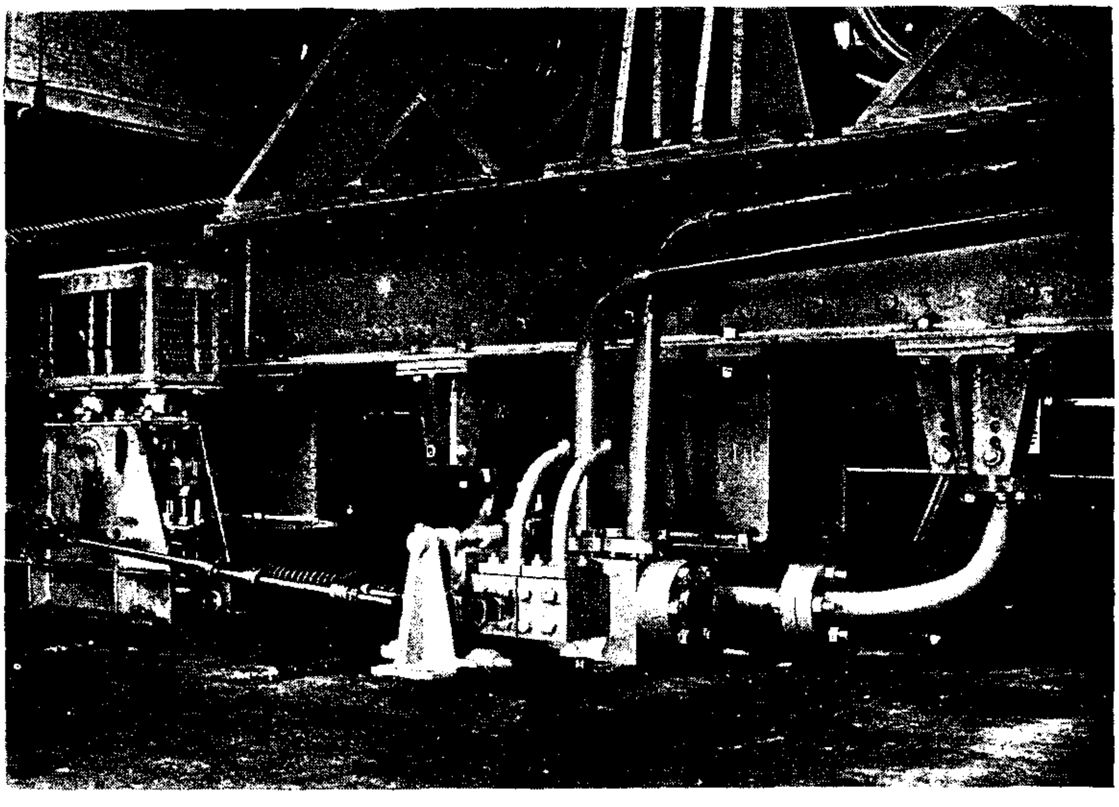


Fig. 3.—Control Gear

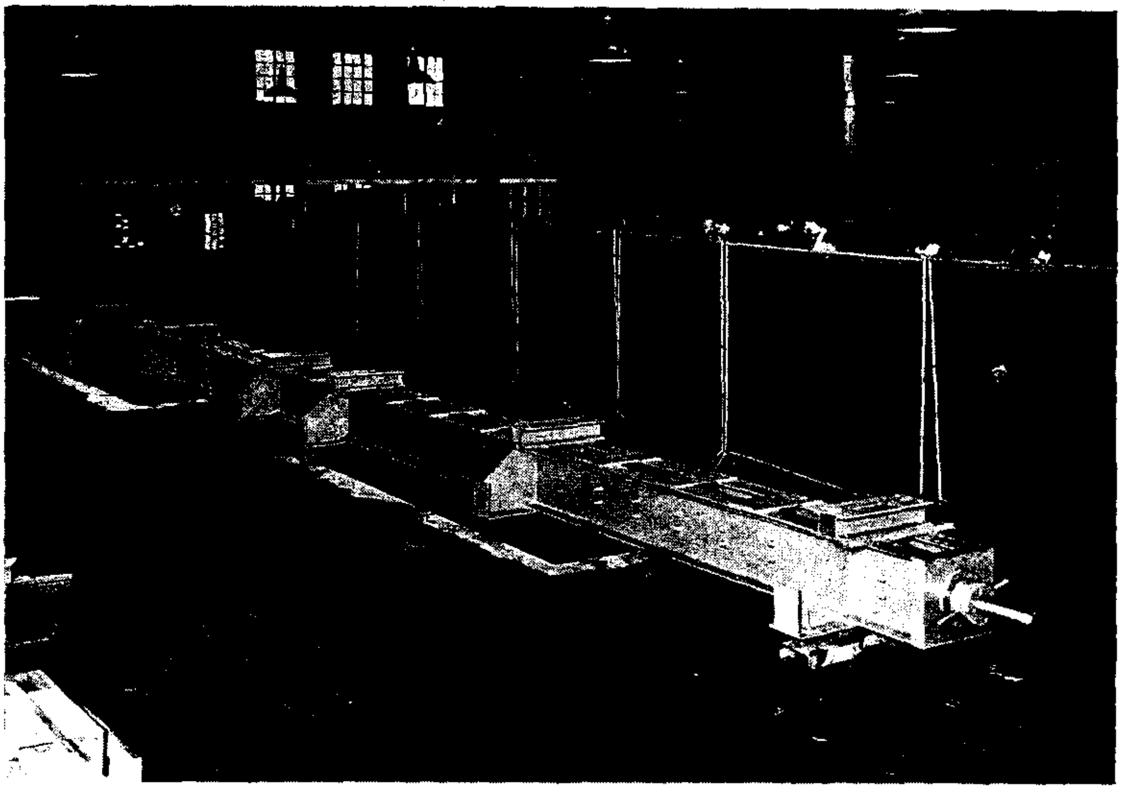


FIG. 4.—WIRE ROPE BREAKING RIG

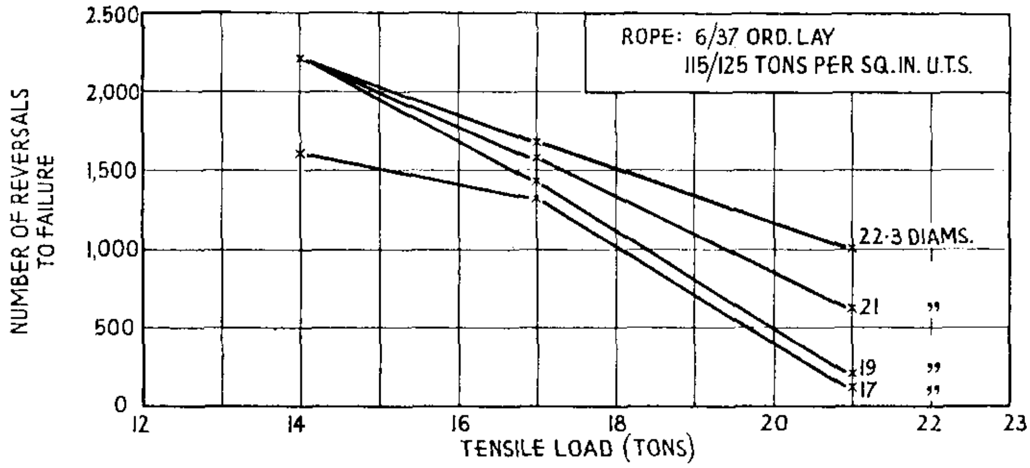
not unravel. The rope makers claim that pre-formed rope takes the load more evenly spread between the wires than the cruder type with locked up stresses.

*Material.* All wire ropes are made from plain carbon steel, the variation in U.T.S. being obtained by varying the amount of cold drawing. Alloy steel is not used.

## WIRE ROPE RESEARCH

In an attempt first of all to evaluate the magnitude of the stresses caused by rope being bent round the pulley, a programme of research was planned. It was immediately decided that static tests would not show up the essential characteristics sufficiently and that it was necessary to bend repeatedly the rope over pulleys in order to try to reproduce actual operating conditions. This was a form of fatigue testing, though the cyclic period was very slow compared with the normal fatigue test.

A suitable machine was designed and made at R.A.E. which is completely automatic in operation. The photograph, Fig. 2, shows the general construction. The rope is led round two free pulleys, or five, depending whether the reversed bending sheaves are in place or not, one of the end sheaves being loaded hydraulically to give the required rope load. The ends of the rope are attached to a piston rod whose piston works in a cylinder to the alternate ends of which pressure or exhaust can be connected so as to work the rope over the pulleys. The control gear, shown in Fig. 3, was adapted from the Brown-Denny ship stabilizer gear and gives 14 strokes per minute. As there is an automatic counter fitted the actual experiments need only comparatively unskilled attention. Preliminary tests showed that the reversed bending sheaves were not essential, and they were in fact not used during the whole series of tests.




GRAPH. 1. VARIATION OF PULLEY DIAMETER

At the same time as the rope fatigue rig was made, a rope breaking rig (Fig. 4) was also constructed, being a simple hydraulic ram test machine, so as to enable static data to be quickly and easily obtained.

Soon after the research had commenced it became very apparent that the behaviour of a 6/37 construction rope was not ideal and the scope of the research was widened to include investigation into the effects of the following variables :—

(1) Variation in pulley diameter.
(2) Variation in rope construction.
(3) Variation of U.T.S. of the wire.
(4) Variation of the rope core.

**Variations in Pulley Diameter**

Owing to the wide divergence which had been discovered in the methods of calculating rope sizes, it was decided to carry out a limited research into the effect of varying pulley diameters on the life of the rope at various tensions, particularly to take advantage of the fact that in both catapults and arresting gear the ropes are not only loaded a comparatively small number of times, but they are rested between loadings. Failure was deemed to have taken place when six visible individual wires had broken.

The results are plotted on graph 1, the actual pulley diameter ratios used being :

22.3, 21, 19 and 17.

From the curve it will be seen that there is no appreciable loss in life until the pulley diameters are reduced below 19 diameter ratio. On the other hand, the decrease from 22.3 diameters to 19 reduced the polar inertia of the pulleys by rather more than 50%, thereby reducing the total equivalent weight of a catapult or arresting gear by about 20%.

*The mechanism of rope failure*

As would be expected, the mechanism of failure of a rope under repeated bending over pulleys differs from the normal direct tensile test. During the series of trials to find the optimum pulley diameter, it was found that the mechanism changed as the load on the rope was increased. At light loads, the wires broke at the crowns of the strands and showed typical fatigue failure. Fig. 5 shows the failures in the rope. At a certain load, however, the character of the failure suddenly altered, occurring on the gussets or gantlings of the

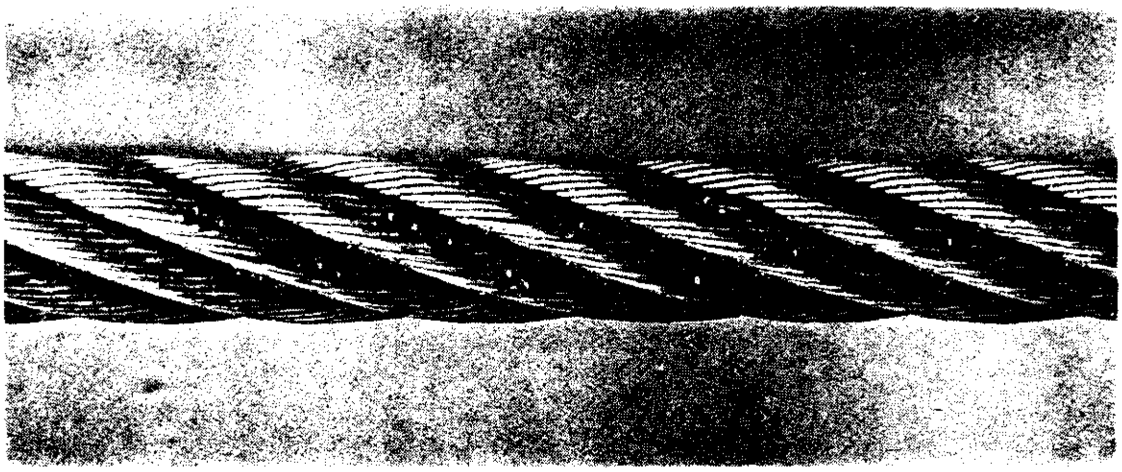


FIG. 5.—PHOTOGRAPH OF 6/37 ORDINARY LAY ROPE AFTER FAILURE IN ROPE TEST RIG. WIRES HAVE FAILED IN FATIGUE

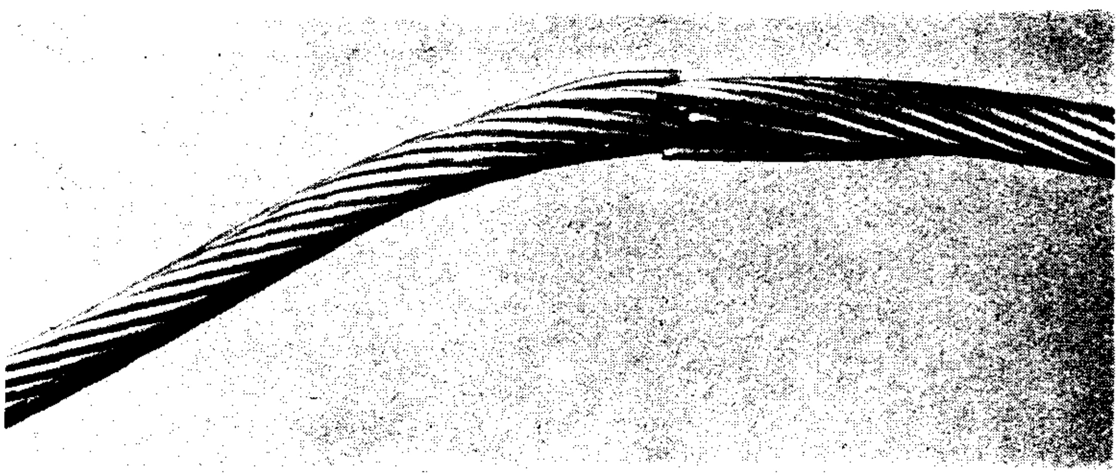


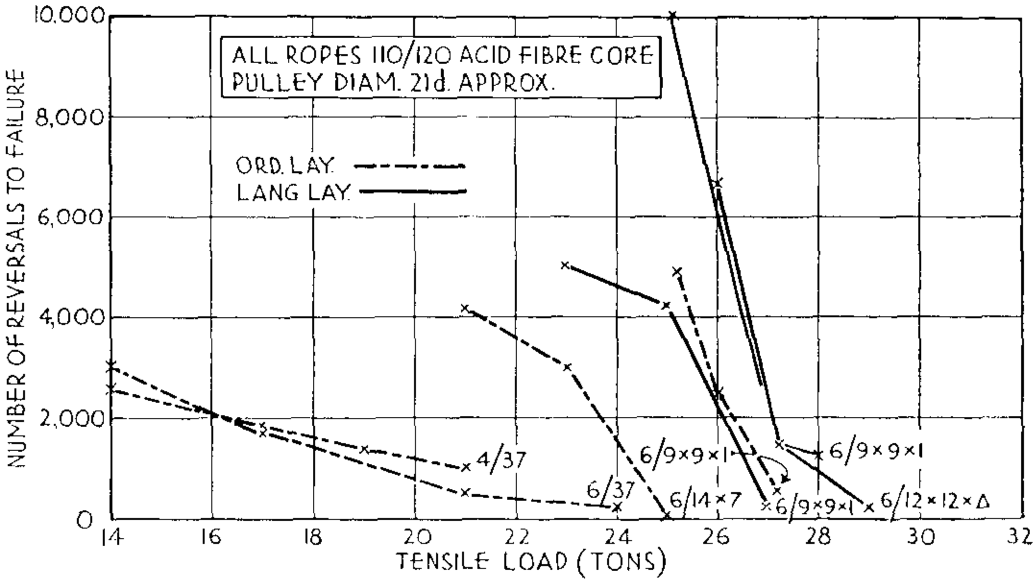
FIG. 6.—PHOTOGRAPH OF 6/37 ORDINARY LAY ROPE (ONE STRAND) SHOWING TYPICAL FAILURE DUE TO INTER-STRAND NICKING

ropes, *i.e.*, where the strands cross. In this case failure was due entirely to inter strand nicking, resulting in reduced area of cross section and failure in pure tension. Fig. 6 shows a typical failure of this sort. The inter-strand nicking occurs when the wire strands become " two-blocks " with each other under load and results in a marked increase in rate of change of life with load.

In a round strand, ordinary lay rope, when the individual wires in a strand touch their neighbours in the next strands they lie approximately at right angles to each other ; there is thus initially point contact between the wires through which the entire inter-strand compressive load must be taken.

## Variation in Rope Construction

The variations of rope construction on the market are many, some of which are more suitable for dynamic work than others. As a result of the first series of tests on the rope research rig, it appeared that certain forms of construction would probably be more suitable than any others, particularly with a view to avoiding inter-strand nicking, which reduces the safe working load of ordinary lay ropes to about one-third the plain tensile breaking load.




GRAPH. 2. VARIATION OF CONSTRUCTION

The results obtained were somewhat startling, as will be seen from Graph 2, on which the results of a number of tests with different rope construction have been plotted. From these it will be seen that the 6/37 construction, which has normally been used in both catapults and arresting gear, gave by far the worst results. As an example, a 6/12 × 12 × △ flattened strand Lang's lay rope can carry a tensile load of 27 tons for as long as a 6/37 ordinary lay rope can carry 16 tons. Looked at from the other point of view, for rope of similar strength and life, the 6/12 × 12 × △ flattened strand Lang's lay rope can be 40% lighter than the 6/37 ordinary lay.

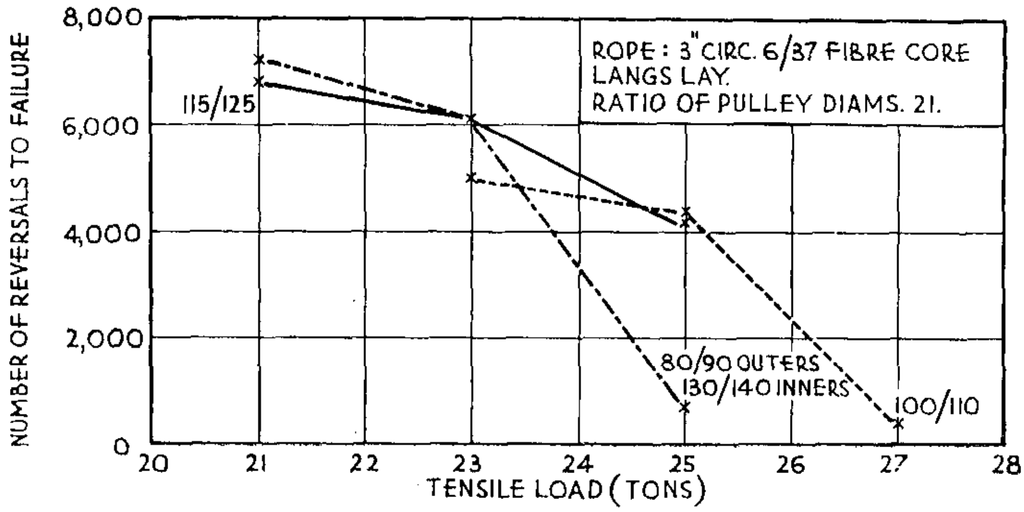
Up to this point, therefore, the results of pulley diameter and rope construction research between them have shown that the total inertia of the system could be reduced by $0.4 \times 53 + 0.5 \times 42 = 40\%$ approximately.

### Variation of U.T.S. of the Wire

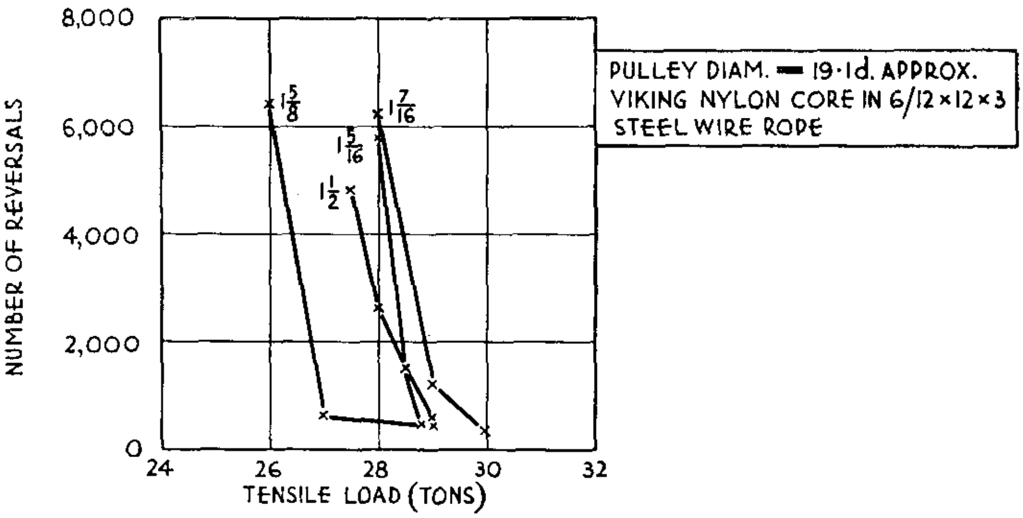
Progress of the research showed that two other variables warranted at least casual inspection, these being items (3) and (4) above. In particular, the rope manufacturers favoured (3).

Results of variation of the wire U.T.S. are shown on Graph 3, from which it will be seen that no benefit accrues from using wire with a U.T.S. in the range 115–125 tons/in.$^2$ when compared with one of 100–110 tons/in.$^2$ On the other hand, 115–125 tons/in.$^2$ U.T.S. wire costs twice as much as 100–110 tons/in.$^2$ U.T.S. wire and is also very much more difficult to make up into ropes, due to its lower ductility. The investigation of the reasons for the lack of improvement in life by using wire of higher U.T.S. is not complete and does not appear to follow from any logical argument ; it is probable that the decreased ductility and the changed grain structure are controlling factors.

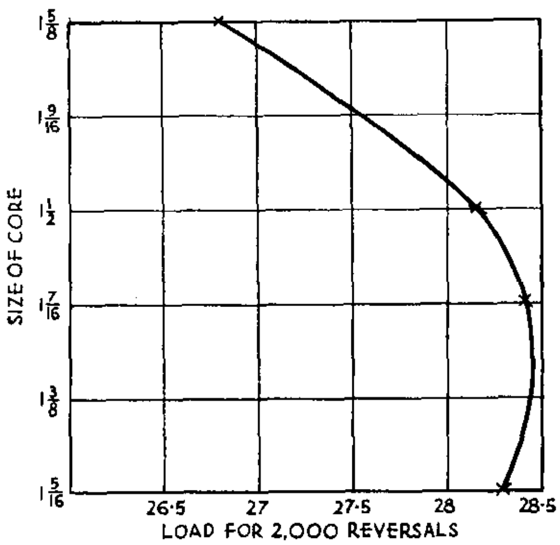
Included in Graph 3 are the results obtained with a composite 6/37 Lang's lay rope, in which the outer 18 wires of each strand were made from 80/90 U.T.S. material and the inner 18 wires from 130–140 U.T.S. material, *i.e.*, the standard breaking strength of the rope was the same as that obtained from a rope made from 110 U.T.S. material. These latter results do not indicate that any great advantages can be expected from this composite construction.



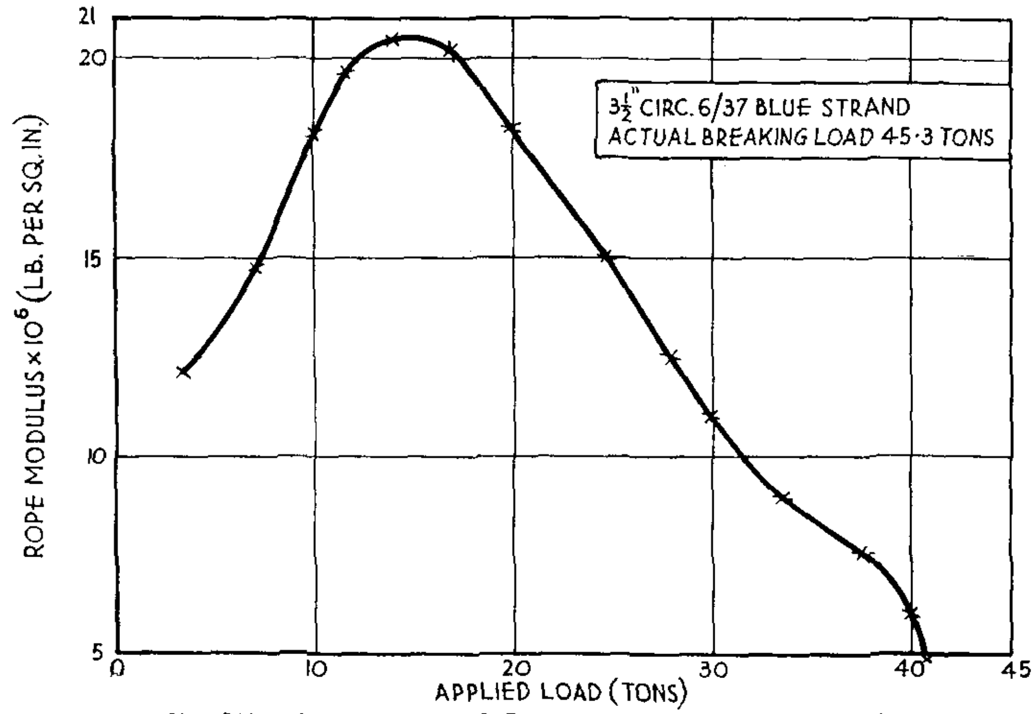

GRAPH. 3. VARIATION OF MATERIAL




GRAPH 4. VARIATION OF CORE SIZE




GRAPH 4A.




GRAPH 5. VARIATION OF MODULUS IN A WIRE ROPE

### Variation of the Rope Core

A study of the effect of varying the rope core diameter and material showed that there was very little information available. It appeared that, when selecting the size of a fibre core, a rule of thumb had been worked to which gave a core diameter of half the finished rope diameter plus $\frac{1}{8}$ in, hardly scientific, though probably good enough when factors of safety of 10 and over were called for by the Board of Trade and the insurance companies.

The results obtained from varying the size of the core are shown on Graph 4, from which Graph 4A has been deduced. From the latter it will be seen that when using 19 diam. pulleys, and requiring a life of 2,000 reversals with a $3\frac{1}{8}$ in circumference 6/25 flattened strand rope, the optimum size of core was $1\frac{3}{8}$ in circumference. Note : For this size of rope it had been the practice to use a core of $1\frac{5}{8}$ in circumference.

In order to obtain an accurately sized core for these experiments Nylon fibre was chosen, and it is quite probable that for really highly stressed ropes the use of this more expensive material is essential.

### The Value of Routine Tests

One of the results of this research has been to cause some doubt to be felt concerning the value of Admiralty and B.S.I. routine tests, which were designed to ensure correct manufacture of the rope. Both call for a completed rope to be subjected to a straight pull, in addition to tension, torsion and bending tests on the individual wires. These tests will not reveal any faults in core diameter, which may have a serious effect on the life of a rope loaded to its maximum possible extent. Only a fatigue test over pulleys will give any indication of how a given rope will behave in service.

### Rope Modulus

One point brought out by the research which was quite unexpected is that the usual formula given for the modulus of elasticity of the rope as a rope can be very misleading, particularly as the moduli usually quoted are the average obtained during the loading of a rope from no load to breaking. On this point, an investigation into the "spot modulus", or load/extension relationship, of a wire rope at various loads, has proved most illuminating. The result obtained varies considerably from the straight line, as is shown in Graph 5.

**Weight comparisons**

An interesting comparison is given by considering the relative weights of ropes designed according to the old methods and as a result of the investigations discussed in this article :—

| *Method* | *Specific Weight* |
|---|---|
| E.-in-C.... | 100 |
| D.N.C.* | 90 |
| U.S.N. ... | 75 |
| C.E.D./R.A.E.... | 60 |

What is much more startling, however, is that the reduction in specific weight shown possible by the C.E.D./R.A.E. experiments should bring about speed increases of 20–30% over those for which the arresting gears and catapults were originally designed.

**Conclusions**

Very little experimental evidence has hitherto been available to help in the selection of wire ropes for different purposes. For the extremely specialized service required in catapults and arresting gear the investigation has shown that, without departing from the manufacturers' standard ranges, it is possible safely to load certain types of rope to very much higher loads than has previously been allowed. The biggest gain is in using Lang's lay Seale construction. The use of flattened strand is also worth while, but only if applied to a Lang's lay rope. Flattened strand spreads the contact load from the single wire in round strand to 3 or 4. Since the work done in accelerating and stopping the ropes is all wasted, reductions in weight for the same strength are very much worth while. The investigations also indicate that the Service insistence on 115–125 tons/in.$^2$ U.T.S. wire is based on a false premise and that considerable expense could be saved, without in any way lessening the life of the rope, by using 100–110 tons/in.$^2$ U.T.S. wire.

It may reasonably be asked why, if such startling results have been obtained without any very extensive equipment, this work has not been done years ago by the rope makers themselves. This is not due to any lack of zeal on their part, but simply due to the fact that, for commercial purposes, the major requirement is a rope with a long life, the weight and inertia being, in general, quite unimportant. For Service use in flight deck machinery we are prepared to accept a very short life by commercial standards in order to reduce the, to us, all important effects of inertia.

**Other Wire Rope Developments**

Whilst the major effort in wire rope research has been directed to the rope itself, attention has also been given to different methods of joining the ends of wires to fittings other than by the traditional splice.

Splices, although proved by many years use, are not the ideal method of joining ropes, partly because they are not easy to make, but chiefly because they cannot develop the full strength of the rope, which therefore has to be

* The rope used by D.N.C. would not have the life of the other three designs at the same load.

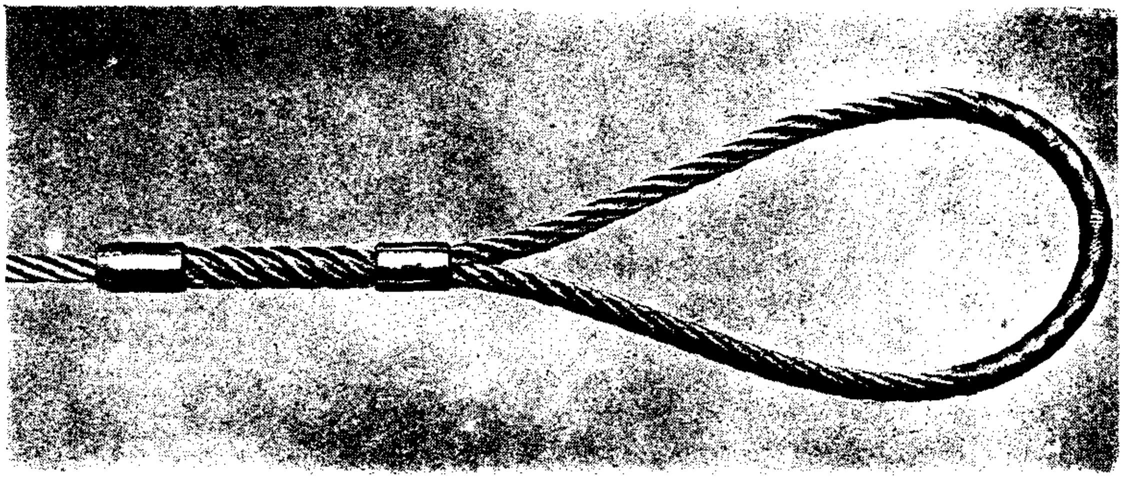


FIG. 7.—FORMED EYE IN 2⅞ INCH 7/37 WIRE ROPE

bigger than it otherwise need be, simply because of the splice at the end. There is also the unpredictable human factor in the making of the splice, a matter of great importance in aircraft work.

A method of attaching fittings to a rope is by swaging, a process only 20 years old but much used in the aircraft and motor industries. Here a sleeve is slid over the wire and cold forged down onto it until it grips firmly. Swaging is done in machines which have rotary jaws which pass over rollers as they rotate, to give a forging action to the fitting held between the jaws. When completed, the swaged sleeve is pressed well into the interstices of the rope and can easily be made to develop the full strength of the rope. The disadvantages are :—

(1) Due to the locked up stresses in the swaged sleeve, it cannot be threaded with confidence after manufacture.

(2) The swaging machine is essentially a power instrument unsuitable for installation on board ship.

(3) The process is most suited to quantity production, as different dies are required for each size of sleeve.

(4) The size of rope on to which swaged fittings can be forged is at present limited to 3½ in circumference, as machines capable of swaging larger sizes do not exist and would be very expensive to make.

Despite these disadvantages, swaging is likely to come into considerable use for such gear as is normally supplied in complete form, *e.g.*, hold backs, launching bridles, etc.

**Unconventional Eye Splices**

There is clearly room for a new method of forming eyes in wire ropes, which does away with the bulky and inefficient splice.

A method which has recently been invented (British Patent No. 602948) does away with the splice by having the wire strands wound round the standing part of the rope, being secured top and bottom by ferrules which are cold forged into the wires and grip them. This eye can be made to develop 100% of the breaking load of the rope with considerable certainty, and, once the technique of preparation has been determined, can be attempted without skilled labour. A portable machine, suitable for use on board ship, is being developed for use with these ferrules.

Fig. 7 shows a detailed view of the form of the splice.