THE SPRING RESEARCH ASSOCIATION

THE PRODUCTION OF SPRING FATIGUE DATA WITH STATISTICAL LEVELS OF CONFIDENCE

Parts 1 of 7 parts
INTRODUCTION AND METHODS OF TESTING

by

G. C. Bird, B.Sc.

Report No. 223

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STRUCTURE OF REPORT

The report is issued in seven parts, each dealing with a separate aspect of the research and its application in design.

Part 1 of the report describes the programme of work and the methods of producing and analysing the fatigue data.

Parts 2 to 5 of the report cover the results obtained from testing of the separate materials, viz:

Part 2	Patented cold drawn spring steel wire to BS 1408
Part 3	Oil hardened and tempered spring wire to BS 2803
Part 4	Annealed steel wire for oil hardened and tempered springs to BS 1429 (En 47)
Part 5	Austenitic stainless steel wire to BS 2056

Part 6 discusses the influence of the various parameters on the results obtained and the difficulties encountered in the research programme.

Part 7 is a design booklet containing Goodman Diagrams of all the materials tested with sufficiently high confidence levels to enable them to be used for all design applications without employing an additional safety factor.

CONTENTS

CONTENTS (Cont.)

Page Number

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INTRODUCTION AND METHODS OF TESTING

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1. INTRODUCTION

In 1969 the Spring Research Association, in conjunction with the Department of Trade and Industry, undertook an extensive programme of work whose aim was the production of spring fatigue data with statistical levels of confidence which could be disseminated to the engineering industry in the form of design data.

The work of the project was concerned with the production of Goodman type fatigue diagrams for the eleven B.S. materials listed in section 3. Each material was tested in both the unpeened and shot-peened condition, in a single wire size. Sufficient springs were tested at a selection of initial and maximum stresses to provide statistical confidence at stated levels in the data which entailed the use of approximately 1000 springs to produce each Goodman diagram. To ensure that the results of the work were representative of what could be expected from springs produced under normal industrial conditions, the tests were carried out on springs made by four manufacturers.

2. GOODMAN DIAGRAMS

An example of a typical Goodman diagram for unpeened and shot peened compression springs of one particular material is shown in Fig. 1. A Goodman diagram is a graphical representation of fatigue data in which the maximum working stress is plotted against the initial working stress for any given life.

The highest maximum stress is the solid stress of the spring design and is limited by the tensile strength of the material used: this is indicated by a horizontal line drawn on the diagram at this stress. The lower line on the diagram, drawn at 45 degrees when the scales are equal, represents the initial stress, and the upper line represents the maximum working stress of the spring. The usefulness of the diagram is that it can be used directly as a guide to spring design under fatigue conditions. For example, if the minimum and maximum design stresses, when plotted on the appropriate Goodman diagram, fall within the enclosed area of safe stress range, the spring will not fail before the stated life span as a result of fatigue stressing.

The first step in the process of producing a Goodman diagram is to fatigue test springs at a fixed initial stress and different maximum stresses and from the data obtained, to plot a graph of maximum corrected torsional stress against cycles to failure, which is called an 'S/N curve'. The cycles to failure are usually plotted on a logarithmic scale. Figs. 2 and 3 show typical S/N curves for initial stresses of 100 N/mm^2 and 300 N/mm^2 respectively. On each diagram it can be noted that there is a maximum stress below which failure never occurs irrespective of how often the fatigue cycle is repeated. This stress is known as the 'fatigue limit' of the spring for that particular initial stress. For example, in Fig. 2 the fatigue limit is 700 N/mm^2 for the initial stress of 100 N/mm^2. For maximum stresses higher than the fatigue limit, the life of the spring is reduced. The fatigue limit of a spring is dependent on such factors as the specification of the material from which the spring is made, its design and whether or not it has been shot-peened.

By testing springs of the same material and design with two or three different initial stresses, separate S/N curves can be drawn and the fatigue limit found for each. To produce a Goodman diagram for infinite life (regarded as 10^7 cycles for this work) the fatigue limit is plotted as the maximum stress on a graph, against the initial stress.

It has been shown that the line representing the maximum safe stress is straight for practical purposes and can be drawn as such through two or three experimental points.

Fig. 4 shows the Goodman diagram produced from the two S/N curves in Figs. 1 and 2. Goodman diagrams can also be drawn for a finite life span by finding the fatigue strength on the S/N curves at any particular life and plotting these against the initial stress as previously. Fig. 5 shows a Goodman diagram for a life of 10^6 cycles produced from the S/N curves in Figs. 2 and 3.

The sloping lines on the S/N curves shown in Figs. 2 and 3 are the 'best-fit' lines through the points on the graphs. These usually represent a 50% confidence limit obtained by a regression calculation of the 'least-squares' method. That is to say that if a batch of springs were to be tested between 100 N/mm^2 minimum stress and 800 N/mm^2 maximum stress, half would have broken at the life indicated on the S/N curve, 10^6 cycles. In spring design, this failure rate would be unacceptable and usually the maximum stresses shown on the Goodman diagram would be reduced by an estimated safety factor.

The object of this research programme was the provision of more accurate fatigue design data for the engineering industry by determining and quoting statistical confidence limits on the S/N curves and Goodman diagrams to be produced. By testing 500 springs at different initial and maximum stresses, confidence limits of 90, 95 and 99% can be placed on the data produced. On the Goodman diagram the 99% confidence level represents the maximum fatigue stress for which less than one spring in 100 would have a fatigue life less than stated.

3. MATERIALS, SPRING DESIGN AND MANUFACTURE

The following eleven materials were tested.

BS 1408C Ranges 1, 2 and 3	(Part 2)
BS 1408D Ranges 1, 2 and 3	(Part 2)
BS 2803 Grades I and II	(Part 3)
BS 1429 (En 47) Grade 1	(Part 4)
BS 2056 (En 58A)	(Part 5)
BS 2056 (En 58J)	(Part 5)

One basic design was used throughout the research programme. The wire size chosen, 4mm, lies in the middle of the range of wire sizes commonly used by the engineering industry. The number of coils in the spring was adjusted to allow for the differences in the modulii of elasticity of carbon steel and stainless steel. The spring design used is shown in Table 1.

Each manufacturer supplied 500 springs of each material. After coiling, the springs were given a heat treatment, which varied according to the material as shown below:-

BS 1408 - 350°C for 30 minutes for stress relieving only
BS 2803 - 400°C for 30 minutes for stress relieving only
BS 1429 - Hardened and tempered to 500/550 HV
BS 2056 - 450°C for 2 hours for stress relieving only

Half the springs produced were subsequently shot peened in the manufacturers own plant and then given a low temperature heat treatment of 220°C for half an hour.

All the springs were fully prestressed by the manufacturer and had closed and ground ends.

4. FATIGUE TESTING MACHINES

4.1 Machine used to produce finite life data

The machine used for the production of the finite life fatigue data, that is the sloping portion of the S/N curve, was designed and built by the Association for this programme of work and is capable of testing 142 springs simultaneously with the same stroke.

The machine, illustrated in Fig. 6, is a resonance machine and the principle of operation is shown in Fig. 7.

As can be seen, there are four sets of transverse beams, the outer pair of each set being connected to the main frame of the machine by two longitudinal shafts. The inner beams of each set are connected to one another by another pair of longitudinal shafts which are supported at each end in a linear bearing and retained by a heavy compression spring. These inner beams are driven from a 5 h.p. motor via a variable speed drive through an eccentric and a clutch.

The springs to be fatigue tested are loaded between opposite faces of the beams as shown in Fig. 6. The stroke of the machine can be adjusted with the eccentric, and the springs are set to the correct length by adjusting the outer beams of each set. When the machine is fully loaded, the speed is altered until the beams are running at their resonant frequency and the clutch is then tightened. With the design of spring used the resonant frequency was approximately 25 Hz but as the spring fail and fall out of the machine the speed has to be reduced to keep the machine running close to its resonant frequency.

4.2 Machine used to produce infinite life data

The machine described in section 4.1 could not be used to produce the infinite life data required because of the long time required to reach 10 million cycles. The data was therefore obtained using the Association's three existing 'forced motion' testing machines (Fig. 8) running at 25 and 50 Hz, each machine capable of testing four pairs of springs simultaneously. The springs were mounted about a central camshaft carrying four cams each adjustable in stroke from zero to one inch. Each spring mounting could be adjusted to suit the maximum length and hence the initial stress of the spring. The stroke and hence maximum stress was determined by the cam setting. Spring failure was detected by a microswitch actuated by the spring which stopped a cycle counter.

5. PRODUCTION OF FATIGUE DATA

5.1 Finite life data

The finite life fatigue data was produced on the fatigue machine described in section 4.1 and the programme of work was devised around springs which were all designed to have the same spring rate and free height. However, some manufacturers found that it was not possible to achieve the high solid stress required and the S.R.A. had to accept the maximum they could achieve without distortion. This resulted in variations in the free lengths of the springs; and differences in rate and outside diameter also occurred between manufacturers.

It was intended to load the springs straight into the machine and adjust the outer beams until the load on all the springs was equivalent to the mean testing stress. The moving beam would then be loaded equally on either side and when the stroke was set and the machine started the spring would be tested under a varying load such that when one side was at maximum stress the springs on the opposite side would be at minimum stress.

The differences in rate and diameter meant that when the springs were tested as described above, although all having the same mean stress and deflection, the minimum and maximum stresses differed from spring to spring. It was found necessary to adjust the heights of the springs in the machine by placing shims underneath so that when tested they all had the same minimum stress but different maximum stresses. The heights for the minimum and maximum stresses were determined by load testing each spring beforehand, as laid down in BS 1726. This method took longer than the original procedure but had the advantage that all the broken springs from one test could be placed on a single S/N curve which enabled a more accurate analysis of the results to be obtained.

5.2 Production of Infinite Life Data

Each spring was load tested according to the method laid down in BS 1726 to determine the heights at the minimum and maximum testing stresses prior to fatigue testing. The springs were tested with initial stresses of 100 N/mm^2, 300 N/mm^2 and for some materials 500 N/mm^2 to differing maximum stresses in order to obtain the fatigue limits.

5.3 Dynamic Relaxation

Springs which had not broken by 10^7 (10 million) cycles in the infinite life testing were removed and were again load tested at the original minimum compressed height.

Any dynamic relaxation which had occured could then be calculated as shown below and taken into consideration in the design data quoted in part 7 of this report.

The relaxation was calculated as the percentage loss in load at a constant length.

If P_1 is original load at length L_1

and P_2 is final load at length L_1

$$\text{Then, Percentage Relaxation} = \frac{P_1 - P_2}{P_1} \times 100$$

6. ANALYSIS OF DATA

6.1 Finite Life Data

The distribution of fatigue failures of springs tested between two stress levels was found not to be a Gaussian distribution. This meant that a confidence limit of 99.9% could not be determined and the method of analysis described below had to be used.

With the revised method of testing adopted, all the broken springs from tests at one initial stress value could be plotted on a single S/N curve. In practice, two different machine strokes, as far apart as possible, were used to produce an S/N curve of the form shown in Fig. 9.

Three confidence lines were drawn on the S/N curve such that for each test 10%, 5% and 1% of the springs tested lay to the left of the line, producing the 90%, 95% and 99% confidence limits respectively. Because of the variation in rate and hence maximum stress in each test, it was found necessary to break about half of the springs to ensure that those not so highly stressed had an opportunity to fail and be included on the S/N curve.

The highest confidence limit that can be produced by this method of analysis is the 99% level since this represents between two and three springs having broken out of the 284 tested. The accuracy of drawing the confidence limits depends on the scatter of the fatigue failures and is worst at the highest confidence limit; it is, however, possible to produce Goodman diagrams to an accuracy of approximately ± 10 N/mm^2. Since the highest confidence limit attainable depends on the number of springs tested at one stress level, for the 99.9% confidence level (that is one spring broken in 1000) ten times as many springs as for the 99% level would be needed to be tested to obtain a Goodman diagram.

The Goodman diagram for 10^5 cycles was determined from the confidence limits on the S/N curves by the method described in section 3. To obtain the Goodman diagram for 10^6 cycles, the confidence limits in some instances had to be extrapolated below the range of testing stresses, as shown in Fig. 10, to meet the fatigue limit before the 10^6 cycles ordinate. In such cases the Goodman diagram for infinite life applied to both 10^6 cycles and 10^7 cycles.

For certain materials, particularly in the shot peened condition, springs did not break before 10^5 cycles. Therefore the Goodman diagram for this life had to be obtained by extending the confidence limits above the maximum testing stress. In some instances (as shown in Fig. 10) the stress at which the confidence lines crossed the 10^5 life lay above the solid stress of the spring. Therefore no points on the Goodman diagram could be obtained at this initial stress with this particular spring design. However, it is reasonable to draw a line through the maximum testing stress of the spring at this initial stress, indicating that it is safe to operate through this stress range without failure through fatigue before 10^5 cycles.

6.2 Infinite Life Analysis

In this report, dealing with helical compression springs, the fatigue limit for infinite life is taken as the maximum stress with springs surviving a life of 10^7 (10 million) cycles. To obtain this life with the machines used, a testing duration of 5 days was required, which restricted the number of springs that could be tested to obtain the fatigue limit. Because of this and the differences between springs of the same material but from different suppliers, again none of the standard statistical methods of determining the fatigue limit could be adopted.

The method adopted to obtain the fatigue limit was to treat each supplier separately and to determine the fatigue limit of each within $\pm$ 10 N/mm^2; the fatigue limit being determined by all of five springs surviving 10^7 cycles. This was done at two or three initial stresses so that a Goodman Diagram for 10^7 life could be drawn for each supplier and the differences between suppliers for finite and infinite life could be compared. The lowest fatigue limit of the four suppliers was quoted as the 95% confidence limit since it represented all of twenty springs (five from each of the four suppliers) surviving at 10^7 cycles. Thus it is better than 95% confidence although it is impossible to place an exact statistical level, and on the Goodman diagrams for infinite life only these 95% confidence limits are given.

7. PRODUCTION OF MATERIALS DATA

An additional investigation was carried out in an attempt to discover the causes of the variation in fatigue properties between suppliers. This involved studying springs from each supplier for each material.

The average rate, solid stress and outside diameter of springs from each batch had been calculated from the load testing carried out prior to fatigue testing.

Samples of the wire used in coiling the springs were not always received from the suppliers as had been requested, but where samples were available the tensile strengths were determined and compared with the specification for the material. In all cases the hardness of sample springs was determined and tensile strength estimated from this figure.

The microstructure of the material was studied from a mounted specimen from each supplier, the grain structures compared and the decarburisation checked. Where points of especial interest arose, photomicrographs were taken and are included in the appropriate part of the report.

In addition, a chemical analysis of each material was carried out on the major alloying elements having a direct effect on fatigue performance to determine whether the composition fell within the specification for the material.

8. GENERAL DISCUSSION

The difficulties encountered in the mass fatigue testing stemmed mainly from the lack of dimensional uniformity between springs from the four suppliers. The fatigue testing machine was designed on the understanding that there would only be a small variation in the free length and rate of springs from different suppliers and a great deal of energy was expended before the revised testing method described previously was adopted.

This variation in spring parameters had two effects. Firstly, springs which had a smaller free height generally had a smaller maximum deflection. The maximum stress to which the springs could be tested was limited by the maximum deflection of the shortest spring, which could have a solid stress up to 150 N/mm^2 below that of the other three batches. That was the reason why sometimes not many springs could be broken at the higher initial stress. Secondly, when springs which had a lower rate were tested with the other batches, they were stressed to a lower maximum stress and consequently did not break as soon as the others. To ensure that these springs had a chance to break and be included on the S/N curves, testing was continued until about half the springs on each test had broken. The maximum practical life to which springs could be tested on the mass fatigue testing machine, as opposed to the individual testing machines, was about 3 million cycles which took about five days to achieve. Beyond this life the times at which the machine was inspected for spring failures, on a uniform logarithmic scale, became only twice a day. Even at this life, there were occasions when very few out of the 144 springs had broken.

This lowering of the maximum testing stress was particularly noticeable on the shot-peened springs where the fatigue limit at an initial stress of 300 N/mm^2 was only slightly lower than the maximum testing stress. This made it difficult to obtain two testing levels far enough apart at which the springs would break quickly. With some materials springs could not be broken before 200 000 cycles and the Goodman diagrams with confidence limits for 10^5 life were not obtained.

The variation in the solid stress of the springs, which for some materials was as much as 20%, had a noticeable effect on the fatigue strength of the springs. Those springs which had a higher solid stress than others of the same material would have received a greater amount of prestressing during manufacture and would have a more beneficial residual stress pattern. When the load is applied to the spring, the actual stress at the inner surface of the wire is less for springs which have received more prestressing and consequently the fatigue life would be expected to be greater. The residual stress pattern after prestressing is also affected by the torsional properties of the wire, the heat treatment it has received and any compressive stress induced by shot-peening.

The variation in the fatigue resistance of springs from different suppliers could be substantially affected by the quality of the wire. This had been obtained independently by each manufacturer and would not be expected to come from the same source.

Previous work has indicated that the range of 10 tonf/in^2 (155 N/mm^2) permitted in the tensile specification could alter the fatigue limit by 20 N/mm^2.

For the shot-peened springs the most important variable is the peening process the spring has received, for the effectiveness of the process varies from plant to plant and is not easily measurable, even in terms of Almen arc rise. It would be expected that differences between manufacturers caused by the shot-peening plant would remain constant through all the materials, and in general this was borne out by the results.

The other important factor with regard to shot-peened springs is the low-temperature heat treatment carried out after shot-peening. If this is not correctly carried out the springs may relax under fatigue loading.

TABLE 1

SPRING DESIGN

WIRE DIAMETER	4 mm	0.157 in
MEAN COIL DIAMETER	30 mm	1.181 in
SPRING INDEX	7.5	
TOTAL NO. OF COILS	5.5 (5.1)*	
ACTIVE NO. OF COILS	3.5 (3.1)*	
FREE LENGTH (AFTER PRESTRESSING)	50 mm	1.969 in
SPRING RATE	27 N/mm	154 lbf/in
SOLID STRESS	1140 N/mm^2	164 000 lbf/in^2

* Figures in brackets apply to stainless steel springs to BS 2056, En 58A and 58J.

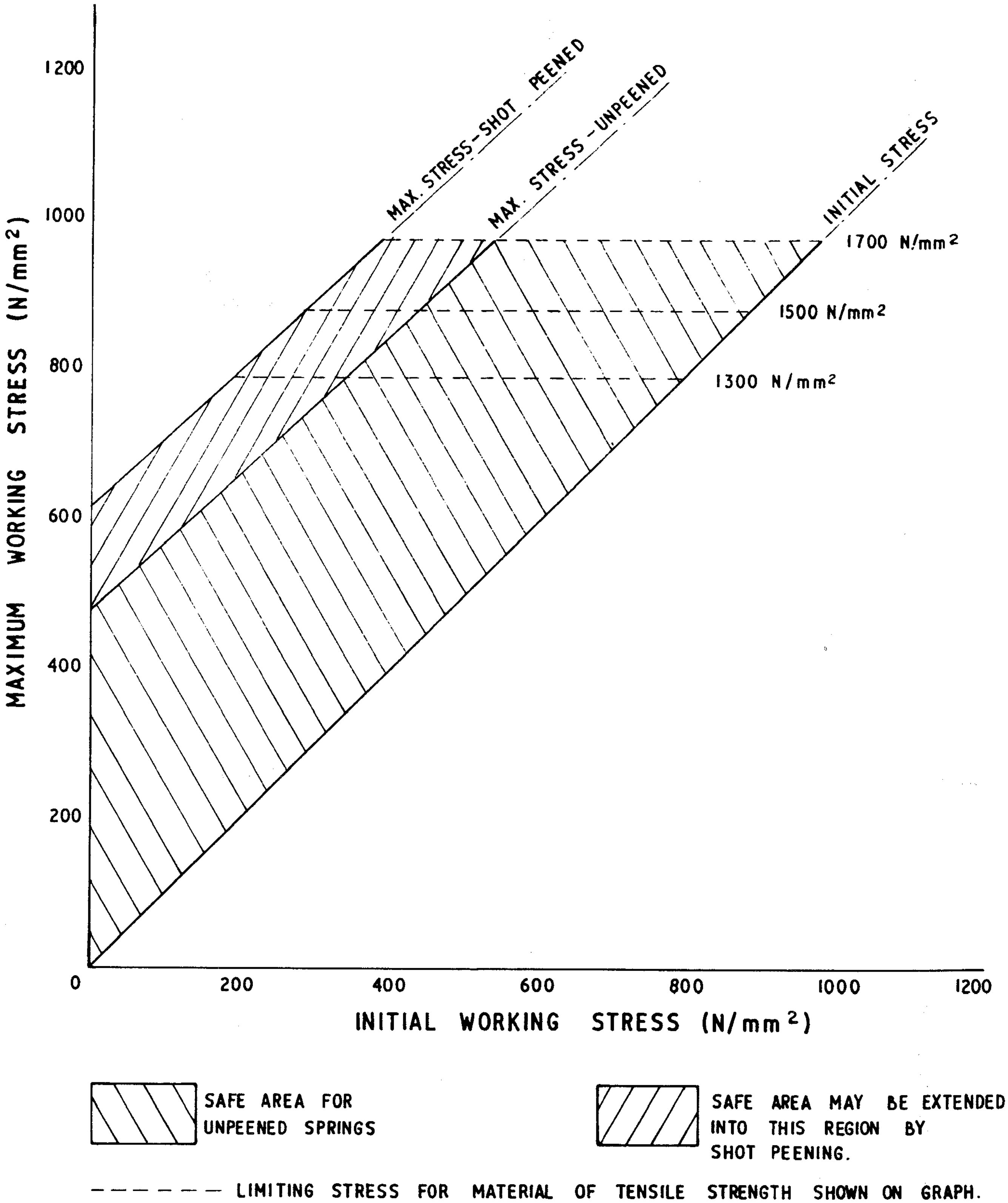

FIG. 1. TYPICAL GOODMAN DIAGRAM.

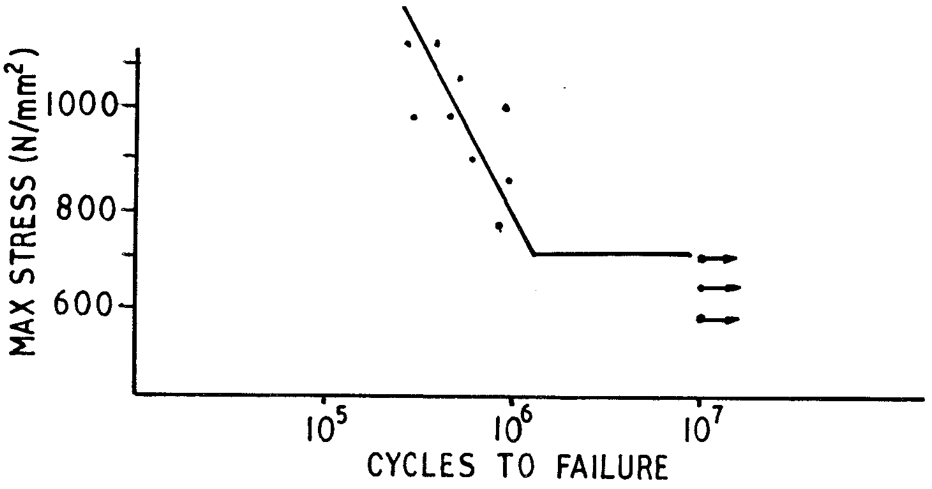

FIG.2 S/N CURVE FOR INITIAL STRESS OF 100 N/mm^2

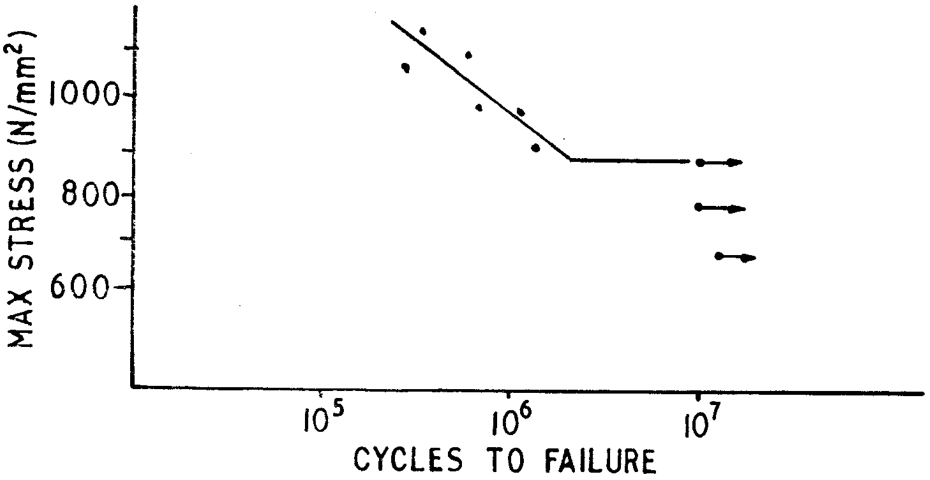

FIG.3 S/N CURVE FOR INITIAL STRESS OF 300 N/mm^2

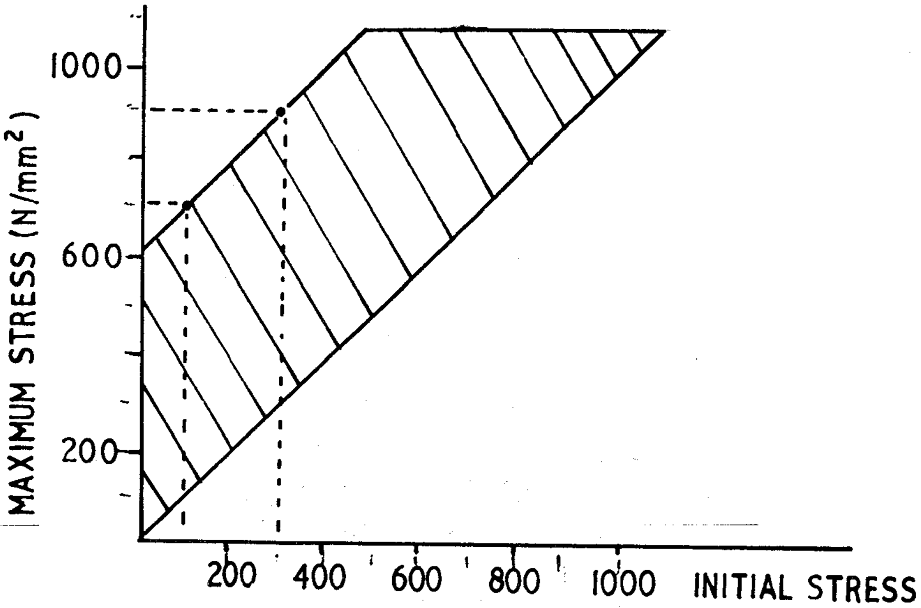

FIG.4 GOODMAN DIAGRAM FOR LIFE OF 10^7 CYCLES

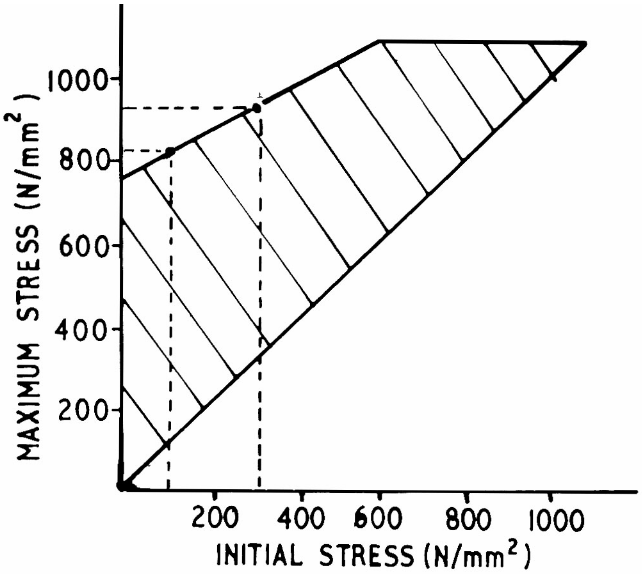

FIG. 5 GOODMAN DIAGRAM FOR LIFE OF 10^6 CYCLES

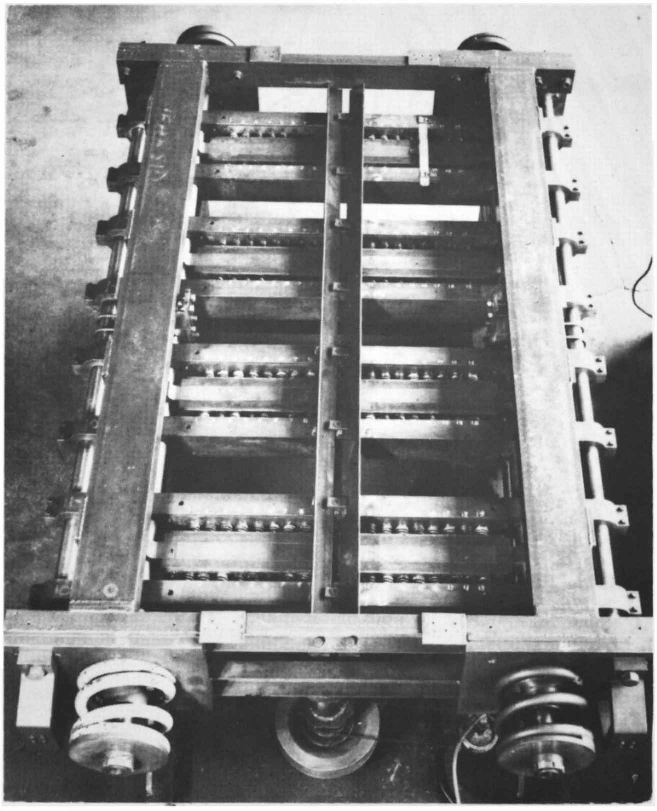

FIG. 6 FINITE LIFE FATIGUE TESTING MACHINE

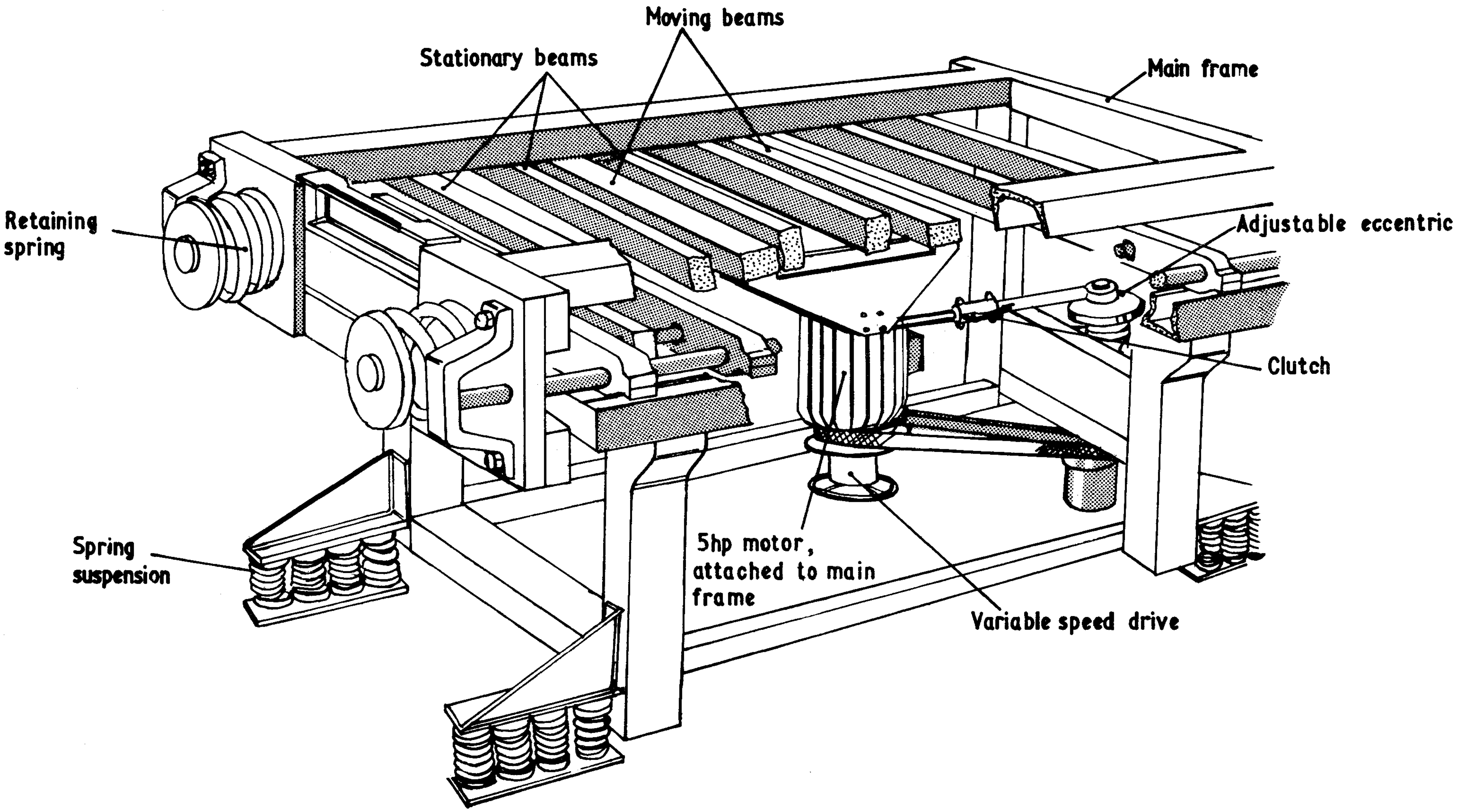

FIG. 7 CUT-AWAY VIEW OF MACHINE USED TO PRODUCE FINITE LIFE DATA

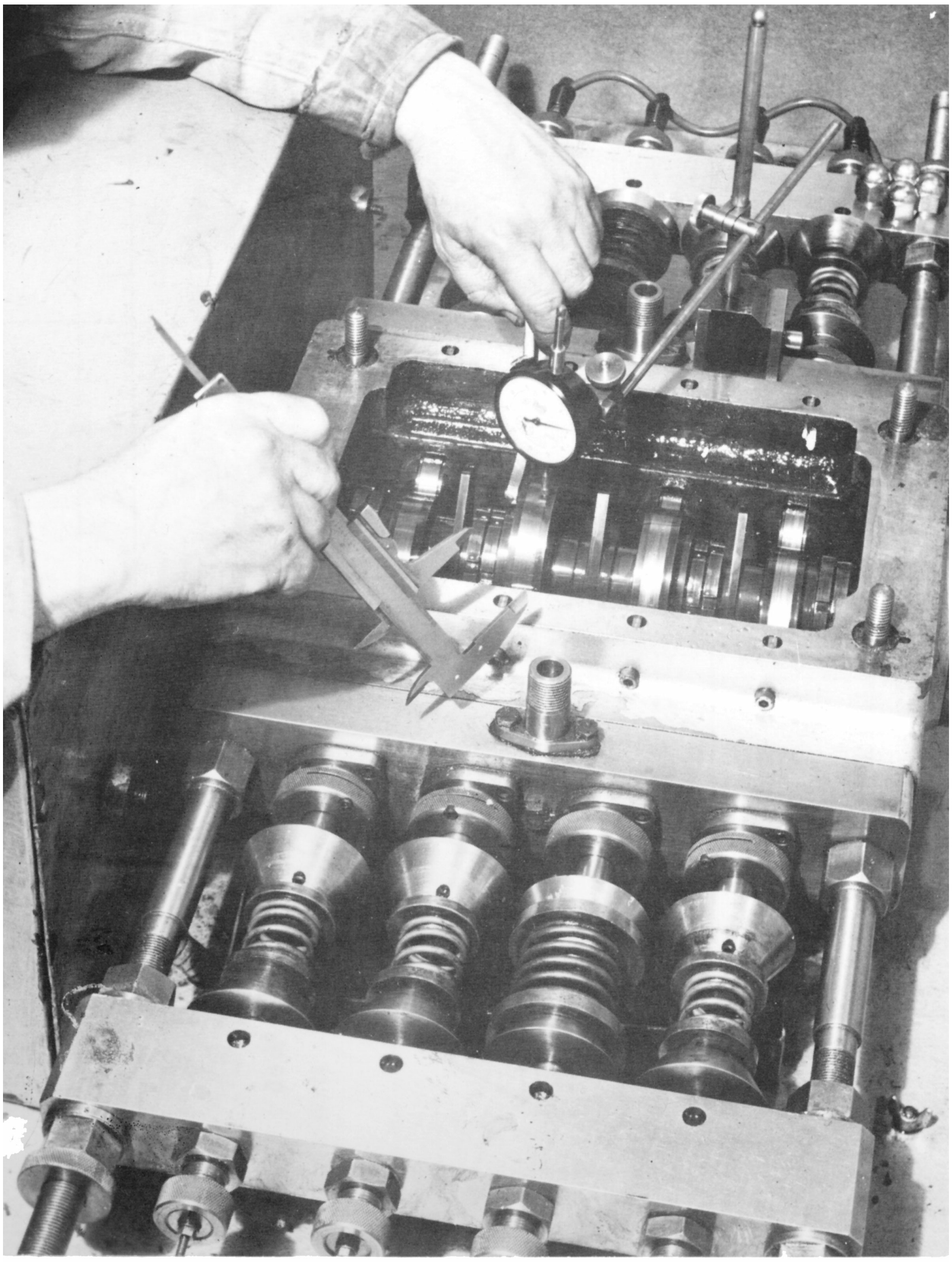

FIG. 8 'FORCED-MOTION' FATIGUE TESTING MACHINE USED TO PRODUCE INFINITE LIFE DATA

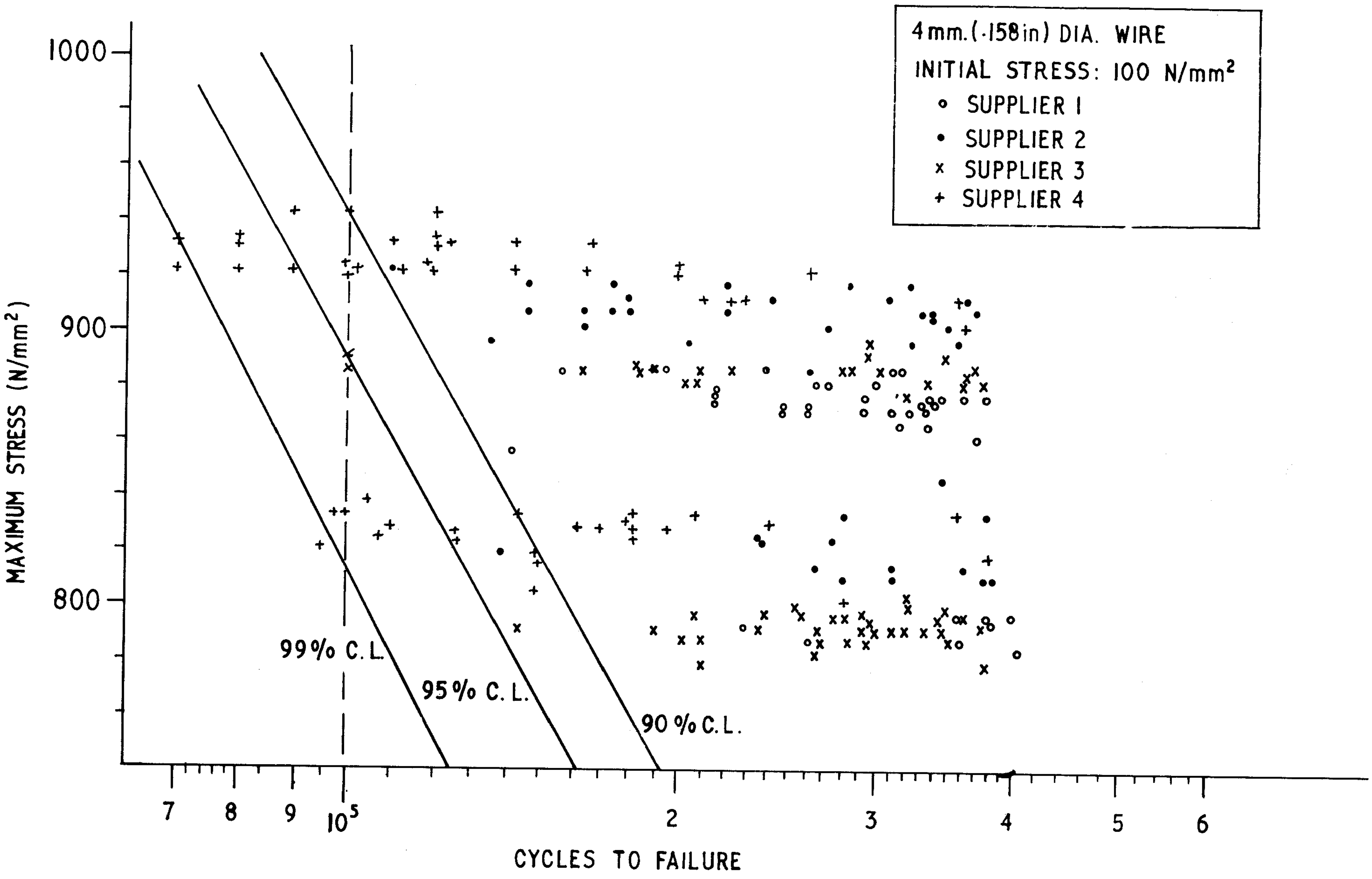

FIG. 9 S/N CURVE WITH CONFIDENCE LIMITS

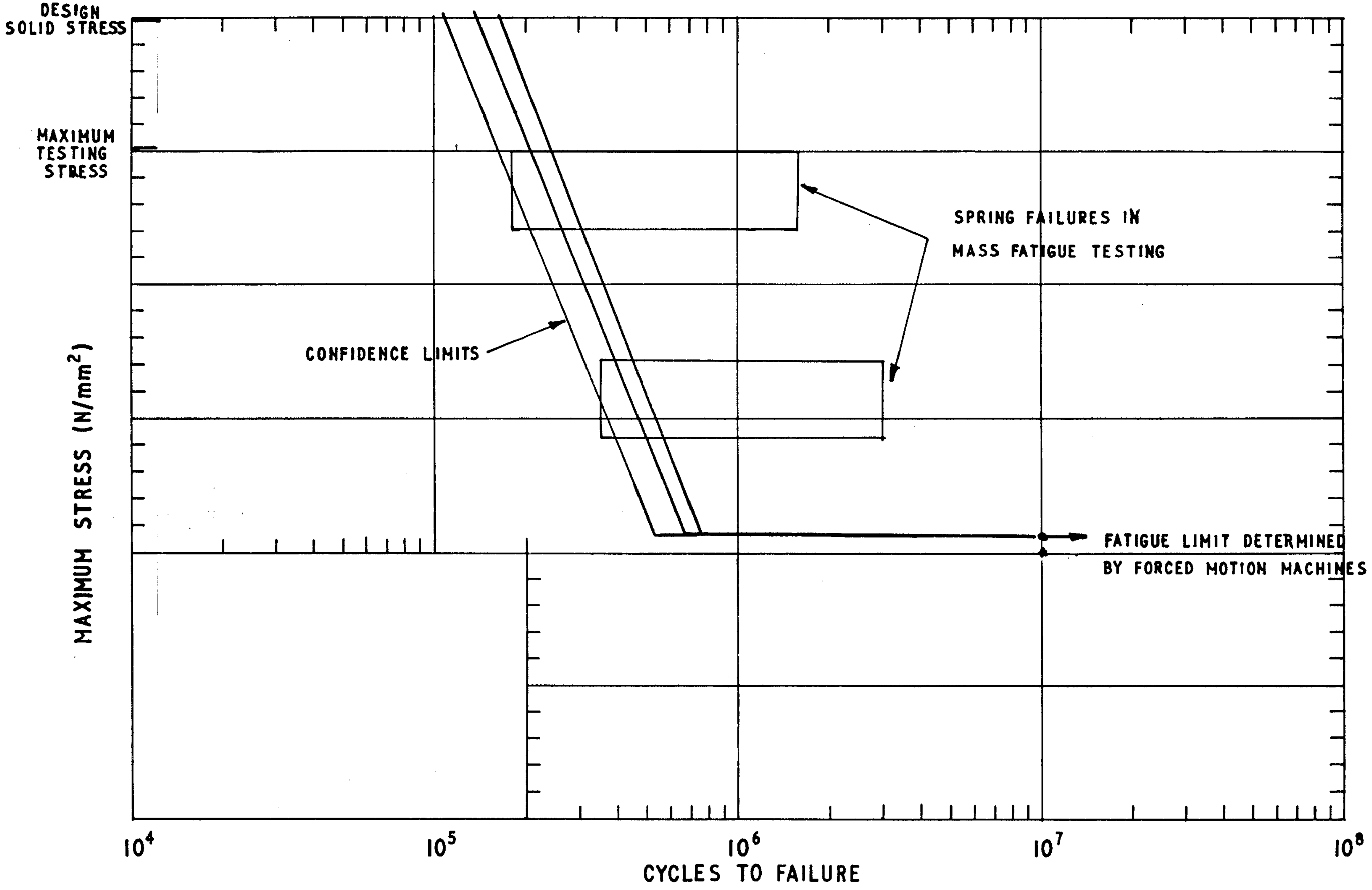

FIG. 10 S/N CURVE OBTAINED FROM MASS FATIGUE TESTING