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FATIGUE LIFE ESTIMATION AND MATERIAL EVALUATION PROCEDURES
FOR STRUCTURAL COMPONENTS SUBJECTED TO VARIABLE AMPLITUDE LOADING

by

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Royal Aircraft Establishment

September 1973

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Thesis submitted to The City University for the degree of Doctor of Philosophy

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SUMMARY

Specimens which represent structural features have been tested under Gaussian narrow band random fatigue loading and an experimental study has been made of the local stresses at stress concentrations under prescribed sequences of variable amplitude loading. From the results of these tests and from relevant results obtained by other authors, the design of structural components subjected to variable amplitude loading is discussed in the context of fatigue life prediction and material evaluation. The thesis is divided into four parts.

In Part 1, factors which influence the validity for service conditions of cumulative damage calculations by the Palmgren-Miner hypothesis are discussed. The term 'elastic interaction' is introduced to cover various interrelated sources of inaccuracy in damage calculations for plain specimens. In specimens containing geometric stress concentrations, particularly in tests with a static mean stress, the local plastic deformation introduces a 'geometric residual stress' effect which is superposed on the effects visible in plain specimens, so that the influence of elastic interaction can be deduced when the geometric residual stresses are separately accounted for. The development of geometric residual stresses is investigated in tests on pinned-lug and notched specimens subjected to 'quasi-static' and continuous random fatigue loading. Palmgren-Miner estimates of endurance, from which the influence of geometric residual stresses has been eliminated - by linear strain approximations combined with use of the alternating/mean stress diagrams for the materials concerned - reveal a distinction between the elastic interaction which occurs in the crack initiation phase (Stage 1 of fatigue) and that which occurs in crack propagation (Stage 2). For a wide range of service-type loadings, elastic interaction in

Stage 1 is found to lead to values of $\sum \frac{n}{N}$ between about 0.2 and 0.6, whereas in Stage 2 elastic interaction generally leads to values between about 0.8 and 2. Thus, if under service conditions the problems of Stage 1 and Stage 2 fatigue are treated separately, the range of values for $\sum \frac{n}{N}$ is narrowed sufficiently for a meaningful application to material evaluation and design.

On the basis of this research, suggestions are made in Parts 2 and 3 for improvements to the procedures used in material evaluation and the prediction, Part 4 gives independently an appraisal of the research which must be done to evaluate the structural fatigue performance of carbon fibre reinforced plastics.

Relevant reports prepared by the author at various stages in the evolution of the thesis, are reproduced (in order of preparation) in Appendices A to G as part of the work submitted.

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PART 1

INVESTIGATION OF FACTORS WHICH INFLUENCE THE VALIDITY FOR
SERVICE CONDITIONS OF THE PALMGREN-MINER HYPOTHESIS

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1.1 INTRODUCTION

For the purposes of material evaluation and fatigue life prediction structures may be considered to consist of two basic elements:-

(a) Components manufactured from extrusion, plate or forgings, where the design problem generally relates to the prediction of a 'safe life' or a 'time to first detectable crack', and

(b) Panels manufactured from sheet material, where the designer is concerned with crack propagation rates for cracks of up to about 1 m in length¹. (A raised number in the text refers to the list of references given at the end of each part of the thesis.)

We are concerned here with the important case (a), that of structural components, where conventionally the starting point in fatigue life prediction is the constant amplitude S-N curve, which relates stress amplitude, S , to endurance, N .

If the component suffers various stress levels, $S_1, S_2, \dots, S_m$, the Palmgren-Miner hypothesis, $\sum_{i=1}^m \left(\frac{n}{N}\right)_i = 1$, is usually applied in damage calculations. It states that if n is the number of cycles actually applied at a given stress level S_i , and if N is the number of cycles that would produce failure at that level, then $\left(\frac{n}{N}\right)_i$ is the proportion of damage inflicted by all the cycles applied at the level S_i and the specimen will fail when the sum of the damage at each stress level adds up to 1. Whilst it is recognised that in practice values of $\sum \frac{n}{N}$ between about 0.1 and 30 can occur, other more complicated cumulative damage theories are seldom used since it is held that they do not give worth-while improvements in accuracy over the range of conditions which must be considered in design.

In section 1.2 influences which contribute to values of $\sum \frac{n}{N}$ deviating from 1 are discussed, and the term 'elastic interaction' is introduced to cover the distinct, but interrelated, influences which can be identified in plain specimens. It is argued that in specimens containing geometric stress concentrations, local plastic deformation influences - 'geometric residual stress' effects - are superimposed on this elastic interaction, and that by accounting separately for geometric residual stresses elastic interaction effects will be revealed. In section 1.3 measurements are presented of the geometric residual

stresses generated in pinned-lug and notched specimens under variable amplitude loading, and in sections 1.4 and 1.5 it is shown that estimates of endurance, which account for these geometric residual stresses, are - as argued in section 1.2 - in good good agreement with published data for plain specimens. Conclusions are presented in section 1.6.

1.2 FACTORS WHICH INFLUENCE THE ACCURACY OF THE PALMGREN-MINER HYPOTHESIS

In order to identify the principal factors which contribute to values of $\sum \frac{n}{N}$ of other than 1, cumulative damage in plain specimens will first be considered and then this will be followed by a discussion of the additional effects of structural features such as fretting and geometric stress concentrations.

1.2.1 Behaviour of plain specimens and 'elastic interaction' effects

In plain specimens the phenomenon of fatigue of metals shows two distinct stages².

Stage 1: crack initiation (shear mode)

Crack initiation generally occurs at the surface where there is greater freedom for dislocation movements. The action of reversed loading causes slip by the movement of dislocations along crystallographic planes closely aligned to the directions of maximum shear stress. This results in the formation of clusters of grooves and ridges appearing to be formed from the edges of fine lamellae buried beneath the surface. The grooves deepen to form crevices which penetrate the material to a depth where damage is concentrated over a very small area at the tip of the crevice and gross slip virtually ceases.

Stage 2: crack propagation (tension mode)

The continued application of fatigue loads causes cracks to propagate from the tips of these crevices by cleavage along crystallographic planes closely normal to the direction of principal tensile stress. As cleavage propagation proceeds, leaving a smooth fracture surface characterised by valleys ('river markings'), in the direction of propagation, a ductile component develops by slip at the crack tip. This leaves a fine ridge, known as a striation, on the fracture surface after the completion of each reversal of load.

As the crack grows the ductile component continues to increase until fracture occurs by shear or other criteria akin to those of static failure.

It has been shown, notably by Wood³, that Stage 1 fatigue damage, as seen in etched sections, can take a number of forms depending on stress amplitude. Wood's idealised S-N curve with three ranges is reproduced in Fig.1.1. At high stress amplitudes damage is concentrated at grain boundaries and at irregular sub-boundaries within the grains. At medium stress amplitudes damage growth occurs along slip planes, whereas at low stress amplitudes the mechanism is characterised by less deformation and fewer centres of damage, although a large number of grains may be affected by faint distortion zones. These observations are consistent with fractographic evidence of a decrease in the number of active fatigue nuclei with a decrease in stress amplitude⁴⁻⁸. Additionally, there is evidence that the proportion of life spent in crack initiation increases with decrease in stress amplitude. For example, Schijve and Jacobs⁹ report that for plain specimens (and also for moderately notched specimens $K_t = 2.6$), the percentage endurance to form cracks of 0.2 mm varies from about 70 per cent at high stress levels to more than 90 per cent at low stress levels. Thus, from constant amplitude tests we have evidence of a dependence of damage growth characteristics on stress amplitude, whereas a single characteristic (not necessarily linear) is implicit in the Palmgren-Miner hypothesis. Kaechele¹⁰ has termed this behaviour 'stress-dependence'. Fig.1.2 shows two constant amplitude curves. From these a fatigue life can be computed for a variable amplitude sequence combining the two amplitudes. For example, if the low level is first applied until a cycle ratio of say 0.5 is reached, we can read across from the low to the high curve at the same damage state - we find that the remaining cycle ratio at the high level is greater than 0.5, so that a value for $\sum \frac{n}{N}$ of greater than 1 is predicted. This calculation assumes that no interaction occurs, i.e. that the low loading does not change the high load damage curve - Kaechele has termed this a stress-dependent interaction-free situation and has extrapolated this simple calculation to show theoretically that $\sum \frac{n}{N}$ will always be less than 1 if the amplitudes are well-mixed. However, this interaction-free assumption is not justified because in practice interaction occurs, and this may be manifest for example in an increase in the number of nuclei at low stress amplitudes^{5,8} in Stage 1 or by changes in striation spacing on the fracture surface¹¹ in Stage 2. As shown by Topper and

Sandor¹², such effects can be produced by a few cycles of the high amplitude stress whereas insignificant damage would be ascribed to the action of these few cycles according to the Palmgren-Miner hypothesis. Alternatively, there may be a low-high effect which would tend to increase the value of $\sum \frac{n}{N}$, e.g. the well known coxing effect in steels. Hence we have two stress-dependent effects:-

(a) stress-dependence *per se* (Fig.1.2), as revealed by constant amplitude tests and,

(b) stress-dependent interaction between amplitudes, which changes the shape of the stress-dependent curves.

Separately from this, the value of $\sum \frac{n}{N}$ is influenced by:-

(c) cycles below the constant amplitude fatigue limit, which may be detrimental on the one hand - as a result of nucleation by higher amplitudes - and beneficial on the other - as a result of 'coxing-type' effects (Fig.1.3, which will be discussed later, shows such an effect)

(d) the loss of a small proportion of the crack propagation phase by failure under high stress acting on the crack.

These distinct, but interrelated, phenomena which influence the value of $\sum \frac{n}{N}$ in plain specimens can be grouped together under the title 'elastic interaction' - whilst it is recognised that these phenomena are not strictly elastic, it is a short expression and serves quite well to distinguish the effect from that due to plastic deformation in specimens containing stress concentrations (this latter effect will be discussed in section 1.2.3).

The influence of elastic interaction on the accuracy of the Palmgren-Miner hypothesis may be judged from the work of Freudenthal and Heller¹¹ on plain specimens of aluminium alloy and steel. The curves of Fig.1.3, taken from their work, represent the average of large numbers of tests under various simulated aircraft gust spectra. For both materials, the values of $\sum \frac{n}{N}$ vary from about 1.0 at an endurance of 10^4 cycles through about 0.2 between 10^6 and 10^7 cycles to about 0.3 at 10^8 cycles (suggesting some slight strengthening effect of low amplitude stresses in both steel and aluminium alloy). The work of other investigators (quoted later) also shows that the value of $\sum \frac{n}{N}$ for plain specimens is less than 1 - values between about 0.2 and 0.6 generally being reported over the endurance range $10^5 - 10^8$ cycles.

1.2.2 Effects of fretting

In the plain specimens discussed so far, the fatigue life is dominated by the Stage 1 crack initiation process described earlier. However, when fatigue damage originates from areas of fretting Stage 1 is virtually eliminated (this is discussed in the paper reproduced here as Appendix B) and the Stage 2 crack propagation process predominates. The effects of elastic interaction can then be expected to be different from those in plain specimens. Indeed, random loading tests by Billingham and Ryman¹³ using fretted-plain specimens (plain specimens fitted with pads) give a value for $\sum \frac{n}{N}$ of about 1.4 for endurance between about 10^5 and 10^7 cycles. This value is similar to that obtained by Fralich¹⁴ using a very sharp notch ($K_t \approx 5$) which probably also virtually eliminates the Stage 1 phase of damage. (These sharply notched tests were made at zero mean stress under Gaussian narrow band random loading, such that any yield occurring would be symmetrical about zero stress. Thus, the value of $\sum \frac{n}{N}$ is unlikely to be influenced by the 'geometric residual stress' effects discussed in the following section).

The slightly beneficial effect of elastic interaction implicit in these results is likely to be attributable to favourable stress-dependent interaction in Stage 2, predominating over any detrimental influence of cycles below the constant amplitude fatigue limit and premature failure under high loads. Evidence that Stage 2 stress-dependence *per se* - i.e. as revealed in constant amplitude tests - differs intrinsically from that in Stage 1 is provided by recent work at RAE¹⁵⁻¹⁹, which suggests that under fretting conditions specimens will show cracks at an earlier proportion of endurance at low than at high stress levels, whilst the opposite is true for unfretted plain specimens. A possible explanation for this is that high stresses lead to gross yield around the fretted notch roots and re-distribute stresses so that crack formation is impeded, whilst low stress amplitudes only deform the notch roots themselves by highly localised slip leading directly to crack formation. In plain specimens the gross yield gives rise to the possibility of many more nuclei, and so to detrimental rather than beneficial interaction.

These considerations show that whilst there is some understanding of the qualitative effects of elastic interaction on the values of $\sum \frac{n}{N}$, these effects cannot yet be accurately predicted theoretically.

1.2.3 Effects of geometric stress concentrations - 'geometric residual stresses'

If the additional effects of geometric stress concentrations, such as holes, notches, and changes in section, are now considered and if size effects are discounted (these will be discussed in Part 2), then the conditions in the localised region of fatigue damage initiation are closely akin to those that would exist throughout a plain specimen subjected to strain amplitudes increased by the elastic stress concentration factor, K_t . It is convenient to think of the loading in terms of strain rather than stress amplitude since it is then possible to liken the notched conditions to those in an 'equivalent plain specimen' and thus to relate them to the stress-strain characteristics of the material. As shown in Fig.1.4, the material within the plastic enclave formed by the application of a high tensile load to a notched specimen will, when the load is removed, be subjected to compressive residual stress by the constraint of the surrounding bulk of material remaining elastic. As a result of this 'geometric residual stress', the equivalent plain specimen experiences a reduction in mean tensile stress so that subsequent smaller amplitude cycles produce less damage than before. Similarly, compressive yield at the notch root results in tensile geometric residual stresses which have a corresponding detrimental effect.

As early as 1955, Gunn²⁰ recognised the importance of geometric residual stresses and showed how these can be accounted for in the derivation of modified Goodman diagrams for notched specimens under constant amplitude loading. Independently, at much the same time, Smith²¹ evolved a similar approach to calculate changes in mean stress under variable amplitude loading and thus to improve the accuracy of life prediction with the Palmgren-Miner hypothesis. Basically, Smith recognised that for design purposes the local strain concentration factor, K_ϵ , $\frac{\text{local strain}}{\text{net strain}}$, can be assumed to be constant and equal to K_t , so that K_t can be used with the assumption of a perfectly elastic - perfectly plastic monotonic stress-strain curve to calculate local mean stresses under variable amplitude loading* - he termed this the 'Linear Strain Theory'.

* In later refinements of this rule, the stress-strain curve in the plastic region has been approximated to a straight line with positive slope, and this has been used with Neuber's rule²² $K_t^2 = K_\epsilon K_\sigma$ to calculate K_σ the local stress concentration factor, and hence a more precise value of local residual stress.

This 'linear strain' calculation does not account for the 'relaxation' of mean stress (sometimes termed 'cyclic creep') observed in materials tested under strain-control to represent notch root conditions²³. Impellizzeri²⁴ has interpreted this phenomenon as a change of residual stress and has proposed an empirically-based expression to account for its effect in cumulative damage calculations. (To give greater accuracy in calculating local mean stress Impellizzeri also employs the Neuber relation, but his cumulative damage rule does not account for elastic interaction or for the important influence of non-linearities in alternating/mean stress diagrams (to be discussed in section 1.4)). However, such a refinement is questionable, since the relaxation phenomenon, which in strain softening materials may be largely attributable to the distinction between monotonic and cyclic stress-strain curves, is accounted for to some extent in the constant amplitude data (for notched specimens, as required by the Palmgren-Miner rule). The influence of the cyclic stress-strain curve in alleviating the local conditions at a notch root has been recognised by Forrest²⁵ (Forrest's work on correlating plain and notched fatigue strengths under constant amplitude loading will be discussed in Part 2). Later work by Landgraf, Morrow and Endo²⁶ shows that the yield point of such curves - measured on reaching stability at about half the fatigue life - can differ from the monotonic value by as much as 50 per cent, as shown in Fig.1.5.

The importance of allowing for geometric residual stress has recently attracted attention in the UK with the publication by the Engineering Sciences Data Unit (ESDU) of a data sheet²⁷ describing in detail how such calculations can be incorporated into design procedures. Specifically it is shown that for a variety of aluminium alloy specimens, values of $\sum \frac{n}{N}$ of between 0.1 and 10 are brought much closer to 1 by the use of the linear strain method. These results rightly attract the designers attention, but it must be remembered that the method does not account for the elastic interaction effects discussed earlier, which in certain cases can lead to marked overestimates of endurance. The data analysed by ESDU all relate to sharply notched ($K_t \geq 3.5$) or fretted specimens (considered to be typical of aircraft structures), so that the close agreement with the Palmgren-Miner hypotheses $\sum \frac{n}{N} = 1$ is likely to be attributable to the predominance of Stage 2 elastic interaction. The 'ESDU method' - which accounts only for geometric residual stresses and not elastic interaction - would therefore not be expected to give a similar accuracy in predicting the endurance of moderately notched unfretted

components, since predominant Stage 1-elastic interaction effects would under these circumstances give values of $\sum \frac{n}{N}$ of up to an order of magnitude less than the assumed value of 1.0, i.e. the endurance might be overestimated by factors of up to about ten. It is noteworthy that other investigators have suggested that it may be more appropriate to assume values of $\sum \frac{n}{N}$ of other than 1.0 to account for some of the apparent anomalies in using the linear strain method for different materials and load spectra - for example, Edwards¹⁵ suggests a value of 0.5 for steels - but as far as the author is aware, it has not previously been recognised that there is a distinction between the values appropriate for Stage 1 and Stage 2 and that this distinction *per se* is likely to explain the apparent inconsistency of the linear strain method.

1.2.4 Conclusions from this introductory survey

From this introductory survey it is concluded that inaccuracies in Palmgren-Miner calculations are attributable to two main influences:-

(1) Elastic interaction - a convenient short term which has been chosen to describe the combined influence of four distinct, but interrelated, phenomena:-

- (a) Stress-dependence (a constant amplitude phenomenon)
- (b) Stress-dependent interaction
- (c) Cycles below the constant amplitude fatigue limit
- (d) Loss of a small proportion of the crack propagation phase by premature failure under high stress.

There is some evidence that the influence of elastic interaction is detrimental when the classical Stage 1 initiation process predominates - as the plain or moderately notched specimens - and neutral to slightly beneficial when Stage 2 predominates - as the plain-fretted or sharply notched specimens.

(2) Geometric residual stresses - these arise due to plastic deformation of the material surrounding a geometric stress concentration. In effect, the mean stress at the root of the stress concentration is changed by the action of geometric residual stresses.

It is considered that these two influences are quite distinct, so that by accounting separately for changes in local mean stress in specimens containing

geometric stress concentrations, elastic interaction errors are likely to be revealed - where these will be appropriate to whether Stage 1 or Stage 2 conditions predominate in the most highly stressed region. In order to provide the necessary experimental basis for such calculations a study - described in the following section - has been made of the changes in local mean stress which occur in pinned-lug and notched specimens under variable amplitude loading. These specimens represent Stage 2 and Stage 1-dominant conditions respectively.

Two materials - aluminium alloy and maraging steel - have been tested to reveal any additional influence of factors such as differences between monotonic and cyclic stress-strain curves.

1.3 MEASUREMENTS OF LOCAL STRESS HISTORIES IN PINNED-LUG AND NOTCHED SPECIMENS

1.3.1 Use of the companion specimen technique

It is possible to deduce the stress history at a fatigue sensitive location such as a notch root by measuring the local strain history under an applied load spectrum and subjecting a plain specimen to the same strains. The resultant stress sequence on the plain specimen will then be representative of the conditions prevailing at the root of the notch (see Fig.1.4). This procedure, known as the 'companion specimen technique', was first suggested by Crews and Hardrath²⁸ and has been widely used in 'quasi-static' studies of the geometric residual stresses generated in notched specimens under fatigue loading²⁸⁻³¹.

The investigation described here is based on pinned-lug and notched specimens of the type used in the cumulative fatigue damage research programme described in the paper reproduced as Appendix A. Two aspects of local stress conditions were selected for quasi-static study:-

- (1) the geometric residual stresses arising from discrete loadings of constant amplitude, and
- (2) the geometric residual stresses generated during a gradual rise to the same amplitude and subsequent decay in a sequence typical of the resonant fatigue testing machines used in the programme.

The stresses derived quasi-statically were compared with those calculated by the linear strain method and with

- (3) the local stress histories obtained during the continuous application of large numbers of cycles of Gaussian narrow band random loading.

In this study the plain specimens were tested simultaneously³¹ without resort to the usual intermediate recording of indicated local strain. This simplified the quasi-static tests and enabled measurements to be made of the local stress histories under continuous random loading. The purpose of these random loading tests was to reveal the possible effects of progressive strain hardening (or softening) on the local stress histories derived from quasi-static tests in which the large numbers of cycles of lower amplitude were not represented.

It is noteworthy that whilst the companion specimen technique provides an indication of the local stress field which prevails during Stage 1 and Stage 2 micro-crack growth in the highly stressed region at the notch root (see Fig.1.4), it does not reproduce the fatigue initiation conditions in the notch, where there is less opportunity for fatigue initiation due to the stability provided by the surrounding material.

1.3.2 Specimens and strain gauges

The materials used were BS.2L65 aluminium alloy and DTD 5212 maraging steel as described in Appendix A. Three types of specimen were used in each material; a notch (central hole with nominal geometric stress concentration, $K_t = 2.3$ on net stress), a pinned-lug ($K_t = 3.0$), and a waisted plain specimen. Dimensions and manufacturing details of these specimens are shown in Figs.1.6-1.12, and the first two types of specimen are described in the Technical Report reproduced as Appendix E.

Strain gauges with a gauge grid length of 0.79 mm were bonded in the positions shown in Fig.1.13 and a very thin protective coat of RTV silicon rubber was applied. Typical specimens are shown in Fig.1.14. Micro-measurement EA type gauges bonded with a room temperature curing adhesive were selected in order to provide a combination of high fatigue life, high strain capability, acceptable zero drift and minimal change in gauge factor^{32,33}. A groove, with the dimensions shown in Fig.1.12 was cut in the loading pin of the lug specimens to provide space for the gauges.

All specimens were degreased with an organic solvent (trichloroethane) and assembled dry.

1.3.3 Fatigue testing machines and instrumentation

The specimens were tested in two 200kN Dowty electro-hydraulic fatigue testing machines. The lug and notched specimens were loaded through pins, whilst the plain specimens were clamped in wedge grips with 30mm unsupported

length between grips. This ensured a negligible perturbation in the stress distribution at the gauges, and was found to give freedom from buckling under the compressive loading encountered during the tests. The two gauges on the plain specimen were connected in series in order to avoid the influence of small bending effects.

The gauges were connected to electronic strain gauge meters to form a strain-coupled servocontrol of the type described by Crews³¹. The output signal from the gauge at the notch root was compared with the average output of the series gauges on the plain specimen. The small difference between these signals was amplified and used to control the loading on the plain specimen by a closed loop system, such that the strains in the plain specimen were maintained the same as those at the notch root. Continuous histories of net stress (load on the notched specimen divided by net area) and local stress (load on plain specimen divided by gross area) and local strain were monitored against time by means of an FM tape recorder and by ultra-violet reflecting light galvanometers. Additionally, for the quasi-static tests, X-Y plotters were used to show curves of indicated local strain against net stress (fatigue specimen), and against local stress (plain specimen). A schematic diagram of the equipment is shown in Fig.1.15.

Each specimen was subjected to one of the three loading sequences given in section 1.3.1. The two quasi-static sequences (1) and (2) were generated using a small digital computer. For sequence (1), this was programmed to give 16 cycles of constant amplitude loading with a frequency of 0.5 Hz. For sequence (2), a rise and decay representative of a very narrow band process (see Fig.16) was programmed to take place over 400 cycles, again with a loading frequency of 0.5 Hz, which enabled the X-Y plotters to be used continuously. The continuous Gaussian narrow band random loading, sequence (3), was produced by a narrow band random generator with a centre frequency of 30 Hz. The rms alternating stress, which was held constant by an internal servo-loop, was monitored by means of an integrating voltmeter with a time constant* of 100 s. In order to simulate the narrow band random loading applied by the resonant machines used in the related programme described in Appendix A, a truncating amplifier was incorporated to clip compressive-going loads at zero stress. An

*The meter time constant is defined as the time taken for the meter pointer to fall to one third of the deflection when the input signal is disconnected.

additional truncating amplifier was also used to clip the higher positive going loads at the truncation levels given in Table 1.1, and a levels-crossed counter was used to confirm that the required truncated Rayleigh distributions were obtained. The truncation levels used in sequence (3) are appropriate to rms alternating stresses for endurances in the range 10^5 to 10^7 cycles. They were derived as described in Appendix B from levels-crossed counter data for each specimen and material^{16,19}.

The calibration accuracy of the load monitoring equipment and of the strain gauge meters was better than 0.5 per cent *viz*, 0.1 kN and 50 $\mu\epsilon$ respectively. Load control was within 2 per cent. The greatest potential source of error was probably in the foil resistance strain gauges, which experience a resistance zero drift^{32,33} and a change in gauge factor under cyclic loading, particularly when subject to high strain amplitudes. However, in the present application strain acts solely as an intermediate variable so that only differences in behaviour between gauges on the two specimens are important. No checks were made with an extensometer, but the satisfactory repetition of tests provided a measure of the performance in this respect.

1.3.4 Details of the tests

In sequences (1) and (2) the appropriate peak net stresses were applied in a series of blocks, each successive block corresponding to an increase in the associated rms alternating stress. Table 1.1 gives details of the stresses used.

In sequence (1), 16 full cycles (tensile stress first) were applied.

In sequence (2), the net stress amplitude was increased gradually within a sinusoidal envelope so that the stated maximum (Table 1.1) was reached in 200 cycles. The amplitude was then decreased symmetrically to zero in another 200 cycles (see Fig.1.16). This was followed by a similar programme of 400 cycles increasing to and decreasing from the next higher stress level, etc, as indicated in Table 1.1.

In sequence (3), each specimen was subjected to Gaussian narrow band random loading at an rms alternating stress corresponding to an endurance of approximately 10^6 cycles. Typical fatigue-test and simulated stress histories are shown in Fig.1.17.

1.3.5 Interpretation of stress-strain hysteresis data for quasi-static loading

A typical X-Y plot of stress against indicated local strain is shown in Fig.1.18. For convenience the net stress applied to the notched specimen and the local stress histories inferred from the gross stress on the companion specimen have been superimposed.

The figure shows as an example the second block of the 16 cycles loading sequence for the aluminium alloy notched specimen (associated random rms alternating stress 33.8 MN/m^2 , see Table 1.1). It can be seen that for the same strain at the gauges a local mean stress of 178 MN/m^2 (companion specimen) was associated with a net mean stress of 138 MN/m^2 (notched specimen). This local mean stress in the companion specimen is less than $K_t \times 138 \text{ MN/m}^2$ due to the local compressive geometric residual stress of approximately 140 MN/m^2 which was generated during the first block of loading applied to this specimen (associated random rms alternating stress 25.2 MN/m^2 , see Table 1.1). As the net stress in the notched specimen was increased to a peak of 280 MN/m^2 local yield occurred thereby limiting the peak local stress to 436 MN/m^2 . As the net stress was returned to the mean value on completion of the first half cycle, the local stress decreased elastically to 106 MN/m^2 (an effective reduction of 72 MN/m^2 in local mean stress). As the net stress was reduced to the minimum in the cycle, the local stress at first decreased approximately elastically, but after passing through zero it was conditioned by the onset of progressive compressive yield associated with the Bauschinger effect. When the net stress was returned to the mean value, the local stress increased to 137 MN/m^2 (i.e. an increase of 31 MN/m^2 over the $\frac{1}{2}$ cycle local stress). During the first complete cycle of loading the local mean stress was therefore effectively reduced by 41 MN/m^2 . It was noted that further small reductions in local mean stress occurred with subsequent cycles of the same amplitude. This behaviour is consistent with greater yield per cycle in the tensile sense due to the tensile local mean stress than in compression. If further cycles were applied, this 'relaxation' process would be expected to continue until the cycle either became fully elastic (according to the cyclic stress-strain curve) or, for very high amplitudes, the local mean stress decreased to zero (due to fully-reversed yield).

Typical curves for a 400 cycles loading sequence on a specimen of this type are presented in Fig.1.19. Figs.1.20 and 1.21 show curves for the same

two sequences on the aluminium alloy pinned-lug. Typical curves for maraging steel specimens are presented in Figs.1.22-25.

Measurements of the local stress corresponding to the $\frac{1}{2}$, 1, $15\frac{1}{2}$ and 16th cycle points of the first sequence and to the 200th and 400th cycle points of the second sequence are presented in Figs.1.26-29. The figures show progressive cyclic reductions in local stress which are generally explainable by the relaxation mechanism noted previously. The only inconsistency with this mechanism is in the behaviour of the aluminium alloy specimens at the higher amplitudes in the 400 cycles loading sequence. These measurements indicate that the local stresses do not stabilize about a mean of zero but continue to decrease by some mechanism as more cycles are applied. It is likely that these measurements, which represent the most stringent test conditions, are the most subject to error, but the consistency of the lug and notch data gives some confidence that the observations are valid.

In order to examine the consistency of the local conditions prevailing in the notched and lug specimens of each material, the measured variations in local peak stress have been compared in Figs.1.30 and 1.31. These show good agreement between the two configurations with the 400 cycles loading giving slightly lower peak stresses in both materials.

1.3.6 Interpretation of data obtained under continuous random fatigue loading

Under Gaussian narrow band random loading, amplitudes equal to the prescribed truncation levels generally occur within the first 10^4 cycles of loading. A typical ultra-violet record showing the change in local mean stress which followed the application of the first stress to reach the truncation level in the aluminium alloy lug specimen is shown in Fig.1.32.

Under further fatigue loading, which was continued until the gauges failed - in one case they survived to almost half the nominal (10^6 cycles) endurance of the specimen - progressive changes in local mean stress were observed as shown in Figs.1.26-1.29. The corresponding peak stresses are shown in Figs.1.30 and 1.31, from which it can be seen that the aluminium alloy strain hardens - increasing local peak stress - and the maraging steel strain softens - decreasing local peak stress - in the manner observed by Landgraf, Morrow and Endo²⁶ in aluminium alloys and steels tested under fully reversed constant amplitude fatigue loading, see Fig.1.5. As in the present work, the

effect was progressive and their tests were run to about half of the fatigue life to achieve acceptable stability. It is noteworthy that these observations show differences between the monotonic and cyclic stress-strain curves in steels to be related to the indentation hardness. The hardness value for maraging steel used in the present work (520-620 HB) is consistent with the small amount of softening which occurred.

The mechanism which causes the *rise* in the local mean stress in the aluminium alloy is not clear. However, a likely explanation is that the local strain amplitude remains approximately constant - being conditioned by gross rather than local deformation - so that the rise in yield point (peak stress, Fig.1.30) is accompanied by a corresponding rise in local mean stress.

1.3.7 Summary of observations

For clarity, the salient features of the above results are reproduced together in Figs.1.33-36. Also shown are estimates of the local mean stress derived using the linear strain method - as discussed in section 1.2.3, this is a convenient 'design' method which employs the elastic stress concentration factor (from data sheets) with the assumption of a perfectly elastic (to 0.2% proof stress)-perfectly plastic stress-strain curve to calculate local mean stresses.

1.3.8 Conclusions from local stress measurements

The local stresses predicted by the linear strain method are in reasonable agreement with those which obtain initially under quasi-static and continuous random loading.

Repeated quasi-static loading (sequences (1) and (2)) reveals in both materials a progressive relaxation of local mean stress by the accumulation of increments of tensile yield in each cycle.

The continuous random tests, on the other hand, show that the local stress progressively increases in the aluminium alloy and decreases in the maraging steel; these long term changes are consistent with the dominance of cyclic strain hardening in the aluminium alloy and cyclic strain softening in the maraging steel. Aluminium alloys and steels are reported to behave in this manner also under constant amplitude loading, where the effect is also reported to be progressive - occurring over approximately the first half of the fatigue life.

The strain softening in the maraging steel is accompanied by a reduction in local mean stress and the strain hardening in the aluminium alloy by an increase in local mean stress - a likely explanation for this increase is that the local strain amplitude remains approximately constant so that the rise in yield point is accompanied by a corresponding rise in local mean stress.

1.4 CORRECTION OF PALMGREN-MINER CALCULATIONS TO ACCOUNT FOR GEOMETRIC RESIDUAL STRESSES IN THE SPECIMENS TESTED

1.4.1 Adjustments in mean stresses according to the data obtained with pinned-lug and notched specimens

In the previous section, the dependence of local mean stress on prior loading history has been demonstrated. It will be immediately evident that constant amplitude data for notched components will also reflect changes in geometric residual stress. In order to make a mean stress adjustment to the damage calculation using the Palmgren-Miner hypothesis, it is therefore generally necessary to adjust the available constant amplitude data from the variable local mean stress datum of the S-N curve to a fixed datum appropriate to the local mean stress prevailing under variable amplitude loading.

It is noteworthy here that conventional plain-specimen alternating/mean stress diagrams relate exclusively to Stage 1-dominant conditions and so strictly speaking these are not applicable to the pinned-lug situation. However, Edwards^{15,34} has made a particular study of geometric residual stress adjustments in pinned-lug specimens and has established correlation between adjusted and achieved endurances under narrow band random loading despite the use of such an approximation. In his work on aluminium alloy pinned-lug specimens, Edwards used a modified Goodman (straight-line) relationship between mean stress and alternating stress, whilst ESDU, in their recent data sheet²⁷, have recommended the use of curves fitted through two fatigue test points - in addition to the static strength - for the alloy concerned.

As a basis for the discussion which follows, constant amplitude data for the pinned-lug and notched specimens^{16,19}, Figs.1.37-40, have been adjusted to the local mean stresses derived in the preceding section (for the 1st and 16th cycle of the first sequence, the 400th cycle of the second and also for the linear strain prediction) using both the modified Goodman and more appropriate - albeit still confined to Stage 1 - mean stress relationships³⁵⁻³⁷, see Fig.1.41. These calculations were executed using the computer programmes of Edwards³⁴, it being necessary to incorporate only simple modifications to

enable the more appropriate mean stress relationships to be used. The predicted and achieved endurances of these specimens under Gaussian narrow band random loading are presented, together with conventional predictions (without adjustment) derived from relevant published data^{15,38-46,49} in Figs.1.42-49.

1.4.2 Design implications - the ESDU method

Figs.1.42-49 reveal two features of great importance in design. Firstly, the predictions based on the linear strain method are in reasonable agreement with the predictions based on the quasi-static measurements. Secondly, it is clear that first order inaccuracies can be introduced by approximating the mean/alternating stress relationship to a modified Goodman line.

The ESDU design procedure²⁷ makes use of the linear strain method and also incorporates the necessary appropriate mean/alternating stress diagram for the material concerned. The ESDU mean stress adjustment is in fact identical to the procedure evolved here and used in calculating the linear strain/Gerber predictions for the aluminium alloys and the linear strain/ $p = \frac{1}{2}$ predictions for the maraging steel.

The values of $\sum \frac{n}{N}$ obtained after using this method to account for the influence of geometric residual stresses in the pinned-lug and notched specimens will be discussed in the following section.

1.5 INFLUENCES REVEALED AFTER ACCOUNTING FOR GEOMETRIC RESIDUAL STRESSES - ELASTIC INTERACTION

Having accounted for the influence of geometric residual stresses in calculating the endurance of these specimens under Gaussian narrow band random loading, the resulting inaccuracies (attributed in section 1 to elastic interaction) will now be compared with published data for Stage 1 and Stage 2-dominant conditions. However, first we will consider another possible source of inaccuracy revealed by the continuous fatigue loading (sequence (3)) - differences between monotonic and cyclic stress-strain curves.

1.5.1 Influence of differences between monotonic and cyclic stress-strain curves

It was noted in section 1.2.3 that the yield point of cyclic stress-strain curves obtained under constant amplitude loading has been shown to differ from the monotonic value by as much as 50 per cent. As discussed in section 1.3.6, under continuous random fatigue loading the aluminium alloy specimens exhibited a progressive increase in local mean stress as more cycles

were applied. This increase was greatest in the lug specimen, Fig.1.27, from which it can be seen that the mean stress of about 210 MN/m^2 (value subsequent to action of maximum geometric residual stress), increased by about 100 MN/m^2 during the course of the test. The corresponding increase of 100 MN/m^2 in the tensile yield stress, as evident from Fig.1.30, is comparable with that reported by Landgraf, Morrow and Endo²⁶ for a similar aluminium alloy, 2024-T4, under constant amplitude loading, see Fig.1.5. Likewise, for maraging steel, the small reduction in local mean stress, see Fig.1.31, is consistent with data for steels of similar hardness.

The evidence therefore indicates that once the local mean stress has been modified by a few cycles (sequence (1) or (2)) of load applications, it is further modified during subsequent fatigue by the difference between the monotonic and cyclic stress-strain curve of the material. However, the monotonic and cyclic stress-strain curves appear to differ by much the same amount under constant amplitude and variable amplitude loading, so that these cyclic changes in local mean stress will be superimposed on the basic constant amplitude data as well as on the local mean stresses which prevail after the action of geometric residual stresses. Differences between monotonic and cyclic stress-strain curves are therefore unlikely to introduce first order errors in calculating the endurance of these specimens, so that errors in Stage 1 and Stage 2 are likely to be principally associated with elastic interaction.

1.5.2 Stage 1-dominant conditions

In moderately notched specimens, such as those studied here, the notch root conditions are closely akin to those in plain specimens, and so the endurance is dominated by the Stage 1 process.

Figs.1.47 and 1.49 show that when account has been taken of geometric residual stresses in these notched specimens, values of $\sum \frac{n}{N}$ between about 0.1 and 0.4 are revealed for the aluminium alloy and values between about 0.1 and 0.7 for the maraging steel - over the endurance range 10^5 to 10^7 cycles (endurances above about 10^7 cycles can be discounted for practical (life prediction) purposes).

Table 1.2 gives comparable data for plain specimens tested under the same type of loading. It can be seen that the value of $\sum \frac{n}{N}$ for aluminium alloy^{7,13,47,48,51} is generally between about 0.2 and 0.6 due to Stage 1

elastic interaction. This corresponds closely to the adjusted notched data. Also, whilst no plain specimen data are available to provide a direct comparison for the maraging steel, the results for mild steel⁵³ and titanium alloy⁵² give some confidence that the error in the adjusted maraging steel predictions is also attributable primarily to elastic interaction.

1.5.3 Stage 2-dominant conditions

In the pinned-lug specimens, the notch root conditions are closely akin to those in a plain specimen fitted with fretting pads and so the endurance is dominated by the Stage 2 process.

Figs.1.43 and 1.45 show that when account has been taken of geometric residual stresses, values of $\sum \frac{n}{N}$ between about 0.7 and 2 are revealed for the aluminium alloy and values between about 1.2 and 2 for the maraging steel - again endurances above about 10^7 cycles can be discounted for practical purposes.

From Table 1.2 we have only one example of plain-fretted data - that of Billingham and Ryman¹³ - which gives a value of $\sum \frac{n}{N} = 1.4$ for Stage 2 elastic interaction in aluminium alloy. However, as noted in section 1.2.2, the similar value obtained by Fralich¹⁴ using sharply notched ($K_t \approx 5$) aluminium alloy specimens gives some confidence that values of $\sum \frac{n}{N}$ are generally neutral to slightly beneficial in Stage 2, and that errors in the adjusted data are again attributable primarily to elastic interaction.

1.5.4 Comparison with cumulative damage data obtained under other forms of variable amplitude loading

In sections 1.3 and 1.4 attention has been confined to Gaussian narrow band random loading for which it has been shown that inaccuracies in Palmgren-Miner calculations are attributable to two main influences - elastic interaction and geometric residual stresses. Additionally, a clear distinction has been identified between Stage 1 elastic interaction (which is detrimental) and Stage 2 elastic interaction (which is neutral to slightly beneficial).

Turning now to other forms of variable amplitude loading, we will look first at Stage 1 conditions and then at data for Stage 2.

1.5.4.1 Elastic interaction in Stage 1

Considering first the effect of increasing the bandwidth of the Gaussian loading - so that we no-longer have a randomly modulated sine wave, but a more

realistic situation involving a greater number of peaks (n_p) than zero crossings (n_0), Fuller⁵¹ has tested identical plain specimens under narrow band (Table 1.2) and wide band loading, $\left(\frac{n_0}{n_p} = 0.75\right)$, and shown that there is no significant difference between the values of $\sum \frac{n}{N}$ obtained. As shown in Table 1.2, under Gaussian narrow band random loading $\sum \frac{n}{N}$ was observed to vary from about 0.3 at 10^5 cycles to about 0.2 at 10^6 cycles.

Moving on now to block programme simulations of service-type loading, a classical example of Stage 1 elastic interaction is provided by the tests on plain specimens reported by Freudenthal and Heller¹¹ - as noted in section 1.2.1. Specimens of 2024 aluminium alloy and SAE 4340 steel were tested under a family of gust load spectra representative of various types of aircraft under various operating conditions. It was found that all the spectra gave values of $\sum \frac{n}{N}$ of less than 1 with a distinct grouping along the fitted curves reproduced in Fig.1.3. Over the endurance range 10^5 to 10^7 cycles, these curves give a value of $\sum \frac{n}{N}$ of about 0.2 for both materials, which again agrees closely with the values obtained under Gaussian narrow band random loading.

1.5.4.2 Elastic interaction in Stage 2

In the absence of suitable data on fretted-plain specimens, it is convenient to examine work by Schijve and Jacobs⁵⁰ on 'fretted-notched' specimens (a riveted joint) tested in fluctuating tension under a range of 19 different forms of block-programmed loading. These results have been analysed by ESDU²⁷ to account for the influence of compressive residual stresses, and their calculations reveal remaining values of $\sum \frac{n}{N}$ between about 0.9 and 2 for Stage 2 elastic interaction. It will be recalled, from section 1.5.4, that much the same values - between about 0.7 and 2 - are also obtained under Gaussian narrow band random loading.

1.6 CONCLUSIONS

It is concluded that inaccuracies in Palmgren-Miner calculations for structural components are attributable to two main influences - 'elastic interaction' and 'geometric residual stresses', each of which can affect $\sum \frac{n}{N}$ by a factor of up to about 10.

Elastic interaction

This is a convenient short term which has been chosen to describe the combined influence of four distinct, but interrelated, phenomena:-

- (a) stress dependence (a constant amplitude phenomenon)
- (b) stress dependent interaction
- (c) cycles below the constant amplitude fatigue limit
- (d) loss of a small proportion of the crack propagation phase by failure under high stress.

There is a clear distinction between the influence of elastic interaction in Stage 1 (shear mode) and in Stage 2 (tension mode). For a wide variety of service-type loadings (block programmes, and narrow and wide band Gaussian - covering the endurance range between about 10^5 and 10^7 cycles) Stage 1 elastic interaction generally gives values of $\sum \frac{n}{N}$ between about 0.2 and 0.6, whereas Stage 2 elastic interaction generally gives values between about 0.8 and 2.

This means that for practical purposes design should be to the appropriate Stage 1 or Stage 2 value of $\sum \frac{n}{N}$ rather than to $\sum \frac{n}{N} = 1$.

When it is not evident whether the endurance of a component is dominated by Stage 1 or by Stage 2, the value of elastic interaction can be obtained, to first order, by testing prototype components under an elementary form of variable amplitude loading, such as Gaussian narrow band random, and comparing the endurance with that predicted by the Palmgren-Miner hypothesis on the basis of constant amplitude tests - note that for components containing geometric stress concentrations the constant amplitude data must first be adjusted for geometric residual stresses.

Geometric residual stresses

Here, there is a clear distinction between the initial local mean stresses - associated with plastic deformation according to the monotonic stress-strain curve - and the local mean stresses which prevail after prolonged loading - these are associated with the cyclic stress-strain curve (which is fully developed by about half the fatigue life).

However, the changes in local mean stress under prolonged loading are likely to be of secondary importance only, since such cyclic effects are also observed under constant amplitude loading so that they are accounted for to some extent in the constant amplitude data.

These prolonged loading effects have been discounted in making successful geometric residual stress adjustments in Palmgren-Miner calculations for notched and pinned-lug specimens tested at tensile mean stress under Gaussian narrow band random loading. (These specimens cover both Stages 1 and 2 fatigue, and strain hardening and strain softening materials.) The adjustments have been

made using an idealised monotonic stress-strain curve (elastic to 0.2% proof stress: perfectly plastic thereafter), stress concentration factor, K_t , from data sheets, and constant amplitude alternating/mean stress diagrams for the materials concerned - in fact the same procedure recently evolved independently by ESDU and published in Data Sheet 71028.

On the basis of this research, suggestions are made in Parts 2 and 3 for improvements in material evaluation and life prediction procedures.

Although we already have sufficient evidence to expedite the important design applications outlined in parts 2 and 3, several extant areas of work are apparent:-

(a) measurement of Stage 1 and Stage 2 elastic interaction under the various 'standard spectra' (these are discussed in part 3) which are being evolved internationally - the object being to compare for a range of endurances, the particular values for each spectrum with those obtained under Gaussian narrow band random loading.

(b) development - as suggested in Parts 2 and 3 - of material evaluation and life prediction techniques which are based on an elementary form of variable amplitude loading - such as Gaussian narrow band random - which contains an inherent allowance for elastic interaction

(c) investigation to confirm applicability of the 'ESDU method' to Stage 1 applications involving compressive yield - the data for compressive yield analysed by ESDU are believed to be confined to Stage 2-dominant conditions.

Table 1.1

COMPANION SPECIMEN TESTS: NET STRESSES APPLIED UNDER THREE LOADING SEQUENCES

Sequence	Specimen	Mean stress	Peak stress	Associated rms alternating stress (Gaussian narrow band random loading)
		MN/m ² (net)		
(1) Each line represents a test of 16 cycles of loading at constant amplitude applied at 0.5 Hz frequency. Each specimen pair was subjected successively to the number of tests shown	BS.2L65 aluminium alloy notch ($K_t = 2.3$)	138 in all cases	244	25.2
			280	33.8, Fig.1.18
			305	39.4
			333	45.8
			352	49.7
	BS.2L65 pinned-lug ($K_t = 3.0$)	110 in all cases	182	19.0, Fig.1.20
			196	22.4
			211	26.3
			225	30.1
			242	34.5
			263	40.0
	DTD 5212 maraging steel notch	517 in all cases	815	77.2, Fig.1.22
			900	99.2
			1000	125
			1100	149
			1210	176
	DTD 5212 pinned-lug	345 in all cases	455	31.5
			490	36.5
			525	45.5
			565	54.4
			610	66.5, Fig.1.24
			645	75.1
(2) 400 cycles loading: build-up and decay representative of very narrow band process (0.5 Hz)	BS.2L65 notch	138 in all cases	238	24.0, Fig.1.19
			270	31.0
			300	38.6
			326	44.2
			354	50.3
	BS.2L65 pinned-lug	110 in all cases	183	19.0, Fig.1.21
			200	23.4
			215	27.3
			226	30.1
			239	33.8
			258	38.6
	DTD 5212 notch	517 in all cases	820	77.8, Fig.1.23
			910	100
			995	122
			1100	154
	DTD 5212 pinned-lug	340 in all cases	455	27.6
			500	38.6
			530	46.2
			575	57.9
			610	66.8, Fig.1.25
			660	79.3
(3) Stationary Gaussian narrow band random fatigue loading (30 Hz)	BS.2L65 notch	138	240 (prescribed truncation level 4.3)	24.5 (more than 5×10^4 cycles applied)
	BS.2L65 pinned-lug	110	195 (prescribed truncation level 3.85)	22.3 (more than 4×10^5 cycles applied)
	DTD 5212 notch	517	876 (prescribed truncation level 3.9)	91.6 (more than 10^4 cycles applied)
	DTD 5212 pinned-lug	340	460 (prescribed truncation level 4.0)	29.0 (more than 3×10^5 cycles applied)

$$\text{Truncation level} = \frac{\text{Peak stress} - \text{mean stress}}{\text{rms alternating stress}}$$

Table 1.2

DATA FOR PLAIN SPECIMENS TESTED UNDER GAUSSIAN NARROW BAND RANDOM LOADING

Material	Mean stress MN/m ²	Approximate value of $\sum \frac{n}{N}$ at nominal endurance:-		Investigator
		10 ⁵ cycles	10 ⁶ -10 ⁷ cycles	
BS.2L65 aluminium alloy	0	1.1	0.6	Billingham and Ryman ¹³
		1.4 (fretted)	1.4 (fretted)	
2024-T4 aluminium alloy	110	0.2	0.2	Swanson ⁷
2024-T3 aluminium alloy	0	0.35	0.2	Hillberry ⁴⁷
	0	0.5	0.3	Brown and Ikegami ⁴⁸
	0	0.3	0.2	Fuller ⁵¹
	0	0.2	0.15	
6061-T6	0	0.5	0.3	Brown and Ikegami ⁴⁸
Titanium alloy 6 Al 4V	0	-	0.3	Cardrick and Perrett ⁵² (Appendix F)
Mild steel EN 1A	0	-	0.4	Booth, Wright and Smith ⁵³
Mild steel EN 15	0	-	0.4	

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37	W. Schütz	On the selection of optimum materials for fatigue-loaded structures. Z.f. Werkstofftechnik/J. of Materials Technology, <u>2</u> , 4, 189-197 (1971), RAE Library Translation 1625, November 1971
38	D.J. White J. Lewszuk	Cumulative damage in fretting fatigue of pinned joints subjected to narrow band random loading. The Aeronautical Quarterly, pp.400-408, November 1970

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<u>No.</u>	<u>Author</u>	<u>Title, etc.</u>
39	P.R. Edwards M.G. Earl	On the fatigue performance of clad and unclad notched specimens in aluminium alloy. RAE unpublished work (1973)
40	T.R.G. Williams J.A. Sova	Studies of fatigue damage in aluminium alloys. Department of Mechanical Engineering, University of Southampton, July 1970
41	J.A. Sova	Fatigue studies of aluminium alloy L16, L71 and L73 with particular reference to discontinuities in the fatigue S-N curve. Ph.D. Thesis, University of Southampton (1972)
42	A.K. Head F.H. Hooke	Random noise fatigue testing. International Conference on Fatigue of Metals (1956)
43	P.W. Smith C.I. Malme	Fatigue tests of a resonance structure with random excitation. The Journal of the Acoustical Society of America, Vol.35, No.1, January 1963
44	J. Kowalewski	Über die beziehungen zwischen der lebensdauer von bauteilen bei unregelmäßig schwankenden und bei geordneten belastungsfolgen. DVL Bericht No.249, September 1963
45	K.J. Marsh J.A. Mackinnon	Random loading and block loading fatigue tests on sharply notched mild steel specimens. J. Mech. Eng. Science Vol.10, No.1, February 1968
46	R.W. Fralich	Experimental investigation of effects of random loading on the fatigue life of notched cantilever beam specimens of SAE 4130 normalised steel. NASA Technical Note D-663, February 1961
47	B. Hillberry	Fatigue of 2024-T3 aluminium alloy due to broad band and narrow band random loading. USA Iowa State University (1967)
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49	W.T. Kirkby P.R. Edwards	A method of fatigue life prediction using data obtained under random loading conditions. RAE Technical Report 66023 (1966)
50	J. Schijve F.A. Jacobs	Program - fatigue tests on notched light alloy specimens of 2024 and 7075 material. National Aeronautical Research Institute, Amsterdam (1960)
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53	R.T. Booth D.H. Wright N.P. Smith	Variable-load fatigue tests on small specimens. Second Report: A comparison of loading patterns and the influence of occasional high loads. MIRA Report 1969/9, April 1969

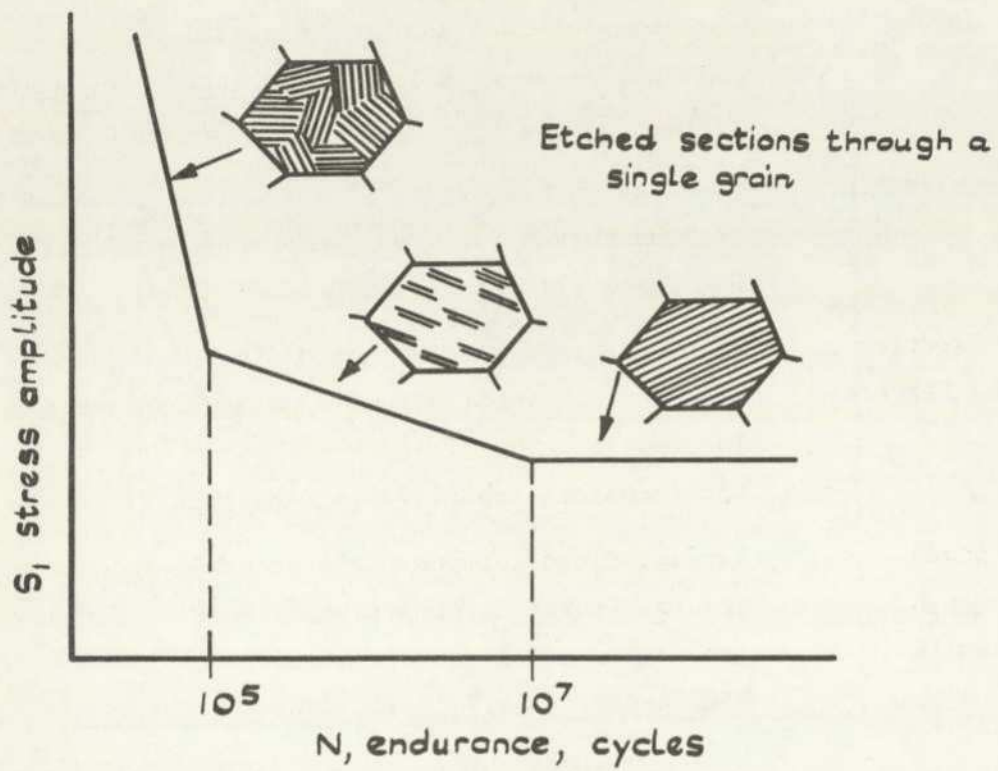


Fig.1.1 Idealised S-N curve showing three damage ranges
(after Wood, Reimann and Sargent. Ref. 3)

Fig.1.2

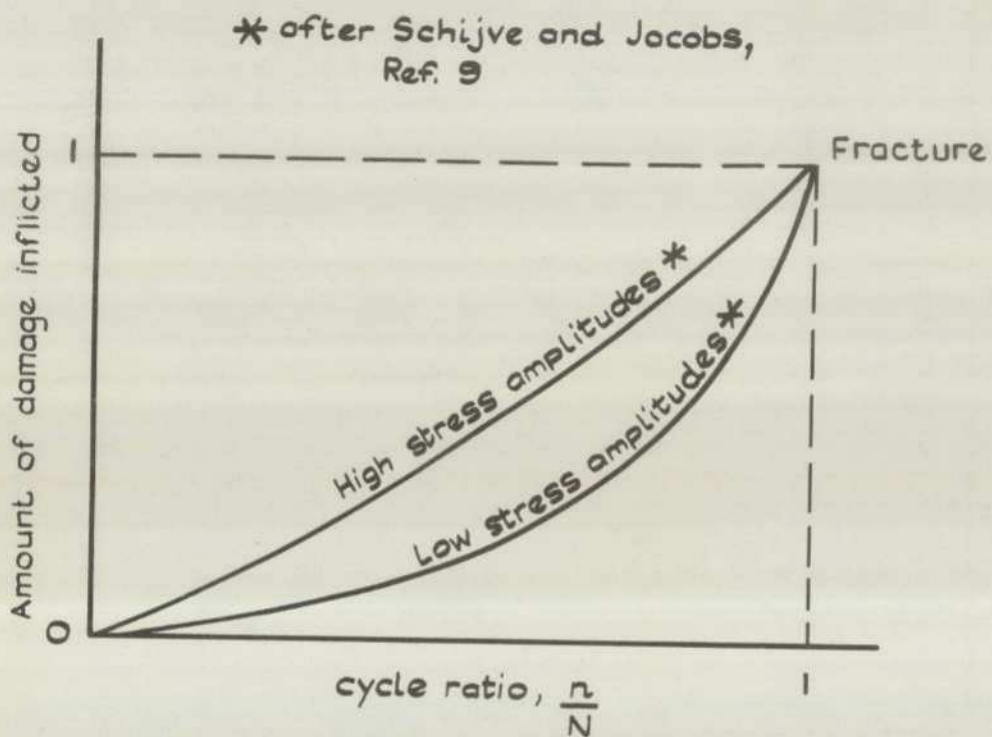


Fig. 1.2 Typical stress-dependent damage-cycle relationships
(after Kaechele, Ref. 10)

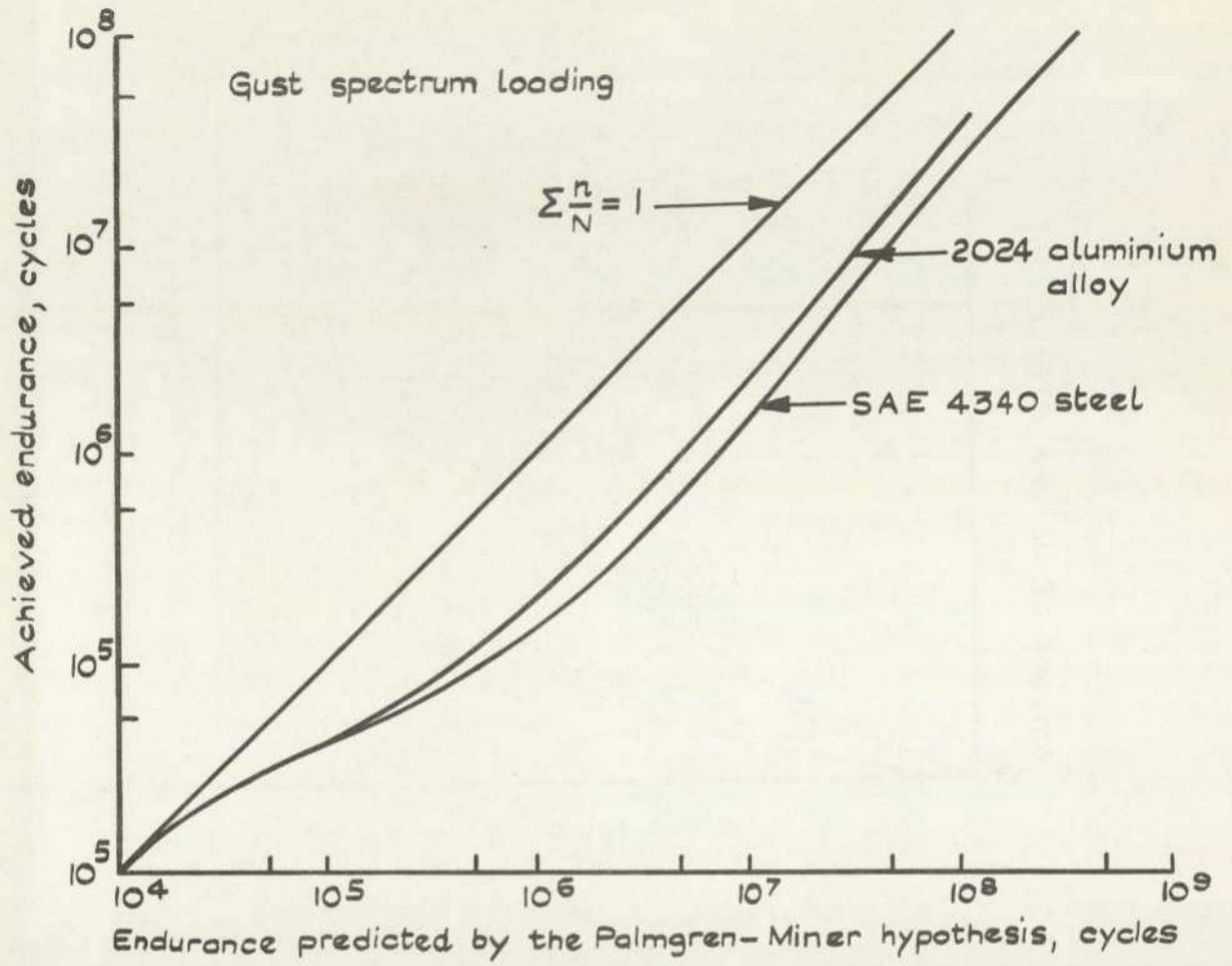


Fig.1.3 Comparison of predicted and achieved endurance for plain specimens
(after Freudenthal and Heller. Ref.11)

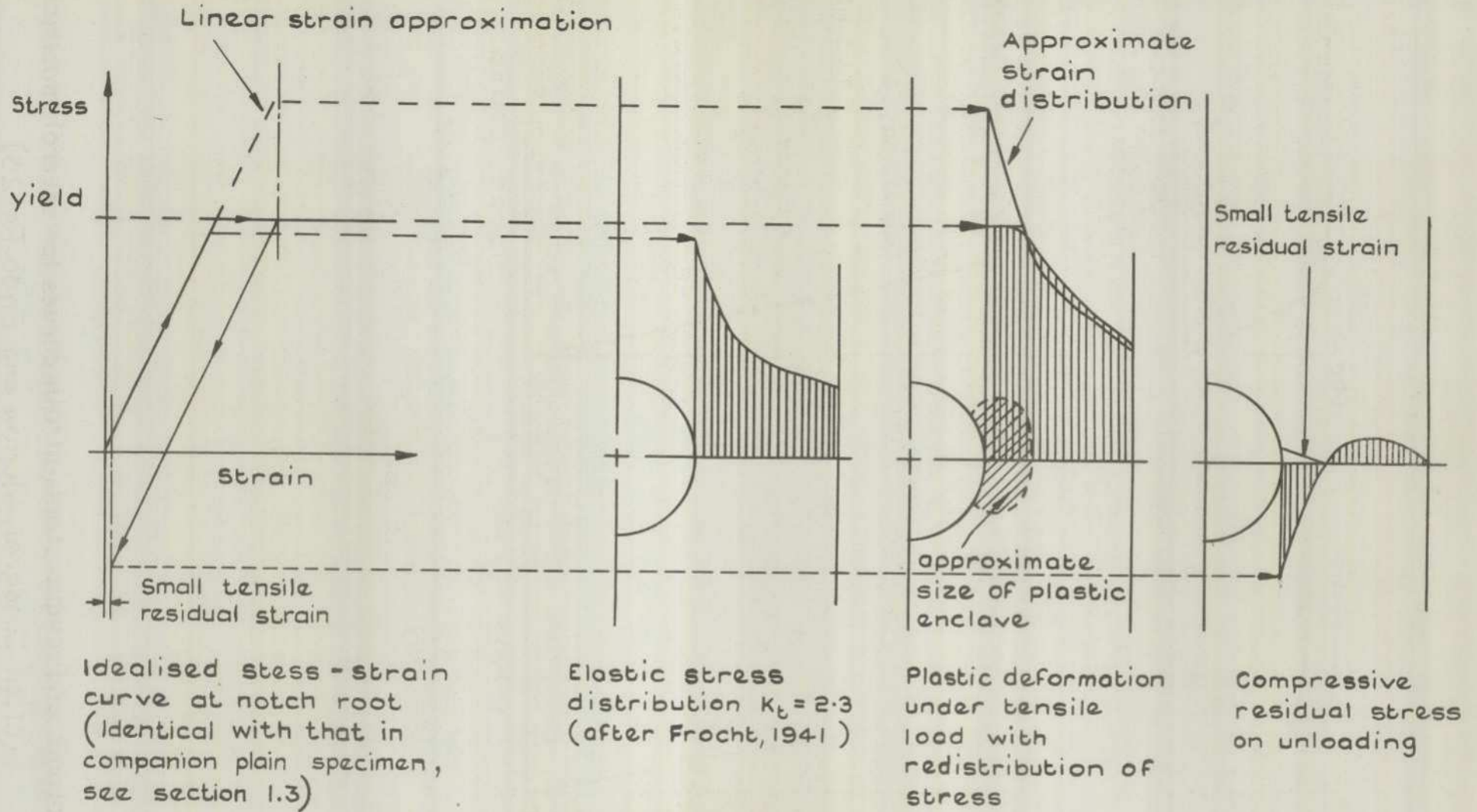


Fig. 1.4 Generation of compressive residual stress at notch root

Fig.1.5

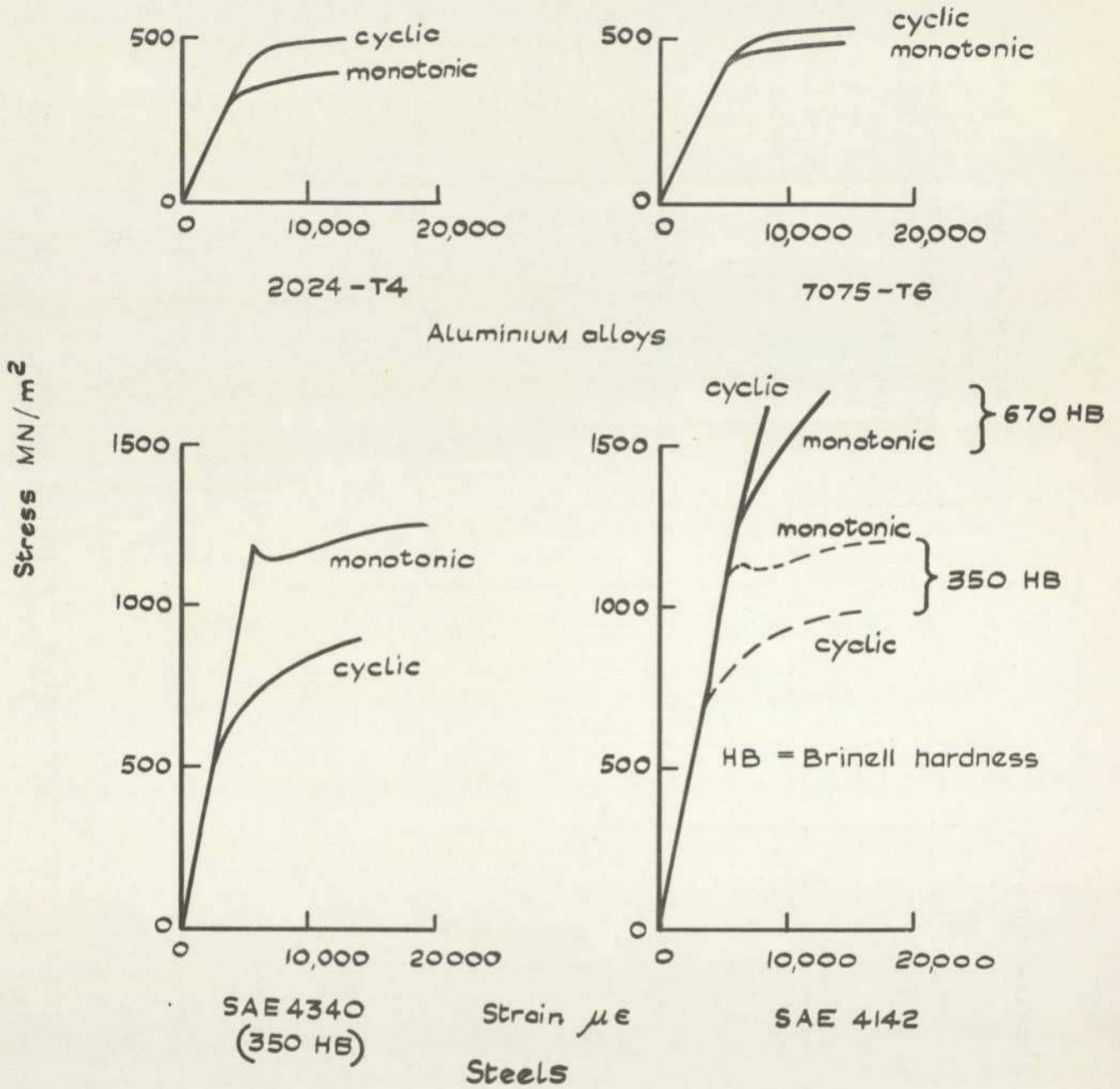
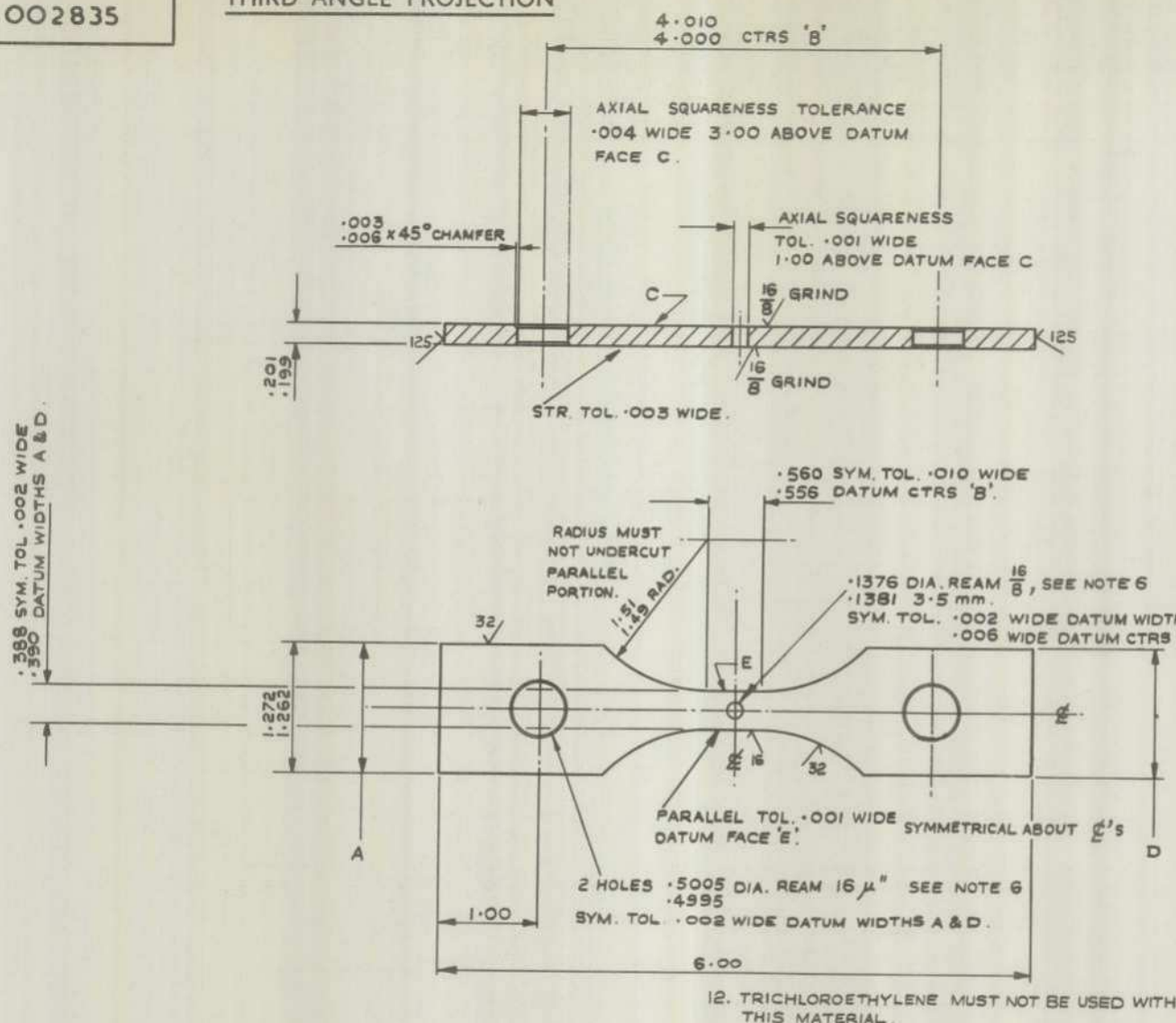


Fig1.5 Monotonic and cyclic stress-strain curves for several materials (after Landgraf, Morrow and Endo. Ref.26)

THIRD ANGLE PROJECTION



12. TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL.

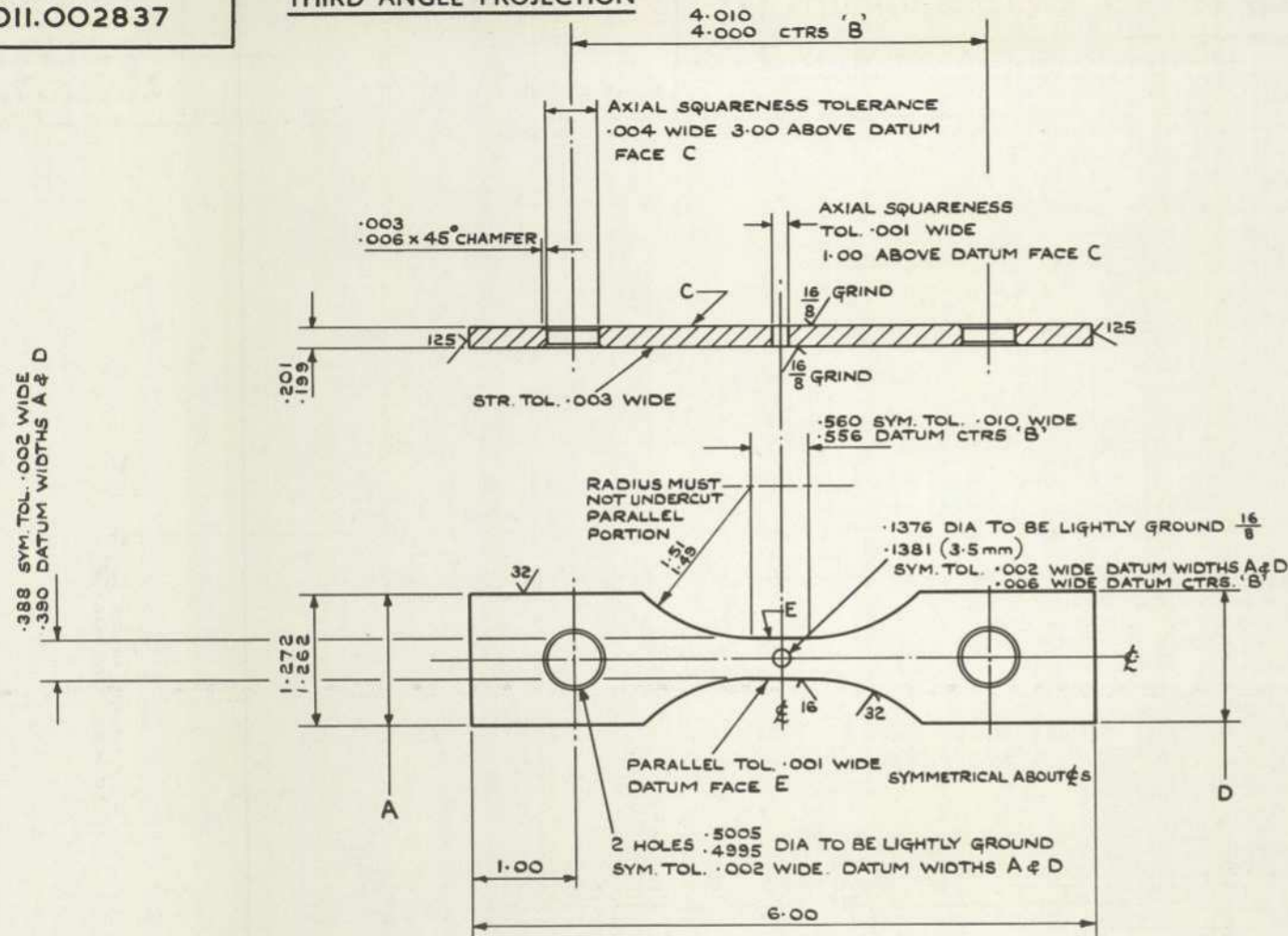
1. ROUGH MACHINING TO BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED,
CHAMFER $\cdot 001 - \cdot 010 \times 45^\circ$
3. SHARP EDGES OF 3.5 mm.
HOLE TO BE LIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER $\cdot 001 - \cdot 005 \times 45^\circ$
4. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
5. BLANKS TO BE MACHINED TO LENGTH & IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED.
9. SPECIMENS TO BE PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS WITH SUITABLE DESSICANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
10. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ ".
11. 3.5 mm. HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING.

					C	14-7-76
					B	25-9-68
					A	9-5-68
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	
CERTIFIED						

CONTRACTOR'S DRAWING REF.	128
DRAWING NUMBER	011 002835 6

011.002837

THIRD ANGLE PROJECTION



NOTES :-

1. ROUGH MACHINING TO BE DONE SYMMETRICALLY
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER $.001 - .010 \times 45^\circ$
3. SHARP EDGES OF 3.5 mm HOLE TO BE SLIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER $.001 - .005 \times 45^\circ$
4. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
5. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
8. MATERIAL TO BE MARAGED TO SPECIFICATION BEFORE FINAL MACHINING
9. SPECIMENS TO BE OILED AND PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
10. WHERE $16/8$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "
11. 3.5mm HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING

						C	8-6-
						B	25-9-6
						A	9-5-6
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE		
CERTIFIED							

CONTRACTOR'S DRAWING REF.	
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130

DRAWING NUMBER

011.002837

MATERIAL
D.T.D. 5212 18NI-CO-MO
O.V.M. MARAGING STEEL
TO BE SUPPLIED SOLUTION
TREATED SOFTENED IN
12 FT. LENGTHS 1½ x 3/8
BY FATIGUE RESEARCH
SECTION STRUCTURES
DEPT.

PROTECTIVE FINISH

TOLERANCES
± .010 UNLESS OTHERWISE
STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE

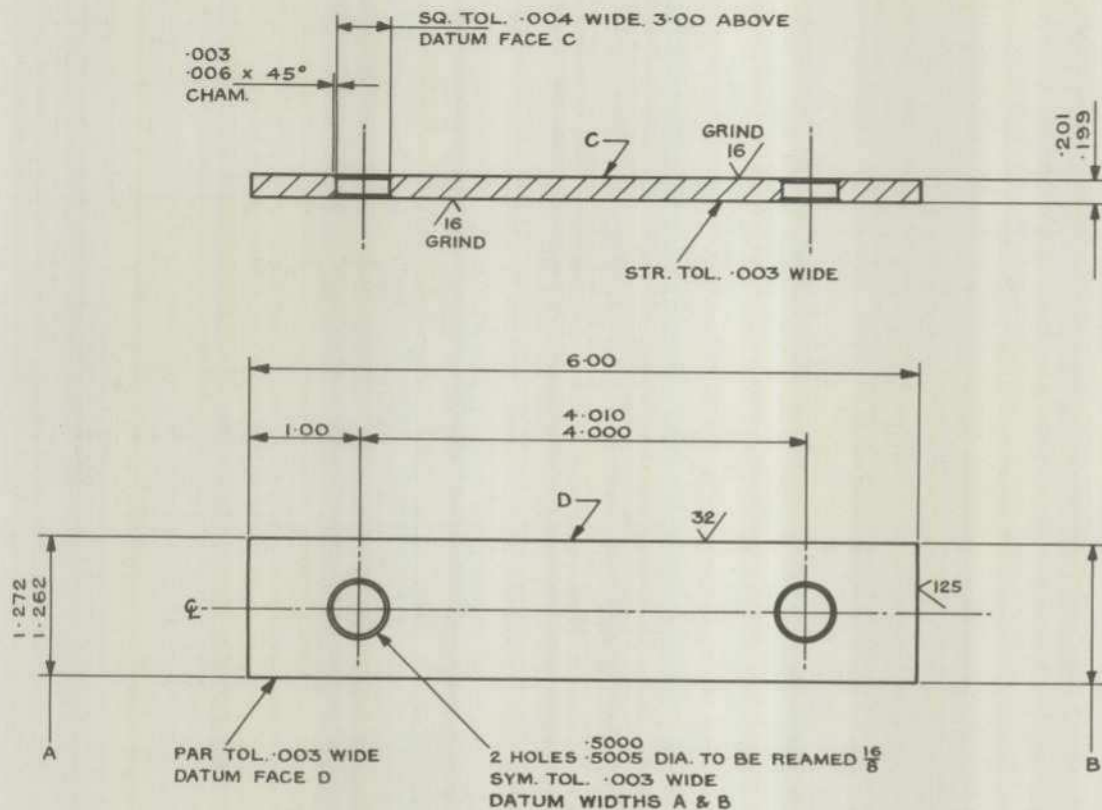
CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE
2-3 K_t NOTCHED SPECIMEN IN DTD 5212
MARAGING STEEL (HELICOPTER PROGRAMME)

THIRD ANGLE PROJECTION



NOTES:-

1. ROUGH MACHINING SHALL BE DONE SYMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES. WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
5. SPECIMENS TO BE PROTECTED BY SEALING IN POLYTHENE BAGS WITH SUITABLE DESSICANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " & 8μ .
10. TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL

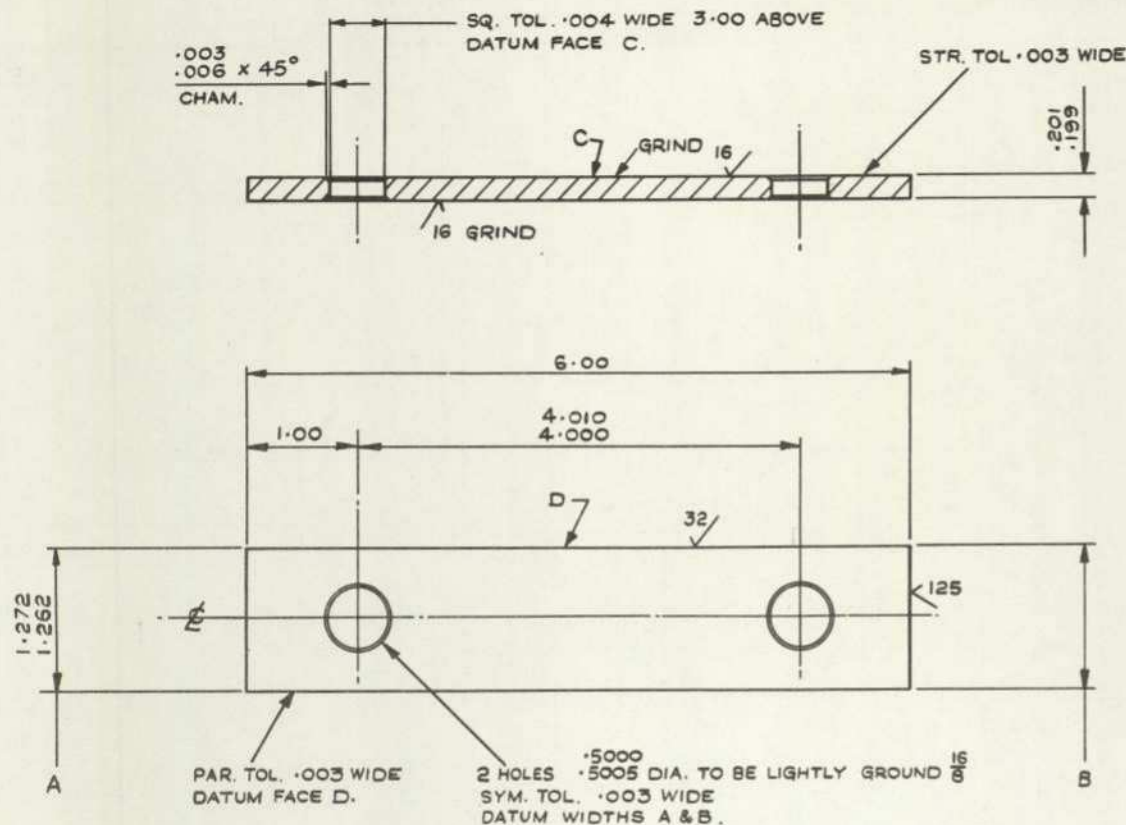
						B	14-7%
							9-5%
MOD. No.	ISSUE	DATE		MOD. No.	ISSUE	DATE	
CERTIFIED							
CONTRACTOR'S DRAWING REF.							
DRAWING NUMBER 011.002821							

Fig. 1.8

DRAWING NUMBER

011 002823

THIRD ANGLE PROJECTION



NOTES -

1. ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBER TO BE STAMPED CENTRALLY ON BOTH END FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
5. SPECIMENS TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL TO BE MARAGED TO SPECIFICATION BEFORE FINAL MACHINING.
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					
CONTRACTOR'S DRAWING REF. 122					
DRAWING NUMBER 011 002823					

MATERIAL
D.T.D. 5212
18 NI-CO-MO D.V.M.
MARAGING STEEL TO
BE SUPPLIED SOLUTION
TREATED SOFTENED
IN 12 FT LENGTHS
1 1/2" x 3/8" BY FATIGUE
RESEARCH SECTION.
STRUCTURES DEPT.

PROTECTIVE FINISH

TOLERANCES

±.010
UNLESS OTHERWISE STATED

DIMENSIONS IN INCHES.

SURFACE ROUGHNESS

SCALE FULL SIZE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE

PINNED LUG SPECIMEN D.T.D. 5212
MARAGING STEEL(HELICOPTER PROGRAMME)

SECURITY
CLASSIFICATION

SERVICE DRAWING No.

011 004460

USED ON

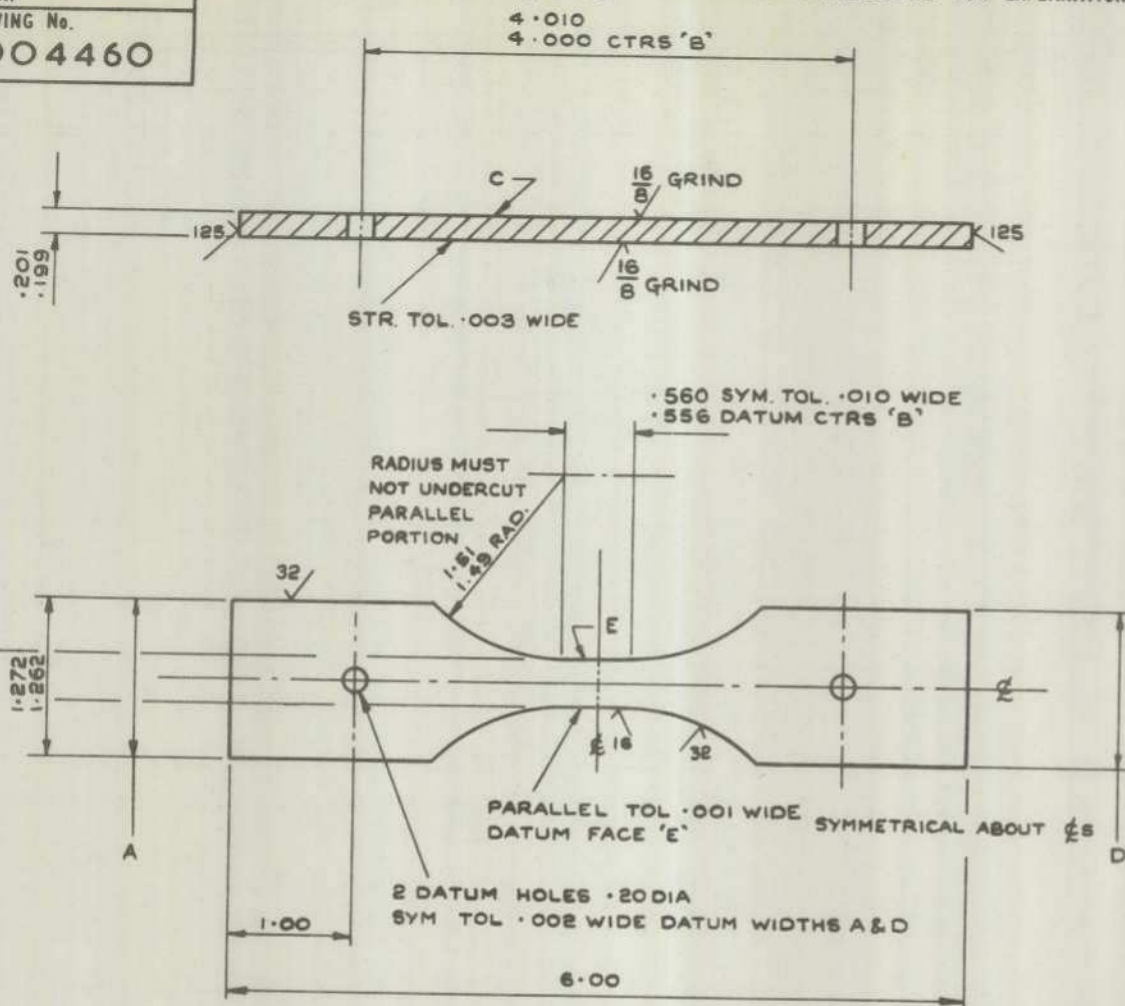
THIRD ANGLE PROJECTION

DIMENSIONS IN INCHES FOR EXPLANATION OF DIMENSIONS, NOTES, SYMBOLS ETC. SEE B.S.308

NOTES

- 1 ROUGH MACHINING TO BE DONE SYMMETRICALLY.
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED.
CHAMFER $.001 = .010 \times 45^\circ$
- 3 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 4 BLANKS TO BE MACHINED TO LENGTH & IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
- 5 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 6 MATERIAL MUST NOT BE HEAT TREATED
- 7 SPECIMENS TO BE PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS WITH SUITABLE DESSICANT
- 8 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ AND 8μ
- 9 TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL

$.388$ SYM. TOL. $.002$ WIDE
 $.390$ DATUM WIDTHS A & B



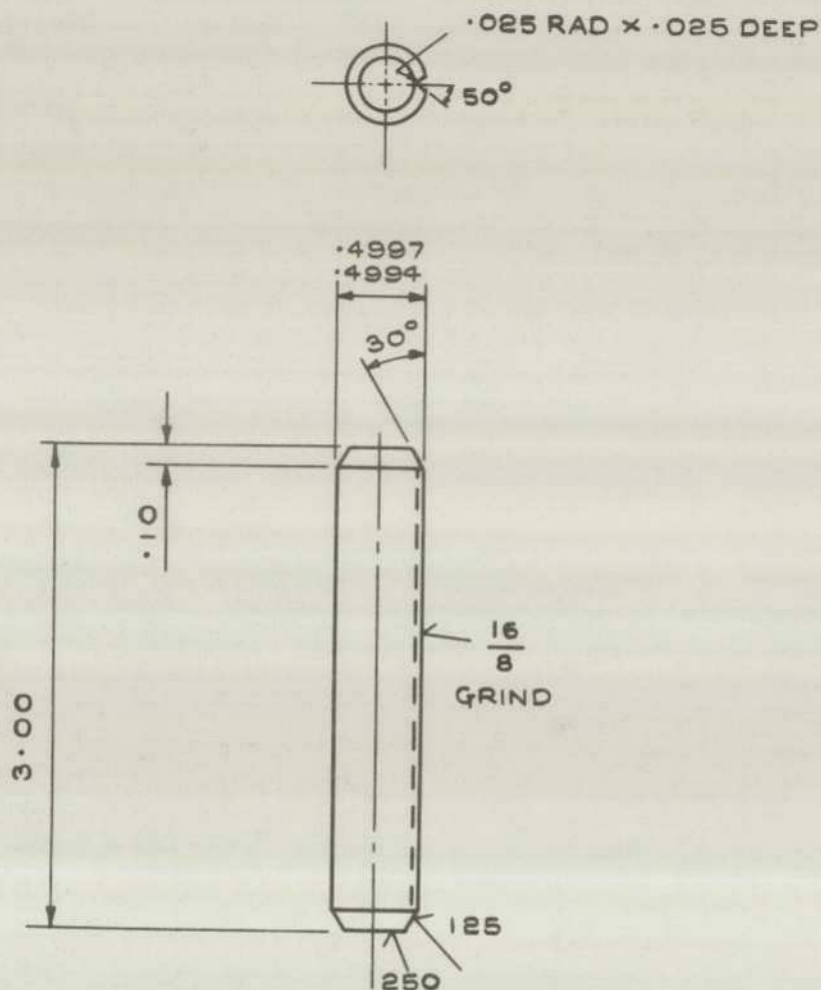
MOD. No.	ISSUE	DATE

DRAWN	CHECKED	SCALE	MATERIAL BS.2L65 BAR & BS TAIL TITANIUM ALLOY BAR TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT. IN 12 FT LENGTHS $1\frac{1}{2}'' \times 3\frac{3}{8}''$	PROTECTIVE FINISH	CONTRACTOR	CERTIFIED	SECURITY CLASSIFICATION	CONTRACTOR'S DRAWING No.	SERVICE DRAWING No. 011 004460	D A 3
DATE				TOLERANCES $\pm .010$ UNLESS OTHERWISE STATED	ROYAL AIRCRAFT ESTABLISHMENT					
					TITLE PLAIN SPECIMEN IN BS.2L 65 AND BS.T11 (COMPANION SPECIMEN INVESTIGATION)					

RETAIN ORIGINAL UNTIL -----

Fig. I.12

THIRD ANGLE PROJECTION
FOR EXPLANATION OF DIMENSIONS, NOTES, SYMBOLS, ETC. SEE BS 308



NOTES

- 1 MATERIAL TO BE HARDENED AND TEMPERED TO SPEC. BEFORE FINAL MACHINING
- 2 CENTRE DRILL HOLES MAY BE LEFT AT ENDS
- 3 PINS TO BE OILED & PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS

WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " & 8μ "

USED ON	MATERIAL BS 2598 BAR TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT IN ANNEALED CONDITION IN 12 FT LENGTHS X 5/8" DIA	TOLERANCE ± .010 UNLESS OTHERWISE STATED PROTECTIVE FINISH	SCALE			
			CONTRACTOR			
				MOD No.	ISSUE	DATE
CHECKED 			CERTIFIED			
DRAWN A.W. CARDRICK DATE	ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF TECHNOLOGY		CONTRACTOR'S DRAWING REF.			
	TITLE SLOTTED LOADING PIN FOR PINNED-LUG SPECIMENS (COMPANION SPECIMEN INVESTIGATION)		DRAWING NUMBER 011004462			

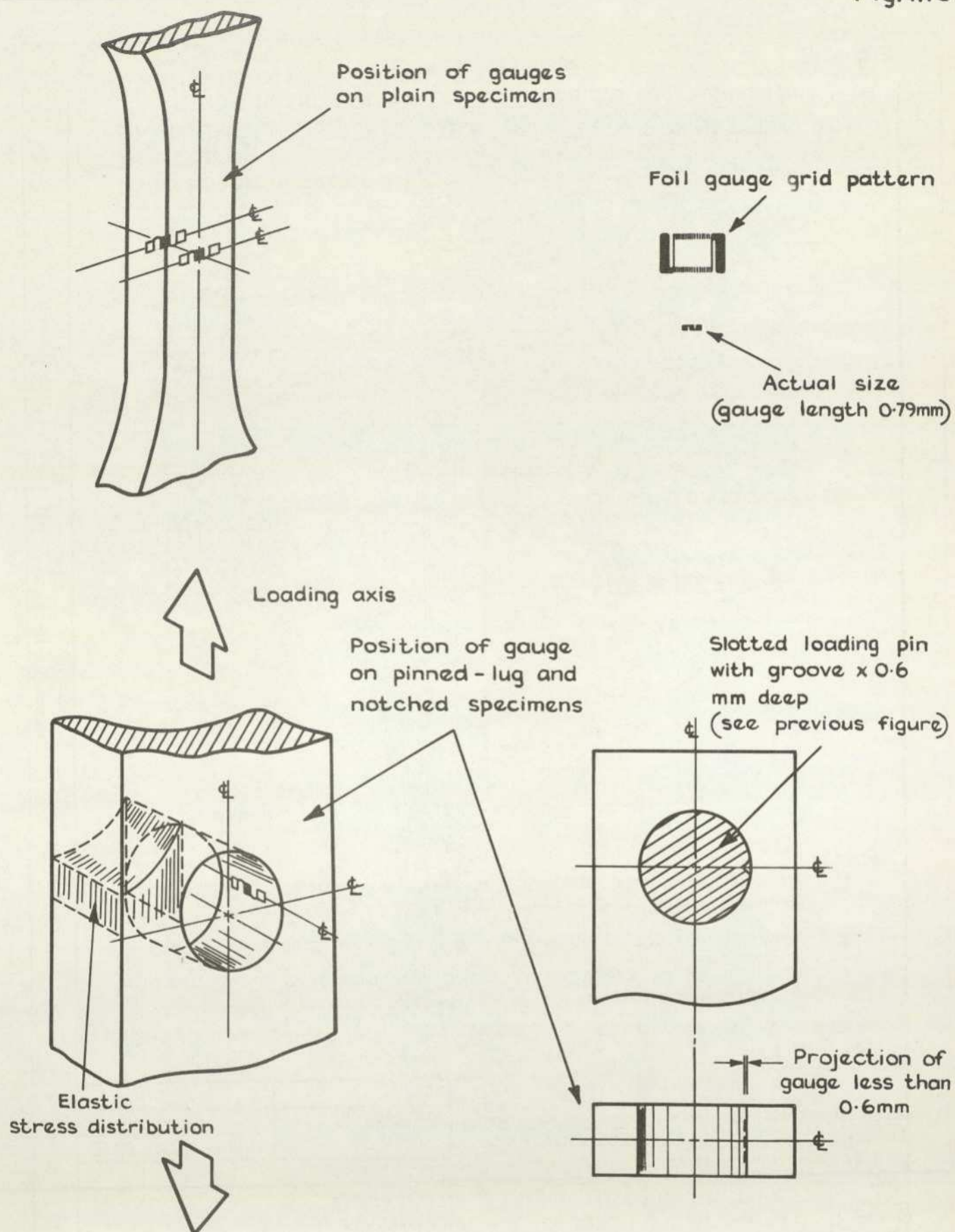


Fig. I.13 Positions of strain gauges on notched, pinned-lug and plain specimens

Fig.1.14

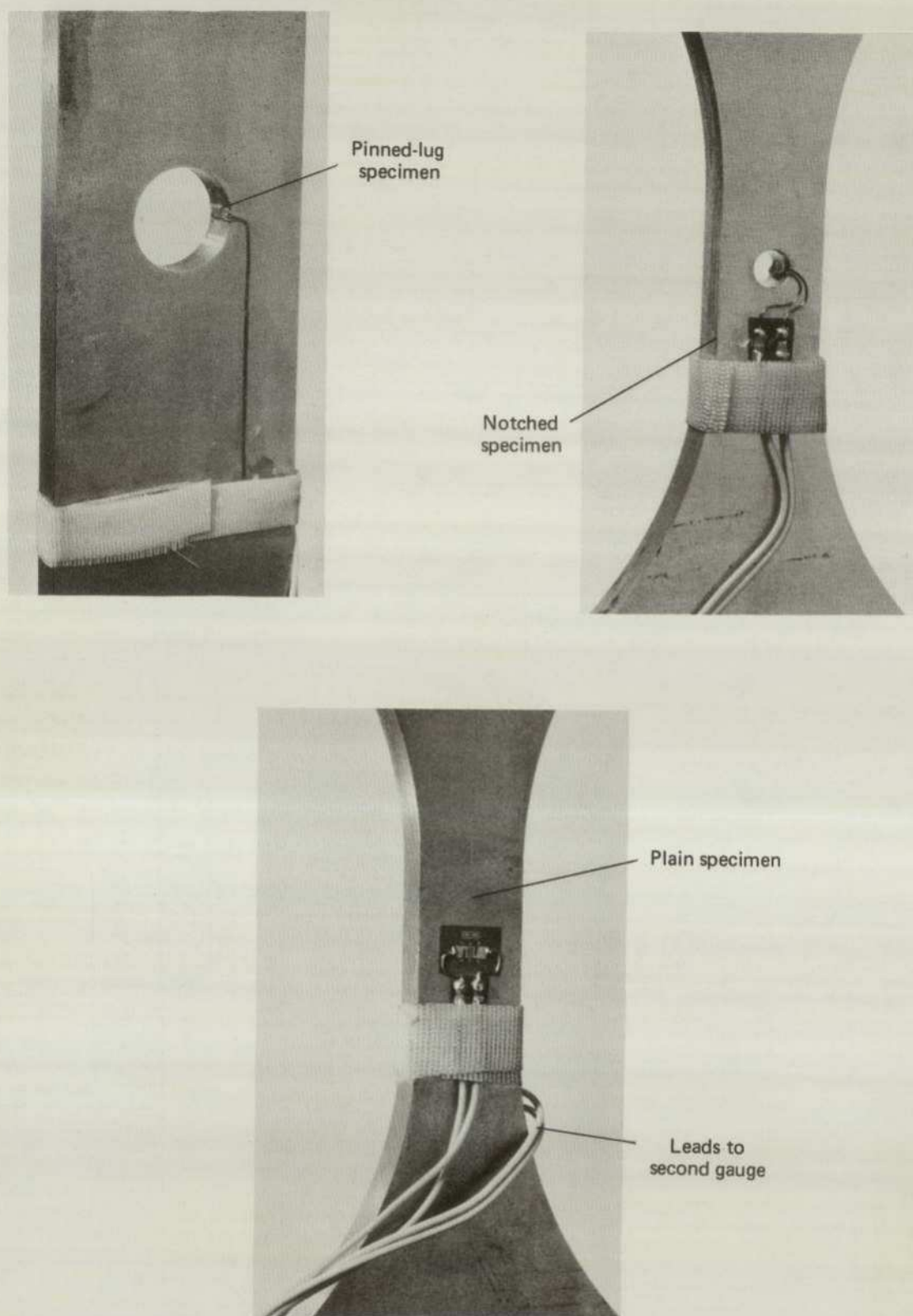


Fig.1.14 Typical specimens showing strain gauges with terminal blocks and leads

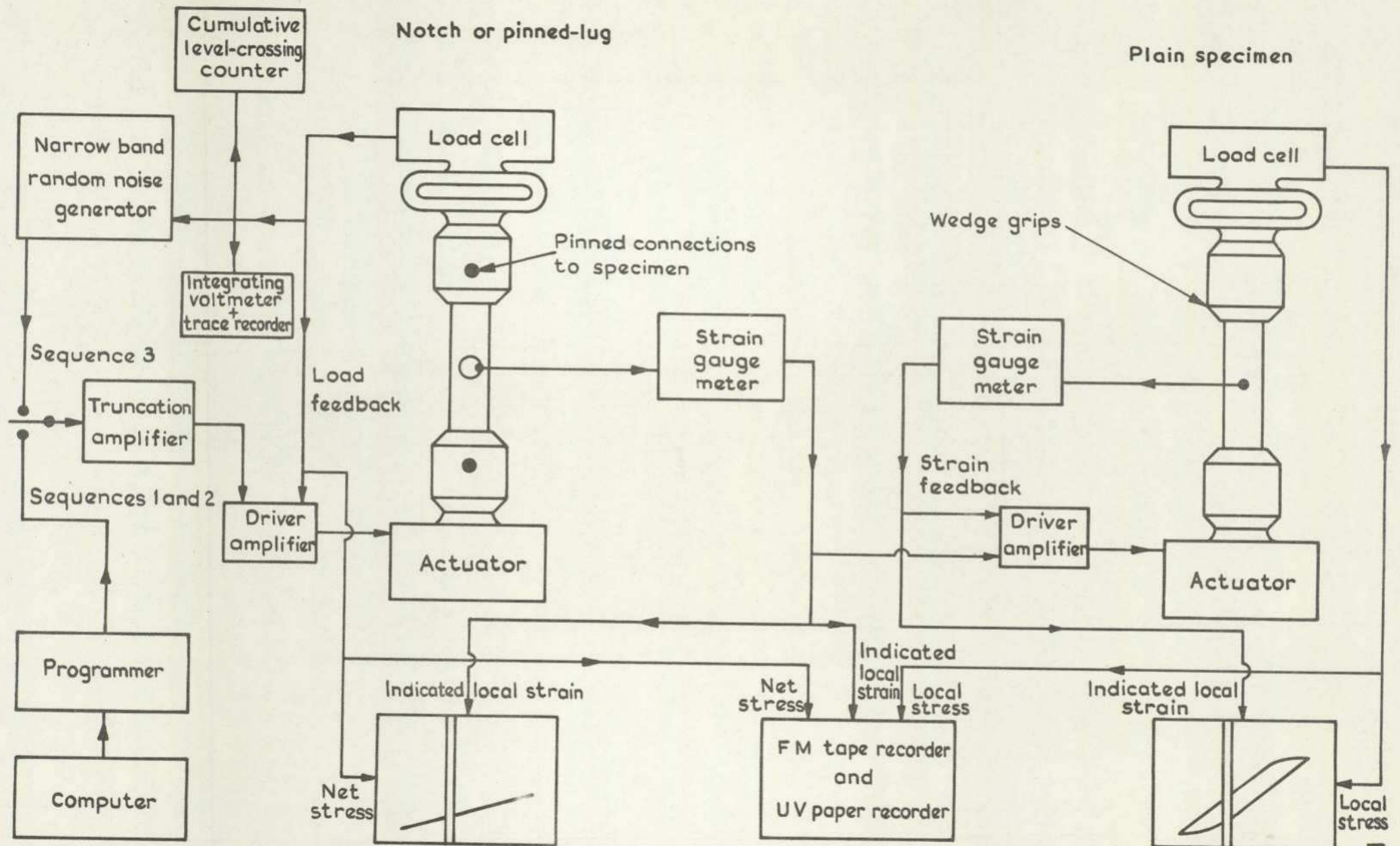


Fig. I.15 Schematic diagram of fatigue testing machines and instrumentation

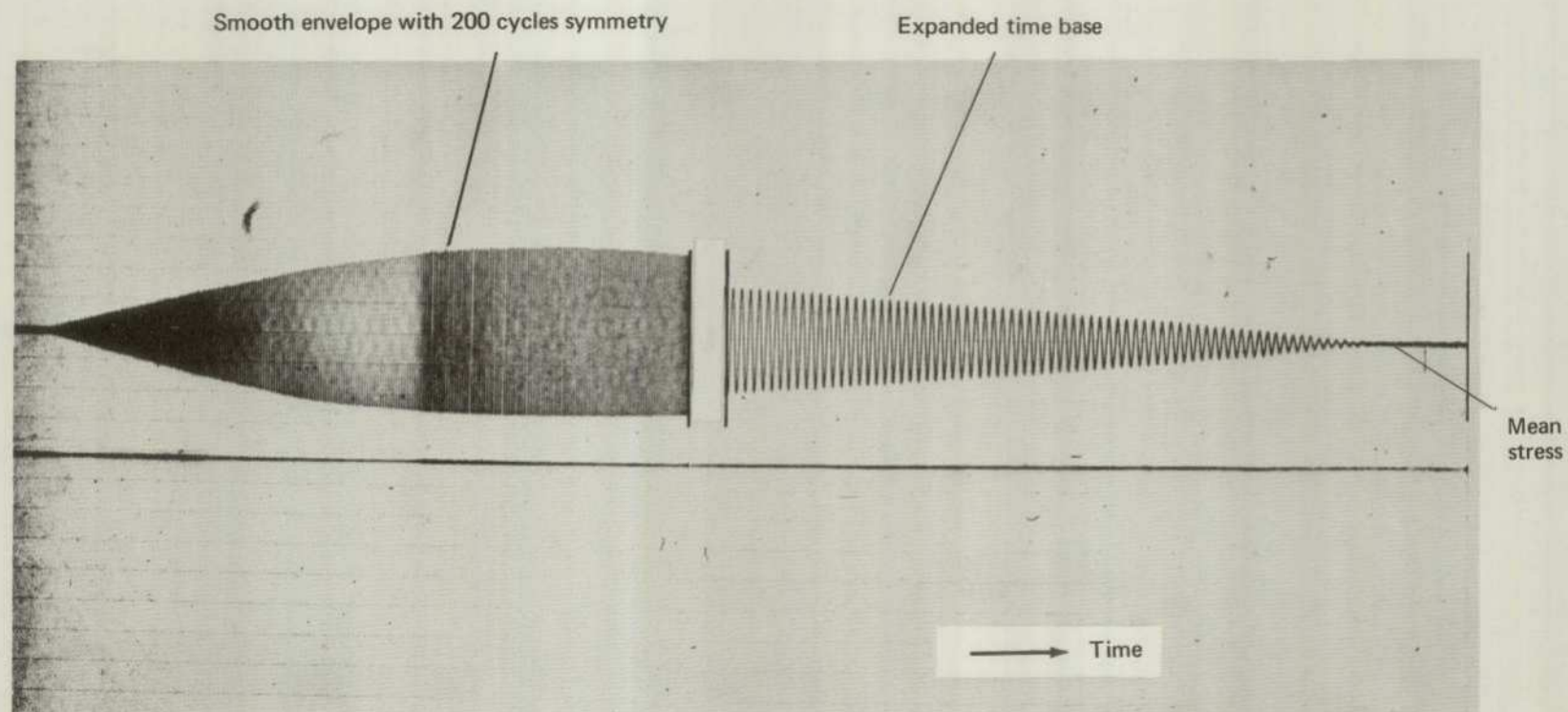
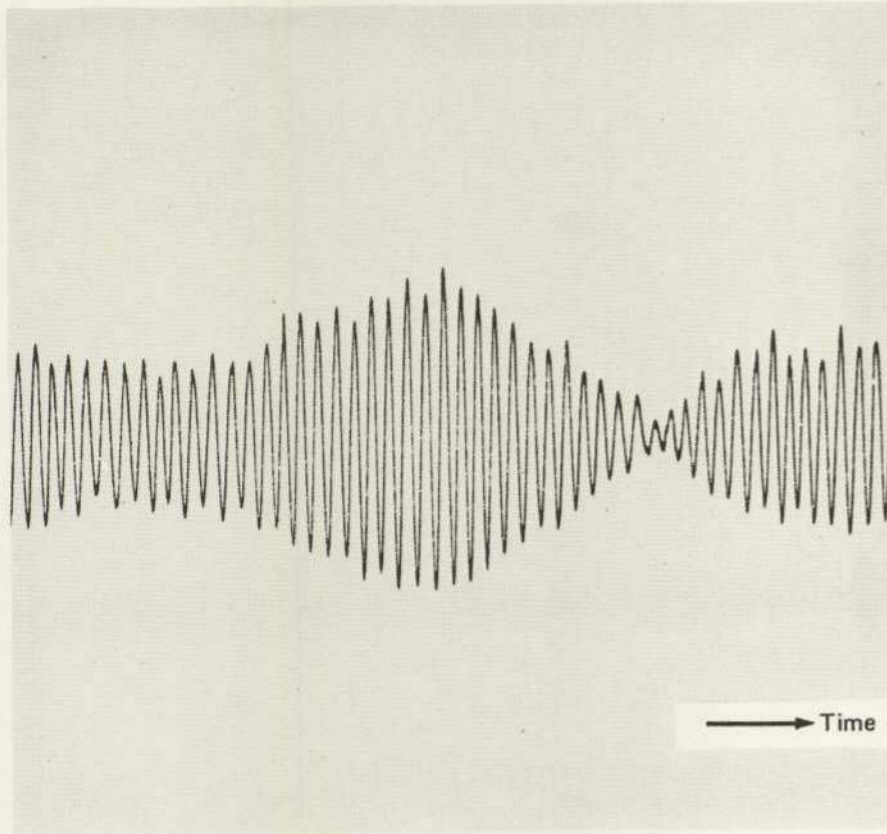


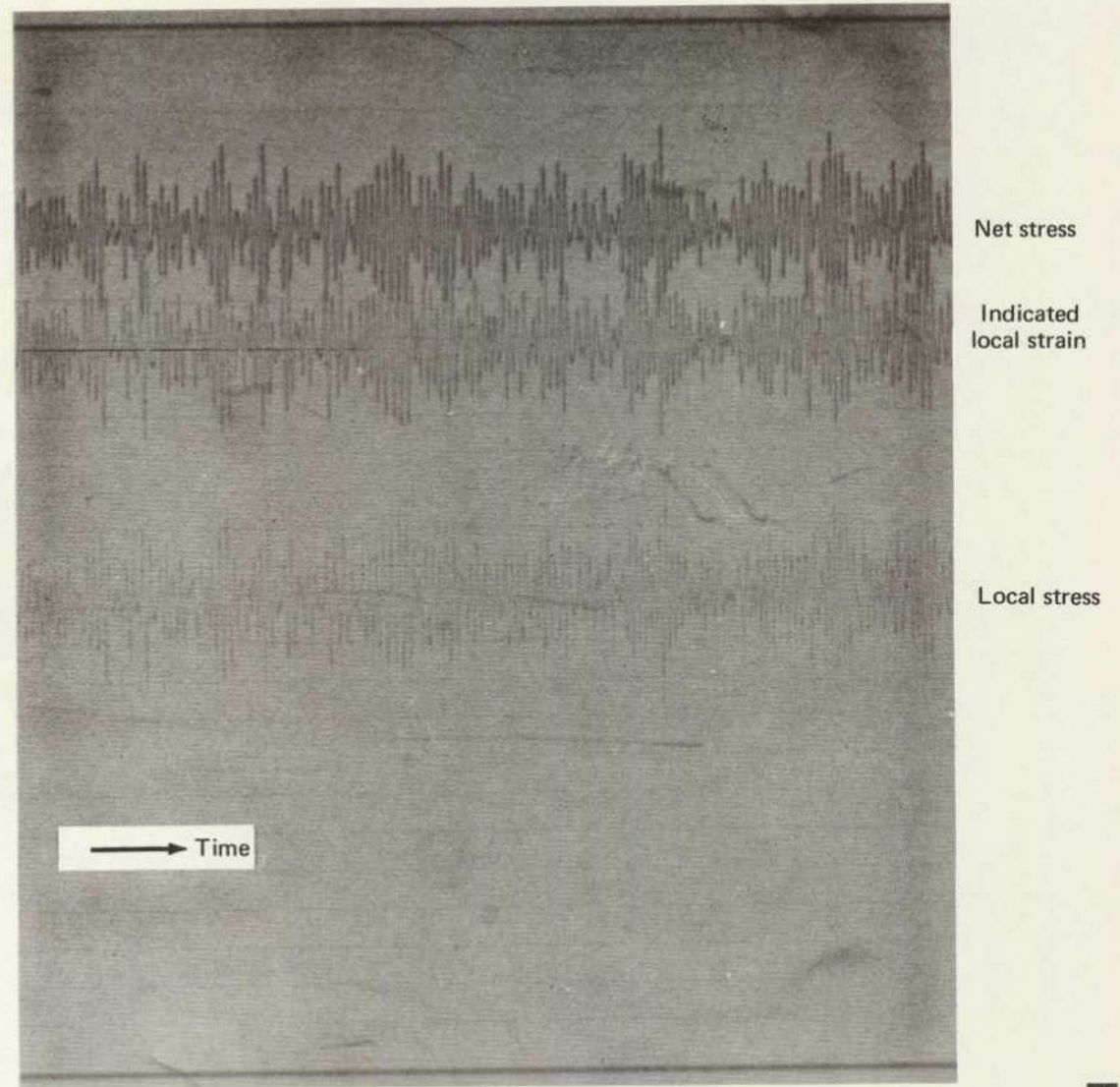
Fig.1.16 Idealised narrow band random net stress history: Sequence 2

Typical net stress history from resonant fatigue machine (maraging steel notch)



(a)

Corresponding simulated stress history using companion specimen



(b)

Fig.1.17 Comparison of typical fatigue-test and simulated stress history: Sequence 3

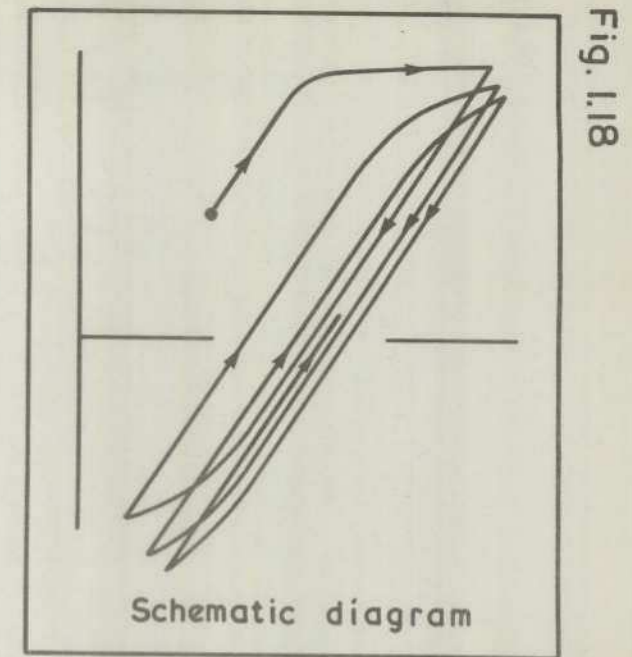
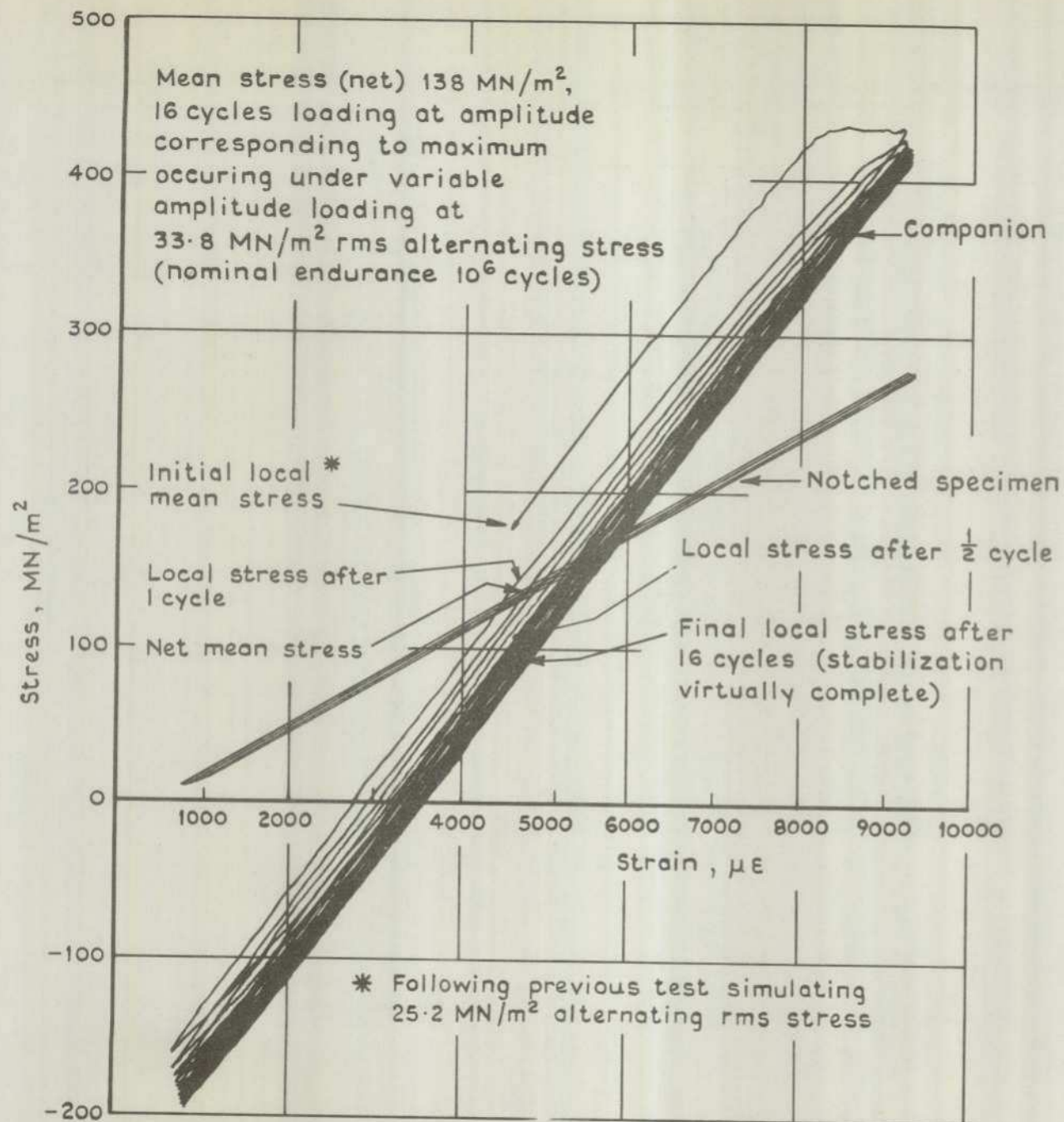


Fig. I.18

Fig. I.18 Sequence I: typical hysteresis data for aluminium alloy notch

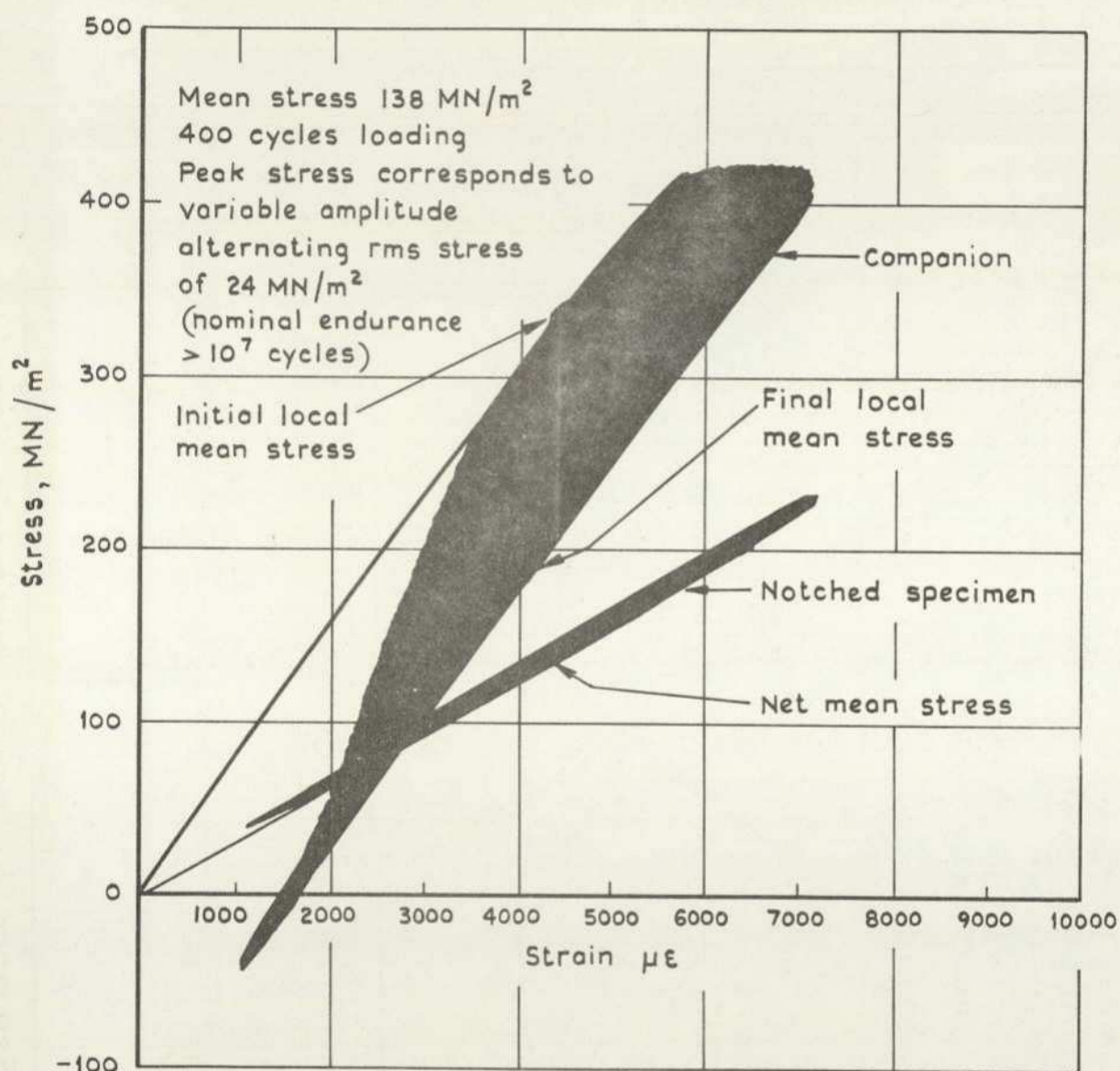


Fig.I.19 Sequence 2: typical hysteresis data for aluminium alloy notch

Fig. I. 20

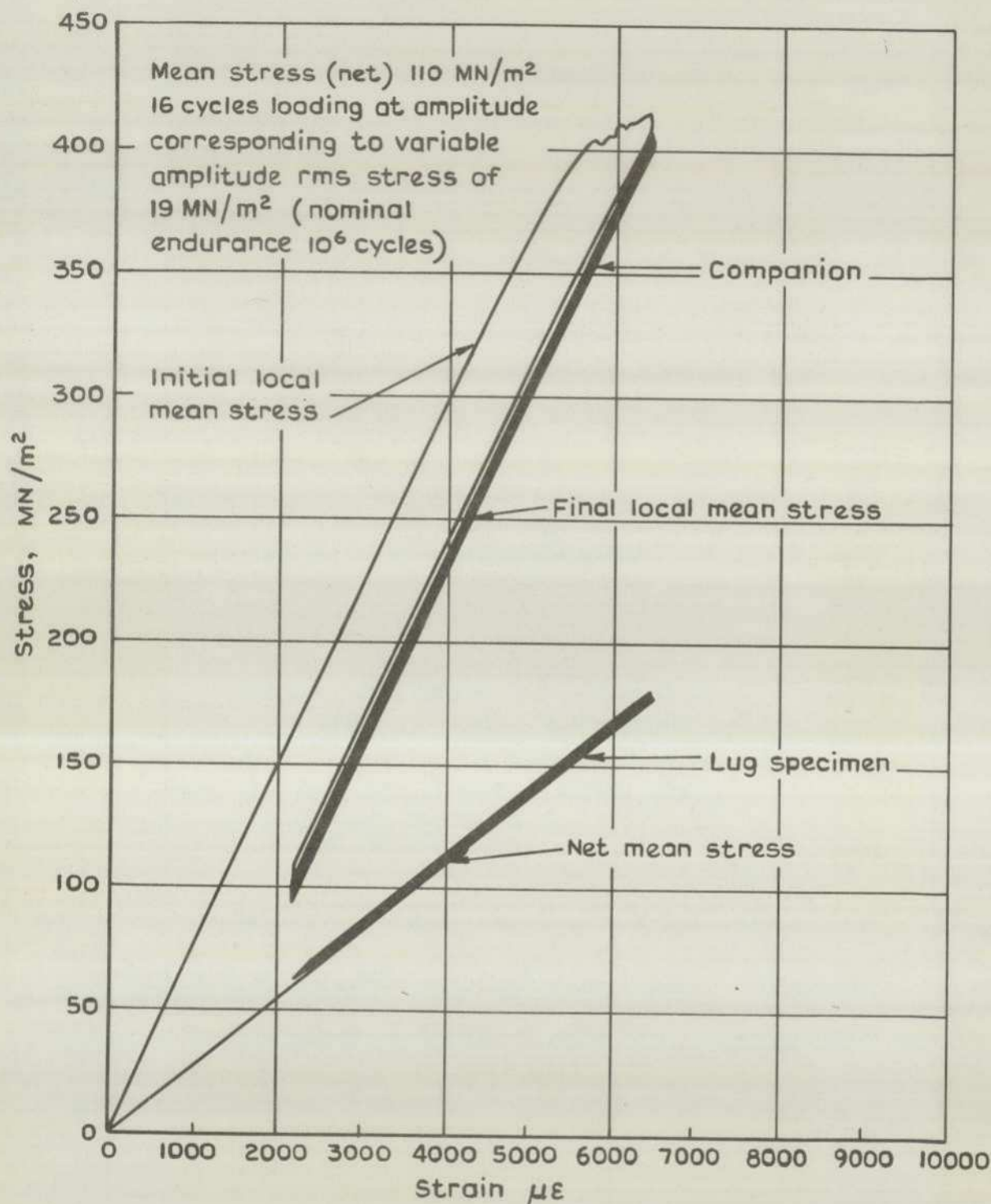


Fig. I.20 Sequence I: typical hysteresis data for aluminium alloy pinned-lug

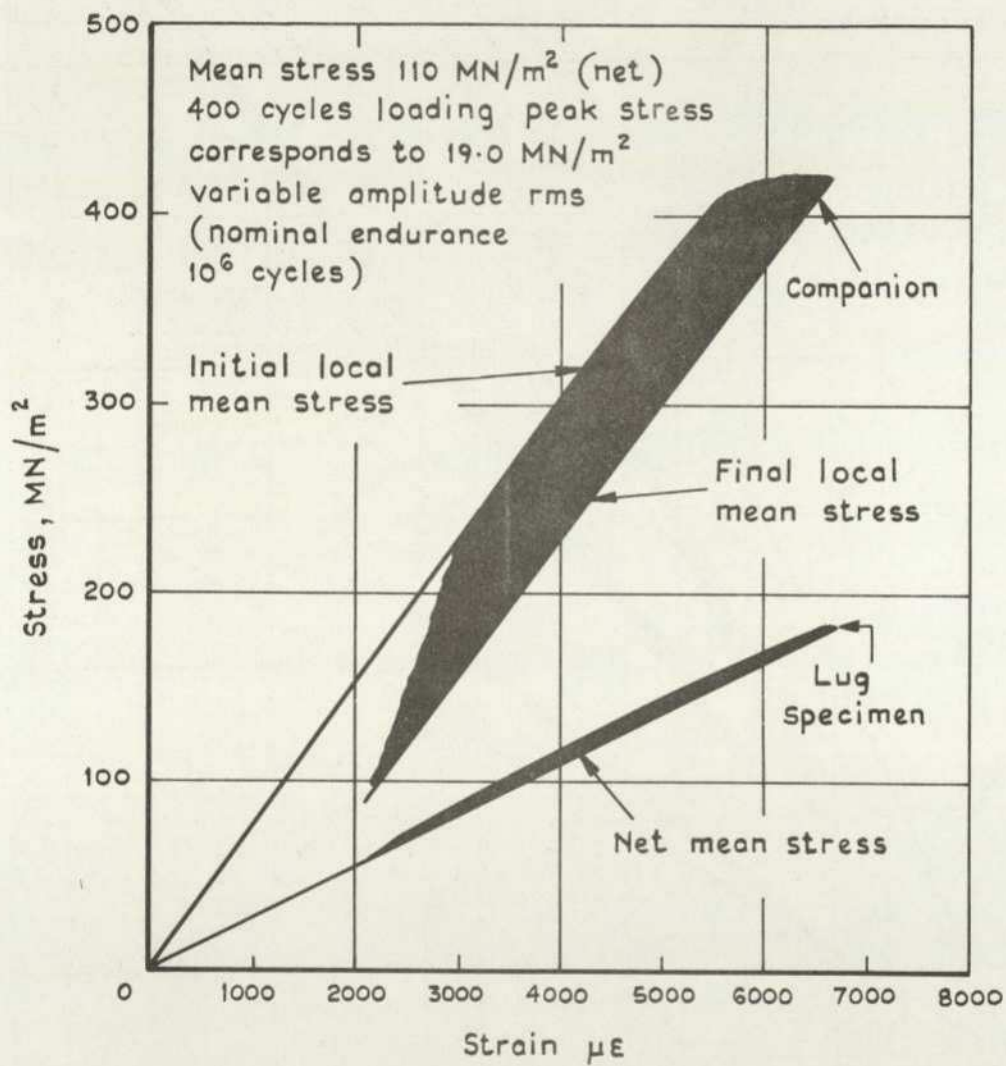


Fig. I.21 Sequence 2 : typical hysteresis data for
 aluminium alloy pinned-lug

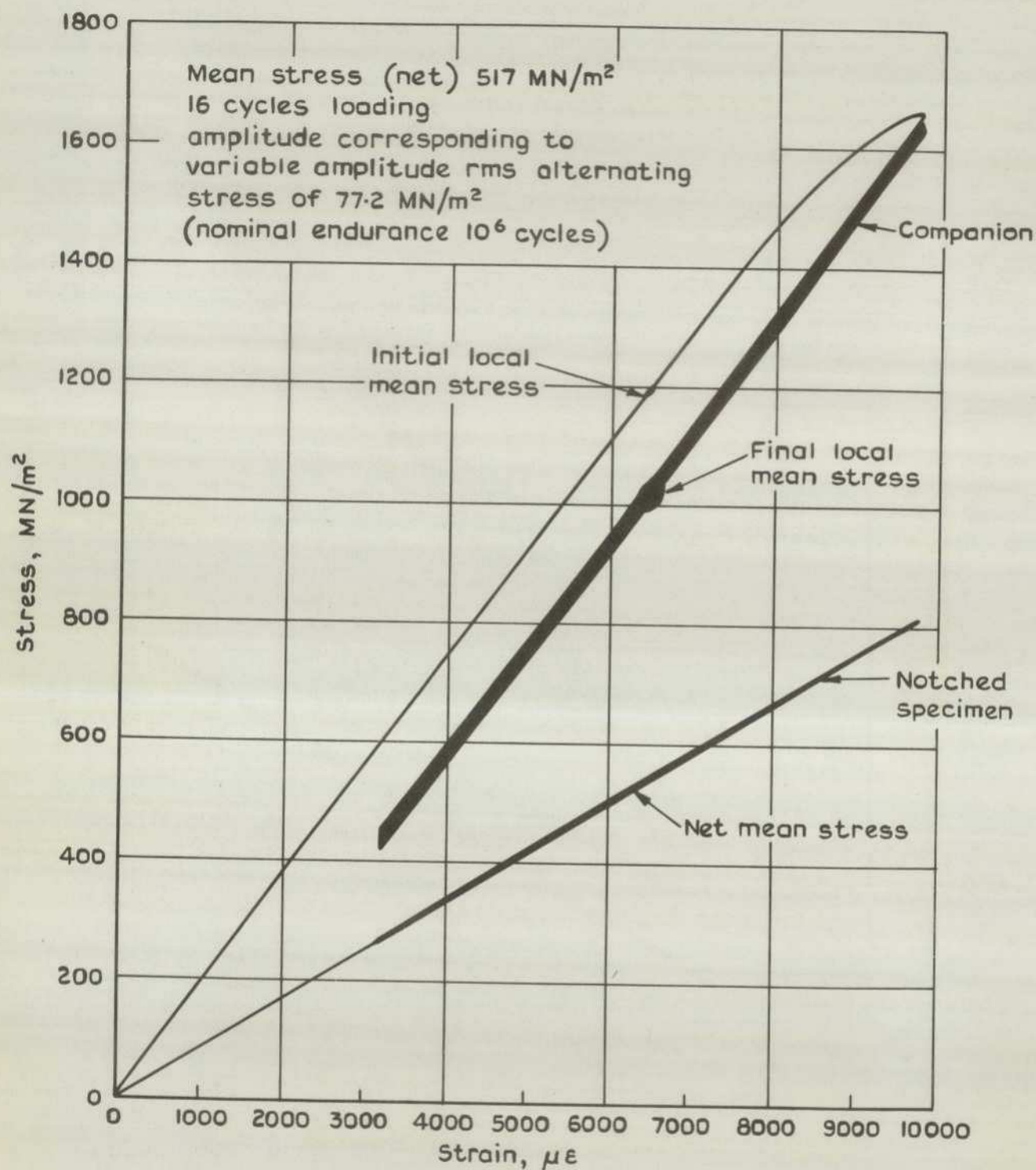


Fig. I.22 Sequence I: typical hysteresis data for maraging steel notch

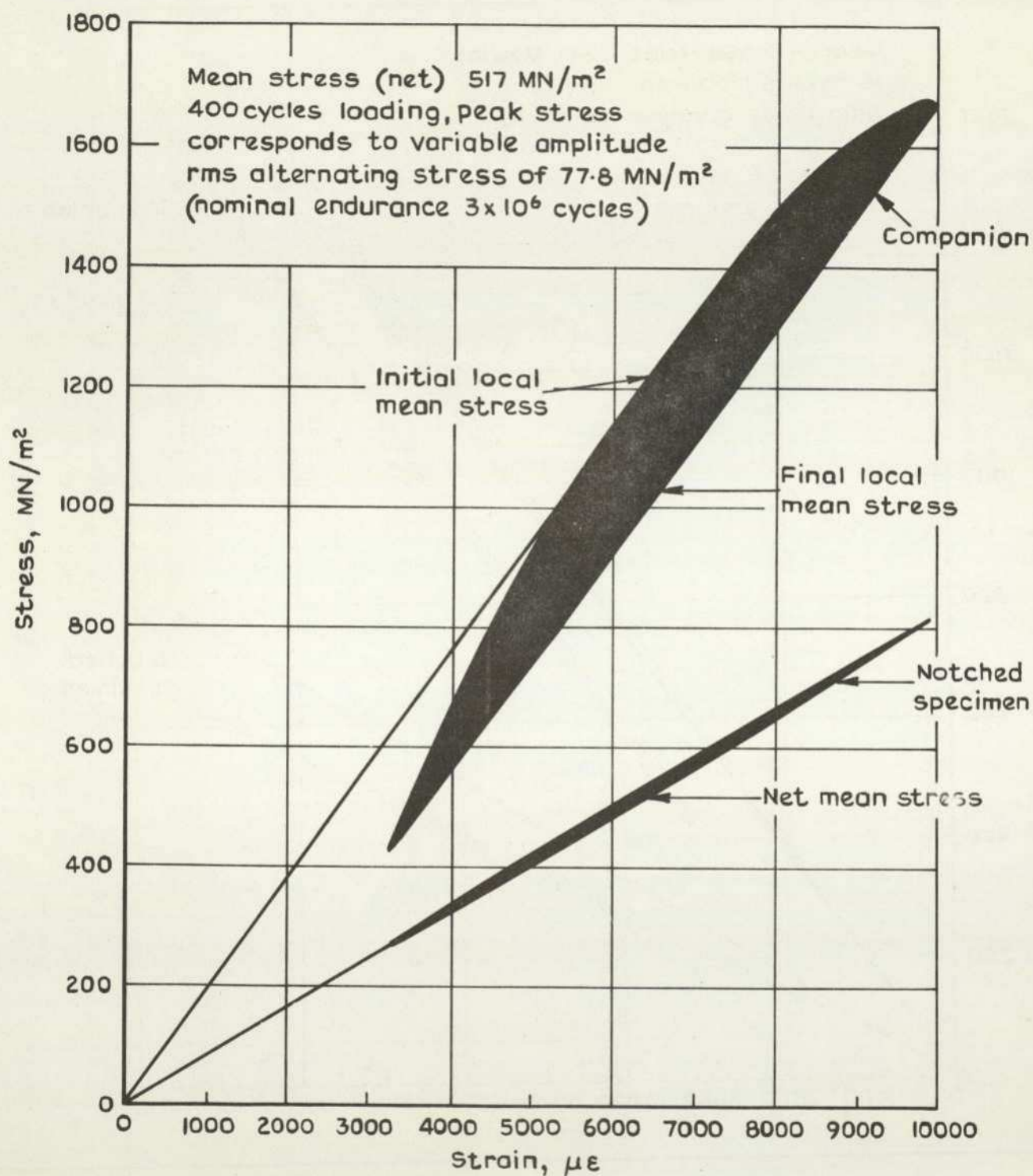


Fig. I.23 Sequence 2: typical hysteresis data for maraging steel notch

Fig. I. 24

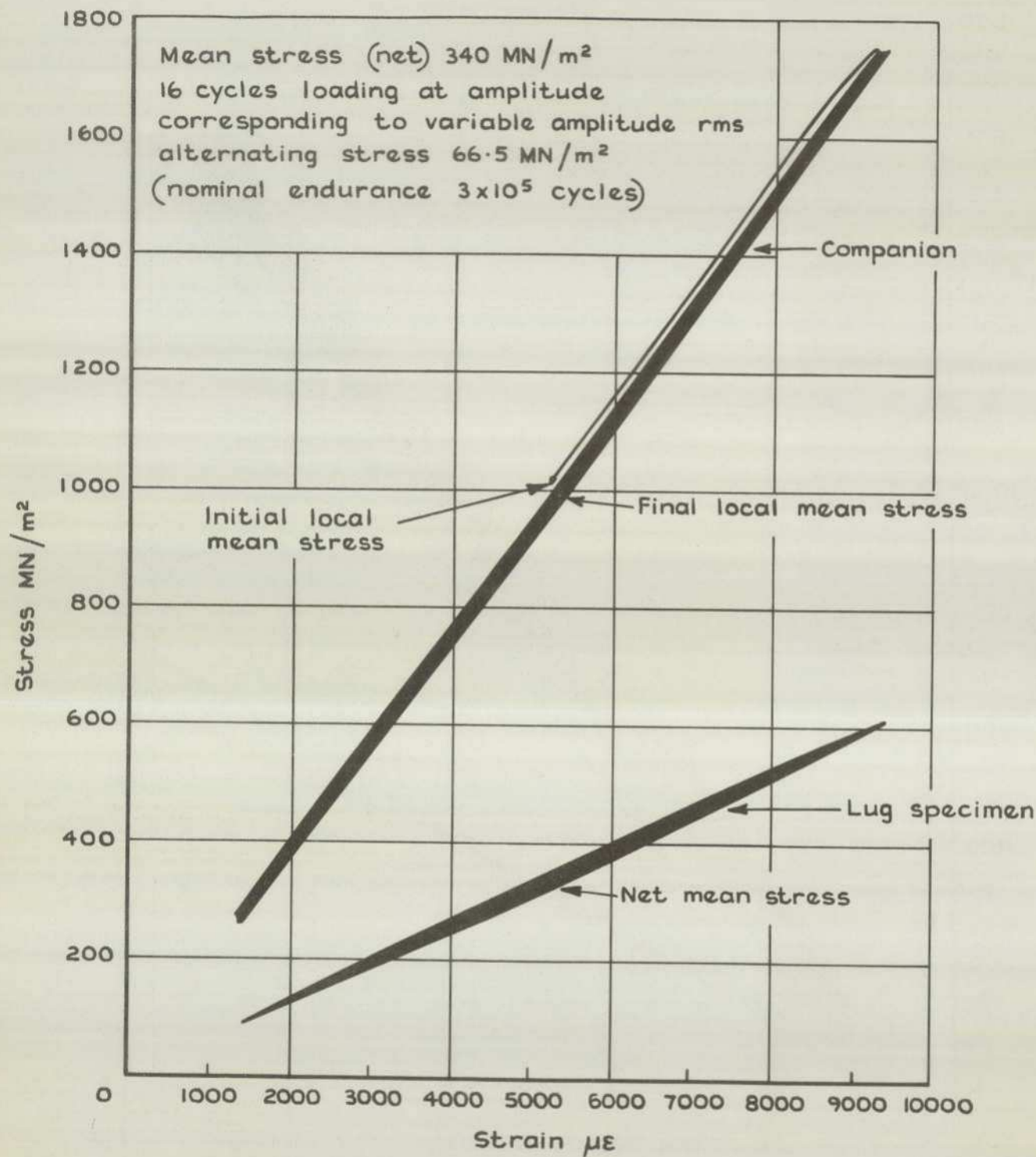


Fig. I. 24 Sequence I: typical hysteresis data for maraging steel pinned - lug

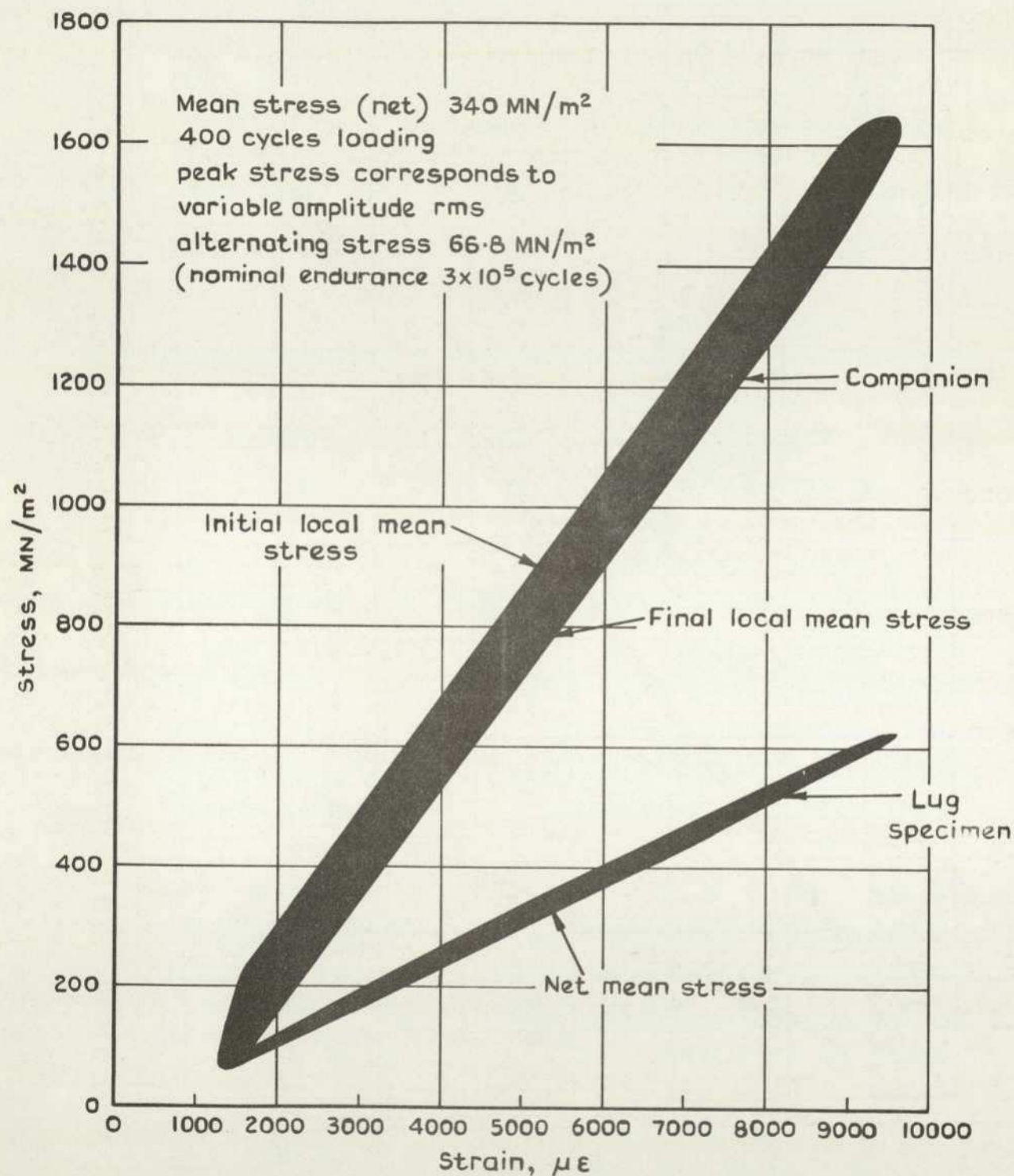


Fig. I. 25 Sequence 2: typical hysteresis data for maraging steel pinned-lug

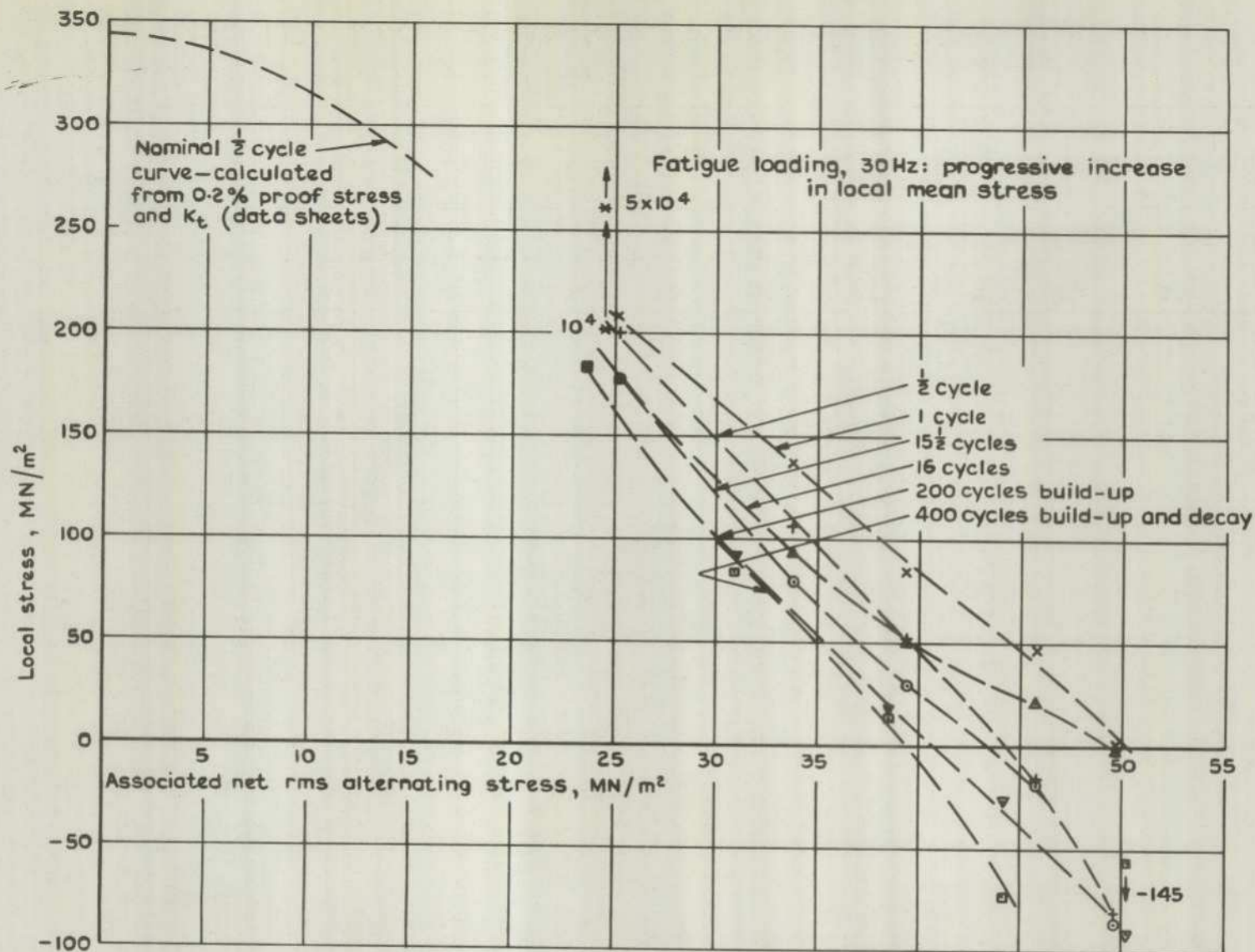


Fig. I.26 Local stress data for aluminium alloy notch

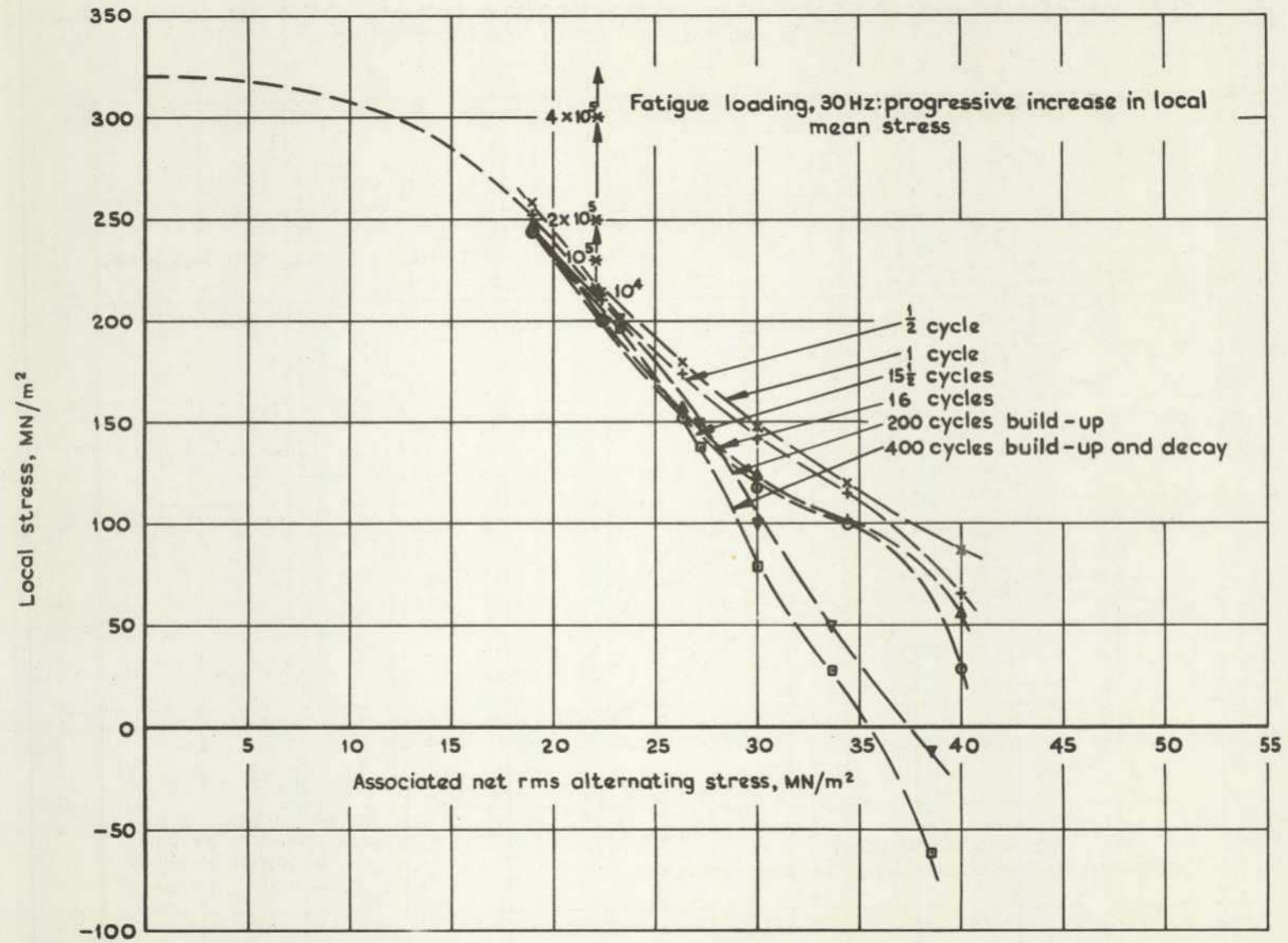


Fig. 1.27 Local stress data for aluminium alloy pinned-lug

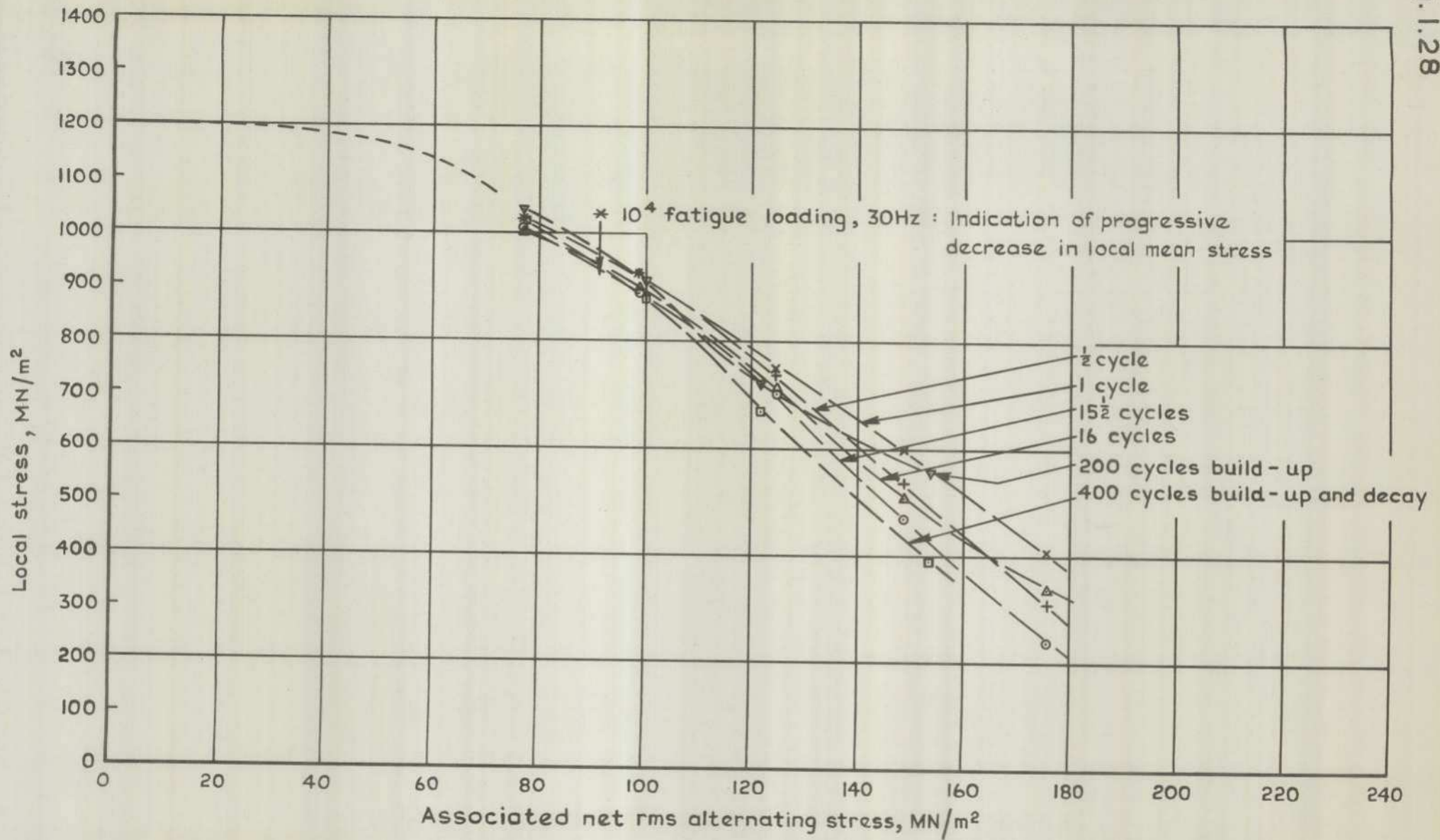


Fig. 1.28 Local stress data maraging steel notch

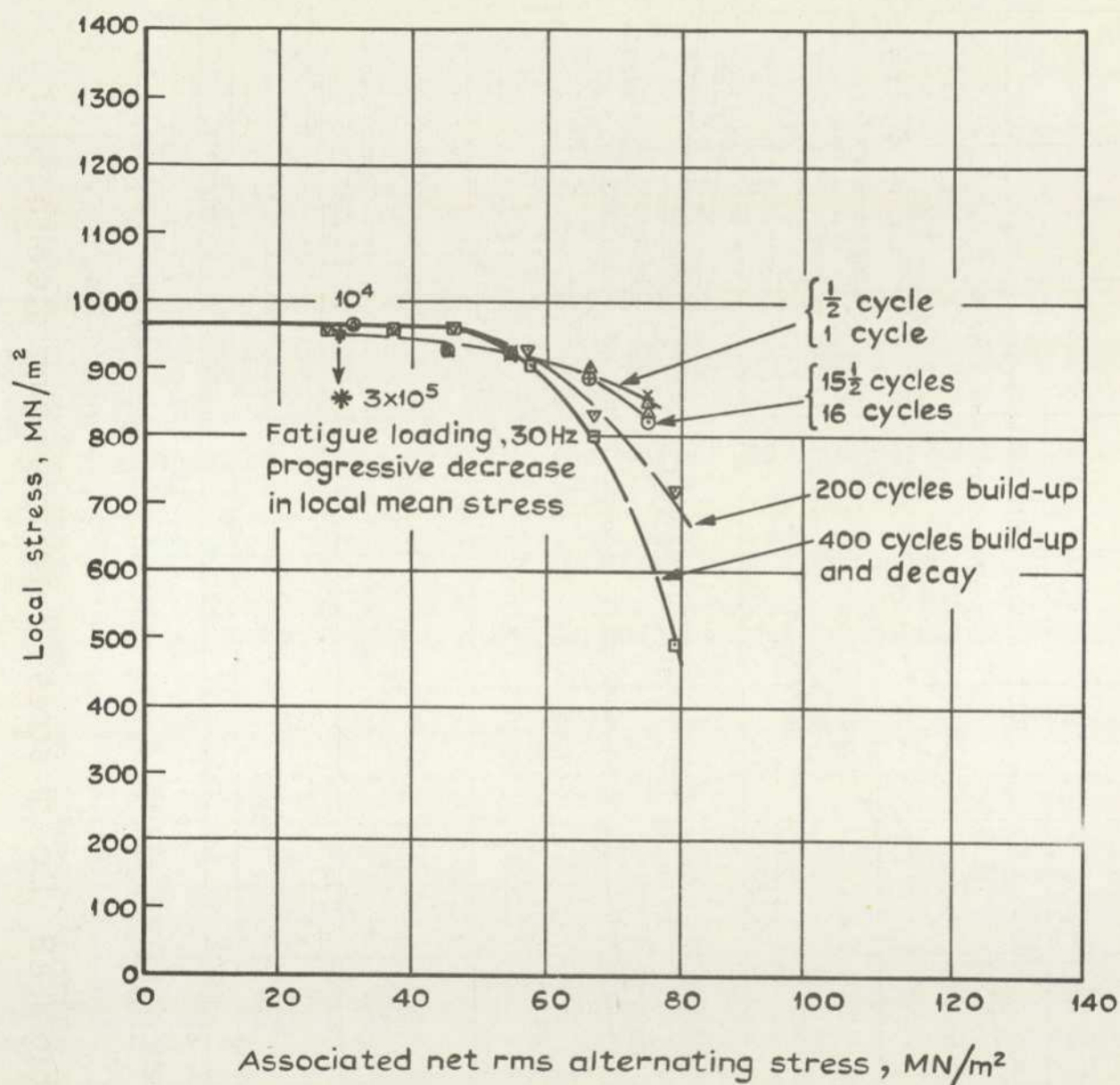


Fig. I. 29 Local stress data for maraging steel pinned-lug

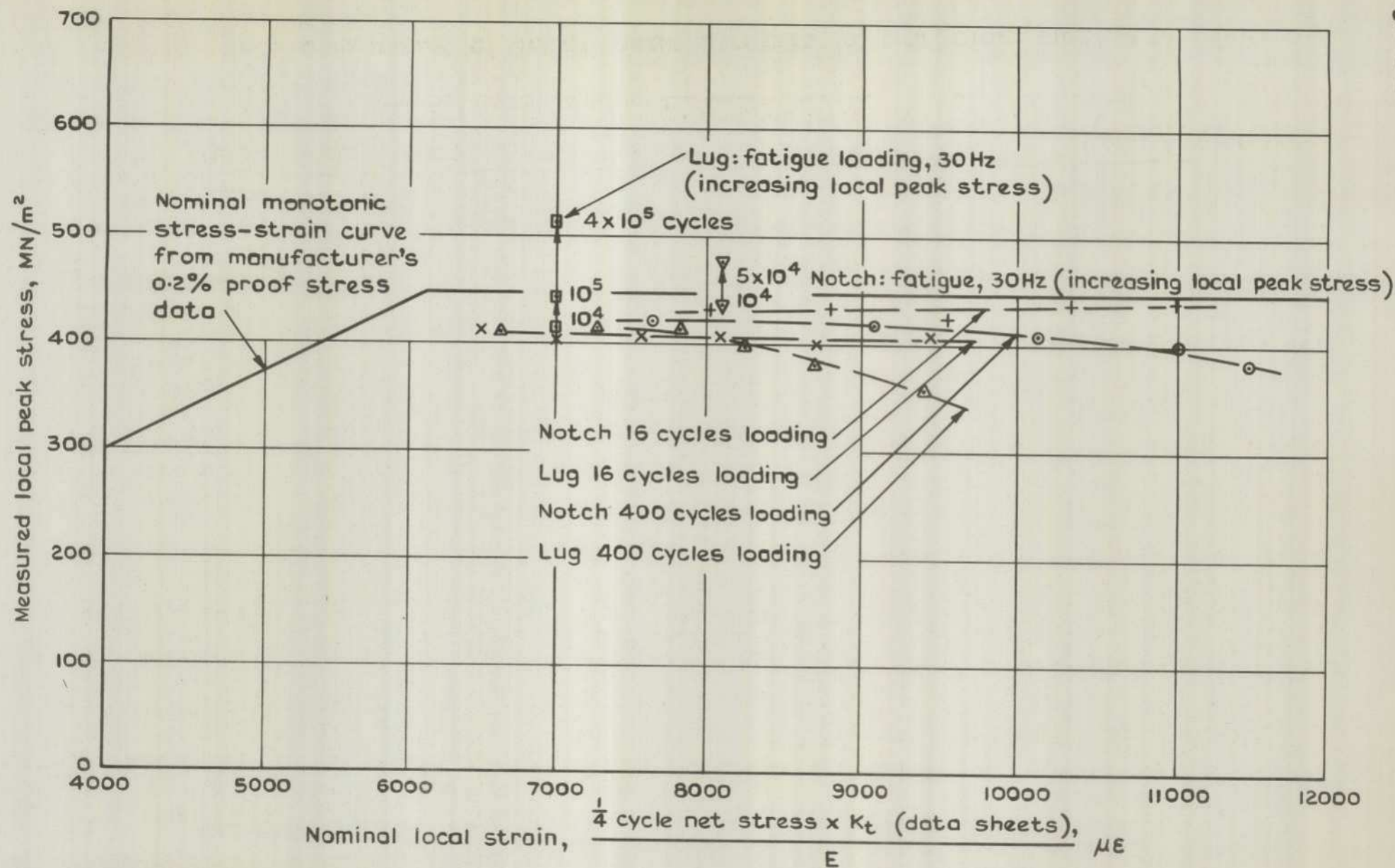


Fig.1.30 Comparison of local peak stresses in aluminium alloy specimens

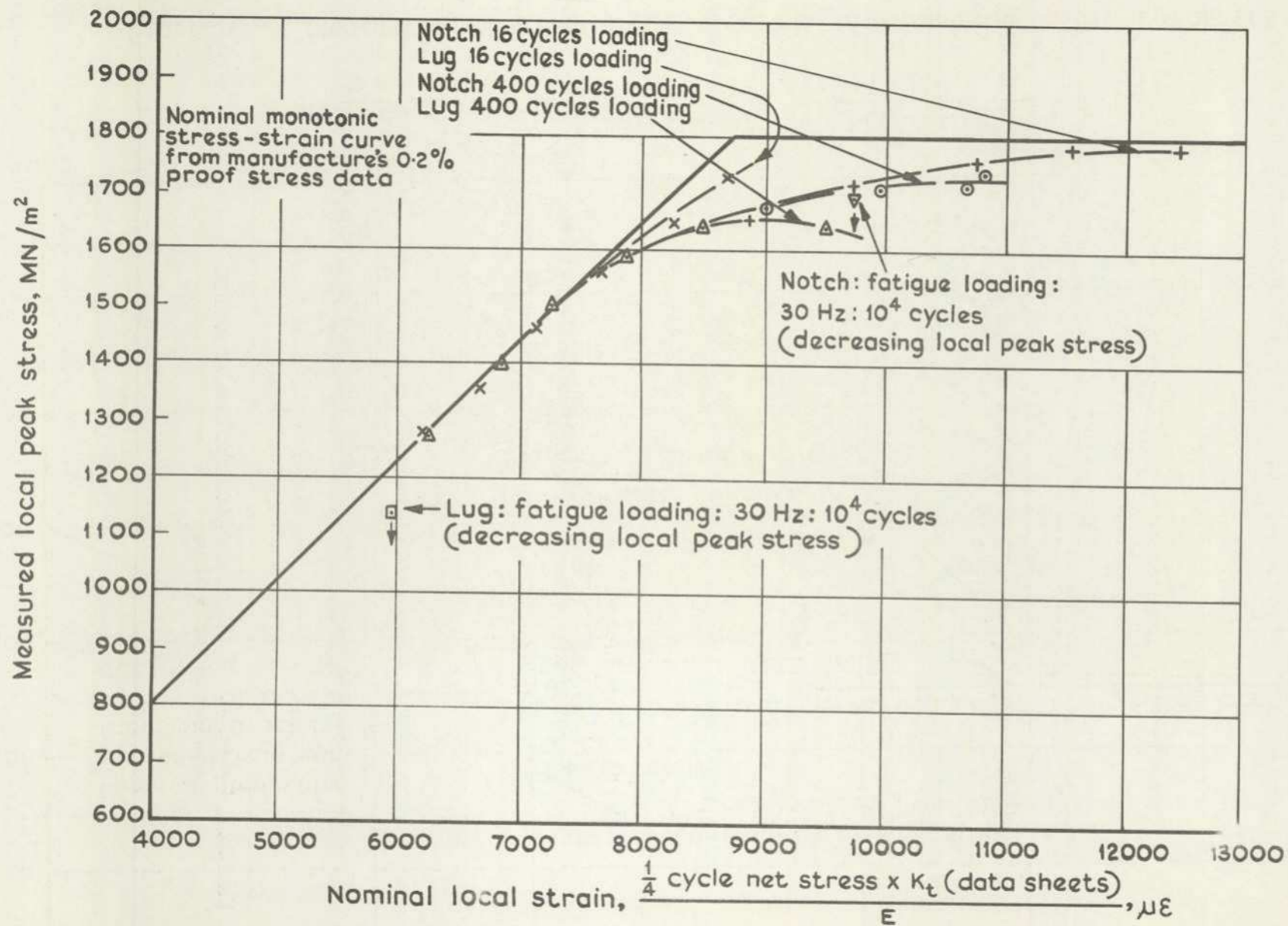


Fig.1.31 Comparison of local peak stresses in maraging steel specimens

Fig.1.32

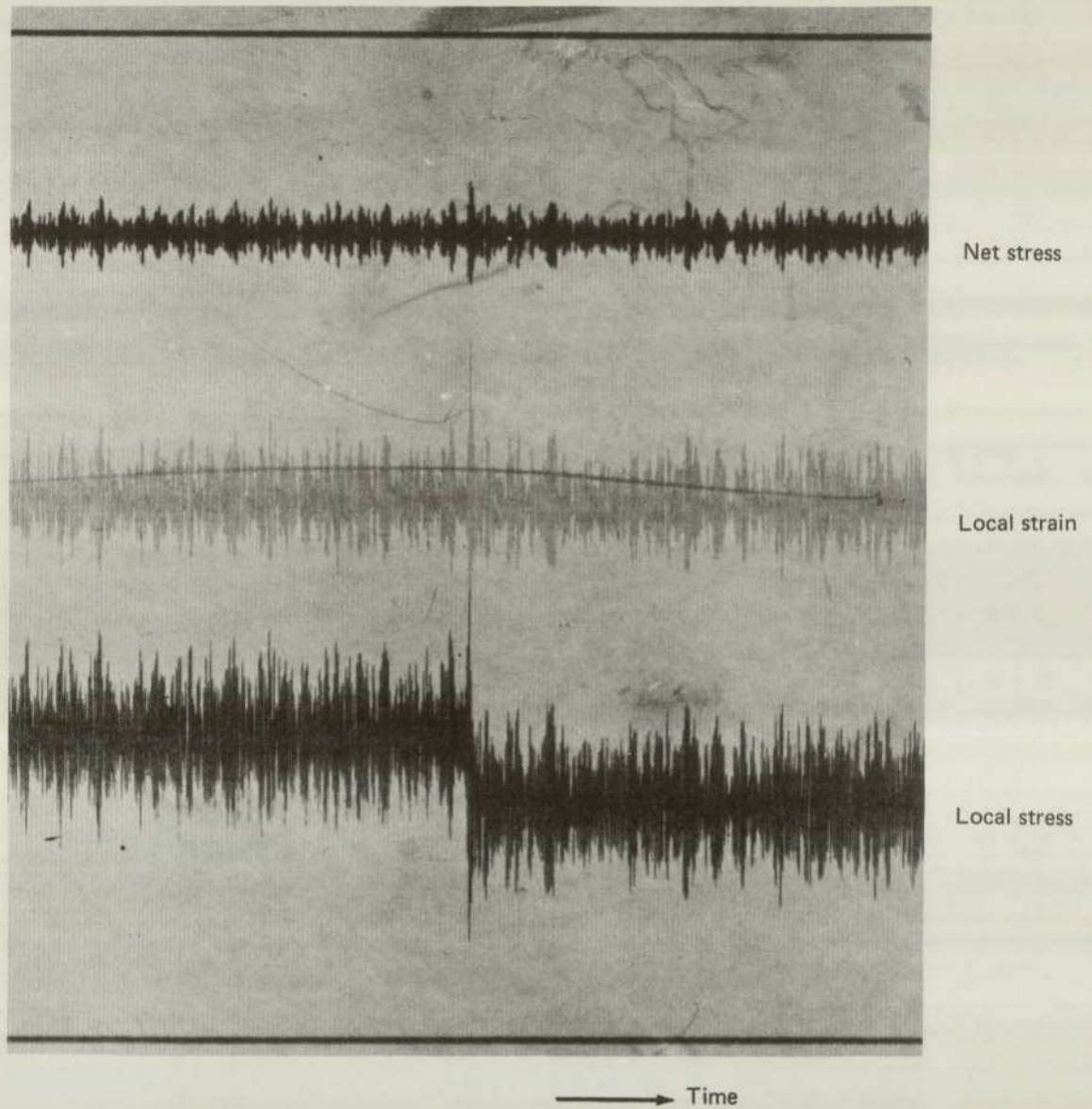


Fig.1.32 Change in local mean stress resulting from the application of a high net stress: aluminium alloy pinned-lug

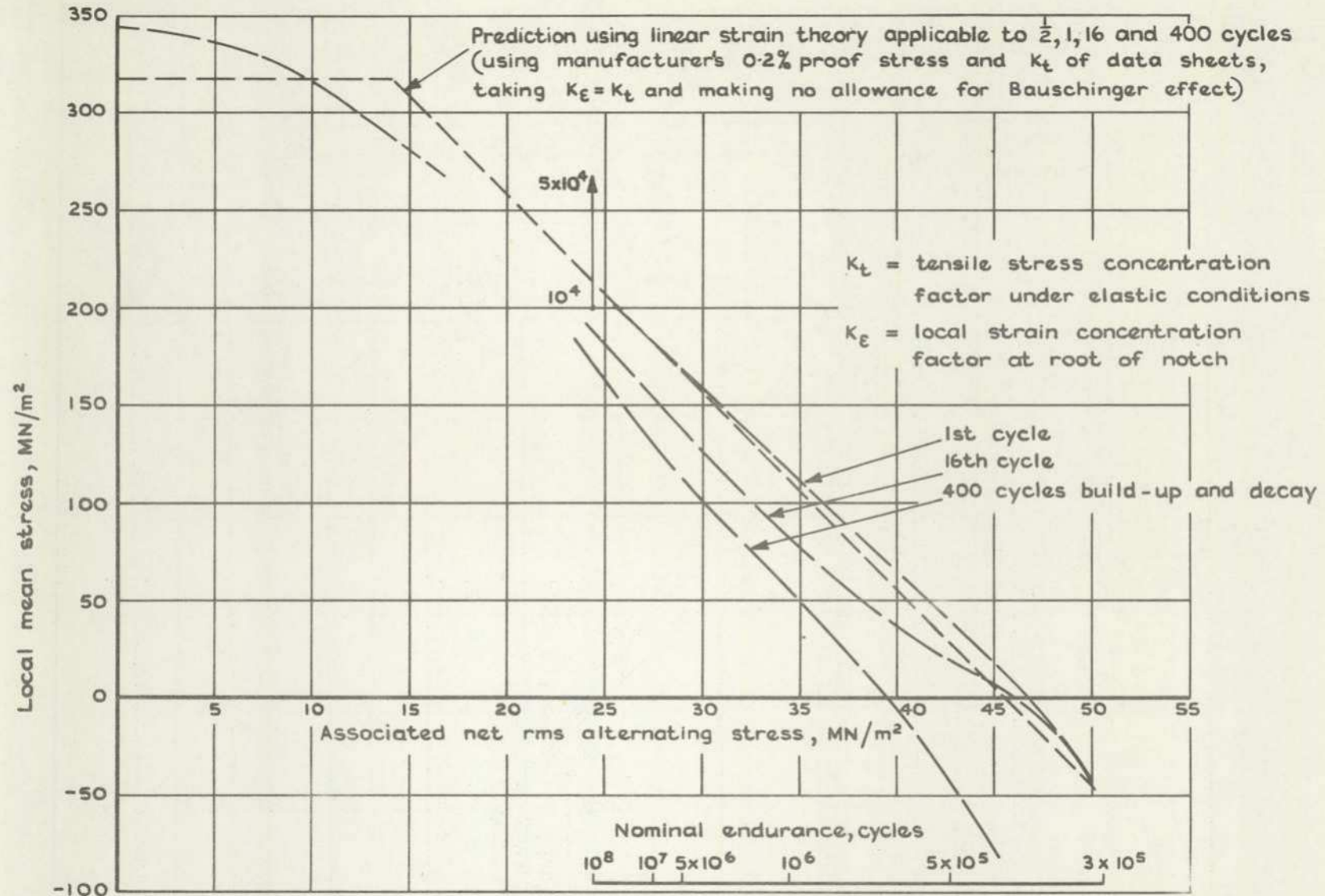


Fig. 1.33 Salient features of local stress data for aluminium alloy notch

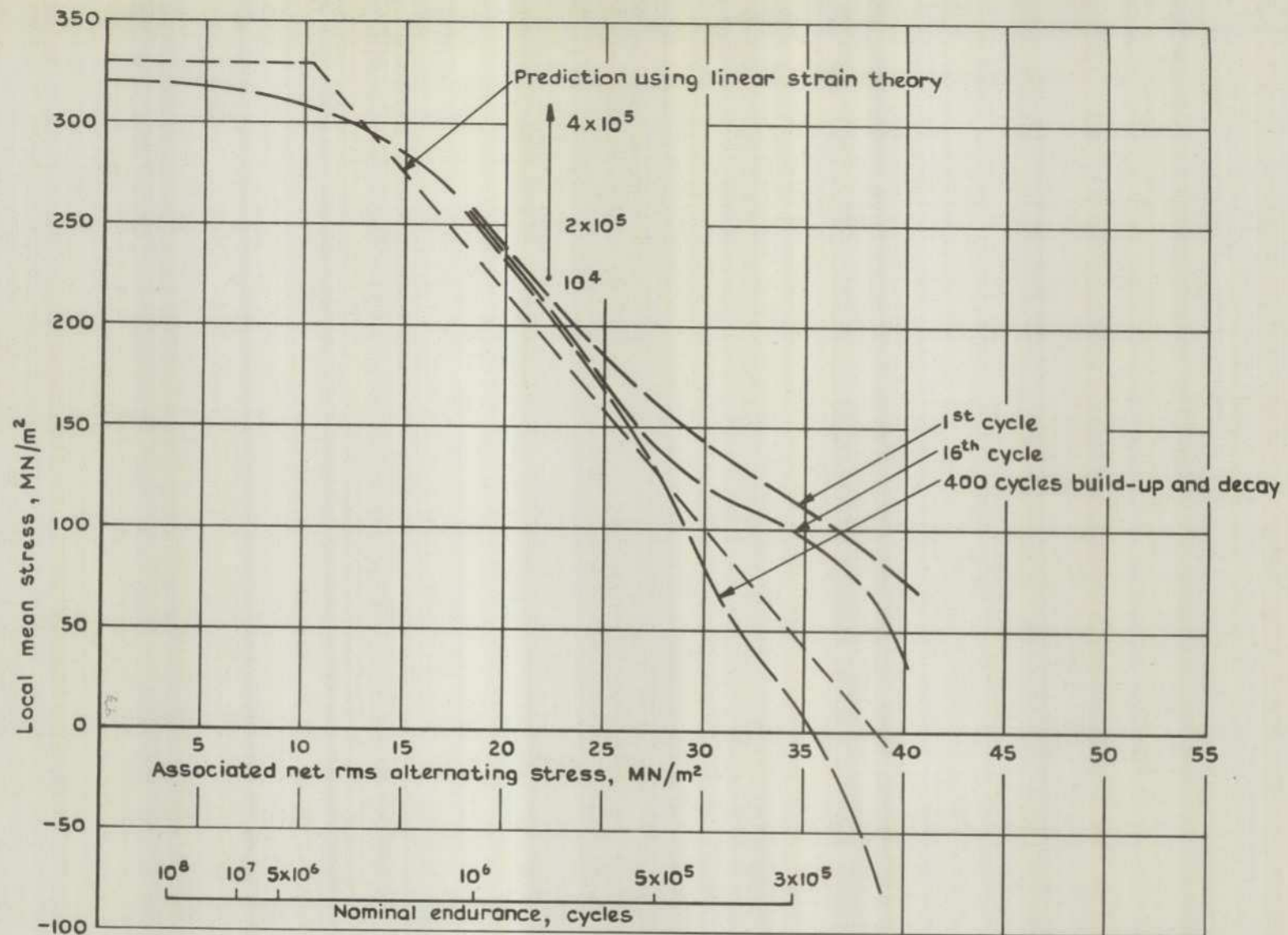


Fig. 1.34 Salient features of local stress data for aluminium alloy pinned-lug

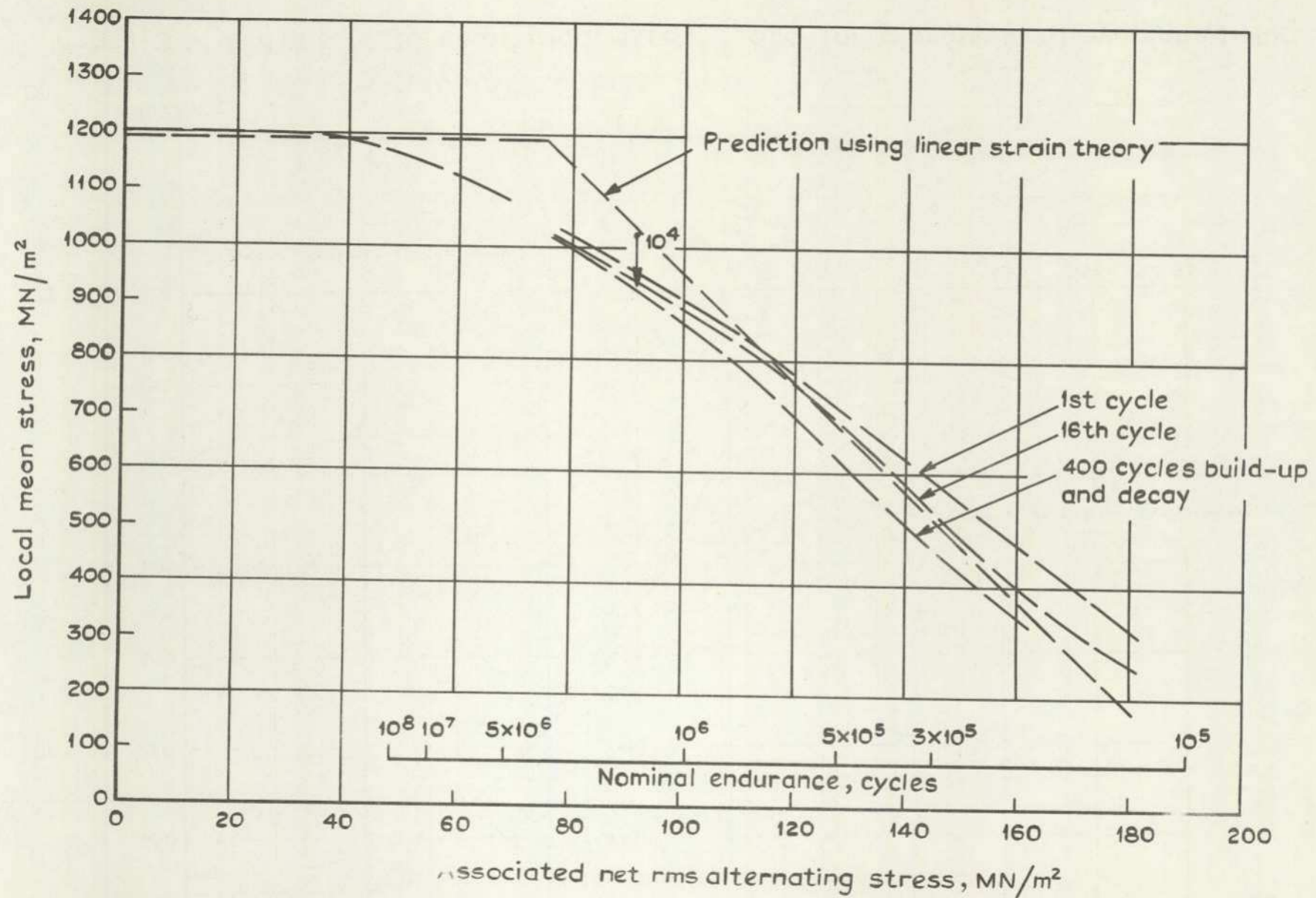


Fig. 1.35 Salient features of local stress data for maraging steel notch

Fig. I.36

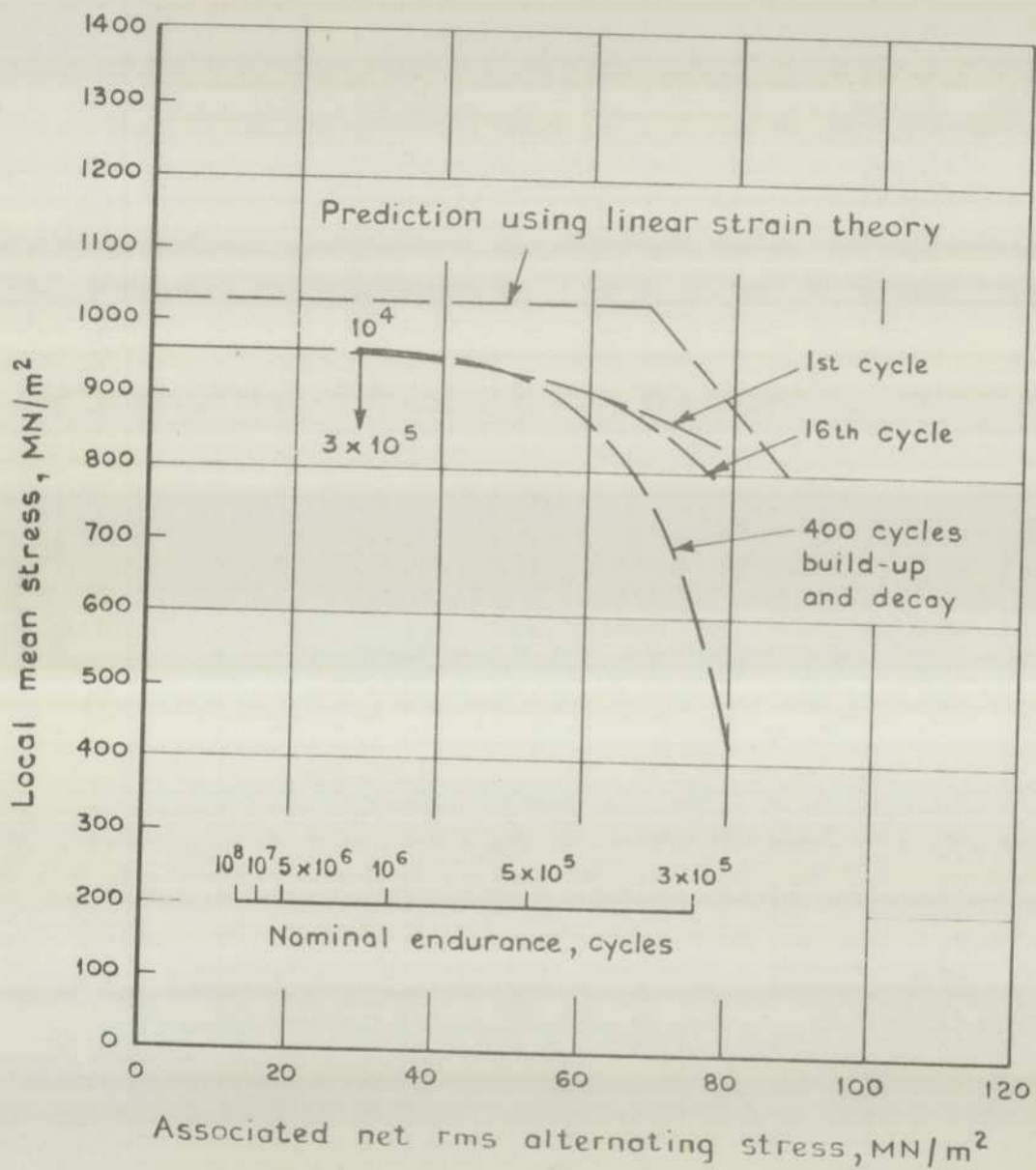


Fig. I.36 Salient features of local stress data for maraging steel pinned-lug

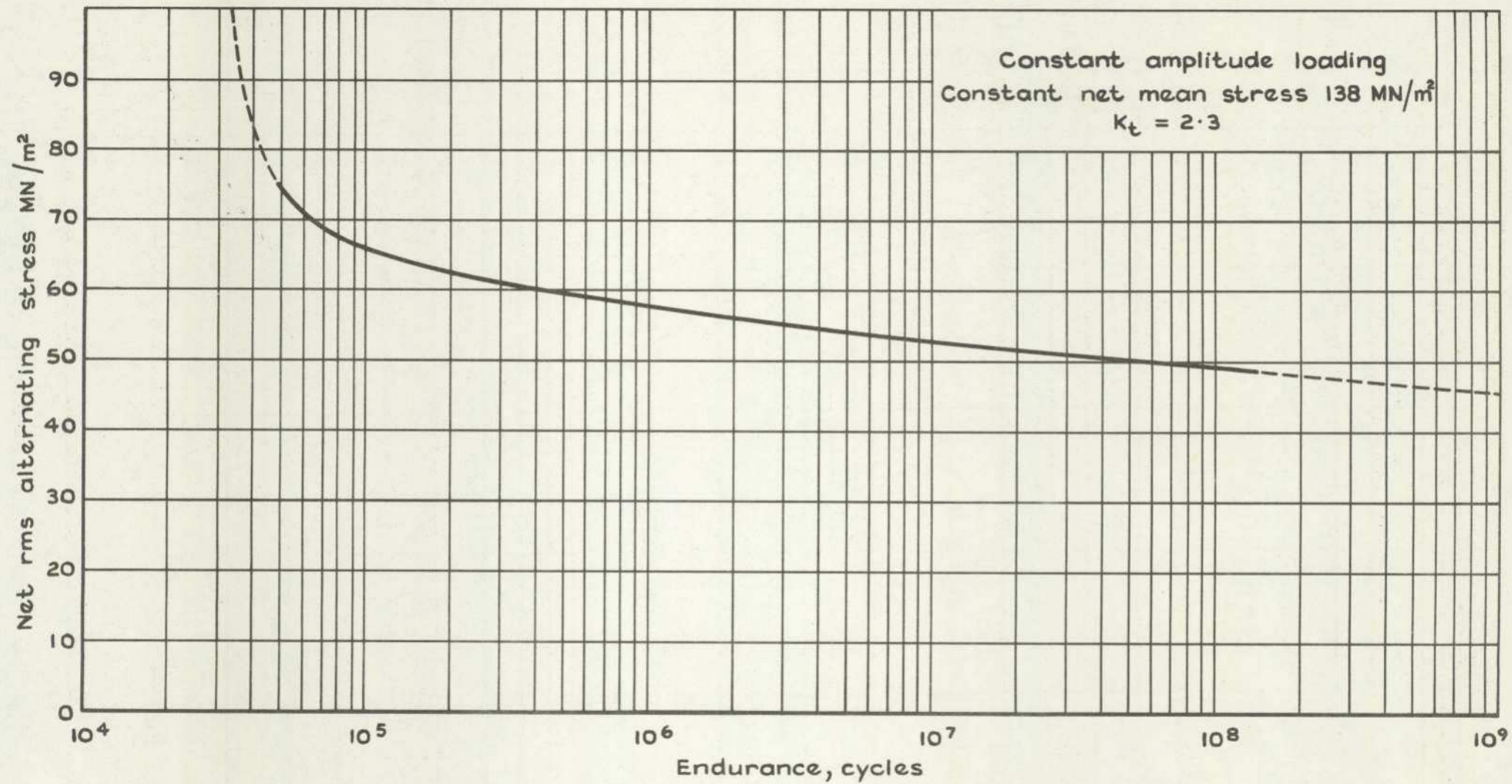


Fig. I.37 S-N curve for aluminium alloy notch

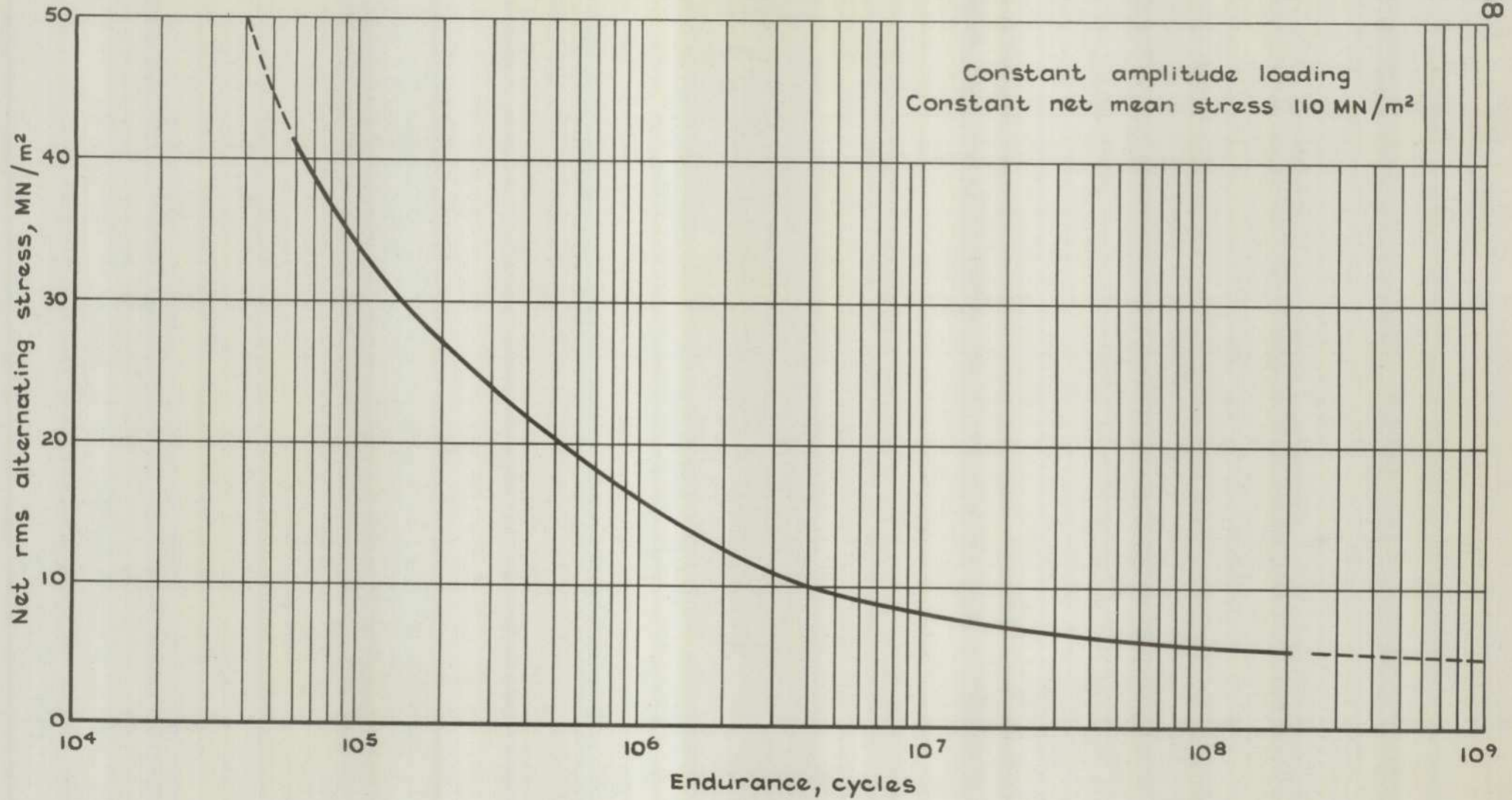


Fig. I.38 S-N curve for aluminium alloy pinned-lug

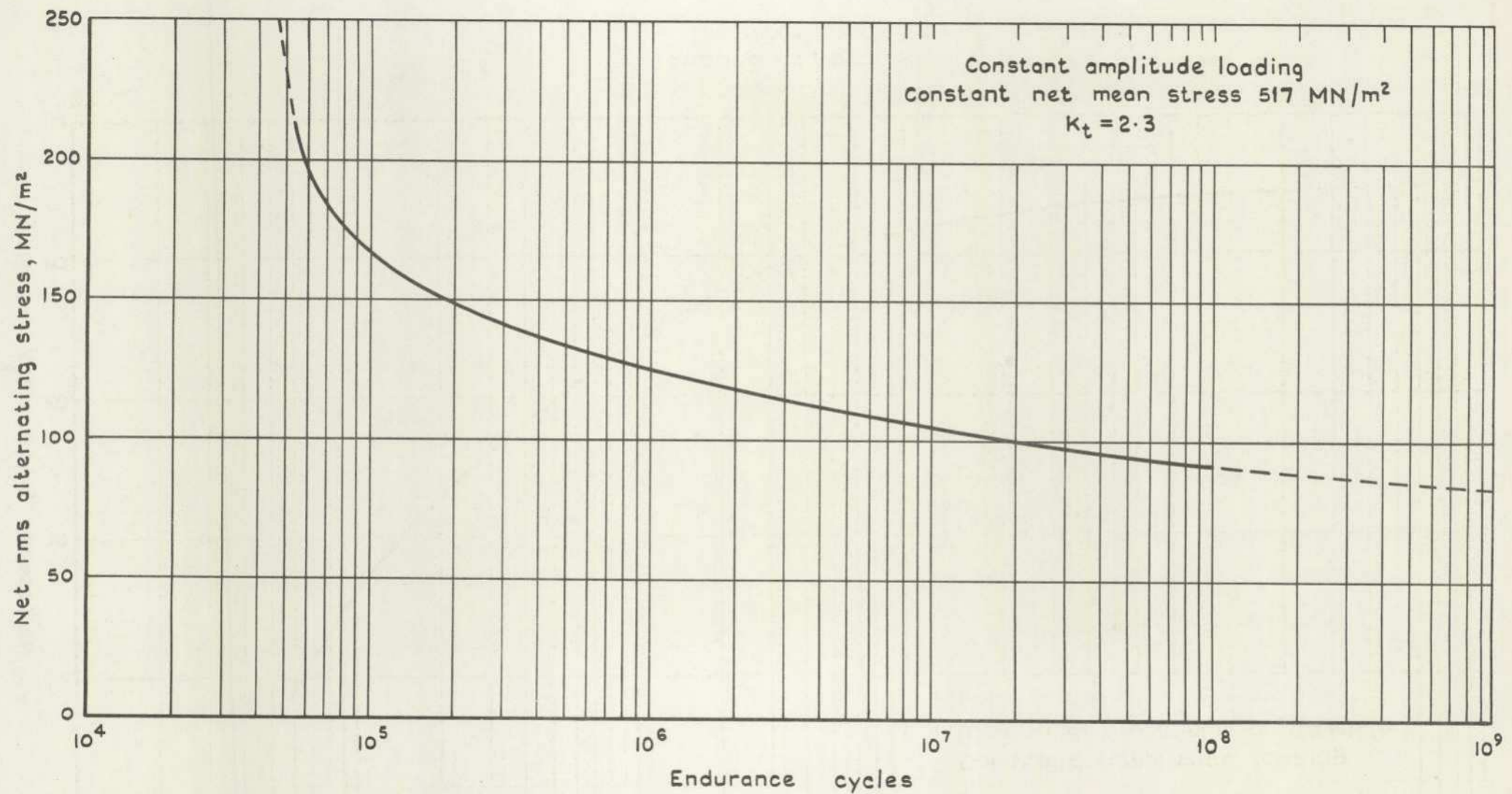


Fig. I.39 S-N curve for maraging steel notch

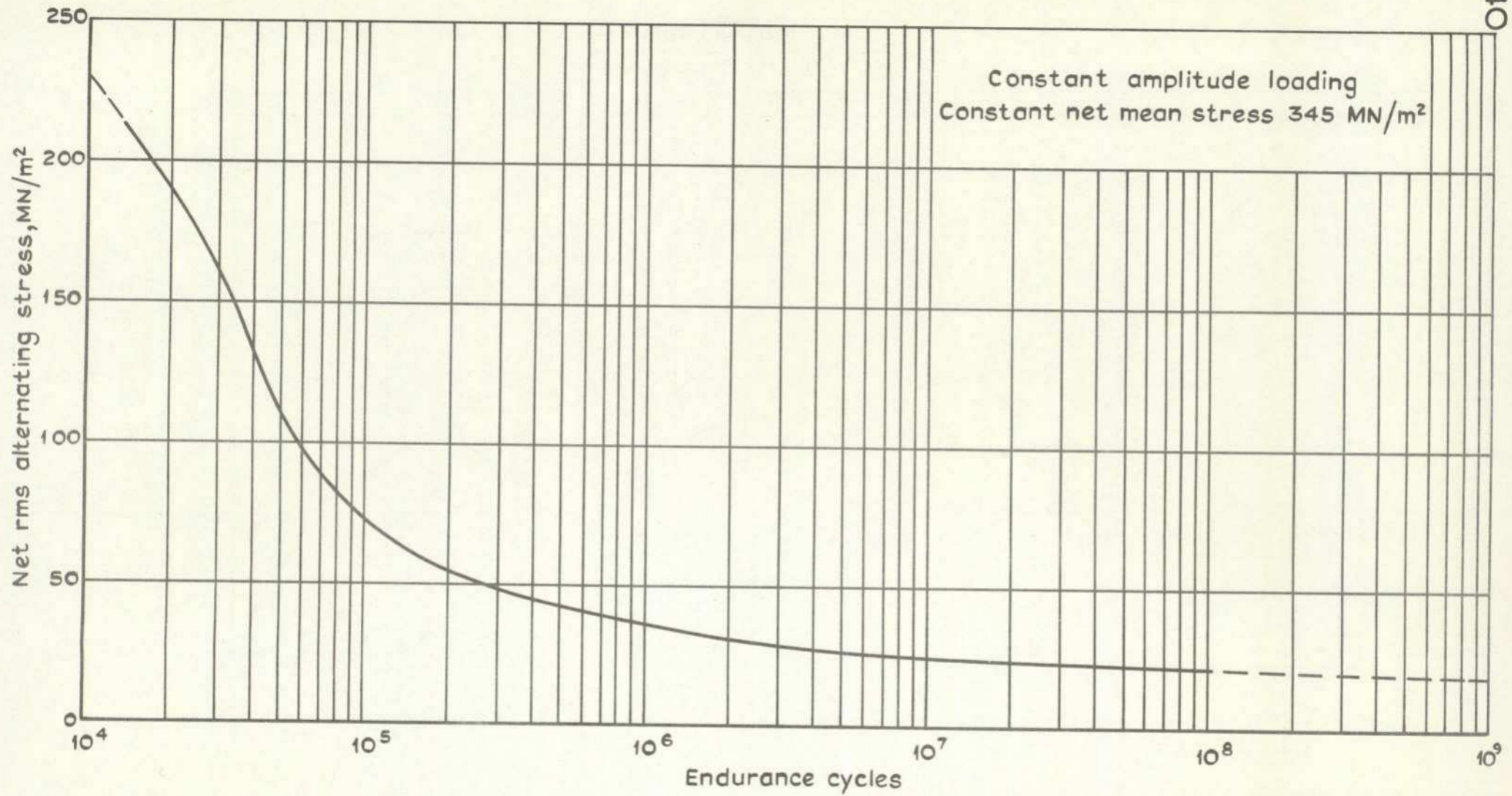


Fig. 1.40 S-N curve for maraging steel pinned-lug

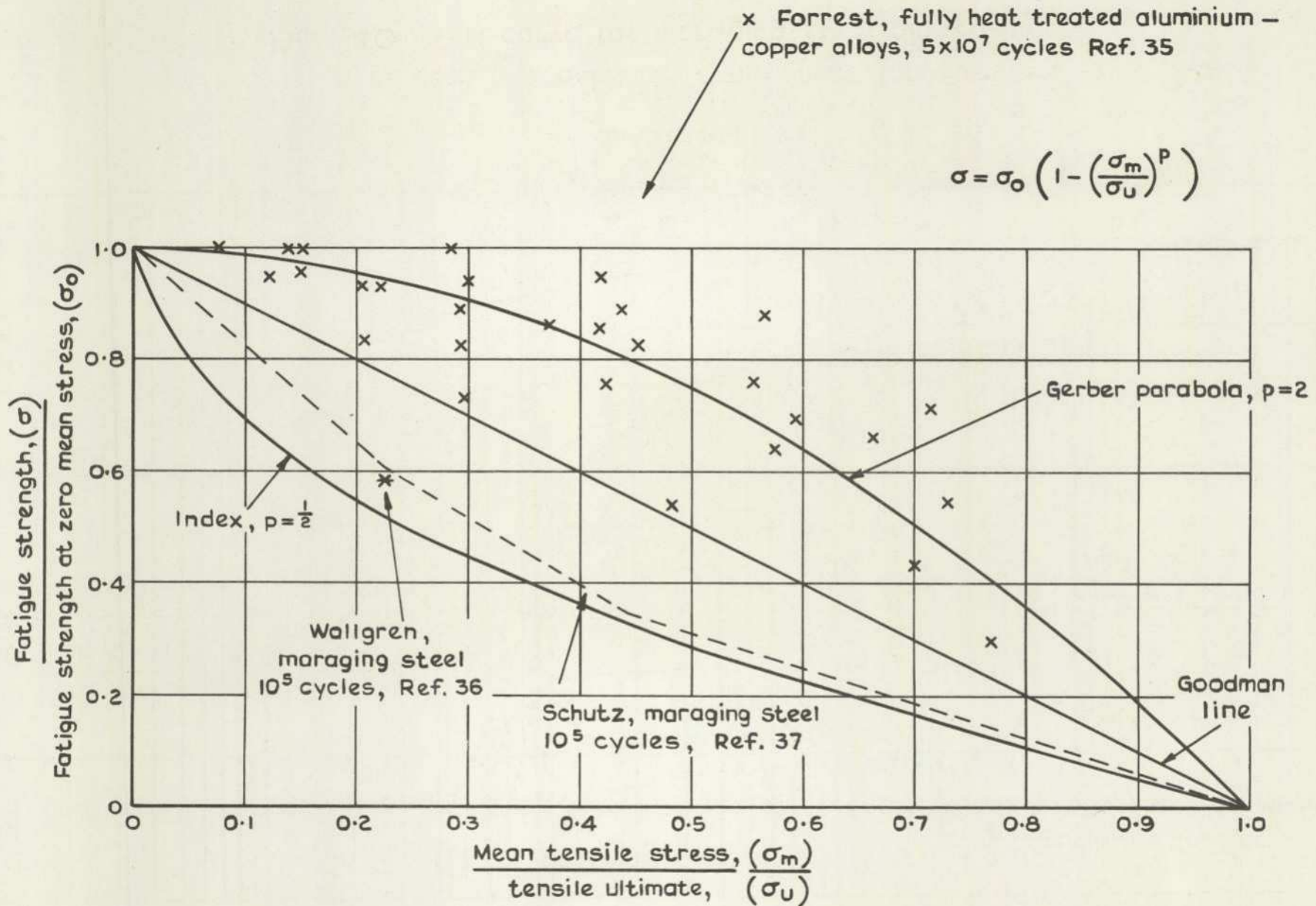


Fig. 1.41 Mean stress — alternating stress data for aluminium alloys and maraging steel

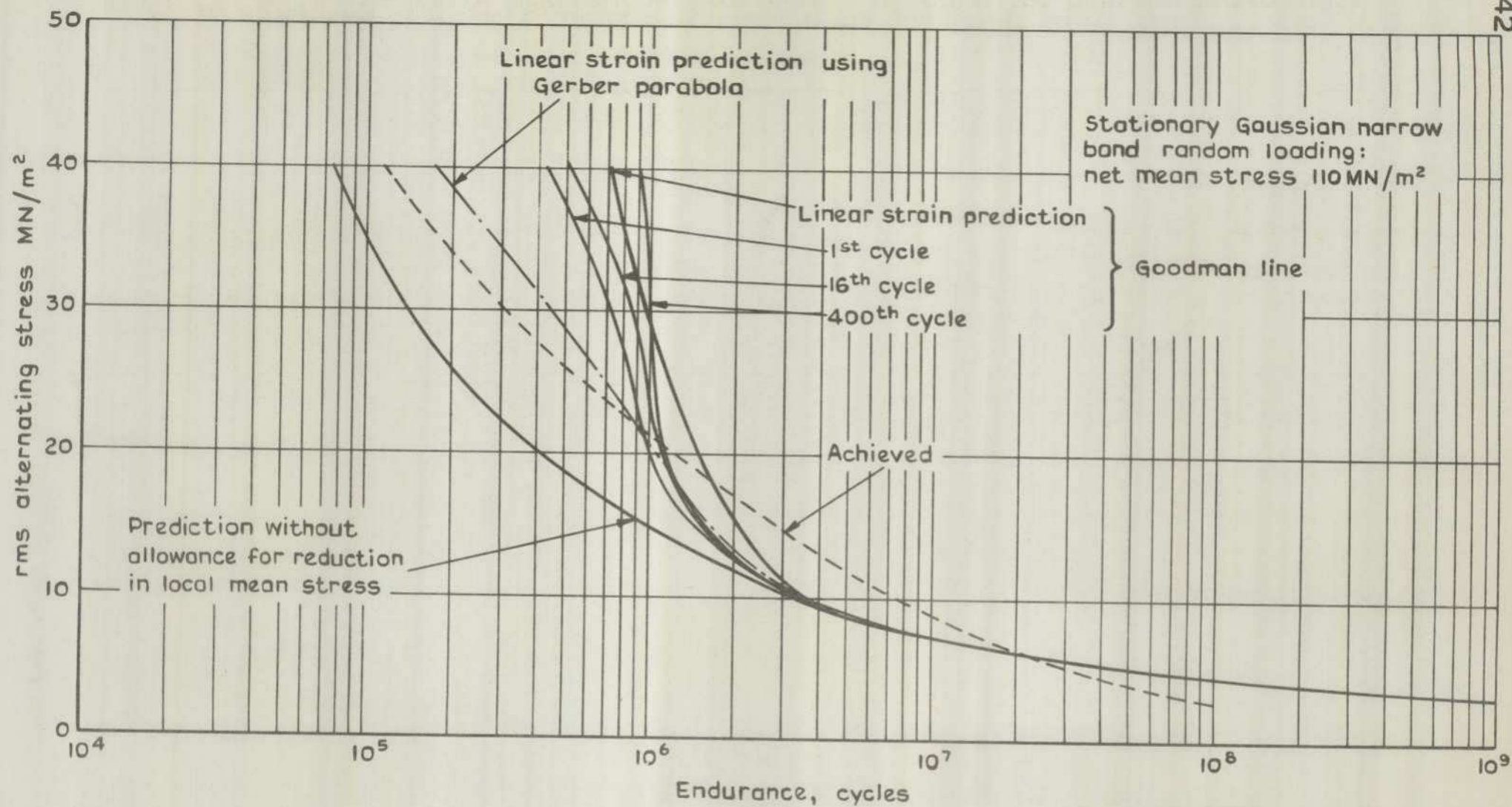


Fig 1.42 Comparison of predicted and achieved endurance for aluminium alloy pinned-lug

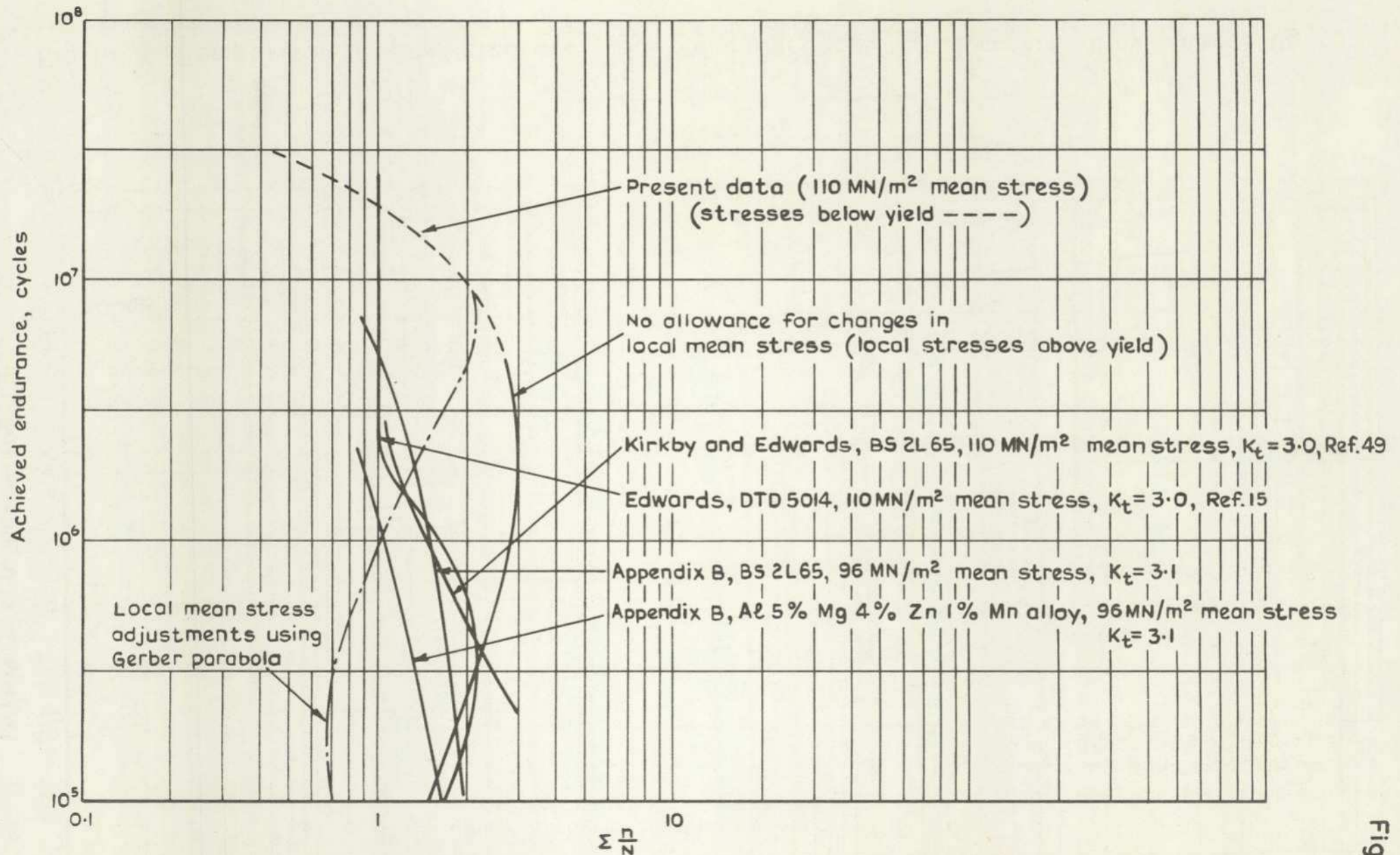


Fig. 1.43 Comparison of predictions with published data for aluminium alloy lugs

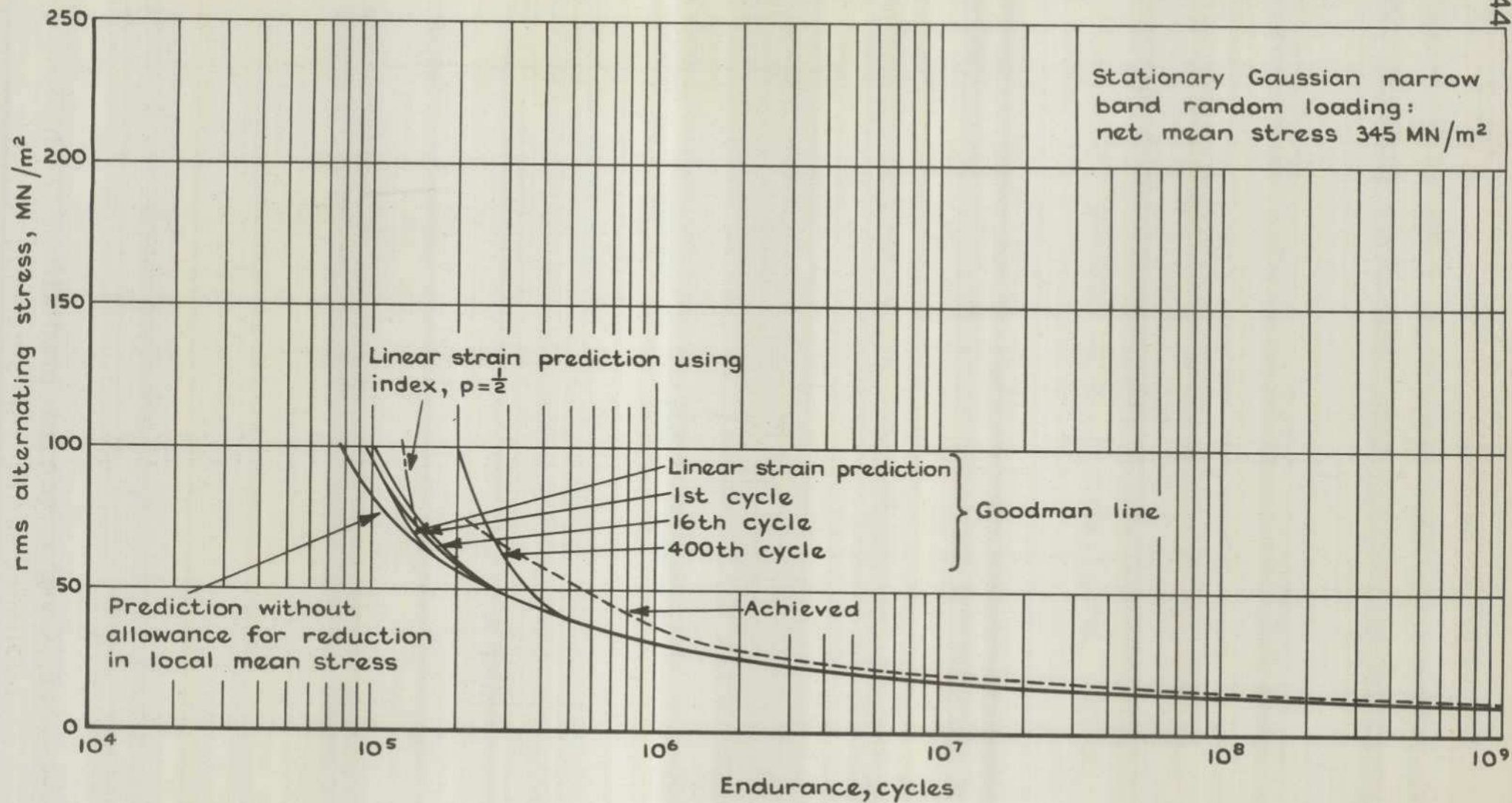


Fig. 1.44 Comparison of predicted and achieved endurance for maraging steel pinned-lug

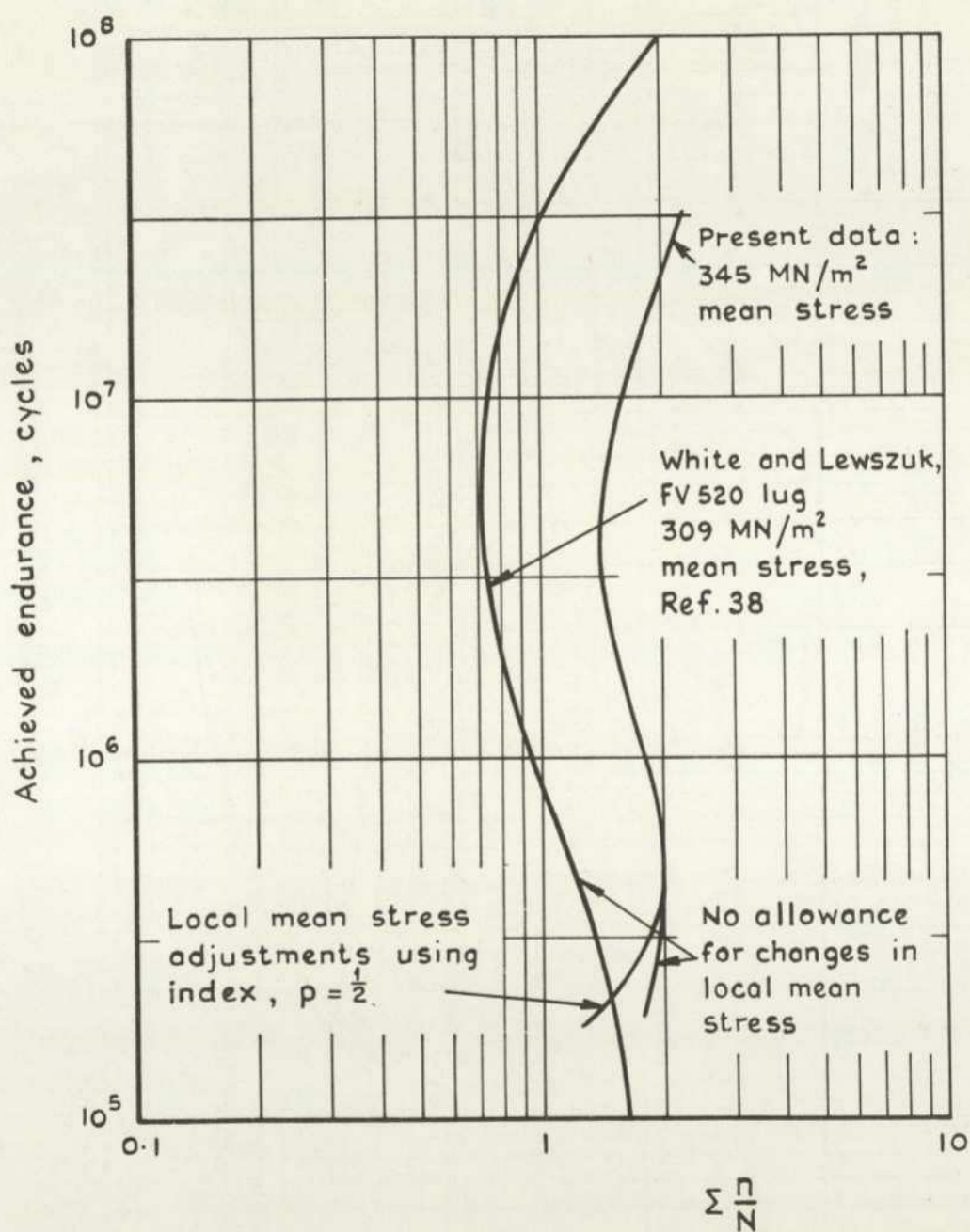


Fig.I.45 Comparison of predictions with published data for steel lugs

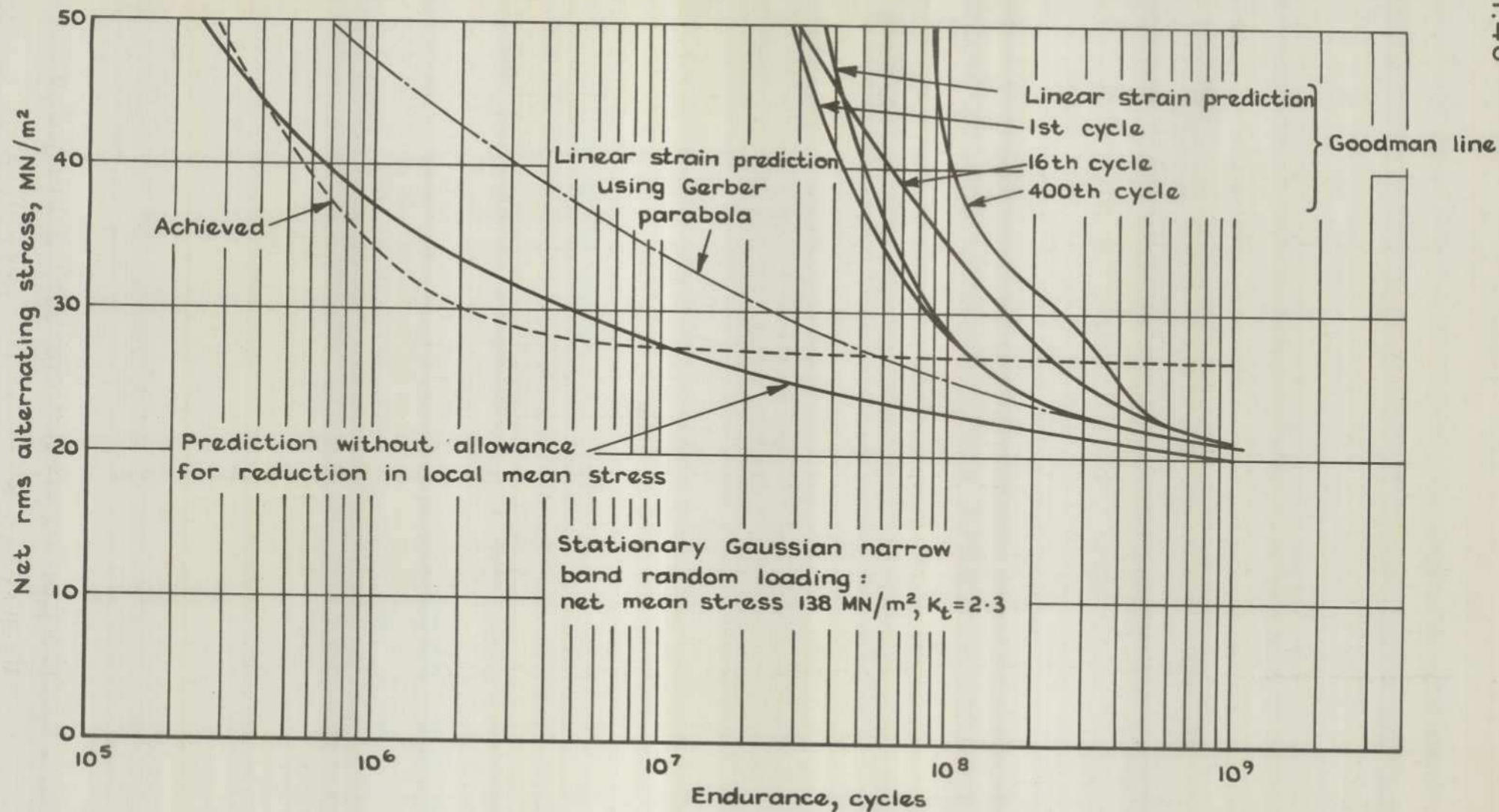


Fig.1.46 Comparison of predicted and achieved endurance for aluminium alloy notch

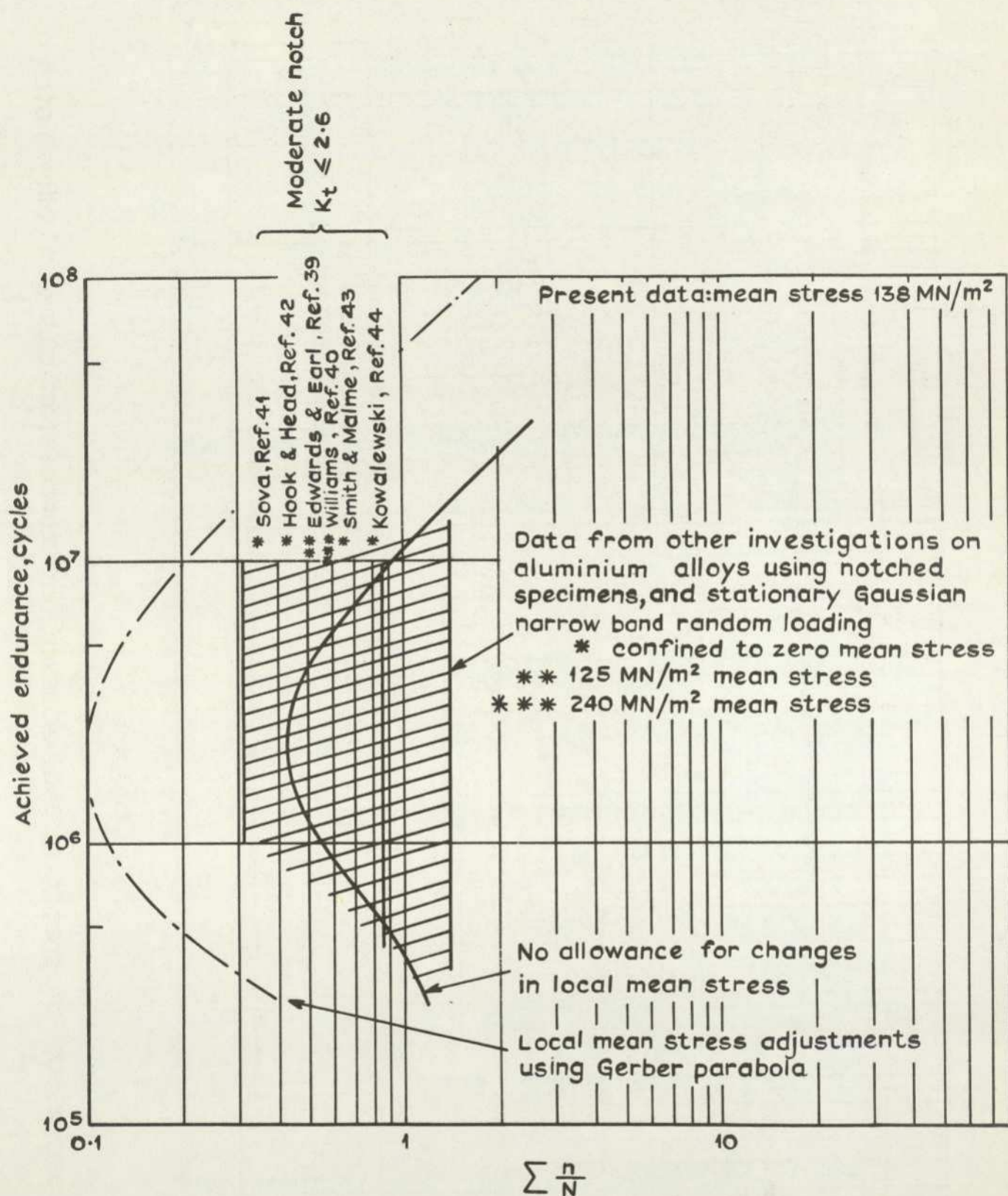


Fig 1.47 Comparison of predictions with published data for aluminium alloy notched specimens

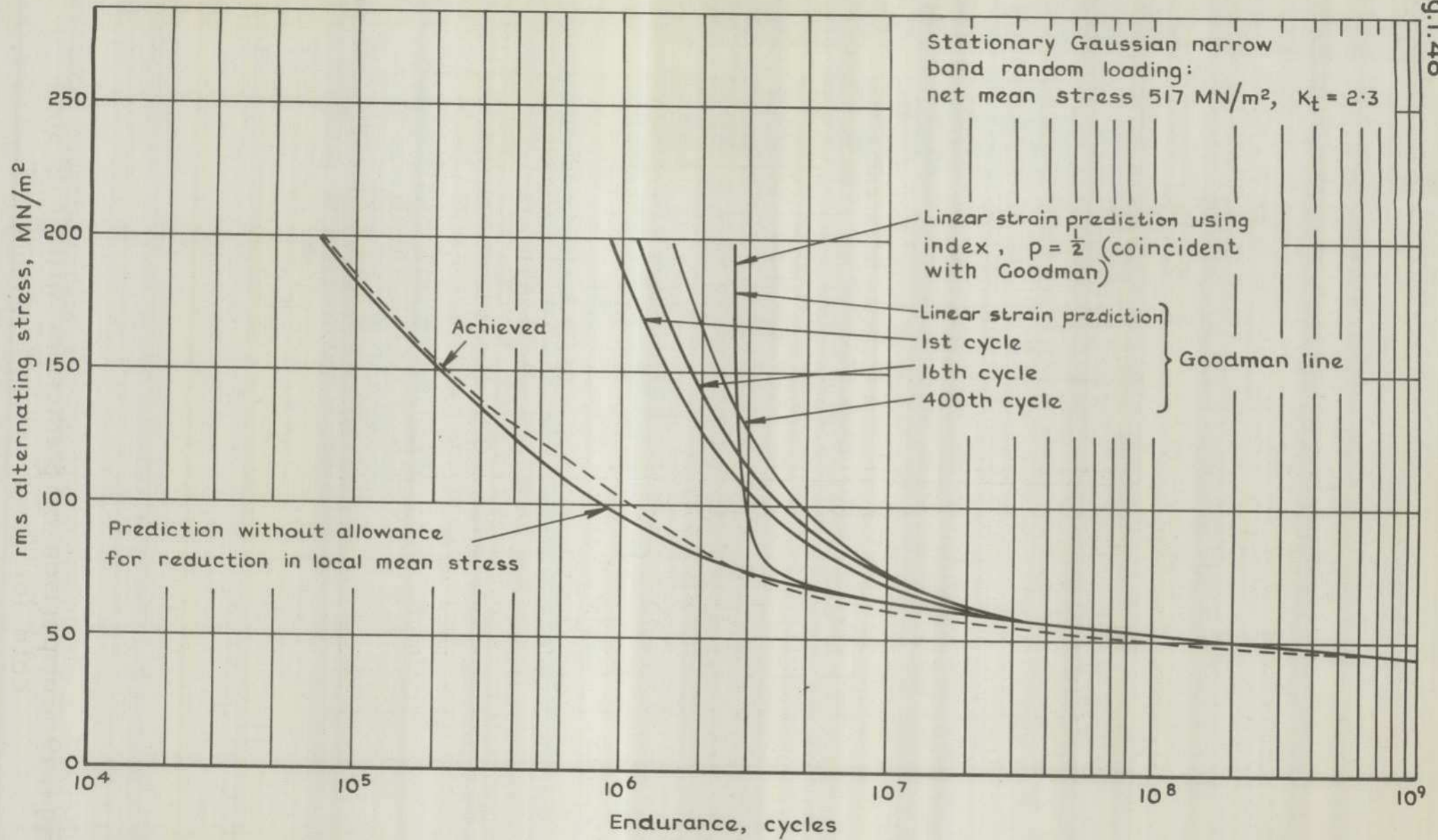


Fig.1.48 Comparison of predicted and achieved endurance for maraging steel notch

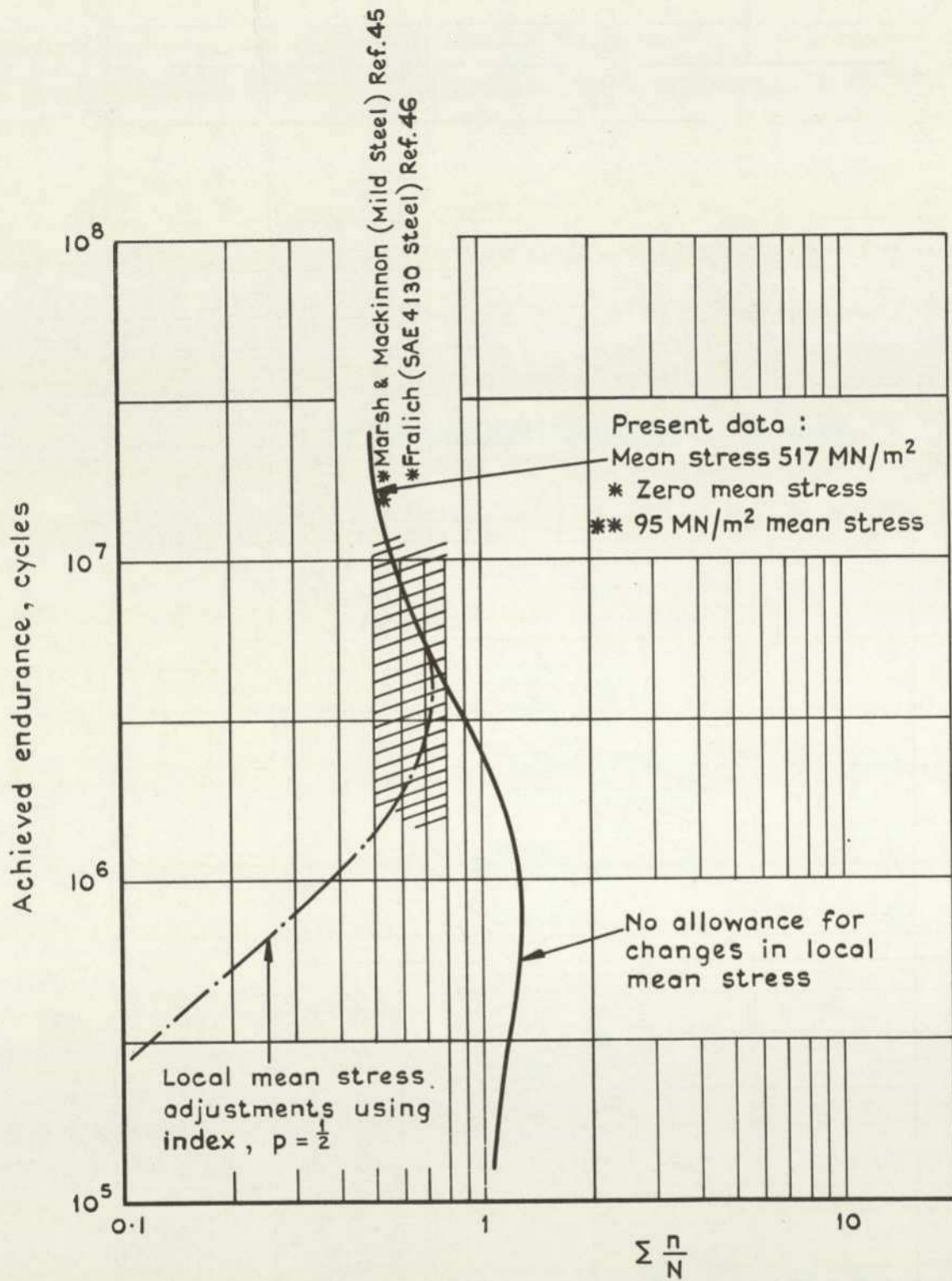
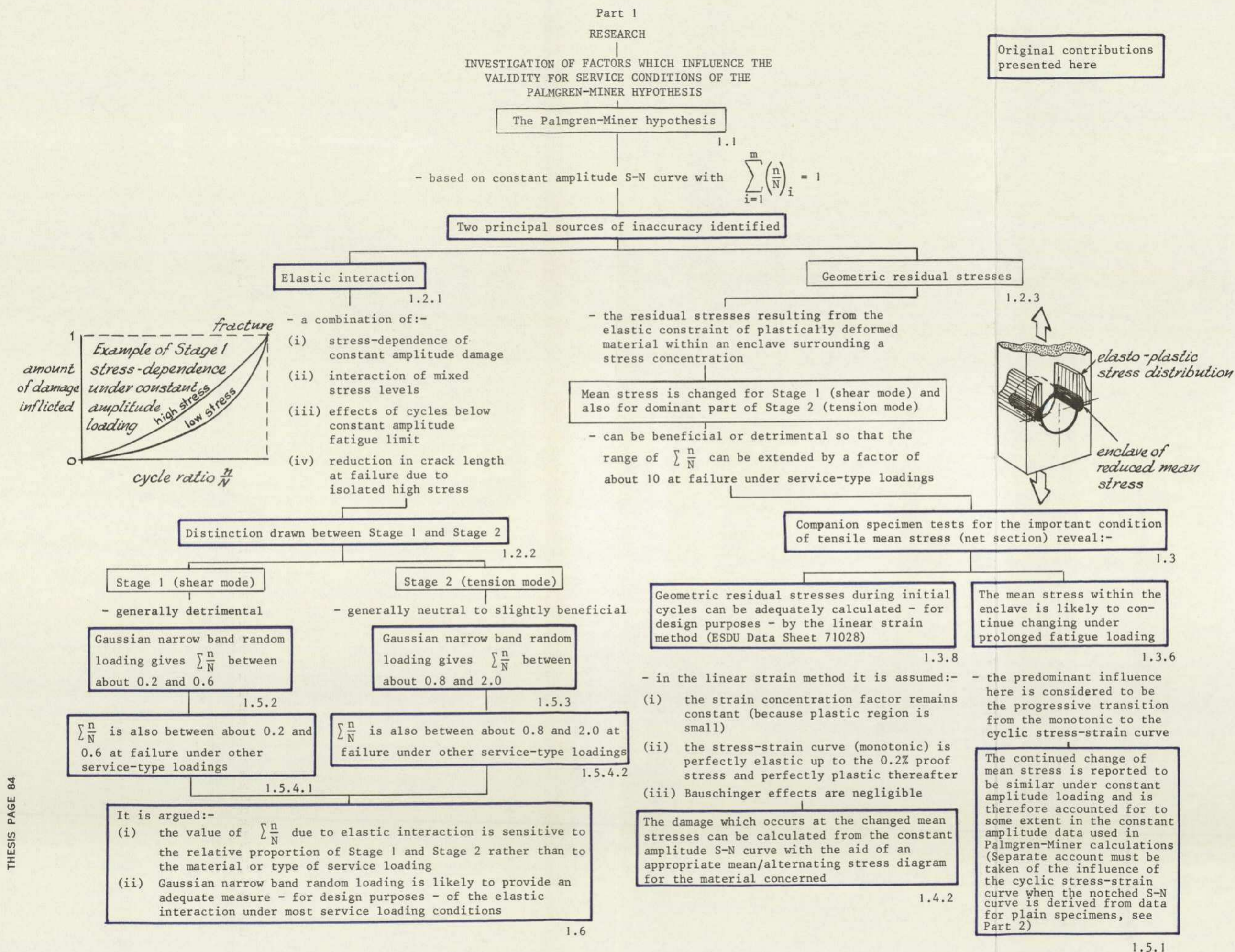


Fig.I.49 Comparison of predictions with published data for steel notched specimens

Original contributions
presented here

PART 2

A PROPOSAL FOR STANDARDISED FATIGUE TESTS FOR
EVALUATING STRUCTURAL ALLOYS

A PROPOSAL FOR STANDARDISED FATIGUE TESTS FOR
EVALUATING STRUCTURAL ALLOYS

SUMMARY

The practice of evaluating the fatigue performance of a material on the basis of constant amplitude tests on plain and notched specimens is discussed in relation to factors which may influence the accumulation of fatigue damage in structural components.

Attention is drawn to deficiencies in the established procedure and it is shown how these may be readily overcome by simple tests to represent fretting and the effects of variable amplitude loading.

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2.1 INTRODUCTION

It is an established practice to evaluate the fatigue performance of the extruded, rolled and forged forms of the alloys used in aircraft structures by means of constant amplitude tests on small plain and moderately notched specimens (K_t between about 2.3 and 3). Whilst this enables a direct comparison to be made with other materials tested under similar conditions, the data so obtained are of limited value to the designer who seeks an indication of the relative fatigue performance of materials in component form.

As distinct from crack propagation studies on sheet material, these tests relate to 'safe life' or 'time to first detectable crack' aspects of design and so, as discussed in Part 1, it is important to recognise that the fatigue performance of a material has an upper boundary in which Stage 1 predominates - the small percentage of Stage 2 being relatively insignificant - and a lower boundary in which Stage 2 predominates - the classical Stage 1 phase having been virtually eliminated by fretting or sharp stress concentrations. With these boundary conditions in mind, consideration is given, in section 2.2, to the criteria required to provide a measure of fatigue damage accumulation in component form. In section 2.3 size effects are considered and in section 2.4 deficiencies in traditional evaluation tests are summarised. Proposals for more meaningful tests are presented in section 2.5.

2.2 CRITERIA FOR STRUCTURAL FATIGUE PERFORMANCE

2.2.1 Stage 1 performance

The work presented in Part 1 suggests that the classical Stage 1 shear mode initiation process (after Forsyth¹) predominates for plain specimens and specimens with stress concentrations (K_t) of up to about 2.6 (the data of Schijve and Jacobs² indicate that Stage 1 still predominates in specimens with a K_t value of 2.6), and that Stage 2 conditions predominate in specimens containing fretting or a stress concentration with a K_t value of about 3.5 and above (the data analysed by ESDU³ all show Stage 2 elastic interaction). The Stage 1 fatigue performance is therefore an important criterion in selecting materials for components in which sharp stress concentrations can be avoided and fretting is suppressed.

2.2.2 Stage 2 performance

The effect of sharp stress concentrations and fretting is to virtually eliminate the Stage 1 portion of the endurance - as discussed in the paper

reproduced here as Appendix B - so that Forsyth's Stage 2 tension mode process predominates. The Stage 2 performance is therefore an important criterion for components containing fretting, for components subject to accidental damage, and for situations where it is impracticable to implement rigorous controls in design and manufacture.

2.2.3 Performance under realistic loading

As discussed in Part 1, the accumulation of fatigue damage under realistic (variable amplitude) loading is affected by two principal influences - elastic interaction and geometric residual stresses.

There is strong evidence that elastic interaction is particularly important in the Stage 1 situation where it can have a detrimental effect of up to tenfold compared with constant amplitude loading $\left(\sum \frac{n}{N} \text{ nearer } 0.1 \text{ than } 1\right)$. Stage 2 elastic interaction generally results in a neutral to slightly beneficial performance compared with constant amplitude loading $\left(\sum \frac{n}{N} \text{ between about } 0.8 \text{ and } 2\right)$, but nevertheless this is an important effect.

The influence of geometric residual stresses on the other hand shows no distinction between Stage 1 and Stage 2. It is strongly dependent on the monotonic yield stress and can be accounted for by calculation rather than test. (The correlation between notched and unnotched fatigue strength is discussed in section 2.3)

2.2.4 Reduction of residual static strength as endurance is consumed

Two factors are of importance here - the variation in residual static strength during the life, and sensitivity to fatigue cracks. These criteria are relevant only in the Stage 2-dominant situation, since it is only under advanced Stage 2 crack growth that significant reductions in static strength occur. For example, in aluminium alloy pinned-lug specimens tested under Gaussian narrow band random loading⁴, reductions in strength of about 10 per cent and 30 per cent are apparent at about 30 per cent and 50 per cent of the Stage 2 life (these figures are based on low stress levels where the influence of geometric residual stresses can be discounted).

2.3 SIZE EFFECTS IN SPECIMEN DESIGN

It is widely recognised that the fatigue strength of large components will be less than that indicated by conventional tests on small specimens. In some instances, for example, if rotating bending data for small notched specimens

were used to predict the fatigue strength of large components with the same geometric stress concentration factor, a ratio of specimen strength to component strength of more than 5 to 1 might be obtained in the worst combination of circumstances. It is generally possible to anticipate such drastic reductions in strength by considering the following factors.

Firstly, the fatigue strength of plain specimens cut from the same parent bar and tested in direct tension could be expected to be practically the same regardless of their size^{5,6}. (It is assumed here that the specimens would be cut from the bulk of the material in order to exclude surface effects, such as changes in grain size produced by working or cooling. It is further assumed that only a small proportion of the life is occupied by crack propagation amenable to fracture mechanics analysis. When this proportion becomes significant - as in panels - a size effect is implicit in the approximate dependence of crack rate on (crack length)²).

Secondly, if plain specimens from this same family were then tested in fully reversed or rotating bending, the strength obtained would be expected to be similar for specimens of about 20mm diameter and above, but higher by a factor of up to about 2:1 for specimens as small as 2-3mm diameter. This effect is generally attributed to the increased stability of the highly stressed material afforded by the stress gradient. Osgood⁶, gives a strengthening factor of 1.7 for the theoretical upper limit for this effect and this is in good agreement with empirical data.

Thirdly, if geometrically identical notched specimens of various sizes were cut from this same parent bar, and tested under fully reversed loading in direct stress, the larger specimens would be expected to show a reduction in strength given approximately by the value of the *local* stress concentration factor at the notch root, K_{σ} . Judging by the results of Phillips and Heywood⁷, notched specimens ($K_t = 2.8$) with a net section of less than about 20mm diameter would be stronger than the larger specimens cut from the same parent bar, by a factor of up to about 1.5. The distinction between K_t , the elastic stress concentration factor, and K_{σ} , the value determined from the dynamic stress-strain curve (assuming $K_e = K_t$), was first recognised by Forrest⁸, who showed correlation between K_{σ} and the fatigue strength reduction factor, K_f , for a wide range of materials.

Later work by Frost⁹ has shown that the Stage 1 cracks which form at 'sharp' vee notches do not propagate (and so do not reduce the fatigue limit by

the expected concentration factor $K_{\sigma} = K_t$) unless the condition $l_d = \frac{C}{f^3}$ is fulfilled

where l_d = crack length plus notch depth
 f = nominal alternating stress (gross area)
 C = material constant

Frost gives values of the constant C , for a range of materials. For large notched mild steel specimens, for example, the limiting value of K_f , (and therefore of K_t), is found to be about 4, as shown in Fig.2.1, this compares with a value of nearer 7 for aluminium alloys. Since notched S-N curves for values of K_t greater than about 4 will seldom be required for design purposes, this effect is unlikely to be of practical significance in scaling down unnotched curves by the local stress concentration factor K_{σ} .

Finally, if blanks of equal size were cut from our bar of parent material and some of these were subsequently forged or in some way mechanically reduced to give a range of cross-sectional areas, plain specimens of equal size cut from these various blanks would be expected to show an increase in fatigue strength of up to about 1.5:1 due to the mechanical working^{6,10}. Again the evidence suggests that this effect should not be of practical importance in specimens with a test section greater than 20mm diameter.

2.4 SUMMARY OF IMPORTANT DEFICIENCIES IN TRADITIONAL FATIGUE EVALUATION TESTS

(a) Tests on moderately notched specimens (K_t between about 2.3 and 3) do not provide a measure of the Stage 2 fatigue performance.

(b) Constant amplitude loading is unrealistic and does not reveal the elastic interaction effects which influence structural fatigue performance in both Stage 1 and Stage 2.

(c) No measure is provided of the significant reduction in static strength which occurs during a Stage 2-dominant endurance.

(d) The multiplicity of specimen sizes and modes of loading (rotating bending, plane bending, axial, torsional) can be misleading by a factor of up to about 5 on *strength*. For instance, the performance of materials in sections of at least 20mm thick (minimal mechanical-working benefits and plane strain conditions) differs from that of thinner sections of say 5mm thick (benefits of mechanical working, plus benefits of plane stress conditions).

(e) No measure is provided of the cyclic stress-strain curve, which is necessary to derive notched S-N curves from unnotched data.

2.5 A PROPOSAL FOR STANDARDISED FATIGUE TESTS FOR EVALUATING STRUCTURAL ALLOYS

Having identified the important criteria for the fatigue performance of components manufactured from extrusion, plate and forgings, specific proposals are now set out for the choice of specimens, loading and test procedure.

2.5.1 Specimens

The Stage 1 performance of a material can be measured by using plain specimens, and the Stage 2 performance by using plain specimens fitted with suitably designed fretting pads (plain-fretted specimens) - such as those employed by Fenner and Field¹¹, and also by Wright¹². Bearing in mind the need to be able to evaluate plate forms of the material in thicknesses down to about 5 mm, it is impracticable to use round specimens since in this instance the necessary waisting would reduce the test section size unacceptably. Waisted plain specimens of rectangular section based on the design shown in Figs.1.10 and 1.11 (companion specimen tests) are therefore more suitable. Two specimen sizes, say 5mm thick and 20mm thick, could be used - in the latter case preserving the same geometrical proportions and tolerances as in Figs.1.10 and 1.11, but scaling-up the dimensions by a factor of about 3 to give the necessary plane strain conditions.

2.5.2 Type of loading

In order to simplify the derivation of the notched performance from the unnotched data, it is suggested that tests should be made at zero mean stress.

As discussed in Part 1, there is strong evidence that the elastic interaction which occurs under service-type loadings is revealed - to first order - by Gaussian narrow band random loading with a truncation level, $\left(\frac{\text{maximum amplitude}}{\text{rms alternating stress}} \right)$, close to 4. This elementary form of random loading has three distinct advantages over other more complex forms of variable amplitude loading:-

(a) Expensive testing facilities are not required - narrow band random loading can usually be generated by adapting conventional constant amplitude fatigue testing machines. (A paper describing such an adaptation is reproduced as Appendix C.)

(b) More complex spectra - whilst providing a more accurate measure of elastic interaction in a particular situation - may limit the applicability of the results obtained.

(c) Gaussian narrow band random data can be used in lieu of constant amplitude data for life prediction purposes - as will be discussed in Part 3.

2.5.3 Test procedure

Bearing in mind the need to retain as far as possible the simplicity of the traditional procedure, it is proposed that specimens should be deployed as follows:-

(a) Stage 1 random 'S-N' curve

Fifteen plain specimens could be tested at 3 rms alternating stress levels (measured as described in Appendix C) to cover the endurance range 5×10^5 to about 5×10^7 cycles. Measurements should also be made of dynamic strain (Ref.8 describes how account can be taken of specimen waisting).

(b) Stage 2 random 'S-N' curve

Nine plain specimens with suitable fretting pads should suffice to establish the corresponding Stage 2 performance at three stress levels covering this same endurance range (again measuring dynamic strain) - it may be convenient here to use the same highest stress level as in (a).

Fig.2.2 shows the expected form of these Stage 1 and Stage 2 random 'S-N' curves.

(c) Progressive loss of static strength during Stage 2

Twelve further plain specimens with pads could be tested at the same three stress levels as in (b), but running two specimens to 30 per cent and a further two to 50 per cent of the nominal endurance in each case - these then to be broken statically to determine their residual strength.

These tests require a total of only 36 specimens (15 plain, plus 21 plain-fretted) for each of the two sizes of specimen (5mm and 20mm thick).

2.6 CONCLUDING REMARKS

It is important to recognise that the fatigue performance of a material has an upper boundary, when Stage 1 predominates, and a lower boundary, when Stage 2 predominates.

Traditional tests on plain and notched specimens using constant amplitude loading for the evaluation of materials have the following important deficiencies:-

- (a) the Stage 2 boundary condition is not defined;
- (b) the influence of elastic interaction is not revealed;
- (c) no measure is provided of the reduction in residual strength during Stage 2;
- (d) no provision is made to account for 'size-effects';
- (e) no measure is provided of the cyclic stress-strain characteristics.

A proposal is set out for standardised fatigue tests which overcome these deficiencies, whilst retaining, as far as possible, the simplicity of the traditional procedure. Specifically, this is based on:-

- (a) plain and plain-fretted specimens;
- (b) Gaussian narrow band random loading;
- (c) Specimens of two thicknesses - 20 mm and 5 mm.

It is necessary to test only 36 specimens to provide, for either plane strain or plane stress conditions, random 'S-N' curves for Stage 1 and Stage 2, and a measure of the reduction in residual static strength during Stage 2. A total of 72 specimens is therefore required to provide additional information on differences between plane strain and plane stress conditions and on the possible effects of mechanical working.

In Part 3 it is shown how such material evaluation data can be used directly in the fatigue design of structural components.

It is noteworthy here that notched specimens have been excluded from this procedure - the argument (a practical one for keeping down the number of tests) being that stress concentrations and geometric residual stresses can be adequately accounted for by calculation. Specifically, it is intended that the random S-N curve for notched specimens should be derived from the unnotched (zero mean stress) curve by scaling-down the stress by K_{σ} , the local stress concentration factor, which is derived from the cyclic stress-strain curve by assuming $K_{\epsilon} = K_t$. The measurements of rms alternating strain under the test conditions should reveal whether the material strain softens under prolonged loading - the condition when K_{σ} is no-longer equal to K_t - and if so, by how

much the cyclic strain increases from the monotonic value. Each cyclic rms alternating strain can then be plotted against the corresponding rms stress level to provide an rms cyclic stress-strain curve from which the value of K_{σ} , $\frac{\text{local rms stress}}{\text{net rms stress}}$, can be derived in the usual way, using

$K_{\epsilon} = K_t = \frac{\text{local rms strain}}{\text{net rms strain}}$. In order to determine the validity of this procedure it is hoped to start a small programme of research in which 5mm and 20mm thick notched specimens ($K_t = 2.3$ based on Fig.1.6) will be tested to complement programmes of unnotched Stage 1 and Stage 2 tests carried out on two materials according to the procedure proposed above.

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Alternating stress v K_t for large notched mild steel specimens — reversed direct stress fatigue loading

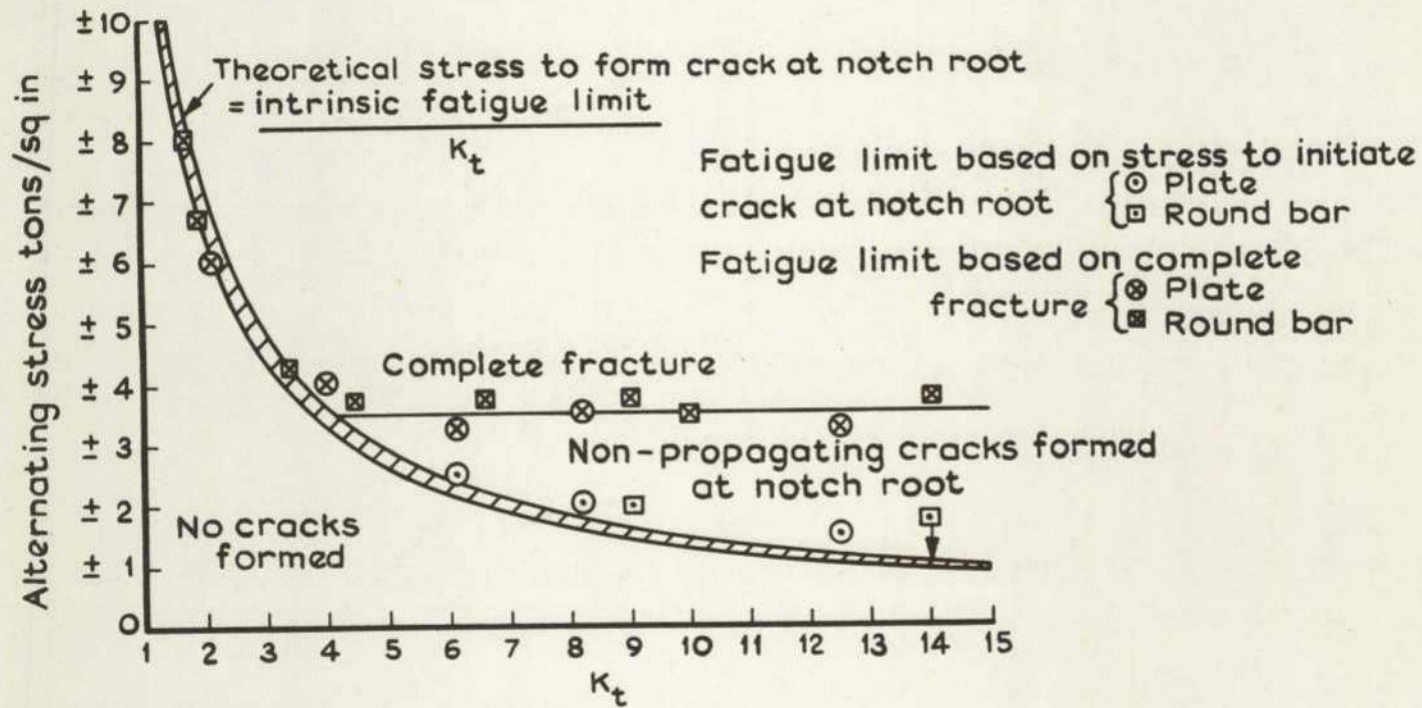


Fig. 2.1 Relation between reduction in plain-specimen fatigue limit and K_t for vee-notched specimens (reproduced from Ref. 9)

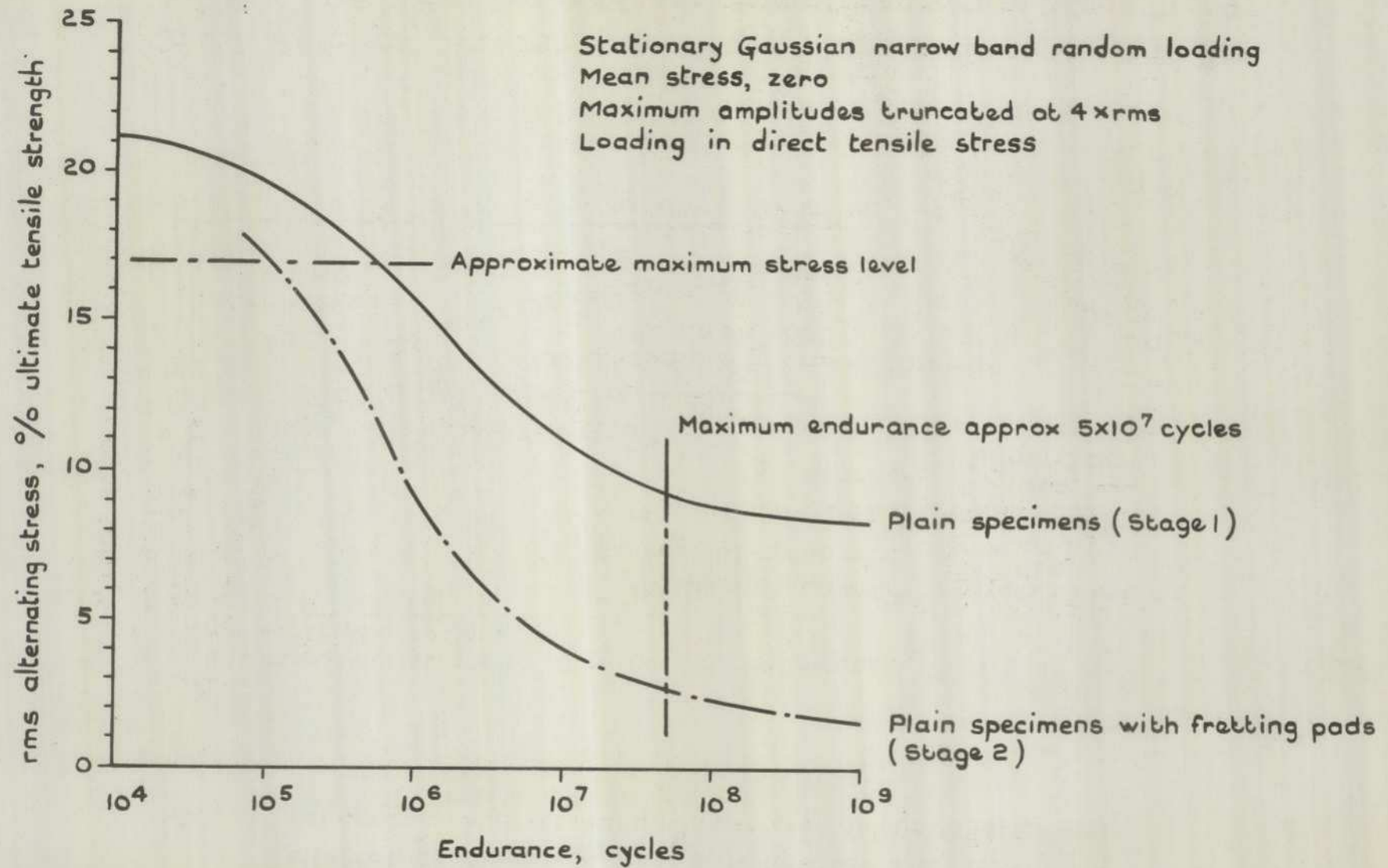


Fig.2.2 Expected form of random 'S-N' curves for the proposed evaluation conditions

PART 3

PROPOSALS FOR STRUCTURAL DESIGN RULES WHICH ACCOUNT FOR BOTH
ELASTIC INTERACTION AND GEOMETRIC RESIDUAL STRESSES

PROPOSALS FOR STRUCTURAL DESIGN RULES WHICH ACCOUNT FOR BOTH
ELASTIC INTERACTION AND GEOMETRIC RESIDUAL STRESSES

SUMMARY

It has been concluded in Part 1 that the most important sources of error in the Palmgren-Miner hypothesis are attributable to elastic interaction and geometric residual stresses. In Part 2 deficiencies in traditional procedures of material evaluation have been identified and it has been shown how these can be overcome by recognising the Stage 1 and Stage 2 boundary conditions of fatigue performance and by using Gaussian narrow band random loading.

In Part 3, corresponding inadequacies in design procedures are identified and proposals are made for alternative design rules which overcome these inadequacies and yet preserve the attractive simplicity of the Palmgren-Miner approach.

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3.1 INTRODUCTION

As discussed in Part 1, the general practice in estimating the fatigue endurance of structural components in service is to use the Palmgren-Miner hypothesis in relation to a given service loading or prescribed load spectrum. Whilst it is generally recognised that in extreme cases deficiencies in this approach can lead to values of $\sum \frac{n}{N}$ of between about 0.1 and 30, other more complicated cumulative damage theories (reviewed in Refs.1-3) are seldom used since it is held that these do not give worthwhile improvements in accuracy over the range of conditions which must be considered in design. It is the practice in estimating the fatigue life of a component to determine first an appropriate constant amplitude S-N curve on which to base the prediction. This curve is often selected from data for similar components, but when these are not available reference may be made to basic data covering a wide range of stress concentration factors or to data for idealised structural components. (Heywood's joint curves⁴ are widely used in the UK.) Alternatively, prototype components may be tested and the results used to locate an S-N curve of suitable shape⁵⁻⁷ for components of this type. This curve is then applied in conjunction with the Palmgren-Miner hypothesis to predict the endurance of the component. (It is UK practice to use $\sum \frac{n}{N} = 1$ except when large numbers of cycles below the fatigue limit are present, in which event $\sum \frac{n}{N} = 0.75$ is used⁵.)

Two alternative design procedures are currently receiving attention in the literature. In the first of these, the conventional Palmgren-Miner approach is retained with one fundamental change - the importance of geometric residual stresses is recognised and a calculated adjustment⁸ is made to the constant amplitude data. However, no allowance is made for elastic interaction and failure is assumed to occur when $\sum \frac{n}{N} = 1$ for the adjusted data. The recent ESDU data sheet⁹ "Cumulative fatigue damage calculations" is an example of such procedures. The second approach, which was first suggested in principle by Kirkby and Edwards¹⁰ and independently at the same time by Gassner¹¹, argues that design studies be based on data obtained under variable amplitude loading. This approach is currently much favoured in Germany and the Netherlands, where research workers are advocating a family of internationally agreed 'standard' load spectra - each of which represents a particular service loading condition, for example, that of the wing root of a transport aircraft^{12,13}. The principle here is to retain also constant amplitude loading and to use the conventional Palmgren-Miner hypothesis to predict the endurance under the 'standard'

spectrum. The difference between the prediction and the test result for the standard spectrum is then used to factor the Palmgren-Miner predictions for similar service spectra.

Whilst a recognition of elastic interaction is implicit in the second approach, no attempt is made to separate its influence from that of geometric residual stresses. In its present form the second method is entirely empirical and requires the availability of fatigue performance data under a wide range of loading spectra. However, this is a daunting prospect if it is borne in mind that, for a given load spectrum, the designer needs data for various configurations or, as is shown here, at least for Stage 1-dominant and for Stage 2-dominant conditions as a starting point in evaluating any material.

In section 3.2, the importance of obtaining design data appropriate to the expected failure mode - Stage 1 or Stage 2 - is first discussed, and then the two mentioned approaches are considered in turn. It is argued that in the standard spectra approach the influence of elastic interaction can be accounted for separately by basing design on a single standard spectrum - Gaussian narrow band random loading - from which more complex load spectra can be synthesised analytically. Alternative design rules which account for both elastic interaction and geometric residual stresses are set out in section 3.3.

3.2 CONSIDERATIONS AFFECTING FATIGUE LIFE ESTIMATION PROCEDURES FOR STRUCTURAL COMPONENTS

3.2.1 Importance of component failure mode in selecting design data

In selecting suitable basic fatigue data the designer must first decide which feature of his component is likely to be most critical in fatigue. This decision will be influenced by the presence or absence of stress concentrations and fretting, and also by the life to which the component is to be designed. This point is illustrated by Fig.3.1, which shows curves for a particular idealised component which may fail either from a notch or due to fretting. For design, consideration of the notch failure is appropriate at low endurances, and that of the fretted failure at high endurances.

A conservative basis for prediction of behaviour under variable amplitude loading is therefore the composite curve for that particular component, as indicated by the arrows in Fig.3.1. However, the designer may also use the entire 'fretted' curve in variable amplitude computations if failure can be confidently expected to occur at high endurances, or he can use the 'notched'

curve if failure is expected at low endurances. This will save material but may give an overestimate of endurance if failure occurs by the alternative damage mode. The argument applies whether the prediction is based on constant amplitude loading or on a 'standard' spectrum of variable amplitude loading.

3.2.2 Corrections for geometric residual stresses

As discussed in Part 1, the ESDU method⁹ can be used to account for the residual stresses which arise from plastic deformation of the material surrounding a geometric stress concentration. The assumptions made are that materials behave perfectly elastically below their 0.2 per cent proof stress and perfectly plastically above it, that there is negligible Bauschinger effect, that the strain concentration factor, K_ϵ , is equal to the elastic stress concentration factor K_t , and that the fatigue strength, σ , is related to mean stress, σ_m , by the expression

$$\sigma = \sigma_0 \left(1 - \left(\frac{\sigma_m}{\sigma_u} \right)^p \right)$$

where σ_0 is the fatigue strength at zero mean stress,
 σ_u is the ultimate static strength of the material
 and p is a positive index.

Since the $\sigma - \sigma_m$ curve formed by this equation passes through the point $\sigma = 0$, $\sigma_m = \sigma_u$, the value of p can be derived from fatigue test data for only two values of mean stress, σ_m .

From consideration of the 0.2 per cent proof stress, the stress concentration factor and the sequence of loading, the local geometric residual stress and hence the local mean stress can be derived for a particular load cycle. The appropriate mean/alternating stress relationship (index p) can then be used to derive the stress level which causes equivalent damage in the constant amplitude tests. Finally, the endurance corresponding to this amplitude can be read from the S-N curve and the damage calculated in the usual way according to the Palmgren-Miner hypothesis.

3.2.3 Corrections for elastic interaction and geometric residual stresses

As noted previously, the data obtained under variable amplitude loading will reflect elastic interaction and, in the case of notched specimens at high loads, also the effects of geometric residual stresses. The analysis of data

for a wide range of materials, specimen configurations and types of loading (presented in Part 1) indicates a clear distinction between the influence of elastic interaction in Stage 1 (plain and moderately notched specimens ($K_t \leq$ about 2.6)) and Stage 2 (fretted or sharply notched specimens ($K_t >$ about 3.5)). For a wide variety of service-type loadings, Stage 1 elastic interaction generally gives values of $\sum \frac{n}{N}$ between about 0.2 and 0.6, whereas Stage 2 elastic interaction generally gives values between about 0.8 and 2. Gaussian narrow band random loading (with a truncation level close to 4) has been shown to reveal this same distinction between Stage 1 and Stage 2 (with the same ranges of values for elastic interaction), and - as discussed in Part 2 - this is an important argument in favour of its selection as a standard spectrum for material evaluation.

Recognising that the distinction between Stage 1 and Stage 2 elastic interaction is more important than the second order distinction between elastic interaction under Gaussian narrow band random loading and that under particular service-type loadings, two alternative life prediction procedures for given service loadings are suggested here:-

(a) The first procedure retains constant amplitude data (appropriate to the expected Stage 1 or Stage 2 failure mode), and uses these with the conventional Palmgren-Miner hypothesis (corrected for geometric residual stresses according to the ESDU method) to calculate the endurance under the prescribed service loading. This calculated value would then be factored to account for elastic interaction. The argument here is that a correction factor for elastic interaction (appropriate to Stage 1 or Stage 2) can be applied as a factor to $\sum \frac{n}{N}$ together with the Palmgren-Miner-ESDU method to predict endurance under most service loading spectra.

(b) The second procedure abandons constant amplitude data and predicts endurance under service loading spectra by synthesising these analytically from several Gaussian narrow band random levels.

The two procedures are discussed in detail in the following section.

3.3 IMPROVED LIFE ESTIMATION PROCEDURES SUITABLE FOR USE IN DESIGN

In the previous section it has been argued that the conventional Palmgren-Miner design procedure is vulnerable to three main sources of error:-

(a) selection of design data for inappropriate failure mode (Stage 1 or Stage 2);

- (b) failure to account for elastic interaction;
- (c) failure to account for geometric residual stresses in components containing stress concentrations.

In this section it is shown, in practical terms, how these influences can be accounted for without sacrificing the attractive simplicity of the Palmgren-Miner approach.

For completeness we will consider the general case of a component of entirely new design for which no design data are readily available from similar components. The initial design will generally be governed by the known or stipulated distribution (amplitude and number) and sequence of loads which the component must withstand and by considerations such as cost, size, weight and operating environment.

3.3.1 Selection of basic fatigue data (Stage 1 or Stage 2 performance)

Having formed some initial ideas on the shape and size of the component, the designer should be able to assess whether the fatigue design should be based on Stage 1 or Stage 2 performance. Stage 1 will predominate in carefully designed components in which sharp stress concentrations are avoided ($K_t \leq$ about 2.6) and fretting is suppressed. Stage 2 will predominate in components which contain fretting or sharp stress concentrations. Components subject to accidental damage, as well as areas of structure where it is impracticable to implement rigorous controls in design and manufacture, will fall into the Stage 2 category.

Reference can then be made to plain or plain-fretted evaluation data as appropriate and a suitable material can be selected. In the absence of suitable 'standard' data of the type proposed in Part 2, the deficiencies of traditional data (section 2.4) must be borne in mind.

Having once decided on the shape and size of the configuration, having anticipated the associated failure characteristics and having selected a suitable material, the designer can then confine his attention to predicting the fatigue endurance. The two alternative life estimation procedures outlined in the previous section are described below.

3.3.2 Use of constant amplitude data adjusted for elastic interaction and geometric residual stresses

Firstly, the designer must consider whether the component is likely to be either Stage 1 or Stage 2-dominated so that he can use the appropriate plain

(Stage 1) or plain-fretted (Stage 2) constant amplitude data for the material chosen. (These data must conform in all respects, other than dynamic loading, to the conditions set out in Part 2.) Fig.3.1 illustrates the transition from Stage 1 to Stage 2 failures which may occur at high endurance and the associated considerations are set out in section 3.2.1.

Having decided whether a Stage 1 or Stage 2 constant amplitude curve (for plain or for plain-fretted specimens) should be used, the designer can predict the endurance under the service loading by means of the Palmgren-Miner hypothesis, together with the ESDU method for components containing geometric stress concentrations. For such components the constant amplitude S-N curve must be scaled-down on stress by the value K_σ , the *local* stress concentration factor, which can be derived as discussed in Part 2. The predicted endurance must then be appropriately factored to account for Stage 1 elastic interaction $\left(\sum \frac{n}{N} \text{ between about } 0.2 \text{ and } 0.6\right)$, or Stage 2 elastic interaction $\left(\sum \frac{n}{N} \text{ between about } 0.8 \text{ and } 2\right)$. The designer's choice of *one* value from within the appropriate range must depend upon 'design' (or 'safety') factors, which are clearly beyond the scope of this thesis. However, broadly the designer must be guided by whether the integrity of the component is vital, in which case the lowest figure must clearly be used, or whether a minimum error in prediction is required (for intervals between inspections), in which case a mean value is likely to be more appropriate.

If the designer cannot decide whether fatigue will be dominated by Stage 1 or Stage 2, he can consider both and choose the safer result or he can use the composite curve (indicated by arrows in Fig.3.1) with a value of $\sum \frac{n}{N}$ between 0.8 and 2. (Again, the lowest figure should be used if the integrity of the component is vital.) This last procedure is based on the recognition that the low value of $\sum \frac{n}{N}$ for Stage 1 fatigue derives to some extent from the damage done at low amplitudes and that variable amplitude computations on the basis of the composite curve attribute greater weight (smaller N) to low amplitude cycles than the 'notched' curve alone.

Alternatively, if it is possible to test a prototype component of the proposed design, the influence of elastic interaction on the value of $\sum \frac{n}{N}$ can be obtained by testing under Gaussian narrow band random loading or under a simulated service load spectrum which will reveal the failure mode and make it possible to compare the experimental endurance with that predicted (for the loading spectrum used) by the Palmgren-Miner-ESDU method. However, if such

tests are necessary, it may be simpler to use the second approach described in the following section or to use the test results directly as the final answer.

3.3.3 Use of Gaussian narrow band random data alone

Having argued that constant amplitude data do not provide the necessary measure of information on elastic interaction under service loadings, and having proposed that Gaussian narrow band random loading should be used in future material evaluation tests, we will now consider a life prediction method based entirely on Gaussian narrow band random loading.

The basis of such a method was suggested as long ago as 1965 by Kirkby and Edwards¹⁰, who prepared a random 'S-N' curve for pinned-lug specimens and used this - with, in effect, a Palmgren-Miner rule - to predict endurance under an aircraft gust loading spectrum. Specifically, Kirkby and Edwards employed a graphical technique similar to that of Press, Meadows and Hadlock¹⁴ to break down the RAeS gust spectrum¹⁵ into three Gaussian narrow band random levels (Gaussian loading components) of different intensity and duration. Fig.3.2 illustrates this procedure.

The relative damage inflicted by each Gaussian component is calculated from the random 'S-N' curve according to its relative duration (a procedure similar to that using the Palmgren-Miner hypothesis for, say, a conventional block-programmed constant amplitude loading with three levels). Failure is assumed to occur when $\sum \frac{n}{N} = 1$. Typically, for the gust spectrum, the method approximately halves the inaccuracy obtained with conventional Palmgren-Miner calculations. The principle of taking additionally into account the effect of geometric residual stresses has also been recognised and outlined by Edwards in a subsequent paper¹⁶.

The following proposals differ from those of Edwards in practical detail, although the principles adopted are similar.

3.3.3.1 Synthesis of service spectra from Gaussian narrow band random components

Before a discussion in detail of how the Kirkby-Edwards approach can be modified to account for geometric residual stresses, it is important to consider whether serious limitations are imposed by the need to synthesise service spectra from Gaussian narrow band random components. In Fig.3.2¹⁰, $\text{Log } E(f)$, the logarithm of 'cumulative levels crossed' is plotted against

$\left(\frac{f}{\lambda}\right)^2$, where f is the stress level and λ "a stress parameter relating to spectrum severity", which is constant for a given load spectrum. Gaussian narrow band random loading has a Rayleigh distribution of amplitudes satisfying $E(f) = \exp\left(-\frac{1}{2}\frac{f^2}{\sigma^2}\right)$, where σ is the rms alternating stress, and this gives a straight line in this graph. Hence any service spectrum which is 'concave' when plotted in such a graph (i.e. which has a power of f not greater than 2) can be synthesised from Gaussian narrow band random components.

In this connection care must be taken in the interpretation of "cumulative levels crossed". For Gaussian narrow band random loading the number of peaks, n_p , is approximately equal to the number of zero crossings, n_0 , so that spectra for which $\frac{n_0}{n_p}$ approximates to 1 can be plotted directly, but for wider band spectra, it is also necessary to ensure that the number of cumulative levels crossed relates to the distribution of fatigue cycles (amplitudes) about a mean value. The multiplicity of counting methods^{17,18} employed in service load analysis prevents a simple assessment of the constraints imposed by the Gaussian synthesis. However, judging by the spectra presented by Bathgate¹⁸ for a wide range of applications, these constraints seem unlikely to present serious practical limitations. Fig.3.3 - reproduced from Ref.19 - shows, for example, how a load spectrum for helicopter control, rotor and transmission components can be synthesised by this method.

Thus, any 'concave' or 'flat' service load spectrum of the type shown in Figs.3.2 and 3.3 is amenable to the type of design procedure proposed here.

3.3.3.2 Adjustments to account for geometric residual stresses

Having synthesised the service spectrum from a number of Gaussian narrow band random components, the designer must calculate in the case of a notched structural component the local mean stress which will prevail under that Gaussian loading component which has the highest rms level. As discussed earlier, it is proposed here that the Gaussian narrow band random loading should be truncated at about 4 times the rms level since this truncation is found to occur naturally on resonant machines (Appendices B and C) and obviously can be prescribed on electro-hydraulic machines. The statistical properties of the loading (Rayleigh distribution) dictate a probability that an amplitude equal to the truncation level occurs within about 10^4 cycles. Hence, providing the service loading is well-mixed and sufficient cycles of the highest Gaussian component are applied in, say, the first 25 or so per cent of the life (this

corresponds closely with the assumption made in the 'standard spectrum' approach¹³) then it may be assumed that the local mean stress corresponding to the highest rms is quickly reached and so dictates the mean stress to which the random 'S-N' data are to be adjusted. This value of local mean stress can be calculated in the usual way by the ESDU method⁹.

In instances where two distinct loading spectra are always applied consecutively, such as the periodic 'ground' and 'flight' spectra for an aircraft, additional data are required to account for the damage contributed by the constant amplitude cycle represented by the mean stress levels in a ground-air-ground cycle. Any geometric residual stress interaction between the periodic loading and the individual spectra must also be accounted for.

Having calculated the local mean stress which predominates under the service spectrum, the designer can now refer to the random 'S-N' curve. As noted earlier, he must first decide whether Stage 1 or Stage 2 is likely to predominate so that he can use the appropriate basic data for material evaluation (Part 2). Evaluation data given in the form of curves for unnotched (plain and plain-fretted) specimens must be scaled-down on stress by the value of K_σ , the local stress concentration factor, which can be derived by the procedure proposed in Part 2.

In order to apply the ESDU method to adjust the damage calculation for the Gaussian components, which in the random 'S-N' tests will have a mean stress of zero, it is convenient to retain the expression

$$\sigma = \sigma_0 \left(1 - \left(\frac{\sigma_m}{\sigma_u} \right)^p \right)$$

where σ_m is the adjusted local mean stress at the notch or the applied mean stress in a plain specimen, p the known index for the material tested, and where the rms alternating stress to failure (from the evaluation tests) is substituted for the fatigue strength σ_0 .

In order to determine the material index, p , for either Stage 1 or Stage 2, it is necessary to duplicate the material evaluation procedure (Part 2) at a second value of mean stress. Until such additional data become available it can be assumed that the 'random' alternating/mean stress diagram has roughly the same index as the constant amplitude diagram over the range employed for

adjustment. Work by Kirkby²⁰ and by Bathgate¹⁸, suggests that this assumption is likely to give a satisfactory approximation.

As described in section 3.2.2 the ESDU method can be used for each of the remaining Gaussian components to derive the stress level (rms) which causes equivalent damage in the random 'S-N' tests and the endurance can be read from the random 'S-N' curve. Finally, from the synthesis of the service spectrum, the number of cycles contributed by each Gaussian component is known, so that the total damage, and hence the predicted endurance can be calculated according to a 'Palmgren-Miner' rule.

It is assumed of course, that $\sum \frac{n}{N} = 1$ at failure, since here the method accounts for both elastic interaction and geometric residual stresses. In work to be reported shortly¹⁹ the accuracy of this method of life prediction will be compared with that of the method outlined in section 3.3.2, and with that of the conventional Palmgren-Miner hypothesis.

3.4 CONCLUSIONS

It is considered that the conventional Palmgren-Miner design procedure is vulnerable to three main sources of error:-

- (a) selection of fatigue data for inappropriate failure mode (Stage 1 or Stage 2);
- (b) failure to account for elastic interaction;
- (c) failure to account for geometric residual stresses in components containing stress concentrations.

Two improved design procedures are currently receiving much attention in the literature. The first of these - 'the ESDU method' - accounts only for geometric residual stresses. The second - the 'standard spectrum approach' - accounts for elastic interaction, but makes only an empirical allowance for geometric residual stresses so that data are required from a daunting number of 'standard' spectra in addition to constant amplitude loading. In neither of these procedures is attention drawn to the important distinction between the Stage 1 and Stage 2 boundary conditions in selecting the basic fatigue data on which to base the prediction.

On the basis of work presented in this thesis, two alternative life estimation rules are proposed:-

(a) Palmgren-Miner rule adjusted to account for elastic interaction and for geometric residual stresses

This approach retains constant amplitude data and consists in essence of the ESDU method with an appropriate factor to allow for elastic interaction. The steps in this procedure are as follows:-

- (1) Select Stage 1 or Stage 2 constant amplitude data appropriate to the failure mode. Divide the unnotched S-N curve by K_{σ} (the *local* stress concentration factor) if the component contains a geometric stress concentration.
- (2) Predict the endurance under service loading by using the Palmgren-Miner hypothesis, which is to be combined with the ESDU method if the component contains a geometric stress concentration.
- (3) Factor this predicted endurance to account for Stage 1 elastic interaction $\left(\sum \frac{n}{N} \text{ between about } 0.2 \text{ and } 0.6 \right)$ or for Stage 2 elastic interaction $\left(\sum \frac{n}{N} \text{ between about } 0.8 \text{ and } 2 \right)$, as appropriate. The designer's choice of one factor from within the appropriate range will be guided by whether the integrity of the component is vital or whether a minimum error in prediction is required. If it is not known whether Stage 1 or Stage 2 fatigue is appropriate, the designer can (i) calculate both cases independently and choose the safer value or (ii) combine the data to one conservative S-N curve for both conditions, apply step 2 to this curve and use a value of $\sum \frac{n}{N}$ between 0.8 and 2, or finally (iii) derive a factor empirically by testing a prototype component under Gaussian narrow band random loading or under a simulated service spectrum. However, the method (iii) can lead directly to the desired result and it may be simpler to use the second approach to be described.

(b) Palmgren-Miner rule based on variable amplitude data and adjusted to account for geometric residual stresses

This second approach abandons constant amplitude data altogether in favour of data obtained under Gaussian narrow band random loading (as proposed in Part 2 for future material evaluation work). The steps involved are as follows:-

- (1) Select Stage 1 or Stage 2 Gaussian narrow band random data as appropriate to the failure mode - again dividing the unnotched 'S-N' curve by K_{σ} if the component contains a stress concentration.

- (2) Synthesise the service spectrum from Gaussian narrow band random components. (This is possible only for 'concave' or 'flat' service spectra, see Figs.3.2 and 3.3.)
- (3) If the structural component contains a geometric stress concentration, calculate by the ESDU procedure the local mean stress which predominates under the service spectrum. This will generally be that produced by the highest Gaussian component (truncation level: $4 \times \text{rms}$). (The damage contributed by periodic constant amplitude loading such as the ground-air-ground cycle for an aircraft must be calculated separately, and any geometric residual stress interaction with the highest Gaussian component must be accounted for.)
- (4) Adjust the damage due to the Gaussian components to account for the mean stress which predominates under the service loading. Again the ESDU procedure is used, but the assumption is made (until suitable data become available) that the shape of the random alternating/mean stress diagram (over the adjustment range) is much the same as that for constant amplitude loading.
- (5) Combine the number of cycles contributed to the service spectrum by each Gaussian component with the corresponding ESDU-adjusted endurance (from the random 'S-N' curve) to calculate the total damage - and hence the predicted endurance - using a 'Palmgren-Miner' summation, with
$$\sum \frac{n}{N} = 1 \text{ at failure.}$$

It is recognised that in addition to the extant work noted in sections 1.6 and 2.6, further research is required in a number of areas before these design rules can be set out in greater detail and applied with more confidence. In particular, it is necessary:-

- (a) to establish the significance of any distinction between constant amplitude and random Stage 1 and Stage 2 alternating/mean stress diagrams (for new and for established structural alloys);
- (b) to analyse service loadings in order to define any constraints imposed by a Gaussian narrow band random synthesis of service spectra.

Research is currently in hand at RAE (Appendix A) from which the validity of these rules can be determined for structural features in a number of materials tested under high and low values of mean stress. However, in this

work the particular service spectrum against which the accuracy of prediction is assessed, is itself generated from Gaussian narrow band random components, and so further testing is required under more irregular loading which has less correlation between consecutive load cycles. In the choice of this loading, consideration will be given to the range of 'standard' spectra which are being evolved internationally.

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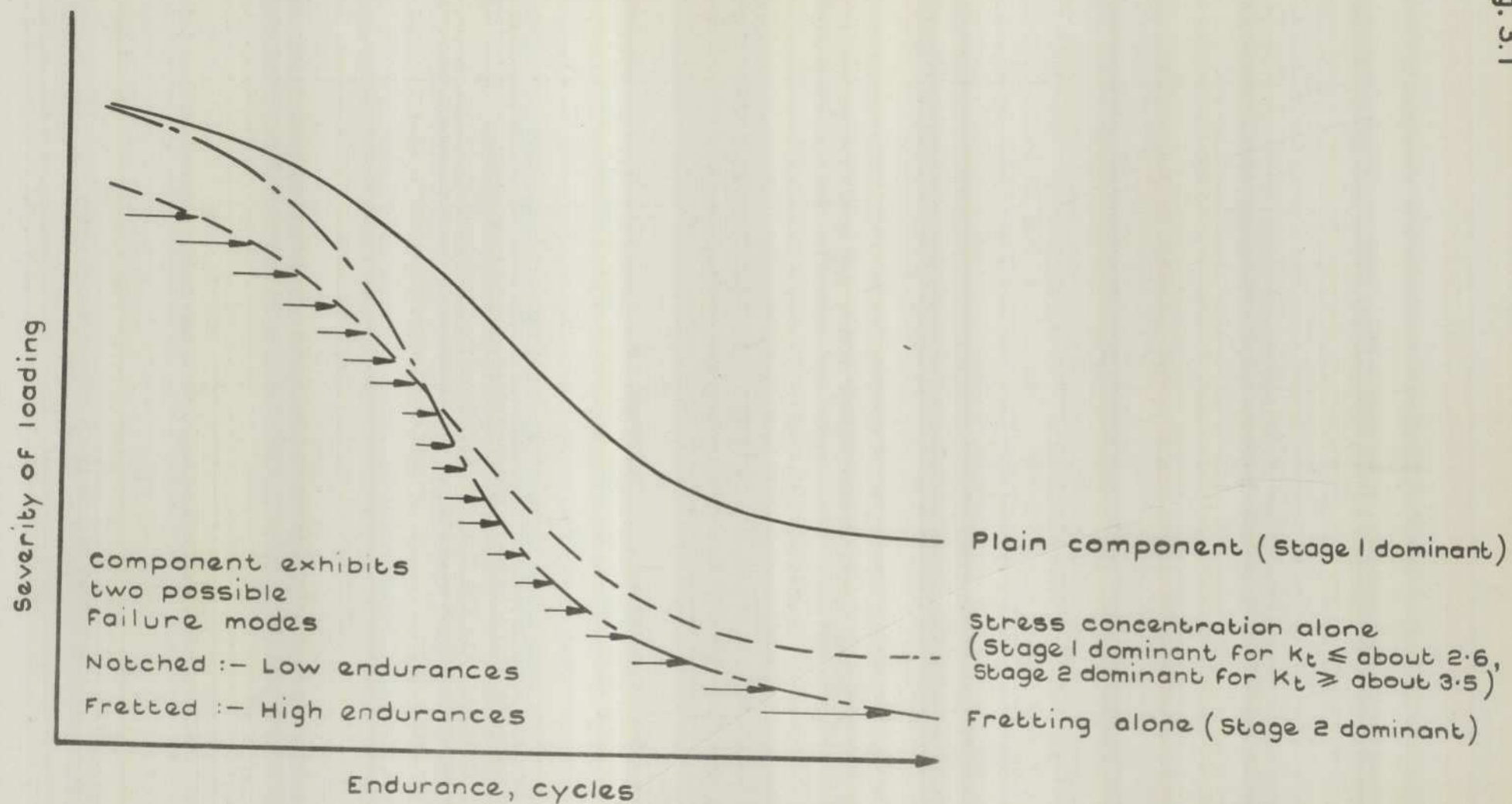


Fig. 3.1 Possible transition from notched to fretted failures at high endurances

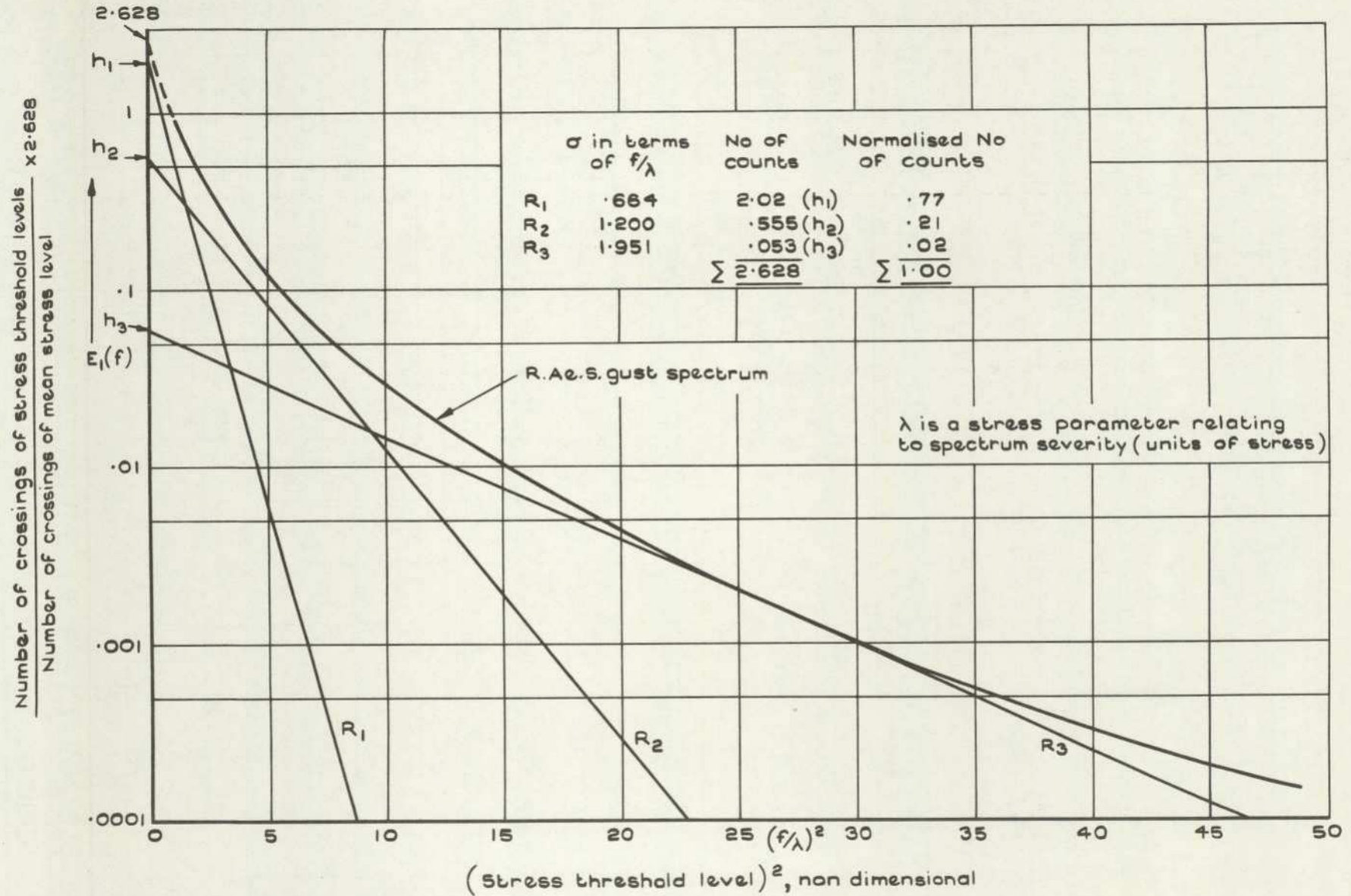


Fig.3.2 Synthesis of aircraft gust spectrum from three Gaussian narrow band random components (reproduced from Ref.10)

Fig. 3.3

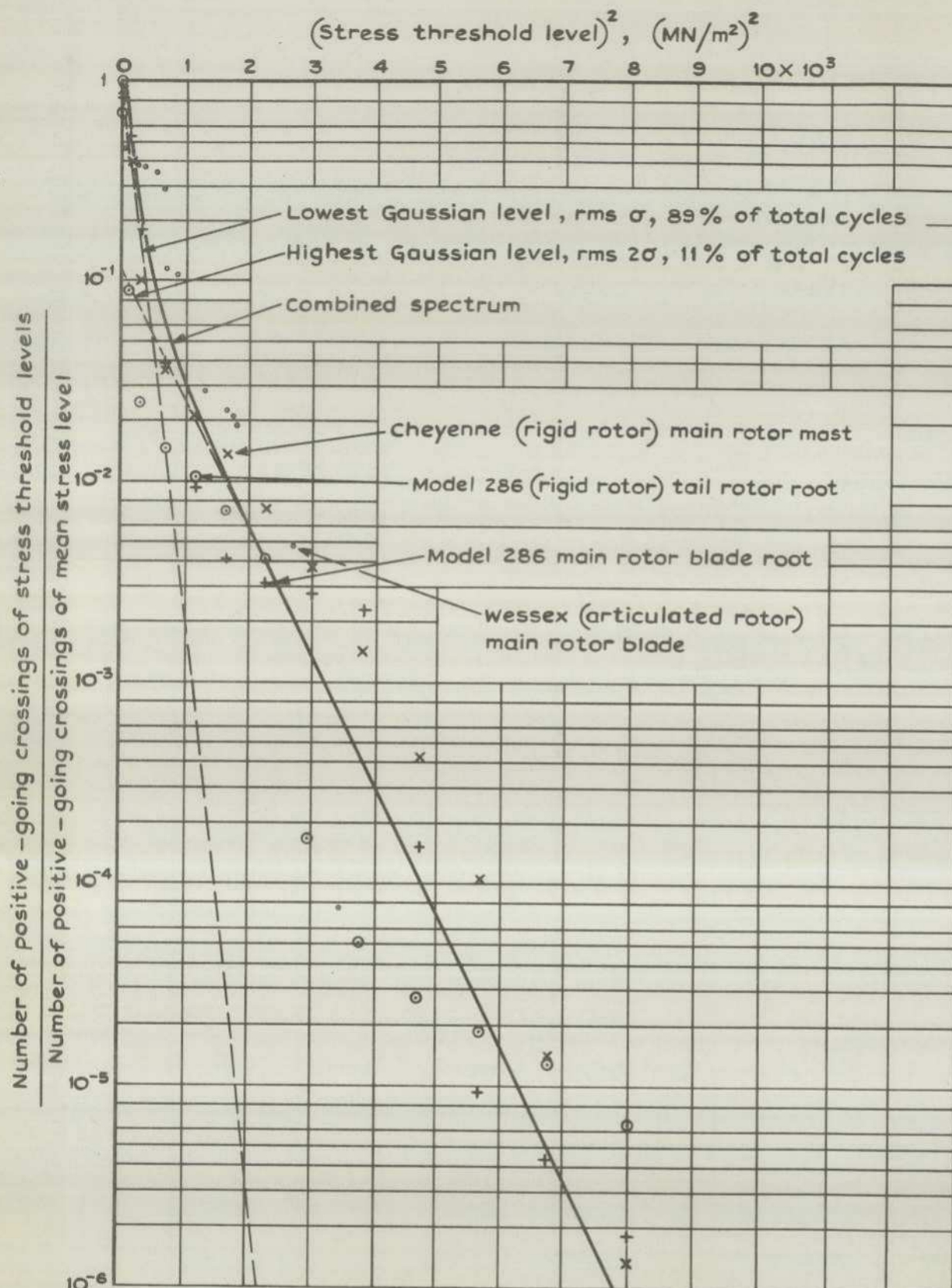


Fig. 3.3 Synthesis of "helicopter spectrum" from two Gaussian narrow band random components (reproduced from Ref.19)

Part 2

A PROPOSAL FOR STANDARDISED FATIGUE TESTS
FOR EVALUATING STRUCTURAL ALLOYS

Provides measure of the Stage 1 and Stage 2 boundary conditions of fatigue performance, and measure of reduction in static strength during Stage 2, under loading which reveals the influence of elastic interaction

- plain and plain-fretted specimens (Stage 1 and Stage 2 respectively)
- axial loading with mean stress zero
- Gaussian narrow band random fatigue loading
- 36 specimens only, but duplication necessary for distinction between plane strain and plane stress performance.

Part 3

PROPOSALS FOR STRUCTURAL DESIGN RULES WHICH ACCOUNT FOR BOTH
ELASTIC INTERACTION AND GEOMETRIC RESIDUAL STRESSES

Two alternative rules are proposed, both of which draw attention to the distinction between Stage 1 and Stage 2 failure modes, and account for elastic interaction and geometric residual stresses.

(a) Palmgren-Miner rule adjusted for elastic interaction and for geometric residual stresses

- 1 Select Stage 1 or Stage 2 constant amplitude data, as appropriate, and divide unnotched S-N curve by K_G , (the local stress concentration factor), if the component contains a stress concentration.
- 2 Predict the endurance using Palmgren-Miner rule - accounting for residual stresses by the ESDU method if the component contains a stress concentration.
- 3 Factor this endurance to account for Stage 1 elastic interaction $\left(\sum \frac{n}{N} \text{ between about } 0.2 \text{ and } 0.6\right)$, or Stage 2 elastic interaction $\left(\sum \frac{n}{N} \text{ between about } 0.8 \text{ and } 2\right)$. The choice of one factor from within the appropriate range will be guided by whether the integrity of the component is vital or whether a minimum error in prediction is required.

(Rules are also suggested for use when it is not known whether Stage 1 or Stage 2 fatigue is appropriate.)

(b) Palmgren-Miner rule based on variable amplitude data and adjusted to account for geometric residual stresses

- 1 Select Stage 1 or Stage 2 Gaussian narrow band random data, as appropriate, and divide unnotched random 'S-N' curve by K_G if the component contains a stress concentration.
- 2 Synthesise the service spectrum from Gaussian narrow band random components.
- 3 If the component contains a stress concentration, use the ESDU method to calculate the local mean stress which predominates under the service spectrum.
- 4 Adjust the damage due to the Gaussian components to account for the predominant mean stress - again retaining the ESDU procedure.
- 5 Combine the number of cycles contributed to the service spectrum by each Gaussian component with the corresponding ESDU-adjusted endurance to calculate the total damage - and hence the predicted endurance - using a 'Palmgren-Miner' summation, with $\sum \frac{n}{N} = 1$.

PART 4

AREAS FOR RESEARCH INTO THE STRUCTURAL FATIGUE PERFORMANCE
OF CARBON FIBRE REINFORCED PLASTICS

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AREAS FOR RESEARCH INTO THE STRUCTURAL FATIGUE PERFORMANCE
OF CARBON FIBRE REINFORCED PLASTICS

SUMMARY

The properties of carbon fibre reinforced plastics are discussed and an attempt has been made to anticipate the more important questions which must be answered in order to aid design and the formulation of airworthiness requirements for fatigue loaded CFRP structures.

Programmes of fatigue research on carbon fibre reinforced plastics are summarised and plans are presented for complementary intramural work in which specimens containing typical structural features will be tested under realistic loading.

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4.1 INTRODUCTION

It has been demonstrated that reductions in weight of up to 60 per cent can be achieved by the use of uniaxial carbon fibre reinforced plastic (CFRP) in the re-design of simple metal components subjected to axial static loading¹⁻¹⁰. Under axial fatigue loading of constant amplitude, plain specimens of uniaxial CFRP show a similar ratio of fatigue/static strength to that for metals. Thus, for simple components subjected to constant amplitude axial fatigue loading, corresponding savings in weight would be expected. However, most structural components are less simple and are subjected to multi-directional loads of variable amplitude. Under multi-directional loading complex "angle-ply" varieties of CFRP are most likely to be used, and so it will be particularly important to obtain an understanding of the fatigue performance of this material under variable amplitude loading. In addition, built-up structures will contain joints and other stress concentrations which have led to fatigue problems in metals and are likely to do so in CFRP or mixed metal/CFRP structures. Although a few moderately complex CFRP components have been built and flown, these have generally required fatigue clearance for only a limited number of hours and it has been accepted that adequate airworthiness safeguards can be provided by testing under realistic loads to life factors several times greater than those applied to metal components. It is clear that such an approach will not be acceptable for future projects, but before more rational requirements can be written or confidence in design obtained, a number of questions must be answered.

What criteria must be used to assess the fatigue performance of CFRP? How sensitive is uniaxial material to secondary loading in shear when matrix properties become critical? What penalties are paid for introducing more fibre axes to reduce anisotropy? Does the lower static strength of CFRP in compression give rise to a proportionally lower fatigue strength than that in tension? How does fatigue scatter compare with that in structural alloys? What are the effects of changes in section and of surface damage? What is the ratio of fatigue to static strength in joints? Can a simple linear damage summation such as the Palmgren-Miner hypothesis be used to calculate the fatigue performance under a spectrum of loads? What are the effects of environment, such as humidity and temperature? How sensitive is CFRP to load frequency? How reliably and to what extent can defects and fatigue damage be detected? Finally, what completely new and unexpected problems might emerge in service from the use of this fundamentally new material?

In view of the time consuming nature of fatigue investigations it is essential that the available effort is placed most effectively. Accordingly, an attempt has been made to determine the most important areas for fatigue research, to summarise existing programmes of work and to identify those areas in which Structures Department can contribute most effectively.

4.2 DISCUSSION OF THE FEATURES OF CARBON FIBRE REINFORCED PLASTICS

4.2.1 Areas of particular concern

4.2.1.1 Fatigue failure criteria

It is generally recognised that reinforced plastics, as a class, fail under tensile fatigue loading by progressive debonding and resin cracking¹¹, which causes serious reductions in stiffness and strength¹² early in the life. Such characteristics necessitate residual stiffness or residual static strength criteria for fatigue endurance, in addition to the simple fracture criterion which has proved adequate for small test specimens of most structural alloys in which stiffness and strength do not generally begin to fall-off appreciably until the last 10 to 15 per cent of the fatigue life. However, recent work by Beaumont and Harris¹³ and by Owston¹⁴ suggests that plastics reinforced axially with carbon fibres may not exhibit these symptoms, so that in both pulsating tension and in flexure the stiffness of uniaxial CFRP may remain virtually unchanged until failure occurs.

Under cyclic shear, however, which might typically occur as a secondary loading, the fatigue strength of CFRP is expected to be dominated by matrix properties, which are essentially the same as those of the conventional reinforced plastics. Characteristic reductions in shear stiffness and strength¹⁵ are therefore expected at an early stage in the fatigue life, so that the vulnerability of CFRP to fatigue loads in shear is likely to be greater than suggested by the ratio of the static shear strength to the tensile strength.

Under compressive loading, the available evidence suggests that cracks are likely to develop early in the fatigue life and to propagate through the material without causing a loss of compressive stiffness. However, crack development will be accompanied by reductions in tensile stiffness and strength which will be important in most practical applications.

4.2.1.2 Fatigue strength in tension

The work of Beaumont and Harris¹³ and Owen and Morris¹⁶ indicates that the fatigue strength of uniaxial CFRP under pulsating tensile fatigue loading, (0-max-0), is similar to that of structural alloys, i.e. the material will endure maximum stresses of about 70 per cent or so of the ultimate static strength for about 10^7 cycles. Work reported by Pullen¹⁷ suggests that the tensile mean stress is of secondary importance, in that amplitudes of about 35 per cent of the static strength give endurances of about 10^7 cycles at zero mean stress (min-0-max).

4.2.1.3 Sensitivity to shear stresses

The interlaminar shear strength of CFRP is generally reported to be about 6 per cent of the tensile strength^{18,19}, i.e. about an order of magnitude less than the shear to ultimate strength ratio for structural alloys. The close similarity of the interlaminar shear strength to that for glass reinforced plastics is consistent with the dominance of matrix, rather than fibre interface properties under shear loading. Hence the work of Lavengood and Anderson¹⁵ on the constant load shear fatigue of 828 epoxy resin, reinforced with glass roving, should be applicable to CFRP. Their work shows that a failure criterion of 10 per cent loss in stiffness gives a shear fatigue strength of about 15 per cent of the interlaminar shear strength*. For CFRP this compares with a tensile fatigue strength (complete rupture) at 10^7 cycles of about 35 per cent of the static strength. Typically, therefore, the shear fatigue strength of uniaxial material would be expected to be less than about 3 per cent of the tensile fatigue strength, i.e. about one half of the ratio of the static interlaminar shear strength to the tensile ultimate and about one twentieth of the ratio of the shear fatigue strength to the tensile fatigue strength of typical structural alloys. Furthermore, under combined axial and shear loading as might arise for instance from torsional loads on a unidirectional rod loaded primarily in tension, expressions such as the Gough ellipse,

$$\frac{(\text{alternating shear stress})^2}{(\text{shear fatigue strength})^2} + \frac{(\text{alternating tensile stress})^2}{(\text{tensile fatigue strength})^2} = 1$$

as used for isotropic materials, suggest that equal fatigue damage may be caused by equal numbers of secondary shear components of only about 3 per cent of the nominal axial fatigue stress. In design terms this means that only when these components are below about 1 per cent of the nominal axial stress may they be

* Some exploratory work on the shear fatigue strength of CFRP has been done by Rao and Hofer²⁰ and by Wadsworth and Hutchings²¹, but unfortunately a comparison is not possible since no stiffness measurements were reported.

safely neglected. Structural alloys, on the other hand might be considered to be uniaxially loaded for damage calculation purposes if shear stresses are less than about 20 per cent of the axial value.

4.2.1.4 Fatigue strength in compression

The static compressive strength of CFRP is reported to be between 60 per cent and 90 per cent of the tensile strength. Compressive fatigue stresses are therefore likely to be more damaging than stresses of equal amplitude in tension. This has been demonstrated by Owen and Morris¹⁶ and by Beaumont and Harris¹³ in four point bending pulsating* flexural tests on Type 1 composite. It is reported that damage initiates early in the fatigue life, with the appearance of local fibre buckling on the compression surface. The damage subsequently propagates slowly as a macroscopic crack toward the neutral axis of the specimen, without substantial loss in bending stiffness. The ratio of fatigue to static strength in pulsating flexure was found to be much the same as that in pulsating tension. Similar fatigue damage would be expected under axial pulsating compressive loading and also under fully reversed loading. In the latter case damage would probably develop more slowly at first in the absence of compressive mean stress. Fully reversed rotating bending tests are reported by Pullen¹⁷. These show the fatigue strength at 10^7 cycles to be 34 per cent of the tensile strength. This is approximately the same as the strength obtained in tension and flexure, despite the absence of a tensile mean stress. Rao and Hofer²⁰ report tests on angle-ply material under axial fully reversed loading. Their work shows the fatigue strength at 10^7 cycles to be approximately 45 per cent of the tensile strength. This figure is shown to be increased by about 5 per cent by the introduction of glass scrim cloth between consecutive CFRP plies.

4.2.1.5 Fatigue strength of angle-ply material

The reduction in specific properties associated with the introduction of additional non-axial fibres to offset anisotropy is fairly severe, but theoretically, static advantages could still be shown even in applications requiring approximately two-dimensional isotropy. The work of Rao and Hofer²⁰, Owen and Morris²² and Dauksys, Pagano and Spain²³ indicates that the ratio of fatigue to static strength of angle-ply material is much the same as that of uniaxial composite. Holmes and Wright²⁴ however, show that the figure may be a little lower. These results contrast with the marked reductions in strength associated with angle-ply glass reinforced plastics¹².

* The term "pulsating" is used to describe repeated (0-max-0) loading as distinct from the term "fully reversed" which will be used for repeated loading at zero mean stress (min-0-max).

4.2.1.6 Scatter in strength

Owen and Morris¹⁶ and Beaumont and Harris¹³ have shown that under axial pulsating fatigue loading, the peak stresses for endurance of up to 10^7 cycles generally fall within the scatter band in static strength. This result should be interpreted with caution, however, since the reported coefficient of variation of 25.5 per cent in the static strength of the carbon fibre used in their work is approximately five times greater than that of structural alloys²⁵.

In view of the features discussed in the preceding sections, the scatter in fatigue performance is expected to depend on the various failure modes which may be encountered.

4.2.1.7 Effects of stress concentrations and surface damage

In ductile materials containing geometric stress concentrations, local deformation under static load generally limits the reduction in ultimate strength to a proportion corresponding to the reduction in gross area. The fatigue strength, on the other hand, is generally much more drastically affected and the factor by which the fatigue strength is reduced approaches the value of the local stress concentration. In view of the elastic fracture characteristics of CFRP, it would be expected that the static strength would be reduced in proportion to the elastic stress concentration, so that the ratio of the fatigue strength to the static strength is likely to be similar to that for plain specimens. However, the ratio could be lower in some instances due to the greater vulnerability to shear mode failures under fatigue loading.

A way-in to the determination of the probable failure modes associated with changes in section and thereby to an assessment of their effects on fatigue performance, is provided by the work of Wadsworth and Hutchings²⁶ on the static properties of unidirectional composite. They show by calculation that, under elastic conditions, the maximum tensile stress parallel to the fibres at the edge of a circular hole is about 7.3 times that at infinity, compared with a figure of 3.0 for isotropic material. In a static test on a small specimen, shear cracks were observed at the edge of the hole, but these did not lead to premature failure under net stresses of at least 30 per cent of the material ultimate. This result is supported by the recent theoretical work of Sarah Bishop²⁷. Since, as discussed earlier, the shear fatigue strength at 10^7 cycles is likely to be only about 15 per cent of the static shear strength, similar shear cracks are likely under proportionally lower fatigue loads.

Little evidence is available of the effects of surface damage on fatigue performance. It is noteworthy however, that Owen²⁸ reports that microscopic examination of the edges of typical fatigue specimens prior to test* usually reveals smearing of the matrix with many fibres broken below the surface.

4.2.1.8 Strength of joints

With the introduction of advanced composites came the hope that many traditional structural problems associated with joints might be overcome by the use of large integral components fabricated using filament winding. Attempts to design aircraft structures in this way have not so far been successful. In fact, as more experience is gained with practical designs, which take into account the constraints of tooling and fabrication, it becomes increasingly clear that the design of bonded and mechanical joints will be of critical importance in the application of advanced composites to aircraft structures.

The pin bearing strength of CFRP is low^{31,32,33} and, as discussed earlier, in its most efficient forms CFRP is highly anisotropic with a low interlaminar shear strength. A number of practical solutions have been proposed to overcome these limitations³¹⁻⁵¹. For example, it has been shown that simple bonded lap joints^{31,35,40,46} can be successful in joining thin CFRP skins to metal structure which is stiff enough to restrict the bending associated with misalignment of the loading axes. Some designs^{6,33,35} incorporate bolts or rivets, but their use would not seem desirable, except perhaps in instances where high peel stresses cannot be avoided.

The misalignment problem, with its associated limitation on adherend thickness, can be minimised by using a shallow scarf or multi-stepped lap joint. Whilst these solutions are intrinsically more efficient than the simple lap they involve greater complexity in manufacture. Bell³⁷ reports interlaminar shear failure in 5° scarf joints between untreated angle-ply 0°, 45°, 90° CFRP and aluminium alloy. It is noteworthy that triple-stepped lap joints of the same material were also said to fail by interlaminar shear, the failure stress of about 20 MN m⁻² suggesting a shear stress concentration factor of just over 3. Such a figure may be typical of well-designed joints, as shown by the photo-elastic studies of Niranjana⁵⁰. In the event of failures by interlaminar shear, the fatigue strength at 10⁷ cycles is likely to be only about 15 per cent or so of the static strength¹⁵. Simple lap joints of the same size are reported to fail at about half the scarf joint load, as are unbonded bolted joints.

* In this context the work of Dastin²⁹ and Huber³⁰ on machining techniques may be helpful to some readers.

However, in the latter case, the net stress appears to reach the ultimate of the angle-ply material, suggesting that the introduction of local two-dimensional isotropic angle-ply into uniaxial material, thickening-up around the stress concentration by about 3:1, should enable the full uniaxial tensile strength to be realised. An alternative joint between CFRP and metal, which uses steel shims scarfed at 4° between splayed pre-preg laminates, has been investigated by Rotorway Components Ltd.³⁹; fatigue test results are to be reported. Keen³⁸ of Rolls-Royce also reports the use of steel laminates with CFRP pre-preg; in this case the laminations are scarfed into the leading edge of the RB-211 fan blades to overcome bird impact failures in the CFRP. This modification is reported to have led to some deterioration in the fatigue properties of the blades associated with the run-out of the laminations at the blade root, but intensive development is said to have produced worthwhile improvements.

A successful joint has been developed by Westland Helicopters⁷ for transmitting load into CFRP torque tubes. The end of the angle-ply CFRP tube is overwound with glass fibre fabric of sufficient thickness to permit bolts to be introduced without generating unacceptable bearing stresses in the composite.

The fatigue strength of idealised aluminium alloy beams with CFRP flange reinforcement is being investigated by O'Neill and Sewell⁵¹ at RAE. Their studies have been made using short beams reinforced with Type 2 treated fibre/828/60 per cent volume fraction/wet lay-up composite cured at 120°C . Under static loading the specimen fails by tensile fracture of the CFRP, following yield in the aluminium alloy at an average interface shear stress of about 22 MN m^{-2} . However, under fatigue loading failures occur by interlaminar tension or shear. Preliminary results suggest that the fatigue strength at 10^7 cycles is about 10 per cent or so of the static strength, i.e., a value comparable to that for well-designed pinned or clamped joints in structural alloys.

4.2.1.9 Applicability of the Palmgren-Miner hypothesis

Cumulative damage calculations of the fatigue performance of structural alloys under a spectrum of loads are generally made using the Palmgren-Miner hypothesis. This has the outstanding advantage of simplicity, predicting failure when $\sum \frac{n}{N} = 1$ on the basis of constant amplitude data. In practice the summation obtained can differ markedly from 1, but some understanding of the inadequacy of the rule has been built-up and it is usually possible to make an allowance at the design stage such that a reasonable estimate can be made of fatigue life. Typically, in simple high-low single-step tests on plain specimens,

$\sum \frac{n}{N}$ for structural alloys is generally between about 0.5 and 1.0, whereas for low-high tests $\sum \frac{n}{N}$ is generally between about 1.0 and 1.5.

Hofer *et al*⁵² report comparable single-step tests on plain specimens of uniaxial and angle-ply glass reinforced plastic. Their results are rather inconclusive, however, since wide scatter was obtained in both materials. The average values of $\sum \frac{n}{N}$ for the uniaxial composite were quite unlike those for structural alloys, being about 2.75 for both high-low and low-high tests, whereas the angle-ply material exhibited average values of approximately 2.1 and 0.9 for high-low and low-high tests respectively. These latter figures suggest that plain specimens of angle-ply glass reinforced plastic exhibit characteristics similar to those for notched specimens of structural alloys, i.e. they exhibit 'notched' behaviour. Shockey, Anderson and Hofer⁵³ report single-step tests on angle-ply boron composite; wide scatter was again obtained, but it was concluded that $\sum \frac{n}{N}$ was, if anything, greater in low-high than in high-low tests, a result inconsistent with the reported 'notched' behaviour of the angle-ply glass reinforced plastic.

If the 'notched' characteristics shown by the angle-ply glass reinforced plastic are associated with the relatively low fibre stiffness, the cumulative damage behaviour of Type 2 CFRP, would be expected to show a closer affinity to that of boron composite (and unnotched structural alloys), the stiffnesses of glass, Type 2 carbon and boron fibre being in the approximate ratio 0.3:1:1.5.

A paper has recently been presented by Brautman and Sahu⁵⁴ in which a cumulative damage theory for fibre reinforced plastics is proposed on the basis of changes in residual strength.

4.2.1.10 Effects of hostile environments

As discussed by Beaumont and Harris¹³, several possible interactions may result when CFRP is exposed to hostile environments. For example, the environment may bring about an immediate reduction in toughness, the resin may become plasticized, or particles may become trapped at the resin-fibre interface. Furthermore, as reported by Donia Coomber and Davis⁵⁵, and by Brown and Donia Coomber⁵⁶, humid conditions accelerate corrosion between CFRP and metals of high negative electrode potential such as aluminium. In such a combination, corrosion of the aluminium is comparable to that of magnesium in contact with brass. Beaumont and Harris¹³ report a comparison of conventional constant

strain torsional fatigue data for Type 1 treated composite, with data from tests in water after exposure to steam at 100°C for 48 hours, and with data from tests in oil at room temperature after exposure to oil at 100°C for 150 hours.

They conclude that exposure to steam and water reduces the torsional fatigue endurance by up to an order of magnitude at all but the lower stress levels, whereas they report no significant difference between data for oil-exposed material, and those for material tested in air. Owen and Morris¹⁶ report tensile and flexural fatigue tests on Type 1 untreated composite immersed in distilled water after prior immersion for two months. The effect is reported to be less than the observed scatter in the results, but as discussed earlier, variability in the static strength of their CFRP was high, and this could cloud an effect of the magnitude reported by Beaumont and Harris¹³, whose criterion of failure was crack density rather than rupture.

4.2.1.11 Effects of load frequency

Owen and Morris¹⁶ have concluded that for uniaxial material loaded in tension frequency effects can be neglected within their test range of about 2-115 Hz, although temperature rises of up to 50°, approximately 25 per cent of the glass transition temperature of the matrix, are reported at the highest frequency. Lower temperature setting resins, as might be used to minimise residual thermal stresses in CFRP-metal composites, would be expected to be most vulnerable to frequency effects in view of their inherently lower glass transition temperatures.

4.2.1.12 Effects of exposure to cryogenic and elevated temperatures

Hanson⁵⁷ reports fatigue tests on carbon fibre filament-wound pressure vessels and shows that the fatigue life at -200°C is similar to that at 25°C.

At elevated temperatures the fatigue performance is expected to be increasingly influenced by matrix instability as the glass transition temperature is approached. The more common polyester, epoxy and phenolic resins have a glass transition temperature of about 200°C, but recent developments have introduced polyimides and polybenzimidazoles, which appear promising for higher temperature applications⁵⁸. Holmes and Wright²⁴ have shown that the fatigue strength of epoxy based CFRP at 120°C is similar to that at room temperature.

In view of the incompatible temperature coefficients of expansion between matrix and fibre - the fibre longitudinal coefficient being slightly negative - repeated thermal cycles might give rise to significant fatigue damage. Work in this area has been reported by Phillips and Sturgeon⁵⁹ of Materials Department, RAE; more recent studies are reported by Chamis⁶⁰ and by Doner and Novak⁶¹.

4.2.1.13 Sensitivity to fretting

In structural alloys, fretting can result in the formation of surface micro-cracks in the first few per cent of the fatigue life, replacing the prolonged reversed slip damage initiation phase by a mechanical process involving surface welding, shear and the formation of abrasive debris. There is some evidence to suggest that the low-friction properties of CFRP⁶² might render it less vulnerable than metals to this form of damage.

4.2.1.14 Fracture toughness

Although structural alloys are not strictly isotropic, homogeneous, Hookian materials, the linear elastic fracture mechanics concept of fracture toughness has been shown to provide a useful index of merit for strength in the presence of a fatigue crack. Although this work is not directly applicable to anisotropic materials it may prove useful to retain a standard fracture toughness specimen configuration to assess composites.

4.2.1.15 Crack propagation characteristics

The crack propagation and residual strength characteristics of a material are particularly important in the design of fail-safe structures. Fracture mechanics has introduced the stress intensity factor concept which provides a useful basis for the comparison of crack propagation data for structural alloys. As in the case of fracture toughness, it may prove useful to retain the specimen configurations generally used for crack propagation studies, recognising that the data so obtained must be regarded as qualitative until the appropriate fracture mechanics analyses have been developed.

4.2.1.16 Creep

Studies of the tensile creep behaviour of uniaxial CFRP are reported by Dobson⁶³ of the University of Southampton. He shows that composites reinforced with untreated fibres creep in much the same way as the unreinforced matrix, whereas composites reinforced with treated fibres exhibit a form of 'saturation creep', which he attributes to fibre straightening by fibre movement through the matrix. Such a mechanism would clearly carry serious implications with regard to the compressive creep properties of CFRP.

An experimental study of tensile creep at stress concentrations has been reported by Phillips⁶⁴. His results suggest that significant stress redistribution is unlikely to occur in uniaxial material. Related work on angle-ply material has been reported by Holmes and Wright²⁴.

4.2.1.17 Application of non-destructive testing

As discussed earlier, under fatigue loading CFRP would generally be considered to fail by progressive debonding and matrix cracking. It is reported that in fluctuating tension tests on uniaxial material, failures are abrupt without the loss in stiffness and macroscopic damage characteristic of reinforced plastics. Losses in stiffness are associated only with failure by loading in shear. In order to guarantee an adequate level of reliability in the use of CFRP, it must be shown that defects and progressive fatigue damage can be detected non-destructively at least as readily as in the currently available structural alloys of high fracture toughness. The application of non-destructive testing to CFRP components has been considered in a recent review by Stone⁶⁵. X-ray techniques, microwaves, ultrasonics, eddy current methods, thermal methods and acoustic emission are all reported to have been used with varying success for the detection of defects in CFRP. Of these techniques acoustic emission is reported to show perhaps the greatest promise, both as a non-destructive testing method and as an aid to fundamental fracture studies.

4.2.2 The most important areas for fatigue research

Having considered the various characteristics of CFRP which are likely to affect the structural fatigue performance it is concluded that important questions remain to be answered in the following areas*:-

- (a) sensitivity to secondary shear stresses
- (b) sensitivity to compressive stresses
- (c) vulnerability to accidental damage and to unforeseen stress concentrations
- (d) design and fatigue substantiation of joints
- (e) cumulative damage characteristics.

Failure criteria and appropriate scatter data are required in each case.

4.3 RELEVANT GOVERNMENT SPONSORED RESEARCH**

4.3.1 Fatigue research

Appropriately, much of the early work on fatigue concerns basic material properties rather than structural fatigue performance and in consequence the

* No attempt has been made to list these items in order of importance; the order is that in which they have been discussed.

** It has not been possible to give a full list of references in this section as much of the work mentioned has not yet been published.

fatigue and static properties of various combinations of matrix, fibre, fibre-orientation and volume fraction are being determined. Plain specimens are used almost exclusively in this work and these are generally tested under axial stress or in flexure, using simple constant amplitude sinusoidal loading. Notable papers presenting some of the first basic fatigue data for CFRP, have been published by Owen and Morris^{16,22} of the University of Nottingham and by Beaumont and Harris¹³ of the University of Sussex. Large programmes of fundamental research of this type are being undertaken by Rolls-Royce Composite Materials and by Materials Department, RAE. In the latter case, however, emphasis is placed on the effects of notches. Plain specimens are included in a comprehensive design data programme which has been started jointly by HSA and BAC; Westland Helicopters are also contributing in this field. Work has also been done by Rotorway Components, and by Pullen¹⁷ of ERDE, who has tested specimens in rotating bending. Gimlett is about to begin a programme of work at British Rail, Derby.

Some of the specific problem areas discussed in the previous section are being studied as part of the above general programmes, others are the subject of more specialised research projects. Understanding of the remainder is at present guided largely by theoretical studies, the knowledge of the basic properties of fibres and matrices and a qualified read-across from work on other composite materials.

On the question of fatigue failure criteria, there will no doubt be inputs from a number of the current projects. It is noteworthy that studies by Professor Levy of The City University are particularly related to failure characteristics.

Perhaps most relevant to the assessment of the sensitivity of CFRP to secondary stresses in shear is the proposal by Rolls-Royce Composites to conduct interlaminar shear fatigue tests. There is also some relevant work by Owen on the biaxial loading of GRP.

Compressive loading is being studied by Cledwyn of the University of Liverpool and by Dukes of AML, whose work relates to the fatigue strength of submerged cylinders.

"Fretting" studies using plain specimens fitted with pads have been proposed by Field of NEL.

Work on the fatigue strength of joints is included in the HSA-BAC Data Collection Programme, in the Westland Helicopters' programme and in the work at Rotorway Components³⁹.

Proposals for cumulative damage studies are confined to the single-step tests included in the Materials Department (RAE) Programme.

Exploratory work on the effects of loading frequency has been reported by Owen¹⁶ of the University of Nottingham and by Owston¹⁴ of Cranfield Institute of Technology; some work has also been done in Materials Department, RAE, and further tests are included in Rolls-Royce Composites' programme.

The effects of exposure to elevated and cryogenic temperatures are to be studied by Rolls-Royce Composites. Loughborough University of Technology will consider the effects of the thermal cycle alone.

Studies of the effects of exposure to hostile environments such as high humidities, water and oil have been reported by Beaumont and Harris¹³ of the University of Sussex and also by Owen¹⁶; work is also included in the Rolls-Royce Composites' programme.

On the question of the strength of CFRP in the presence of a fatigue crack, fracture toughness tests are included in the Joint HSA-BAC Data Collection Programme and in the work of Harris at the University of Sussex. The work of Bradshaw and Sidey of Materials Department, RAE, should also be relevant here.

Studies of a more fundamental nature, which relate to the fatigue mechanism in unreinforced plastics have been undertaken by Professor Andrews of Queen Mary College, London, and by Professor Benham of Queen's University, Belfast.

Some fatigue studies are reported to have been started by Professor Bailey of the University of Surrey and acoustic fatigue work has been undertaken by the University of Southampton.

4.3.2 Associated studies

A number of projects in the more general CFRP research programme may also assist in the formulation on interpretation of future programmes of fatigue research. For instance, Adams of the University of Bristol and Harris of the University of Sussex are investigating damping properties, and Professor Holmes-Walker of Brunel University and Giltrow and Lancaster of Materials Department, RAE, are investigating wear and friction. The static strengths of joints and notches are being considered by Sage at The City University, by

Professor Gordon at Reading University and also by Rotorway Components³⁹. Work on joints has also been done by Sturgeon⁴⁴ of Materials Department and Collings⁶⁶ of Structures Department, RAE. The general effects of temperature are being studied by Professor Holliday of Brunel University. Elevated temperature effects in particular are being studied by Nash of BAC; Midgley of RPE and Mead of Yarsley Testing Laboratories are studying cryogenic effects. The effects of exposure to hostile environments - in some cases when CFRP is bonded to metals - are being studied by Donia Coomber, Brown, Davis and Phillips^{55,56} of Materials Department, RAE, Harris of the University of Sussex, Dukes of AML, Mead of Yarsley Testing Laboratories, Steel of MEXE and Antill of AERE: ERA, Leatherhead have conducted some work on the effects of lightning strikes. The creep behaviour of CFRP has been studied by Professor Bell and Dobson⁶³ of the University of Southampton, by Larke of Materials Department and Phillips⁶⁴ of Structures Department, RAE, by Harris of the University of Sussex and by Professor Benham of Queen's University, Belfast. The compressive strength of CFRP is being studied by Professor Gordon of the University of Reading and there is work at the University of Sussex concerned with the compressive strength of CFRP-aluminium foil tubes.

General studies of the static properties of fibre reinforced materials have been undertaken by Professor Leach of the University of Nottingham, Professor Wood of The Royal Military College of Science, Ham² and Harris¹ of Structures Department, RAE, Wadsworth²⁶ of Materials Department, Merrall of Shell Technical Service Laboratories, Wilson of CIBA (ARL) Ltd, Wells¹⁸ of AERE, Russell House Laboratories and the Rubber and Plastics Research Association.

Finally, evaluations of the potential uses of CFRP have been undertaken by various organisations. Phillips of Materials Department, RAE, Holden of NEL and Pearce of AERE are studying general applications, including sports equipment. Ham² and Harris¹ of Structures Department, RAE, McKenzie of HSA, Taig¹⁰ of BAC and Tetlow of Cranfield Institute of Technology are studying aerospace structures including the Harrier wing-tip, Vulcan airbrake, Provost tab and Jaguar spoiler. Winny⁷ of Westland Helicopters and Clemens of Rotorway Components are studying helicopter applications including rotor blades, torsion bars and drive shafts, torque tubes, tail booms and tailplanes. Jones of Summerfield Research Laboratories, Parmee of RPE and Trigg of Bristol Aero-jet are studying rocket motor applications. Roberts of RARDE is studying applications in the armaments field. Hancock of SRDE and Sinnock of RRE are studying aerial applications and Williams of Dowty-Rotol and Ketley of HSD are considering applications in the design of hovercraft propellers.

4.4 PLANS FOR FATIGUE RESEARCH IN STRUCTURES DEPARTMENT, RAE

In section 2 it was concluded that certain important questions remain to be answered. The research described in section 3 includes some work in each of these areas. Appropriately, the design and fatigue substantiation of joints has the greatest coverage, but much more work needs to be done before the designer can achieve the confidence which has been established in the design of metal joints. Questions relating to the sensitivity to secondary shear stresses, vulnerability to accidental damage and to stress concentrations, and sensitivity to compressive stresses are adequately covered by the research proposed elsewhere. However, there remains an urgent need for effort on cumulative damage characteristics, which are covered only by the single-step tests proposed by Materials Department, RAE.

Structures Department's main effort is therefore to be directed to meet this need for research into cumulative damage characteristics. Realistic specimens which represent structural features will be used and information will be obtained on the variation of strength and stiffness during the fatigue life, the scatter in these properties and the modes of failure appropriate to each configuration.

The choice of specimens to represent structural features will be guided by the design problems which are revealed when components and full-scale structures are fatigue tested. At the present time bonded scarf and lap joints are being developed, but work may also be done on notched and plain specimens⁶⁷. It is planned that, as in work with metals, Gaussian narrow band random loading will be used with a mean stress representative of service loading. Having gained experience of behaviour under fairly realistic loading conditions it will then be appropriate to test under simpler forms of loading in order to assess the significance of load interaction effects. The aim will be to establish the adequacy of simple constant amplitude loading to reproduce the appropriate modes of failure and scatter characteristics and also to provide data which will be suitable for estimating life under complex load spectra.

In order to cover the broad field of interest in a reasonable time the programme will be confined to two combinations of fibre orientation (0° uniaxial and a balanced $0^\circ \pm 60^\circ$ two-dimensionally pseudo-isotropic lay-up more representative of general applications), a single volume fraction (60 per cent is generally considered to provide optimum properties), and a single fibre-resin system (ERLA 4617/DDM pre-preg formed from continuous Type 2 treated fibre (Type 2 SC/10000) is favoured). It is anticipated that it will be necessary to

determine at the outset of the investigation, the sensitivity of each specimen configuration to loading frequency — heat generation from internal damping in the bonded specimens may be significant and could limit the loading frequencies selected for the subsequent programme of testing.

Bearing in mind that the fatigue performance may be dominated by basic material properties it would seem wise to initiate parallel extramural work on a second fibre-resin system at an early stage; we will be guided here by the most likely lines of development.

4.5 CONCLUSIONS

Considering the content of a survey of the various characteristics of CFRP which are likely to affect structural fatigue performance, it is believed that important questions remain to be answered in the following areas:-

- (a) sensitivity to secondary shear stresses
- (b) sensitivity to compressive stresses
- (c) vulnerability to accidental damage and to unforeseen stress concentrations
- (d) design and fatigue substantiation of joints
- (e) cumulative damage characteristics.

Failure criteria and appropriate scatter data are required in each case.

Existing research will not satisfy the need to predict the fatigue life of CFRP components under service load spectra. It is in this area that Structures Department can contribute most effectively. Accordingly an exploratory programme is planned in which specimens representing structural features will be fatigue tested under both realistic and simple load spectra to obtain information on load interaction effects, modes of failure, scatter and the effects of fatigue damage on strength and stiffness.

As a result of the general survey certain tentative conclusions can be drawn:

- (1) Under axial tensile loading, the stiffness of uniaxial material is reported to remain unchanged until failure, which is abrupt with no macroscopic signs of damage. If the potential safety levels inherent in the use of structural alloys of high fracture toughness are to be realised in CFRP, it must be shown that fatigue damage can be detected non-destructively well before failure occurs. (Section 4.2.1.1)

- (2) The reported data suggest that the tensile fatigue strength of uniaxial CFRP is similar to that of structural alloys, i.e. typically 35 per cent or so of the ultimate static strength, for an endurance of 10^7 cycles at zero mean stress. (Section 4.2.1.2)
- (3) The available evidence suggests that under shear loading the stiffness will decrease progressively so that the fatigue strength of uniaxial material will be only 15 per cent or so of the static shear strength based on a failure criterion of about 10 per cent loss in stiffness. This figure reflects the fatigue properties of the matrix. Since the static shear strength is generally only about 7 per cent of the tensile strength, the shear fatigue strength is likely to be less than 3 per cent of the tensile fatigue strength. In practical terms, this means that in fatigue damage calculations, a uniaxial CFRP component can be considered to be purely axially loaded only if the secondary fluctuating shear stresses are less than about 1 per cent of the axial stress. In structural alloys, secondary shear stresses below about 20 per cent of the axial stress may generally be discounted. (Section 4.2.1.3)
- (4) Fatigue damage is reported to develop more rapidly under compressive loading than in tension. It is noteworthy that the fatigue strength at zero mean stress is reported to be no greater than that in pulsating tension. (Section 4.2.1.4)
- (5) There is evidence that the ratio of fatigue to static strength for angle-ply CFRP may be similar to that for uniaxial material. (Section 4.2.1.5)
- (6) The scatter in fatigue performance is expected to depend on the various failure modes which may be encountered. (Section 4.2.1.6)
- (7) In the presence of a notch, uniaxial CFRP would generally be expected to be most vulnerable to damage in shear. In view of the elastic failure characteristics of CFRP, the ratio of the fatigue strength to the static strength of notched material is likely to be similar to that for plain specimens. However, the ratio could be lower in some instances due to the greater vulnerability to shear mode failures under fatigue loading. The absolute fatigue strength is likely to be much lower than that of structural alloys, reflecting the high static notch sensitivity of uniaxial CFRP. (Section 4.2.1.7)
- (8) Practical bonded joints between CFRP and metals are likely to fail in fatigue by interlaminar tension or shear, such that the fatigue strength at 10^7 cycles is typically 15 per cent or so of the static strength. This value

is comparable with that for well-designed pinned or clamped joints in structural alloys. (Section 4.2.1.8)

(9) The evidence is inconclusive on the significance of cumulative damage effects and in particular on the applicability of the Palmgren-Miner hypothesis for calculations of the fatigue performance of CFRP under a spectrum of loads. (Section 4.2.1.9)

(10) The fatigue strength of CFRP is reported to be little affected by exposure to either oil or water, but there is some evidence that the torsional fatigue endurance may be reduced by up to an order of magnitude after exposure to steam. (Section 4.2.1.10)

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APPENDIX A

ROTARY-WING FATIGUE RESEARCH PROGRAMME - CUMULATIVE
FATIGUE DAMAGE IN STRUCTURAL ELEMENTS

RAE Technical Memorandum Structures 748, April 1970

ROYAL AIRCRAFT ESTABLISHMENT

Technical Memorandum Structures 748

April 1970

ROTARY-WING FATIGUE RESEARCH PROGRAMME - CUMULATIVE FATIGUE DAMAGE
IN STRUCTURAL ELEMENTS

by

A. W. Cardrick

SUMMARY

Details are presented of a programme of cumulative damage research on four materials, BS.TA11 titanium alloy, DTD 5212 maraging steel, BS.2S 98 Ni-Cr-Mo steel and BS.2L65 aluminium alloy, each of which is used in fatigue sensitive helicopter components. Each material will be tested in structural element form, under both constant amplitude loading and variable amplitude loading spectra over the endurance range 10^5 - 10^8 cycles.

This work should further our understanding of the accumulation of fatigue damage, particularly under load spectra in which a high proportion of the associated stress cycles are below the fatigue limit.

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Conversions: $1 \text{ ksi} = 1000 \text{ lbf/in}^2 = 6.895 \text{ MNm}^{-2} = 0.6895 \text{ hb.}$

1 INTRODUCTION

In this Memorandum details are presented of a fatigue test programme which has recently been started at R.A.E. The programme was planned after discussions with Industry; it should contribute significantly to our understanding of the accumulation of fatigue damage and associated loss of static strength in built-up structures, with particular reference to the fatigue life prediction and life substantiation of rotorcraft. The work is essentially long-term and the research objectives will not be achieved for several years; however, there will be a continuous fall-out of design data which will be reported separately as it becomes available.

Data will be obtained on the fatigue performance in fluctuating tension of titanium alloy, maraging steel, BS.2S98 Ni-Cr-Mo steel and BS.2L65 aluminium alloy in the form of structural elements, each of which represents in simplified form a structural feature which presents the designer with difficulty in ensuring a satisfactory balance between component weight and fatigue strength. Both constant and variable amplitude loading will be used at two values of mean stress, over the endurance range 10^5 - 10^8 cycles.

2 SPECIMENS

Three specimen configurations have been chosen, a pinned-lug, a clamped-lug and a notch. These represent, in turn, fretting at a marked stress concentration, fretting between clamped surfaces and the somewhat less complex situation of a structural discontinuity which gives rise to a moderate stress concentration. All four materials will be tested in each of these configurations and detailed specimen drawings have been prepared in which care has been taken to specify representative manufacturing processes.

The pinned-lug specimens are shown in Figs.1-3. It will be observed that the geometrical configurations are the same in the four materials, the differences being only in the specification of appropriate manufacturing techniques. A BS.2S98 steel loading pin, Fig.4, is used with a minimum practicable clearance of between 0.0006 in and 0.0022 in per inch diameter; past experience suggests that variations in clearance between these limits will have no significant effect on fatigue performance. Under tensile loading an elastic peak stress concentration of about 2.94 is produced on the net cross-section at the transverse hole diameter^{1,2}. Specimens and pins will be cleaned in trichloroethane degreasing agent and assembled dry to avoid the introduction of variables associated with lubrication or anti-fretting compounds. Fatigue cracks

in the pinned-lug originate from lines of fretting in the region of the peak stress concentration. Subsequent propagation normally results in a planar transverse crack surface which persists until failure occurs (see Fig.5).

The general arrangement of the clamped-lug specimen is presented in Fig.6. This has been designed to represent the conditions of clamping pressure and slip which contribute to service failures. Fatigue cracks originate from the area of fretting at the interfaces of the side plates and centre plate. Subsequent cracks propagate through the centre plate on parallel transverse surfaces normal to the axis of principal stress. A complex failure occurs associated with the strength reduction of the centre plate caused by the combined effect of fatigue cracks on the several surfaces. This results in a stepped fracture surface associated with intersurface shear and the proximity of the hole (see Fig.7). Figs.8, 9 and 10 show the centre plates in all four materials. BS.2S98 side plates, Fig.11, will be used in conjunction with high tensile steel bolts, Fig.12. As in the case of the pinned-lug, the components will be assembled dry to avoid the introduction of further variables. Bolt extension will be carefully controlled to maintain a standard clamping load, which, in aluminium alloy specimens, has been shown to correspond to a clamping pressure of about 30 ksi.

The notched specimen ($K_t = 2.3$) is shown in Figs.13, 14 and 15. Fatigue crack propagation is similar to that in the pinned-lug specimen, but in the absence of fretting the positions of crack nucleation sites along the lines of maximum stress concentration through the bore, reflect to a greater extent the occurrence and orientation of microstructural defects in the specimen, surface irregularities and the variation in stress concentration through the bore due to residual stresses and other effects associated with manufacture (see Fig.16).

The design and development of the three specimen configurations is to be reported in an R.A.E. Technical Report³

3 MATERIALS

Detailed specifications have been prepared for the four materials - BS.TA11 titanium alloy (Ti-6Al-4V, 130-168 ksi), BS.2L65 aluminium alloy (63-70 ksi), BS.2S98 Ni-Cr-Mo steel (168-190 ksi) and DTD 5212 18 Ni-Co-Mo maraging steel (260-291 ksi) - these are presented in Appendix A.

4 FATIGUE TEST PROGRAMME

The specimens will be tested in resonant fatigue machines with a sinusoidal loading waveform, which can be stabilized to apply constant amplitude

loading or appropriately modulated to apply narrow band random loading with pre-determined statistical properties. The following loading actions have been chosen:-

4.1 Constant amplitude loading

This provides the simplest form of data and may be used for comparison with that obtained from more complex loading actions.

4.2 Variable amplitude loading with a Rayleigh distribution of peak amplitudes (stationary Gaussian random loading)

This is a widely used form of variable amplitude loading^{4,5} and provides a simple standard load spectrum for the assessment of life prediction methods.

4.3 Variable amplitude loading with a large proportion of low amplitude peaks

This spectrum will be based on operational stress data typical of helicopter rotor, control and transmission components and should be particularly valuable in investigating the significance of large numbers of stress cycles near and below the fatigue limit.

The loading will be applied in the form of a large number of statistically identical programmes, each consisting of two components of stationary Gaussian random loading, each of pre-determined intensity and duration⁴.

Two mean stresses will be used which represent upper and lower boundaries of design practice in the use of each material, and the programme will involve the preparation of some 72 S-N diagrams, each of which will be based on approximately 25 fatigue tests. In addition, data on the variation of residual static strength through the fatigue life will be obtained from say, two residual strength tests at say 10, 20, 40 and 60 per cent of the average fatigue life, at three stress levels on each S-N diagram; this will involve a similar number of tests. An overall total of approximately 4000 specimens will be required.

Appendix AMATERIAL SPECIFICATIONSA.1 BS.TAll titanium alloy (Ti-6Al-4V in rolled condition)(1) Material

Rolled titanium alloy bar to British Standard TAll. To be supplied in 12 ft lengths of rectangular section $1\frac{1}{2}$ in x $\frac{3}{4}$ in.

(2) Quantity

744 ft comprising 62 x 12 ft lengths.

(3) Inspection and testing procedure

British Standard TA.100 shall be observed in conjunction with specifications TAll and DTD.5173. British Standard TAll shall be overriding where requirements are incompatible. The material shall be subject to AID release and in any respects not specified shall be typical of that supplied for use in aircraft structures.

(4) Chemical composition

To ensure uniformity of chemical composition it is essential that the entire quantity is produced from one melt. Should the melt be continuous the material must be produced from one holding without any further addition of metal having been made.

(5) Heat treatment

The material shall be supplied in the annealed condition as given by the specification and consideration shall be given to obtaining uniformity of properties throughout the material.

(6) Mechanical defects

The material shall be tested at the bar stage by ultrasonic equipment. The position of any defect greater than $5/64$ in shall be marked and bars containing such defects shall be submitted for approval.

(7) Identification

It is necessary to know the billet from which each bar was rolled, the rolling direction and its position in the rolled length. The following items shall be metal stamped on the broad face near the leading end of each bar: material identification, melt number, batch number, Inspector's stamp, billet

number and the position of the bar in the rolled length. In addition, the other end of the bar shall be stamped 'BACK'.

(8) Tensile tests

One tensile test is required on a specimen extracted centrally and longitudinally from the material preceding and following each 12 ft bar.

(9) Information required from the manufacturer

- (a) Chemical composition of the melt.
- (b) List of those bars containing defects greater than 5/64 in.
- (c) Details of identification code.
- (d) Temperature and time of heat treatment.
- (e) Ultimate tensile strength, 0.2% proof stress and elongation on 2 in related to the front and back of each bar.

A.2 BS.2L65 aluminium alloy (4.3% Cu)

(1) Material

Extruded aluminium alloy bar to British Standard 2L.65. To be supplied in 12 ft lengths of rectangular section $1\frac{1}{2}$ in x $\frac{3}{8}$ in and $2\frac{1}{8}$ in x $\frac{7}{8}$ in.

(2) Quantity

<u>Item</u>	<u>Section</u>	<u>Quantity, ft</u>	<u>Number of 12 ft lengths</u>
1	$1\frac{1}{2}$ in x $\frac{3}{8}$ in	744	62
2*	$2\frac{1}{8}$ in x $\frac{7}{8}$ in	252	21

(3) Inspection and testing procedure

British Standard 2L.100 sections 1 and 6 shall be observed in conjunction with the material specification. The material shall be subject to AID release and in any respects not specified the material shall be typical of that supplied for use in aircraft structures.

(4) Chemical composition

To ensure uniformity of chemical composition it is essential that the entire quantity of each item shall be produced from one melt, although it would be preferable if both items could together be produced from a single melt. Where the melt is continuous the material shall be produced from one holding without any further addition of metal having been made.

*Ordered for an associated programme of fatigue research.

(5) Heat treatment and cold work

The material shall be given solution treatment and controlled stretch to the specification. The material shall be precipitation treated at the specified temperature for as long as is necessary to just reach its maximum ultimate tensile strength. In carrying out heat treatment, consideration shall be given to obtaining uniformity of properties throughout the material.

(6) Grain size

Item 1

The depth of coarse grain from the surface shall be limited to 0.08 in on the long sides of the cross section, but this depth may be exceeded within 0.10 in of the corners.

Item 2

The depth of the coarse grain from the surface shall be limited to 0.125 in on the long sides of the cross section, but this depth may be exceeded within 0.25 in of the corners.

(7) Mechanical defects

The material shall be tested at the bar stage by ultrasonic equipment. The position of any defect greater than 5/64 in shall be marked and bars containing such defects must be submitted for approval.

(8) Identification

It is necessary to know the billet from which each bar was extruded, its direction of extrusion and its position in the extruded length. The following items shall be metal stamped on the broad face near the leading end of each bar: material identification, melt number, batch number, inspector's stamp, billet number, position of the bar in the extrusion and die aperture. In addition, the other end of the bar shall be stamped 'BACK':

(9) Tensile tests

One tensile test is required on a specimen extracted centrally and longitudinally from the material immediately preceding and following each 12 ft bar.

(10) Information required from the manufacturer

(a) Chemical composition of each melt.

(b) List of those bars containing defects greater than 5/64 in.

(c) Details of identification code.

(d) Temperatures and times of solution and precipitation treatment.

(e) Ultimate tensile strength, 0.2% proof stress and elongation on 2 in related to the front and back of each bar.

A.3 BS.2S98 Ni-Cr-Mo steel (2.6% Ni, 0.7% Cr, 0.6% Mo, 0.6% Mn)

(1) Material

Black steel bar to British Standard 2S.98 to be supplied softened (annealed) in 12 ft 0 in/12 ft 2 in lengths suitable for machining.

(2) Quantity

<u>Item</u>	<u>Section</u>	<u>Quantity, ft</u>	<u>Number of 12 ft lengths</u>
1	1½ in x ¾ in	744	62
2	1½ in x ¾ in	2664	222
3	¾ in dia	2376	198
4	¾ in dia	1188	99

(3) Inspection and testing procedure

British Standard 3S.100 sections 1 and 2 shall be observed in conjunction with the material specification. The material shall be subject to AID release and in any respects not specified the material shall be typical of that supplied for use in aircraft structures and helicopter rotor components.

(4) Chemical composition

To ensure uniformity of chemical composition it is essential that the entire quantity of each item shall be produced from one melt.

Where the melt is continuous the material shall be produced from one holding without any further addition of metal having been made.

(5) Heat treatment

The material shall be supplied 'annealed' and suitable for machining as covered by the specification. In carrying out heat treatment, consideration shall be given to obtaining uniformity of properties throughout the material.

(6) Mechanical defects

The material shall be tested at the billet stage by ultrasonic equipment to ensure that defects greater than 5/64 in shall not be present at the bar stage.

(7) Identification

For the material of rectangular section (Items 1 and 2) it is necessary to know the billet from which each bar was rolled, the rolling direction and its position in the rolled length. The following items shall be metal stamped or otherwise permanently marked on the broad face near the leading end of each bar: material identification, melt number, batch number, inspector's stamp, billet number and the position of the bar in the rolled length. In addition, the other end of the bar shall be stamped 'BACK'.

No special requirements apply to the round bar (Items 3 and 4) with the proviso that identification must be provided if separate melts are used.

(8) Tensile tests

One tensile test blank is required (suitable for BS.A4) extracted centrally and longitudinally from the material immediately preceding and following each 12 ft bar of rectangular cross section. No special conditions apply to the round stock. These blanks are required in lieu of the tensile tests called for in the original specification for BS.2S98B material. As the material is now to be hardened and tempered after component manufacture, the blanks will be used as under section 7 of BS.3S.100 and these must therefore be annealed with the 12 ft bars. For convenience in identification additional material may be left on the 12 ft bars to cover these items.

(9) Information required from the manufacturer

- (a) Chemical composition of each melt.
- (b) Details of tests conducted under BS.3S100 sections 1 and 2.
- (c) Details of identification codes (bars and tensile blanks).
- (d) Temperatures and times of heat treatments.

A.4 18 Ni-Co-Mo maraging steel (Now DTD 5212) (18% Ni, 8% Co, 5% Mo)

(1) Material

Double vacuum melted maraging steel bar to DTD draft specification 0000M206. To be supplied in the solution treated condition in 12 ft lengths suitable for machining.

(2) Quantity

<u>Item</u>	<u>Section</u>	<u>Quantity, ft</u>	<u>Number of 12 ft lengths</u>
1	1½ in × ¾ in	744	62

(3) Inspection and testing procedure

British Standard 3S100 sections 1 and 2 shall be observed in conjunction with the draft material specification 0000M206, which shall be overriding where requirements are incompatible. The material shall be subject to AID release and in any respects not specified the material shall be typical of that supplied to aircraft manufacturers.

(4) Chemical composition

To ensure uniformity of chemical composition it is essential that the entire quantity shall be produced from one melt. Where the melt is continuous the material shall be produced from one holding without any further addition of metal having been made.

(5) Heat treatment

The material shall be supplied in a solution treated condition suitable for maraging by heating at a temperature between 470°C and 500°C for not less than three hours. In carrying out solution treatment, consideration shall be given to obtaining uniformity of properties throughout the material.

(6) Mechanical defects

The material shall be tested at the bar stage by ultrasonic equipment. The position of any defect greater than 5/64 in shall be marked and bars containing such defects shall be submitted for approval.

(7) Identification

It is necessary to know the billet from which each bar was rolled, the rolling direction and its position in the rolled length. The following items shall be metal stamped or otherwise permanently marked on the broad face near the leading end of each bar: material identification, melt number, batch number, inspector's stamp, billet number and the position of the bar in the rolled length. In addition, the other end of the bar shall be stamped 'BACK'.

(8) Tensile tests

One tensile test is required on a maraged specimen extracted centrally and longitudinally from the material immediately preceding and following each 12 ft bar of solution treated material. The specimen shall be heat treated as required in clause 5 above and shall be cooled in air.

(9) Information required from the manufacturer

- (a) Chemical composition of each melt.
- (b) List of those bars containing defects greater than 5/64 in.
- (c) Details of identification code.
- (d) Temperatures and times of solution treatments.
- (e) Temperatures and times of the maraging treatments of the tensile test specimens.
- (f) Maraged ultimate tensile strength, 0.2% proof stress and elongation on 2 in related to the front and back of each bar.

REFERENCES

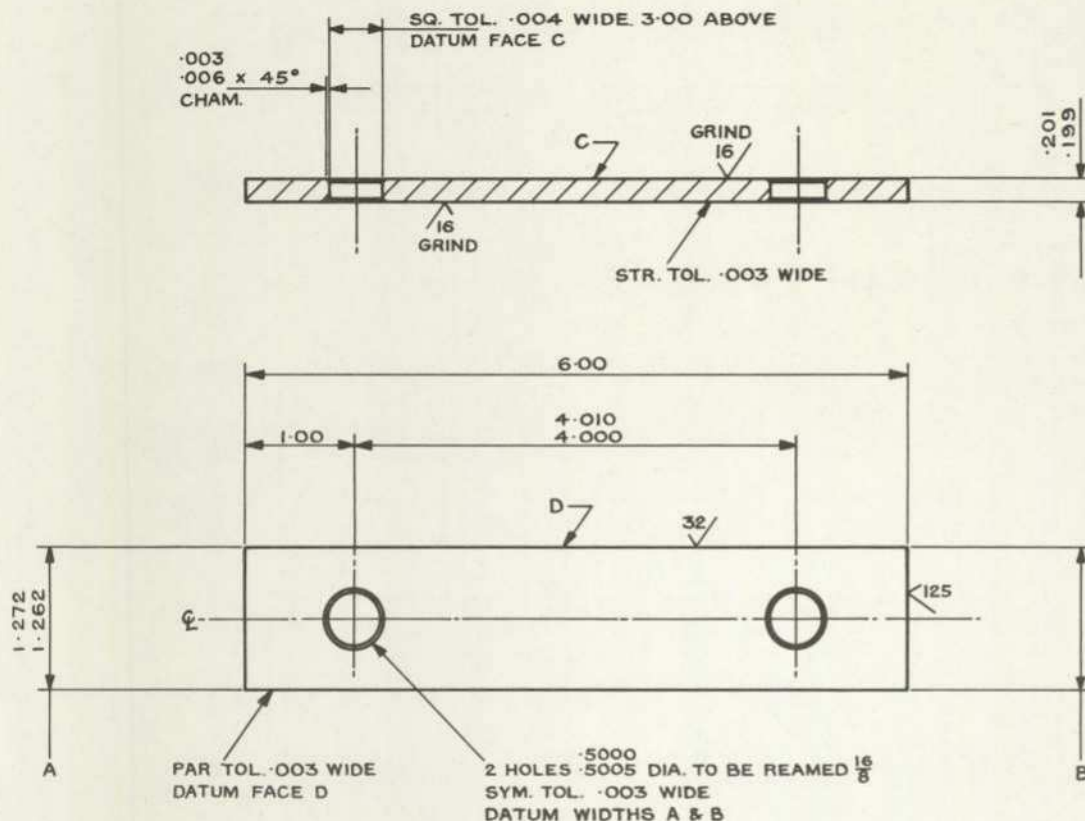
<u>No.</u>	<u>Author</u>	<u>Title, etc.</u>
1	RAeS/I.Mech.E	Stress concentration data. Engineering Sciences Data Unit, Item 65004, September 1965
2	H. L. Cox A. F. C. Brown	Stresses round pins in holes. Aeronautical Quarterley, November 1964
3	A. W. Cardrick B. H. E. Perrett	Rotary-wing fatigue research - Design of pinned-lug, clamped-lug and notched structural elements in aluminium alloy, titanium alloy and steel. R.A.E. Technical Report to be published
4	W. T. Kirkby P. R. Edwards	A method of fatigue life prediction using data obtained under random loading conditions. R.A.E. Technical Report 66023, (1966)
5	S. R. Swanson	Random load fatigue testing: a state of the art survey. MTS Systems Corp. Report, June 1967

DRAWING NUMBER

OII. 002821

USED ON

THIRD ANGLE PROJECTION



NOTES:-

1. ROUGH MACHINING SHALL BE DONE SYMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001-.010 x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES. WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
5. SPECIMENS TO BE PROTECTED BY SEALING IN POLYTHENE BAGS WITH SUITABLE DESSICANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ & 8μ .
10. TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL.

App.A

NTBD

CHECKED

TRACED

21.4.69

DRAWN

HE. PERRETT

MATERIAL
B.S. 2L 65 BAR AND B.S. TAIL
TITANIUM ALLOY BAR TO BE
SUPPLIED BY FATIGUE RESEARCH
SECTION, STRUCTURES DEPT.
IN 12 FT. LENGTHS $1\frac{1}{2} \times \frac{3}{8}$

PROTECTIVE FINISH

TOLERANCES

$\pm .010$
UNLESS OTHERWISE STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE

PINNED LUG SPECIMEN IN B.S. 2L 65 & B.S. T.A. II
(HELICOPTER PROGRAMME)

MOD. No. ISSUE DATE MOD. No. ISSUE DATE

CERTIFIED

CONTRACTOR'S DRAWING REF.

120

DRAWING NUMBER

OII. 002821

Fig.1

DRAWING NUMBER

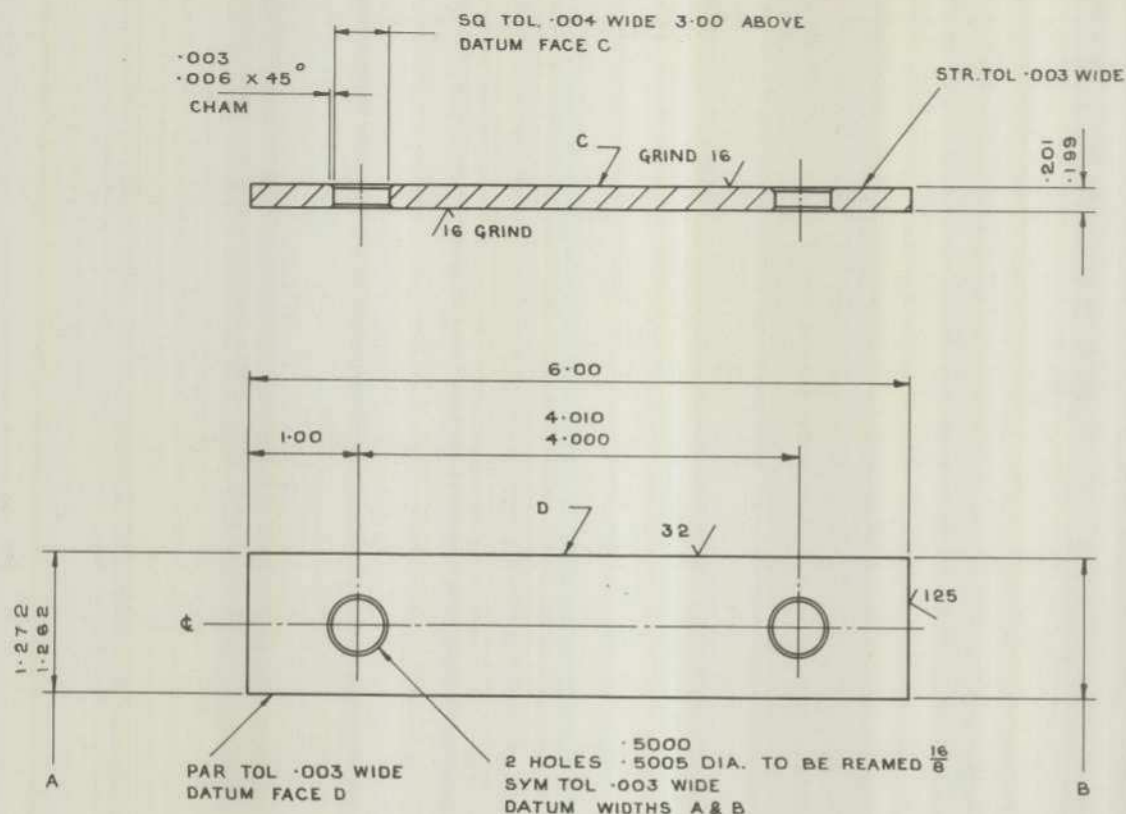
011 002822

THIRD ANGLE PROJECTION

USED ON

NOTES

- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 X 45°
- 3 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 4 BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES, WITH BASE OF NUMBERS PARALLEL TO DATUM FACE C
- 5 SPECIMENS TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL TO BE HARDENED & TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING
- 9 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16 μ " AND 18 μ "

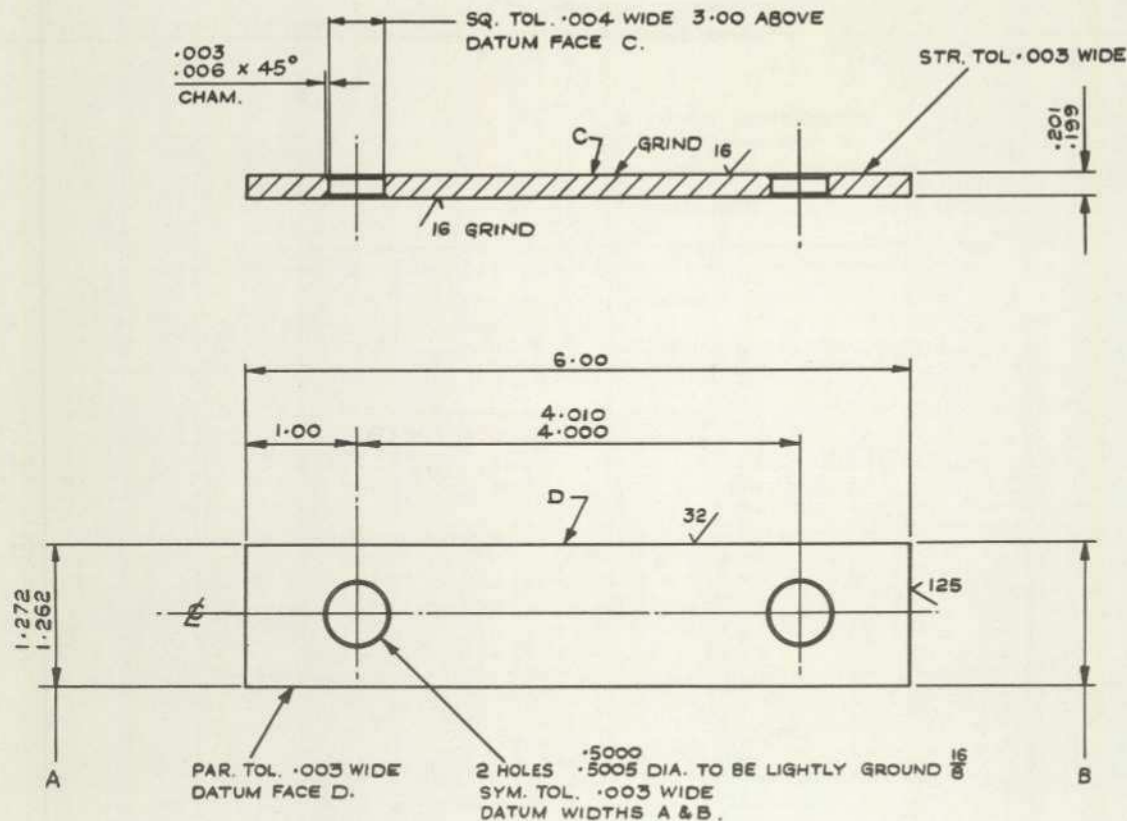


CHECKED	MATERIAL BS 2598 TO BE SUPPLIED BY FATIGUE RESEARCH SECTION	PROTECTIVE FINISH	TOLERANCES ± 0.010 UNLESS OTHERWISE STATED	CONTRACTOR		CERTIFIED	CONTRACTOR'S DRAWING REF.
TRACED DKC.25.4.69	STRUCTURES DEPT IN ANNEALED BARS		DIMENSIONS IN INCHES	ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION			121
DRAWN B.H.E. PERRETT	$1\frac{1}{2} \times \frac{3}{8} \times 12$ FT LONG		SURFACE ROUGHNESS	TITLE PINNED LUG SPECIMEN IN BS. 2598 (HELICOPTER PROGRAME)		SERVICE LETTER	DRAWING NUMBER
			SCALE				011 002822

DRAWING NUMBER
011 002823

THIRD ANGLE PROJECTION

USED ON



NOTES—

1. ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBER TO BE STAMPED CENTRALLY ON BOTH END FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
5. SPECIMENS TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL TO BE MARGED TO SPECIFICATION BEFORE FINAL MACHINING.
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ AND 8μ

App.A

CHECKED	MATERIAL D.T.D. 5212. 18 NI-CO-MO D.V.M. MARGING STEEL TO BE SUPPLIED SOLUTION TREATED SOFTENED IN 12 FT LENGTHS 1 1/2" x 3/8" BY FATIGUE RESEARCH SECTION. STRUCTURES DEPT.	PROTECTIVE FINISH	TOLERANCES ± .010 UNLESS OTHERWISE STATED	CONTRACTOR ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION	SERVICE LETTER
TRACED S.H.E.S. 2.4.69			DIMENSIONS IN INCHES.	TITLE PINNED LUG SPECIMEN D.T.D. 5212 MARGING STEEL (HELICOPTER PROGRAMME)	
DRAWN A.W. CARDRICK.			SURFACE ROUGHNESS	DRAWING NUMBER 011 002823	
			SCALE	CONTRACTOR'S DRAWING REF. 122	

Fig.3

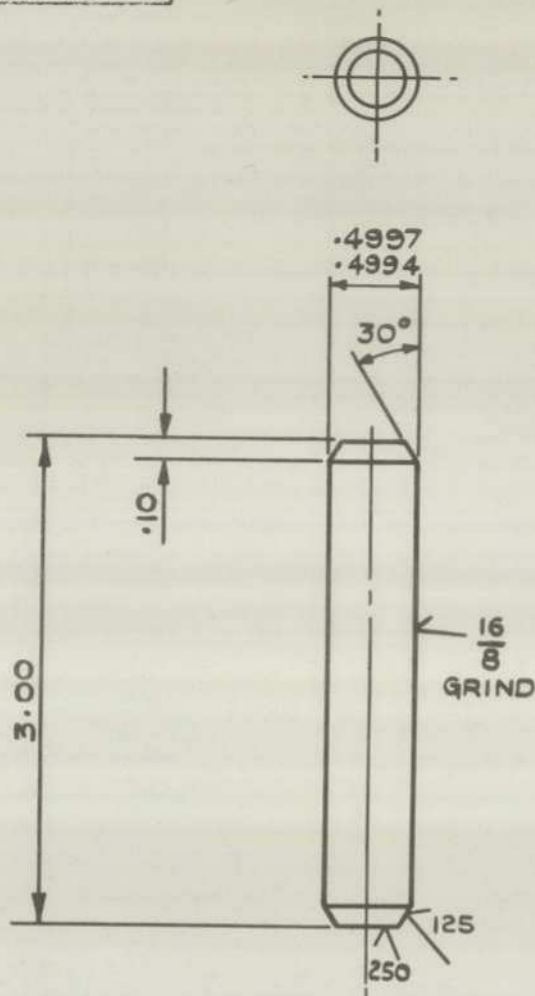
Fig.4

USED ON

DRAWING NUMBER

OII 002824

THIRD ANGLE PROJECTION App.A

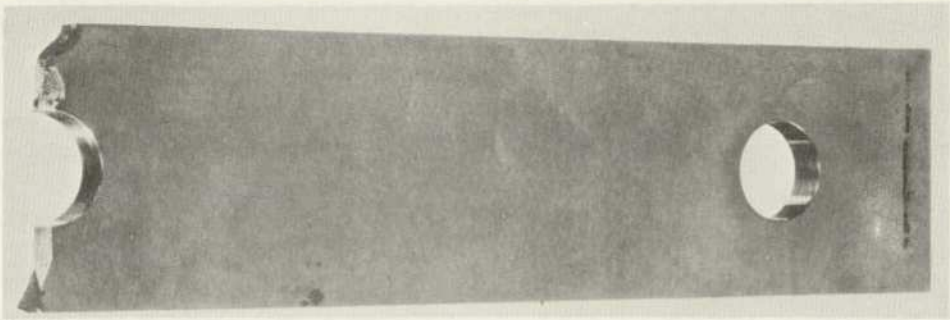


NOTES :-

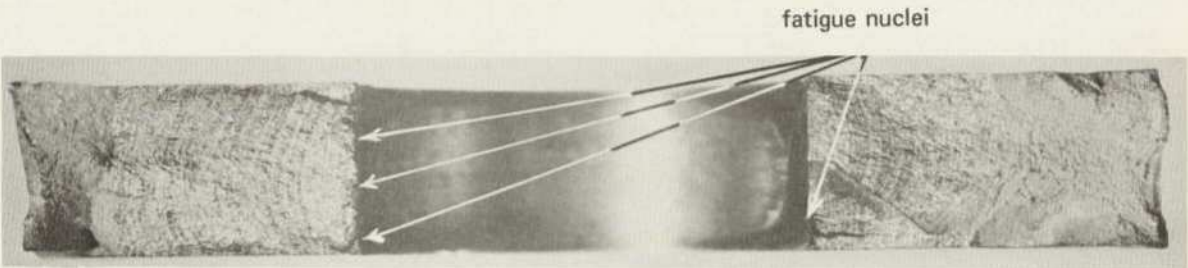
1. MATERIAL TO BE HARDENED AND TEMPERED TO SPEC. BEFORE FINAL MACHINING.
2. CENTRE DRILL HOLES MAY BE LEFT AT ENDS.
- 3 PINS TO BE OILED & PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS.

WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ & 8μ .

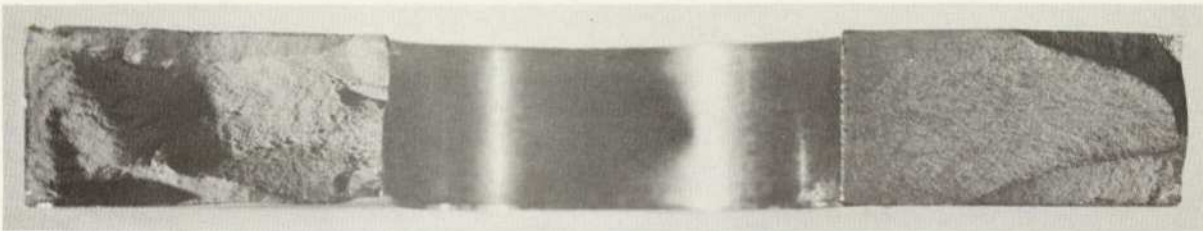
MATERIAL B.S. 2598 BAR, TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT. IN ANNEALED CONDITION IN 12 ft LENGTHS X 5/8" DIA.	PROTECTIVE FINISH						
		MOD N°	ISSUE	DATE	MOD N°	ISSUE	DATE
		CERTD.					
DIMS. IN INCHES	SURFACE ROUGHNESS	TOLERANCES ± .010					
SCALE		UNLESS OTHERWISE STATED					
CONTRACTOR					SERVICE LETTERS		
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION		CONTRACTOR'S DRG. REF.			187		
TITLE LOADING PIN FOR PINNED LUG SPECIMENS (HELICOPTER PROGRAMME)		DRAWING NUMBER			OII 002824		



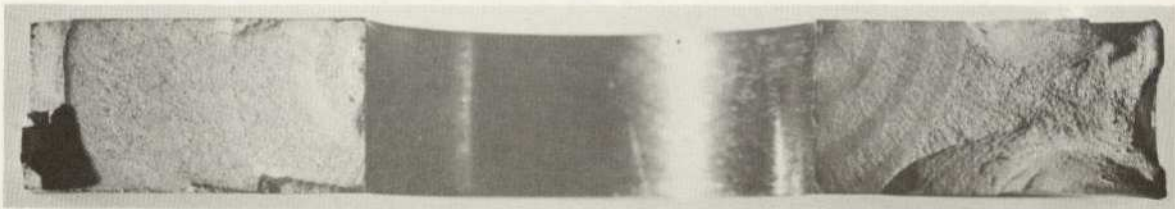
Typical failure



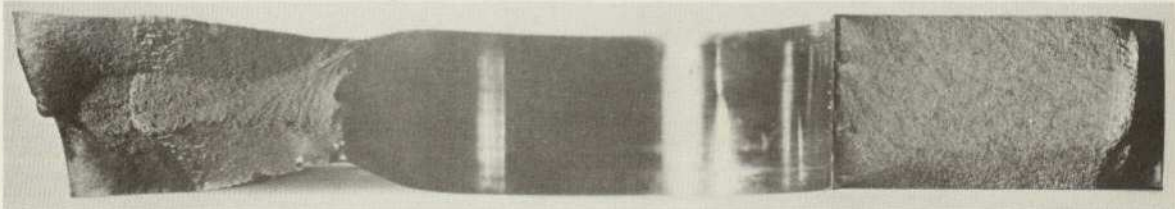
BS 2L65 aluminium alloy



BS TA11 titanium alloy



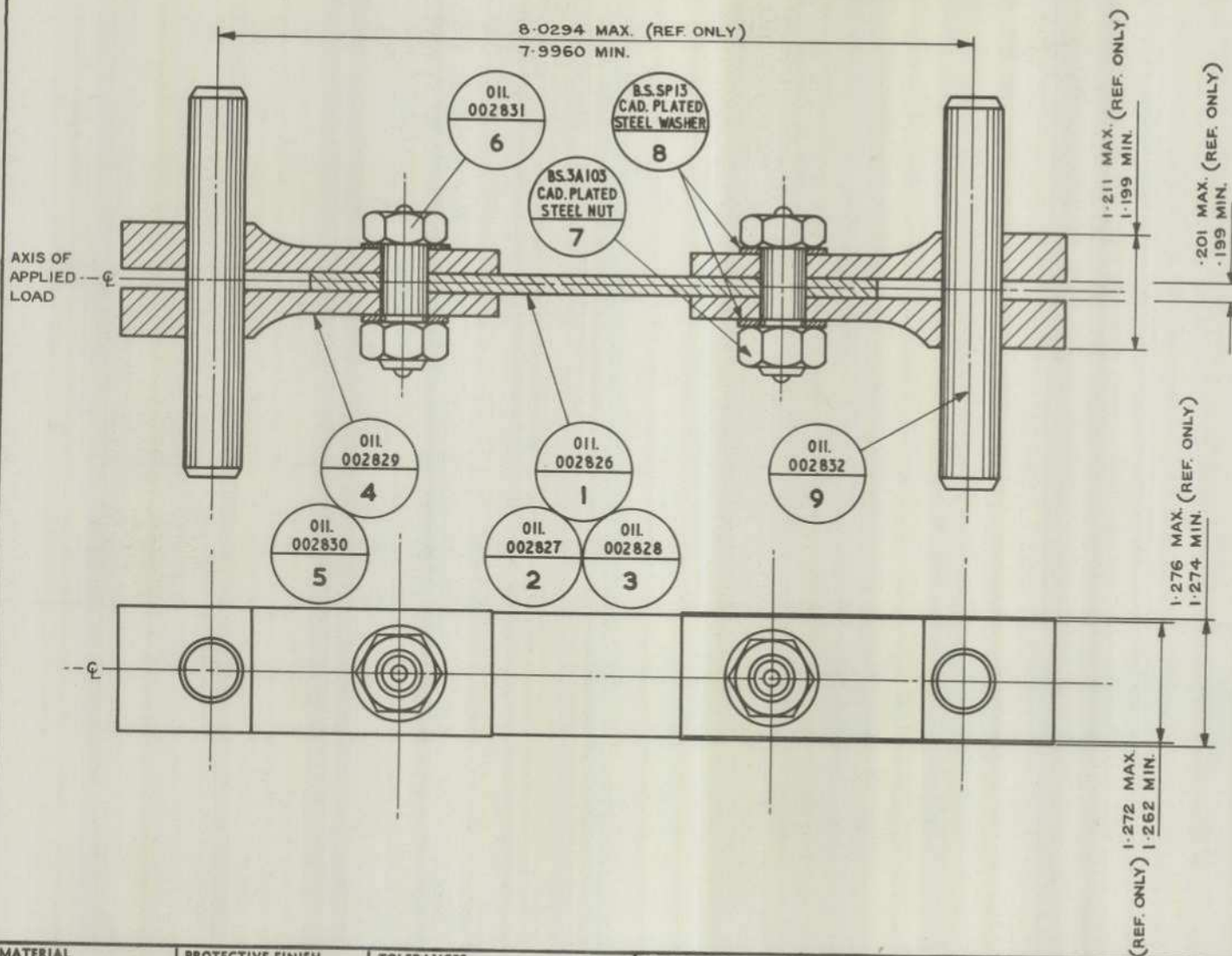
DTD 5212 maraging steel



BS 2S98 NiCrMo steel

Fig.5 Fatigue fractures typical of pinned-lug specimens

USED ON



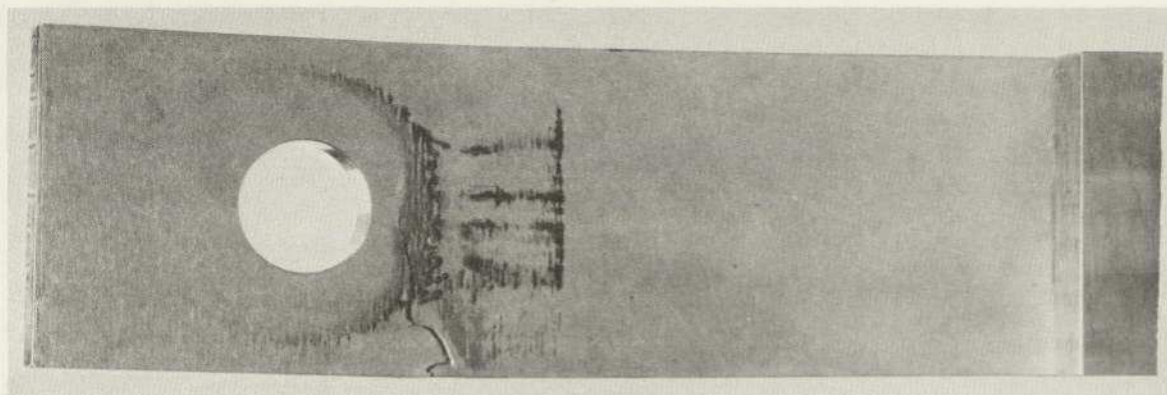
CHECKED	MATERIAL	PROTECTIVE FINISH	TOLERANCES	CONTRACTOR	
TRACED	_____	_____	_____	ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION	
25-3-69			DIMENSIONS IN INCHES	SERVICE LETTER	
DRAWN			SURFACE ROUGHNESS	TITLE	
A.W. CARDRICK			SCALE	CLAMPED-LUG SPECIMEN (HELICOPTER PROGRAMME)	

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					
CONTRACTOR'S DRAWING REF.					

119

DRAWING NUMBER

OIL OO2825



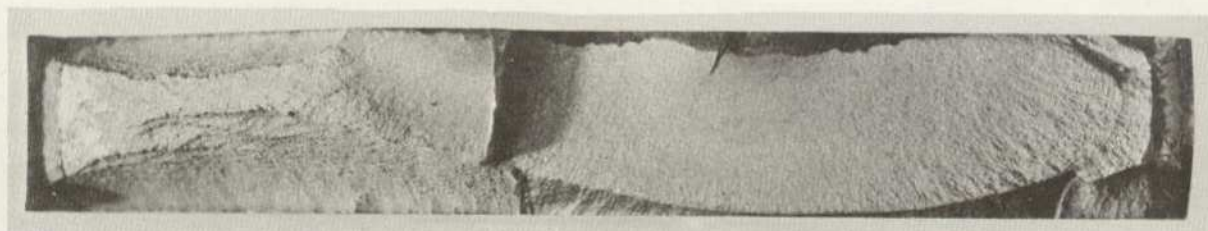
Typical failure



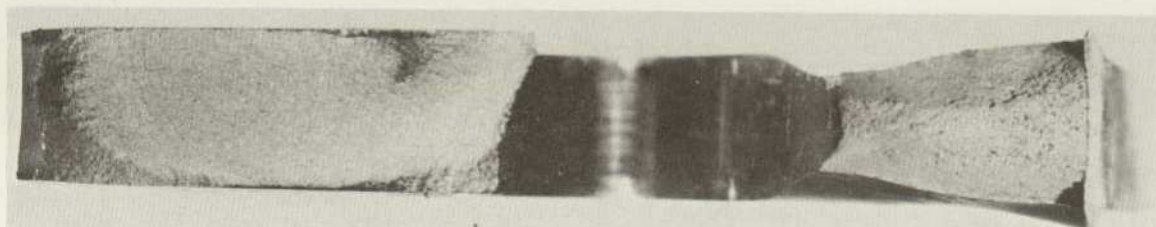
BS 2L65 aluminium alloy



BS TA11 titanium alloy



DTD 5212 maraging steel



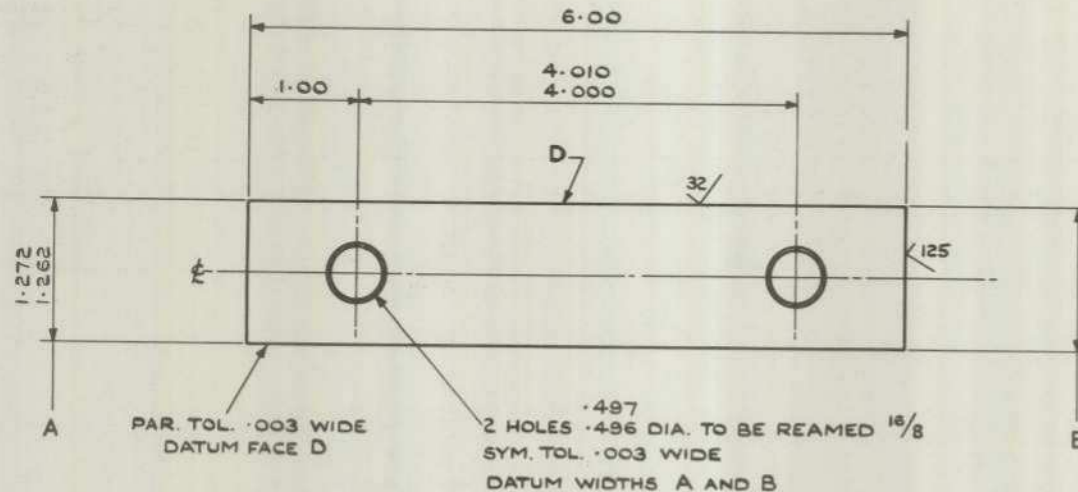
BS 2S98 NiCrMo steel

Fig.7 Fatigue fractures typical of clamped-lug specimens

NOTES:-

Technical drawing of a mechanical part with the following specifications:

- Top Surface:** SQ. TOL. .004 WIDE 3.00 ABOVE DATUM FACE C
- Left Chamfer:** .003, .006 x 45° CHAM
- Internal Features:** C7, GRIND 16/8, 16/8 GRIND
- Bottom Surface:** STR. TOL. .003 WIDE
- Right End:** .201, .193



				B	14.770
				A	9.569
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE

CERTIFIED

CONTRACTOR'S DRAWING REF.

123

DRAWING NUMBER

011.002826

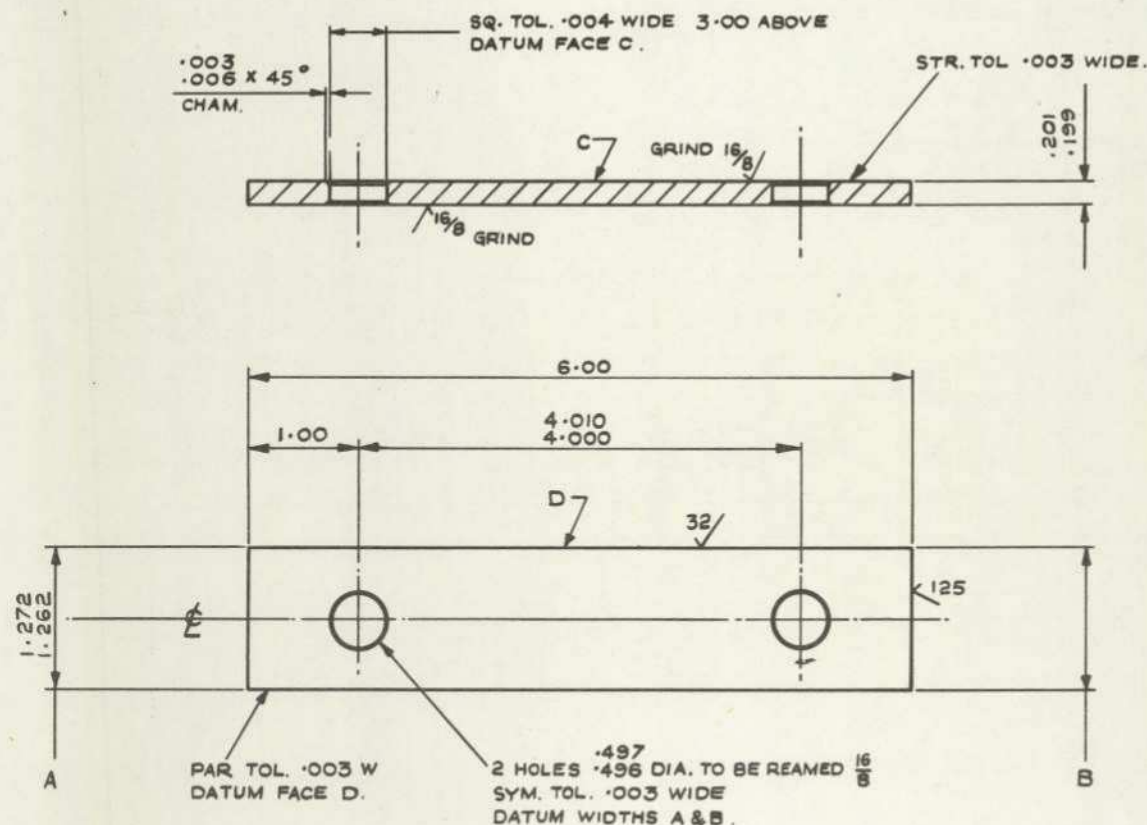
CHECKED	MATERIAL	PROTECTIVE FINISH	TOLERANCES	CONTRACTOR	
TRACED O.P. 25-3-69 DRAWN J.H. PERRETT	BS.2 L65 BAR AND BS. TA. 11 TITANIUM ALLOY BAR TO BE SUPPLIED BY FATIGUE RESEARCH SECTION, STRUCTURES DEPT. IN 12ft LENGTHS 1 1/2 x 3/8		± .010 UNLESS OTHERWISE STATED	ROYAL AIRCRAFT ESTABLISHMENT	MINISTRY OF AVIATION
			DIMENSIONS IN INCHES	SERVICE LETTER	
			SURFACE ROUGHNESS	TITLE	
			SCALE	CENTRE PLATE IN BS.2 L65 & BS.TA11 (HELICOPTER PROGRAMME)	

DRAWING NUMBER

011 002827

USED ON

THIRD ANGLE PROJECTION



NOTES :-

1. ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES, WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
5. CENTRE PLATES TO BE OILED AND PROTECTED, BY SEALING IN POLYTHENE BAGS CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL TO BE HARDENED AND TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING.
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
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CERTIFIED

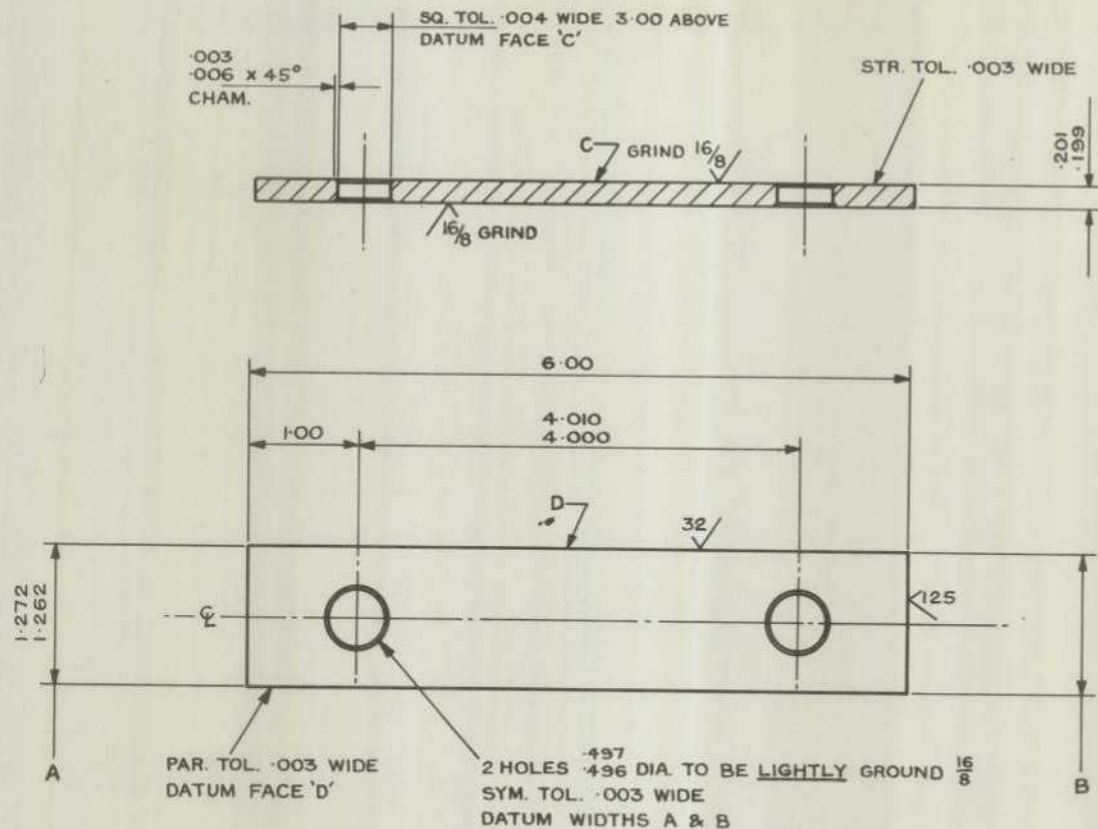
CONTRACTOR'S DRAWING REF.

124

DRAWING NUMBER

011 002827

CHECKED	MATERIAL B.S. 2598 TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT. IN ANNEALED BARS :- 1 1/2" x 3/8" x 12ft LONG	PROTECTIVE FINISH	TOLERANCES ±.010 UNLESS OTHERWISE STATED.	CONTRACTOR ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION
TRACED S.L.E.B. 28.3.60			DIMENSIONS IN INCHES	SERVICE LETTER
DRAWN B.H.E. PERNETT			SURFACE ROUGHNESS	TITLE CENTRE PLATE IN BS. 2598 (HELICOPTER PROGRAMME)
			SCALE	



- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001-.010 x 45°
- 3 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
- 4 BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBER TO BE STAMPED CENTRALLY ON BOTH END FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE 'C'
- 5 CENTRE PLATES TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL TO BE MARRAGED TO SPECIMEN BEFORE FINAL MACHINING.
9. WHERE $16/\sqrt{R}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN $16 \mu"$ AND $8 \mu"$

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					

CONTRACTOR'S DRAWING REF.	
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125

DRAWING NUMBER	0
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011.002828

CHECKED	MATERIAL D.T.D. 5212 18NI-CO-MO D.V.M. MARAGING STEEL	PROTECTIVE FINISH	TOLERANCES $\pm .010$ UNLESS OTHERWISE STATED	CONTRACTOR	
TRACED <i>Nong</i> 27.3-69	TO BE SUPPLIED SOLUTION TREATED (SOFTENED) IN 12 FT. LENGTHS $1\frac{1}{2} \times \frac{3}{8}$ BY FATIGUE RESEARCH SECTION. STRUCTURES DEPT.		DIMENSIONS IN INCHES	ROYAL AIRCRAFT ESTABLISHMENT	MINISTRY OF AVIATION
DRAWN			SURFACE ROUGHNESS	TITLE	
A.W. CARDRICK			SCALE	CENTRE PLATE IN D.T.D. 5212 MARAGING STEEL (HELICOPTER PROGRAMME)	

USED ON

2829

THIRD ANGLE PROJECTION

AXIAL SQUARENESS TOLERANCE
·004 WIDE 3·00 HIGH FROM
DATUM FACE C

RADIUS MUST NOT UNDERCUT
PARALLEL PORTION

PARALLEL TOLERANCE
·003 WIDE DATUM FACE C

·003
·006 $\times 45^\circ$
CHAM

1·039
1·033

·755 RAD
·745

63

16
8 GRIND

C

·250
·255

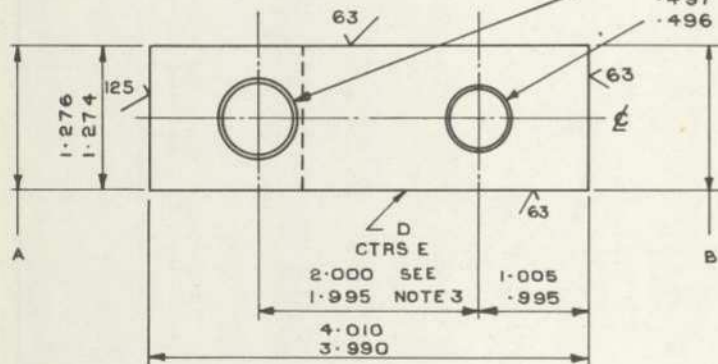
STR. TOLERANCE ·003 WIDE

Technical drawing of a mechanical part in third angle projection. The part is a horizontal shaft with a central section. The left end has a chamfer labeled $.003 \ .006 \times 45^\circ$ CHAM. The central section has a radius labeled $.755 \text{ RAD } .745$ and a width of 1.039 and 1.033 . The right end has a width of $.250$ and $.255$. A datum C is indicated at the right end. Tolerances are specified: AXIAL SQUARENESS TOLERANCE $.004$ WIDE 3.00 HIGH FROM DATUM FACE C , RADIUS MUST NOT UNDERCUT PARALLEL PORTION, PARALLEL TOLERANCE $.003$ WIDE DATUM FACE C , and STR. TOLERANCE $.003$ WIDE. A grinding operation is indicated as $\frac{16}{8}$ GRIND.

STR. TOLERANCE .003 WIDE

.6310 DIA
 .6295 DIA
 .497 DIA
 .496 DIA

SYM.TOL .002 WIDE DATUM
 WIDTHS A & B SEE NOTE 3
 FINISH 16 μ " SEE NOTE 4



- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001--0.01x45°
- 3 SIDE PLATES TO BE MACHINED AND SUBSEQUENTLY RETAINED IN PAIRS TO MAINTAIN TOLERANCE .001 WIDE BETWEEN CENTRES 'E' AND DIAMETRAL TOLERANCE .0005 WIDE FOR EACH PAIR SEE DRG 011002825
- 4 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 5 HOLES MAY BE REAMED, BORED OR LIGHTLY GROUND
- 6 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 7 MATERIAL TO BE HARDENED AND TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING
- 8 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 9 SIDE PLATES TO BE OILED AND SEALED IN PAIRS IN POLYTHENE BAGS, CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
- 10 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ & 8μ "

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					

CONTRACTOR'S DRAWING REF.	
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126

DRAWING NUMBER

011.002829

CHECKED	MATERIAL BS 25 98 TO BE SUPPLIED BY FATIGUE RESEARCH SECTION	PROTECTIVE FINISH	TOLERANCES ± .010 UNLESS OTHERWISE STATED	CONTRACTOR	
TRACED DKC 2-4-69	STRUCTURES DEPT IN ANNEALED BARS	_____	DIMENSIONS IN INCHES	ROYAL AIRCRAFT ESTABLISHMENT	MINISTRY OF AVIATION
DRAWN A.W. CARDRICK	1" 5" / 2 x 8 x 12' LONG		SURFACE ROUGHNESS	TITLE	
			SCALE	SIDE PLATE IN BS.2598 (HELICOPTER PROGRAMME)	

Fig. 11

Fig.12

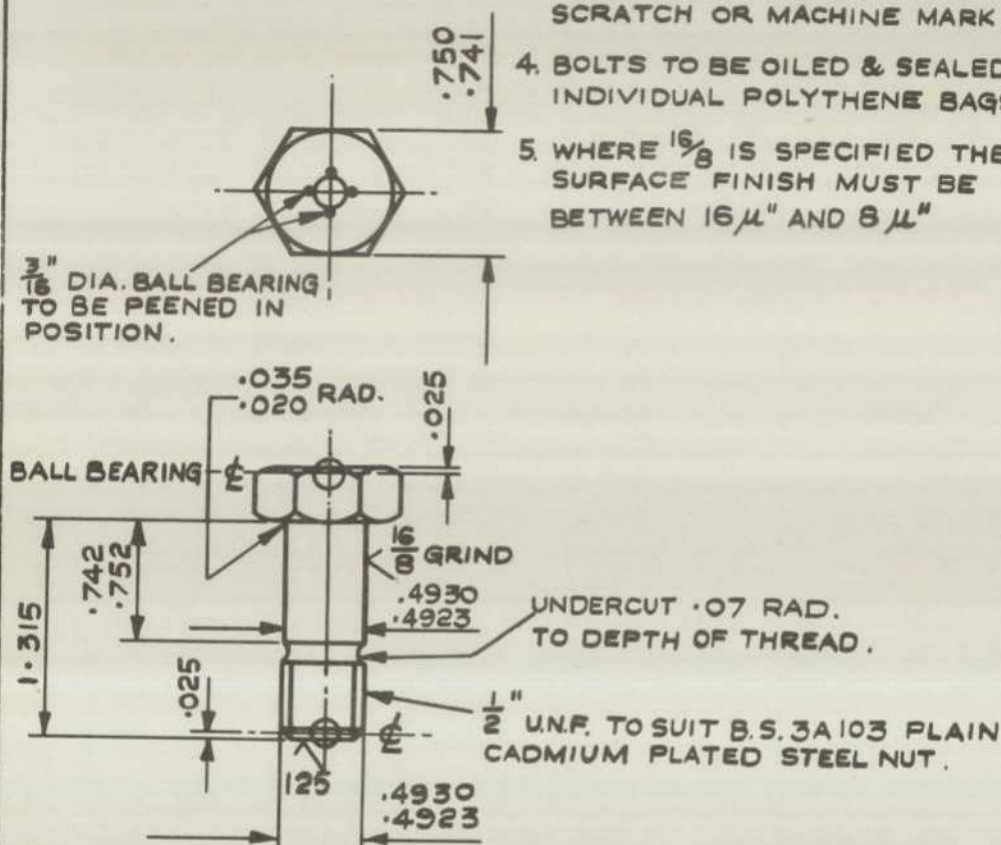
DRAWING NUMBER
OII 002831

THIRD ANGLE PROJECTION

App.A

USED ON

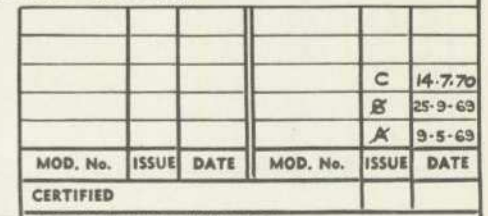
1. ALL BOLTS TO BE SUPPLIED FROM MATERIAL WHICH SHALL HAVE A U.T.S. OF NOT LESS THAN 55 TON F/in²
2. CENTRE DRILL HOLES MAY BE LEFT AT ENDS.
3. PLAIN LENGTH OF BOLT TO BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
4. BOLTS TO BE OILED & SEALED IN INDIVIDUAL POLYTHENE BAGS.
5. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "



REFER TO DRWG. OII 003299 FOR BOLTS MANUFACTURED FROM $\frac{1}{2}$ UNF BS 3A 102 BOLTS.

MATERIAL ALL BOLTS TO BE MADE FROM ONE OF THE FOLLOWING S.94, S95, OR S.96.	PROTECTIVE FINISH SEE NOTE 4						
			B	9/12/69			
		MOD NO	ISSUE	DATE	MOD NO	ISSUE	DATE
		CERTD. <i>30/10/69 2. 1. 69</i>					
DIMS. IN INCHES	SURFACE ROUGHNESS	TOLERANCES $\pm .010$					
SCALE		UNLESS OTHERWISE STATED					
CONTRACTOR					SERVICE LETTERS		
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION		CONTRACTOR'S DRG. REF.					
TITLE HIGH TENSILE STEEL BOLT (HELICOPTER PROGRAMME)		DRAWING NUMBER OII 002831					

1. ROUGH MACHINING TO BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED,
CHAMFER $.001 - .010 \times 45^\circ$
3. SHARP EDGES OF 3.5 mm.
HOLE TO BE LIGHTLY REMOVED WITH
FINE ABRASIVE PAPER, CHAMFER
 $.001 - .005 \times 45^\circ$
4. IT IS ESSENTIAL THAT
TOLERANCES ARE NOT EXCEEDED.
5. BLANKS TO BE MACHINED TO
LENGTH & IDENTIFICATION NUMBERS
STAMPED CENTRALLY ON BOTH FACES
WITH BASE OF NUMBER PARALLEL
TO DATUM FACE C.
6. IT IS ESSENTIAL THAT THE
HOLE FINISHES SHALL BE FREE
FROM THE SLIGHTEST SCRATCH
OR MACHINE MARK.
7. PARTICULAR CARE MUST BE
TAKEN TO AVOID LOCAL HEATING
DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED.
9. SPECIMENS TO BE PROTECTED BY
SEALING IN INDIVIDUAL POLYTHENE
BAGS WITH SUITABLE DESSICANT.
CONVENIENT BATCHES TO BE
PACKED IN WOODEN BOXES.
10. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE
FINISH MUST BE BETWEEN $16\mu"$ AND $8\mu"$.
11. 3.5 mm. HOLE TO BE MACHINED AFTER FINAL
SURFACE GRINDING.



128

011 002835

TITLE
2.3 K_t NOTCHED SPECIMEN IN BS. 2L 65 AND
BS. T 11. (HELICOPTER PROGRAMME)

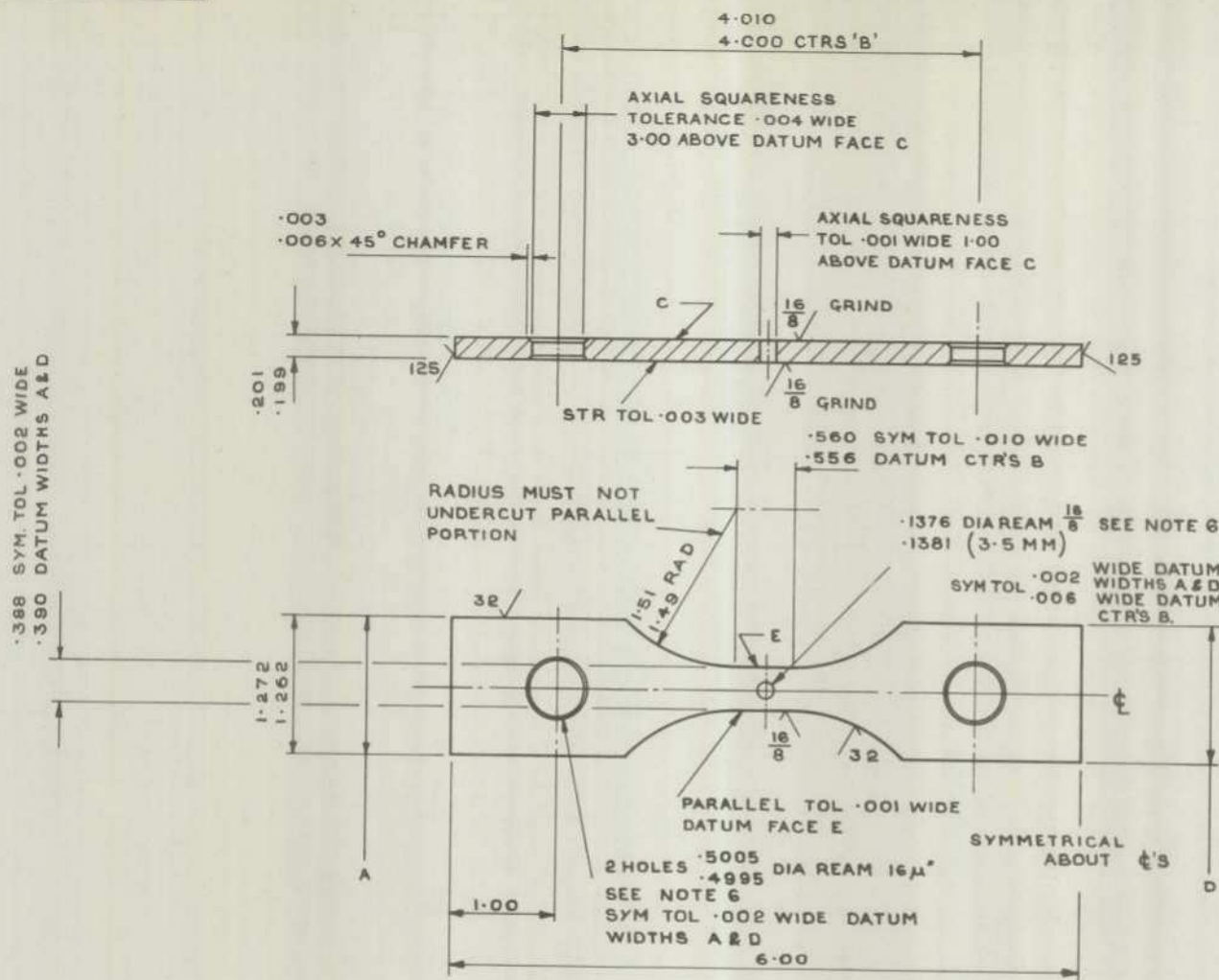
Fig. 13

USED ON

Fig. 14

NOTE

- 1 ROUGH MACHINING TO BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001-.010x45°
- 3 SHARP EDGES OF 3.5 MM HOLE TO BE LIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER .001-.005x45°
- 4 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 5 BLANKS TO BE MACHINED TO LENGTH & IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL TO BE HARDENED AND TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING
- 9 SPECIMENS TO BE OILED AND PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOX
- 10 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "
- 11 3.5 MM HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING



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				A	9-5-68
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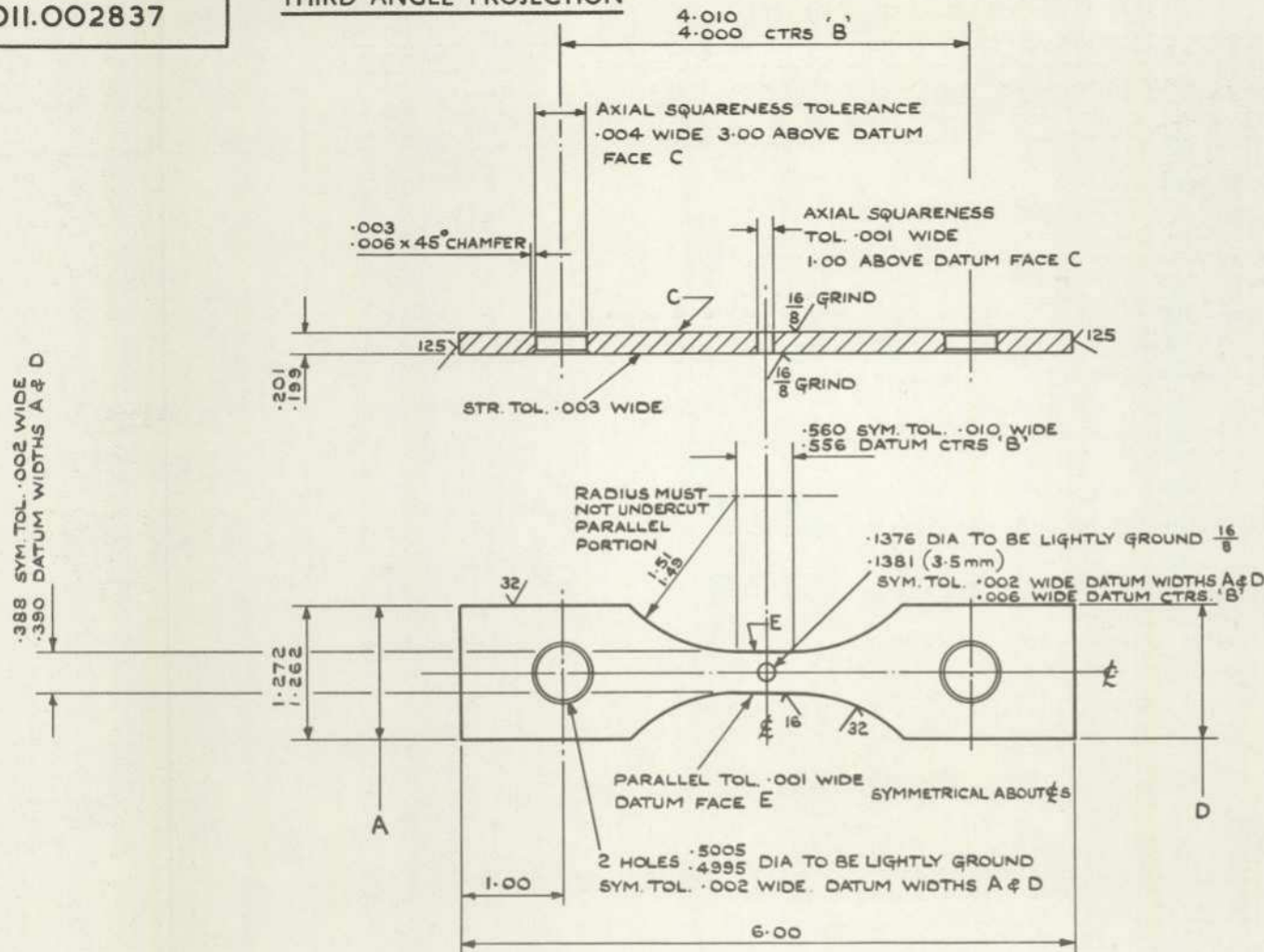
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CHECKED	MATERIAL BS 2598 TO BE SUPPLIED BY FATIGUE RESEARCH SECTION	PROTECTIVE FINISH	TOLERANCES ·010 UNLESS OTHERWISE STATED	CONTRACTOR	
TRACED	STRUCTURES DEPT IN ANNEALED BARS $1\frac{1}{2} \times \frac{3}{8} \times 12$ FT LONG		DIMENSIONS IN INCHES	ROYAL AIRCRAFT ESTABLISHMENT	MINISTRY OF AVIATION
D.K.C.65-69			SURFACE ROUGHNESS	SERVICE LETTER	
DRAWN			SCALE	TITLE 2.3K _t NOTCHED SPECIMEN IN BS 2598 (HELICOPTER PROGRAMME)	
A.W.CARDRICK					

NOTES :-

1. ROUGH MACHINING TO BE DONE SYMMETRICALLY
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER $.001 - .010 \times 45^\circ$
3. SHARP EDGES OF 3.5 MM HOLE TO BE LIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER $.001 - .005 \times 45^\circ$
4. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
5. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
6. IT IS ESSENTIAL THAT THE HOLE FINISHES MUST BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
8. MATERIAL TO BE MARAGED TO SPECIFICATION BEFORE FINAL MACHINING
9. SPECIMENS TO BE OILED AND PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
10. WHERE $18/8$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN $16 \mu''$ AND $8 \mu''$
11. 3.5 MM HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING



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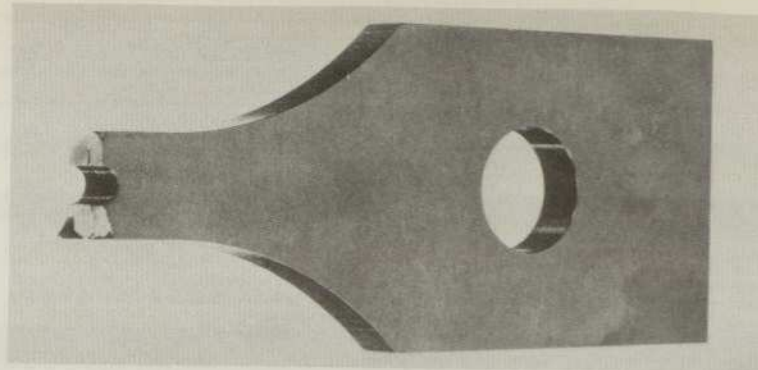
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Fig. 15

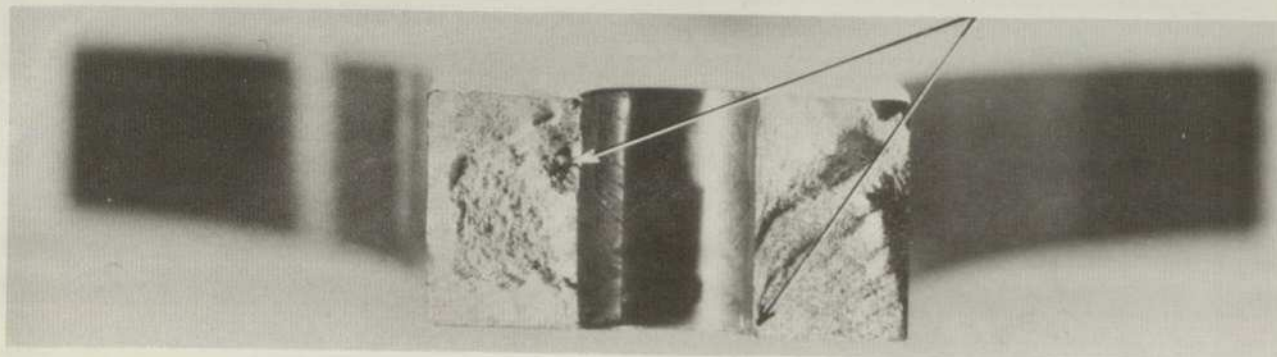
NTBD

CHECKED	MATERIAL D.T.D. 5212 18NI-CO-MO	PROTECTIVE FINISH	TOLERANCES ± .010 UNLESS OTHERWISE STATED	CONTRACTOR	
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DRAWN	BY FATIGUE RESEARCH SECTION STRUCTURES DEPT.		SURFACE ROUGHNESS	TITLE	
A.W. CARDRICK			SCALE	2-3 K _t NOTCHED SPECIMEN IN DTD 5212 MARAGING STEEL (HELICOPTER PROGRAMME)	

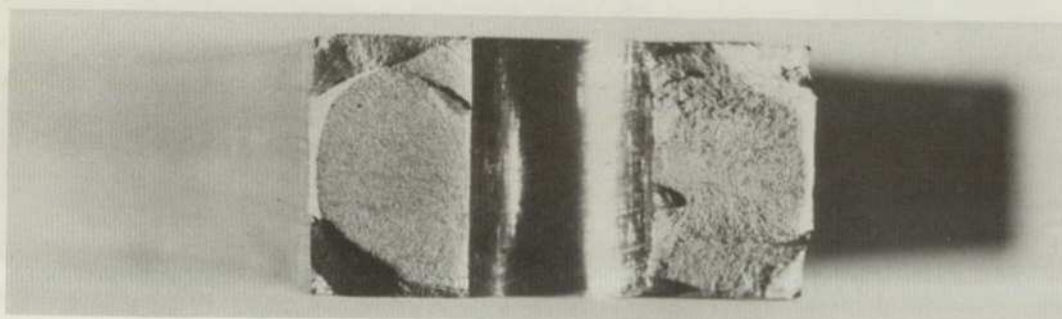


Typical failure

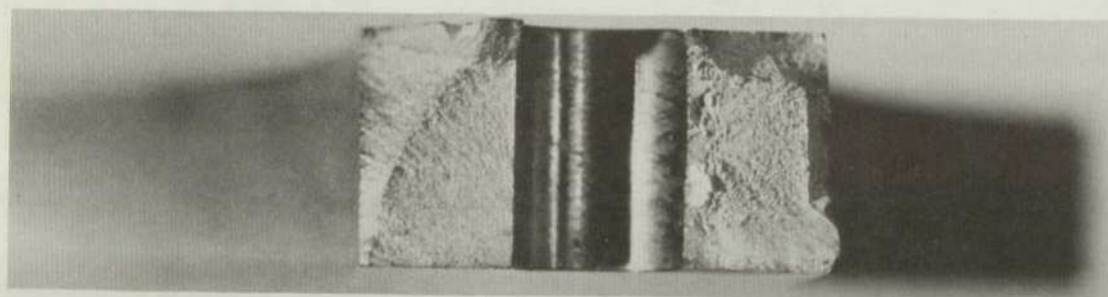
fatigue nuclei



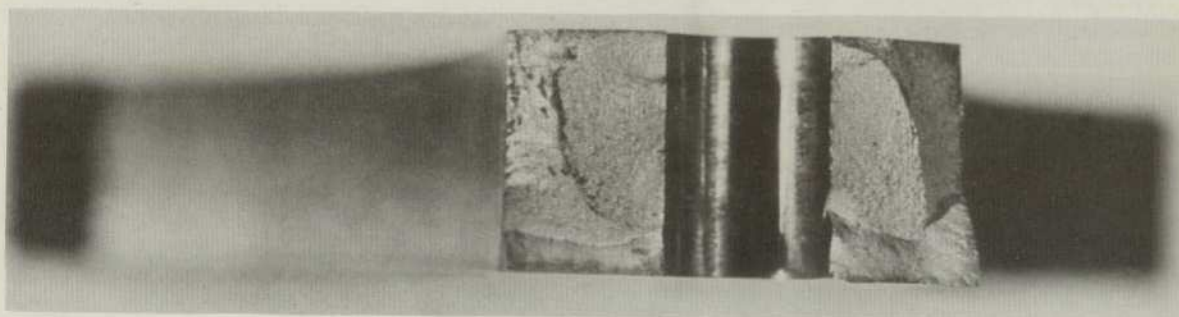
BS 2L65 aluminium alloy



BS TA11 titanium alloy



DTD 5212 maraging steel



BS 2S98 NiCrMo steel

Fig.16 Fatigue fractures typical of notched specimens

APPENDIX B

AN ASSESSMENT OF THE FATIGUE PERFORMANCE OF AN EXPERIMENTAL
Al 5% Mg 4% Zn 1% Mn ALLOY IN THE FORM OF PINNED-LUG AND
CLAMPED-LUG SPECIMENS

Draft RAE Technical Report, August 1971.

R O Y A L A I R C R A F T E S T A B L I S H M E N T

Draft Technical Report

August 1971

AN ASSESSMENT OF THE FATIGUE PERFORMANCE OF AN EXPERIMENTAL
Al 5% Mg 4% Zn 1% Mn ALLOY IN THE FORM OF PINNED-LUG AND
CLAMPED-LUG SPECIMENS

by

A. W. Cardrick

SUMMARY

An assessment has been made of the fatigue performance of an experimental alloy using specimens which represent structural features. The material, which exhibits higher plain and notched fatigue strengths than BS 2L65 in conventional tests on small specimens, is shown to be weaker under both constant and variable amplitude loading when fatigue damage originates from areas of fretting. The inferior performance is attributed primarily to a higher crack propagation rate and secondly to its greater crack sensitivity.

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1 INTRODUCTION

During the course of a Materials Department (RAE) development programme on a family of Al Mg Zn alloys, a 5% Mg 4% Zn 1% Mn alloy with a high ultimate strength and good stress corrosion properties, was shown to have a slightly higher fatigue strength than BS 2L65 (Al 4.3% Cu) when tested under constant amplitude loading in the form of simple plain and notched specimens.

In order to compare the fatigue performance of these two materials under conditions more representative of structural applications, pinned-lug and clamped-lug specimens have been tested under constant and variable amplitude loading. It is shown that the relative performance of the two materials is at variance with that derived from the conventional plain and notched tests and some possible explanations are advanced in terms of the effects of fretting on the growth of fatigue damage.

The materials and specimens used in this investigation are described in sections 2 and 3 and the test conditions in section 4. The relative fatigue performance of the two materials in the form of pinned-lug and clamped-lug specimens is discussed in sections 5 and 6 respectively, and in section 7 a comparison is drawn with plain and notched specimen data. Conclusions are presented in section 8.

2 MATERIALS

The two aluminium alloys, BS 2L65 (Al 4.3% Cu) and the experimental Al 5% Mg 4% Zn 1% Mn alloy, were tested in the extruded, solution treated and artificially aged condition. Each alloy was cast from a single melt. The ends of each extruded length were discarded and sufficient surface material was removed in subsequent machining to ensure freedom from coarse grain effects.

The nominal chemical compositions and average mechanical properties of the BS 2L65 and the experimental alloy are presented in Tables 1 and 2 respectively.

In conventional metallurgical tests¹ the experimental alloy had been shown to have a higher ultimate strength than BS 2L65 and slightly higher plain and notched fatigue strengths - at all but the lowest endurances - as shown in Figs. 1 and 2, together with much better stress corrosion properties than either BS 2L65 or the high strength type DTD 683, Al 6% Zn 3% Mg alloys.

3 SPECIMENS

Pinned-lug and clamped-lug specimens were chosen for this investigation in order to represent the structural conditions of fretting at an appreciable stress concentration and fretting between clamped surfaces.

3.1 The pinned-lug specimen

The pinned-lug specimen is shown in Fig.3. A BS S94 steel loading pin was used with a clearance of between 16 μm and 64 μm (0.1 and 0.4 per cent), such that under tensile loading an elastic stress concentration of 3.1 was produced approximately on the transverse diameter of the hole^{2,3}. Specimens and pins were cleaned in trichloroethane degreasing agent and assembled dry to represent severe fretting conditions. Fatigue cracks in the pinned-lug originate from local areas of fretting in the vicinity of the peak stress concentration at the minimum net section through the pin. Subsequent propagation normally results in a planar crack surface which persists until fracture occurs, see Fig.4.

3.2 The clamped-lug specimen

The clamped-lug specimen is shown in Fig.5. This has been designed to represent the conditions of clamping pressure and slip in a bolted joint. The side plates were of BS S514 steel and, as in the case of the pinned-lug, the specimens were assembled dry. BS S94 steel bolts were used, and the clamping pressure was closely controlled by standardising bolt extension, rather than torque, to give a bolt stress of approximately 60% of the UTS. Fatigue cracks in the clamped-lug specimen originate from the areas of fretting at the interfaces of the side plates and lug. The cracks propagate through the lug on parallel surfaces normal to the longitudinal axis of the specimen. A complex failure occurs associated with the strength reduction of the lug caused by the joining-up of several such cracks, see Fig.6. Measurement of the area within the fretted annulus on typical specimens indicates a nominal 'clamping pressure' of approximately 200 MN/m^2 .

4 TEST CONDITIONS

4.1 General

All specimens were tested in fluctuating tension ($0 < R < 1$) at a mean stress of 96.5 MN/m^2 . Stress levels were based on the failure section for each configuration, i.e. the net cross section at the hole diameter for the pinned-lug

and the gross cross section for the clamped-lug. Suitable fatigue stresses, measured as rms alternating stress, were chosen to reveal the fatigue performance of the materials at endurance between approximately 10^4 and 10^7 cycles under both constant and variable amplitude loading.

A Gaussian narrow band random loading spectrum was used. This conformed closely to a Rayleigh distribution of amplitudes, with some truncation at amplitudes above about $3.5 \times \text{rms}$, when the minimum dynamic load approached zero. Truncation levels corresponding to each rms alternating stress were determined as described in Appendix A by measurements of cumulative level crossings using a statistical analyser.

4.2 Fatigue tests on pinned-lug specimens

The pinned-lug specimens were tested in a 200 kN short base Schenck⁴ resonant fatigue machine modified to apply narrow band random loading as well as constant amplitude loading at a frequency of about 110 Hz.

Results are presented for constant amplitude loading in Fig.7 and for variable amplitude loading in Fig.8.

4.3 Fatigue tests on clamped-lug specimens

The clamped-lug specimens were tested in a 200 kN Schenck resonant fatigue machine with standard inertial excitation and in a 600 kN Schenck resonant machine modified to apply narrow band random loading as well as constant amplitude loading. The test frequency in both machines was approximately 28 Hz. Both machines were used to obtain the constant amplitude data and these are presented in Fig.9. The variable amplitude data were obtained in the modified machine and these are presented in Fig.10.

5 FATIGUE PERFORMANCE OF PINNED-LUG SPECIMENS

5.1 General

As can be seen from Figs.7 and 8, in the pinned lug configuration the BS 2L65 proved stronger than the experimental alloy throughout the endurance range under both constant and variable amplitude loading. In seeking an explanation for the variance of this result with that obtained from tests on plain and notched specimens (see Figs.1 and 2), stages of fatigue damage in the pinned-lug specimen will be considered in turn. Where possible an assessment will be made of the effects on fatigue performance of observed differences between the materials in failure characteristics and static properties.

5.2 Fatigue crack nucleation in the pinned-lug specimen

As discussed in section 3, fatigue cracks originate from local lines of fretting in the vicinity of the peak stress concentration at the minimum section. The experimental evidence provides no direct indication of the severity of fretting damage, but the absence of any marked difference between the two materials in the numbers and location of fatigue nuclei along the lines of fretting - see Figs.11a and b - suggests a similarity between the materials in factors such as the occurrence and orientation of microstructural defects and the distribution of residual stresses.

5.3 Influence of geometric residual stresses in the pinned-lug specimen

It is widely recognised that when aluminium alloy specimens containing stress concentrations are tested in fluctuating tension, plastic deformation can occur in an enclave of material at the stress concentration. The elastic constraint of the surrounding material results in compressive 'geometric residual stress', which effectively reduces the mean stress in this enclave and so increases the life of the specimen.

The relation between alternating stress and this reduction in local mean stress may be derived approximately by the procedure* illustrated in Fig.12. This is based on the stress-strain curve for the BS 2L65 material used in this investigation. The application of the mean load produces a mean stress of 96.5 MN/m^2 at the net area. At the point of fatigue initiation, this results in a local stress of 196 MN/m^2 due to the geometric stress concentration factor of 3.1. Similarly, application of the first quarter cycle of constant amplitude alternating load results in a net peak stress of approximately 172 MN/m^2 , which under fully elastic conditions would result in a local peak stress of approximately 525 MN/m^2 . However, plastic deformation occurs and the local stress corresponds more closely to that derived from the stress-strain curve at the same value of strain. Thus, from Fig.12, the achieved local stress is approximately 465 MN/m^2 . In the second quarter cycle of alternating load, the local stress reduces elastically until the load strain returns to its mean value; this results in a local stress of approximately 226 MN/m^2 , thereafter dynamic loading continues about this reduced local mean. The approximate

* This assumes that the local strain concentration factor, K_ϵ , remains constant and that the associated local stress concentration factor, K_σ , is conditioned by the monotonic stress-strain characteristics of the material. It has been shown elsewhere⁵ that this is a good approximation for specimens of this type.

variation in local mean stress with alternating stress for the two materials is shown in Fig.13 - the measured truncation levels were used to calculate the peak stresses under variable amplitude loading.

The influence of geometric residual stress is therefore to create less-severe (lower mean stress) conditions in the experimental alloy rather than to account for its generally lower fatigue performance.

5.4 Crack propagation mode angle in the pinned-lug specimen

The angle between the crack growth plane and the axis of maximum tensile stress was studied to see if any deviations were evident which could contribute to the observed differences in the fatigue performance of the two materials, since changes in mode angle are known to accompany changes in the crack growth mechanism, see Fig.14. The behaviour of both materials was similar in this respect; under both constant and variable amplitude loading low stress levels are characterised by tension mode crack growth and high stress levels by shear mode cracks as shown in Fig.15.

5.5 Residual static strength of pinned-lug specimen

In view of the very low plane strain fracture toughness of the experimental alloy, $15.4 \text{ MNm}^{-3/2}$ compared with approximately $31 \text{ MNm}^{-3/2}$ for the BS 2L65, it was expected to fail at shorter crack lengths. In both materials, the semi-circular crack fronts resulting from nucleation in the bore and at the edges of the hole, combine to form through cracks at all but the higher stress amplitudes. A comparison of the residual static strengths of the two materials has been made on the basis of fatigue-cracked areas symmetrical about the loading pin to within a nominal 5 per cent of the net area. Additional data were obtained by breaking the unfailed ends of the specimens by the application of a static load through the pin. This information is presented in Figs.16a and b. It is immediately evident that the experimental alloy exhibits high crack sensitivity whereas the residual strength of the BS 2L65 reduces approximately linearly with increase in cracked area. The approximate thickness for plane strain fracture is given by the expression

$$t = 2.5 \left(\frac{K_{IC}}{\sigma_y} \right)^2 ,$$

which is used to calculate the minimum thickness for plane strain fracture in fracture toughness specimens. For the experimental alloy this gives a thickness

of 3.3 mm, so that the specimen thickness (7.6 mm) should be sufficient for fracture to occur under approximately plane strain conditions. This view is supported by macroscopic examination of the fracture surfaces, which indicates brittle terminal fracture in the plane of the fatigue crack. In contrast, the fractures in the BS 2L65 were typically ductile with shear faces at 45° to the plane of the fatigue crack. In this material the approximate minimum thickness for plane strain fracture under ideal conditions is 11.2 mm which considerably exceeds the thickness of the pinned-lug specimen.

In view of the strong indications of plane strain fracture in the experimental alloy, the stress intensity factor at medium crack lengths might be expected to correspond approximately to that derived for a crack in an infinite sheet with uniform stress field f . Under these conditions

$$K_I = f\sqrt{\pi a} \quad ,$$

then at failure in plane strain

$$K_I = K_{IC} \quad .$$

This expression has been used to derive values of gross stress, f , corresponding to medium crack lengths, and, as can be seen from Fig.16a, there is good agreement with the measured data. Thus, the crack sensitivity of the experimental alloy is broadly consistent with that predicted from elementary fracture mechanics.

However, the extent to which the endurance of a material can be influenced by fracture toughness will depend critically on the relative proportion of the fatigue endurance occupied by nucleation and by crack propagation. This will be discussed in section 7.

6 FATIGUE PERFORMANCE OF CLAMPED-LUG SPECIMENS

6.1 General

As can be seen from Figs.9 and 10, the BS 2L65 again proved stronger than the experimental alloy throughout the endurance range under both constant and variable amplitude loading. In seeking an explanation for this behaviour attention will be confined to fatigue crack nucleation - the concept of geometric residual stress is inapplicable and considerations of crack mode angle and residual static strength are clouded by the complexity of the fracture surface.

6.2 Fatigue crack nucleation in the clamped-lug specimen

As discussed in section 3, fatigue cracks originate from the areas of fretting at the interfaces of the side plates and lug, and then propagate on parallel planar surfaces normal to the axis of principal stress. Fretting damage of the form shown in Fig.6 is characteristic of both materials. In both materials similar numbers of pitting 'lines' appeared under both types of loading. Microscopic evidence is consistent with their formation by the propagation of fretting pits away from the annular area of clamping, apparently along axes of relative slip at the interface. There was no obvious correlation between the length of the pitting lines and the applied stress.

7 COMPARISON WITH PLAIN AND NOTCHED SPECIMEN DATA

In this section the relative fatigue strength of the two materials, as derived from the fatigue tests described above, is compared with that derived from constant amplitude pulsating tension tests on conventional plain and 3.1 K_t notched specimens cut from adjacent material in the bars (see Figs.1 and 2). It is immediately evident that the conventional data are at variance with those obtained using the pinned-lug and clamped-lug specimens, since the experimental alloy is shown to be superior to the BS 2L65 at endurance above about 2×10^5 cycles.

The principal distinguishing factor between the two series of tests is the fretting at the position of fatigue initiation in the lug specimen. An estimate of the reduction in endurance associated with the introduction of fretting alone can be obtained from a comparison of the pinned-lug and notched data, where the geometric stress concentration factor in both cases is 3.1 and an approximate allowance can be made for the difference in loading conditions (fluctuating and pulsating tension respectively). The reduction due to fretting varies from about 60 per cent at low endurance to about 99 per cent near the fatigue limit, where the reduction in strength is about 95 per cent. These reductions in endurance, which are consistent with those reported⁶⁻⁸ using plain specimens of BS 2L65 aluminium alloy fitted with steel fretting pads, correspond closely to the proportions of endurance generally attributed to the classical Stage 1 (after Forsyth⁹) initiation mechanism of reversed slip and slip band extrusion. Fretting initiation would therefore seem to occur sufficiently rapidly to virtually eliminate Stage 1, so that the fretted life is dominated by the Stage 2 crack propagation phase of damage. Evidence consistent with this

argument has been obtained by Fenner and Field^{6,7} and more recently by Billingham and Ryman⁸, who show that fretting initiation - i.e. the equivalent 'fretted Stage 1' - is complete by about 5 per cent of the fretted endurance under variable amplitude loading. More rapid fretting initiation in the experimental material could not therefore account for its lower endurance which was about 50 per cent lower than that of the BS 2L65 under fretting conditions.

The significance of the greater crack sensitivity of the experimental alloy, as revealed by the residual strength tests discussed in section 5.5, will now be considered. From Figs. 16a and b it can be seen that failure under the highest fatigue stress (100 MN/m^2) would occur - regardless of the type of loading - with a reduction in gross area, $\frac{a}{b}$, of about 50 per cent for the experimental material and about 85 per cent for the BS 2L65. Judging from data obtained by Edwards¹⁰, on small pinned-lug specimens tested under narrow band random loading, the gross area of the BS 2L65 would be reduced to a value of $\frac{a}{b}$ of 50 per cent at about 80 per cent of the life and to $\frac{a}{b}$ of 85 per cent only as failure is approached. It can therefore be argued that if the crack propagation rates were much the same in the two materials, the greater crack sensitivity of the experimental alloy would account for a difference in endurance of up to about 20 per cent.

We have seen that differences in endurance due to fretting initiation and greater crack sensitivity are likely to be confined to less than 5 per cent and 20 per cent respectively which are insufficient to account for the endurance of the experimental alloy being 50 per cent lower than that of the BS 2L65 under both types of loading. We must conclude therefore that the lower performance of the experimental alloy is attributable primarily to a greater crack propagation rate (Stage 2). It does not necessarily follow that this higher crack rate is due to the lower fracture toughness, since it is only in the last few per cent of the life that the stress intensity at the tip of the crack approaches this critical value.

8 CONCLUSIONS

An experimental Al 5% Mg 4% Zn 1% Mn alloy, which exhibits higher strength than BS 2L65 in conventional tests, is shown to be weaker than BS 2L65 when tested under constant and variable amplitude loading in the form of specimens in which fatigue damage originates from areas of fretting. A comparison with the conventional data indicates that the effect of fretting under constant

amplitude loading is to reduce the endurance and fatigue limit of both materials by about 90 per cent.

It is argued that the crack propagation phase - Forsyth's Stage 2 - dominates the endurance under fretting conditions and that the lower endurance of the experimental alloy can be attributed primarily to a higher crack propagation rate and to a lesser extent to its greater crack sensitivity.

This work shows that conventional plain and notched specimen tests can be misleading in the evaluation of a material for applications subject to fretting damage.

Appendix ADERIVATION OF VARIABLE AMPLITUDE TRUNCATION LEVELS

The response characteristics of the resonant machines used in this investigation were such that a progressive truncation from a Rayleigh distribution of amplitudes occurred as the minimum dynamic load approached zero. At each of five values of rms alternating stress, σ , the truncation level was derived from measurements of the cumulative level crossings as follows:-

The equation of a Rayleigh probability density distribution of stress amplitudes, f , takes the form

$$P(f) = \frac{f}{\sigma^2} \exp \left(-\frac{1}{2} \left(\frac{f}{\sigma} \right)^2 \right)$$

which may be expressed in terms of $E(f)$, the fractional number of peaks exceeding f by integration between f and ∞ i.e.,

$$E(f) = \exp \left(-\frac{1}{2} \left(\frac{f}{\sigma} \right)^2 \right) .$$

Considering a particular random history having a total of n peaks, it follows that the number of times f is exceeded by a positive going stress is given by $nE(f)$, i.e.,

$$n \exp \left(-\frac{1}{2} \left(\frac{f}{\sigma} \right)^2 \right)$$

therefore

$$\log_e nE(f) = \log_e n - \frac{1}{2} \left(\frac{f}{\sigma} \right)^2$$

Therefore, by plotting as ordinate the logarithm of the measured cumulative positive level crossings against the square of the threshold level i.e. $\log_e nE(f)$ against f^2 , a straight line should result with slope $-\frac{1}{2\sigma^2}$.

In practice, because of truncation effects, there will be divergence from this straight line and the resultant curve is asymptotic to the square of the truncation level.

Measured distributions with corresponding truncation levels are presented in Figs.17 and 18.

Table 1CHEMICAL COMPOSITION AND AVERAGE MECHANICAL PROPERTIES OF BS 2L65 ALLOY

Chemical composition (nominal)%	4.3 Cu, 0.6 Mg, 0.7 Si, 0.8 Mn, balance Al
Tensile properties (measured)	UTS 524 MN/m ² (76 ksi)
	0.1% proof 462 MN/m ² (67 ksi)
	Elongation 10.7%
Plane strain fracture toughness K _{IC} (nominal)	Longitudinal transverse 28.6-33 MN m ^{-3/2} (26-30 ksi √in)

Table 2CHEMICAL COMPOSITION AND AVERAGE MECHANICAL PROPERTIES OF
EXPERIMENTAL Al 5% Mg 4% Zn 1% Mn ALLOY

Chemical composition (nominal)%	5 Mg, 4 Zn, 1 Mn, balance Al
Tensile properties (measured)	UTS 558 MN/m ² (81 ksi)
	0.1% proof 420 MN/m ² (61 ksi)
	Elongation 10%
Plane strain fracture toughness K _{IC} (measured)	Longitudinal transverse 15.4 MN m ^{-3/2} (14 ksi √in)

NOTATION

a	half crack length
E(f)	fractional number of stresses exceeding amplitude f
f	stress amplitude
f_y	yield stress
K_I	plane strain tension mode stress intensity factor
K_{IC}	plane strain fracture toughness
K_t	tensile stress concentration factor under elastic conditions
K_σ	local tensile stress concentration factor at the root of
	a notch = $\frac{\text{local stress}}{\text{net stress}}$
K_ϵ	local strain concentration factor at the root of a notch = $\frac{\text{local strain}}{\text{net strain}}$
n	number of stress cycles
N	number of stress cycles to failure
P(f)	probability of occurrence of stress amplitude f
R	stress ratio: $\frac{\text{minimum stress in cycle}}{\text{maximum stress in cycle}}$
σ	rms alternating stress

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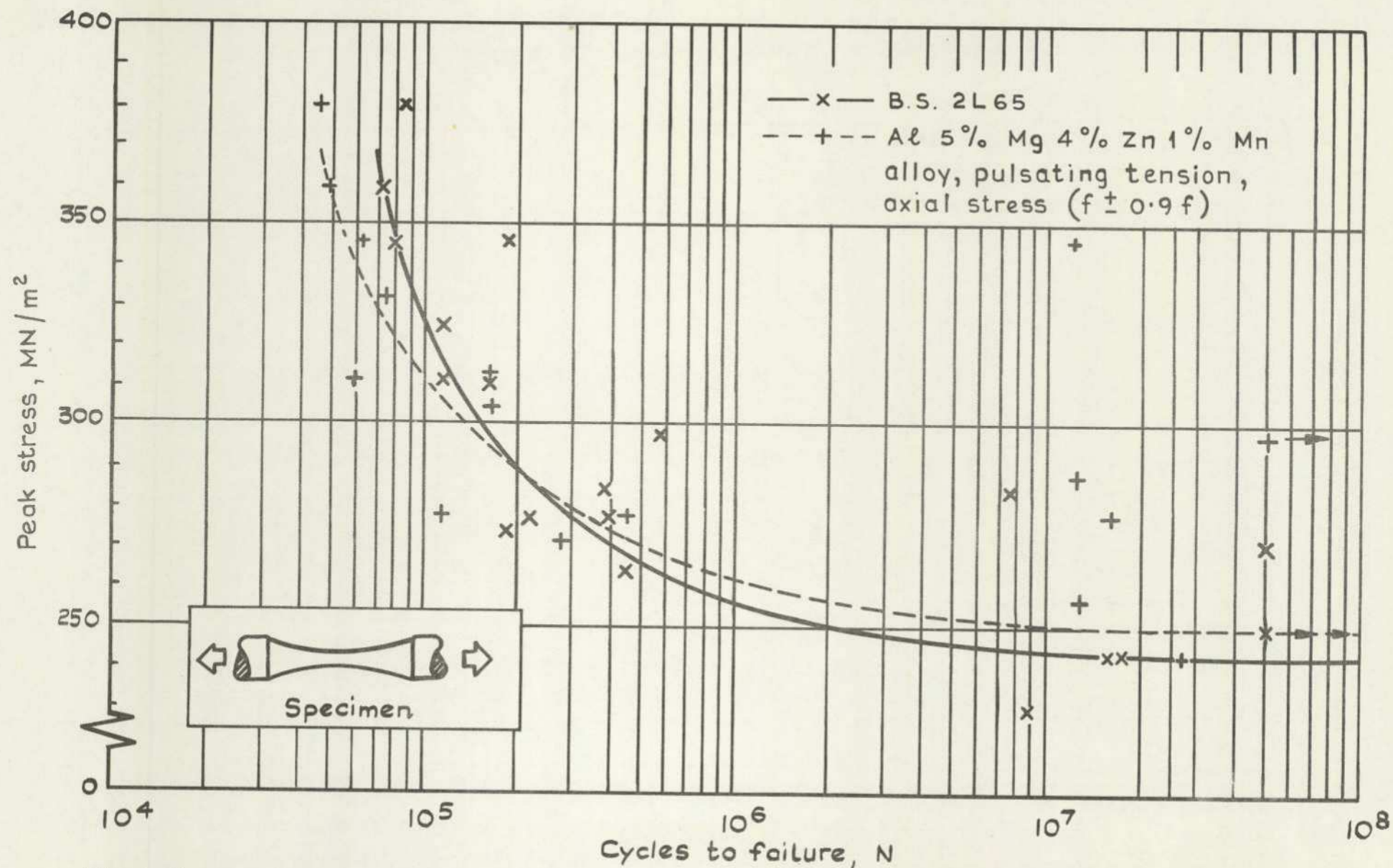


Fig. 1 Comparison of plain specimen results under constant amplitude loading (reproduced from Ref. 1)

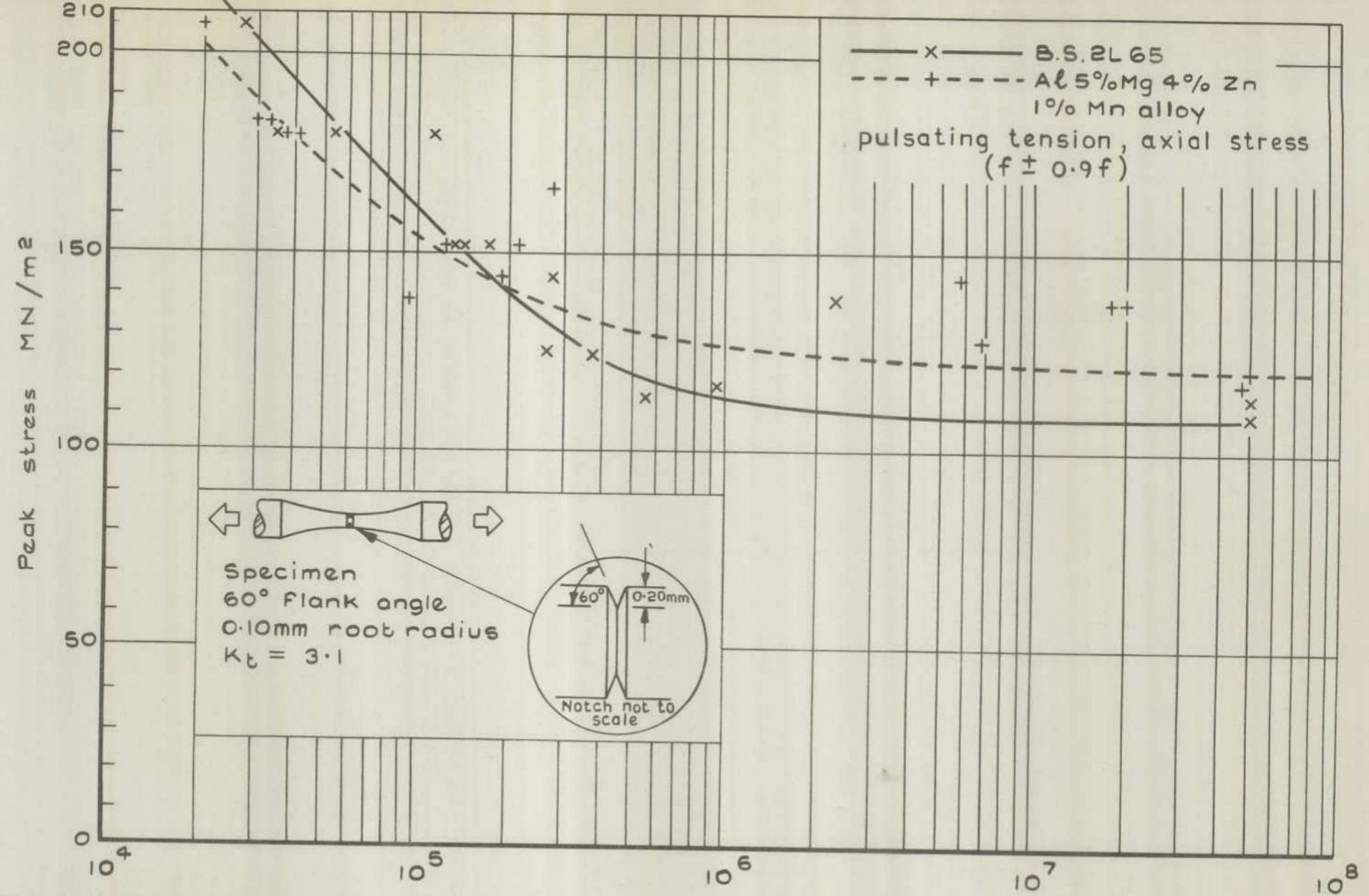


Fig. 2 Comparison of $3.1K_t$ notched specimen results under constant amplitude loading
(reproduced from Ref.1)

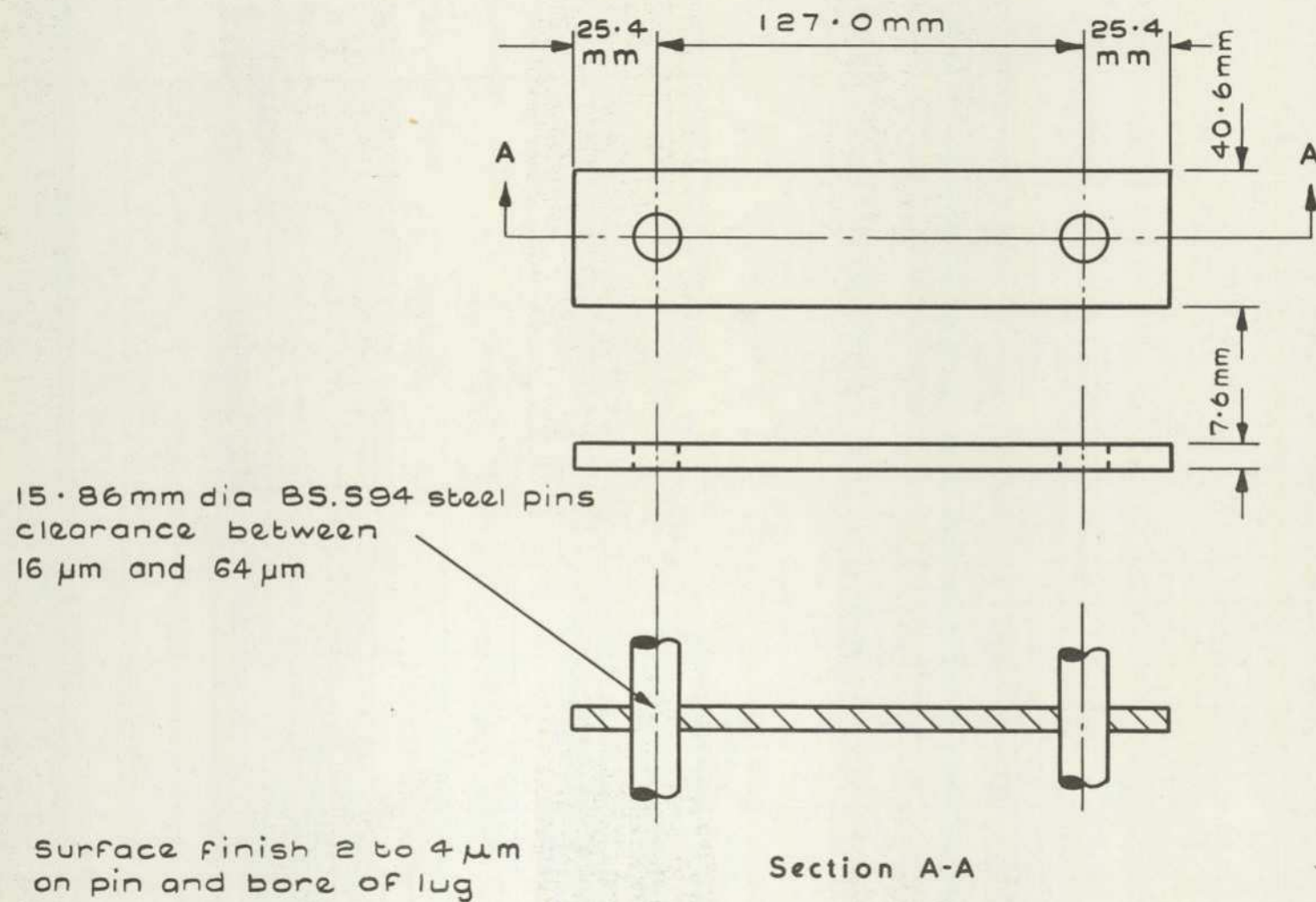
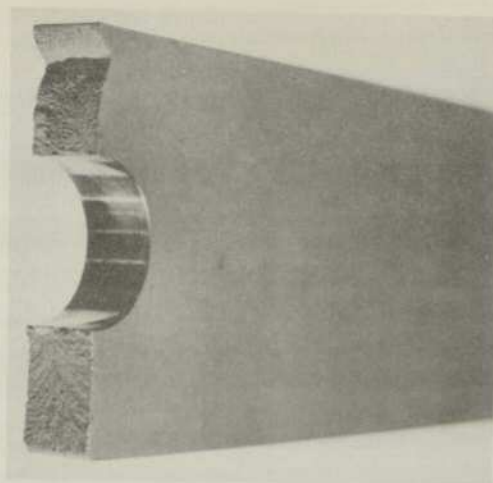
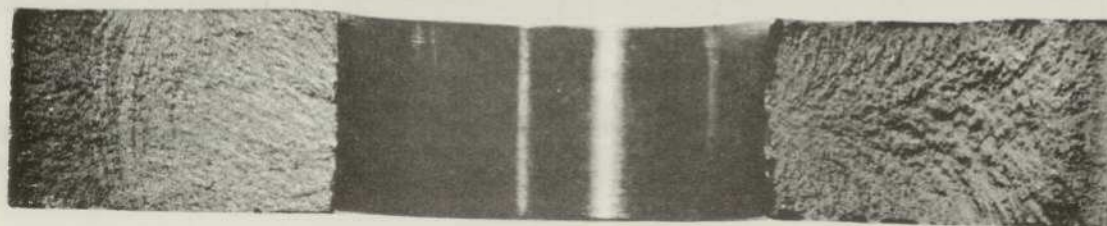


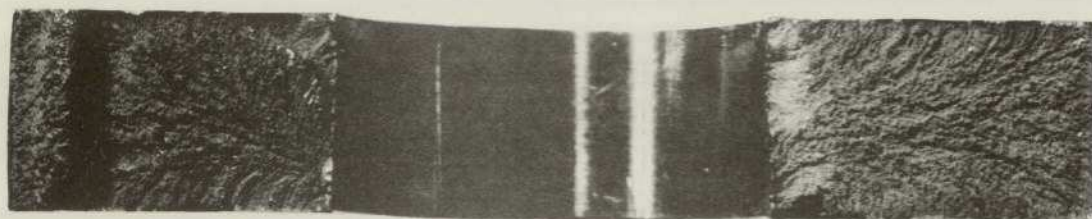
Fig. 3 Pinned-lug specimen



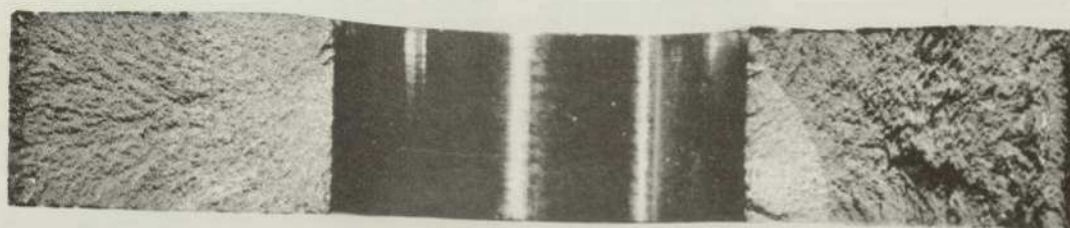
Typical failure



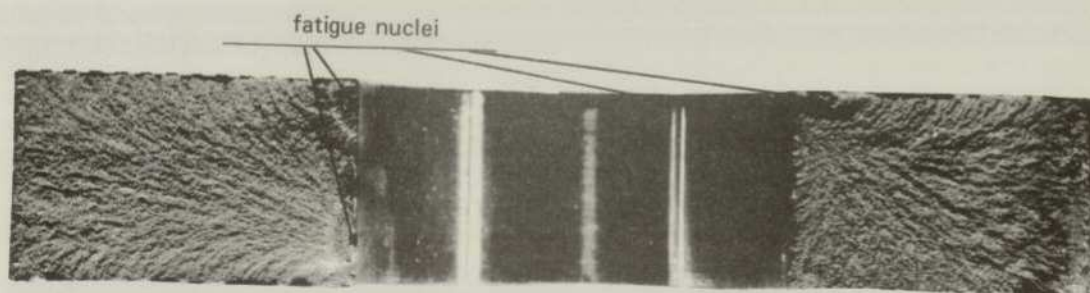
6.9 MN/m² rms constant amplitude



51.6 MN/m² rms constant amplitude

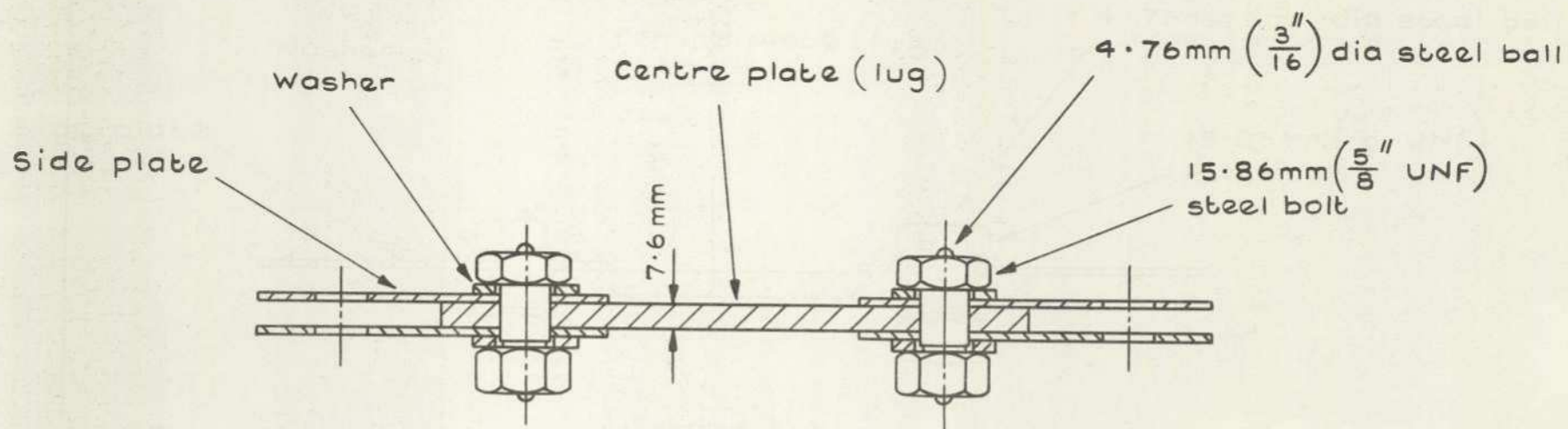
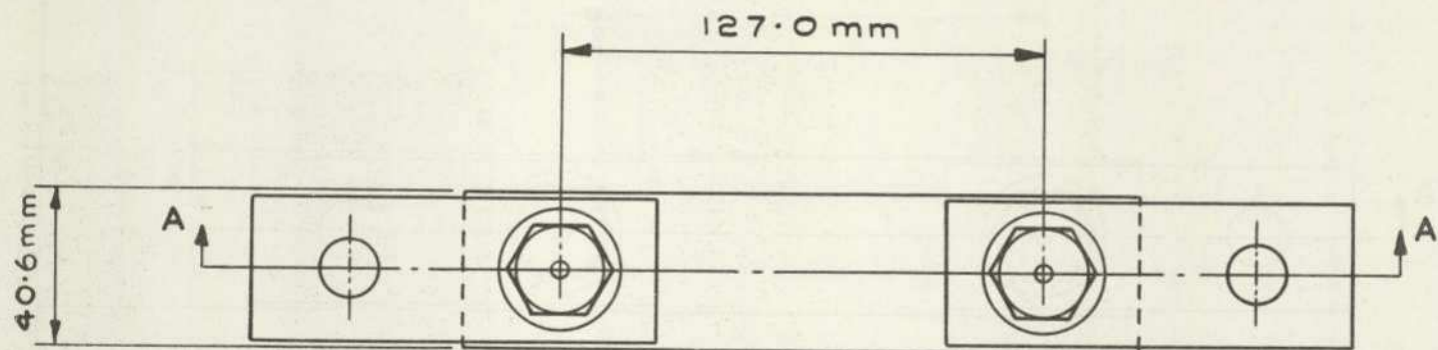


10.3 MN/m² rms variable amplitude



31.0 MN/m² rms variable amplitude

Fig.4 Fractures typical of pinned-lug specimens

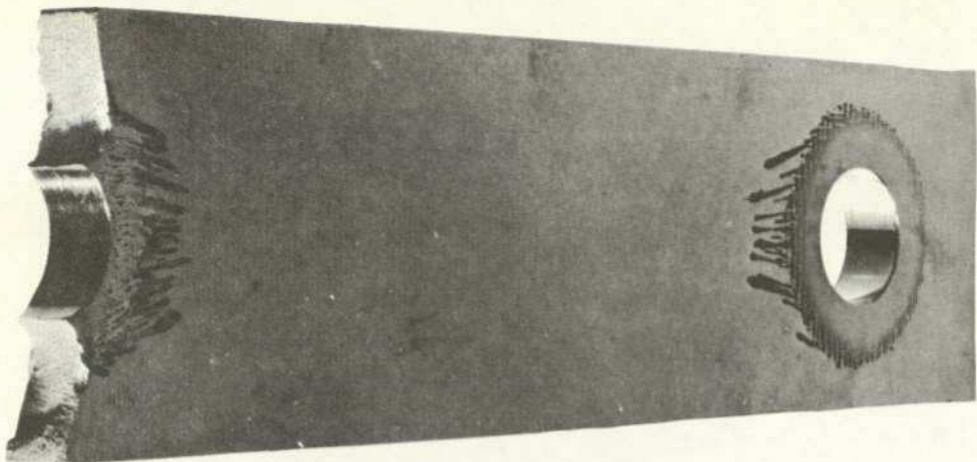


Surface finish
2 to 4 μ m on lug
and side plate surfaces

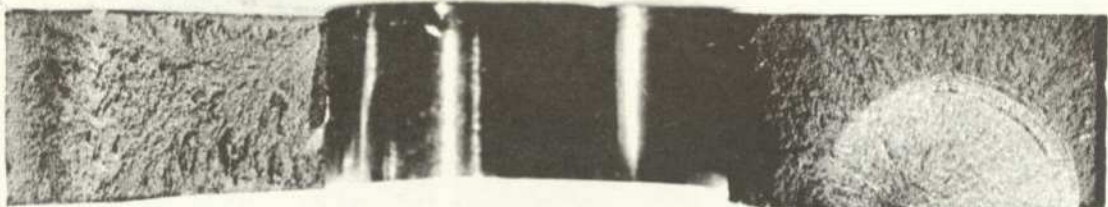
Section A A

Fig. 5 Clamped-lug specimen

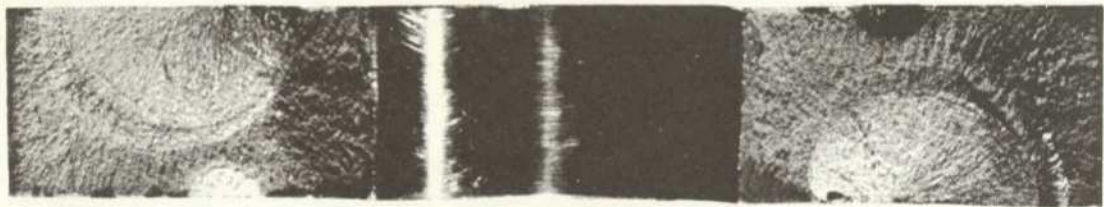
Pitting lines



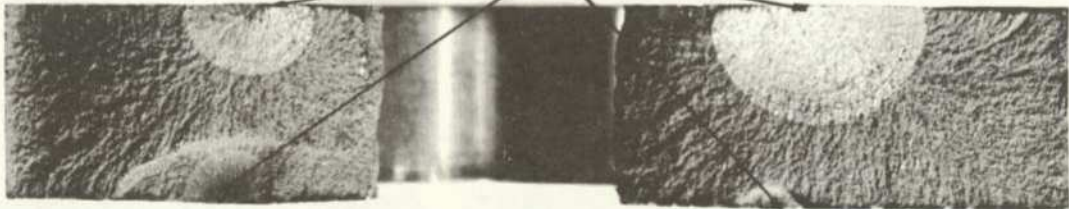
Typical failure



10.3 MN/m² rms variable amplitude



17.25 MN/m² rms variable amplitude
fatigue nuclei



25.8 MN/m² rms variable amplitude



31.0 MN/m² rms variable amplitude

Fig.6 Fractures typical of clamped-lug specimens

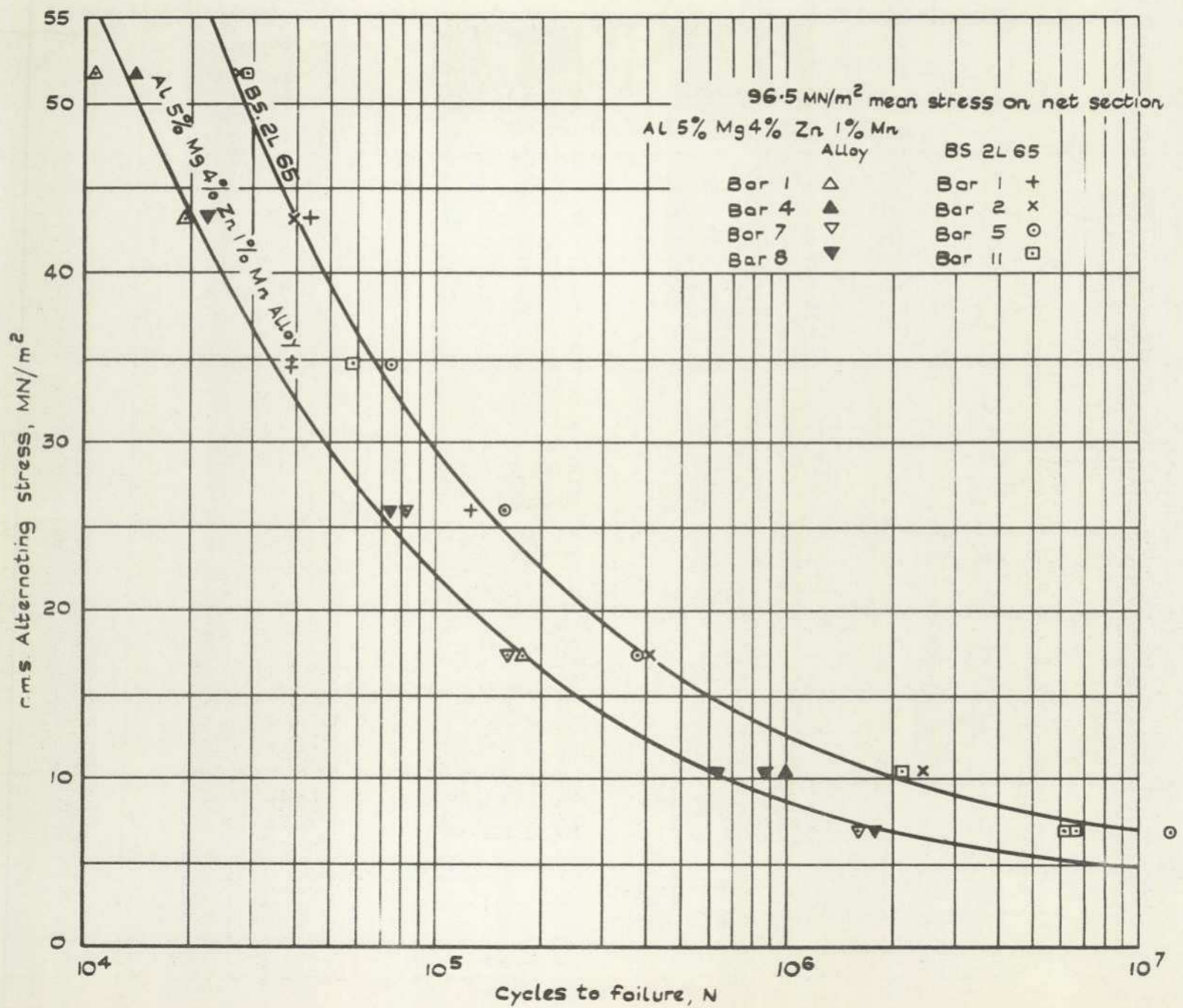


Fig.7 Constant amplitude endurance of pinned-lug specimens

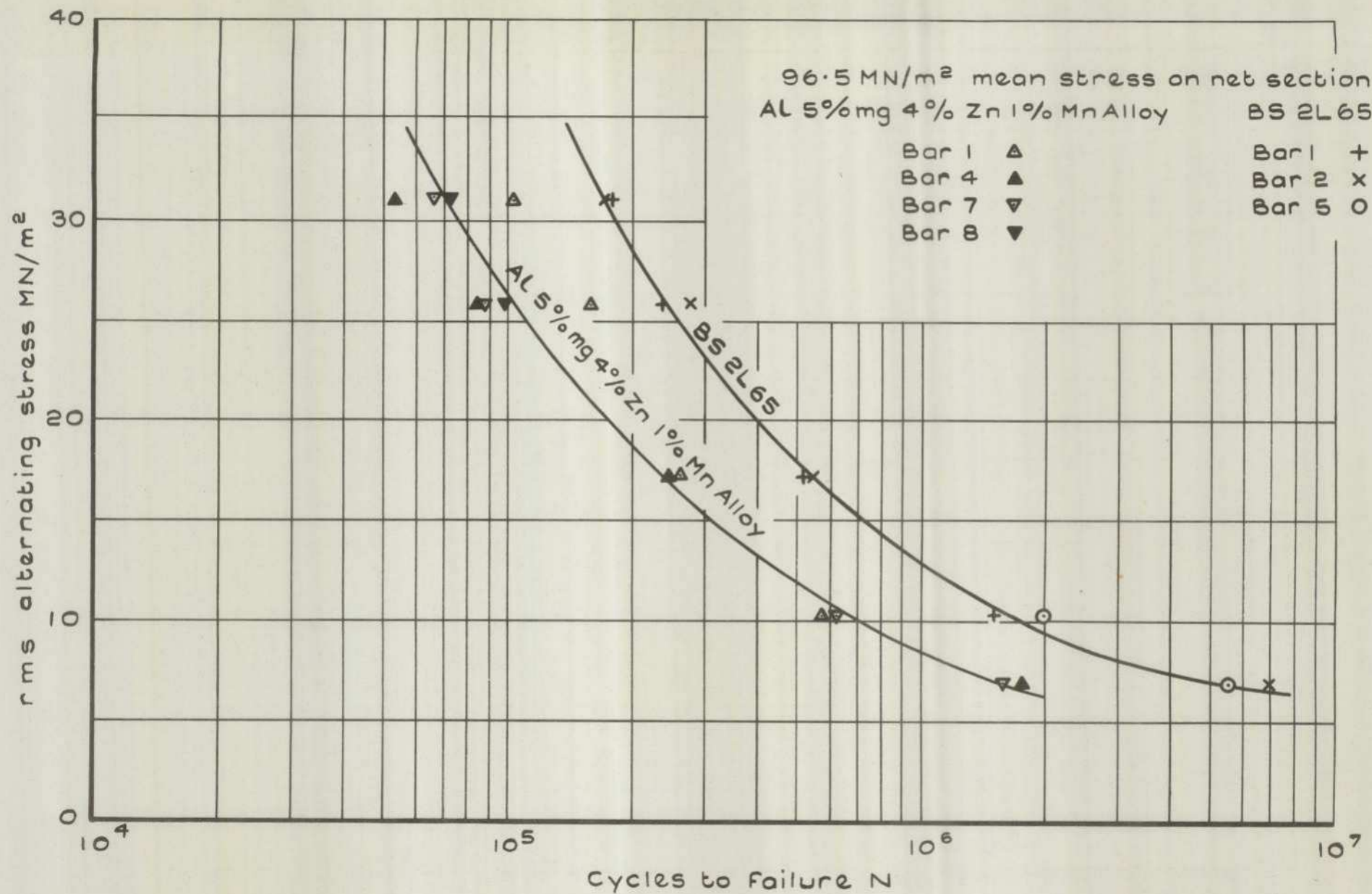


Fig.8 Variable amplitude endurance of pinned-lug specimens

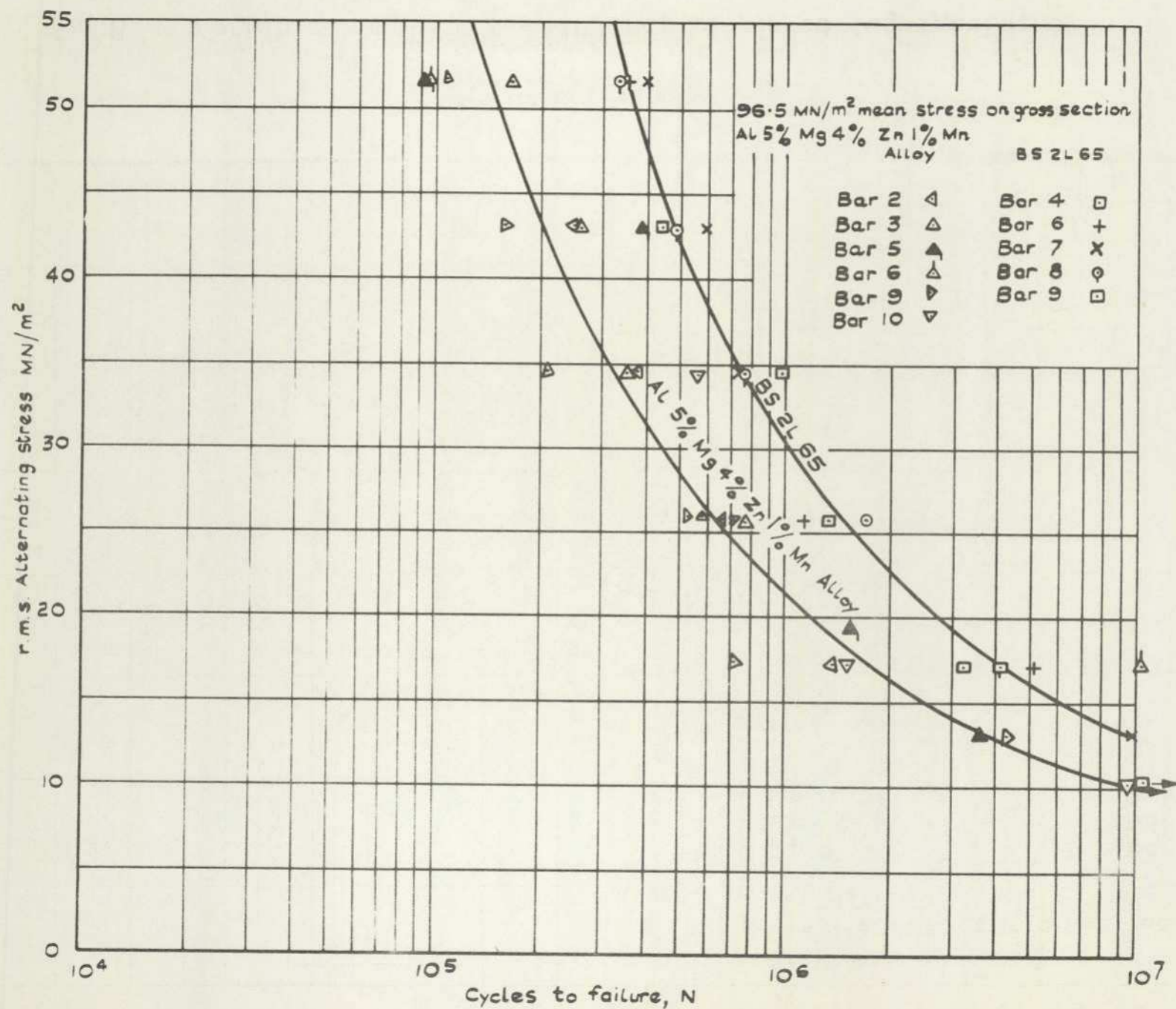


Fig.9 Constant amplitude endurance of clamped-lug specimens

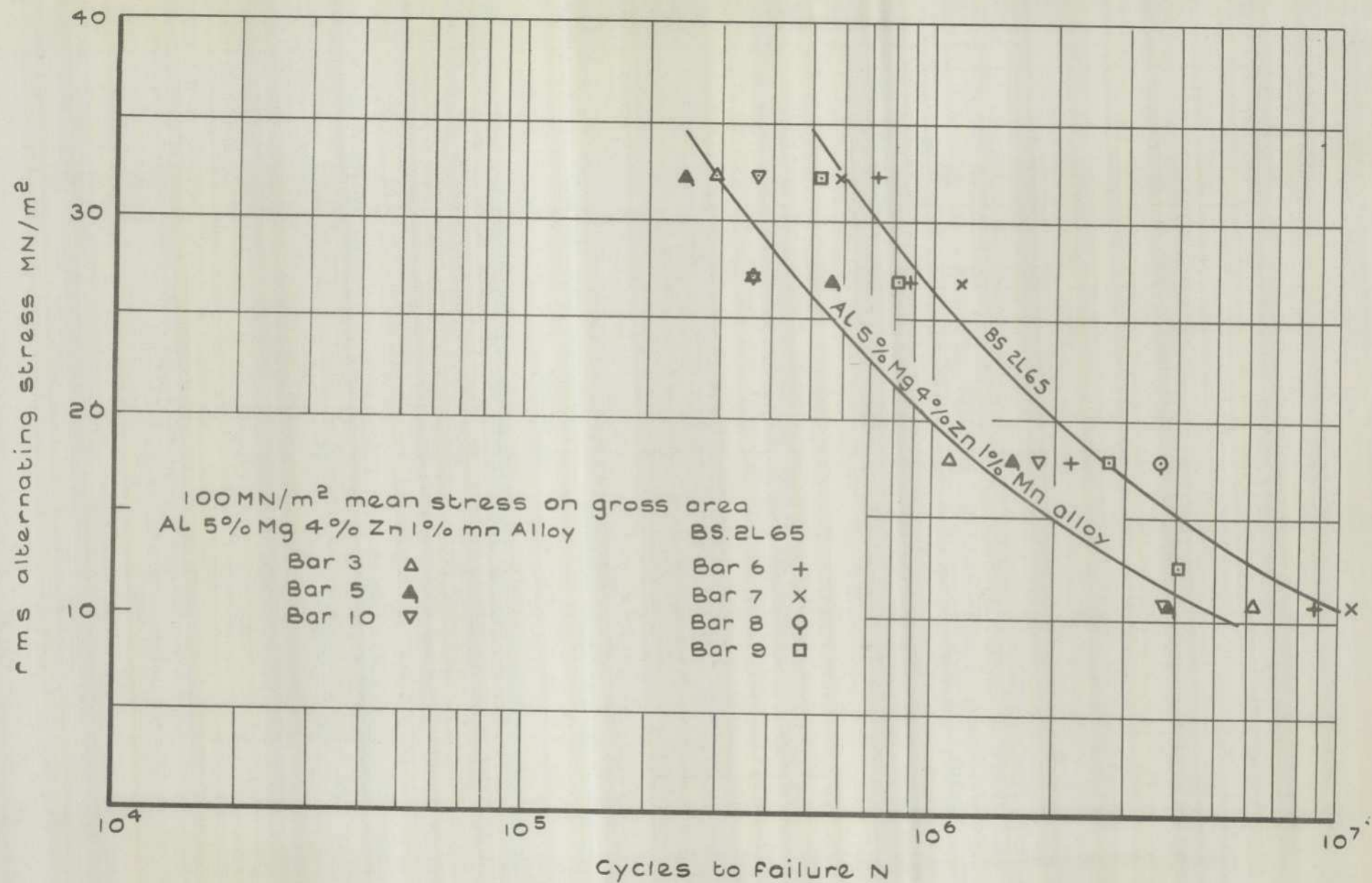


Fig. 10 Variable amplitude endurance of clamped-lug specimens

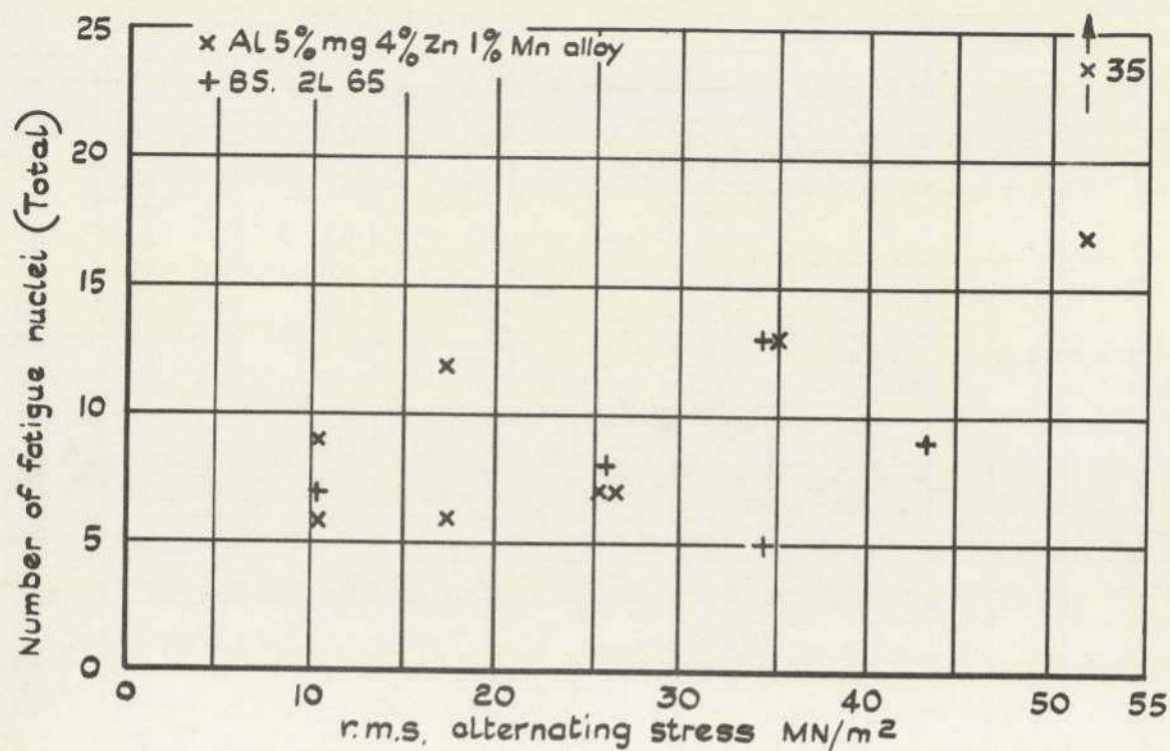


Fig.IIa Variation of numbers of fatigue nuclei with constant amplitude stress

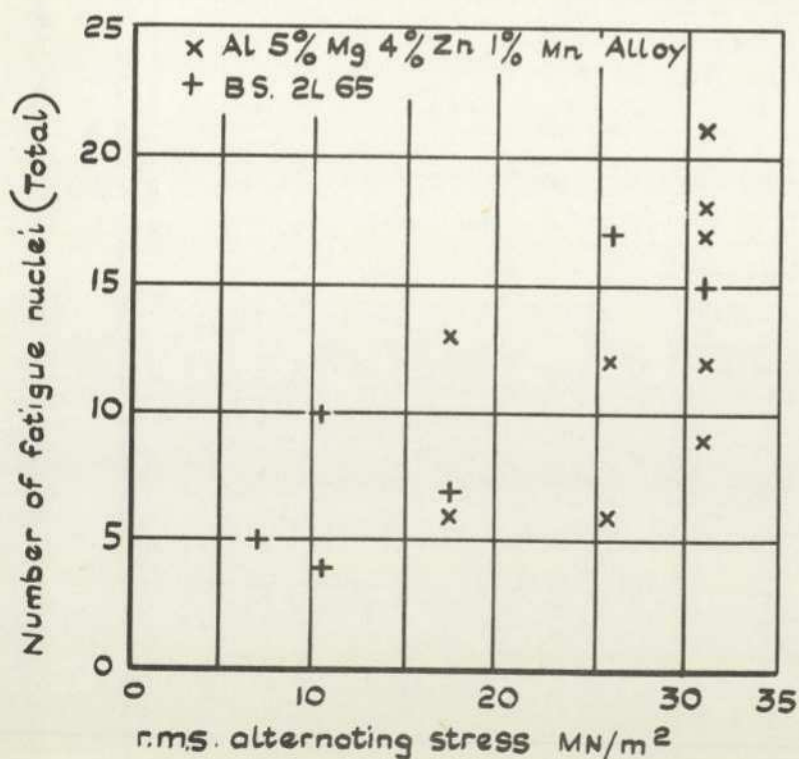


Fig.IIb Variation of numbers of fatigue nuclei with variable amplitude stress

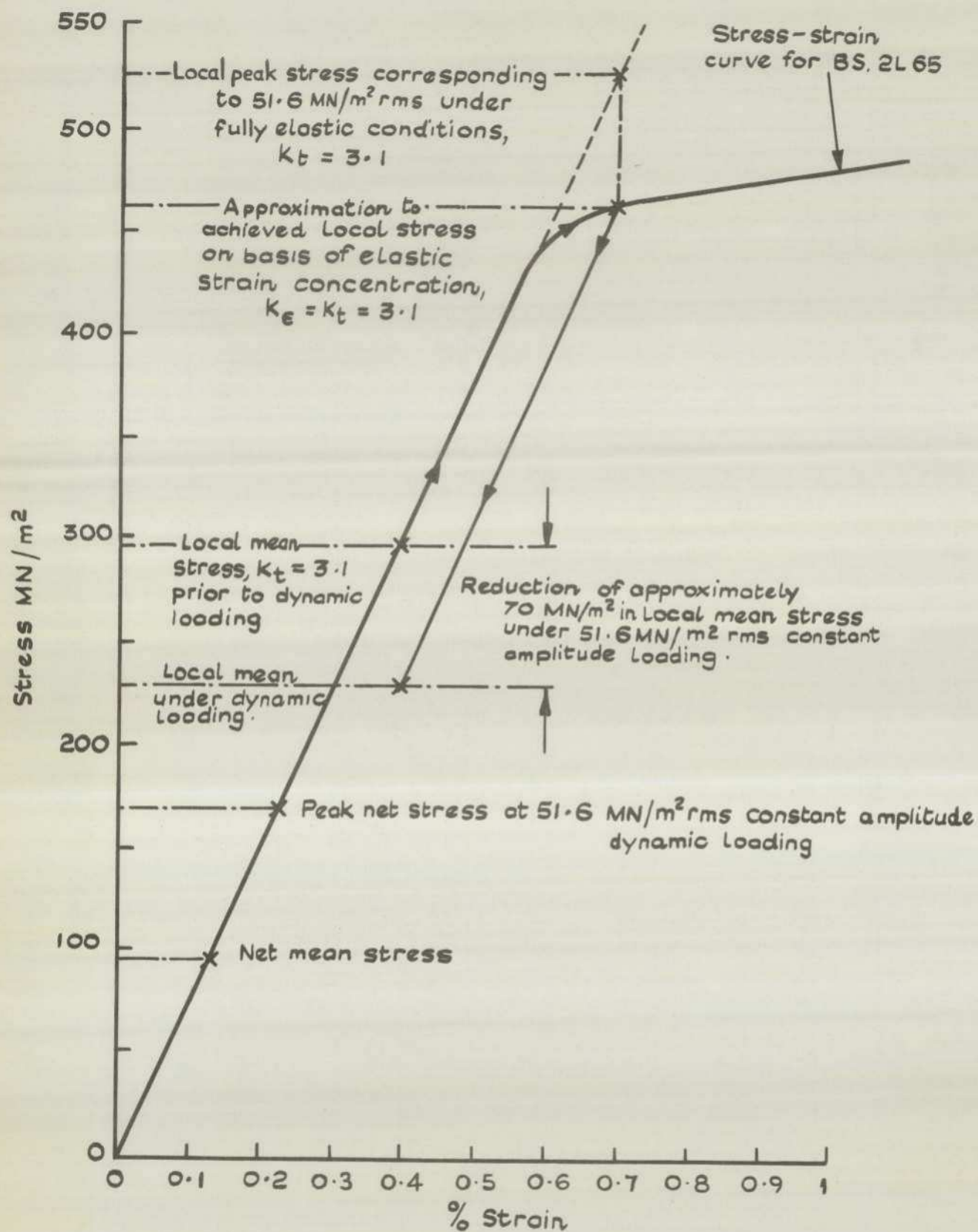


Fig. 12 Derivation of approximate reduction in local mean stress resulting from yield under dynamic loading

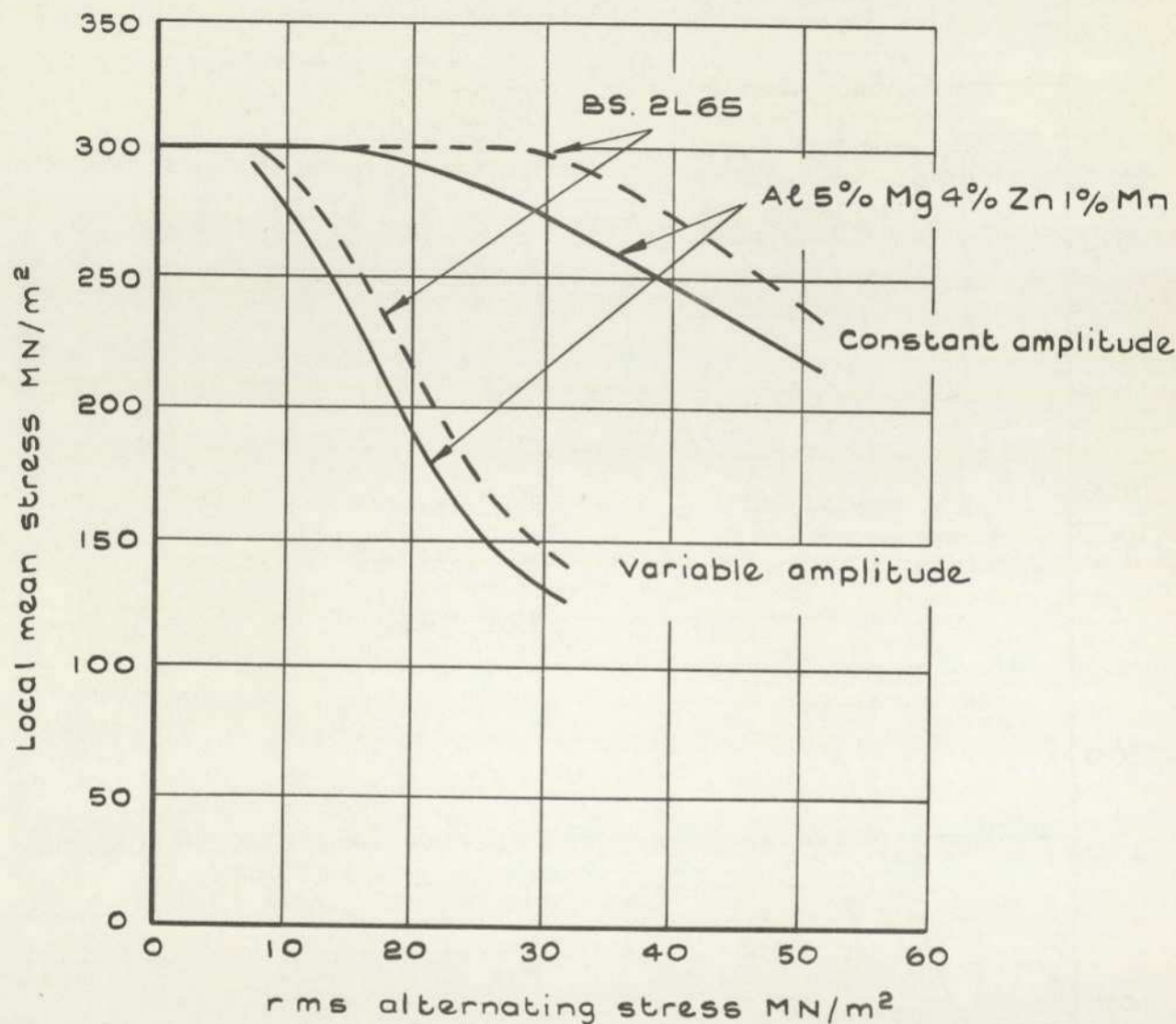
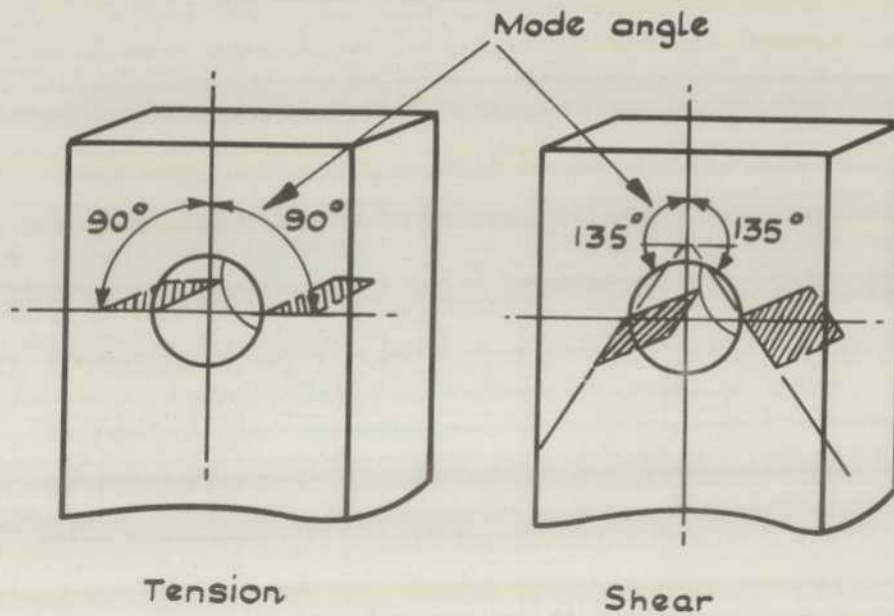
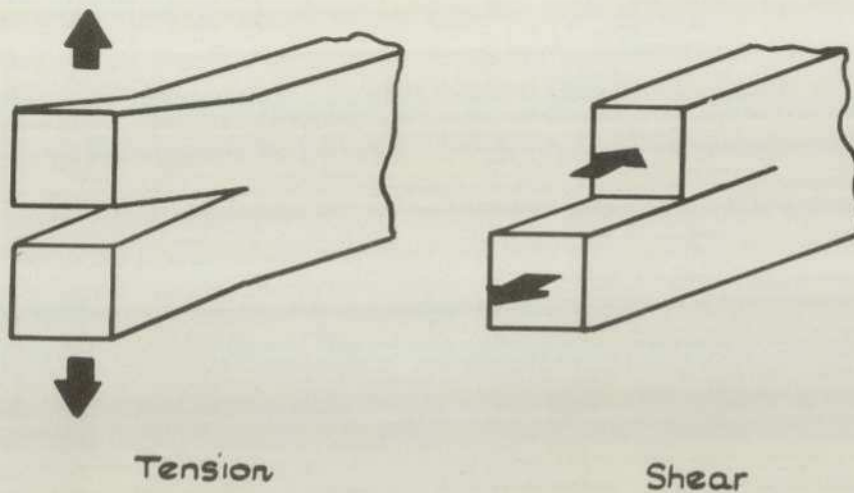


Fig. 13 Approximate variation in local mean stress with alternating stress



Crack propagation modes



Mechanism of crack surface displacement

Fig. 14 Diagrammatic presentation of pinned-lug crack propagation modes

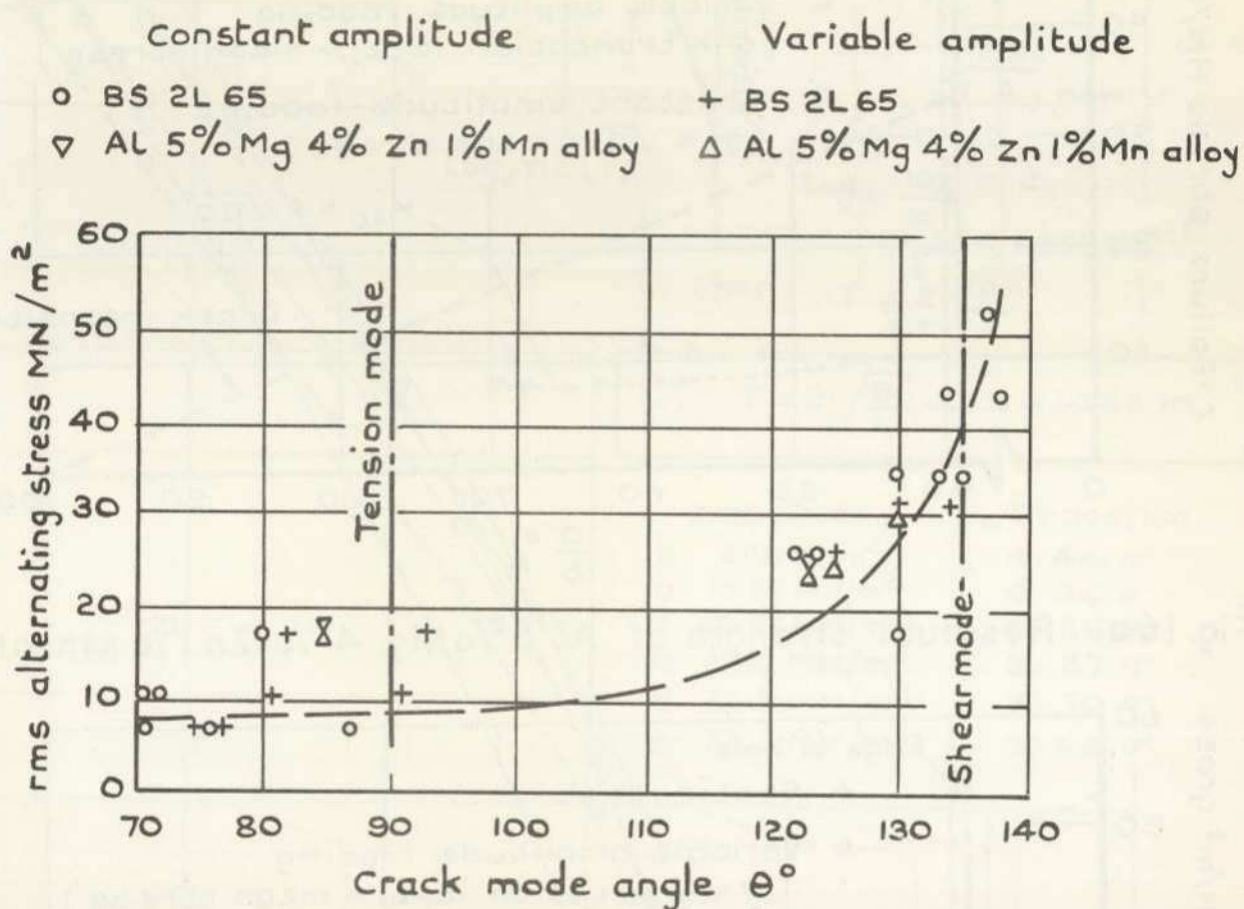


Fig. 15 Variation of crack mode angle with rms stress in pinned-lug specimen

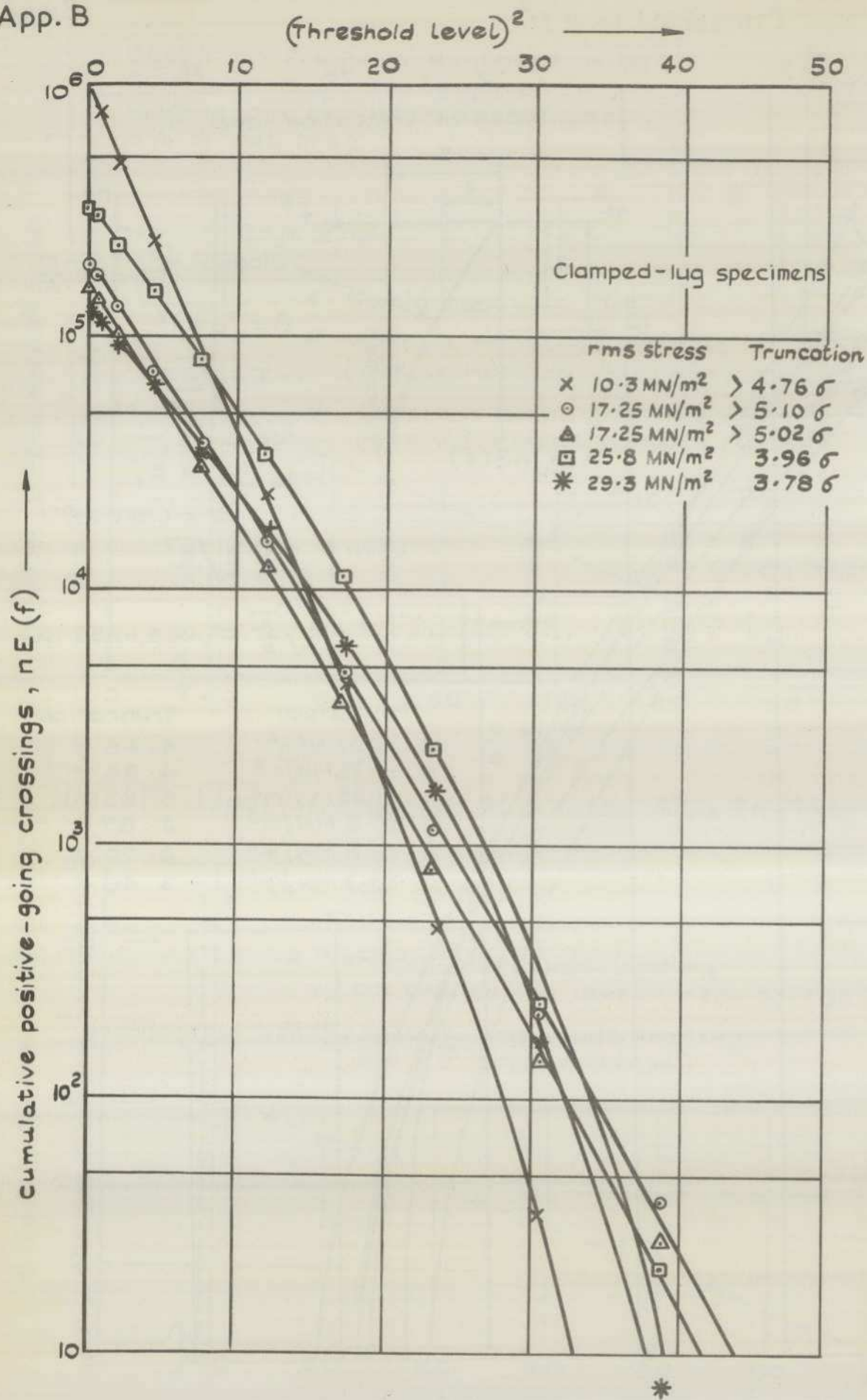


Fig.18 Cumulative level crossings measured under variable amplitude loading
— 600 kN Schenck machine

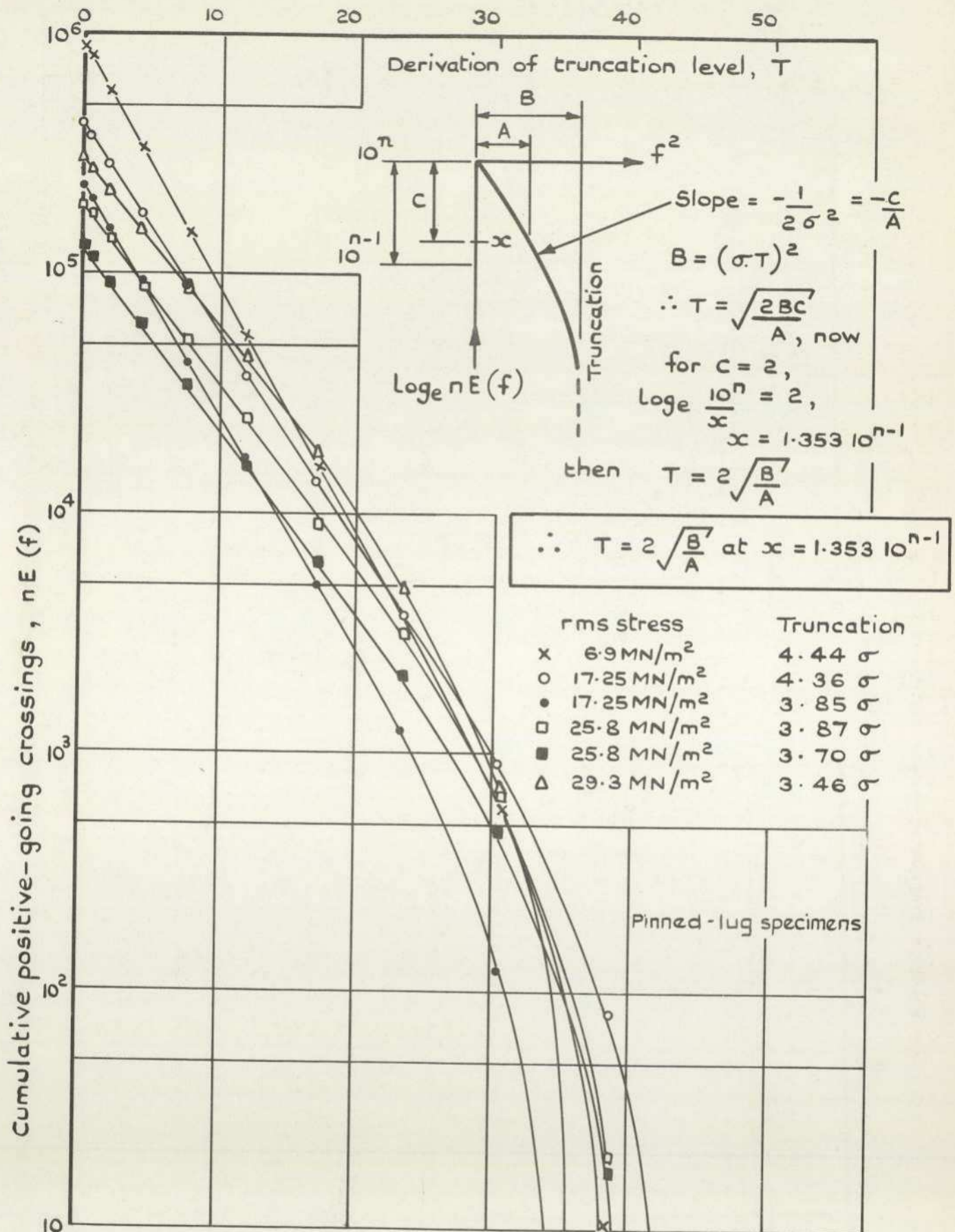


Fig.17 Cumulative level crossings measured under variable amplitude loading—short base Schenck machine

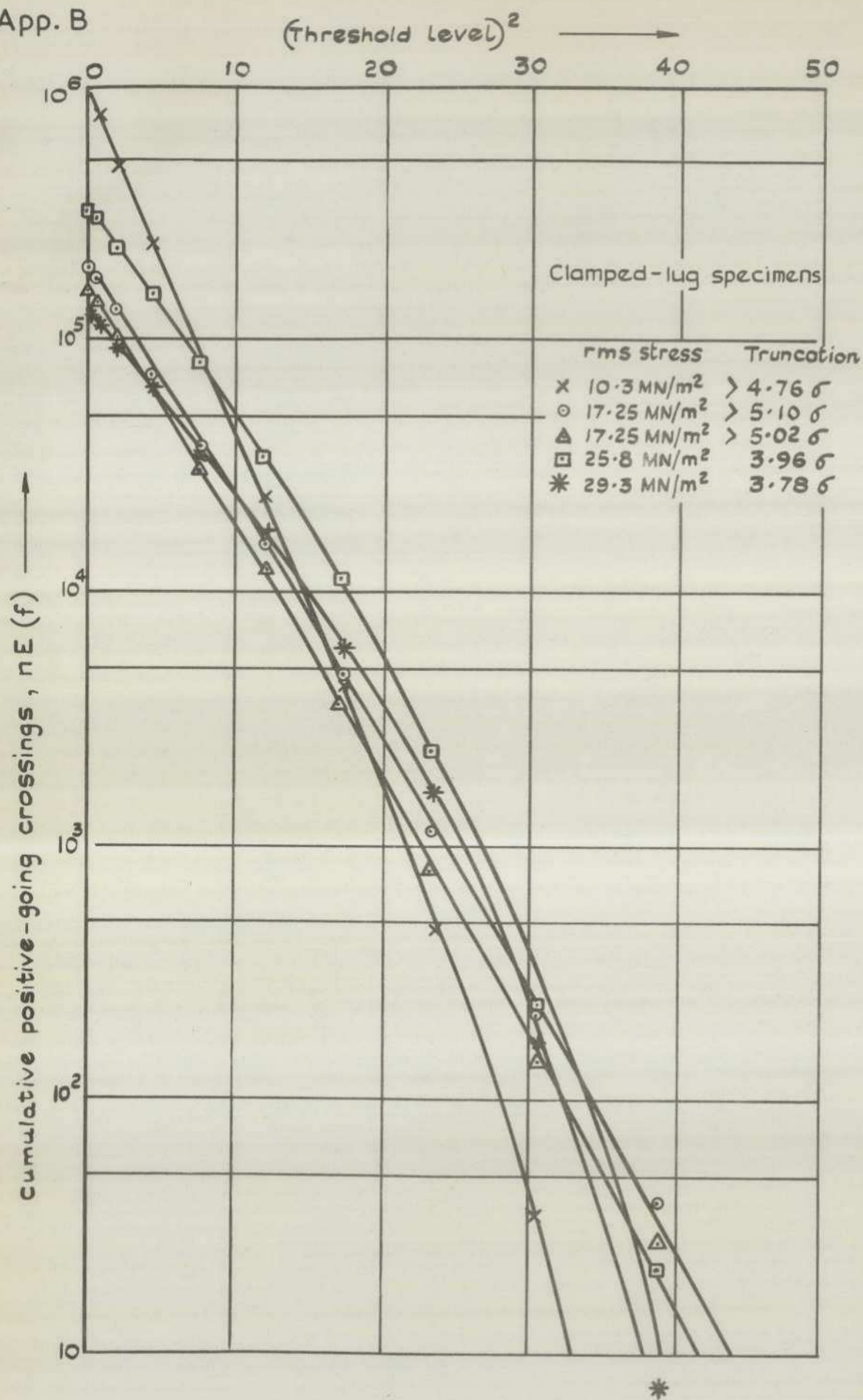


Fig.18 Cumulative level crossings measured under variable amplitude loading
— 600 kN Schenck machine

APPENDIX C

ADAPTATION OF AN AMSLER VIBROPHORE FOR NARROW BAND RANDOM LOADING

*Draft RAE Technical Report, previously RAE Technical Memorandum Structures 770,
February 1972*

R O Y A L A I R C R A F T E S T A B L I S H M E N T

Draft Technical Report

February 1972

ADAPTATION OF AN AMSLER VIBROPHORE FOR NARROW BAND RANDOM LOADING

by

A. W. Cardrick

G. J. Crewe

SUMMARY

Details are presented of modifications to an Amsler Vibrophore fatigue testing machine to provide a narrow band random loading capability. The machine can be used to apply a Rayleigh distribution of amplitudes and also to synthesise service load spectra by adding together several distributions with different rms levels.

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3 PROVISION OF INDEPENDENT LOAD MONITOR	4
4 MODIFICATIONS FOR VARIABLE AMPLITUDE LOADING	4
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1 INTRODUCTION

In cumulative fatigue damage research it is often necessary to apply loading of variable amplitude. One way of achieving this is to modify standard resonant fatigue machines so that the amplitude of the sinusoidal load waveform is randomly modulated.

In the case of resonant machines with inertial excitation this modification can be quite involved and require both mechanical and electronic workshop facilities^{1,2}. However, for machines with electrodynamic excitation, such as the Amsler Vibrophore, it is necessary to adapt only the electronic control system, which can be done conveniently and inexpensively using commercial equipment³.

This Report describes such modifications to the control system of a 100kN Vibrophore in Structures Department, RAE, so that the machine may be used to apply Gaussian narrow band random loading. Also described is an independent load monitoring circuit and a programming unit for the synthesis of operational load spectra by adding together several stationary Gaussian processes with different rms levels.

2 DESCRIPTION OF STANDARD MACHINE

The Amsler Vibrophore machine is illustrated in Fig.1, and the control system in Figs.2, 3 and 4. Referring to Fig.3, the dynamometer (7), the spring (2) and the specimen (5) form the elastic part of the resonant system, the natural frequency of which can be varied over a limited band of frequencies within the range 60 to 300 Hz, by changing the main mass (4). A steady mean load can be applied to the specimen by the spring (2) *via* the screw (1). The machine is mounted on a concrete block (9) supported by four springs (10).

Machine excitation is by means of an electromagnet (3) which is energised by an alternating current at a frequency equal to the first harmonic of the resonant system. The driving current is supplied by a valve amplifier (15) which responds to a voltage input from an impulse transducer (6) connected to the dynamometer.

The load is controlled by optical means. A beam of light from a projector (11) is reflected by a mirror (8) mounted on the dynamometer on to a scale (12). With a steady load, the beam of light appears as a sharp line on the scale. Dynamic loading produces a band of light, the extremities of which represent

the maximum and minimum values of load. Initial setting of the loading is by manual control of the amplifier. During normal running at constant amplitude the loading is controlled automatically by the light beam which falls on a diaphragm (13) and photocell assembly (14). Should the amplitude exceed the set value, the light beam will pass over the control edge of the diaphragm, striking the photocell and causing a correction signal to be sent to the amplifier.

Relays are provided to shut down the machine automatically should variations in load amplitude exceed chosen limits. These relays are sensitive to changes in input voltage to the machine amplifier. When the resonant frequency of the system is reduced by the development of a fatigue crack, there is a corresponding reduction in impulse transducer output voltage and this causes the Specimen Fracture Relay to operate. Conversely, should the voltage increase due to say a projection lamp failure, the Specimen Overload Relay would operate.

A cycle counter is provided; driven by a synchronous motor, it incorporates a stop-off device so that the machine may be shut down automatically after a predetermined number of cycles.

3 PROVISION OF INDEPENDENT LOAD MONITOR

In this section an independent load monitoring and measuring system is described; such a facility is desirable but not essential in the adaptation of the machine to variable amplitude loading. Eight 350 ohm semiconductor strain gauges, four P-type and four N-type, have been positioned on the dynamometer, as shown in Fig.5, forming two arms of a bridge network.

Under static load, the strain gauge output can be displayed directly on a trace recorder, while under dynamic conditions signals from the network are presented as the rms value of the alternating load waveform on a random noise voltmeter, the output of which is connected to the trace recorder to provide a permanent record of load. By calibration (see Fig.6) it is possible to obtain a direct reading of load either on the voltmeter or the trace recorder.

4 MODIFICATIONS FOR VARIABLE AMPLITUDE LOADING

4.1 General

A control system for the application of variable amplitude loading is shown in block diagram form in Fig.7. A Brüel and Kjaer Sine-Random Generator, Type 1024, is placed in the control loop between the impulse transducer and the

machine amplifier. To meet the input requirements of the Sine-Random Generator at very low loads, an additional amplifier may be necessary to raise the impulse transducer signal voltage to at least 0.5V rms.

When the Sine-Random Generator is used to drive the machine, the photocell control must be rendered inoperative by moving the photocell away from the light band. The Generator incorporates a compressor circuit which modifies the output to the machine amplifier such that the load, as measured by the impulse transducer, remains constant.

4.2 Gaussian narrow band random loading with a Rayleigh distribution of amplitudes

To set up a test, it is first necessary to determine the natural frequency of the system by switching the 'Bandwidth Selector'* of the Generator to 'Sine' and varying the frequency at a low 'Output Level' with the 'Compressor Speed' switched 'off', noting the frequency at which a maximum reading is obtained on the random noise voltmeter. The 'Output Level' is then reduced to zero, the frequency set to the resonant value noted above and the minimum Generator bandwidth, 10 Hz at 3 dB, selected to minimise the power required from the machine amplifier. A low 'Compressor Speed' (relatively slow response) is selected to prevent peak clipping and with a low machine amplifier gain the 'Compressor Voltage' and 'Output Level' are set to their maximum positions. The 'Compressor Voltage' is then carefully reduced and the machine amplifier gain increased until a reading corresponding to the required load is obtained on the random noise voltmeter with input and output voltages to the Generator within the range recommended by the manufacturer.

The Specimen Fracture Relay will not operate under Generator control, but with the drive frequency at resonance or slightly above, the Overload Relay can be used to sense specimen failure. The Overload Relay is operated by the increased amplifier input voltage supplied by the Generator to compensate for the reduction in load which accompanies the development of a fatigue crack. Although the Overload Relay is used it should perhaps be emphasised that the machine is in no way overloaded, since the circuit can be set to respond to extremely small increases in amplifier input voltage.

Since the cycle counter of the machine will not operate under variable amplitude loading, a digital counter may be incorporated in the control circuit;

* Words '.....' relate to the legends on the Sine-Random Generator.

this can be linked to a stop-off counter so that the machine can be shut down automatically after a predetermined number of cycles.

The load history is recorded on the trace recorder in which micro-switches are provided to shut down the machine should variations in rms alternating load exceed acceptable upper and lower limits.

A typical strain gauge output is shown in Fig.8, and typical amplitude distribution measurements are presented in Fig.9. These were obtained with a pinned-lug specimen loaded in fluctuating tension at high, medium and low alternating stresses. The divergence from the Rayleigh distribution at the higher stresses is associated with approximately symmetrical attenuation of the maximum amplitudes due to non-linearities of the system such as the changes in stiffness of the pinned connection which occur as the minimum load approaches zero. This behaviour is usually known as "truncation", the derivation of truncation levels from data of the form shown in Fig.9 is discussed in an Appendix to Ref.4.

4.3 Synthesis of operational load spectra

As discussed by Kirkby and Edwards¹, some forms of operational load spectra can be represented by a block programme of several Rayleigh distributions of different rms level and duration, the programme being repeated a large number of times during a test.

To produce a sequence of rms levels on the Vibrophore it has been found convenient to modify the control system as in Fig.10 in which a three-level programmer is associated with the Sine-Random Generator. The programmer can easily be extended to provide more levels if required. The required distribution is obtained by adjusting the individual rms levels by means of potentiometers. Each level has two associated potentiometers, one on the input and one on the output side of the Generator. In a block programme rapid changes in the rms level may be demanded and consequently the finite response time of the Generator compressor circuit could be inadequate if only one potentiometer were used. Adjustment of the output potentiometer modifies the signal received by the machine amplifier, thus altering the rms level of the load on the specimen. The input potentiometer is then adjusted to compensate for the resultant change in signal from the impulse transducer. The duration of each rms level can be selected by using a pegboard linked to a uniselector pulsing circuit.

Typical measurements of two stress spectra, each synthesised from three rms levels, are shown in Fig.11; for comparative purposes the measured spectra have been normalised to a single overall rms level and it can be seen that there is good agreement with the demanded spectrum.

5 CONCLUDING REMARKS

Standard commercial equipment has been used to adapt an Amsler Vibrophore fatigue testing machine to apply narrow band random loading, in the manner proposed by White and Lewszuk.

A Brüel and Kjaer Sine-Random Generator is used to drive the machine amplifier and the control loop is completed by connecting the output of the dynamometer impulse transducer to the automatic output regulator of the Generator. The amplitude spectrum has been shown to approximate to a Rayleigh distribution. Some truncation of the higher amplitudes occurs and this is believed to be associated with mechanical non-linearities such as those which occur when the minimum load on a pinned-lug specimen approaches zero.

A programming unit is described which enables certain types of service load spectra to be synthesised by the application of a repeated sequence of rms levels.

Details are also presented of an independent load monitoring network based on a semi-conductor strain gauge bridge.

REFERENCES

<u>No.</u>	<u>Author</u>	<u>Title, etc.</u>
1	W.T. Kirkby P.R. Edwards	A method of fatigue life prediction using data obtained under random loading conditions. RAE Technical Report 66023 (1966)
2	P.R. Edwards	A controller for random and constant amplitude loading on resonant and electrohydraulic fatigue machines. RAE Technical Report 72226 (1973)
3	D.J. White J. Lewszuk	Narrow band random fatigue testing with Amsler Vibrophore machines. Journal of Mechanical Engineering Science, Vol.11, No.6 (1969)
4	A.W. Cardrick	Comparative fatigue performance of pinned-lug and clamped-lug specimens in BS 2L65 and an experimental Al5%Mg4%In1%Mn alloy under constant and variable amplitude loading. RAE Technical Report, to be published shortly.

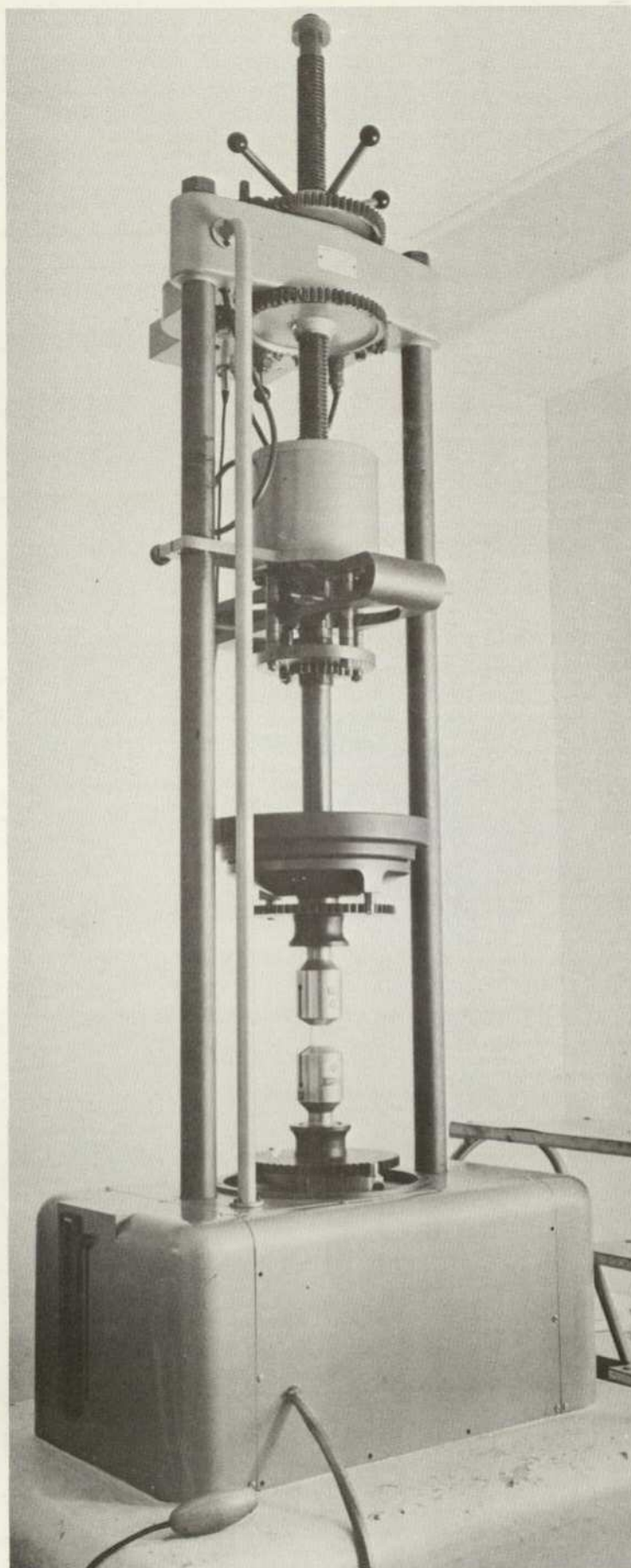


Fig.1 Amsler 100 kN Vibrophore fatigue testing machine

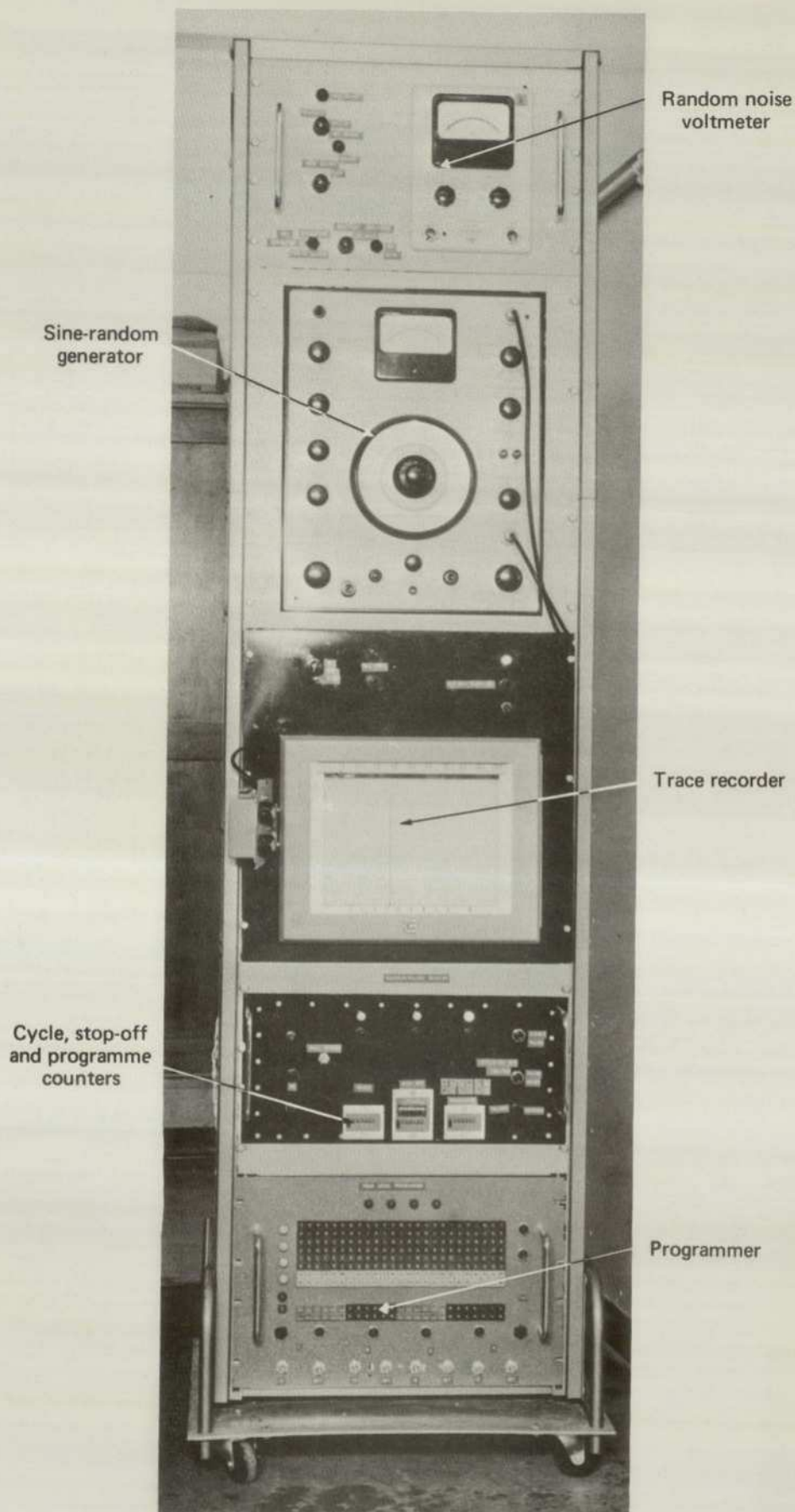


Fig.2 Load monitoring and control equipment

Key to diagram

- 1 Mean load adjustment screw
- 2 Spring
- 3 Electromagnet
- 4 Main mass
- 5 Specimen
- 6 Impulse transducer
- 7 Dynamometer
- 8 Mirror
- 9 Concrete block
- 10 Shock absorbing springs
- 11 Projector
- 12 Load scale
- 13 Diaphragm
- 14 Photocell
- 15 Machine amplifier

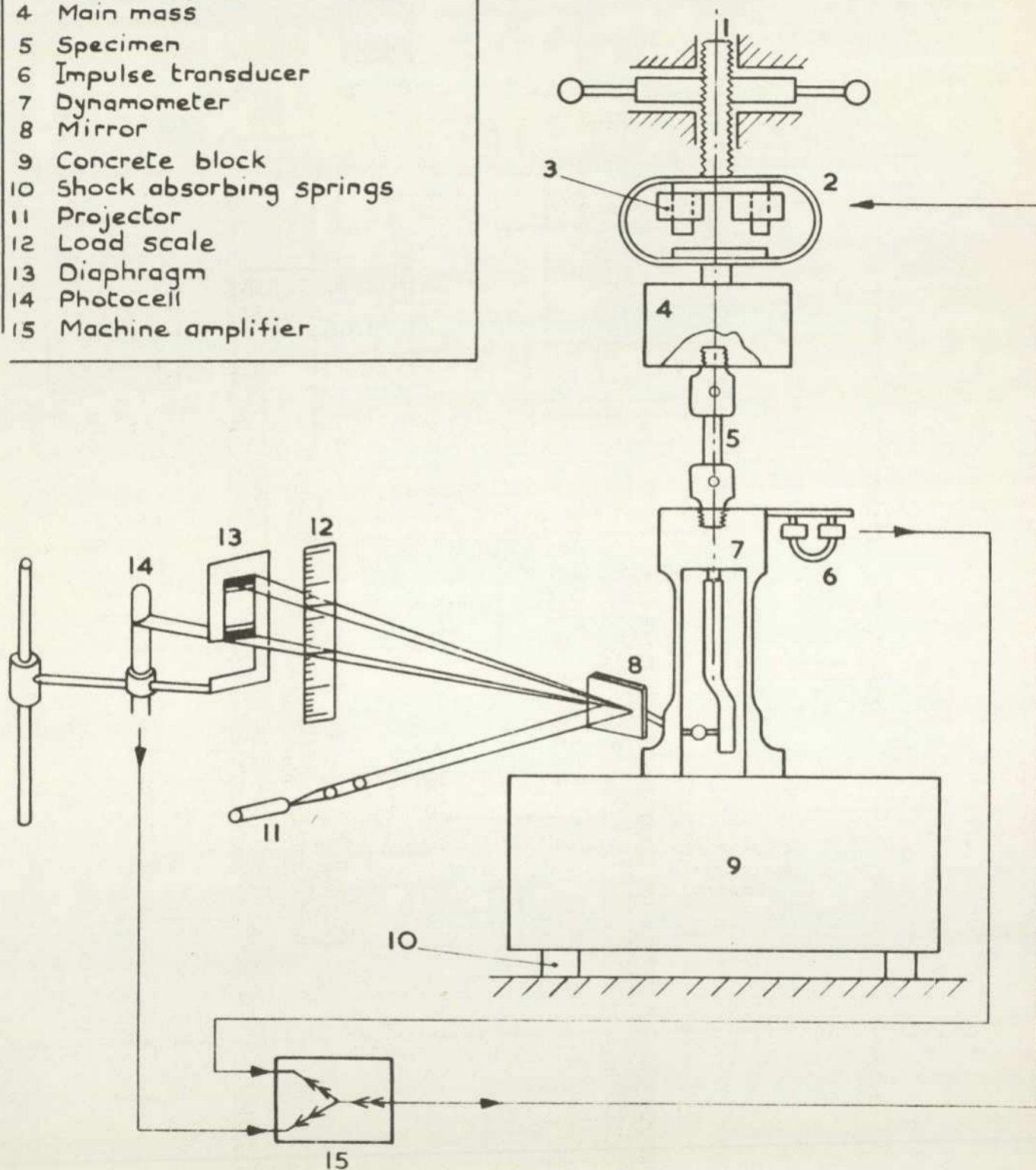


Fig. 3 Amsler Vibrophore control system

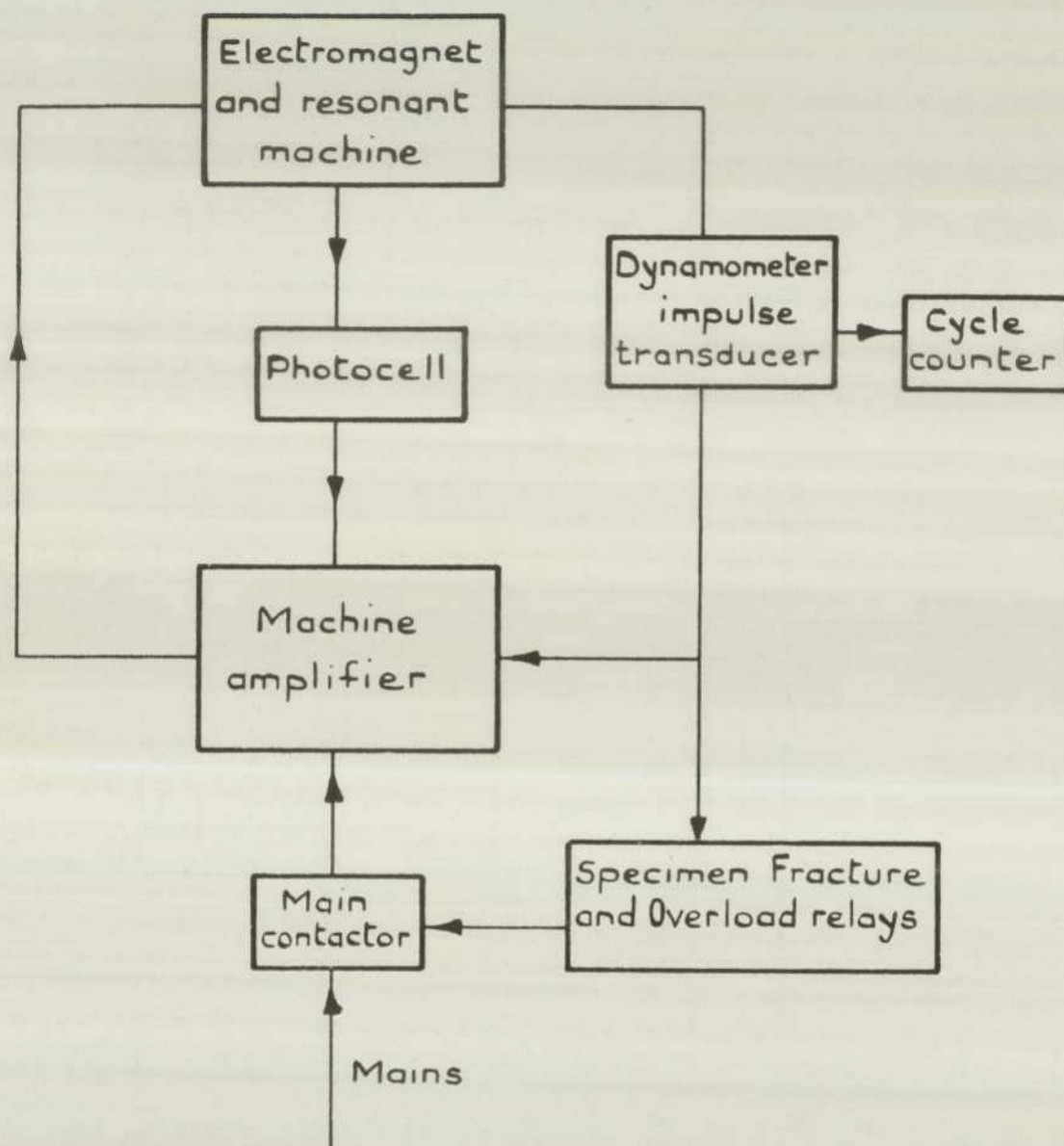
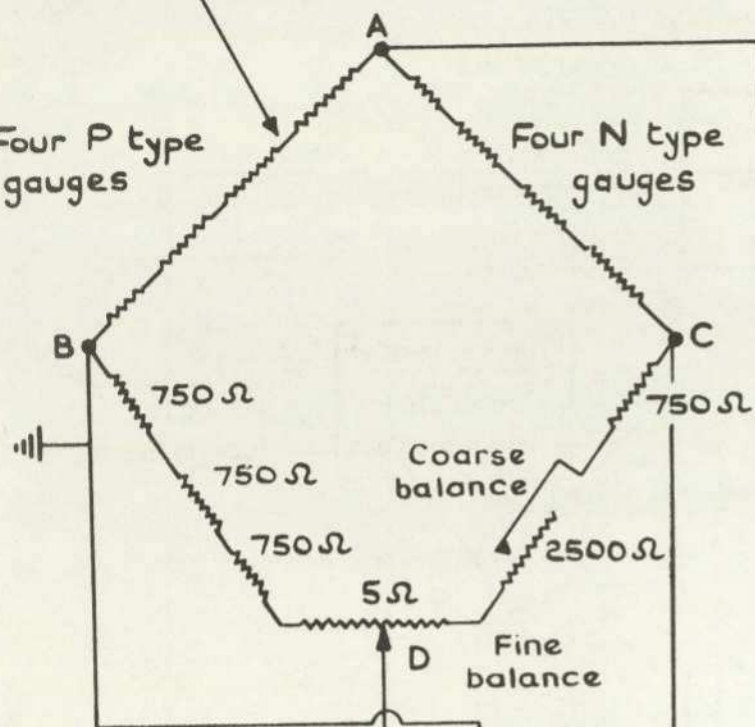


Fig.4 Block diagram showing machine operation under sinusoidal loading

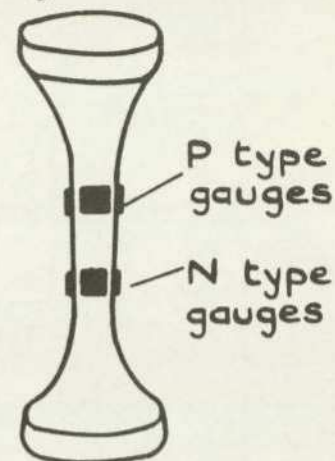
Semiconductor strain gauge bridge

Four P type gauges

Four N type gauges



Strain gauge arrangement on dynamometer



Position

1. Ref voltage adjust
2. Static load (conventional bridge AD)
3. Dynamic load ($\frac{1}{4}$ bridge AB: has been found to be less sensitive to noise than conventional bridge, dc component unimportant)

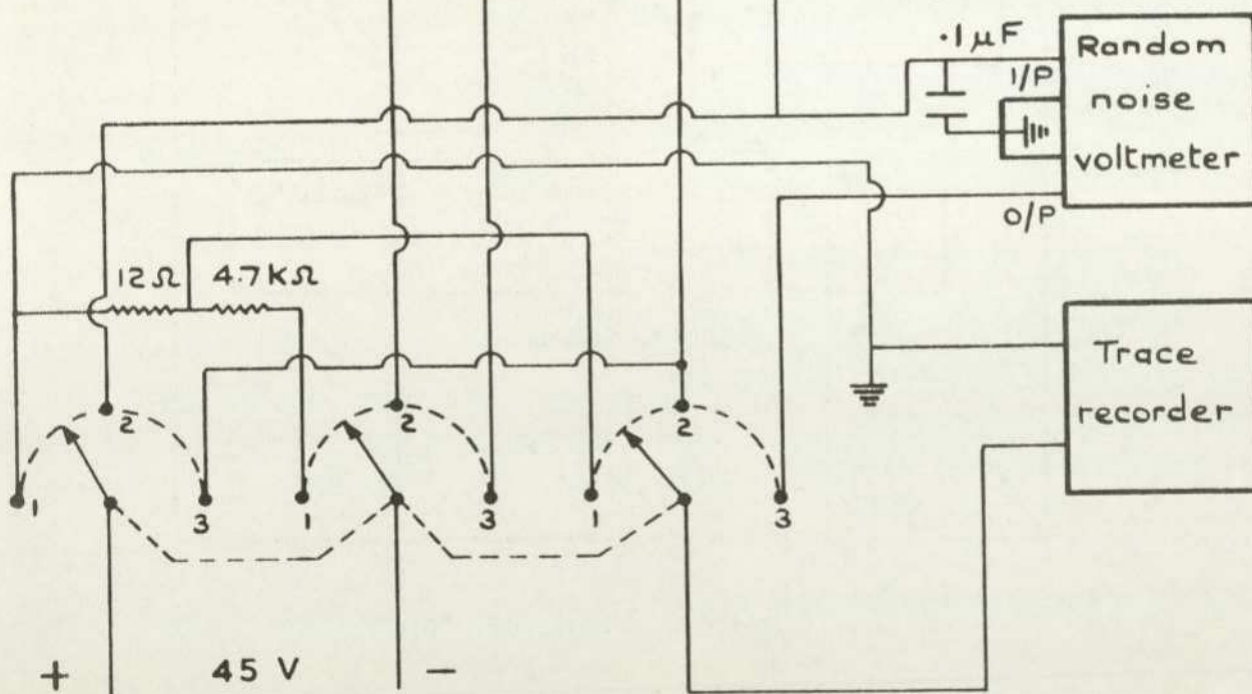


Fig 5 Load monitoring system

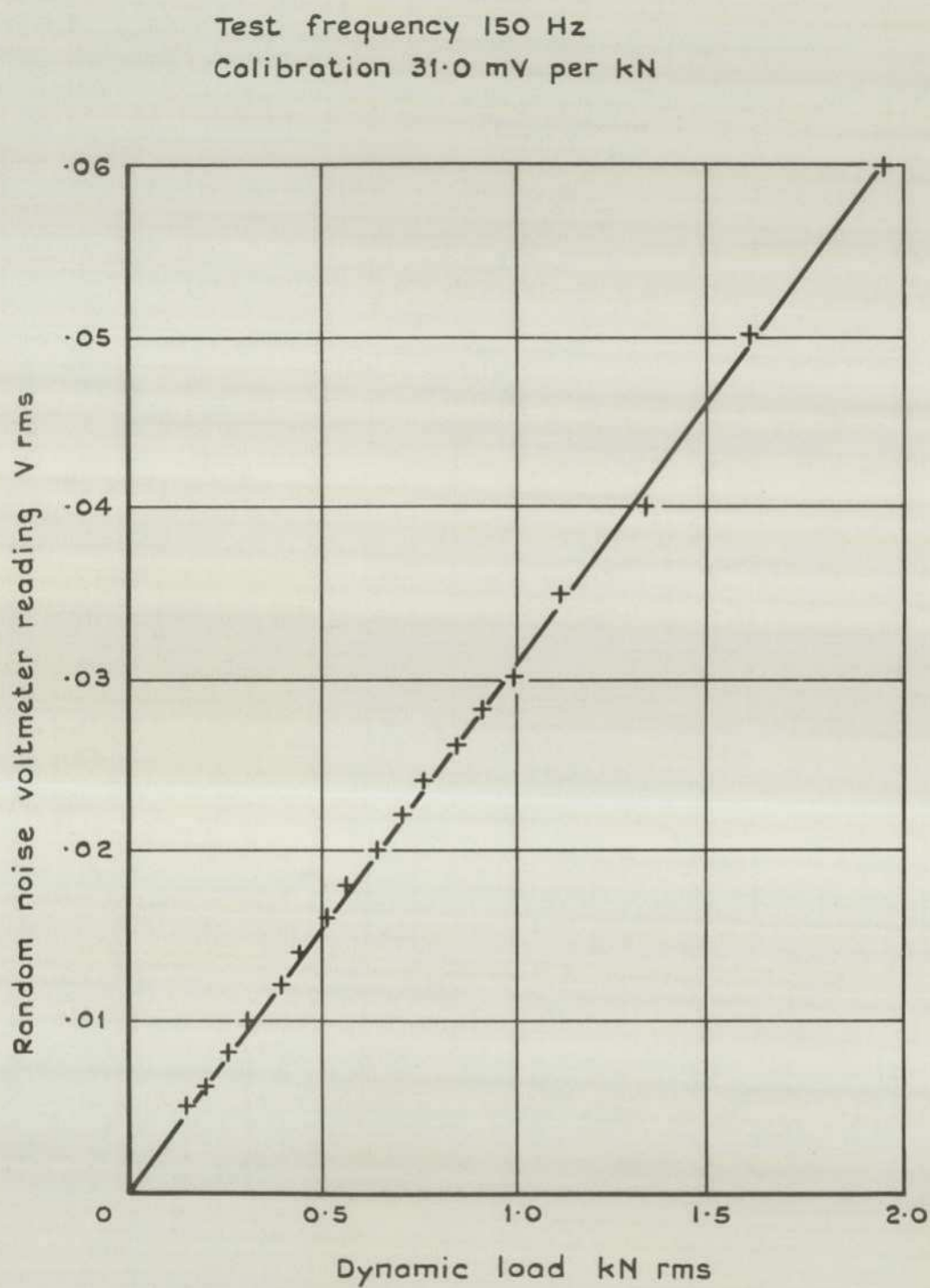


Fig.6 Dynamic calibration of Amsler Vibrophore

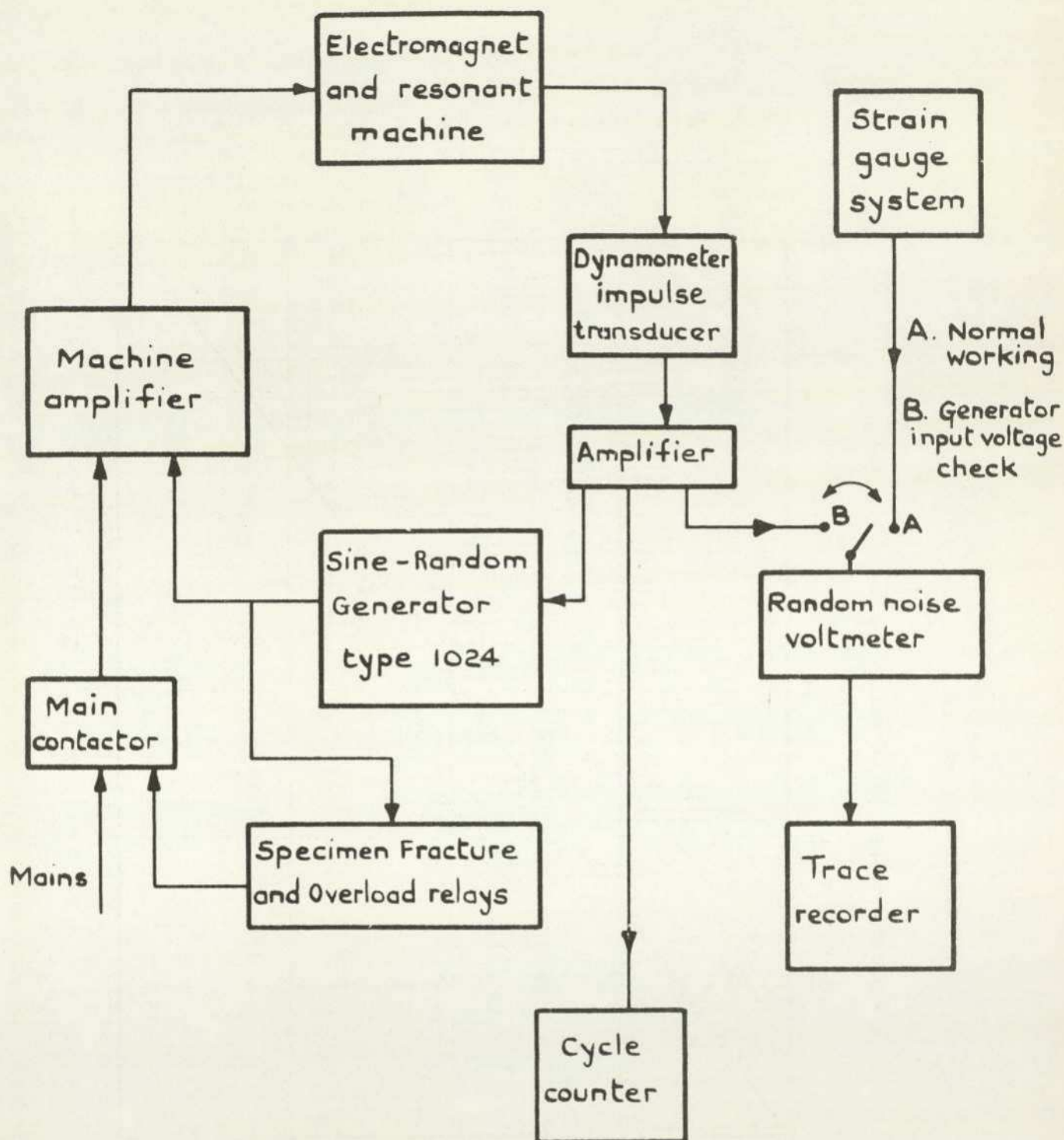


Fig. 7 Block diagram showing machine operation under variable amplitude loading

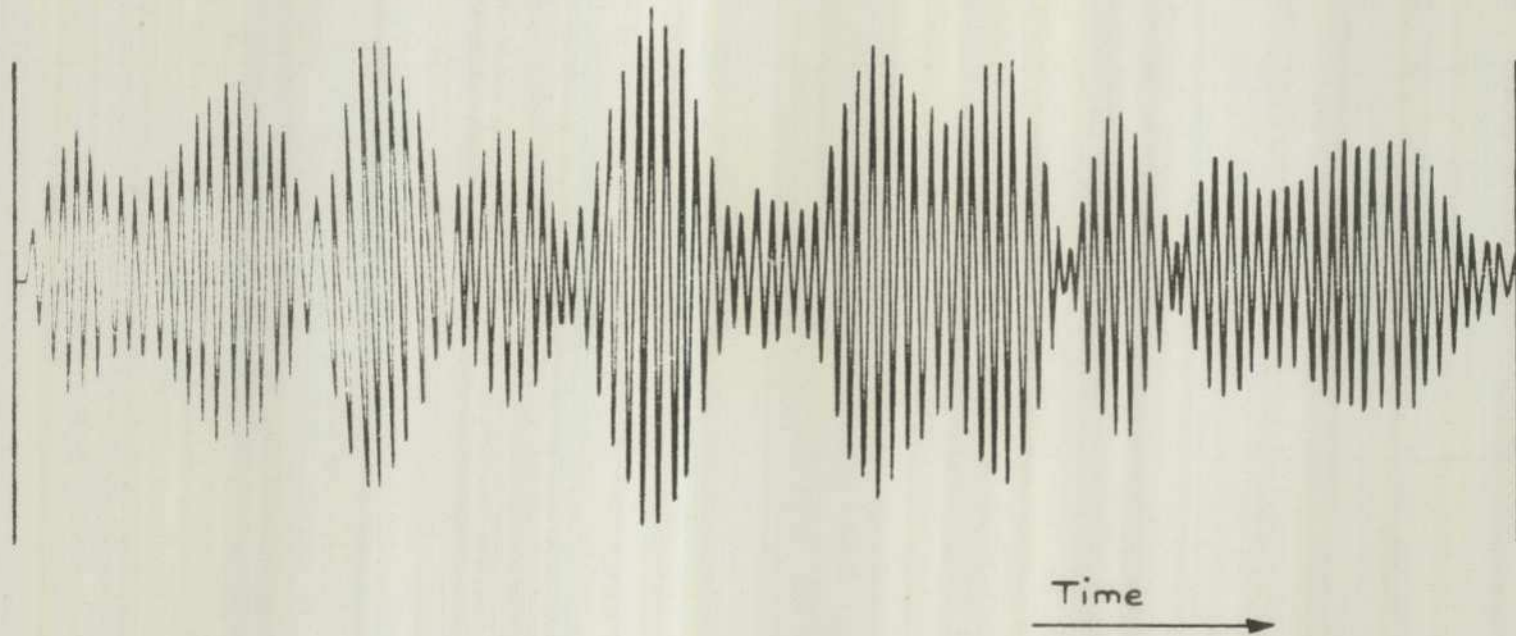


Fig. 8 Typical strain gauge output under variable amplitude loading

Number of positive-going crossings of stress threshold levels
Number of positive-going crossings of mean stress level

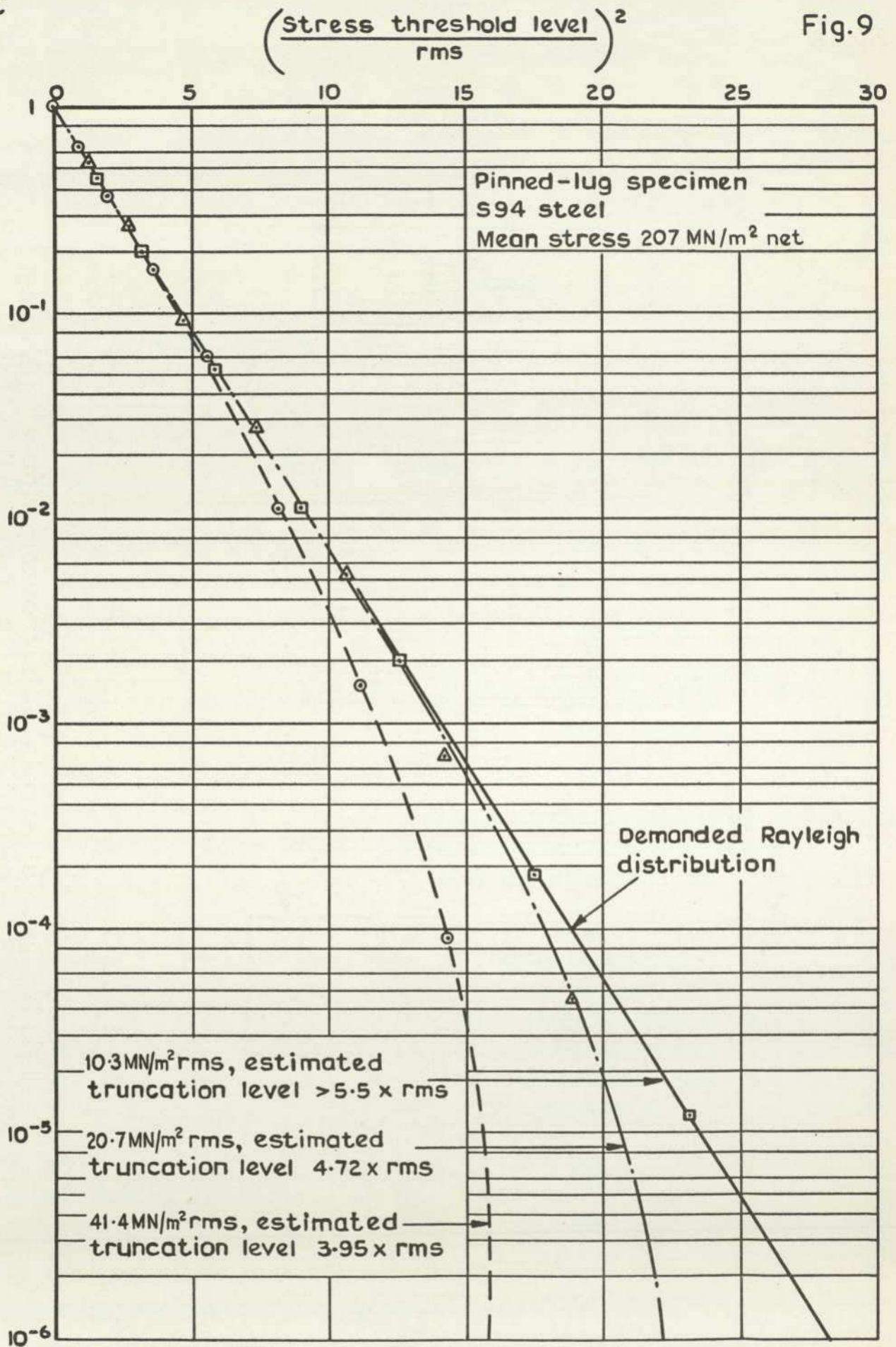


Fig.9 Typical measured stress spectra under single level variable amplitude loading

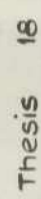


Fig.10 Block diagram showing machine operation under programmed variable amplitude loading

Number of positive-going crossings of stress threshold levels
 Number of positive-going crossings of mean stress level

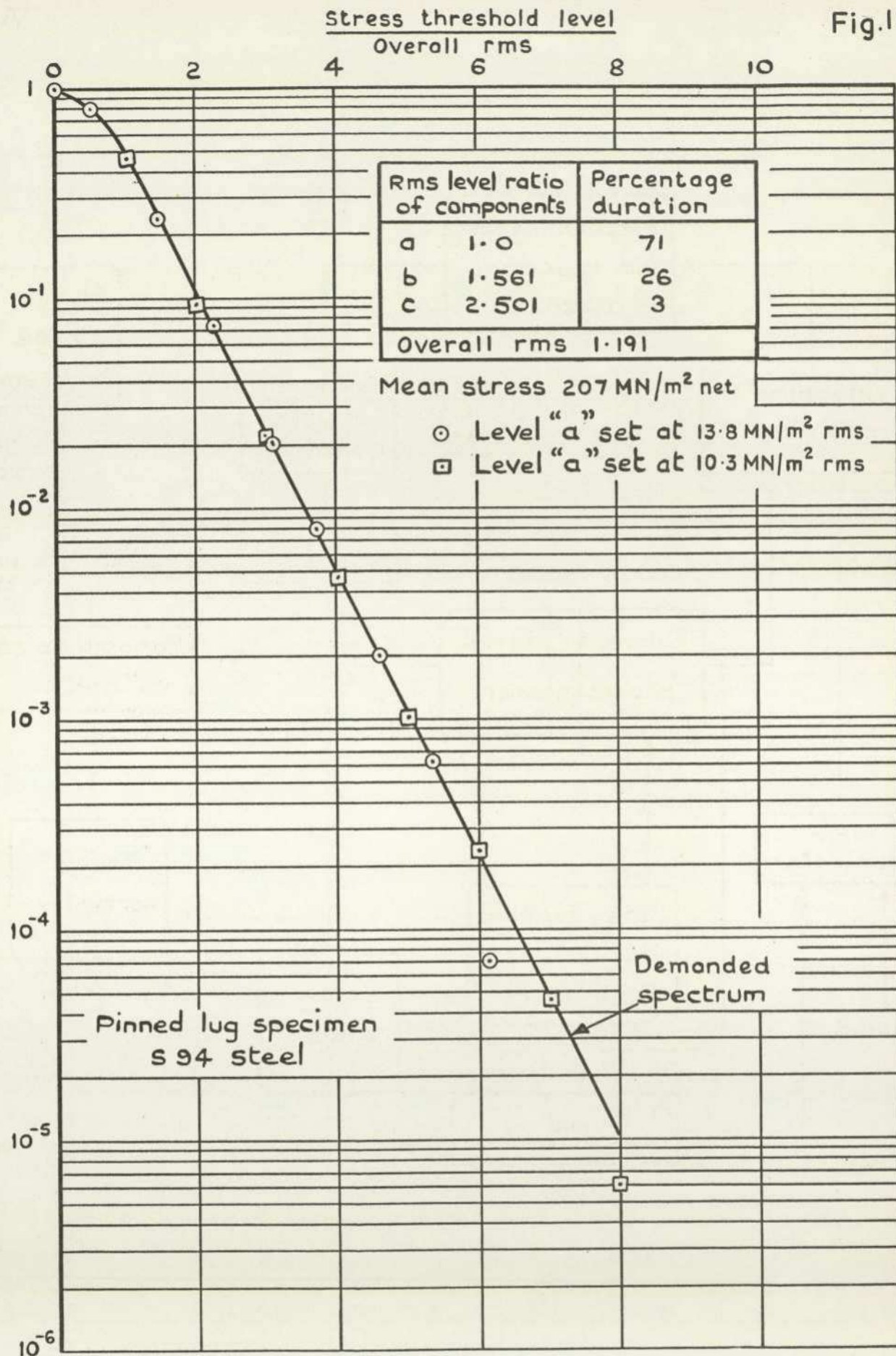


Fig.11 Typical measured stress spectra under three level variable amplitude programmed loading

APPENDIX D

A REPLICA METHOD FOR RECORDING THE SURFACE GROWTH OF
FATIGUE MICROCRACKS

RAE Technical Report 72210, March 1973

UDC 620.187.5 : 539.219.2 : 539.388.1

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 72210

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A REPLICA METHOD FOR RECORDING THE SURFACE GROWTH OF
FATIGUE MICROCRACKS

by

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SUMMARY

A simple replica technique has been developed to demonstrate the feasibility of obtaining crack propagation data for structural components containing surface microcracks as small as 20 μm in length.

Departmental Reference: Structures YSE/B/0358

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3 MEASUREMENTS OF SURFACE MICROCRACK PROPAGATION IN A NOTCHED COMPONENT	4
4 CONCLUDING REMARKS	5
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1 INTRODUCTION

There are well established techniques for the measurement of crack growth in comparatively thin, wide panels in which cracks grow to a substantial length during test. Specimens of thick section however often sustain only short cracks before failure and present special difficulties in the observation of crack growth. This Report describes a simple replica technique which has been developed to obtain crack propagation data for structural components containing surface microcracks as small as 20 μm in length.

2 SELECTION OF A SUITABLE TECHNIQUE FOR MEASURING MICROCRACK PROPAGATION

Two alternative approaches were considered to the problem of obtaining information on the growth of microcracks; either to fit an automatic camera attachment to a microscope with stroboscopic illumination as used by Schijve and Jacobs¹, or to devise some means to enable advantage to be taken of one of the replica methods²⁻⁷ available for microscopic surface examination. Such methods, which involve the preparation of an impression of the specimen surface, vary widely in complexity according to the degree of stability and resolution required.

The photographic technique was considered less attractive, because of the difficulties envisaged both in attenuating vibration and in obtaining sufficient depth of focus at high magnifications to give adequate definition of both peaks and troughs in the machined specimen surface.

Of the replica methods available, that employing commercially pure cellulose acetate sheet with an acetone solvent², was considered most attractive in this application because of its simplicity and adaptability for use with either an optical or electron microscope^{3,4}. The simplicity was considered to outweigh the improved stability offered by the precise technique for strain measurement developed by Hickson⁵ which employs replicas in a fusible alloy of Wood's metal and indium, applied *via* a heated platten.

The acetate replica technique has been used previously in fatigue studies, notably by Hunter and Fricke^{6,7} who observed fatigue crack propagation in rotating cantilever specimens of aluminium alloy by interrupting their fatigue tests to apply a thin ribbon to the curved specimen surface. The principal aim of their work was to observe, at high magnifications, the surface initiation and development of fatigue cracks and some measurements were presented of microcrack propagation from lengths of about 10 μm . It is noteworthy that this degree of resolution was obtained despite the difficulties undoubtedly encountered due to specimen curvature.

3 MEASUREMENTS OF SURFACE MICROCRACK PROPAGATION IN A NOTCHED COMPONENT

For the present application the cellulose acetate replica technique was used to record the growth of fatigue microcracks from the corners of a sharply notched specimen with a surface finish and geometric stress concentration both of which are representative of structural components.

It was convenient to use BS 2L65 specimens of the type shown in Fig.1 loaded axially in the fatigue testing machine shown in Fig.2. A positive mean stress of 125 MN/m^2 was applied at the net section adjacent to the central hole and a fatigue stress amplitude of 55 MN/m^2 was applied at 10 Hz to give an endurance approaching a million cycles. The specimens generally developed a single crack from the corner of the notch, as shown in Fig.3.

Replica blanks measuring approximately $40 \text{ mm} \times 10 \text{ mm}$ were cut from 1.5 mm thick commercial cellulose acetate sheet. It was found that under typical laboratory temperatures and humidities excellent replicas could consistently be produced by wetting a face of the blank with approximately 0.5 ml of acetone, allowing this to gel for 10-15 seconds, applying the gelled blank to the specimen surface using light pressure; and then allowing approximately three minutes drying time before removing the completed replica. Replicas obtained in this way showed a consistent shrinkage of about 2 per cent, as evidenced by their slight curvature when removed from the specimen surface, see Fig.4.

In order to obtain replicas automatically at regular intervals during a fatigue test a simple apparatus was devised. The operating principle is shown pictorially in Fig.5. A flexible suction pad (a) was employed to extract a numbered blank from a magazine (b). The blank was then held on the pad and a small quantity of acetone was applied to gel the surface (c,d). The pad was then rotated (e) and the blank pressed lightly onto the specimen (f), any vibratory motion of the specimen and replica being accommodated by the flexibility of the pad. After about 3 minutes, the suction pad was retracted and the finished replica removed from the surface (g) and transferred to a collector box (h).

Typical replicas, obtained at intervals of approximately 2000 cycles, are shown in Figs.6, 7, 8 and 9. Fig.6 shows a well developed crack of approximately 4 mm in length; this crack is also shown in Fig.7 at a length of approximately 2 mm. Fig.8 shows a crack of approximately 100 μm in length observed in a second specimen and this crack is shown at a length of approximately 50 μm in

Fig.9. Cracks were measured retrospectively through the sequence of replicas obtained for each specimen using a micrometer stage and a binocular bench microscope with a magnification of about 150. This enabled cracks as small as 20 μm in length to be identified and to be measured to within 5 μm . Measurements of crack length derived from two specimens subjected to the same loading are presented in Figs.10 and 11. The measurements shown in Fig.10 were commenced at a crack length of 70 μm when the crack emerged from beneath a slight burr at the edge of the hole. The first of the replicas used for the measurements presented in Fig.11 was obtained at about 40 per cent of the fatigue life; the analysis shows that the crack length was then 20 μm .

4 CONCLUDING REMARKS

A simple replica technique has been used to demonstrate the feasibility of obtaining crack propagation data for structural components containing surface microcracks as small as 20 μm in length.

The method offers the advantage that retrospective examination of a sequence of replicas enables surface cracks to be identified at an earlier stage of the life than would be possible with conventional inspection techniques.

Applications are envisaged in studies of cumulative fatigue damage and fracture mechanics.

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DRAWING NUMBER

OIL 002480

THIRD ANGLE PROJECTION

USED ON

TEST MANDREL

AXIAL SQUARENESS
TOL. .001 DIA.
2" HIGH FROM DATUM

L 65

SPECIMEN
NUMBER

FINISH HOLE EDGES SQUARE.
IT IS ESSENTIAL THAT THE
HOLE FINISHES SHALL BE
FREE FROM THE SLIGHTEST
SCRATCH OR M/C MARK.
SHARP EDGES OF HOLE TO BE
LIGHTLY REMOVED
WITH FINE ABRASIVE
PAPER.

.2955 DIA. REAM (USE 7.5 MM. REAMER)
.2950
SYM. TOL. .002 WIDE DATUM ϕ 'A'
.005 WIDE DATUM CRS. 'B'

PARALLEL PORTION & REAMED HOLE
TO BE FINISHED ϕ .015 MICRO/INS.

DATUM
 ϕ 'A'

.827
.828
SYM. TOL.
.002 WIDE
ABOUT DATUM
 ϕ 'A'

 ϕ 'A'

SPECIMENS TO BE PROTECTED FROM
SURFACE DAMAGE & CORROSION BY
SEALING THEM INDIVIDUALLY IN
POLYTHENE BAGS CONTAINING A
SUITABLE DESICCANT. EACH BATCH
BEING THEN STORED IN SPECIAL
GROOVED WOODEN BOXES TO KEEP
THEM APART.

RADIUS TO BE FINISHED
32 MICRO/INS. & MUST
NOT UNDER-CUT
CENTRAL PARALLEL
PORTION.

1.180
1.185
SYM. TOL.
0.015 WIDE
DATUM CRS. 'B'

2.24 RAD.
2.25
CRS. 'B'

N.T.B.D.

CHECKED
D.A.I.TRACED
19-11-68DRAWN
J. B. ROGAN

MATERIAL

ALUMINIUM ALLOY
ONLY MAT^{ls}
SPECIALLY SUPPLIED
TO BE USED.

PROTECTIVE FINISH

CLEAN

TOLERANCES

$\pm$.01 EXCEPT WHERE
OTHERWISE STATED.

DIMENSIONS IN INCHES

SURFACE ROUGHNESS
SEE ABOVE

SCALE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE

LARGE NOTCH SPECIMEN (K_t 2.3)

MOD. No. ISSUE DATE MOD. No. ISSUE DATE

CERTIFIED

CONTRACTOR'S DRAWING REF.

819

DRAWING NUMBER

OIL 002480

Fig. 1

Fig.2

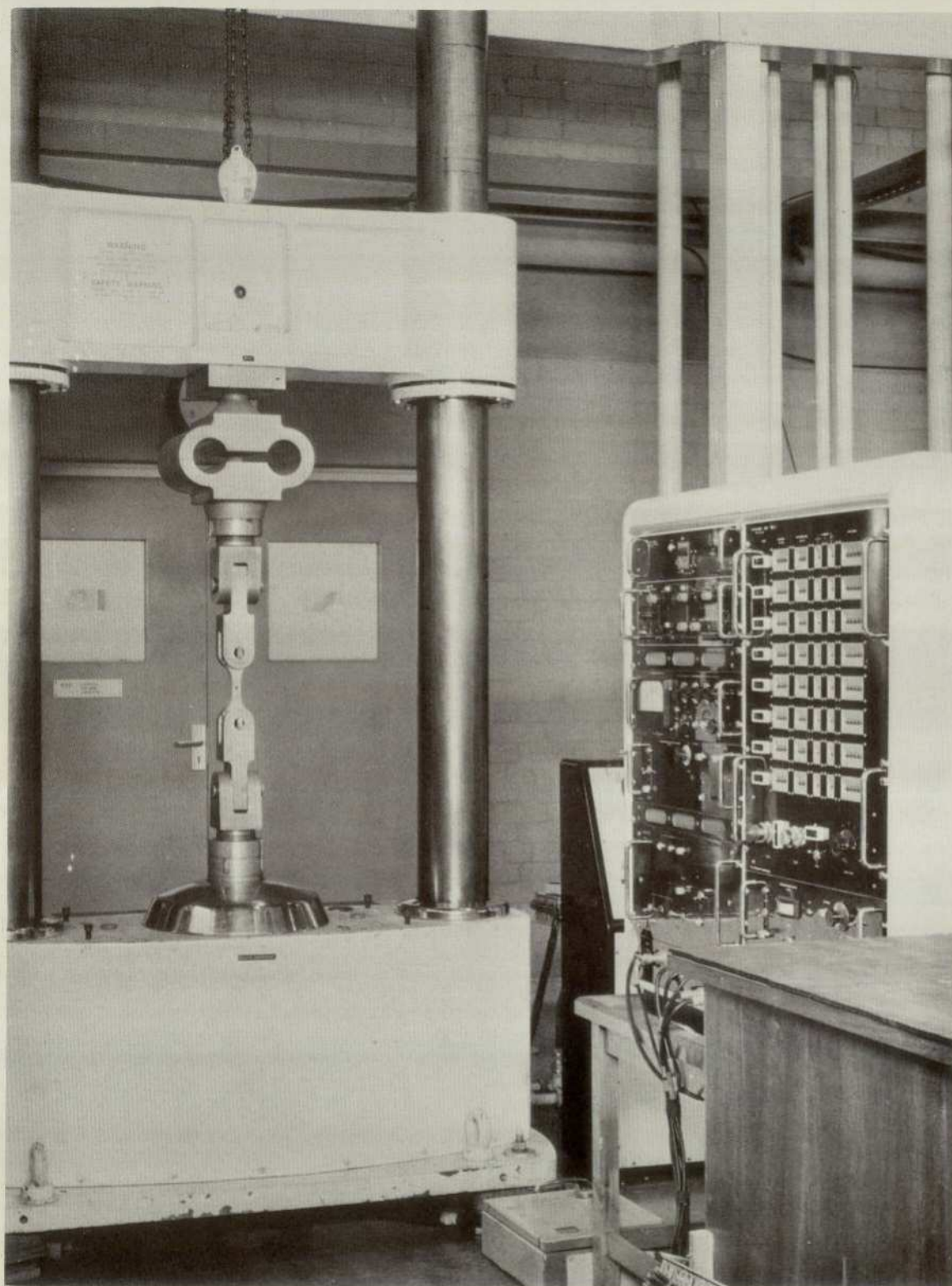


Fig.2 Specimen mounted in fatigue testing machine

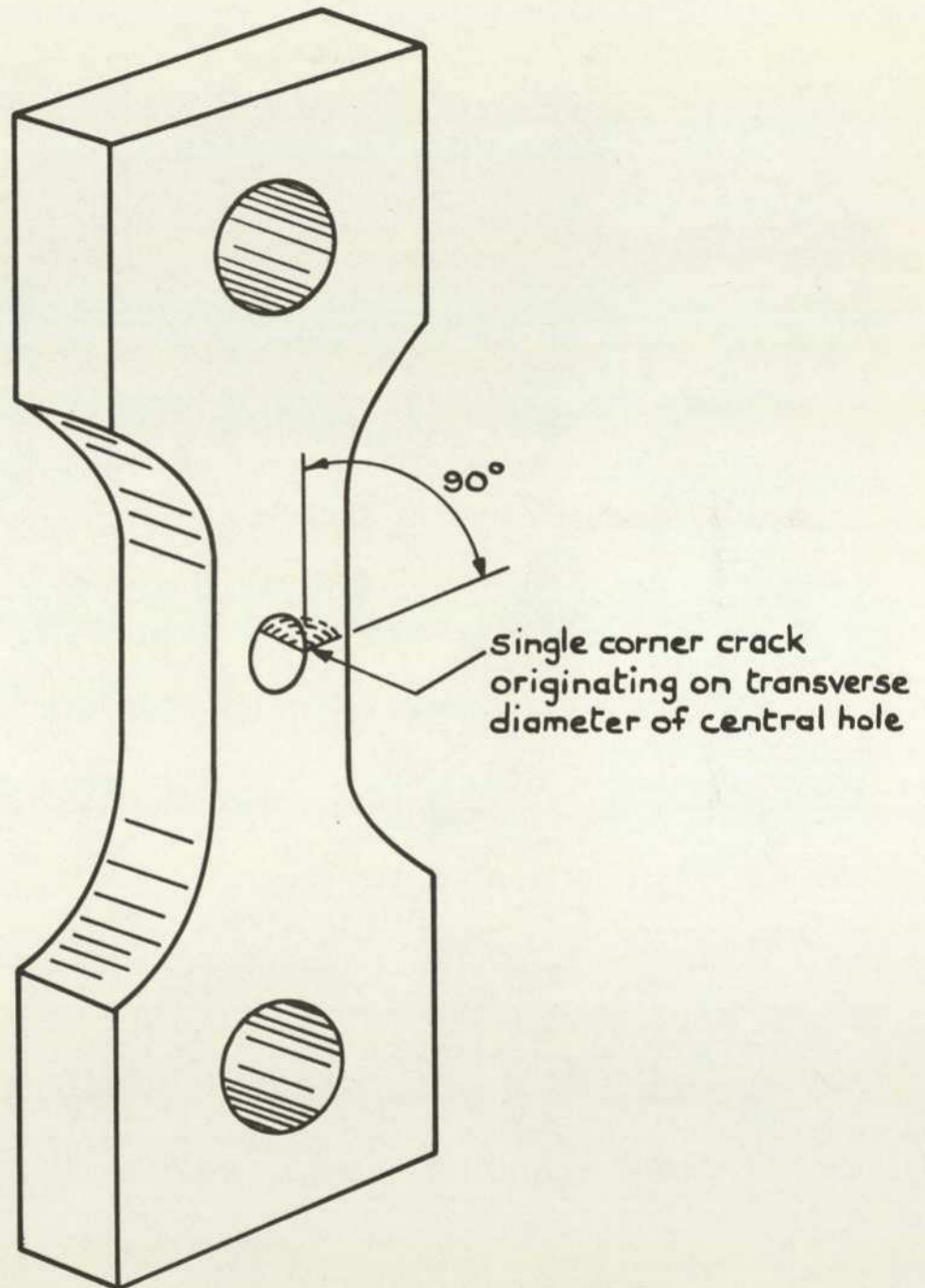


Fig. 3 Source of fatigue failure in notched specimen used for this investigation

Fig.4

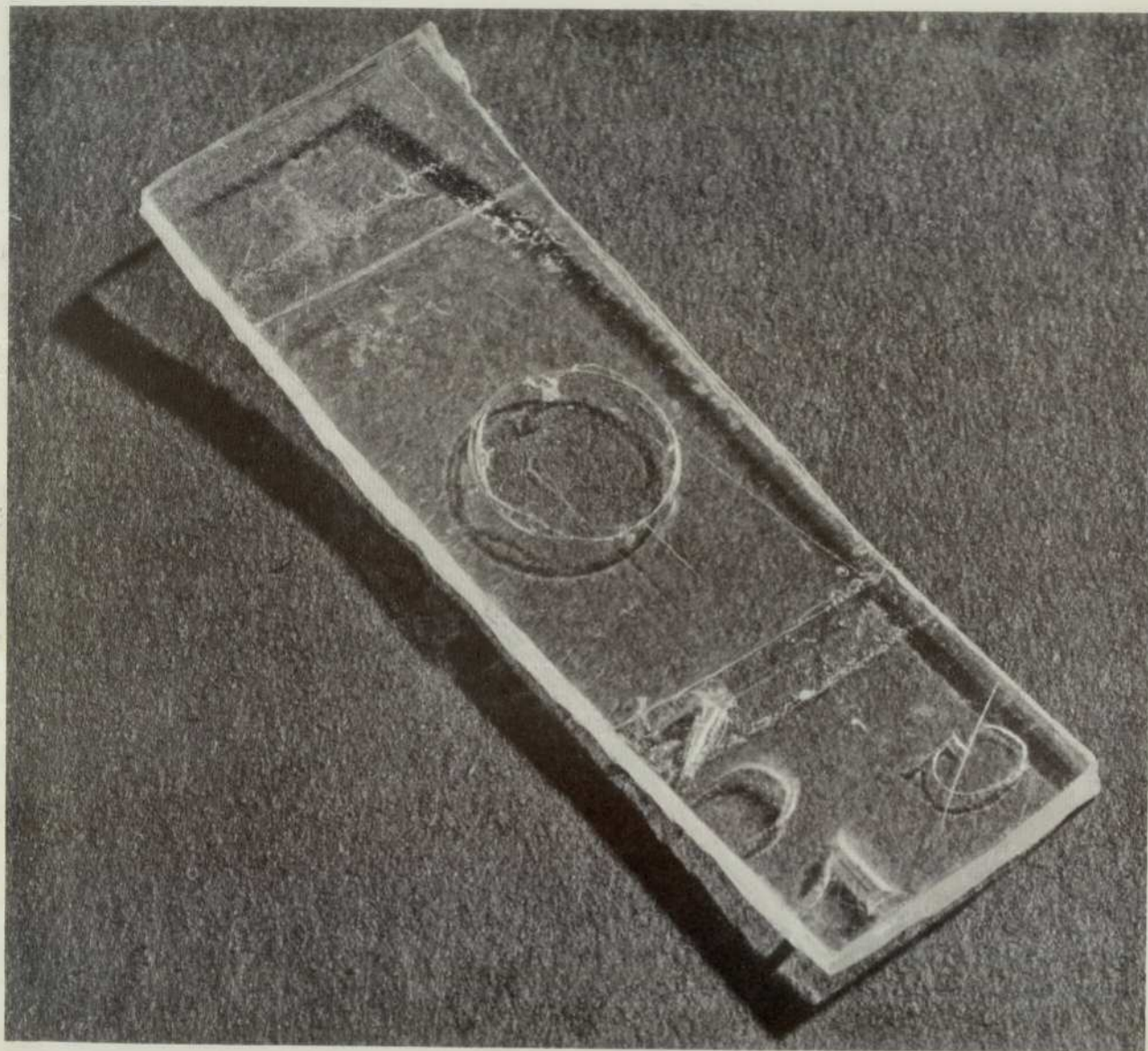


Fig.4 Typical replica

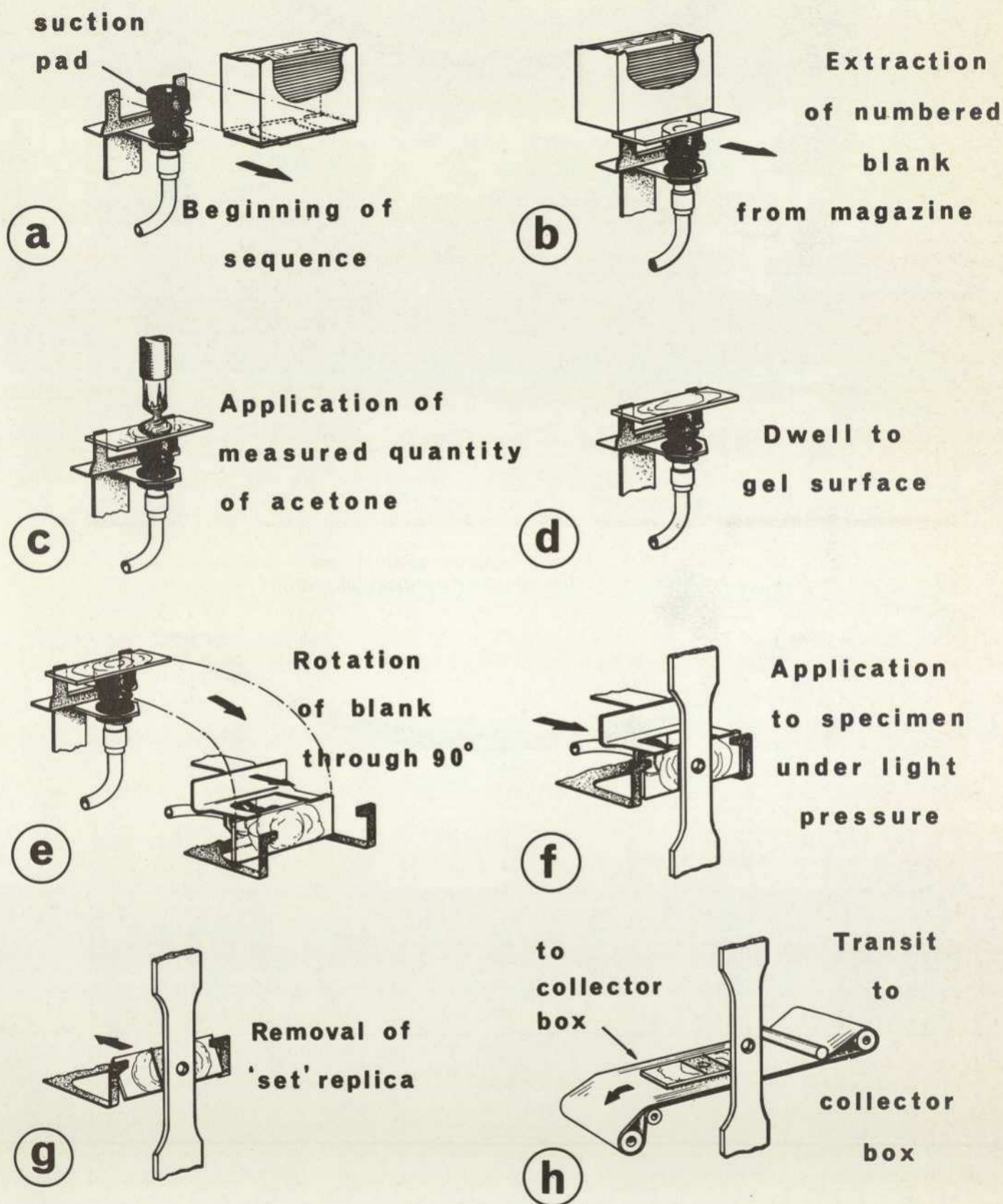


Fig.5 Pictorial presentation of automated sequence

Fig.6&7

Grinding
marks
over whole
surface

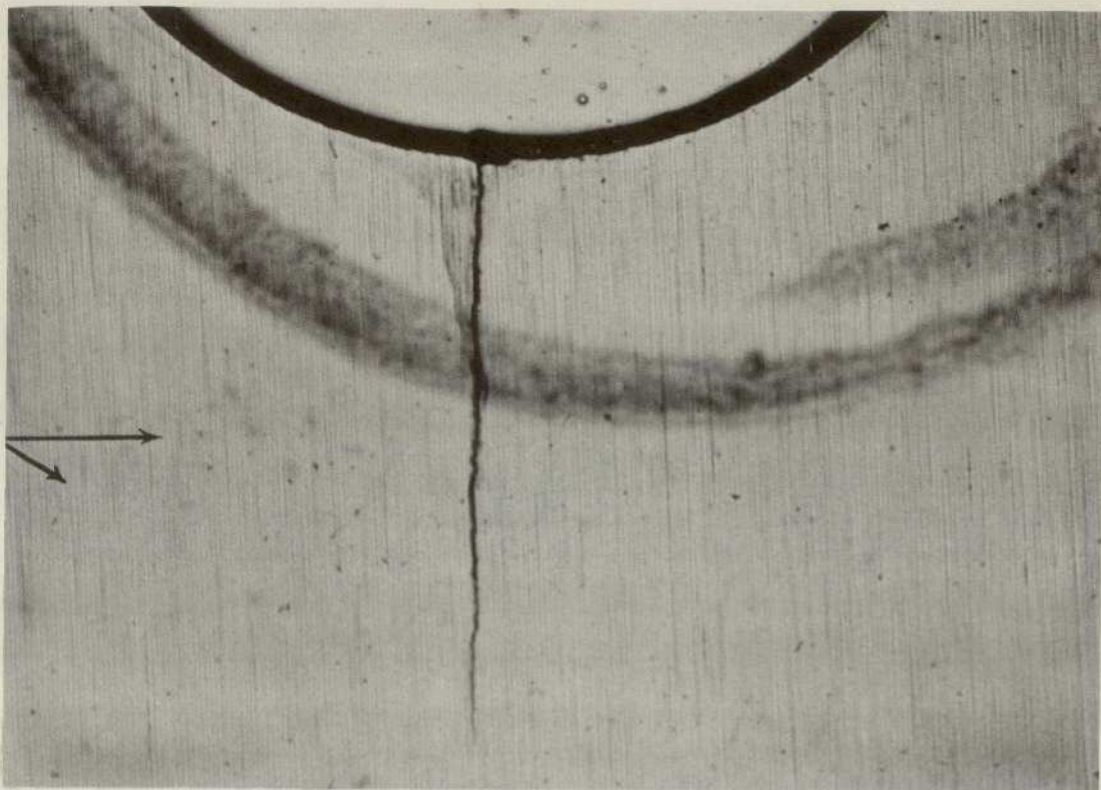


Fig.6 Crack of approximately 4 mm
(approximate magnification: x20)



Fig.7 Crack of approximately 2 mm
(approximate magnification: x27)

NB
Depth of
focus too
small to
enable crack
to be clearly
identified in
a single
photograph

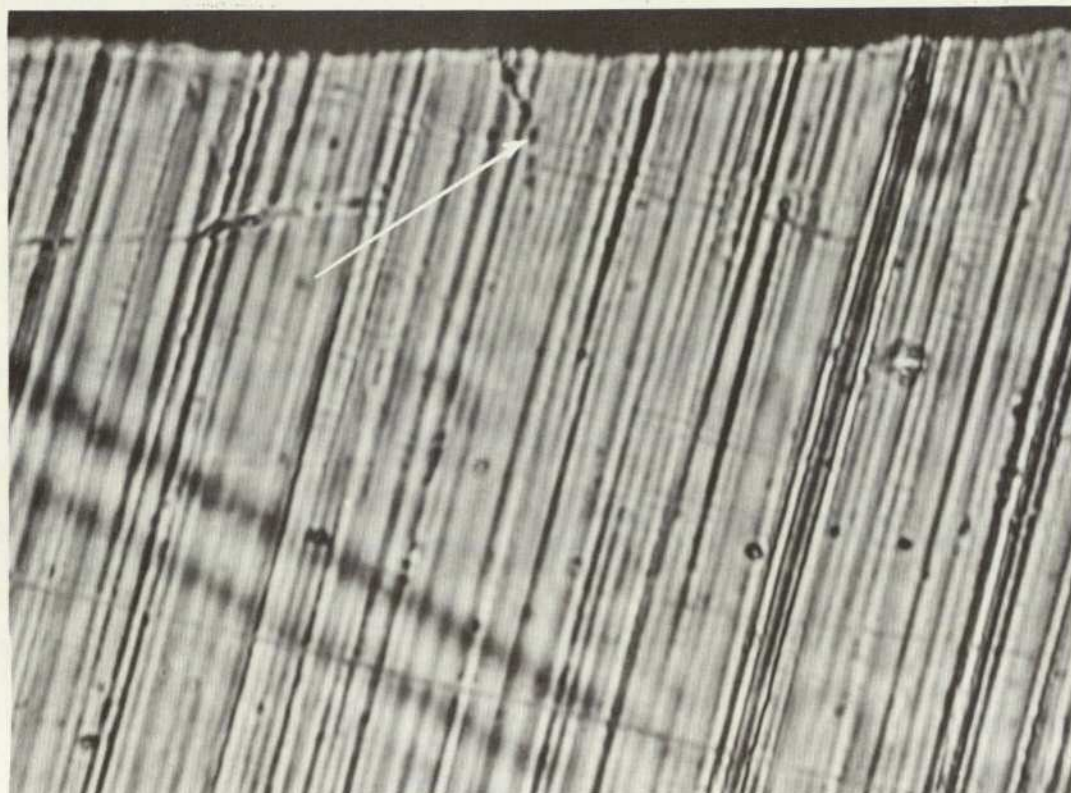


Fig.8 Crack of approximately 0.1 mm
(approximate magnification: x316)

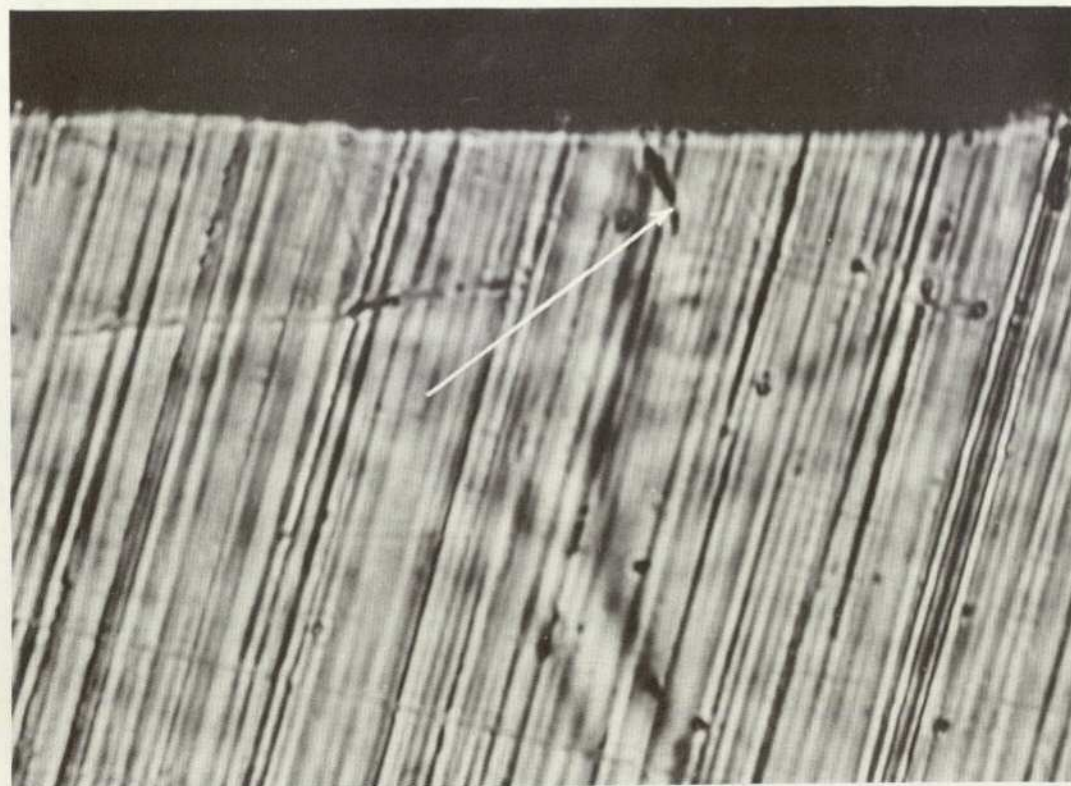


Fig.9 Crack of approximately 0.05 mm
(approximate magnification: x355)

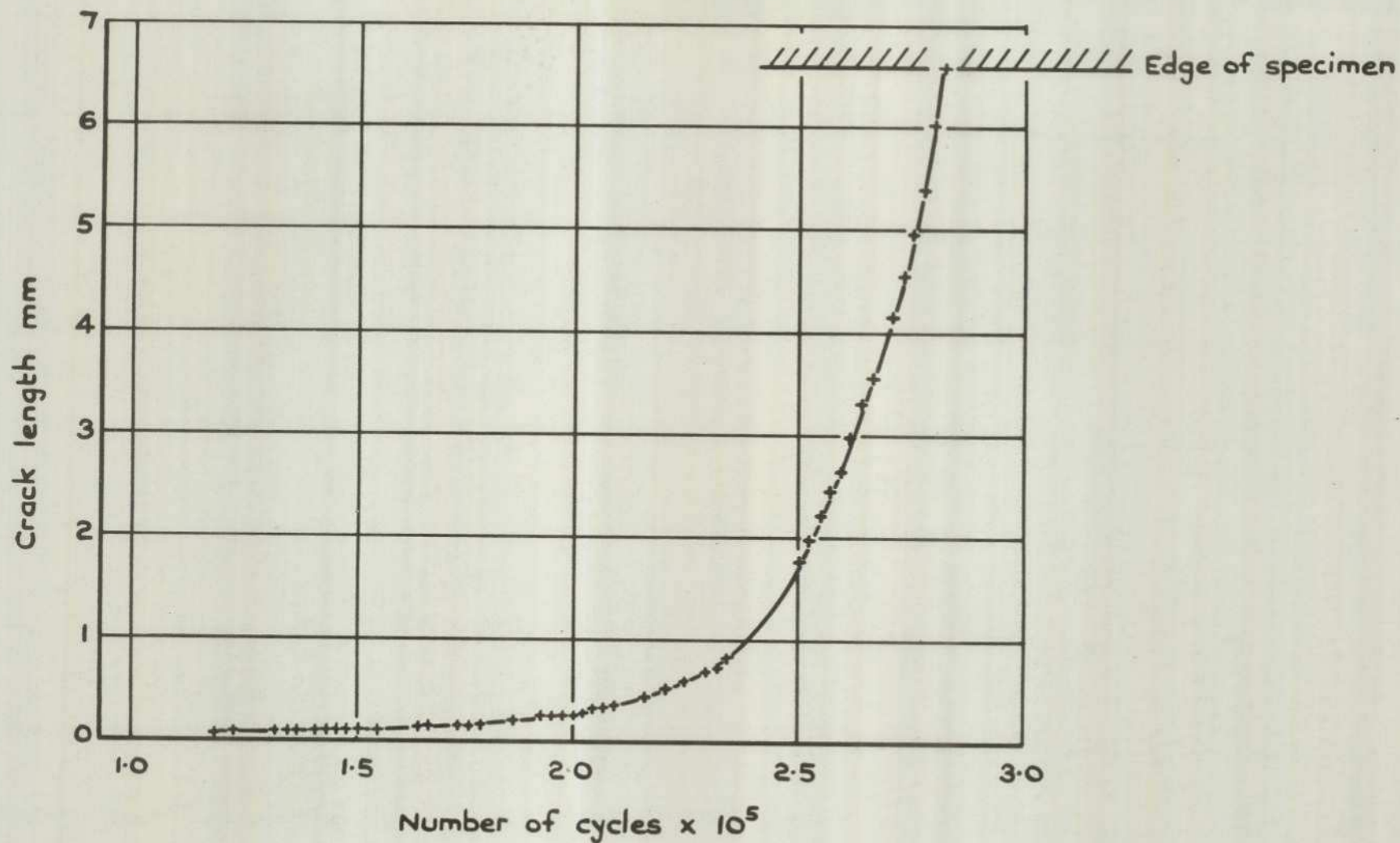


Fig.10 Crack propagation measurements for specimen with endurance 2.94×10^5 cycles

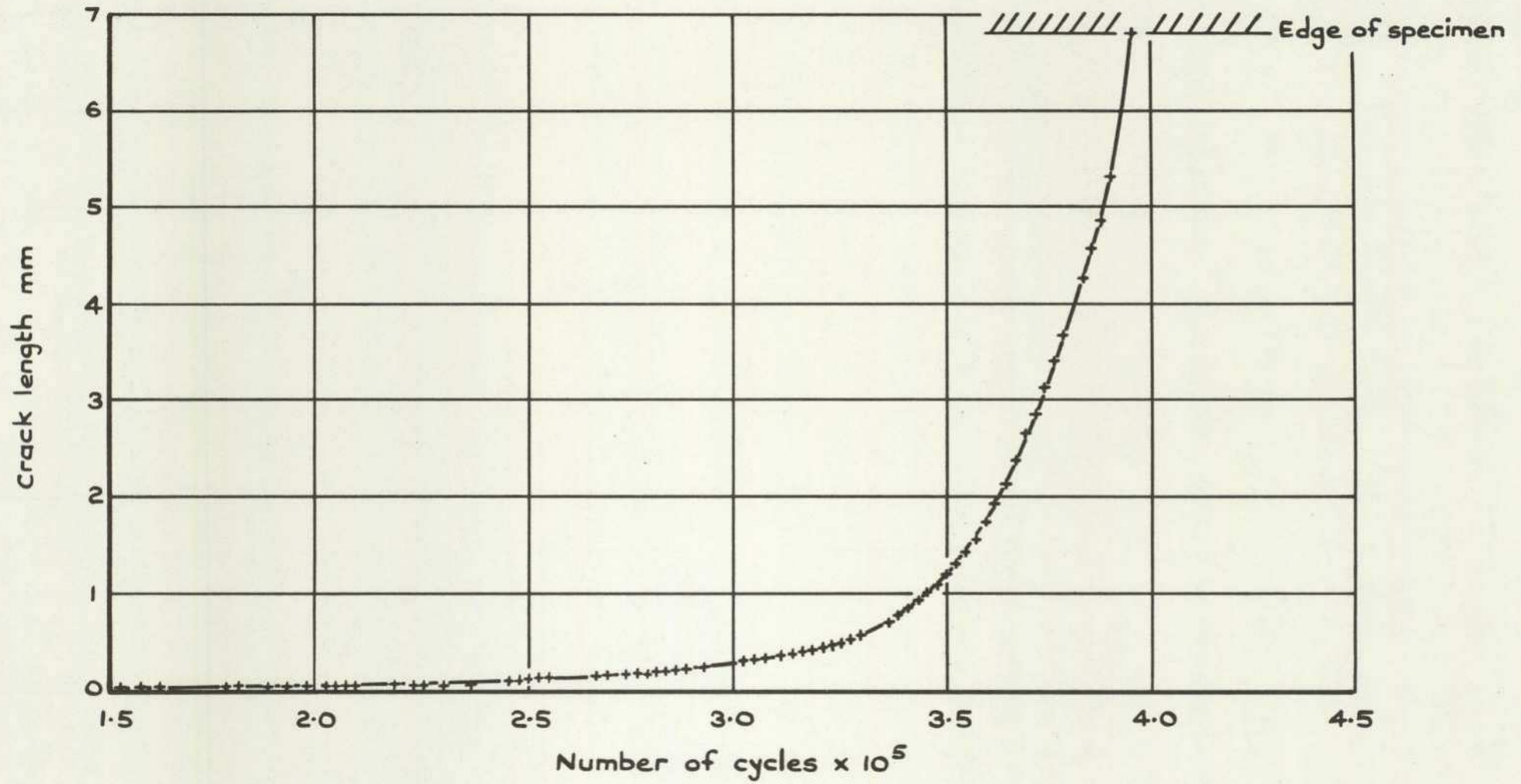


Fig. II Crack propagation measurements for specimen with endurance 4.04×10^5 cycles

APPENDIX E

THE DESIGN OF PINNED-LUG, CLAMPED-LUG AND NOTCHED FATIGUE TEST
SPECIMENS IN ALUMINIUM ALLOY, TITANIUM ALLOY AND STEEL

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 73003

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THE DESIGN OF PINNED-LUG, CLAMPED-LUG AND NOTCHED FATIGUE TEST SPECIMENS IN
ALUMINIUM ALLOY, TITANIUM ALLOY AND STEEL

by

A. W. Cardrick

B. H. E. Perrett

SUMMARY

Details are presented of the design and development of pinned-lug, clamped-lug and notched fatigue specimens for a programme of cumulative damage research on aluminium alloy, titanium alloy and steels.

Large numbers of tests have been made on each type of specimen and these show that the required failure characteristics have been achieved.

Departmental Reference: Structures YSE/B/0302

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2 DESIGN CONSTRAINTS	3
3 THE PINNED-LUG SPECIMEN	3
3.1 Design of the pinned-lug specimen	3
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1 INTRODUCTION

In studies of cumulative fatigue damage in structures, specimens are used which represent, in simplified form, those features which are important in fatigue design.

For a current programme of cumulative damage research¹ three specimen configurations have been chosen, a pinned-lug to represent fretting at a position of appreciable stress concentration, a clamped-lug to represent fretting between clamped surfaces, and a notch to represent a structural discontinuity of moderate stress concentration.

This Report gives details of the design and development of such specimens suitable for testing aluminium alloy, titanium alloy, maraging steel and Ni-Cr-Mo steel. The principal design constraints are outlined in section 2, the pinned-lug is described in section 3, the clamped-lug in section 4 and the notched specimen in section 5.

2 DESIGN CONSTRAINTS

In order that the three types of specimen could be manufactured from single material melts and from bar stock subjected to the same degree of reduction the three specimen designs were based on a single blank size. It was necessary to limit the cross section so that the strongest specimen in fatigue could be tested in a 100kN Vibrophore fatigue testing machine. The peak fatigue stress required was estimated to be approximately 650 MN/m^2 , which corresponds to a gross area of approximately 150 mm^2 .

A further constraint was imposed by the available distance, 540 mm, between the loading heads of the Vibrophore*; this was of importance in the design of the clamped-lug specimen.

3 THE PINNED-LUG SPECIMEN

3.1 Design of the pinned-lug specimen

The pinned-lug specimen is intended to represent those parts of a structure in which fatigue initiation occurs in a region where fretting is combined with an appreciable stress concentration.

* Special loading heads were designed for this machine, details of these may be obtained from Structures Department, RAE: Drawing numbers 011/002840 (pinned-lug and notch) and 011/002842 (clamped-lug).

A double ended configuration loaded by close fitting pins was chosen for the test specimen, so that failures would occur in the lug from fretting nucleation at the minimum net section through the diameter of the pin. It was recognised that in consequence each failure would represent the weaker of two single lugs, but this slight loss of generality was considered to be outweighed by the availability of information on residual static strength from the unfailed end and also by the ease of loading afforded by a double pinned arrangement.

In selecting suitable proportions for the lug, reference was made to the recommendations contained in AvP.970². These are reproduced in abbreviated form in Fig.1. It was deduced that the three failure criteria, i.e. tension, shear and bearing would be satisfied simultaneously if both the minimum width, c , and the pin diameter, d , were made equal to approximately half the end distance, a , i.e.

$$c \simeq d \simeq \frac{a}{2},$$

so that the gross area would be given approximately by $3at/2$. Bearing the recommendations in mind, a value of 2.5 was chosen for d/t , so that by making the gross area equal to the nominal limiting value of 150 mm^2 the nominal dimensions were derived. These correspond closely to the dimensions of an existing pinned-lug design³.

	<u>Nominal dimensions of existing design</u>	<u>Nominal dimensions derived here</u>
a	25.4 mm	22.4 mm
c	9.7 mm	11.2 mm
d	12.7 mm	11.2 mm
t	5.1 mm	4.5 mm

The nominal dimensions of the existing specimen were retained.

The dimensional limits on the pin and hole were chosen to provide the closest and most consistent fit which could be obtained economically. This resulted in a clearance of between $8 \text{ }\mu\text{m}$ and $28 \text{ }\mu\text{m}$ (0.06 per cent to 0.22 per cent of the diameter).

Having decided upon lug proportions, overall dimensions and pin fit, it remained only to specify the manufacturing processes such as machining, grinding and reaming most appropriate to engineering practice in the use of each of the

four materials, together with the minimum tolerances on all dimensions consistent with the use of batch production methods.

Design drawings for the specimen in four materials are shown in Figs.2, 3 and 4. The dimensions are given in inches, since this was the preferred workshop standard at the time of issue.

A steel pin was considered to be most representative and it was convenient to use BS.2S98. The loading pin is shown in Fig.5.

The elastic stress concentration factor⁴ on net stress for a lug of this geometry is approximately 3.0; in view of the low pin clearance this occurs approximately on the transverse hole diameter⁵.

3.2 Failure characteristics of the pinned-lug specimen

Fatigue cracks in the pinned-lug specimen originate as required from positions along lines of fretting through the bore in the region of the peak stress concentration. The cracks coalesce to form through cracks at all but the lowest endurances. In many cases cracks grow symmetrically from each side of the hole. Typical failures in specimens of each material are shown in Fig.6.

4 THE CLAMPED-LUG SPECIMEN

4.1 General considerations

The clamped-lug specimen is intended to represent hose parts of a structure in which fatigue initiation occurs in a region of fretting between clamped surfaces. Typical examples are the many joints in an aircraft in which the members are clamped together by bolts or rivets and a substantial part of the load is transmitted by friction. By careful design of side plate stiffness and degree of clamping, the load transferred at the obvious stress concentrations at the bolt holes and side plate edges can be reduced and the life of the joint increased. This process can be followed until the fatigue failure is transferred to the region of fretting between these two stress concentrations. To represent this situation it was decided to utilize the lug specimen described in the previous section as a centre plate*, clamped between side plates of equal width so that axial load would be transferred primarily by friction at the faces of the lug. A diagram of the arrangement is given in Fig.10.

* The centre plate is in essence a lug specimen with the hole tolerances relaxed to avoid unnecessary expense in manufacture. Drawings are presented in Figs.7, 8 and 9.

In order to simplify the alignment of the specimens in the fatigue testing machine a pinned connection to the end fittings was favoured. It was decided to make all sideplates from the same material and to use BS.2S98 (the loading pin material used for the pinned-lug). Approximate calculations showed the pinned connection to be feasible, using suitably thick side plates and a loading pin of sufficient stiffness to prevent significant pin bending problems. Careful design was however necessary to ensure failure in the centre plate before failure of the side plates, loading pins or end fittings; relevant factors will be discussed in the following sections.

4.2 Design of the side plates

4.2.1 The pinned connection to the end fitting

The first consideration was to ensure that the pinned connection to the end fitting was of superior fatigue strength to the clamped test section. Suitable comparative data^{6,7} were available only for aluminium alloys tested in the form of pinned and clamped-lugs. These showed that on the basis of cross-sectional area at the failure section, the pinned-lug (net area) was weaker than the clamped-lug (gross area) by a stress factor of between 2 and 5. The greatest strength ratio was observed at low endurances under constant amplitude loading. Information obtained by White⁸ on the strength of steel pinned-lugs showed that by introducing a pin clearance of 0.8 per cent of the diameter an increase in strength of about 2:1 could be expected, thus reducing the necessary ratio of net to gross area from 5:1 to about 2.5:1. Approximate calculations showed that a loading pin diameter of not less than about 16mm was necessary to limit the shear stress in the pin and bending associated with the use of thick sideplates. Such a geometry gives rise to a stress concentration factor⁴ of about 2.5 on net stress, whereas the data of Refs.6 and 7 refer to a lug with a geometric stress concentration factor of about 3.1. It was argued therefore that the ratio of net to gross area could be reduced further by the ratio of the stress concentration factors, i.e. from 2.5:1 to about 2:1. Therefore the required net area of sideplates of the same material for equal strength under the most critical conditions is approximately $2(d + 2c)t$, i.e. about 330 mm^2 ; the side plate thickness was chosen to give a net area about 30 per cent greater than this.

There remained some concern however, that the BS.2S98 steel side plates might prove inadequate in combination with a maraging steel centre plate of higher static strength, and consequently a small investigation was conducted to

assess the relative pinned strength of these two materials to determine if the situation might be improved by the use of maraging steel side plates. A number of pinned-lug specimens in the two materials were tested under constant amplitude loading, since this was expected to be most critical; loads were applied in fluctuating tension at a mean stress of approximately 200 MN/m^2 . The results, which are presented in Fig.11, showed the BS.2S98 lugs to be superior to those in maraging steel, despite the greater plain fatigue strength of the latter material. Experience of analogous behaviour in aluminium alloys⁶ in both pinned and clamped form gave some confidence that the maraging steel centre plates would also be weaker than those in BS.2S98.

4.2.2 Effect of side plate thickness on centre plate failure characteristics

In order to determine whether it would be necessary to reduce the thickness of the side plates locally in the region of clamping, a small investigation was conducted to see if the mode of failure at the clamped joint was significantly affected by side plate thickness.

It was convenient to use BS.2L65 aluminium alloy centre plates with steel side plates of 2.5, 5, and 12.5mm thickness, as shown in Fig.12. The clamping load was applied by controlled bolt extension, such that the core stress in the bolt was approximately 60 per cent of the ultimate strength*. Specimens of each type were tested under narrow band random loading at an rms alternating stress of 17.5 MN/m^2 with a mean stress of 100 MN/m^2 , based on the gross section through the centre plate.

The results are presented together with an indication of fracture characteristics in Fig.13. In all cases fatigue damage originated in the area of fretting at the interfaces of the side plates and centre plate and cracks propagated through the centre plate on parallel transverse surfaces normal to the axis of the specimen. Failures were associated with the combined effect of fatigue cracks propagating on different planes.

The joint with the 2.5mm thick side plates showed severe fretting in the region of the bolt and fractured into the bolt hole. The pattern of fretting and source of failure was little affected by increasing the side plate thickness

* This figure, which corresponds closely to aircraft engineering practice, represents a practical upper limit above which the relation between extension and load is likely to be significantly influenced by plasticity.

to 5 mm, but with 12.5mm thick side plates failure took place from a leading edge of the side plate. It has been argued that both of these failure modes would be considered premature in a well designed bolted joint in which such severe conditions could be eliminated by an appropriate distribution of side-plate stiffness and clamping load. Some additional work was therefore done to determine the sideplate thickness appropriate to the generation of consistent failures through the gross section of the centre plate between the bolt hole and the edge of the sideplates. In consequence it was decided to reduce the thickness of the pinned side plates to approximately 6.5 mm in the region of clamping.

Details of the side plate design are shown in Fig.14.

4.3 Design of the bolt and loading pin

At the test section, load transfer is partly by friction and partly by bearing at the bolt hole. To lessen the chance of failure from the bolt hole a clearance fit of between 0.6 per cent and 0.9 per cent of the diameter was chosen. As mentioned previously, the clamping load is determined by measurement of bolt extension and this was facilitated by incorporating steel balls at both ends of the bolt as shown in Fig.15. In order to produce the required core stress an extension of approximately 50 μm is required.

The loading pin which is shown in Fig.16, has been designed as discussed in section 4.2.1 to give a nominal clearance fit of 0.8 per cent of the diameter.

4.4 Assembly of the clamped-lug specimen

The general arrangement of the clamped-lug specimen is shown in Fig.17. On assembly it is desirable to apply a small axial tensile load of about 450 N before tightening the bolts; this ensures that the clearances are taken-up consistently in all specimens.

4.5 Failure characteristics of the clamped-lug specimen

As stated in section 4.1, the clamped-lug specimen was designed to produce consistent failures through the gross section of the centre plate between the bolt hole and the edge of the side plates. As can be seen from Fig.18, this objective has been achieved in all four materials. It is noteworthy that premature side plate failures have been experienced during a few of the low endurance constant amplitude tests on the BS.2S98 specimens; this confirms that a reasonable balance was achieved between the conflicting design requirements

of high side plate strength and correct failure mode (between hole and edge of side plate), since it will be recalled that this condition was taken as the most critical design case for the side plates.

5 THE NOTCHED SPECIMEN

5.1 Design of the notched specimen

The notched specimen is intended to represent conditions of moderate stress concentration from which failures originate in the absence of fretting.

In designing the specimen the centre section of the standard blank has been waisted and the pin clearances increased sufficiently to ensure freedom from failure at the loading pins, whilst preserving a cross-sectional area compatible with a 100kN fatigue testing machine. The notch, which has a geometric stress concentration factor of 2.3, has been produced by making a central hole of appropriate size⁴ in the parallel centre section.

Detailed drawings for notched specimens in each of the four materials are presented in Figs.19, 20 and 21; the loading pin is shown in Fig.22.

5.2 Failure characteristics of the notched specimen

Fatigue cracks in the notched specimen are associated with the lines of maximum stress concentration through the bore of the hole. Typical failures are shown in Fig.23.

6 CONCLUDING REMARKS

Three structural elements, a pinned-lug, a clamped-lug and a notch, have been designed for a programme of cumulative damage research on four materials, aluminium alloy, titanium alloy, maraging steel and Ni-Cr-Mo steel.

The specimens, which represent in turn, fretting at an appreciable stress concentration, fretting between clamped surfaces and a structural discontinuity of moderate stress concentration, are most suitable for tests in fluctuating tension using fatigue machines of about 100kN capacity. The specimens have been designed for manufacture from a single material blank size using representative engineering techniques and dimensional tolerances appropriate to close consistency at moderate cost.

Large numbers of tests have been conducted on each type of specimen and these show that the required failure characteristics have been achieved.

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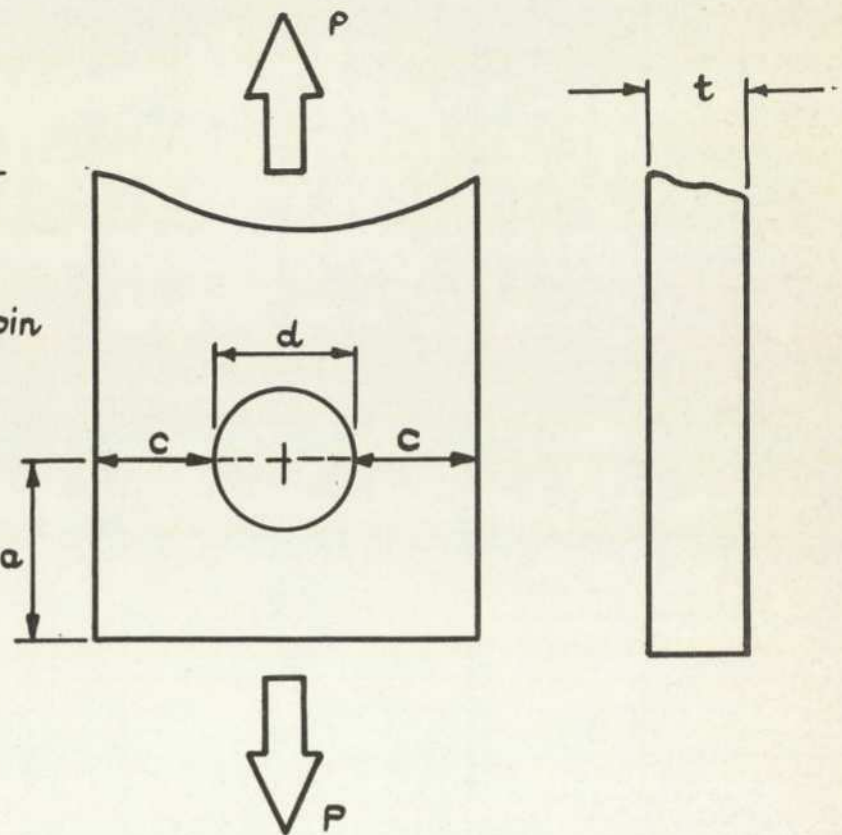
<u>No.</u>	<u>Author</u>	<u>Title, etc</u>
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2		Design requirements for aircraft of the Royal Air Force and Royal Navy. AvP 970, Vol.1, Leaflet 404/2 (1958) Ministry of Aviation
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5	H. L. Cox A. F. C. Brown	Stresses round pins in holes. Aeronautical Quarterly, November 1964.
6	A. W. Cardrick	Comparative fatigue performance of pinned-lug and clamped-lug specimens in BS.2L65 and an experimental Al 5% Mg 4% Zn 1% Mn alloy under constant and variable amplitude loading. RAE Technical Report, to be published shortly.
7	F. E. Kiddle	A study of fatigue endurance, crack nucleation characteristics and crack sensitivity of four copper-aluminium alloys in the form of notched, lug and joint specimens. RAE Technical Report 72107 (1972)
8	D. J. White	Fatigue strength of small pinned connections made from alloy steel FV.520B. Proceedings of the Institution of Mechanical Engineers, Vol.182, part 1, No. 28 (1967-68)

$$\text{Lug tensile stress, net} = \frac{P}{2ct}$$

where P is the load transmitted through the pin

$$\text{Lug shear stress} = \frac{P}{2at}$$

$$\text{Lug bearing stress} = \frac{P}{dt}$$



The geometry of the lug should satisfy simultaneously the following conditions:-

1. $\frac{a}{d}$ greater than 1.5
2. $\frac{d}{t}$ from 1.0 to 8.0 inclusive
- 3 Tensile stress $\nlessgtr$ 0.90 material tensile strength
- 4 Shear stress $\nlessgtr$ 0.46 material tensile strength
- 5 Bearing stress $\nlessgtr$ 1.85 material tensile strength

Fig.1 Recommendations for the design of lugs
(as given in AvP 970-Volume I)

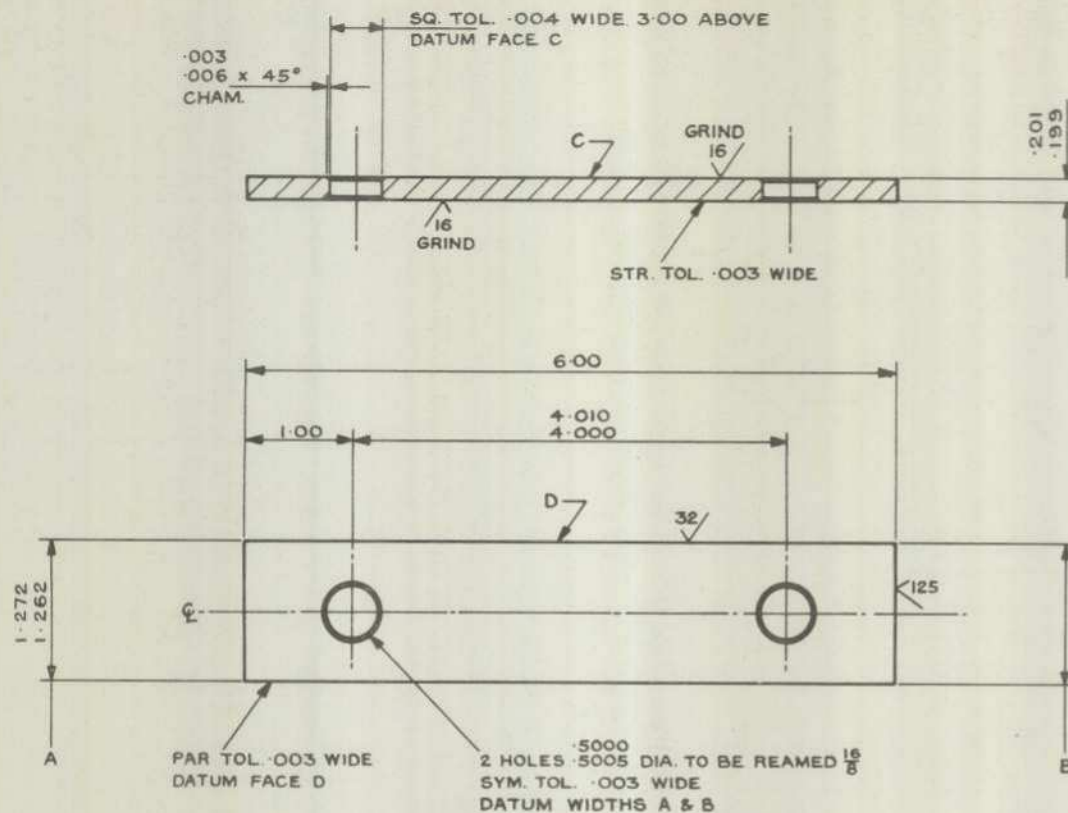
THIRD ANGLE PROJECTION

USED ON

NOTES:-

1. ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001" - .010" x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES. WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
5. SPECIMENS TO BE PROTECTED BY SEALING IN POLYTHENE BAGS WITH SUITABLE DESICCANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " & 8μ .
10. TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL

Fig. 2



							B	14-7-78	
								9-5-6	
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TRACED
ALONG
21-4-69

DRAWN

J.E. PERRETT

MATERIAL
B3.2L 66 BAR AND 85 TAIL
TITANIUM ALLOY BAR TO BE
SUPPLIED BY FATIGUE RESEARCH
SECTION, STRUCTURES DEPT.
IN 12 FT. LENGTHS $1\frac{1}{2} \times \frac{3}{8}$

PROTECTIVE FINISH

TOLERANCES

† -010
UNLESS OTHERWISE STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE	DATE	BY	NO.	PRICE	REMARKS
...	...	...	...	...	...

PINNED LUG SPECIMEN IN B.S. 2L 65 & B.S. T.A. II
(HELICOPTER PROGRAMME)

DRAWING NUMBER	
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011.002821

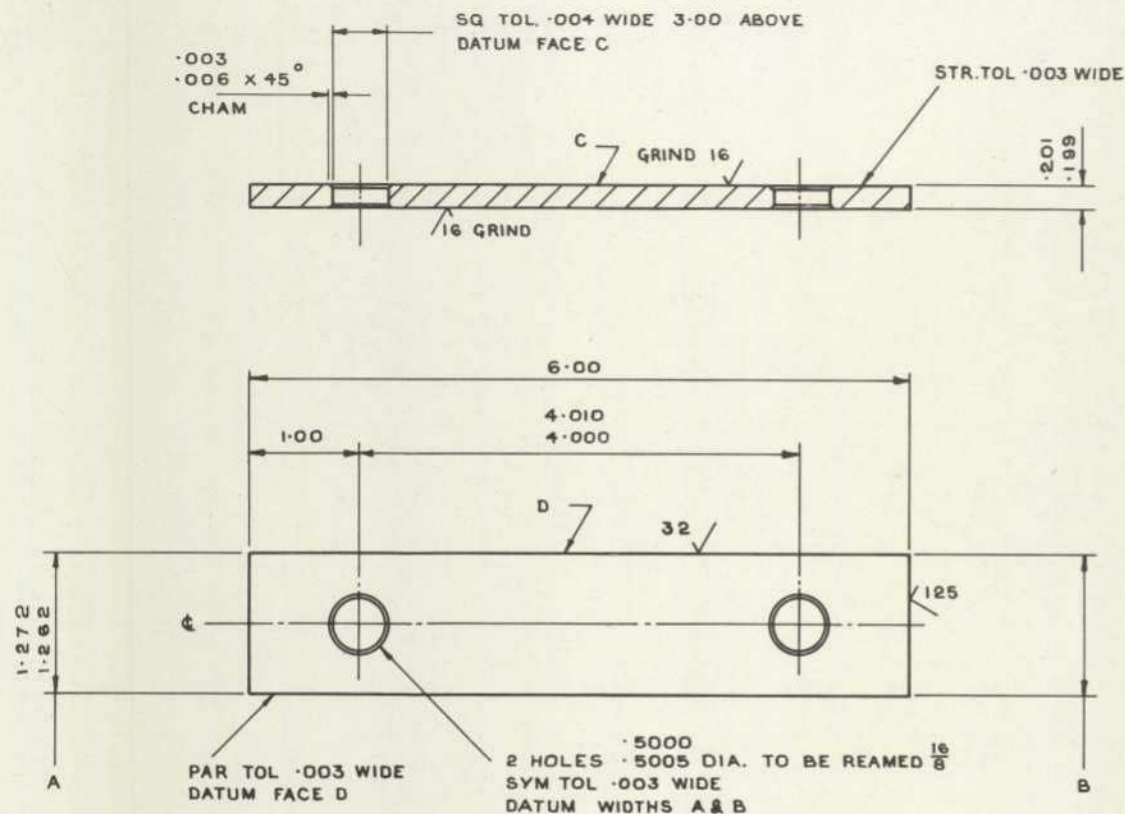
DRAWING NUMBER

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THIRD ANGLE PROJECTION

NOTES

- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER $\cdot 001 - \cdot 010 \times 45^\circ$
- 3 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 4 BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES, WITH BASE OF NUMBERS PARALLEL TO DATUM FACE C
- 5 SPECIMENS TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL TO BE HARDENED & TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING
- 9 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ AND 18μ



MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	
CERTIFIED						

CONTRACTOR'S DRAWING REF.	
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121

DRAWING NUMBER

011 002822

MATERIAL
BS 2598 TO BE
SUPPLIED BY FATIGUE
RESEACH SECTION
STRUCTURES DEPT
IN ANNEALED BARS
 $\frac{1}{2} \times \frac{3}{8} \times 12$ FT LONG

PROTECTIVE FINISH

TOLERANCES

±.010 UNLESS OTHERWISE
STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE

CONTRACTOR

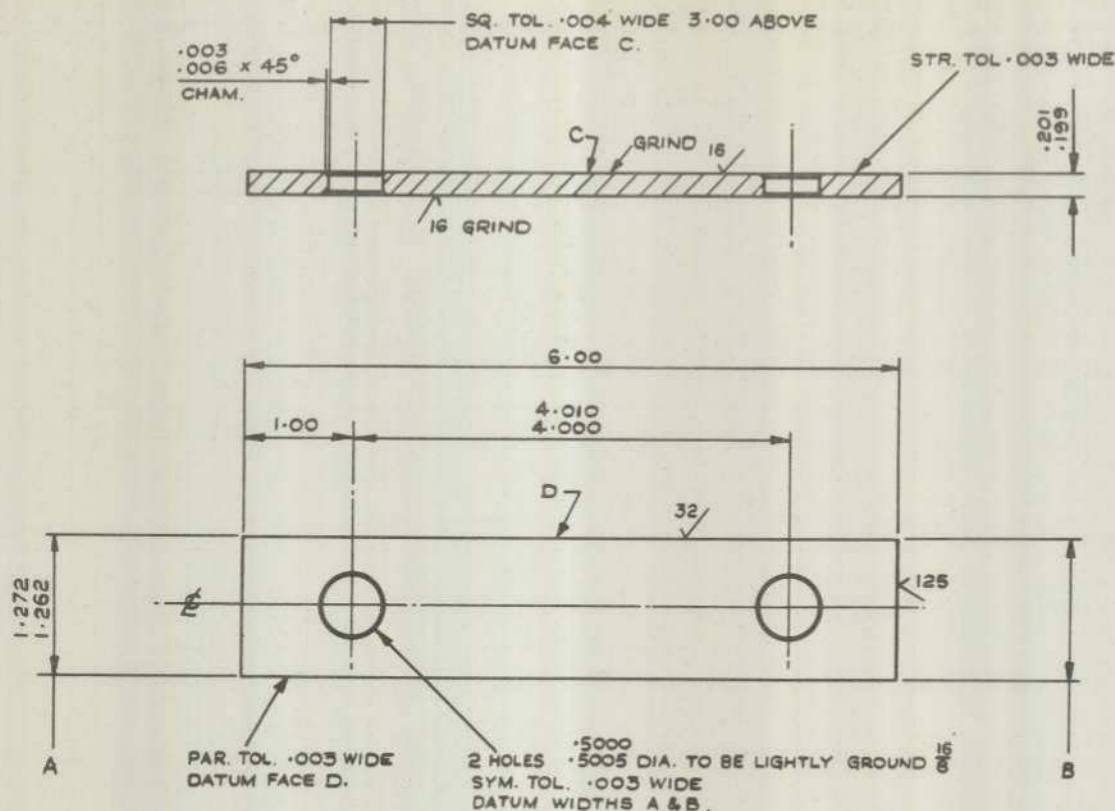
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE PINNED LUG SPECIMEN IN BS. 2598
(HELICOPTER PROGRAME)

Fig. 3

USED ON



NOTES -

1. ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER
-001 - -010 $\times 45^\circ$
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBER TO BE STAMPED CENTRALLY ON BOTH END FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
5. SPECIMENS TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL TO BE MARAGED TO SPECIFICATION BEFORE FINAL MACHINING.
9. WHERE $\frac{1}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "

MOD. No.

ISSUE

DATE

MOD. No.

ISSUE

DATE

CERTIFIED

CONTRACTOR'S DRAWING REF.

122

DRAWING NUMBER

OII OO2823

CHECKED	MATERIAL D.T.D. 5212 18 NI-CO-MO D.V.M. MARAGING STEEL TO BE SUPPLIED SOLUTION TREATED SOFTENED IN 12 FT. LENGTHS 1 1/2" x 3/8" BY FATIGUE RESEARCH SECTION. STRUCTURES DEPT.	PROTECTIVE FINISH	TOLERANCES ± .010 UNLESS OTHERWISE STATED	CONTRACTOR
TRACED S.H.E.B. 2-4-65			DIMENSIONS IN INCHES.	ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION
DRAWN A.W. CARDRICK.			SURFACE ROUGHNESS	SERVICE LETTER
			SCALE	TITLE PINNED LUG SPECIMEN D.T.D. 5212 MARAGING STEEL (HELICOPTER PROGRAMME)

Fig.5

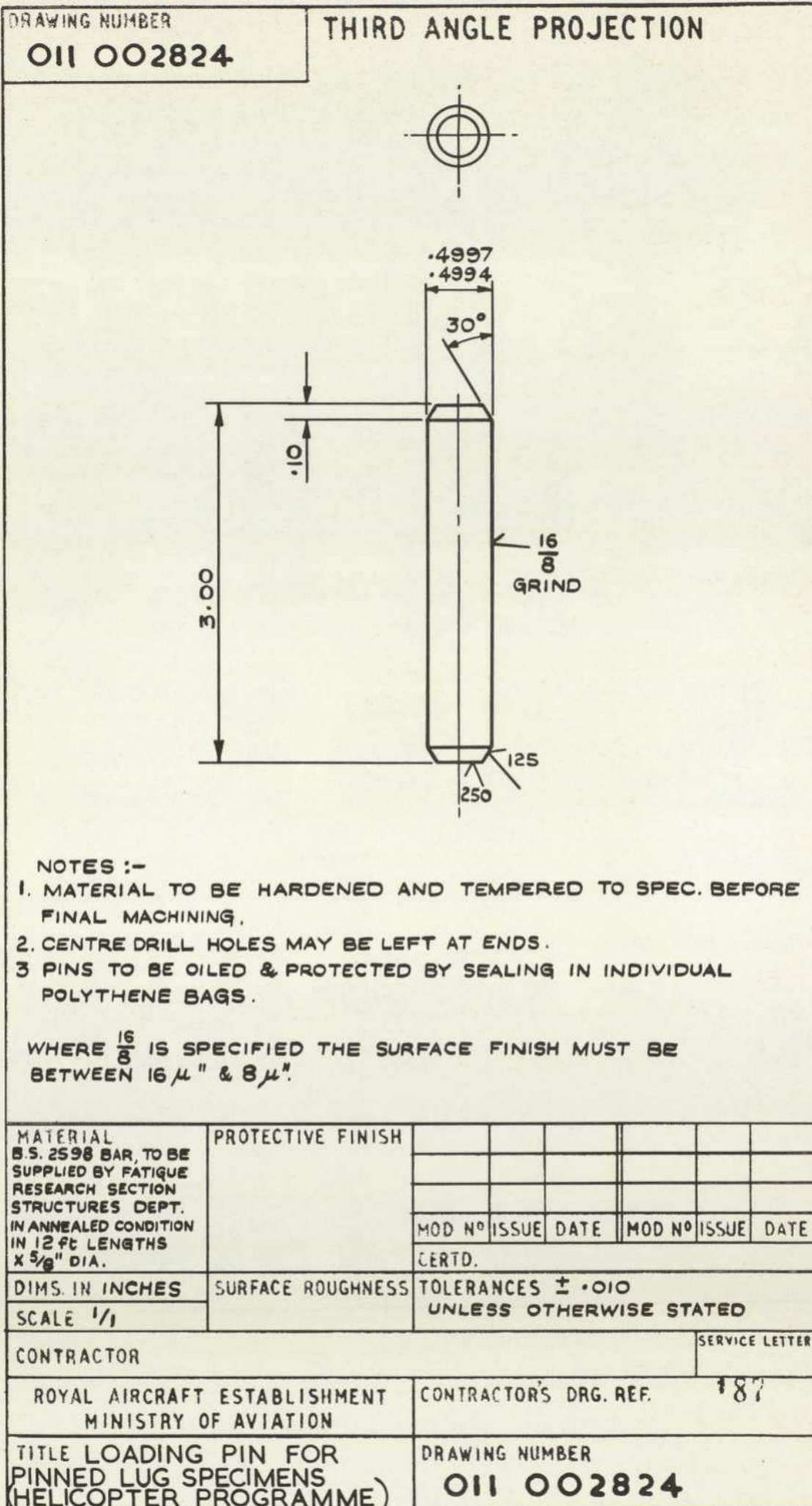
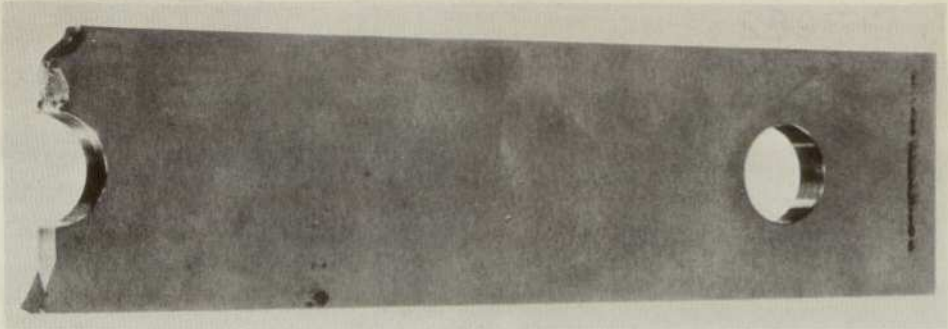
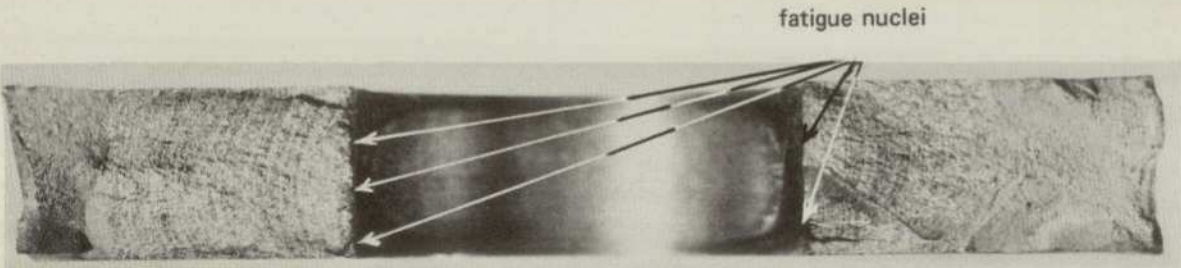


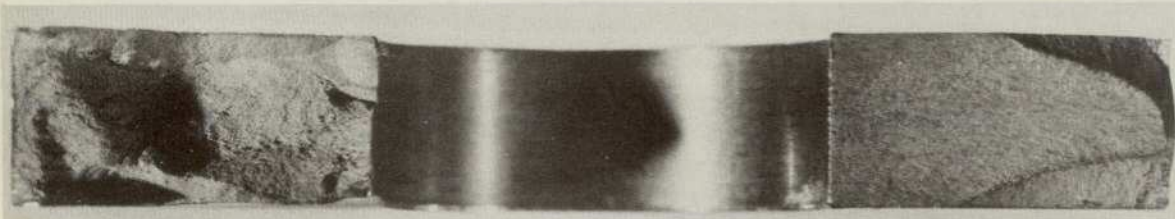
Fig.6



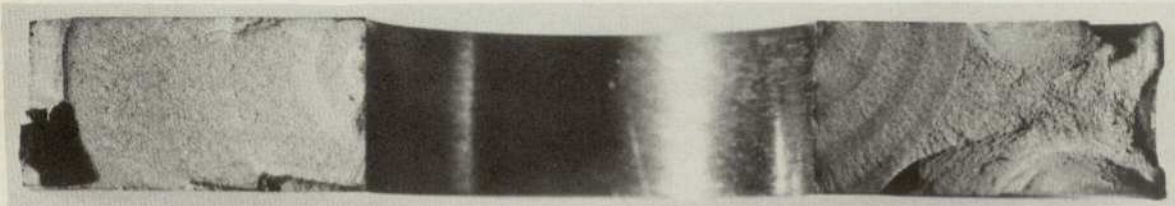
Typical failure



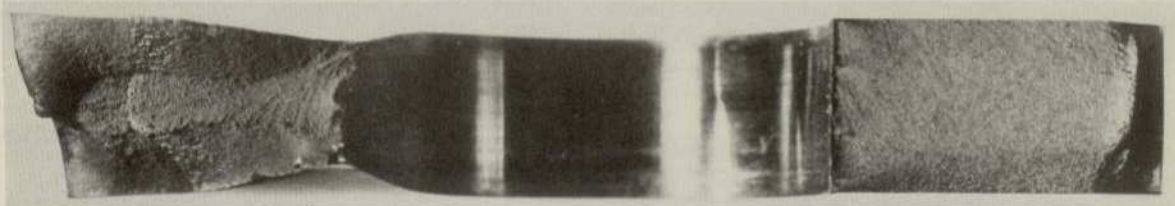
BS 2L65 aluminium alloy



BS TA11 titanium alloy



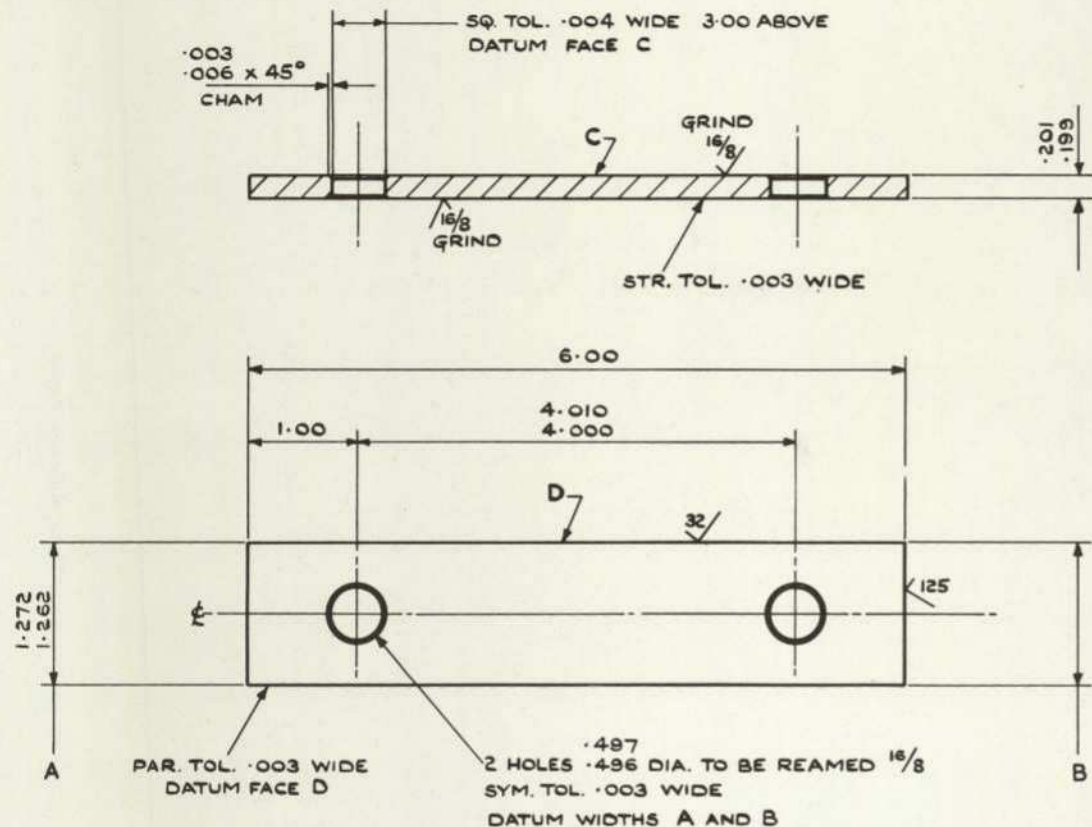
DTD 5212 maraging steel



BS 2S98 NiCrMo steel

Fig.6 Fatigue fractures typical of pinned-lug specimens

THIRD ANGLE PROJECTION



- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 x 45°
- 3 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 4 BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES, WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
- 5 CENTRE PLATES TO BE PROTECTED BY SEALING IN POLYTHENE BAGS WITH SUITABLE DESSICANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL MUST NOT BE HEAT TREATED
- 9 WHERE $16/8$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "
- 10 TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL

MATERIAL
B.S.2. L.65 BAR AND
B.S. TA.11
TITANIUM ALLOY
BAR TO BE SUPPLIED
BY FATIGUE RESEARCH
SECTION. STRUCTURES
DEPT. IN 12ft LENGTHS
1 1/2 x 3/8

PROTECTIVE FINISH

TOLERANCES

± .010 UNLESS OTHERWISE
STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE	DATE	BY	NO.	PRICE	REMARKS
...	...	...	...	...	...

**CENTRE PLATE IN BS.2 L65 & BS.TAIL
(HELICOPTER PROGRAMME)**

					B	14.7.70
					A	9.5.65
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	
CERTIFIED						

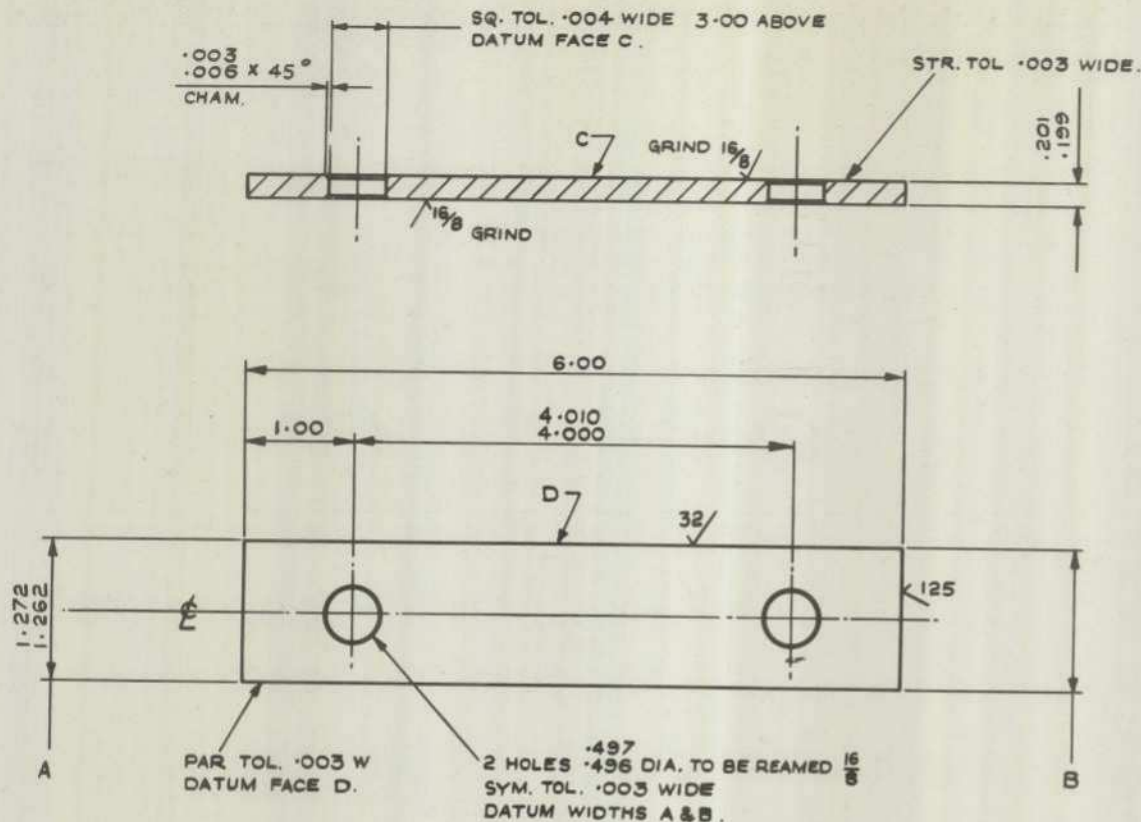
CONTRACTOR'S DRAWING REF.	
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123

	DRAWING NUMBER
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OII.OO2826

THIRD ANGLE PROJECTION



NOTES:-

- ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
- EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER $.001 - .010 \times 45^\circ$
- IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
- BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES, WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
- CENTRE PLATES TO BE OILED AND PROTECTED BY SEALING IN POLYTHENE BAGS CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
- IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
- PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
- MATERIAL TO BE HARDENED AND TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING.
- WHERE $16\frac{1}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ AND 8μ

MATERIAL
B.S. 2S98 TO BE
SUPPLIED BY FATIGUE
RESEARCH SECTION
STRUCTURES DEPT. IN
ANNEALED BARS:-
 $1\frac{1}{2} \times 3\frac{1}{8} \times 12$ FT LONG

PROTECTIVE FINISH

TOLERANCES

$\pm .010$ UNLESS OTHERWISE
STATED.

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE.

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE

CENTRE PLATE IN BS. 2S98
(HELICOPTER PROGRAMME)

MOD. No. ISSUE DATE MOD. No. ISSUE DATE

CERTIFIED

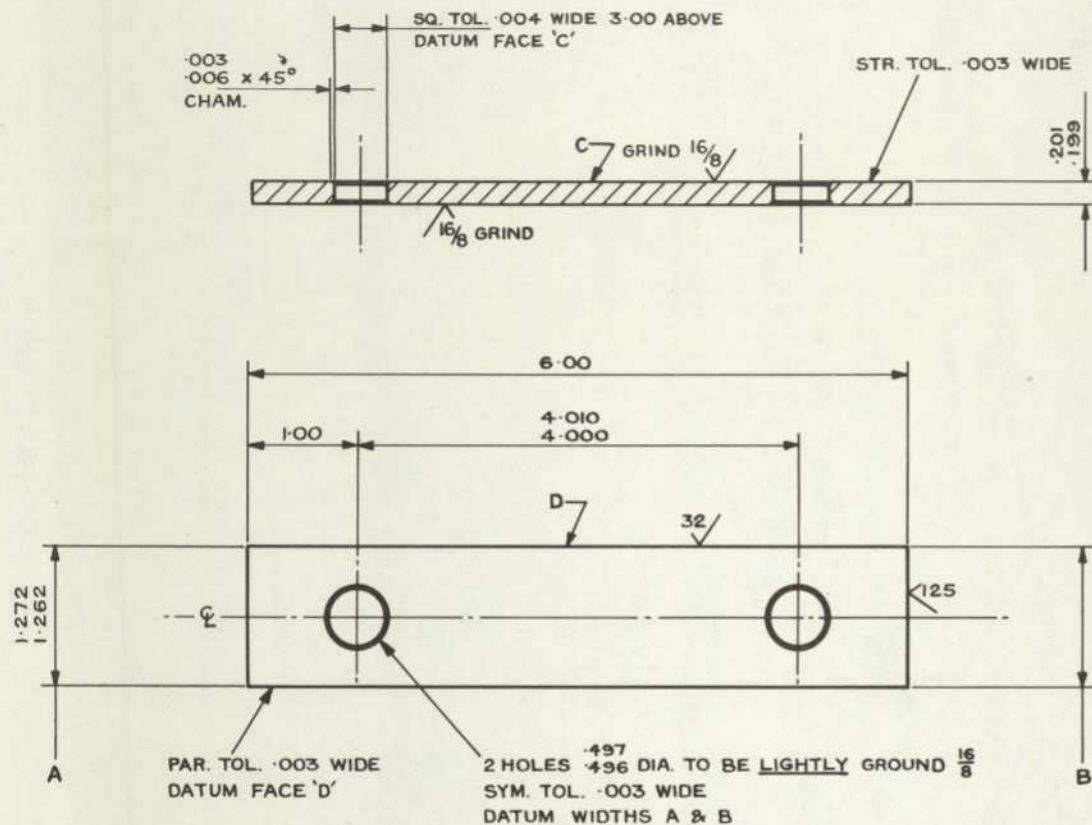
CONTRACTOR'S DRAWING REF.

124

DRAWING NUMBER

OII 002827

THIRD ANGLE PROJECTION



- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY.
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001-.010 x 45°
- 3 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
- 4 BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBER TO BE STAMPED CENTRALLY ON BOTH END FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE 'C'
- 5 CENTRE PLATES TO BE OILED & PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL TO BE MARAGED TO SPECIMEN BEFORE FINAL MACHINING.
9. WHERE $16/\sqrt{R}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN $16 \mu"$ AND $8 \mu"$

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					

CONTRACTOR'S DRAWING REF.

125

DRAWING NUMBER	
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011.002828

MATERIAL
D.T.D. 5212 18NI-CO-MO
D.V.M. MARAGING STEEL
TO BE SUPPLIED
SOLUTION TREATED
(SOFTENED) IN 12 FT.
LENGTHS $1\frac{1}{2} \times \frac{3}{8}$ BY
FATIGUE RESEARCH
SECTION. STRUCTURES
DEPT.

PROTECTIVE FINISH

TOLERANCES
 $\pm .010$
 UNLESS OTHERWISE STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE

CONTRACTOR

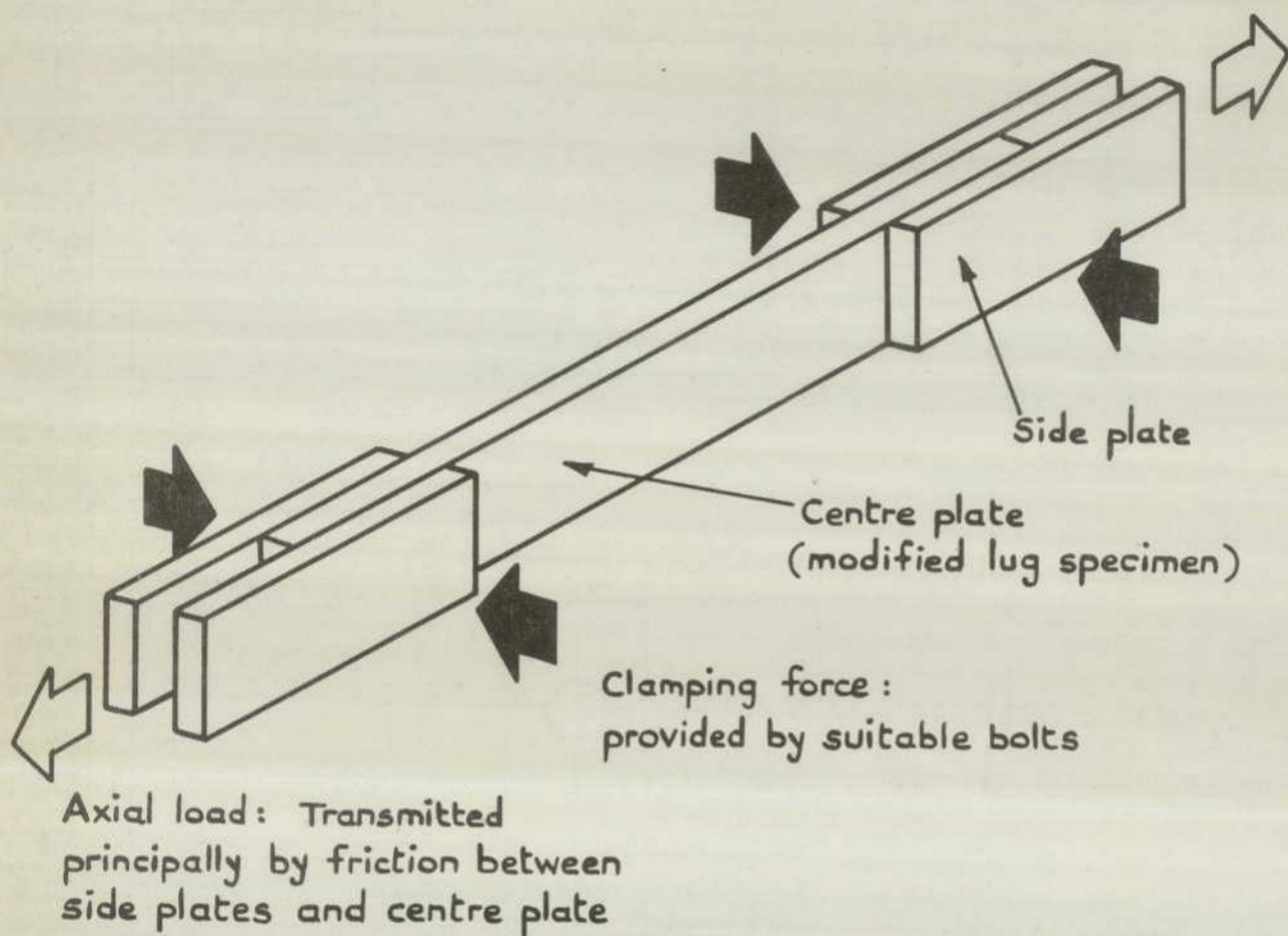
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE	AUTHOR	DATE	TIME	PAGE	REMARKS

CENTRE PLATE IN D.T.D. 5212
MARAGING STEEL (HELICOPTER PROGRAMME)

Fig. 10



TR 73003

Fig.10 Diagrammatic arrangement of clamped-lug specimen

011 907342

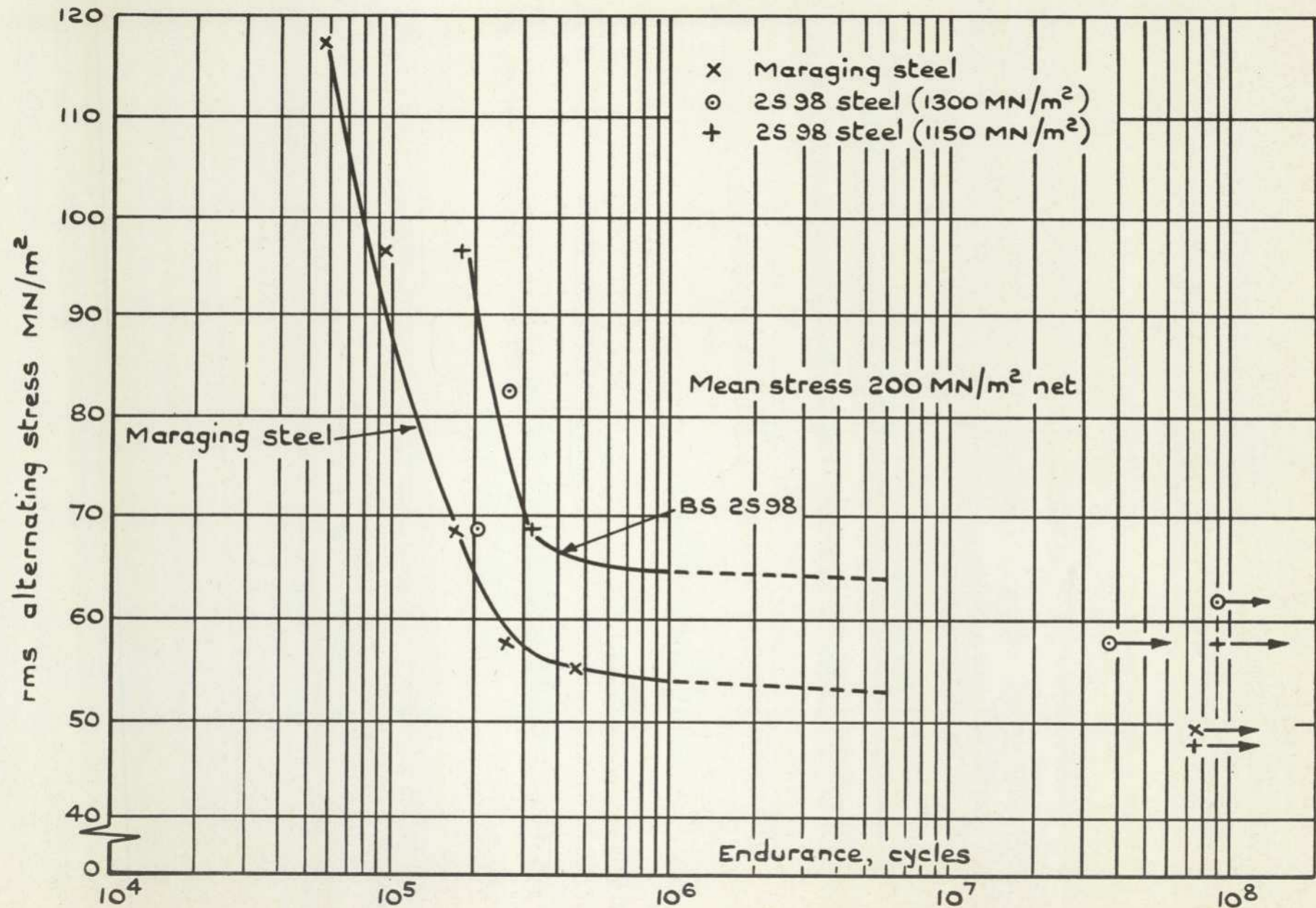


Fig. 11 Endurance of BS 2S98 and maraging steel pinned-lug specimens under constant amplitude loading

Fig.12

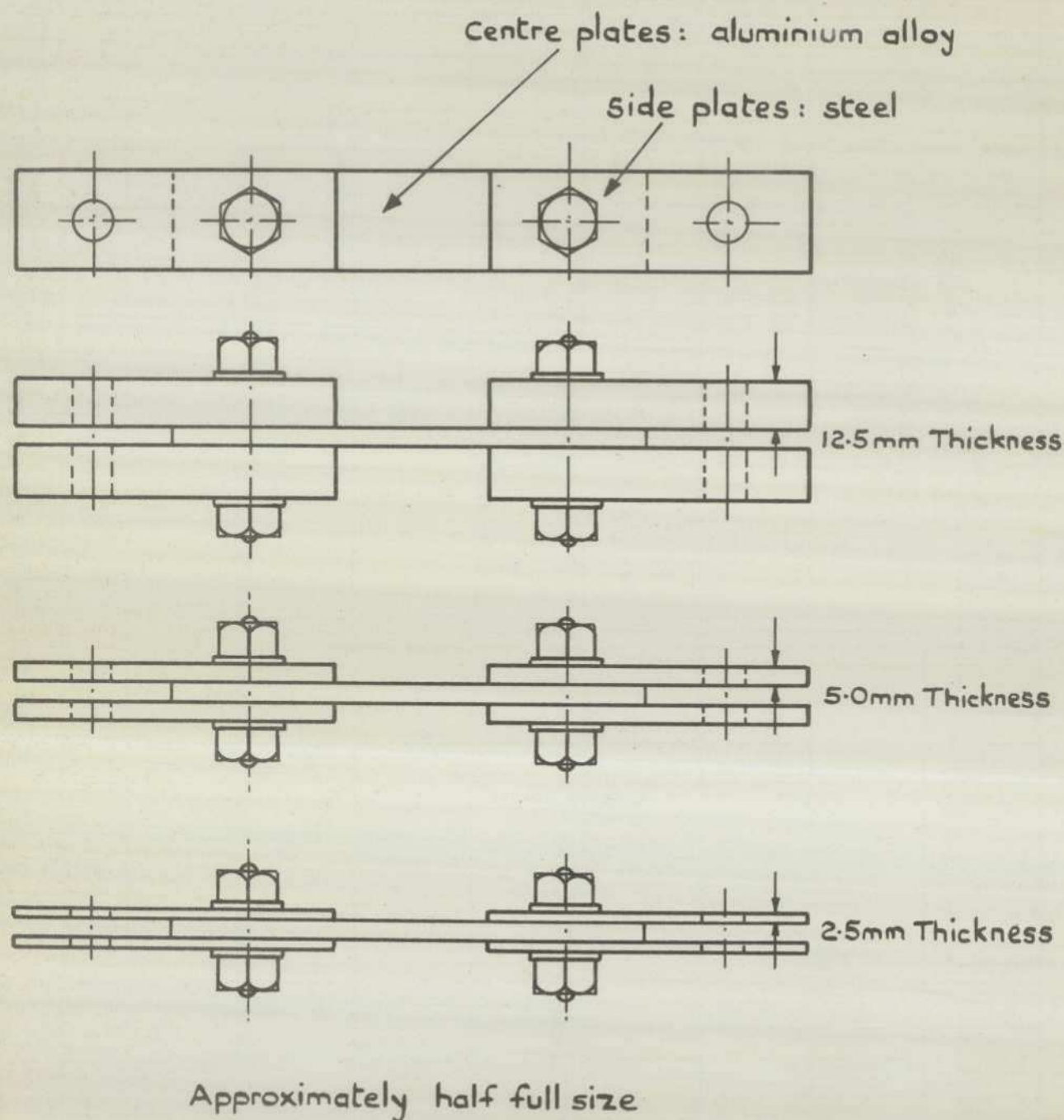


Fig.12 Specimen configurations for side plate thickness investigation

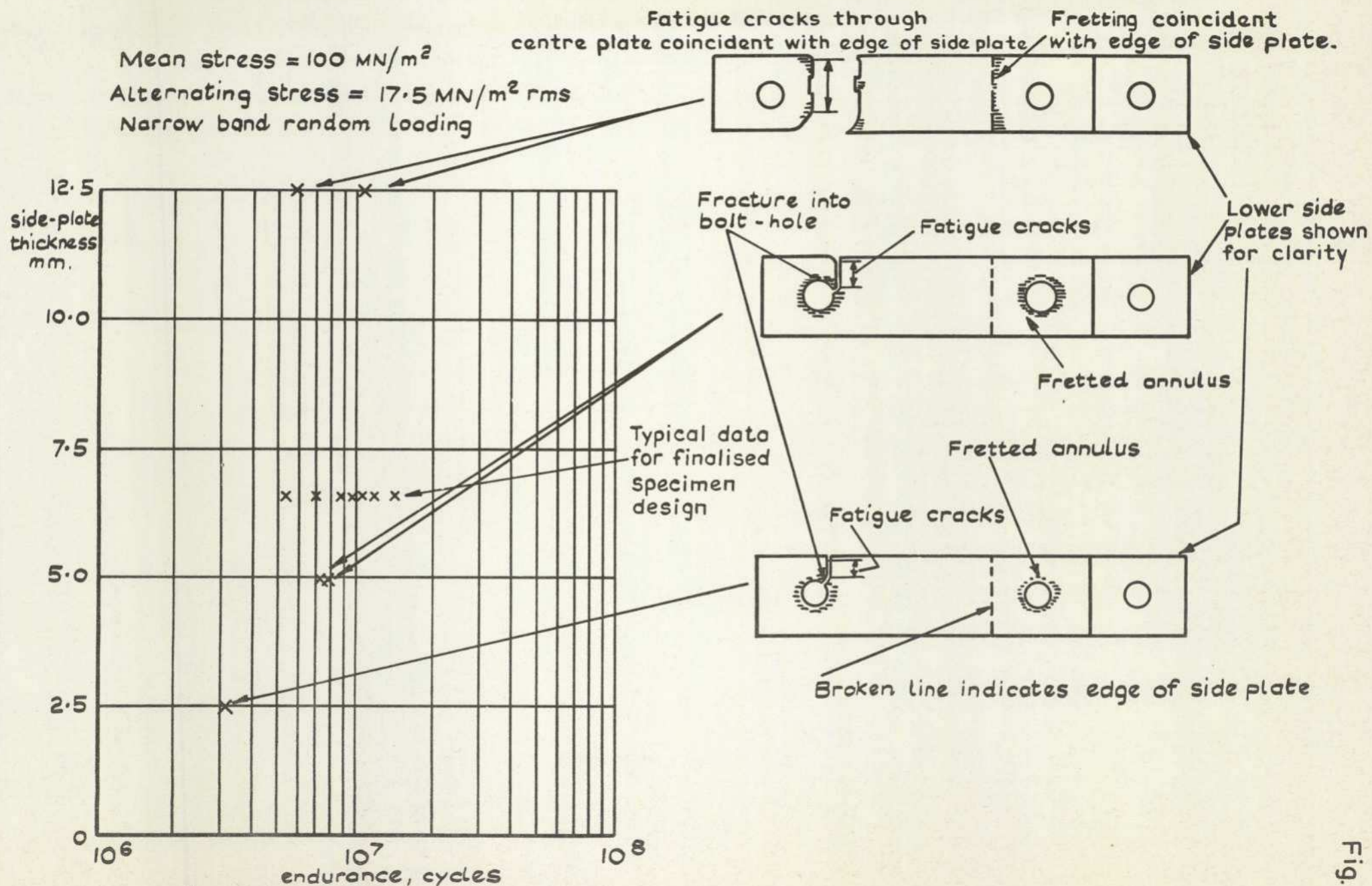
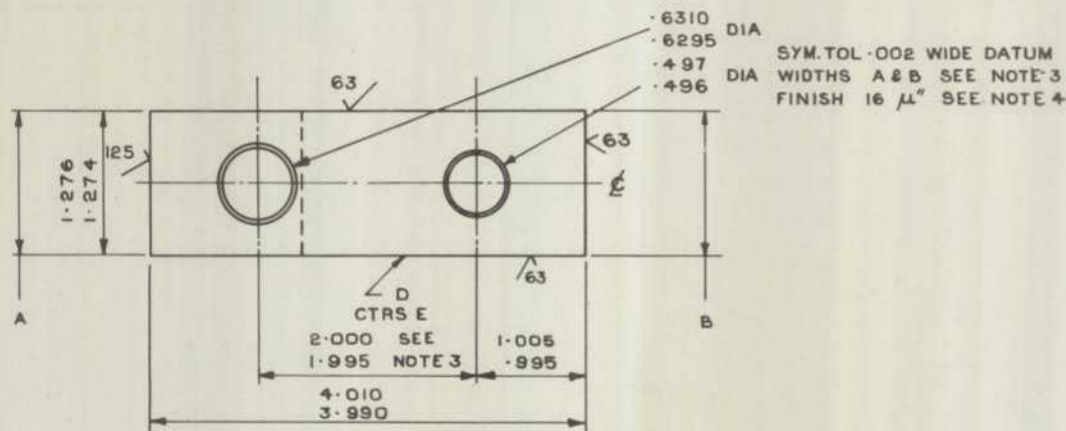
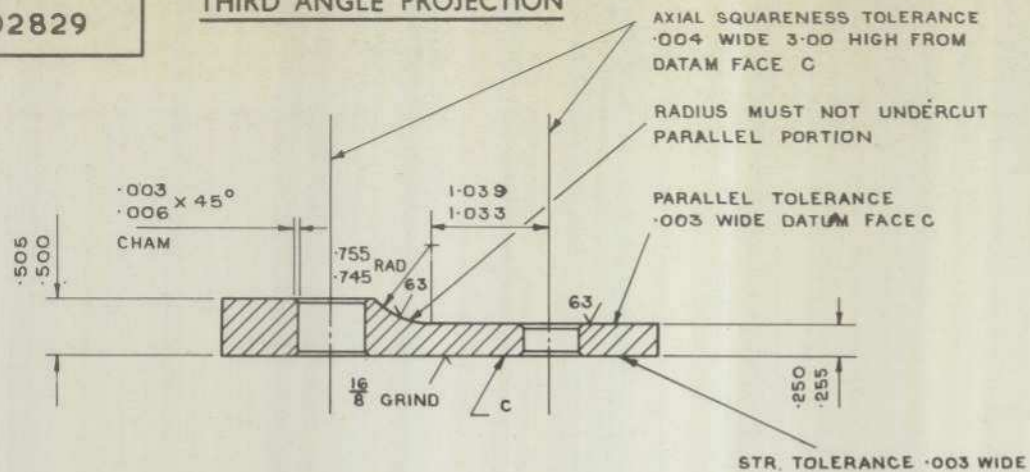


Fig 13 Variation in fracture characteristics with side plate thickness.

THIRD ANGLE PROJECTION



NOTE—

- 1 ROUGH MACHINING SHALL BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001--.010x45°
- 3 SIDE PLATES TO BE MACHINED AND SUBSEQUENTLY RETAINED IN PAIRS TO MAINTAIN TOLERANCE .001 WIDE BETWEEN CENTRES 'E' AND DIAMETRAL TOLERANCE .0005 WIDE FOR EACH PAIR SEE DRG 011002825
- 4 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 5 HOLES MAY BE REAMED, BORED OR LIGHTLY GROUND
- 6 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 7 MATERIAL TO BE HARDENED AND TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING
- 8 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 9 SIDE PLATES TO BE OILED AND SEALED IN PAIRS IN POLYTHENE BAGS, CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
- 10 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN $16 \mu"$ & $8 \mu"$

[illegible]

MATERIAL
BS 25 98 TO BE
SUPPLIED BY FATIGUE
RESEARCH SECTION
STRUCTURES DEPT IN
ANNEALED BARS
 $1\frac{1}{2} \times \frac{5}{8} \times 12'$ LONG

PROTECTIVE FINISH

TOLERANCES

± .010
UNLESS OTHERWISE STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

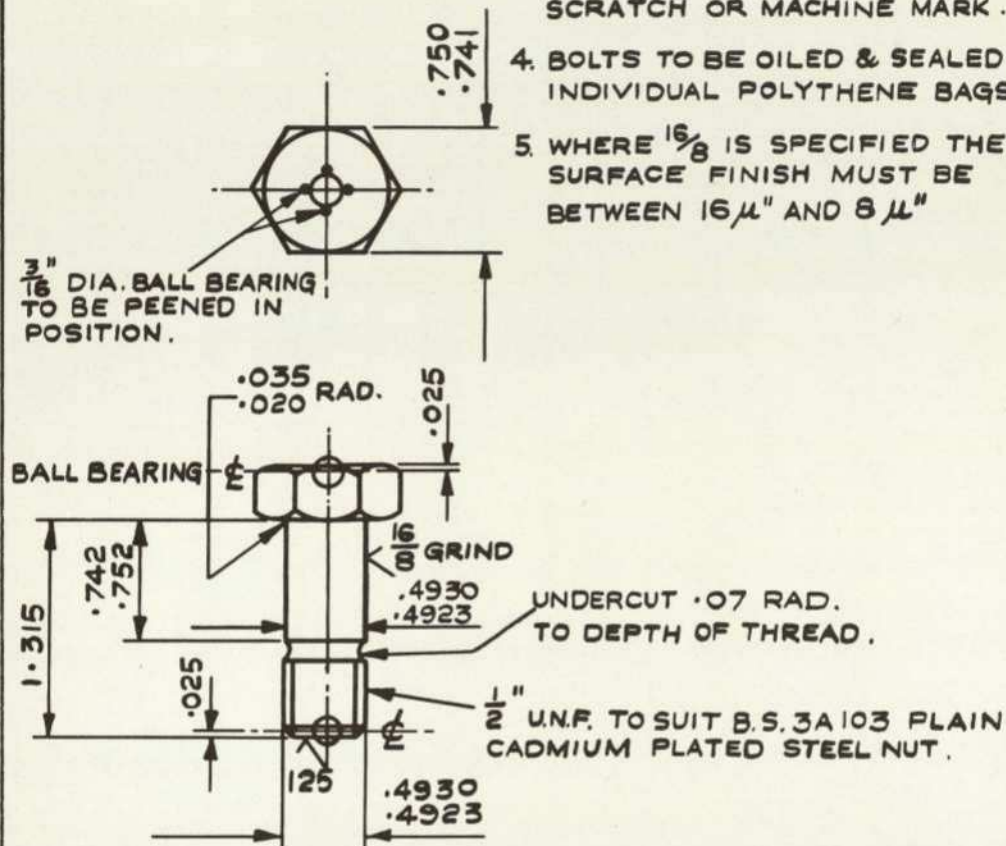
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97	97. TITLE
98	98. TITLE
99	99. TITLE
100	100. TITLE

SIDE PLATE IN BS.2 598
(HELICOPTER PROGRAMME)

DRAWING NUMBER
OII 002831

THIRD ANGLE PROJECTION

1. ALL BOLTS TO BE SUPPLIED FROM MATERIAL WHICH SHALL HAVE A U.T.S. OF NOT LESS THAN 55 TON F/in²
2. CENTRE DRILL HOLES MAY BE LEFT AT ENDS.
3. PLAIN LENGTH OF BOLT TO BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
4. BOLTS TO BE OILED & SEALED IN INDIVIDUAL POLYTHENE BAGS.
5. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "



REFER TO DRWG. OII 003299 FOR BOLTS MANUFACTURED FROM $\frac{1}{2}$ UNF BS 3A 102 BOLTS.

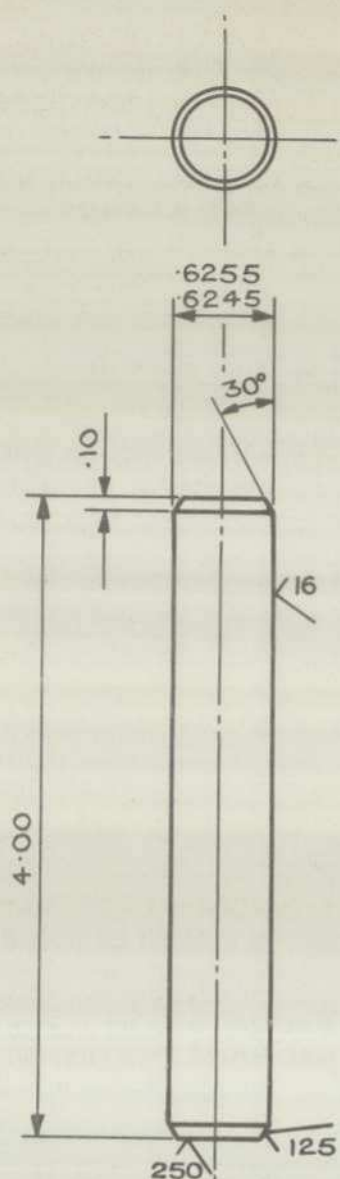
MATERIAL ALL BOLTS TO BE MADE FROM ONE OF THE FOLLOWING S. 94, S 95, OR S. 96.	PROTECTIVE FINISH SEE NOTE 4						
			B	9/12/69			
		MOD NO	ISSUE	DATE	MOD NO	ISSUE	DATE
		CERTD. <i>[Signature]</i>					
DIMS. IN INCHES	SURFACE ROUGHNESS	TOLERANCES $\pm .010$					
SCALE 1:1		UNLESS OTHERWISE STATED					
CONTRACTOR							SERVICE LETTERS
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION				CONTRACTOR'S DRG. REF.			
TITLE HIGH TENSILE STEEL BOLT (HELICOPTER PROGRAMME)				DRAWING NUMBER OII 002831			

Fig.16

DRAWING NUMBER

OII.OO2832

THIRD ANGLE PROJECTION



NOTES:-

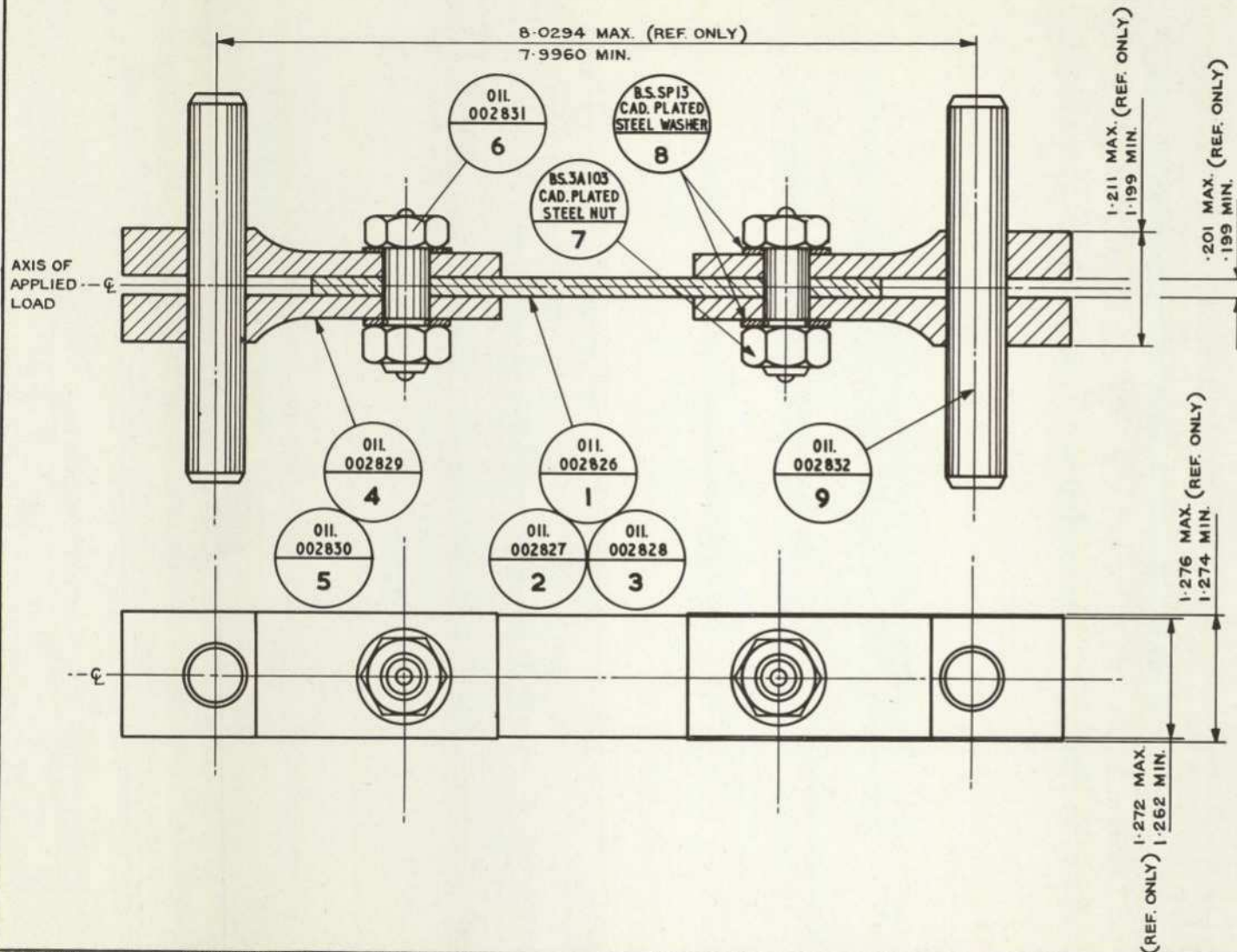
1. MATERIAL TO BE HARDENED & TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING.
2. CENTRE DRILL HOLES MAY BE LEFT AT ENDS.
3. CLEAN, OIL & PROTECT BY SEALING IN INDIVIDUAL POLYTHENE BAGS.

MATERIAL B.S. 2598 BAR, TO BE SUPPLIED BY FATIGUE RESEARCH SECTION, STRUCTURES DEPT. IN ANNEALED CONDITION IN 12ft. LENGTHS x $\frac{3}{4}$ " DIA.	PROTECTIVE FINISH						
		MOD NO	ISSUE	DATE	MOD NO	ISSUE	DATE
CERTD.							
DIMS IN INCHES	SURFACE ROUGHNESS	TOLERANCES $\pm .010$					
SCALE 1:1		UNLESS OTHERWISE STATED					
CONTRACTOR							SERVICE LETTERS
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION				CONTRACTOR'S DRG. REF. 150			
TITLE LOADING PIN FOR CLAMPED-LUG SPECIMENS (HELICOPTER PROGRAMME)				DRAWING NUMBER OII.OO2832			

DRAWING NUMBER

OII. 002825

THIRD ANGLE PROJECTION



MATERIAL

PROTECTIVE FINISH

TOLERANCES

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE FULL SIZE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE

CLAMPED-LUG SPECIMEN
(HELICOPTER PROGRAMME)

MOD. No. ISSUE DATE MOD. No. ISSUE DATE

CERTIFIED

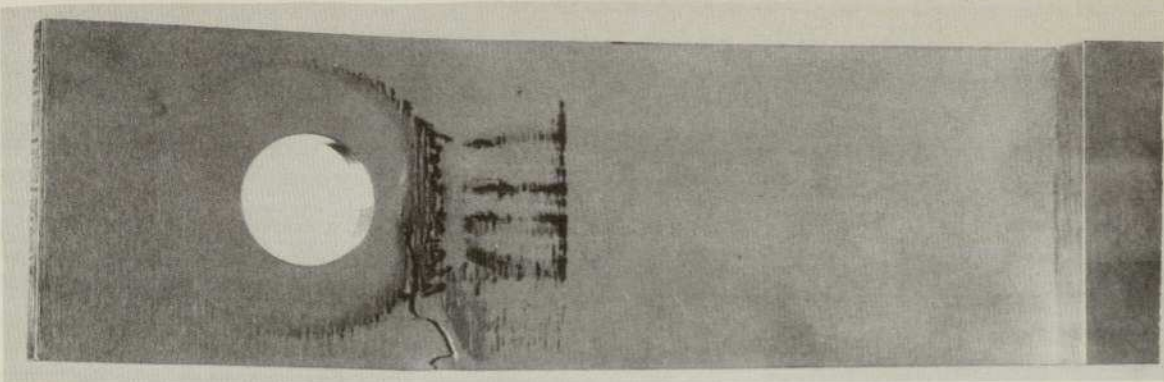
CONTRACTOR'S DRAWING REF.

119

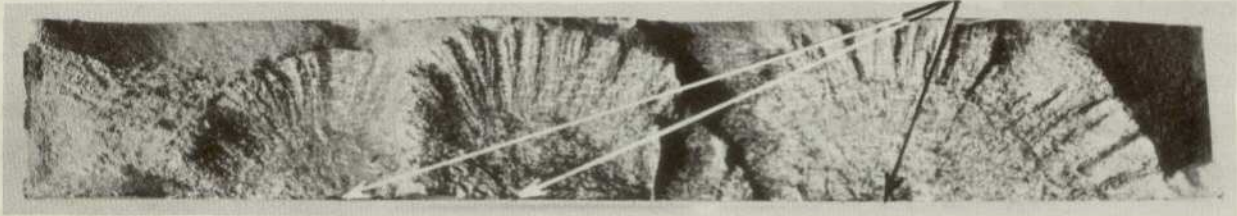
DRAWING NUMBER

OII. 002825

Fig.18

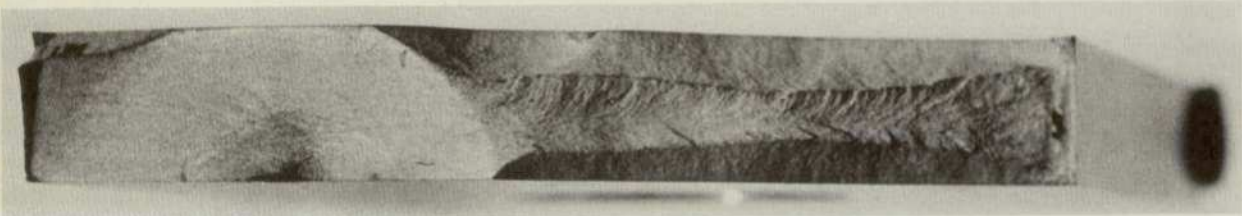


Typical failure

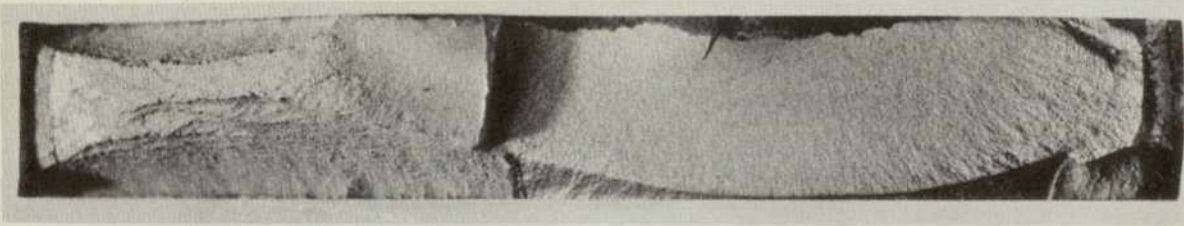


fatigue nuclei

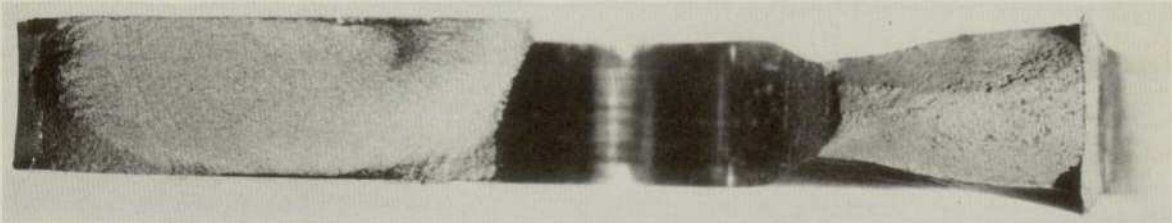
BS 2L65 aluminium alloy



BS TA11 titanium alloy



DTD 5212 maraging steel



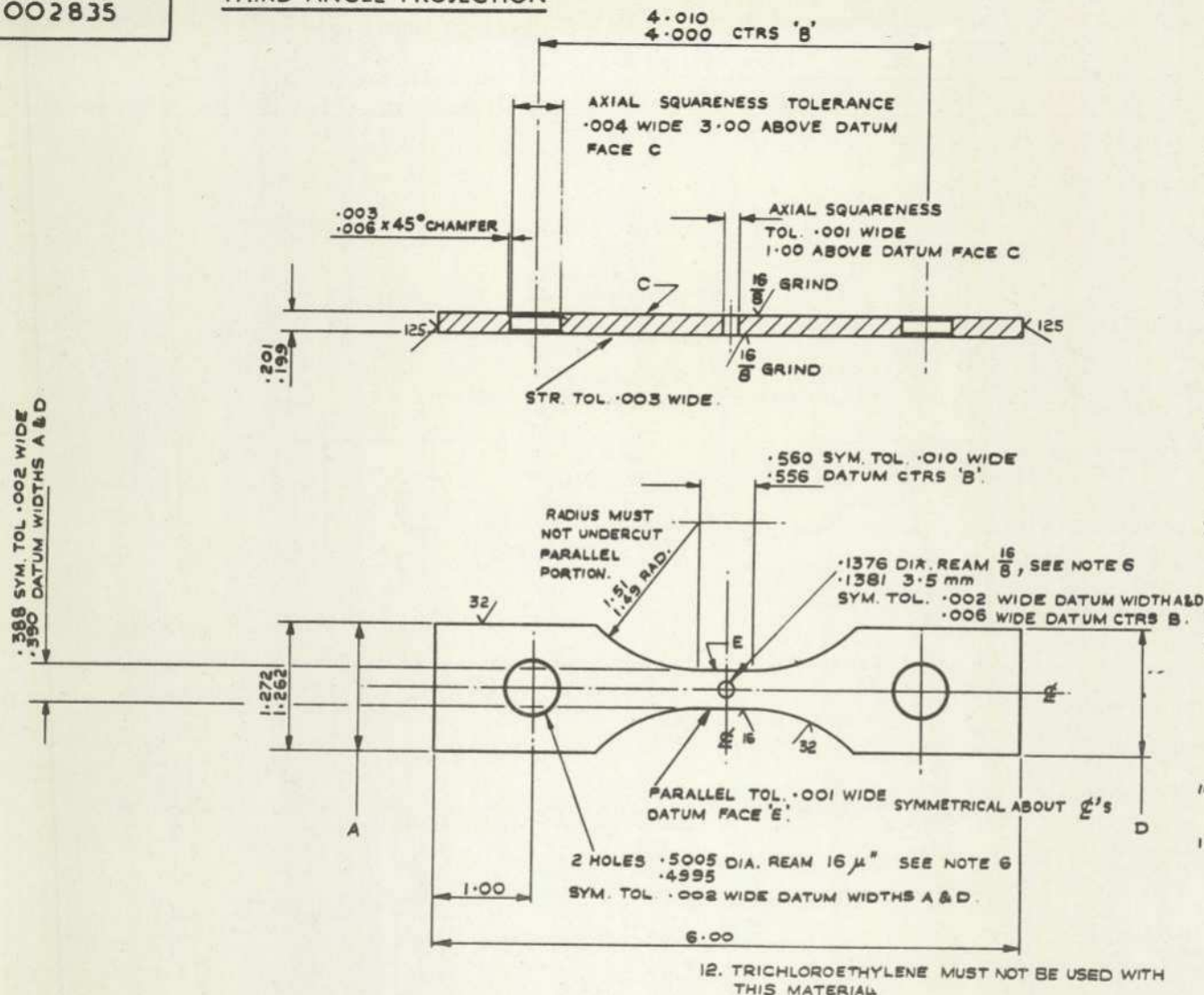
BS 2S98 NiCrMo steel

Fig.18 Fatigue fractures typical of clamped-lug specimens

011 002835

USED ON

THIRD ANGLE PROJECTION



1. ROUGH MACHINING TO BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED,
CHAMFER $.001 - .010 \times 45^\circ$
3. SHARP EDGES OF 3.5 mm.
HOLE TO BE LIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER $.001 - .005 \times 45^\circ$
4. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
5. BLANKS TO BE MACHINED TO LENGTH & IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED.
9. SPECIMENS TO BE PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS WITH SUITABLE DESSICANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
10. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ ".
11. 3.5 mm. HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING.

				C	14-7-7
				B	25-9-65
				A	9-5-65
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					

CONTRACTOR'S DRAWING REF.	
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DRAWING NUMBER

011 002835

Fig. 19

1980

CHECKED

TRACED
S. E. B.
29.4.69

DRAWN
BY W. CARDRICK

MATERIAL
B.S. 2L 65 BAR & B.S. TA 11
TITANIUM ALLOY BAR
TO BE SUPPLIED BY
FATIGUE RESEARCH
SECTION, STRUCTURES
DEPT. IN 12 FT
LENGTHS 1 1/2" x 3/8"

PROTECTIVE FINISH

TOLERANCES
± .010 UNLESS OTHERWISE
STATED.

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE

CONTRACTOR

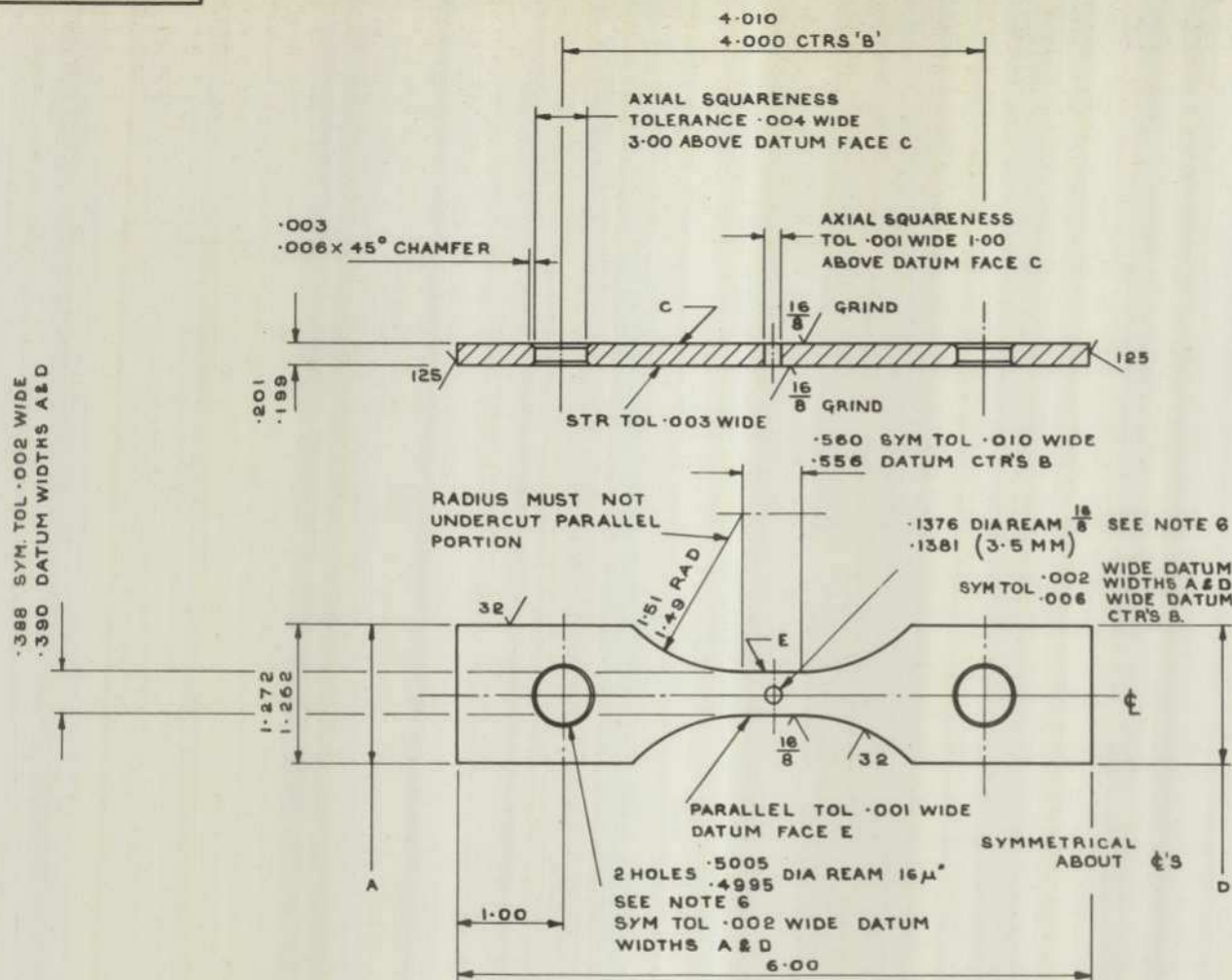
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

SERVICE LETTER

TITLE
2.3 K_t NOTCHED SPECIMEN IN BS. 2L 65 AND
BS. T A 11. (HELICOPTER PROGRAMME)

† 28

THIRD ANGLE PROJECTION



NOTE

- 1 ROUGH MACHINING TO BE DONE SYMMETRICALLY
- 2 EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001-.010x45°
- 3 SHARP EDGES OF 3.5MM HOLE TO BE LIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER .001-.005x45°
- 4 IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
- 5 BLANKS TO BE MACHINED TO LENGTH & IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
- 6 IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
- 7 PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
- 8 MATERIAL TO BE HARDENED AND TEMPERED TO SPECIFICATION BEFORE FINAL MACHINING
- 9 SPECIMENS TO BE OILED AND PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOX
- 10 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ " AND 8μ "
- 11 3.5MM HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING

				B	25-9-6
				X	9-5-6
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					

MATERIAL BS 2598 TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT IN ANNEALED BARS $1\frac{1}{2} \times \frac{3}{8} \times 12$ FT LONG	PROTECTIVE FINISH	TOLERANCES .010 UNLESS OTHERWISE STATED	CONTRACTOR		CONTRACTOR'S DRAWING REF. 129
			ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION	SERVICE LETTER	
		DIMENSIONS IN INCHES	TITLE 2.3K _t NOTCHED SPECIMEN IN BS 2598 (HELICOPTER PROGRAMME)		DRAWING NUMBER 011002836
		SURFACE ROUGHNESS			
		SCALE FULL SIZE			6

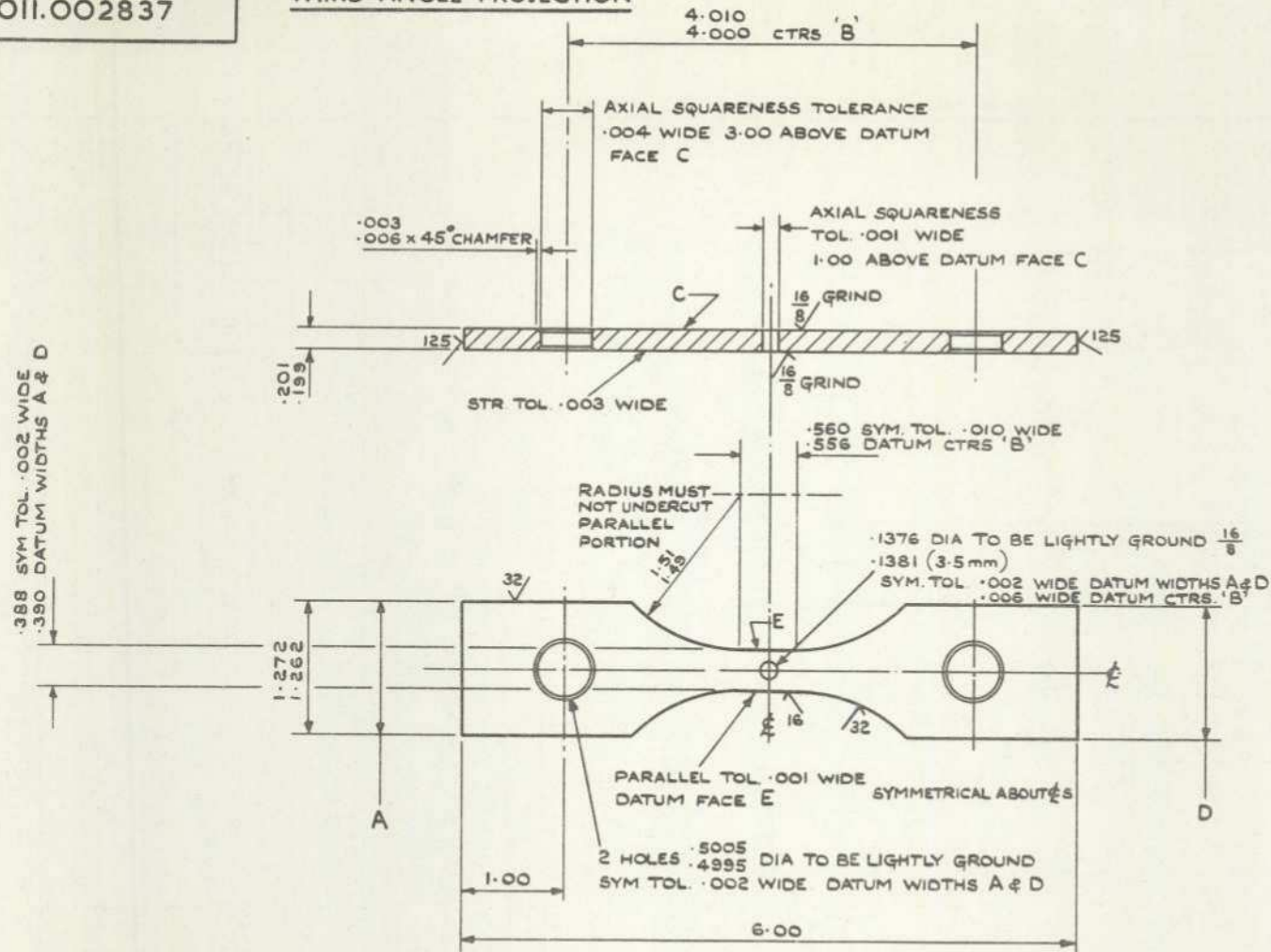
011.002837

THIRD ANGLE PROJECTION

4.010
4.009 ETR5 R

NOTES :-

1. ROUGH MACHINING TO BE DONE SYMMETRICALLY
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER $\cdot 001 - \cdot 010 \times 45^\circ$
3. SHARP EDGES OF 3.5 mm HOLE TO BE LIGHTLY REMOVED WITH FINE ABRASIVE PAPER, CHAMFER $\cdot 001 - \cdot 005 \times 45^\circ$
4. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED
5. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS STAMPED CENTRALLY ON BOTH FACES WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING
8. MATERIAL TO BE MARAGED TO SPECIFICATION BEFORE FINAL MACHINING
9. SPECIMENS TO BE OILED AND PROTECTED BY SEALING IN POLYTHENE BAGS. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES
10. WHERE $18/8$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ AND 8μ
11. 3.5 mm HOLE TO BE MACHINED AFTER FINAL SURFACE GRINDING



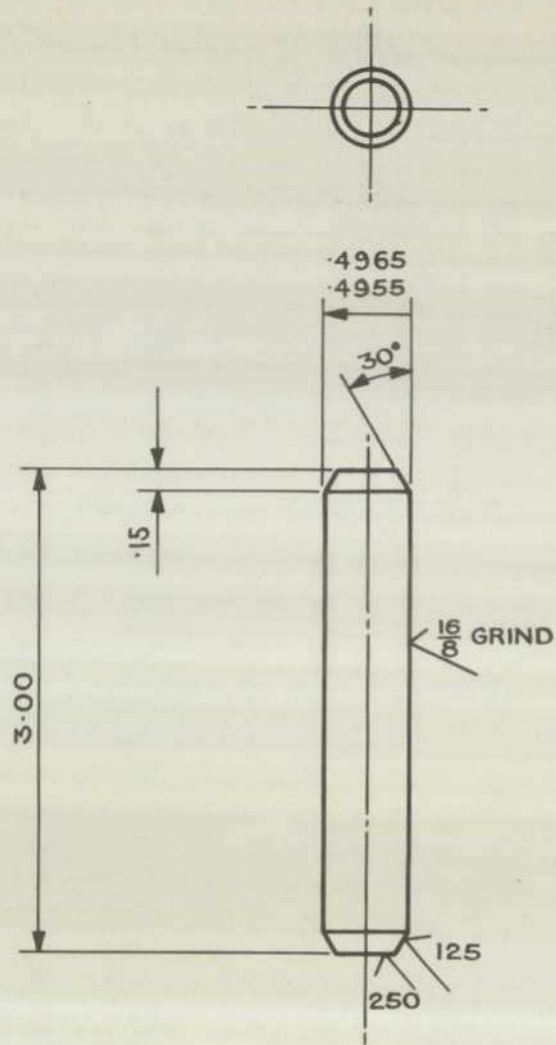
NTBD

CHECKED	MATERIAL DTD 5212 18NI-CO-MO O.V.M. MARAGING STEEL TO BE SUPPLIED SOLUTION TREATED SOFTENED IN 12 FT. LENGTHS 1 1/2 x 3/8	PROTECTIVE FINISH	TOLERANCES ± .010 UNLESS OTHERWISE STATED	CONTRACTOR		CONTRACTOR'S DRAWING REF. 130
TRACED O.P. 9-5-69			DIMENSIONS IN INCHES	ROYAL AIRCRAFT ESTABLISHMENT	MINISTRY OF AVIATION	
DRAWN	BY FATIGUE RESEARCH SECTION STRUCTURES DEPT		SURFACE ROUGHNESS	SERVICE LETTER		
AW/CARDRICK			SCALE	TITLE 2-3 K _t NOTCHED SPECIMEN IN DTD 5212 MARAGING STEEL (HELICOPTER PROGRAMME)		DRAWING NUMBER OIL.002837

F-19.21

Fig.22

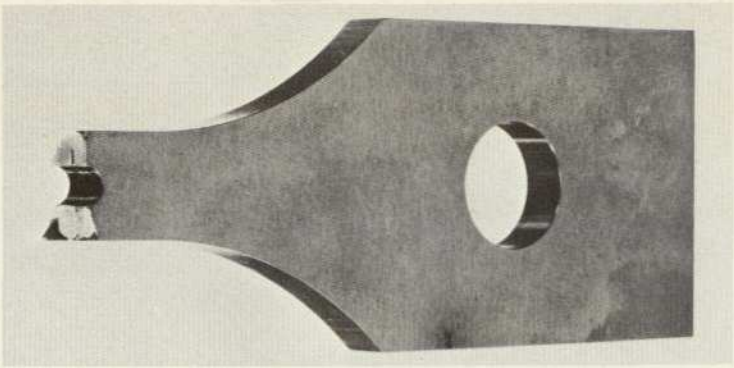
DRAWING NUMBER OII. 002838	THIRD ANGLE PROJECTION
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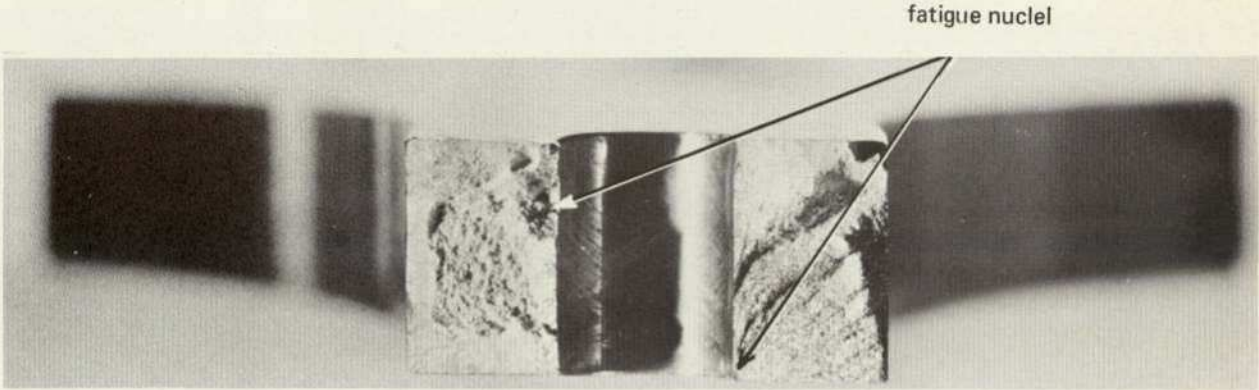
- NOTES :-
- 1. MATERIAL TO BE HARDENED AND TEMPERED TO SPEC. BEFORE FINAL MACHINING.
 - 2. CENTRE DRILL HOLES MAY BE LEFT AT ENDS.
 - 3. PINS TO BE OILED & PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS.

MATERIAL BS 2398 BAR, TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT. IN ANNEALED CONDITION IN 12 ft. LENGTHS x $\frac{5}{8}$ " DIA.	PROTECTIVE FINISH						
		MOD NO	ISSUE	DATE	MOD NO	ISSUE	DATE
DIMS. IN INCHES	SURFACE ROUGHNESS	CERTD.					
SCALE 1:1		TOLERANCES $\pm .010$ UNLESS OTHERWISE STATED					
CONTRACTOR							SERVICE LETTERS
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION		CONTRACTOR'S DRG. REF.					191
TITLE LOADING PIN FOR 2.3 Kt NOTCHED SPECIMENS HELICOPTER PROGRAMME		DRAWING NUMBER OII. 002838					

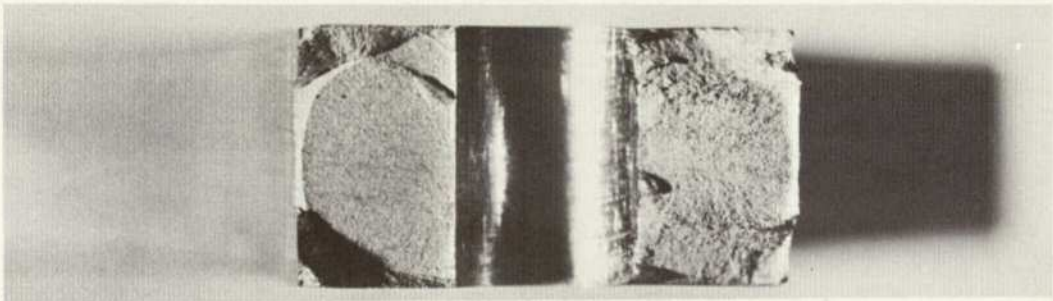
Fig.23



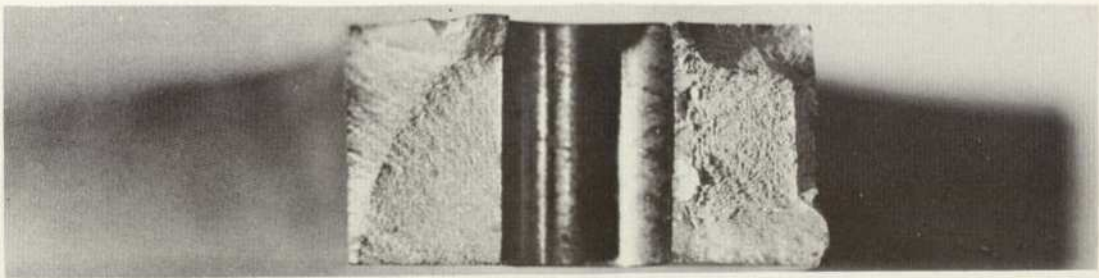
Typical failure



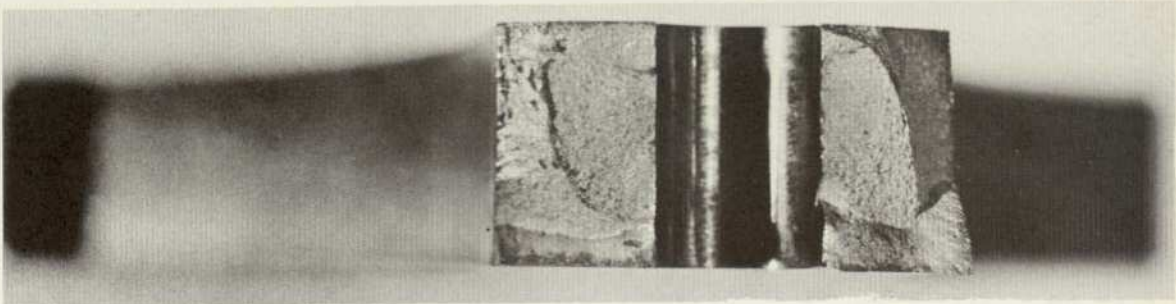
BS 2L65 aluminium alloy



BS TA11 titanium alloy



DTD 5212 maraging steel



BS 2S98 NiCrMo steel

Fig.23 Fatigue fractures typical of notched specimens

APPENDIX F

FATIGUE TESTS ON PLAIN SPECIMENS OF TITANIUM 6Al-4V UNDER
VARIABLE AMPLITUDE LOADING

RAE Technical Report 73029, March 1973

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 73029

Received for printing 6 February 1973

FATIGUE TESTS ON PLAIN SPECIMENS OF TITANIUM 6Al-4V UNDER
VARIABLE AMPLITUDE LOADING

by

A. W. Cardrick

B. H. E. Perrett

SUMMARY

Plain specimens extracted from annealed and stress relieved titanium 6Al-4V forged bar of 330mm × 57mm section were tested at zero mean stress, under constant amplitude and narrow band random loading.

A comparison of the fatigue performance under random loading with that predicted from the constant amplitude data using Miner's rule gives a value for $\sum \frac{n}{N}$ of approximately 0.3 for endurances in the region of 10^7 cycles. This falls within the band of values between 0.15 and 0.6 commonly obtained for aluminium alloys and mild steel tested under similar conditions.

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1 INTRODUCTION

The fatigue endurance of components subjected to variable amplitude loading is generally predicted from constant amplitude data using Miner's rule. Briefly, this states that if n is the number of cycles applied at a given stress amplitude S_i , and if N is the number of cycles of constant amplitude that would produce failure, then $\left(\frac{n}{N}\right)_i$ is the proportion of damage caused by all the cycles applied at the level S_i . Failure is predicted when the proportions of damage caused by the various levels add up to 1, i.e. when $\sum \frac{n}{N} = 1$.

Clearly, such a simple rule is subject to a number of inaccuracies and it is found that, for plain specimens of aluminium alloys and steels, values of $\sum \frac{n}{N}$ between about 0.15 and 0.6 are obtained for well-mixed load spectra, such as Gaussian narrow band random loading.

This Report presents comparable information for titanium 6Al-4V.

A limited number of plain specimens were tested under Gaussian narrow band random loading and the results indicate that the material behaves in much the same way as aluminium alloys and steels.

2 MATERIAL AND SPECIMENS

A drawing of the specimen is shown in Fig.1. Specimens were extracted longitudinally from a 330mm wide $\times$ 57mm thick forged titanium alloy bar to DTD 5173, annealed (700°C, 2 h, air cooled) and stress relieved (625°C, 4.5 h, air cooled). The chemical composition and mechanical properties of the material are presented in Table 1.

3 FATIGUE TESTS

The specimens were tested at zero mean stress and loaded axially at a frequency of 117 Hz. A short-base Schenck fatigue testing machine, adapted for electrodynamic excitation in the manner described elsewhere¹, was used for both the constant and variable amplitude loading.

Eight tests were made under constant amplitude loading in order to extend to longer endurance, data obtained earlier from the same bar using identical specimens². Results are shown in Fig.2. Curves were fitted through the endurance data using a least squares polynomial regression analysis with dependent variable $\log \sigma$. In order to assess the damage due to the peak stresses in the random spectrum, it was necessary to extrapolate the constant amplitude curve in Fig.2 to an rms alternating stress of approximately 500 MN/m². Two curves were drawn between the test data and the point

corresponding to the material tensile strength ($\frac{1}{2}$ fatigue cycle) in order to represent possible upper and lower limits of fatigue strength in this region.

Seven specimens were tested under variable amplitude loading. As far as possible, stress levels were chosen to give endurance of about 10^7 cycles in order to obtain long life data without introducing too much scatter. Measurements obtained with a statistical analyser showed that at these stress levels amplitudes of up to approximately five times the rms level occurred and, as shown by the straight lines in Fig.3, the spectrum conformed closely to a Rayleigh distribution. Lives obtained under random loading are shown in Fig.4, which also shows the lives predicted by Miner's rule from the constant amplitude data in Fig.2. As can be seen, the Miner prediction is insensitive to the extrapolation in the endurance range of interest.

4 DISCUSSION

Fig.4 shows that Miner's rule overestimates the endurance of the specimens by a factor of about 3, when the achieved endurance is approximately 10^7 cycles. The corresponding value for $\sum \frac{n}{N}$ of about 0.3 can be seen from Table 2 to be within the range of values (0.15 to 0.6) reported for aluminium alloys and mild steel³⁻⁸ tested under the same fatigue loading. It is noteworthy that the published data shown in Table 2 indicate some increase in the value of $\sum \frac{n}{N}$ at lower endurance; the single low endurance test point shown in Fig.4 is consistent with similar behaviour in the titanium alloy specimens. This increase in $\sum \frac{n}{N}$ may be attributable to a decrease in the proportion of damage due to low amplitude cycles below the constant amplitude fatigue limit.

The values of $\sum \frac{n}{N}$ discussed are all related to well-mixed load spectra and do not necessarily compare with those obtained under single step loading, which introduces rather special effects not found in service spectra.

5 CONCLUSIONS

Specimens representative of plain components of titanium 6Al-4V have been tested under constant amplitude and also under variable amplitude loading representative of service load spectra containing large numbers of low amplitude stresses.

A comparison of the variable amplitude endurance with that predicted by Miner's rule gives a value for $\sum \frac{n}{N}$ of about 0.3 for endurance in the region of 10^7 cycles. This suggests that the material behaves in much the same way as aluminium alloys and mild steel, for which values of between 0.15 and 0.6 are commonly obtained when these are tested under similar conditions.

Table 1

MATERIAL PROPERTIES

Chemical composition and mechanical properties of annealed and stress relieved DTD 5173 forged bar of 330mm × 57mm section (from Ref.2).

Chemical composition (% by weight)

6.11 Al, 4.01 V, 0.03 Fe, 0.18 O, 0.0012 H, balance Ti

Mechanical properties

limit of proportionality	- MN/m ²	(485 MN/m ²)
0.1% proof stress	847 MN/m ²	(870 MN/m ²)
0.2% proof stress	861 MN/m ²	(880 MN/m ²)
0.5% proof stress	882 MN/m ²	(905 MN/m ²)
Tensile strength	916 MN/m ²	(944 MN/m ²)
Stiffness, E	115 GN/m ²	(115 GN/m ²)
Elongation on 4 √A	14.0%	(15.0%)

Properties prior to stress relief are shown in brackets.

Table 2

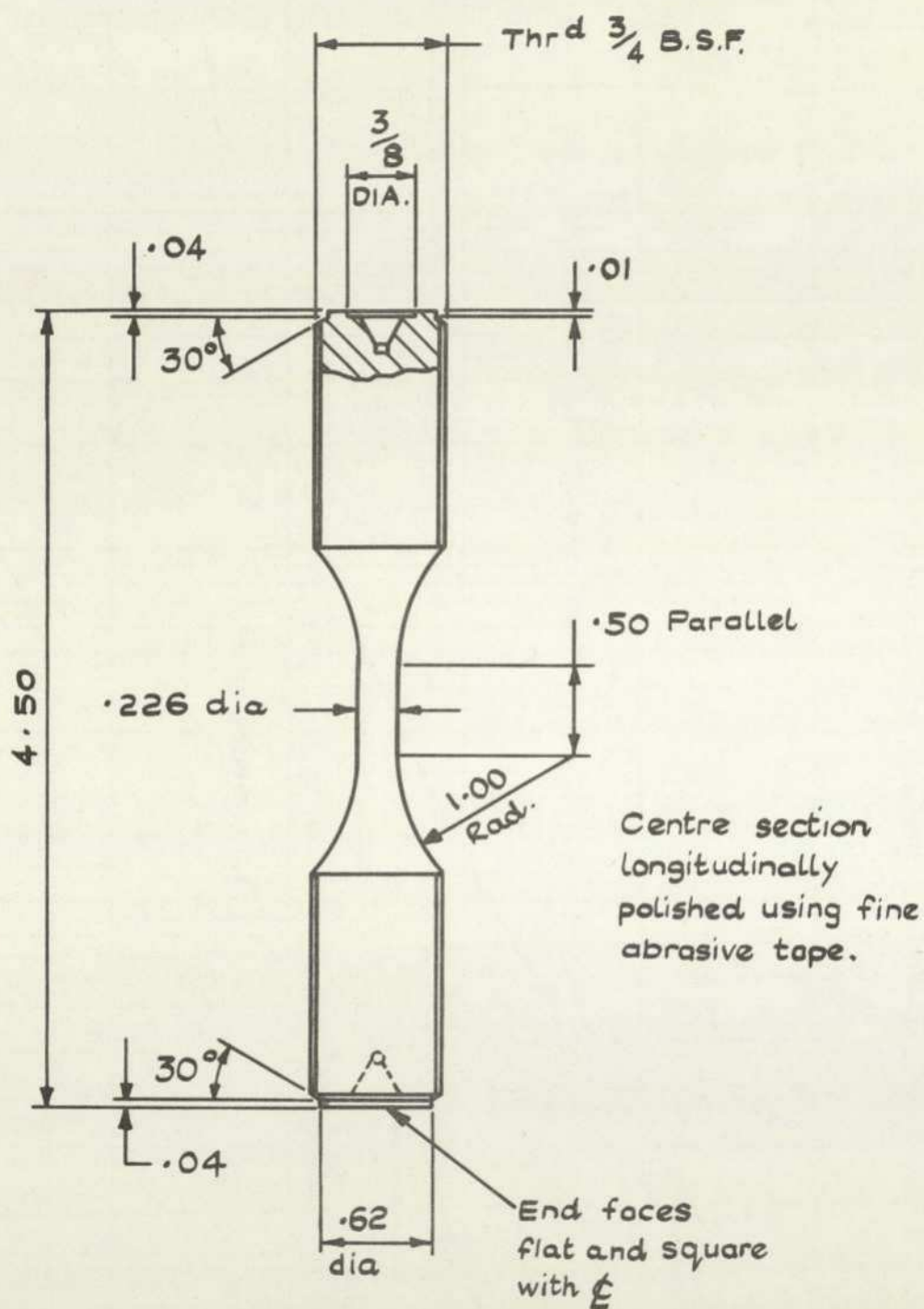
DATA FOR PLAIN SPECIMENS TESTED UNDER GAUSSIAN NARROW BAND RANDOM LOADING

Material	Mean stress MN/m ²	Approximate value of $\sum \frac{n}{N}$ at nominal endurance:-		Investigator
		10 ⁵ cycles	10 ⁶ - 10 ⁷ cycles	
BS 2L65 aluminium alloy	0	1.1	0.6	Billingham and Ryman, Ref.3
2024-T4 aluminium alloy	110	0.2	0.2	Swanson, Ref.4
2024-T3 aluminium alloy	0	0.35	0.2	Hillberry, Ref.5
	0	0.5	0.3	Brown and Ikegami, Ref.6
	0	0.3	0.2	Fuller, Ref.7
	0	0.2	0.15	
6061-T6 aluminium alloy	0	0.5	0.3	Brown and Ikegami, Ref.6
Mild steel EN 1A	0	-	0.4	Booth, Wright and Smith, Ref.8
Mild steel EN 15	0	-	0.4	

REFERENCES

<u>No.</u>	<u>Author</u>	<u>Title, etc.</u>
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4	S.R. Swanson	An investigation of the fatigue of aluminium alloy due to random loading. Inst. of Aerophysics, University of Toronto UTIA Report No.84, February 1963
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6	G.W. Brown R. Ikegami	The fatigue of aluminium alloys subjected to random loading. Experimental Mechanics, August 1970
7	J.R. Fuller	Research on techniques of establishing random type fatigue curves for broad band sonic loading. SAE Paper 671C, April 1963
8	R.T. Booth D.H. Wright N.P. Smith	Variable-load fatigue tests on small specimens. Second Report: A comparison of loading patterns and the influence of occasional high loads. MIRA Report 1969/9, April 1969

Fig.1



Dimensions in inches.
(Preferred unit at time of manufacture)

Scale Full size

Fig.1 Plain fatigue test specimen

Titanium 6Al 4V: plain specimens: zero mean stress
constant amplitude loading

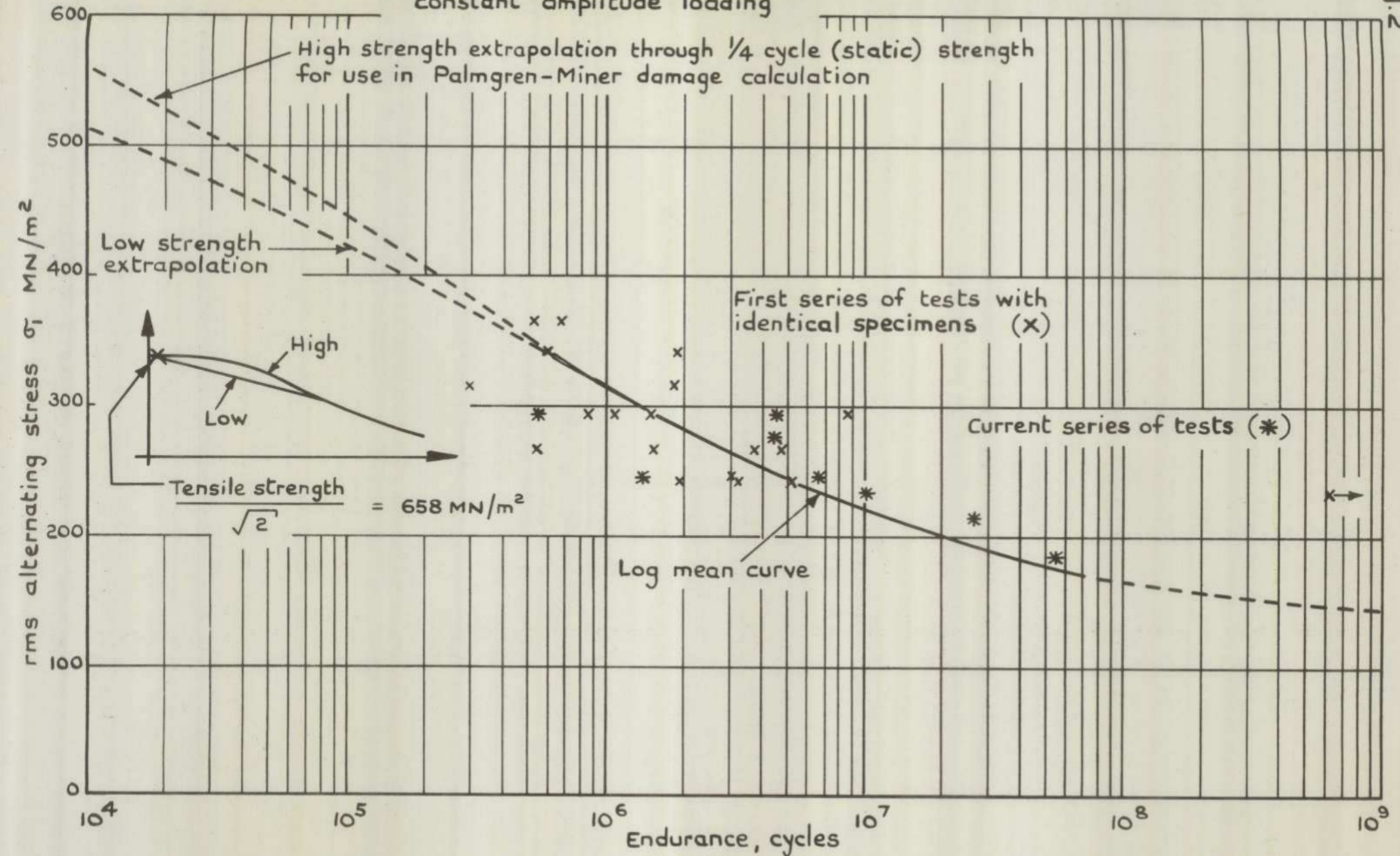


Fig.2 Endurance of specimens under constant amplitude loading

Fig.3

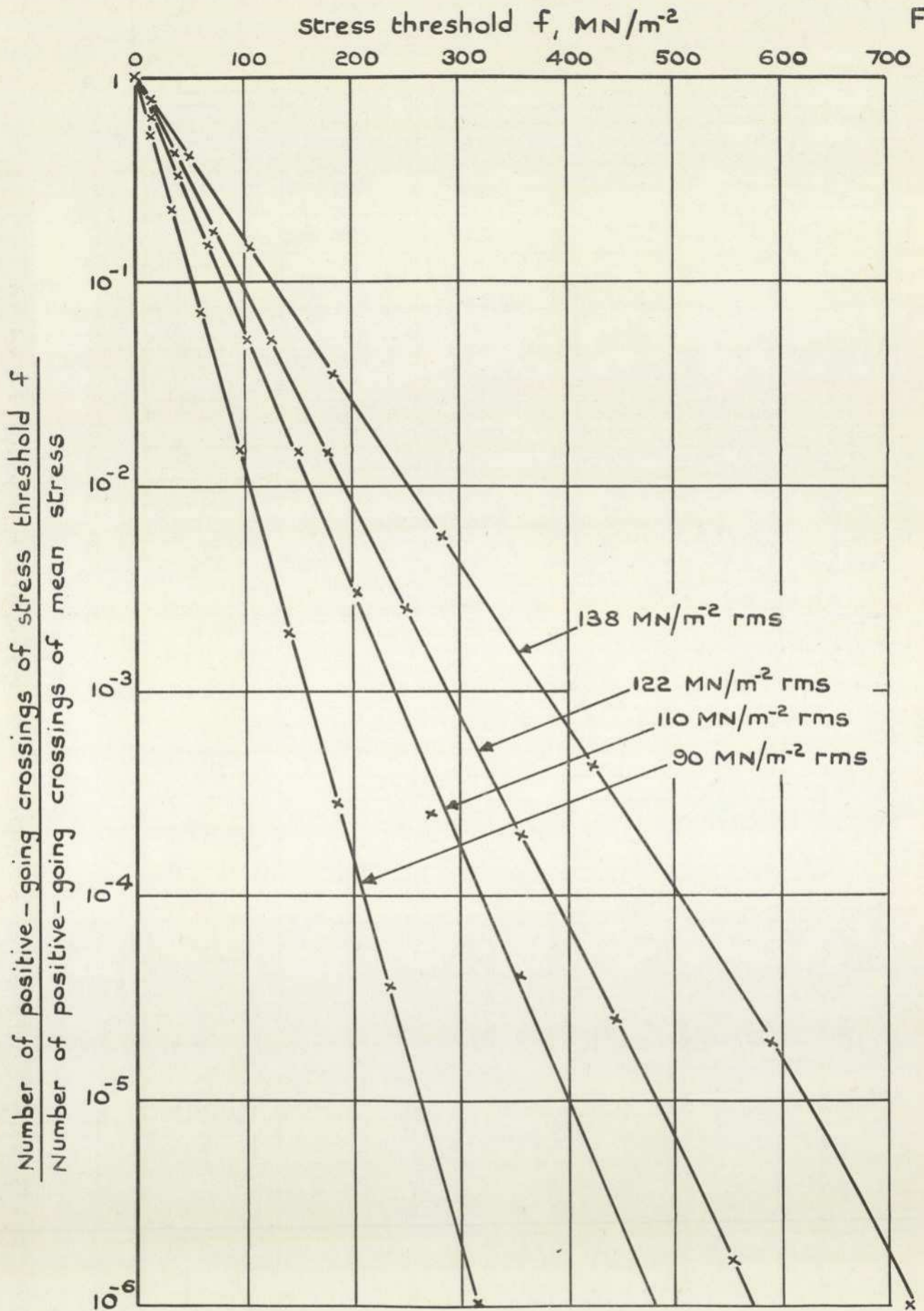


Fig.3 Measurements of cumulative level crossings under variable amplitude loading

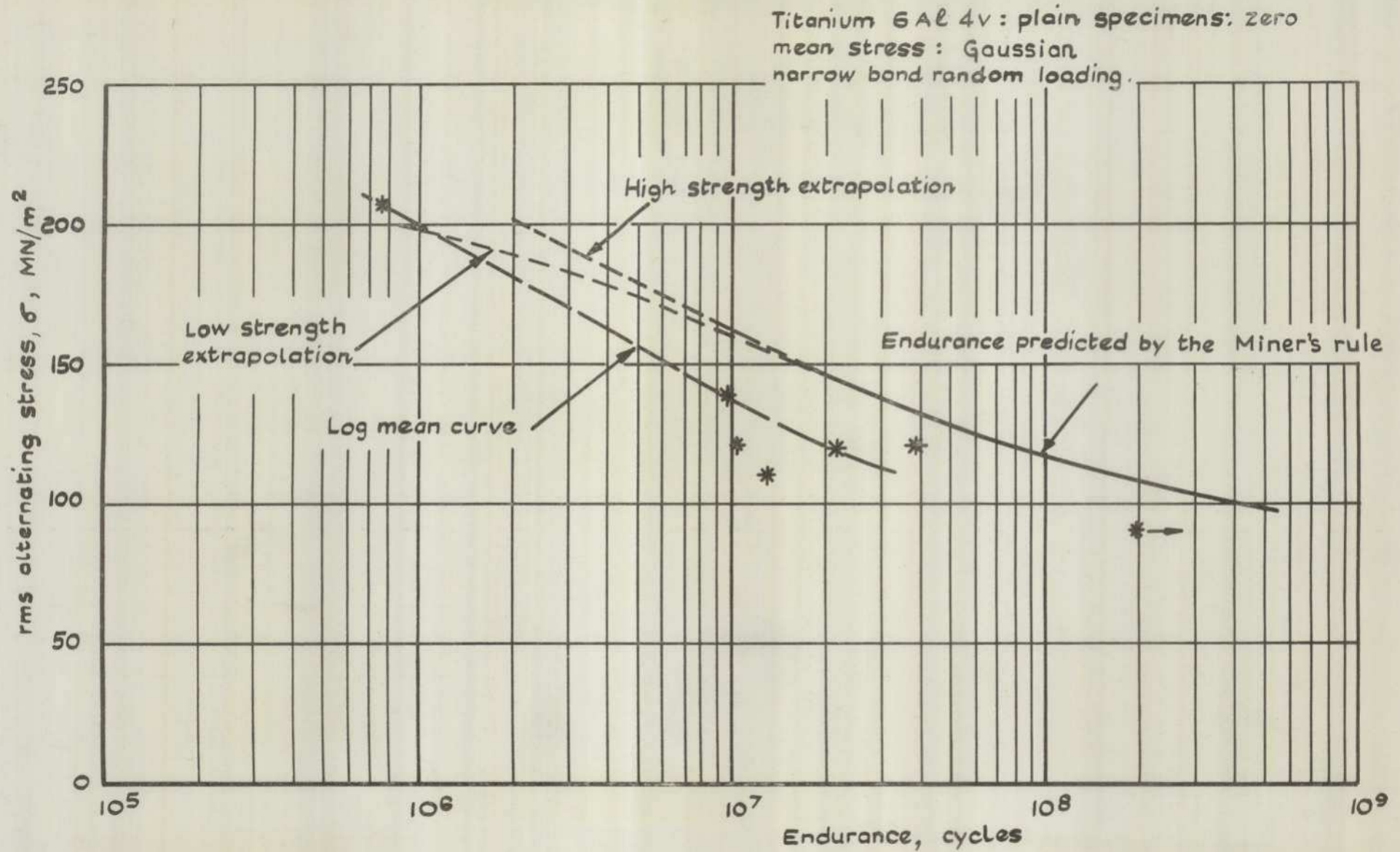


Fig. 4 Endurance of specimens under variable amplitude loading

APPENDIX G

AN ASSESSMENT OF THE STRUCTURAL FATIGUE PERFORMANCE
OF AN EXPERIMENTAL Al 4% Mg 4% Zn ALLOY

Draft RAE Technical Report, June 1973

R O Y A L A I R C R A F T E S T A B L I S H M E N T

Draft Technical Report

June 1973

AN ASSESSMENT OF THE STRUCTURAL FATIGUE PERFORMANCE
OF AN EXPERIMENTAL Al 4% Mg 4% Zn ALLOY

by

A. W. Cardrick

B. H. E. Perrett

B. Gosden

SUMMARY

The fatigue performance of an experimental Al 4% Mg 4% Zn alloy intended for aircraft forgings has been compared with that of DTD 5024, an aluminium alloy currently used in such applications.

Pinned-lug and moderately notched specimens ($K_t = 2.3$) were used in order to represent structural features, and these were tested under variable amplitude loading representative of service conditions.

It is concluded that the experimental alloy has a slightly lower fatigue performance than DTD 5024 in both Stage 1 and Stage 2 of fatigue. However, in moderately notched unfretted components subjected to tensile yield, its slightly lower Stage 1 performance may be offset by the greater beneficial residual stresses attracted by its lower tensile yield strength.

Departmental Reference: YSE/B/0462

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1 INTRODUCTION

Fatigue failures in structural components are usually associated with such features as stress concentrations and regions of fretting. In order to obtain an indication of the structural fatigue performance of a new material, it is important to use specimens which contain these features and to test under variable amplitude loading representative of that encountered in service.

In Structures Department, RAE, features such as fretting at an appreciable stress concentration and moderate structural discontinuities without fretting are represented by two types of specimen, a pinned-lug and a notch. In order to represent the mixed amplitudes which occur in most service load spectra, it is usual to test under an elementary form of variable amplitude loading - Gaussian narrow band random loading with a Rayleigh distribution of amplitudes truncated at about four times the rms level.

This Report presents data of this type for a limited number of specimens of an experimental Al 4% Mg 4% Zn alloy intended for aircraft forgings. Similar numbers of specimens of DTD 5024 aluminium alloy, a material currently used in such applications, have also been tested for comparison. The materials and specimens are described in section 2, fatigue tests are described in section 3 and the results obtained are discussed in section 4. In section 5 it is concluded that the experimental alloy is likely to be weaker than the DTD 5024 except in moderately notched unfretted components, where it may be slightly stronger due to the greater beneficial residual stresses attracted by its lower tensile yield strength.

2 MATERIAL AND SPECIMENS

2.1 Material

Both materials were supplied in the form of cast, forged and solution treated bars measuring 160mm long with a cross-section of approximately 150 mm $\times$ 80 mm. The nominal chemical composition and typical tensile properties of each material are given in Table 1.

2.2 Specimens

Pinned-lug and notched specimens of the type chosen for this investigation¹ are being used in cumulative damage research in Structures Department. They are based on a single blank size measuring approximately 36mm $\times$ 8mm $\times$ 160mm long. Thirty of these blanks were cut from each material and these were divided

between pinned-lugs and notches in the ratio 12/18 to make some provision for scatter.

Figs.1 and 2 show* the pinned-lug specimen and the close-fitting loading pin; the clearance on assembly is between 8 μm and 28 μm . Failures occur in the lug from fretting nucleation at the minimum net section through the diameter of the pin, where the stress concentration factor², K_t , on net stress is about 3.0. Typical examples of failures in the two materials are shown in Fig.3.

Fig.4 shows the notched specimen. In this case nucleation occurs in the region of maximum stress concentration ($K_t = 2.3$, from Ref.2) through the bore of the hole. Typical examples of failures in the two materials are shown in Fig.5.

3 FATIGUE TESTS

In order to represent service loading conditions, the pinned-lug specimens were tested at a mean stress of 100 MN/m^2 (approximately 20 per cent of the static strength of the materials). The notched specimens, where fatigue initiation conditions are less severe, were tested at a mean stress of 125 MN/m^2 . The stresses were based on the failure sections in each case, i.e. the net area at the 12.5mm diameter hole in the pinned-lug and that at the 3.5mm diameter hole in the notched specimen.

The specimens were tested in an Amsler Vibrophore machine adapted, as described elsewhere³, to apply narrow band random loading at a frequency of about 150 Hz. A typical loading waveform - obtained from strain gauges on the dynamometer - is shown in Fig.6. At all but the higher stresses the loading conforms to a Rayleigh distribution of amplitudes. At amplitudes above about four times the rms level, truncation occurs due to mechanical non-linearities such as those caused when the minimum load on the loading pins approaches zero. This behaviour was much the same in both materials, but for completeness - this data may be required in subsequent cumulative damage studies - the truncation levels are given in Table 2. Stress levels were chosen to cover the endurance range between about 10^5 and 10^8 cycles and curves were fitted through the data using a polynomial regression (least squares) analysis described elsewhere⁴.

The relative fatigue performance of the two materials in pinned-lug form is shown in Fig.7 and their performance in notched form is shown in Fig.8.

* Imperial units were used at the time of specimen design.

4 DISCUSSION

Fig.7 shows that in pinned-lug form the experimental alloy has a lower fatigue performance than the DTD 5024 at all endurance below about 10^7 cycles. In this type of specimen, the classical Stage 1 initiation process (after Forsyth⁵) - reversed slip along planes closely aligned to the direction of maximum shear stress - is supplanted by fretting. In aluminium alloys the fretting initiation process under Gaussian narrow band random loading is complete in the first few per cent of the life^{6,7}, so that Stage 2 - tension mode crack propagation - predominates. So the pinned-lug gives a measure of the relative Stage 2 fatigue endurance in the two materials.

In the notched specimen, on the other hand, the Stage 1 initiation process predominates⁸ and, as may be seen from Fig.8, the experimental alloy in this case shows a slightly higher fatigue performance than the DTD 5024.

It is noteworthy that the nominal yield stress of the experimental alloy - as given in Table 1 - is about 5 per cent lower than that of the DTD 5024. Under all test conditions, except the lowest stress level for the pinned-lug, the maximum amplitudes in the load spectrum were sufficient to cause plastic deformation at the stress concentrations in both materials - and hence induce compressive residual stresses in the region of fatigue initiation. The effect of these residual stresses is to reduce the local mean stress and thereby increase the fatigue endurance. Specifically, in both types of specimen the nominal local mean stress in both materials was about 300 MN/m^2 at the lower stress levels, reducing to about 50 MN/m^2 at the higher levels. Because of the lower yield stress of the experimental alloy, its local mean stress was generally about 20 MN/m^2 lower than that in the DTD 5024 and for this reason the experimental alloy could be expected to give slightly longer endurance. Whilst this bias in favour of the experimental alloy will not affect the conclusion that it has a lower performance when Stage 2 predominates (as deduced from the pinned-lug specimens), it may contribute to its apparently higher performance when Stage 1 predominates (as deduced from the notched specimens). An estimate of the lower notched strength of the experimental alloy due to an increase in mean stress of 20 MN/m^2 can be made if it is assumed - in the absence of suitable variable amplitude data - that the shape of the constant amplitude alternating/mean stress diagram for solution treated aluminium-zinc alloys⁹ is appropriate for variable amplitude loading. With this adjustment, the notched curve for the experimental alloy - Fig.8 - is lowered by about 1.5 MN/m^2 at the

lower stress levels and by about 3 MN/m^2 at the higher stresses. This suggests that the experimental alloy has in fact a slightly lower Stage 1 fatigue performance than the DTD 5024.

5 CONCLUSIONS

It is concluded from tests on notched and pinned-lug specimens that the experimental alloy has a slightly lower fatigue performance than DTD 5024 in both Stage 1 and Stage 2 of fatigue.

However, in moderately notched unfretted components subjected to tensile yield, its slightly lower Stage 1 performance may be offset by the greater beneficial residual stresses attracted by its lower tensile yield strength.

Table 1

NOMINAL CHEMICAL COMPOSITION AND TYPICAL TENSILE PROPERTIES
OF THE TWO ALUMINIUM ALLOYS

Experimental Al 4% Mg 4% Zn alloy

Chemical composition, % 4.0 Mg, 4.0 Zn, 0.2 Si, 0.2 Zr, balance Al
 Tensile properties UTS 465 MN/m²
 0.1% proof stress 385/400 MN/m²

DTD 5024

Chemical composition, % 5.7 Zn, 2.7 Mg, 0.5 Mn, 0.5 Cu, balance Al
 Tensile properties UTS, not less than 495 MN/m²
 0.1% proof stress, not less than 415 MN/m²

Table 2

TRUNCATION LEVELS UNDER GAUSSIAN NARROW BAND RANDOM LOADING

Specimen type	rms alternating stress, σ , MN/m ²	Measured truncation level, T, (highest amplitude = $T \times \sigma$)
pinned-lug	0-14	4.3
	15-24	4.2
	25-35	3.8
notch	0-29	5.0
	30-34	4.7
	35-39	4.2
	40-50	4.0

REFERENCES

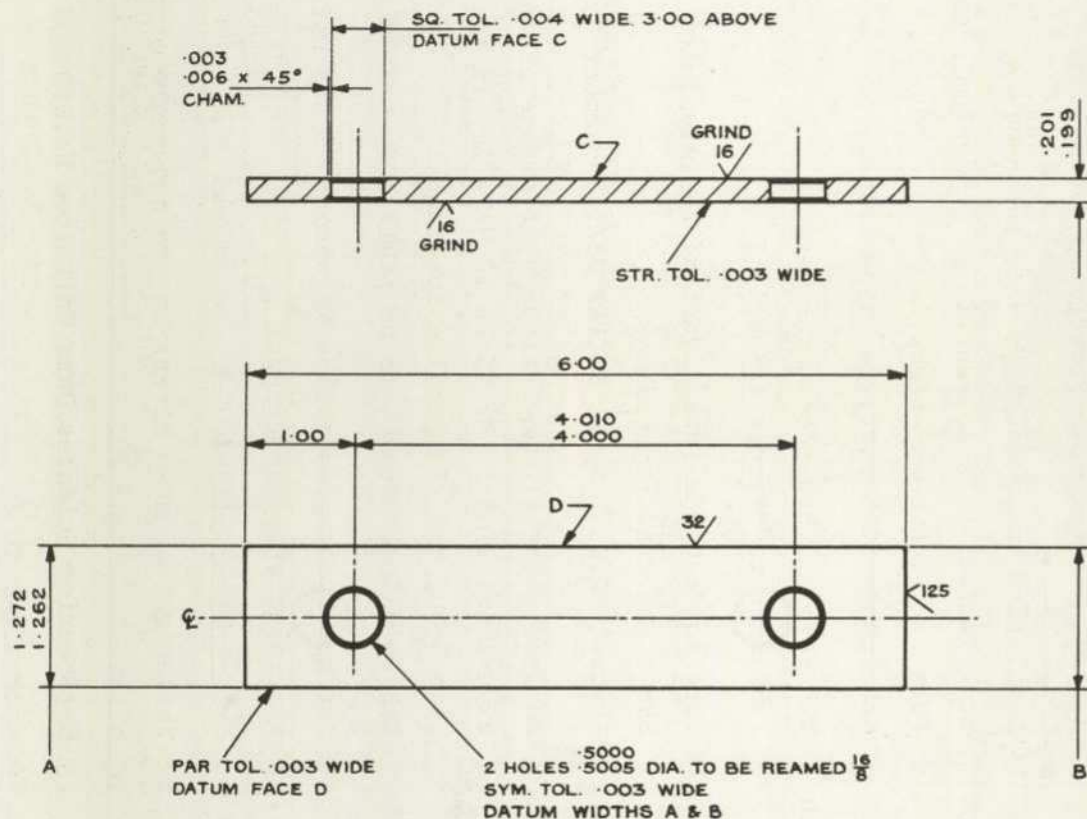
<u>No.</u>	<u>Author</u>	<u>Title, etc.</u>
1	A.W. Cardrick B.H.E. Perrett	On the design of pinned-lug, clamped-lug and notched fatigue test specimens in aluminium alloy, titanium alloy and steel. RAE Technical Report 73003 (1973)
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9	RAeS/I.Mech.E	The effect of mean stress on the endurance of aluminium alloys. Engineering Sciences Data Unit Item No.E.07.03 (1965)

USED ON

THIRD ANGLE PROJECTION

NOTES:-

1. ROUGH MACHINING SHALL BE DONE SYMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED, CHAMFER .001 - .010 x 45°
3. IT IS ESSENTIAL THAT TOLERANCES ARE NOT EXCEEDED.
4. BLANKS TO BE MACHINED TO LENGTH AND IDENTIFICATION NUMBERS TO BE STAMPED CENTRALLY ON BOTH END FACES. WITH BASE OF NUMBER PARALLEL TO DATUM FACE C
5. SPECIMENS TO BE PROTECTED BY SEALING IN POLYTHENE BAGS WITH SUITABLE DESSICANT. CONVENIENT BATCHES TO BE PACKED IN WOODEN BOXES.
6. IT IS ESSENTIAL THAT THE HOLE FINISHES SHALL BE FREE FROM THE SLIGHTEST SCRATCH OR MACHINE MARK.
7. PARTICULAR CARE MUST BE TAKEN TO AVOID LOCAL HEATING DURING MACHINING.
8. MATERIAL MUST NOT BE HEAT TREATED
9. WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN 16μ & 8μ .
10. TRICHLOROETHYLENE MUST NOT BE USED WITH THIS MATERIAL



						B	14-7-70
							9-5-65
MOD. No.	ISSUE	DATE		MOD. No.	ISSUE	DATE	
CERTIFIED							

CONTRACTOR'S DRAWING REF.

12.

DRAWING NUMBER	
----------------	--

011.002821

Fig. 1

NTBD

CHECKED

TRACED

4 LONG

21-4-69

DRAWN

HE DEARS

MATERIAL

PROTECTIVE FINISH

TOLERANCES

‡ .010
UNLESS OTHERWISE STATED

DIMENSIONS IN INCHES

SURFACE ROUGHNESS

SCALE

CONTRACTOR

ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION

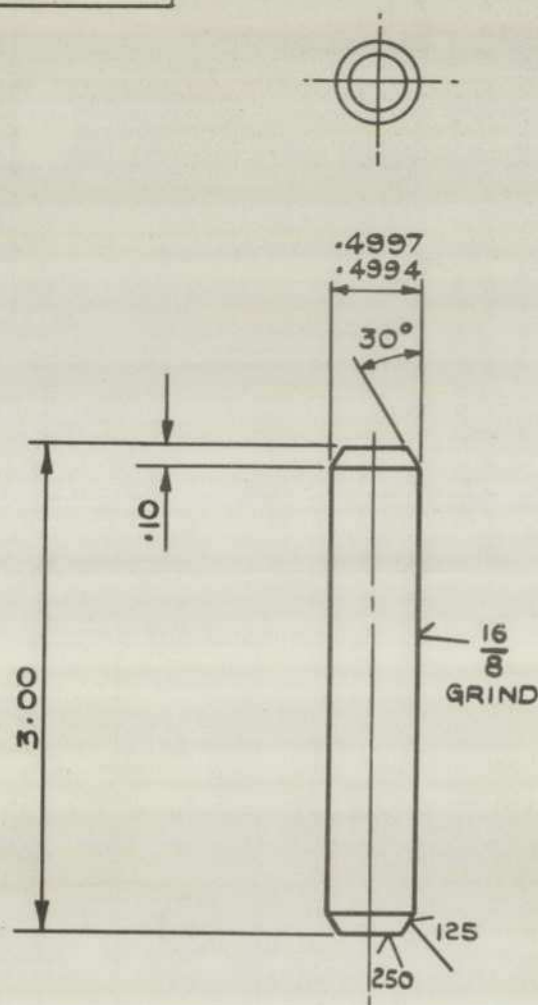
SERVICE LETTER

TITLE

FINNED LUG SPECIMEN

DRAWING NUMBER	
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011.002821

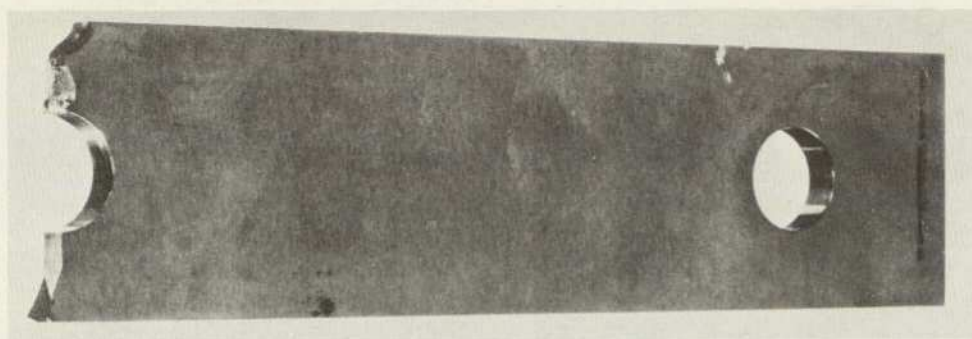


NOTES :-

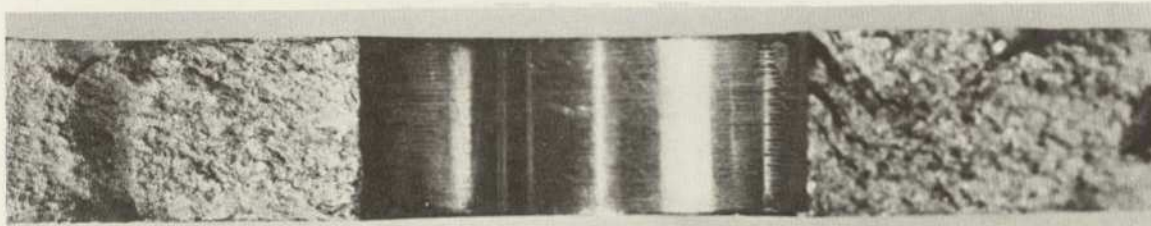
1. MATERIAL TO BE HARDENED AND TEMPERED TO SPEC. BEFORE FINAL MACHINING.
2. CENTRE DRILL HOLES MAY BE LEFT AT ENDS.
3. PINS TO BE OILED & PROTECTED BY SEALING IN INDIVIDUAL POLYTHENE BAGS.

WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE FINISH MUST BE BETWEEN $16\mu"$ & $8\mu"$.

MATERIAL B.S. 2598 BAR, TO BE SUPPLIED BY FATIGUE RESEARCH SECTION STRUCTURES DEPT. IN ANNEALED CONDITION IN 12 ft LENGTHS X 5/8" DIA.	PROTECTIVE FINISH						
		MOD N ^o	ISSUE	DATE	MOD N ^o	ISSUE	DATE
		CERTD.					
DIMS. IN INCHES	SURFACE ROUGHNESS	TOLERANCES $\pm .010$ UNLESS OTHERWISE STATED					
SCALE 1/1							
CONTRACTOR							SERVICE LETTERS
ROYAL AIRCRAFT ESTABLISHMENT MINISTRY OF AVIATION							CONTRACTOR'S DRG. REF. 187
TITLE LOADING PIN FOR PINNED LUG SPECIMENS (HELICOPTER PROGRAMME)							DRAWING NUMBER OII 002824



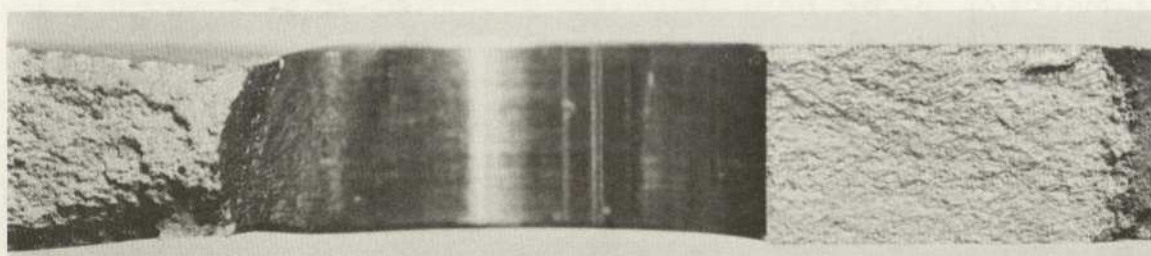
Typical failure



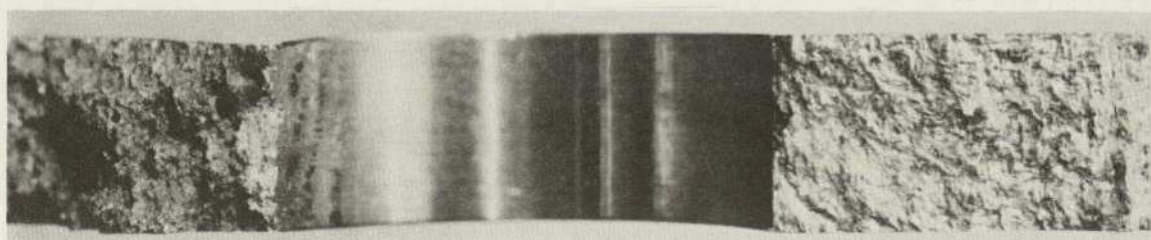
30 MN/m² rms experimental alloy



30 MN/m² rms DTD 5024



5 MN/m² rms experimental alloy



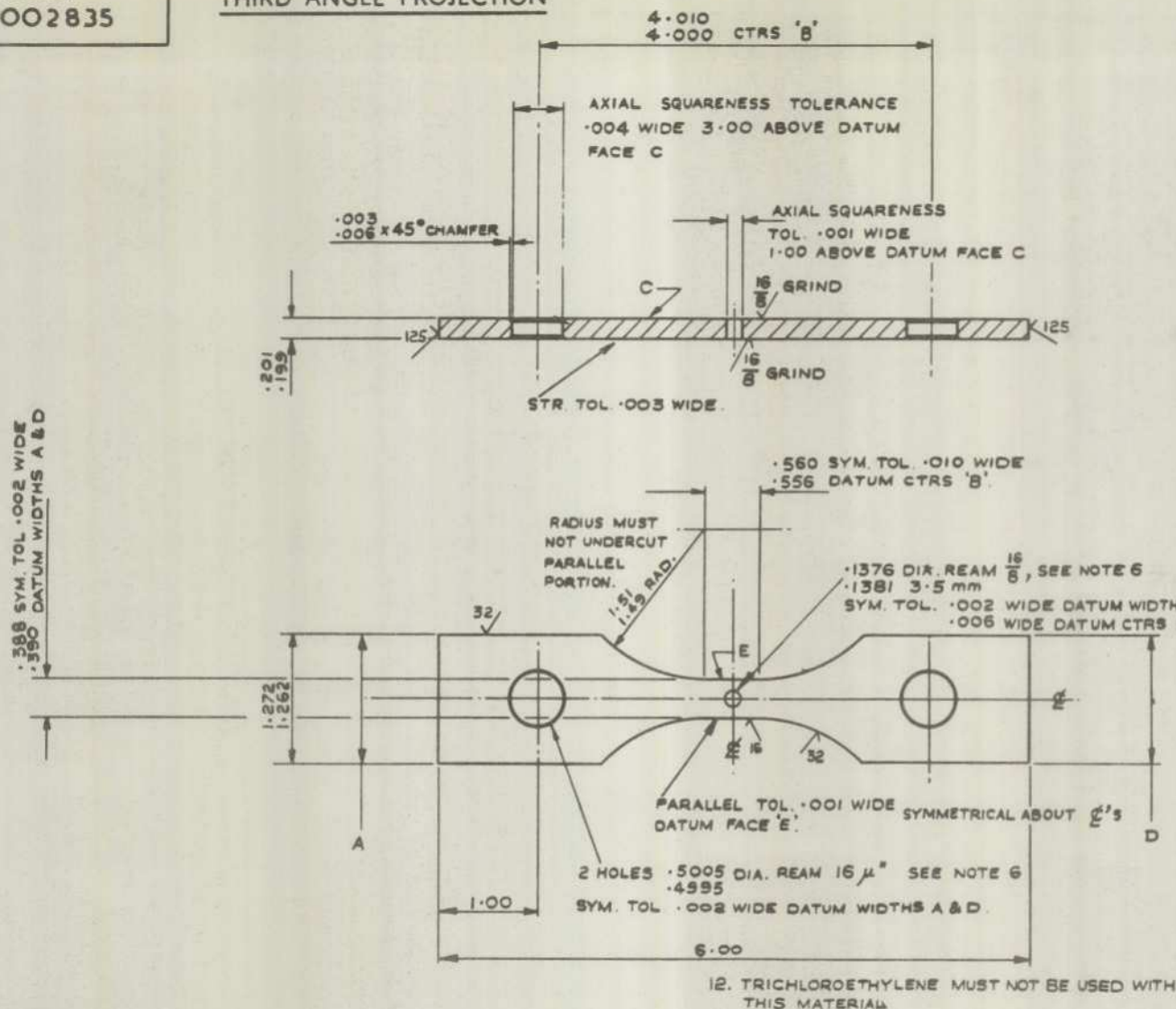
5 MN/m² rms DTD 5024

Fig.3 Fatigue fractures typical of pinned-lug specimens

011 002835

THIRD ANGLE PROJECTION

USED ON



NOTES

1. ROUGH MACHINING TO BE DONE SYMMETRICALLY.
2. EDGES OF PROFILE TO BE CAREFULLY DEBURRED,
CHAMFER $.001 - .010 \times 45^\circ$
- 3 SHARP EDGES OF 3.5 mm.
HOLE TO BE LIGHTLY REMOVED WITH
FINE ABRASIVE PAPER, CHAMFER
 $.001 - .005 \times 45^\circ$
- 4 IT IS ESSENTIAL THAT
TOLERANCES ARE NOT EXCEEDED
- 5 BLANKS TO BE MACHINED TO
LENGTH & IDENTIFICATION NUMBERS
STAMPED CENTRALLY ON BOTH FACES
WITH BASE OF NUMBER PARALLEL
TO DATUM FACE C.
- 6 IT IS ESSENTIAL THAT THE
HOLE FINISHES SHALL BE FREE
FROM THE SLIGHTEST SCRATCH
OR MACHINE MARK
- 7 PARTICULAR CARE MUST BE
TAKEN TO AVOID LOCAL HEATING
DURING MACHINING.
- 8 MATERIAL MUST NOT BE HEAT TREATED.
- 9 SPECIMENS TO BE PROTECTED BY
SEALING IN INDIVIDUAL POLYTHENE
BAGS WITH SUITABLE DESSICANT.
CONVENIENT BATCHES TO BE
PACKED IN WOODEN BOXES.
- 10 WHERE $\frac{16}{8}$ IS SPECIFIED THE SURFACE
FINISH MUST BE BETWEEN 16μ " AND 8μ "
- 11 3.5 mm. HOLE TO BE MACHINED AFTER FINAL
SURFACE GRINDING

				C	14-7-7
				B	25-9-6
				A	9-5-6
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
CERTIFIED					

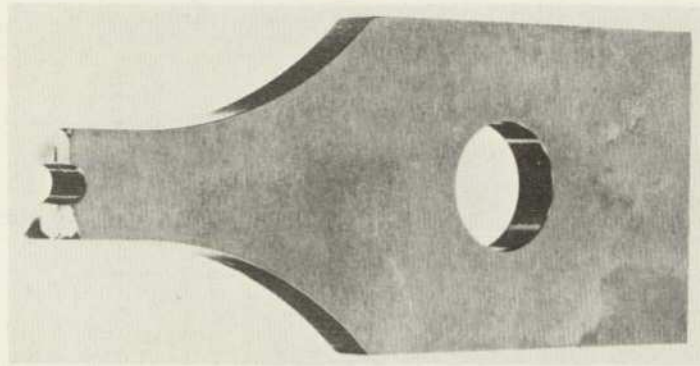
CONTRACTOR'S DRAWING REF.	
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	128	Ap
DRAWING NUMBER		

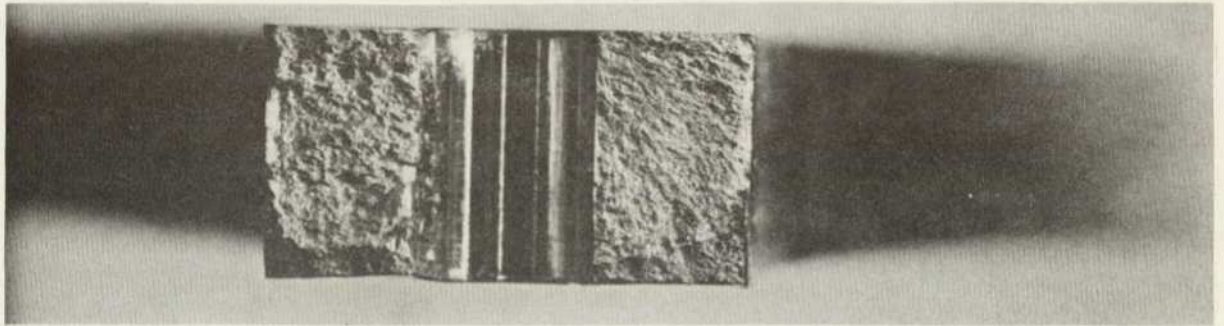
011 002835

1980

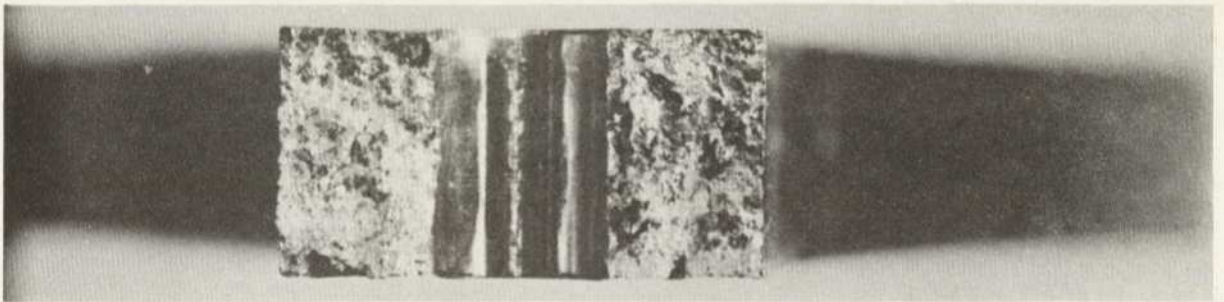
CHECKED	MATERIAL	PROTECTIVE FINISH	TOLERANCES ± .010 UNLESS OTHERWISE STATED	CONTRACTOR	
TRACED 5.4.8.8. 20.4.69				ROYAL AIRCRAFT ESTABLISHMENT	MINISTRY OF AVIATION
DRAWN			DIMENSIONS IN INCHES	TITLE	
W. CARDRICK			SURFACE ROUGHNESS	2.3 K _t NOTCHED SPECIMEN	
			SCALE		



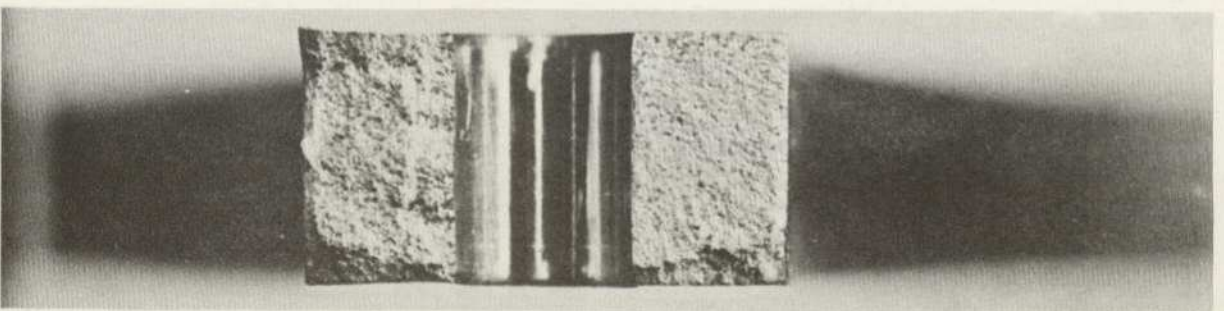
Typical failure



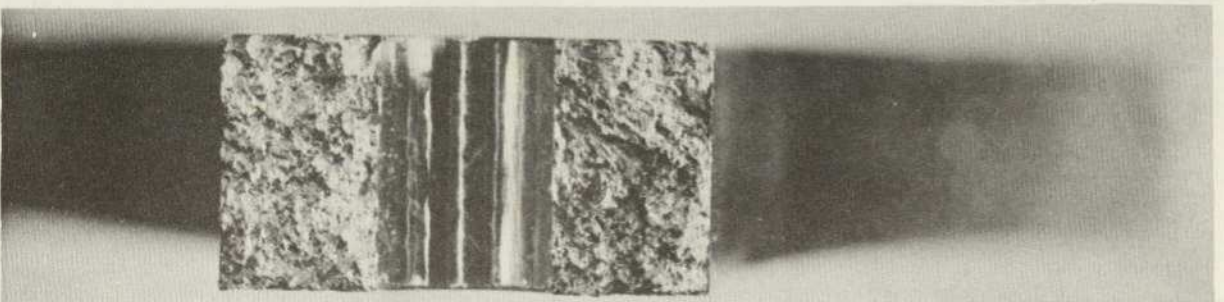
40 MN/m² rms experimental alloy



40 MN/m² rms DTD 5024



27.5 MN/m² rms experimental alloy



27.5 MN/m² rms DTD 5024

Fig.5 Fatigue fractures typical of notched specimens

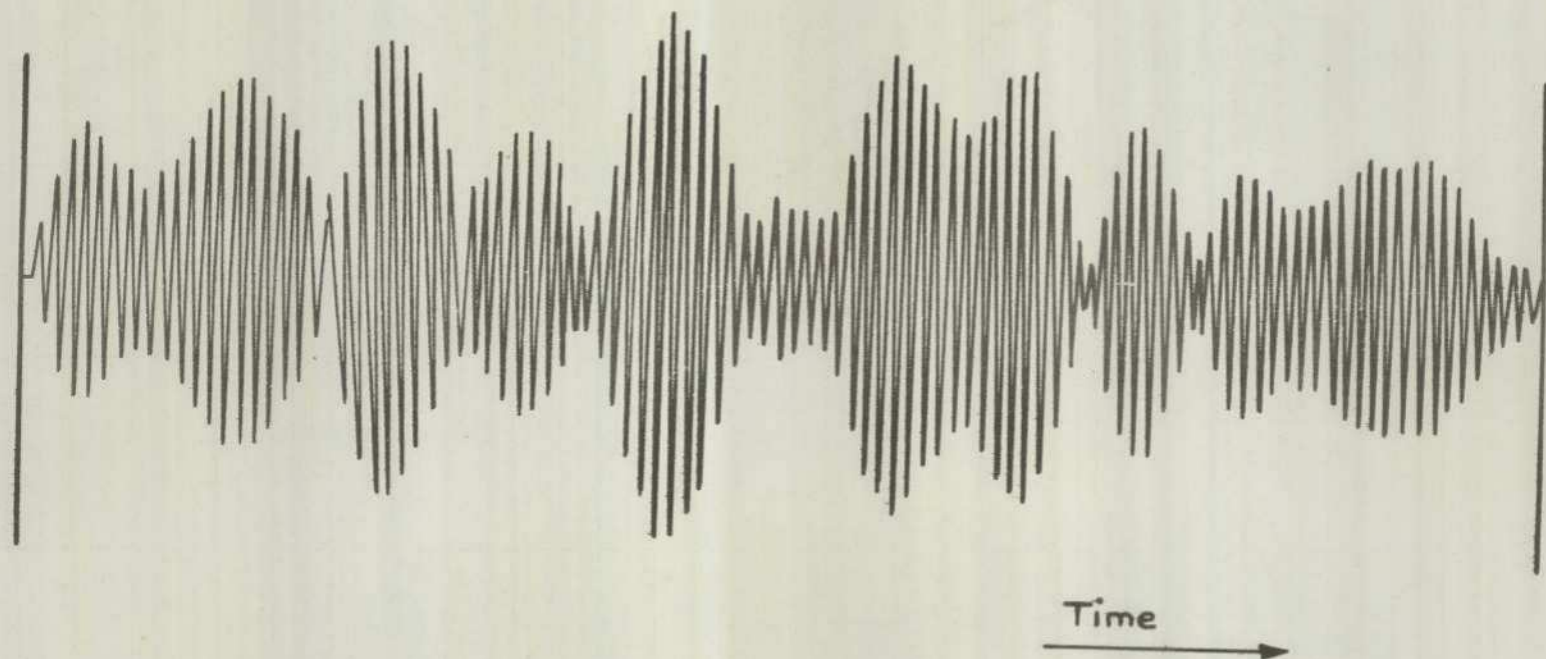


Fig.6 Typical strain gauge output under variable amplitude loading

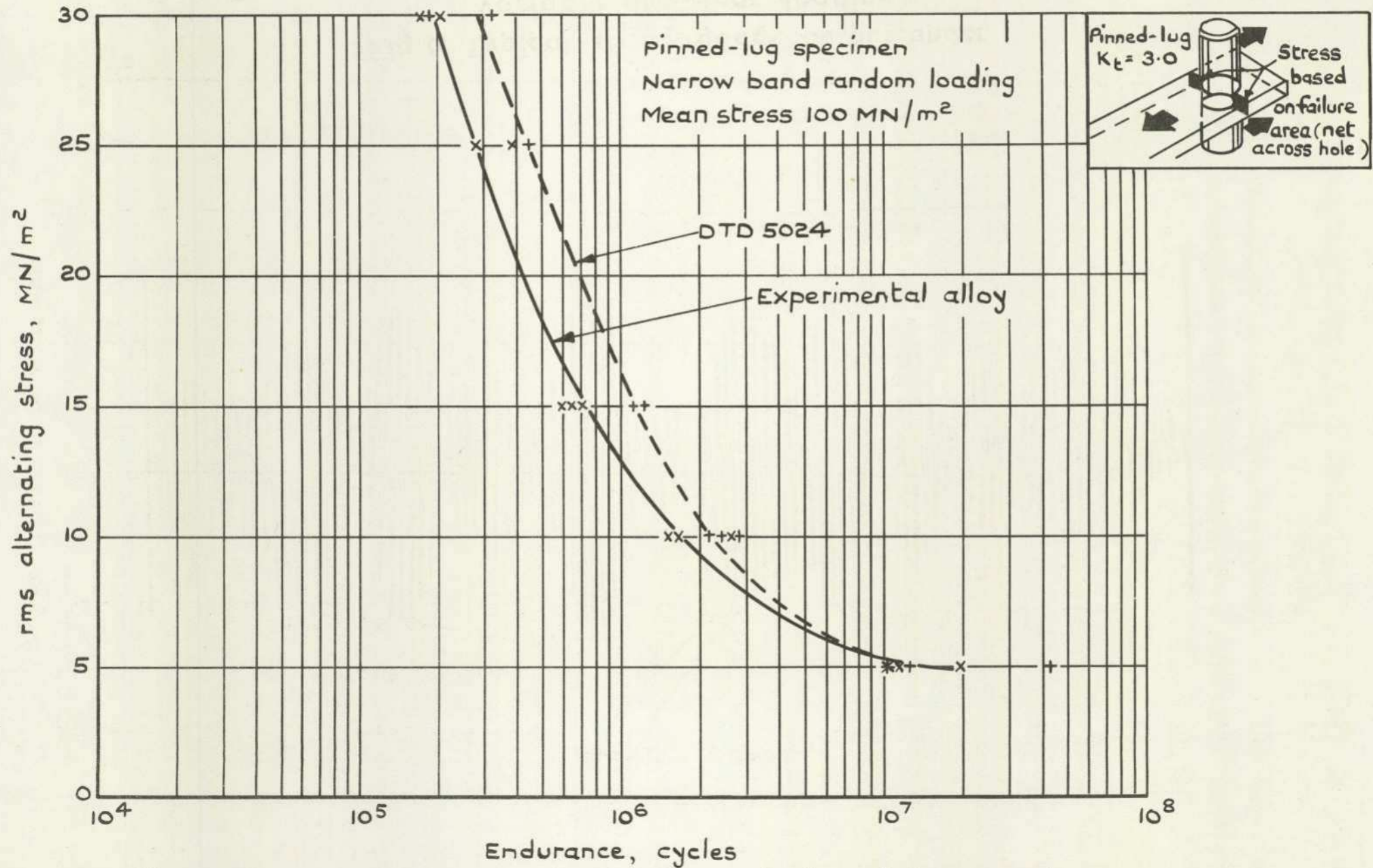


Fig.7 Fatigue performance in the form of pinned-lug specimens

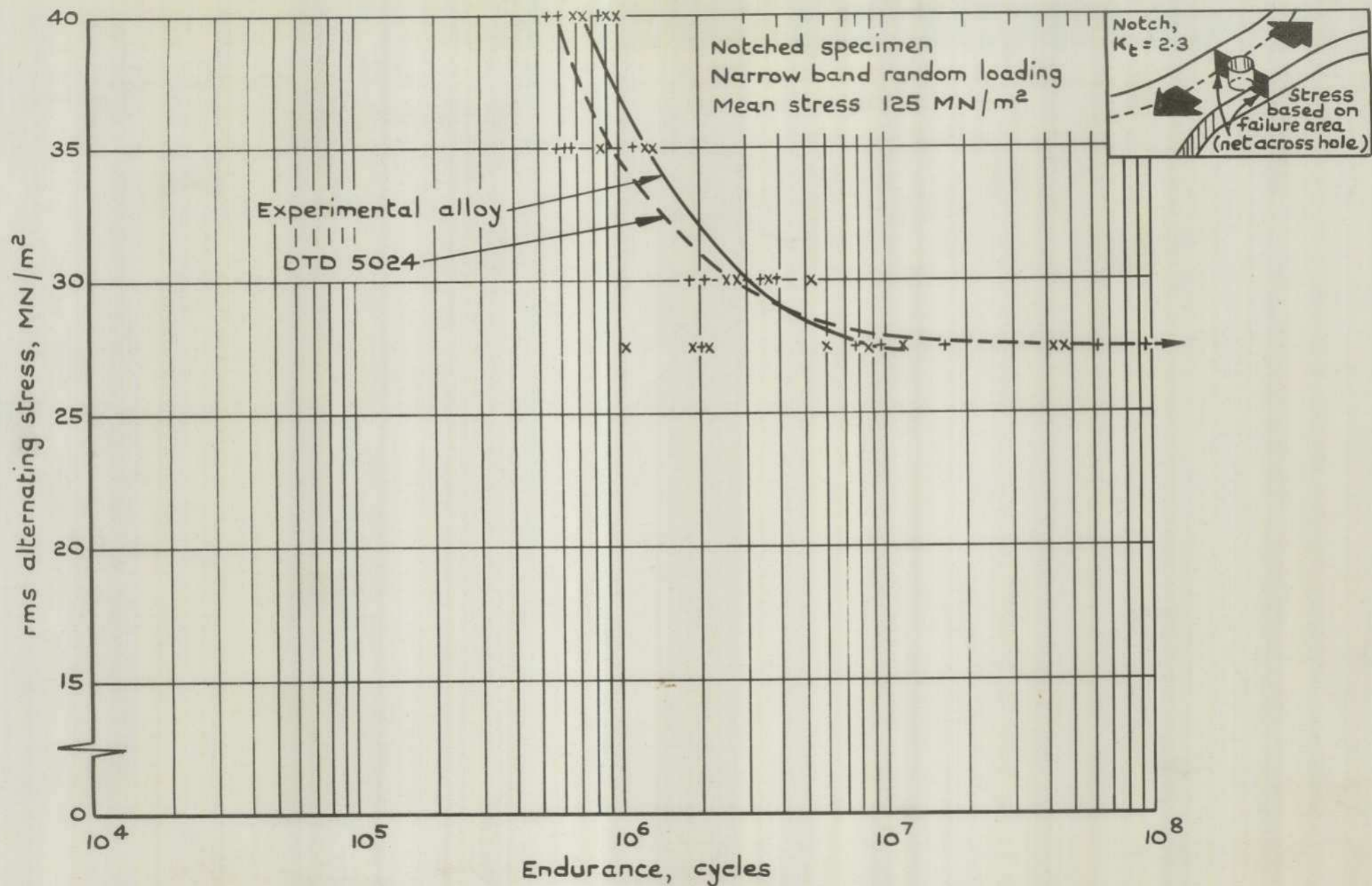


Fig.8 Fatigue performance in the form of notched specimens