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CUMULATIVE FATIGUE DAMAGE STUDIES OF PINNED-LUG AND CLAMPED-LUG STRUCTURAL ELEMENTS IN ALUMINIUM ALLOY**

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SUMMARY

In this paper the results of cumulative fatigue damage studies are given for pinned-lug and clamped-lug specimens in aluminium alloys. The growth of fatigue damage under constant amplitude loading and under variable amplitude loading is discussed and the effects of static pre-load on subsequent fatigue performance are illustrated. Explanations of the observed patterns of behaviour are put forward based on consideration of the residual stresses which may be induced by plastic deformation at stress concentrations within the test specimens.

It is concluded that, in the present state of knowledge, it is advisable to use variable amplitude loading for component evaluation. The importance of using specimens having engineering configurations when evaluating new materials is also stressed.

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* Replaces R.A.E. Technical Report 69182 - A.R.C. 31669

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CONTENTS

Conversions: 1 ksi = 1000 lb(f) in^{-2} = 6.894 MNm^{-2} = 0.685 Hb.

1 INTRODUCTION

1.1 Many of the loads experienced by aircraft in service are of a variable amplitude rather than constant amplitude nature. The difficulties of predicting fatigue life under such loadings with acceptable accuracy, from data obtained under constant amplitude loading, have been appreciated for many years. Because of this, considerable effort has been devoted in recent years to the development of fatigue life prediction methods e.g. Refs.1-4 and, in particular, it has been suggested that fatigue data obtained under variable amplitude loading may be used in the associated calculations[5,6]. There has been a corresponding trend in the evolution of test methods for components and structures towards greater realism - and hence complexity - in the representation of the true service environment, which entails the application of complicated loading patterns.

In considering the desirability of changing to a design method based on the use of variable amplitude data, much weight must be placed on the fact that a vast quantity of data on fatigue performance under constant amplitude loading has been acquired over many years - this data would be set aside to a large extent if such a change were to be generally accepted. Moreover, it will be readily appreciated that the acquisition of a comparable body of variable amplitude data would be a long-term and expensive task. It may also be argued that proposals to use variable amplitude data stem from a lack of a sufficiently deep understanding of the fatigue process and that in due course, as more knowledge of cumulative damage in fatigue is gained, it may be possible to read across with sufficient accuracy from constant amplitude data to behaviour under the more complicated loading conditions which arise in service.

1.2 It is appropriate therefore to consider results of cumulative fatigue damage investigations, as they become available, in order to see what light they shed on the problems of life prediction and component testing. In this paper some results are given of cumulative fatigue damage studies that have been in progress at the R.A.E. over the past two to three years. As a first step, available evidence on the fatigue of aluminium alloys was considered, to try to assess the relative importance of several factors which may affect the accuracy of life prediction when using Miner's Rule - see section 3, below. It was concluded that one of the most important factors which affect cumulative damage behaviour was the formation of residual stresses at stress concentrations in the elements concerned - such stresses are associated with local plastic deformation under the applied loading and can affect the rate of growth of fatigue damage.

Following this evaluation, cumulative fatigue damage investigations were made on pinned-lug and clamped-lug specimens as described in the sections below and an analysis of the results was made to see whether the differences in behaviour of the specimens under constant amplitude and variable amplitude loading (stationary Gaussian random) could be explained adequately by consideration of residual stress effects. Presentation of the results of this work in sections 4, 5 and 6 below is preceded by an outline in section 3 of the conditions which govern the formation and subsequent relaxation of residual stresses, so that the results subsequently presented may be more readily understood. Section 7 is concerned with a different, but equally important, aspect of the overall problem of component evaluation - attention is drawn in this section to the misleading results that may be obtained when the fatigue performance of materials is assessed by using plain and notched specimens rather than by using structural elements in which fretting may occur.

2 FACTORS AFFECTING THE GROWTH OF FATIGUE DAMAGE

2.1 In the course of the work at R.A.E. on cumulative fatigue damage[7] an assessment has been made of the relative importance of several factors which may affect the accuracy of fatigue life prediction for mixed load spectra, when the prediction is based on constant amplitude data. This assessment was based on the study of results from a variety of sources and included consideration of variation of relative damage rate with stress level, effect of low level stress cycles, effect on life of the load at which a component fails, effect of fretting, and the effect of residual stresses associated with plastic deformation at stress concentrations. Each of these factors may affect cumulative damage - the effect of any one factor on the growth of damage, and consequently on life, may depend on whether the loading waveform is constant or variable in amplitude. An attempt was made to quantify, where possible, the magnitude of error in life prediction associated with each factor though, as will be readily appreciated, the various factors are to some extent interacting. For example, the influence on life of the factors which affect nucleation of cracks, more than the growth of cracks, will be reduced if fretting is present at the failure origin with consequent reduction in the nucleation period relative to the crack growth period. Of the factors considered, it was shown that residual stresses at stress concentrations could have a large effect on the rate of growth of damage and consideration of the effects of such stresses could explain, in many cases, large departures of $\Sigma \frac{n}{N}$ from unity when applying Miner's Rule. Variations of relative damage rate with stress level, and consideration of residual static strength in the cracked state, generally did not appear to account for significant errors in life prediction. The effects of low level stress cycles (i.e. those lying below the "fatigue limit") could not be convincingly assessed with available data, though it is believed that in certain circumstances the effects could be considerable.

In the next section the conditions which govern the formation of residual stresses are outlined and their general effects on cumulative fatigue damage are discussed.

3 SOME EFFECTS OF RESIDUAL STRESSES ON CUMULATIVE FATIGUE DAMAGE

3.1 Studies of the importance of residual stresses in relation to cumulative fatigue damage behaviour have been made by a number of investigators[2,8,9,10] and before turning to the experimental evidence presented in sections 4, 5 and 6 below it is worthwhile to consider, in a general way, some probable effects of residual stresses on the growth of fatigue damage. Such consideration may be of help in understanding the experimental results as they are presented.

The design of aircraft structures is such that many of the higher loads in the overall load spectrum will cause local yielding at stress concentrations. For example, in a transport aircraft the mean (1 g) stress in aluminium alloy components may, typically, be 12 ksi (gross) with net stresses of approximately 15 ksi. Under a gust loading spectrum stress peaks of ±15 ksi, and higher, may be added to this mean value giving rise to net stresses exceeding 30 ksi. A typical value of 0.1% proof stress in a copper bearing aluminium alloy is approximately 60 ksi, consequently local plastic deformation will occur at stress concentrations having factors (K_t) greater than 2.0.

3.2 Considering the behaviour of a structural component under tensile loading, containing a stress concentration and initially free from residual stresses, the volume of material that will undergo plastic deformation will be dependent on the size of the specimen, the yield strength of the material, the value of the stress concentration factor (K_t) and the magnitude of the applied load. The volume of material which deforms plastically is generally small compared with the surrounding volume of the material which deforms elastically. If the applied load is then diminished, the elastic restoring forces in the bulk of the component will tend to compress the material which has deformed plastically, so that it will be in a state of compressive stress relative to the stress in the surrounding material. If variable amplitude fluctuating tensile loading of the form P ±p, P > p is considered, then the application of a high peak load (P + p) will effectively result in a reduction in the local stress associated with the mean load P. Such a reduction in local mean stress will tend to reduce the rate of growth of fatigue damage, particularly the rates of growth associated with the lower loads in the applied spectrum.

3.3 Taking the discussion somewhat further, it is important to consider the conditions which govern relaxation or intensification of any such beneficial residual stress under continued fatigue loading of the component. There are two main factors which govern the subsequent stress state at the concentration - the magnitude of the subsequent peaks and troughs in the loading waveform relative to the yield stress of the material and any subsequent gradual relaxation of local stresses under fatigue loading. It is difficult to define precise behaviour but, at the risk of over simplification, it may be said that any peak loads which exceed preceding peaks in magnitude will cause further reduction in effective local mean stress and conversely any troughs in the loading waveform which cause compressive yielding to occur at the stress concentration will cause an increase in local mean stress. At first sight it may appear that since we are considering varying tensile loading of the component the latter situation - compressive yielding - is most improbable. However, it must be borne in mind that the local mean stress may fall far below the nominal mean stress in the component and even if the nominal stresses always remains tensile, the local stresses will not necessarily do so[11,12] (i.e. the alternating stresses could exceed the mean stress locally). It is important to remember also that compressive yielding may occur under very small negative stresses, due to the Bauschinger effect (the raising of the compressive yield stress following tensile yielding[13]). Further, as fatigue loading continues, there may be changes in the tensile and compressive yield stress associated with cyclic strain hardening, or softening, of the material[14]. In this context it should be made clear that the term "cyclic strain hardening" or "cyclic strain softening" refers to change in yield stress brought about by cyclic straining below the yield point - there is not necessarily any direct correlation between the cyclic strain hardening characteristics of a particular material and the strain hardening characteristics of the same material under a single application of a tensile or compressive load of sufficient magnitude to cause general yielding. Any such changes in the tensile or compressive yield stress will clearly alter the values of residual stresses associated with subsequent yielding.

Changes in residual stresses may also occur during the fatigue life by a cycle by cycle relaxation of the value of local mean stress. It has been shown that such relaxation may occur to a small extent even at loading below the fatigue limit[15].

3.4 How then would the fatigue behaviour of aluminium alloy components under constant amplitude loading in fluctuating tension be expected to compare with behaviour under variable amplitude loading? The answer must of course depend on the severity of the loadings - in particular it will depend on whether or not the loads are of sufficient severity to cause local yielding under the two forms of loading and the extent of such yielding. The effect on fatigue performance can be partly assessed by comparing local mean stresses under variable amplitude loading and under the constant amplitude loading required to predict the variable amplitude fatigue life by means of Miner's Rule. In the case of variable amplitude loading the local mean stress will be governed at any instant by residual stresses produced by the highest load applied up to that point in the fatigue life, as discussed above. Assuming a well mixed spectrum, loads approaching the highest load will generally occur comparatively early in life, and will to a large extent determine the residual stress state. Under the constant amplitude loading, which is used to provide data for life prediction, the local mean stress will depend on the alternating stress level. Therefore under constant amplitude loading at any individual alternating stress contained in the variable amplitude spectrum, the local mean stress will be greater than (or equal to) the local mean stress which actually exists under variable amplitude loading. Hence, under the constant amplitude loading, fatigue damage accumulates faster than if the local mean stress were the same as for the specimens under variable amplitude loading. Consequently Miner's Rule will tend to underestimate life. This beneficial effect would progressively be reduced with reduction of the overall severity of the spectrum until the situation would be reached in which no significant residual stresses would be induced by the peak loads in the spectrum. In such conditions one would expect values of $\Sigma \frac{n}{N}$ as for plain specimens.

With this overall pattern of behaviour in mind, consideration will be given in subsequent paragraphs to the results of a number of relevant experimental investigations.

4 THE EFFECTS OF RESIDUAL STRESSES ON THE FATIGUE PERFORMANCE ON PINNED-LUG AND CLAMPED-LUG SPECIMENS

4.1 The results presented in this section illustrate the differing effects of residual stresses on the fatigue performance of specimens with pinned-lug and clamped-lug configurations. They are taken from a series of tests[16] which were undertaken primarily to evaluate the fatigue performance of a high strength aluminium-magnesium-zinc alloy - see also section 7 below. In the course of the evaluation, tests were made on the above types of specimen under both constant amplitude and variable amplitude (random) loading. The tests were repeated on B.S.2L65 specimens of identical configurations to provide a direct comparison with the fatigue performance of an aluminium alloy in common use.

4.2 Details of the pinned-lug specimen are shown in Fig.1a. The clamped-lug specimen is illustrated in Fig.2; this type of specimen was chosen to represent in an elementary form the conditions obtaining in a bolted joint. It will be seen that the bolted joint was assembled from the same type of centre-plate as used in the pinned-lug specimen. In order to ensure uniformity of clamping pressure, the bolts were tightened to give an extension corresponding to a core stress of 83 ksi (about 60% UTS). The chemical compositions and the static tensile properties of the Al-Mg-Zn alloy and the B.S.2L65 aluminium alloy are given in Tables 1 and 2 respectively.

Fluctuating tensile loading $(P \pm p,\ P > p)$ was used throughout the tests; in all cases the mean stress was 14 ksi (net) across the sections where fatigue failures occurred (see below). The variable amplitude loading tests were conducted using narrow band Gaussian random loading - the waveform of "p" corresponded to random modulation of a sinusoid having a ratio of positive-going zero crossings to positive peaks close to unity, as used in previous work at R.A.E.[6]. Truncation of the peak distribution occurred at levels varying between 4.4 σ[≠] at low values of σ and 3.5 σ at high values of σ.

4.3 The results of the tests on both types of specimen under constant amplitude loading are shown in Fig.3; the stress is expressed in terms of the root mean square value of the sinusoidal stress waveform. The corresponding results under variable amplitude loading are shown in Fig.4. In Fig.5 the failure modes of the two types of specimen are shown diagrammatically. Under both forms of loading, failures of the pinned-lug specimen originated from fretting between the pin and the bore of the hole. In contrast, the failures of the clamped lug specimen originated from fretting between the side-plates and the centre-plate approximately 0.2 in. distant from the edge of the bolt hole.

From the results of the tests under constant amplitude loading (Fig.3) it may be seen that ratio of fatigue endurance of the pinned-lug to that of the clamped-lug is approximately 1:10 for both materials over the greater part

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[≠] σ is used to denote the root mean square value of the variable amplitude loading.

of the endurance range covered. This large difference in fatigue endurance is believed to be associated with the different stress concentration factors in the two types of specimen. The calculated stress concentration factor for the pinned-lugs was 3.12. Examination of the clamped-lug specimens after failure showed no sign of bearing or fretting in the bore of the bolt hole and it is inferred from this that the load was transmitted mainly, if not entirely, through the clamped surfaces. In such circumstances it is difficult to ascribe a value of stress concentration to this type of joint. Consideration of relative fatigue strength of the two types of specimen at 10^6 cycles (Fig.3) shows that the strength of the clamped-lug is approximately 2.3 times that of the pinned-lug - this suggests that the stress concentration factor for the clamped-lug is effectively slightly less than 1.4.

4.4 The results of the variable amplitude tests (Fig.4) show a rather different picture. With this form of loading it is seen that the ratio of lives between the pinned-lug and clamped-lug specimens is approximately 1:5 over the greater part of the endurance range as compared with 1:10 in the constant amplitude tests. Again, this is broadly the same for both materials. This difference in the relative fatigue performance of the two types of specimen, which is evident when comparing the results of the constant amplitude tests with those of the variable amplitude tests, is reflected in the values of $\Sigma \frac{n}{N}$ obtained from life prediction using Miner's Rule. In Fig.6 $\Sigma \frac{n}{N}$ is plotted against the root mean square stress of the variable amplitude load spectrum for both types of specimen, in each material. The most striking result of this analysis is that $\Sigma \frac{n}{N}$ values lying between 1.0 and 2.0 are obtained for the pinned-lug specimens whereas the $\Sigma \frac{n}{N}$ values for the clamped lugs lie between 0.6 and 0.9.

4.5 It is believed that this difference in behaviour can be explained qualitatively in terms of the residual stresses induced by plastic deformation at stress concentrations in the two types of specimen. The behaviour of the pinned-lug specimen follows the pattern discussed in section 3 above. Consider, for example, the behaviour of the pinned-lug specimens in B.S.2L65 which has a 0.1% proof stress of 67 ksi. With a mean stress of 14 ksi, and assuming that the K_t of 3.12 is realised, local yielding would not be expected to occur under sinusoidal loading below stress levels of 5.3 ksi (rms) i.e. 7.5 ksi (peak). Under the variable amplitude loading in which the ratio of maximum stress in the spectrum to overall rms stress is approximately 4.3, yielding would occur at stresses exceeding 1.7 ksi (rms). Thus, under the variable amplitude loading at rms stresses above this value, a progressively increasing number of peaks in the spectrum will cause yielding and induce beneficial residual stresses. This behaviour accounts for the increasing value of $\Sigma \frac{n}{N}$ as the severity of the overall amplitude of loading is increased and for the fact that values of $\Sigma \frac{n}{N}$ well in excess of unity are achieved - see section 3 above.

In contrast it is doubtful whether any significant plastic deformation occurs in the clamped-lug until a crack large enough to give an appreciable stress concentration has been formed. In section 4.3 above it was suggested that the clamped-lug had a stress concentration factor (K_t) slightly less than 1.4. It might be unwise to use a factor so derived to predict the stress above which yielding would occur; nevertheless some indication of the probability of yielding may be given by consideration of the minimum stress concentration required to cause yielding under the peak sinusoidal load, and under the peak load in the variable amplitude loading. Virtually no stress peaks exceeding the mean stress (14 ksi) occurred under either form of loading and a stress concentration factor exceeding 2.4 would be required to cause yielding under such loading. If it is accepted therefore that yielding has not occurred, the observed behaviour may be explained - no beneficial residual stresses would be induced in the clamped-lug and lower values of $\Sigma \frac{n}{N}$ would be obtained, than for the pinned-lug specimens.

4.6 To sum up; in this section the difference in cumulative damage behaviour of pinned-lug and clamped-lug specimens under fluctuating tension have been demonstrated: the differences have been attributed to the action of residual stresses in the pinned-lug specimen. It has been shown that evaluations of the relative fatigue performance of the two types of specimen under constant amplitude loading and under variable amplitude loading may differ considerably. Life predictions based on constant amplitude loading may be optimistic (unsafe) for clamped joints under the loading considered whereas the corresponding predictions for pinned-lug specimens will tend to be safe.

In the next section the examination of fatigue performance under constant amplitude and variable amplitude loading is extended to include consideration of the effects of residual stresses that may be deliberately induced, prior to fatigue loading, with the object of improving fatigue performance.

5 THE EFFECTS OF RESIDUAL STRESSES INDUCED BY A STATIC PRE-LOAD ON SUBSEQUENT FATIGUE BEHAVIOUR UNDER CONSTANT AMPLITUDE AND VARIABLE AMPLITUDE LOADINGS

5.1 The results presented in this section are taken from a cumulative fatigue damage study, now in progress, which includes examination of the effect of a static pre-load on the subsequent fatigue performance of a pinned-lug specimen in aluminium alloy. The beneficial effects of such pre-loading on the subsequent fatigue performance of aluminium alloy specimens under constant amplitude loading have been recognized for many years[17,18]. The improvement is generally attributed to the beneficial effects of the residual stresses induced by the pre-load and it is clearly of importance to establish whether corresponding benefits are obtained under subsequent variable amplitude loading, where the conditions governing the retention or relaxation of the favourable residual stresses are different.

5.2 An aluminium alloy pinned-lug specimen in B.S.2L65 was used for this study, as shown in Fig.1b. The tests were conducted in fluctuating tensile ($P \pm p$, $P > p$) loading with a mean stress of 14 ksi (net) and for the tests with pre-loading a stress of 45 ksi (net) was applied to each specimen prior to test. Sinusoidal loading was used in the subsequent constant amplitude tests and narrow band random loading, with a Rayleigh distribution of peak amplitudes, was used in the variable amplitude tests, as in the work described in section 4 above. The S/N curves obtained under the constant amplitude loading, with and without pre-load, are shown in Fig.7. It may be seen that, as anticipated, the pre-load has had a markedly beneficial effect on fatigue endurance. Over a considerable part of the stress range covered the life has been increased following the pre-load, by a factor of approximately 5, with a corresponding increase in the fatigue strength at 10^6 cycles of approximately 70%. The σ/N curves obtained under variable amplitude loading, with and without pre-load, are shown in Fig.8. It will be seen that the pre-load has not been so effective in improving fatigue performance as in the constant amplitude tests. The fatigue life has been increased by a factor of rather less than 2.5 over much of the stress range, as compared with the factor of 5 shown by the S/N curves - similarly the increase in fatigue strength is not so marked, being approximately 45% as compared with 70%. In all cases the failures occurred across the lug with evidence of fretting damage between the pin and the bore as in Fig.5a.

The values of $\Sigma \frac{n}{N}$ obtained when using Miner's Rule to predict fatigue performance under variable amplitude loading from the constant amplitude test results, with and without pre-load, are shown in Fig.9. The prediction of fatigue life under variable amplitude loading with and without pre-load was performed using constant amplitude data, with and without pre-load respectively. For specimens not subjected to pre-load values of $\Sigma \frac{n}{N}$ close to unity are obtained at low stress levels, rising to more than 2.5 at the higher stress levels. In contrast, the corresponding values of $\Sigma \frac{n}{N}$ for specimens tested after pre-loading range from 0.8 at low stress levels to 1.6 at higher stress levels.

5.3 Again, it is suggested that this overall pattern of behaviour is, to a large extent, explicable from consideration of the residual stress state in the vicinity of the fatigue origin. Considering first the behaviour of the specimens which have not been subjected to a pre-load, it is apparent that the relative fatigue performance under constant amplitude and variable amplitude loading corresponds broadly to the behaviour of the pinned-lug specimens in section 4 above which showed similar trends in values of $\Sigma \frac{n}{N}$ over the same range of stress - Fig.6. The favourable values of $\Sigma \frac{n}{N}$ in the former work were attributed to the fact that the higher stress peaks in the variable amplitude spectrum induced beneficial residual stresses under such loading, whereas the residual stresses induced in the specimens subjected to the constant amplitude loading were much less significant. The same argument applies to the pinned-lug tests without pre-load reported in this section. However, when considering the results of the tests following pre-load, it is clear that the fatigue performance under both constant amplitude and variable amplitude loading is influenced by the presence of the high residual stresses induced by the pre-load. In the latter case (variable amplitude loading) it is to be expected that the higher peaks in the spectrum have little further beneficial effect on fatigue performance since, even at the highest rms stress conditions, they fall considerably below the pre-load stress. Indeed, it is possible that the pre-load reduces the local mean stress so much that compressive yield may occur under fatigue loading - if this occurs there will be a tendency for the beneficial effect of the pre-load to be reduced. Such a reduction will generally be greater under variable amplitude loading than under constant amplitude loading. Thus it is argued that the beneficial effects of pre-load will be relatively greater under the constant amplitude loading than under variable amplitude loading, thus leading to lower values of $\Sigma \frac{n}{N}$ than are obtained in the absence of a pre-load.

5.4 It will be seen from the results of this study of the effects of pre-load that the improvement in fatigue performance predicted on the basis of test data obtained from constant amplitude tests was not fully realised under variable amplitude loadings. This result may not be, in itself, particularly significant to the designer or test engineer since pre-loading applied in this work, is not generally used to improve fatigue performance. However, it may be of considerable significance in relation to other methods aimed at improving fatigue performance which are based on the induction of beneficial residual stresses during manufacture - for example the "balling" or "coining" of holes. Though the methods of inducing the residual stresses and their geometric distribution when "balling" or "coining" differ from the corresponding conditions using a pre-load, the principle of increasing fatigue life by reducing local mean stress following plastic deformation is the same. It would clearly be advisable to assess the benefits of such techniques under variable amplitude loading when this is in accord with service conditions.

6 THE RELATIONSHIP BETWEEN THE RESIDUAL STATIC STRENGTH OF A COMPONENT AND THE PROPORTION OF FATIGUE LIFE CONSUMED

6.1 In this section evidence is presented which shows that there may be a significant difference in the rate at which fatigue damage grows throughout life under constant amplitude and variable amplitude loading. In this context "fatigue damage" is measured in terms of the reduction in residual static strength of a component at any given percentage of the fatigue endurance of the component. The evidence presented also indicates that residual stress effects associated with plastic deformation, under the conditions discussed in the foregoing sections, may have more influence on the rate of growth of fatigue damage during the nucleation phase of the fatigue process than in the subsequent crack growth phase.

6.2 The results are taken from an extensive investigation[7] of cumulative fatigue damage in pinned-lug specimens in DTD 5014 aluminium alloy. The design of the specimen is shown in Fig.1c - the chemical and mechanical properties are given in Table 3. The technique used was to establish average life to failure (log-mean endurance) at a particular stress level and to perform a series of tests subsequently in which the fatigue loading was stopped at a chosen percentage of the average life, the specimen was then removed from the fatigue machine and a static strength test was performed. By carrying out such static tests at different chosen percentages of fatigue life, a curve could be drawn showing residual static strength vs percentage of fatigue life consumed. When using this technique it was found that there was considerable scatter in static strength at any chosen percentage of the average fatigue life, probably because of scatter in the individual lives to failure, relative to the average life to failure. Indeed, it was difficult to acquire results for endurances beyond 75% of average life without experiencing an unacceptable number of fatigue failures, prior to achieving the intended percentage of average life. Nevertheless, despite the scatter problem, trends can be discerned from the results which are of considerable value in understanding the overall fatigue damage process.

6.3 In Figs.10a and 10b results are shown for residual strength tests at three rms stress levels under both constant amplitude (sinusoidal) and variable amplitude (random) loading, respectively. It may be seen that, under constant amplitude loading, there is a significant difference in the shapes of the curves at the three stress levels - for example, at a stress level of 1.5 ksi rms the specimens have fallen to 80% of their original strength when 50% of the fatigue life has been consumed, whereas at 6.5 ksi rms the specimens retain approximately 80% of their strength at 80% of life. The tendency for the original strength to be maintained to a higher percentage of fatigue life, as stress level is increased, is believed to be associated partly with the beneficial residual stresses associated with local yielding. The yield strength (0.1% proof) of the material used in the foregoing residual strength tests was approximately 51 ksi and, with a stress concentration factor K_t of 2.96, local yielding would occur at and beyond alternating stresses of 0.8 ksi (rms) when superimposed on a mean stress of 16 ksi. Local yielding will therefore occur over the range of alternating stresses illustrated and the residual stress effects will become more significant as stress level is increased. This observed pattern of behaviour may be explained if it is assumed that the residual stresses have a more beneficial affect during the nucleation phase of the fatigue damage process than in the subsequent crack propagation phase and that there is no significant reduction in static strength of the specimen until cracking occurs on a macro-scale. There is a considerable body of evidence to support the latter assumption[16,19], and if the first assumption is accepted it would follow that beneficial residual stress effects would lead to retention of the original static strength to a higher percentage of life to failure.

6.4 The results obtained from the residual strength tests under variable amplitude loading - Fig.10b - differ markedly from those under constant amplitude loading. There is a tendency for the curves for variable amplitude loading at the three stress levels to group more closely together and the general shape corresponds to the curve for the highest constant amplitude stress - 6.5 ksi rms. This is broadly in keeping with the effects of residual stresses discussed above since the higher peaks in the variable amplitude load spectra would be expected to cause more local yielding than would occur under constant amplitude loading at stresses appropriate to the same life to failure.

6.5 In considering the above results in relation to testing components in fluctuating tension it is apparent that when testing under constant amplitude loading conditions at medium and low stress levels cracking on a macroscopic scale with consequent fall off in residual strength may occur earlier in life than would be the case under variable amplitude loading. For example, in comparing constant amplitude and variable amplitude results for an endurance of approximately 2×10^6 cycles (under each form of loading), cracks of sufficient magnitude to cause a 5% reduction in static strength will have developed with the former type of loading at about 20% of life to failure whereas, under variable amplitude loading, a corresponding amount of damage would not have developed until some 55% of life had been consumed.

The tentative hypothesis that such effects are associated with beneficial residual stresses and are more significant in the nucleation phase than in the crack growth phase leads to two considerations in relation to development of life prediction methods. Firstly, much more weight will have to be placed on loads giving rise to residual stress effects, be they beneficial or adverse, when they occur during the pre-crack phase of damage than when they occur later in life. The second point arising is that residual stress effects discussed in the preceding section may generally be of greater importance where failures originate from notches in the absence of fretting, since fretting will markedly reduce the initiation phase as a proportion of the total life to failure.

7 THE ASSESSMENT OF THE FATIGUE PERFORMANCE OF MATERIALS TO BE USED IN STRUCTURAL CONFIGURATIONS, BASED ON TESTS ON PLAIN AND NOTCHED SPECIMENS

7.1 The work described in the above sections has been related primarily to the behaviour of specimens containing stress concentrations and subject to fretting - thus they may be said to be representative of many structural components. Attention has been drawn to errors which may arise when using data on fatigue performance obtained under constant amplitude loading to predict behaviour under variable amplitude loading. In this section the emphasis is quite different - attention is drawn to the danger of assessing the fatigue performance of materials in plain and notched configurations where fretting does not occur and using such data to anticipate fatigue performance in structural configurations which include the effects of fretting.

7.2 The discussion is based on the results of the evaluation of the fatigue performance of a high strength aluminium-magnesium-zinc alloy[15] referred to in section 4 above. The evaluation was made using plain, notched ($K_t = 3.1$), pinned-lug, and clamped-lug specimens - the results of the tests on the pinned-lug and clamped-lug specimens have been presented in section 4 above, where they were used in a different context to illustrate some effects of residual stresses. All of the tests on the Al-Mg-Zn alloy were repeated using specimens of identical geometry in B.S.2L65 alloy to provide a basis for comparison. For each material, the specimens were taken from extruded bars in the same manufacturing batch and melt; care was also taken to minimise the possibility of biasing the results, by appropriate selection within the bar length. The tests on the plain and notched specimens were made under constant amplitude axial loading in fluctuating tension (P ±0.9 P, $R \simeq 0.05$). The results of the tests on the plain specimens in both materials are shown in Fig.11 and the corresponding results for the notched specimens in Fig.12. It will be seen that there was little difference in the fatigue performance of the two materials at the same stress levels though, if anything, the Al-Mg-Zn alloy had slightly superior fatigue performance at endurances beyond 5×10^5 cycles. This was so for both plain and notched specimens.

The pinned-lug and clamped-lug specimens were subsequently tested under both constant amplitude and variable amplitude loading, as detailed in section 4 above - the results being shown in Figs.3 and 4. In both of the configurations the performance of the Al-Mg-Zn specimens was found to be markedly inferior - under both types of loading the life achieved by the specimens in Al-Mg-Zn alloy was about half that achieved by the 2L65 specimens over the greater part of the endurance range covered. Considered on a strength basis, the fatigue strength of the specimens in Al-Mg-Zn alloy was generally less than 75% of the strength of the 2L65 specimens at given lives.

7.3 The reasons for the relatively poor fatigue performance of the Al-Mg-Zn alloy in structural configuration are not clear. Reference to Tables 1 and 2 show that it has higher static strength, lower proof strength, and much the same elongation at failure as B.S.2L65. Examination of the failure surfaces of specimens in both materials showed that the Al-Mg-Zn specimens failed with a somewhat smaller cracked area than was evident with the 2L65 specimens - subsequent tests to establish fracture toughness (K_{1c}) values confirmed that the Al-Mg-Zn was somewhat weaker in this respect. Certainly, the effect of relatively low K_{1c} on endurance would be more evident in specimens in which fretting takes place than in the plain and notched specimens, since the fretting will reduce initiation time and the former type of specimens will generally spend a greater percentage of their lives in a cracked condition. It is possible that the Al-Mg-Zn alloy may be more susceptible to fretting than the 2L65 material and that this, in combination with the lower fracture toughness of the former alloy, may have contributed to the overall result. There appears to be little or no information available on the relative susceptibility of differing aluminium alloys to fretting, and further investigation of this aspect of fatigue behaviour appears to be desirable.

7.4 In the absence of adequate understanding of the effect of such factors on the fatigue damage process, it is evident that tests should be made on specimens having engineering configurations during the evaluation of the fatigue performance of new materials.

8 SOME FURTHER CONSIDERATIONS

8.1 The work presented in the preceding sections has added considerably to the understanding of cumulative fatigue damage; in particular, explanations of the observed behaviour of components have been put forward which are based on considerations of the residual stresses induced at stress concentrations under the applied loadings. Such residual stresses are believed to be important in that they modify the local mean stress in a volume of material at the stress concentration in the region where fatigue damage may originate.

8.2 In parallel with the experimental investigation, work has been carried out on the further development of a method of life prediction which was based on the use of data obtained under constant amplitude loading and included allowance for residual stress effects. In this method an attempt was made to adjust constant amplitude data by means of the Goodman relationship to allow for changes in the local value of mean stress under the effects of plastic deformations. In order to do this it was necessary to obtain S/N curves for the pinned-lug specimens, which were used in the cumulative damage studies, under different nominal mean stresses and also to determine the local mean stress conditions. Estimates of residual stresses and consequent changes in local mean stress were made theoretically and some confirmation of these values was obtained from load cycling and strain cycling tests on notched and plain specimens[12]. In this latter work strain gauges were used to provide recordings of the local strains (elasto-plastic) in the notch under specified nominal stress conditions in the specimen. Since Hooke's Law could not be invoked at the high strains recorded, in order to deduce stresses, plain specimens in the same material were loaded to give the same recorded strain history and the associated load history, and hence stress history, was noted. The stresses so measured were then used to estimate the local residual stress situation in the notched specimens. The results of the life prediction method so developed have been encouraging in that the behaviour observed experimentally can be predicte qualitatively - however, the quantitative agreement achieved so far is not satisfactory. In the work on life prediction completed to date it has been assumed in the first instance, for simplicity, that residual stress effects are of similar significance throughout fatigue life to failure and this has been found, for all the loading histories considered, to lead to a considerable overestimate of fatigue life. Further development of the method is now in progress based on consideration of the evidence presented in section 6 above, which suggests that residual stress effects may be of greater significance during the nucleation of fatigue damage than during subsequent crack propagation. This aspect will be clarified further as more information becomes available from crack propagation studies under comparable load histories. Consideration is also being given to an adaptation of the above general method in which variable amplitude data, which is already partially conditioned for residual stress and other effects, will be used instead of constant amplitude data.

8.3 The experimental technique outlined in 8.2 above in which load cycling and strain cycling is used to estimate local residual stress states is being used by other investigators[8] in cumulative fatigue damage studies. In view of the apparent importance of residual stresses, it is felt that such work should be strongly encouraged. The technique can be used to estimate the stress state at the point of initiation of fatigue under any form of fatigue loading such as ground-air-ground load cycles or other manoeuvres involving negative loadings. Much basic work could be done using such a technique to establish the probable effect of these loadings on fatigue behaviour. Such work can then be followed by a limited number of confirmatory fatigue tests. It is believed that such an approach will lead to an overall economy of time and money in cumulative fatigue damage studies.

9 CONCLUDING OBSERVATIONS

9.1 Cumulative fatigue damage studies have been made on pinned-lug and clamped-lug specimens in aluminium alloy under constant amplitude and narrow band random loading. The results of the studies suggest that residual stresses associated with plastic deformation and stress concentrations strongly influence the growth of fatigue damage. The values of $\Sigma \frac{n}{N}$ which were obtained when using Miner's Rule were significantly different for the pinned-lug and clamped-lug specimens and the differences could be explained qualitatively from consideration of the residual stresses induced in the two types of specimen.

9.2 Tests were also made on pinned-lug specimens to assess the effect of a pre-load on the subsequent fatigue behaviour under constant amplitude and variable amplitude loading. The results of this work showed that residual compressive stresses which may be introduced during manufacture with the intention of prolonging fatigue life can give greater increase in life under the former type of loading than under the latter type - consequently the values of $\Sigma \frac{n}{N}$ which are obtained may be lower than expected.

9.3 The relationship between residual static strength of pinned-lug specimens and the percentage of fatigue life consumed was investigated and it was shown that, in general, under fluctuating tensile loadings, strength was maintained to a higher percentage of life under variable amplitude loading than under constant amplitude loading. Consideration of the results indicated that residual stress effects were more significant during nucleation of fatigue damage than in subsequent crack propagation on the macroscopic scale.

9.4 A comparison was made of the fatigue performance of two different aluminium alloys in plain specimen, notched specimen, pinned-lug and clamped-lug configurations. This showed that under both constant amplitude and variable amplitude loading the relative performance of the two materials in the engineering configurations was markedly different from the indications given by the tests on simpler specimens. It is suggested that the observed behaviour may be associated principally with the differing sensitivity to fretting of the two materials, and their differing values of fracture toughness.

9.5 Overall, the experience gained in all of the foregoing work supports the view that, in the present state of knowledge, it is essential to evaluate the fatigue performance of new materials in engineering configurations and under variable amplitude loading - such loading should also be used for component proving tests.

Table 1

CHEMICAL COMPOSITION AND TENSILE PROPERTIES OF Al-Mg-Zn ALLOY

Chemical composition (nominal) %	5% Mg, 4% Zn, 1% Mn, balance Al.	
Tensile properties (measured)	UTS	80.5 ksi
	0.1% proof	60.5 ksi
	Elongation	10%.

Table 2

CHEMICAL COMPOSITION AND TENSILE PROPERTIES OF B.S.2L65 ALLOY

Chemical composition (nominal) %	4.4 Cu, 0.7 Mg, 0.7 Si 0.6 Mn, balance Al.	
Tensile properties (measured)	UTS	75 ksi
	0.1% proof	67 ksi
	Elongation	10%.

Table 3

CHEMICAL COMPOSITION AND TENSILE PROPERTIES OF DTD 5014 ALLOY

Chemical composition (measured) %	2.26 Cu, 1.4 Mg 0.25 Si, 1.06 Fe 0.06 Mn, 0.02 Zn, 1.02 Ni 0.06 Ti balance Al.	
Tensile properties (measured)	UTS	58.5 ksi
	0.1% proof	50.8 ksi
	Elongation	13%.

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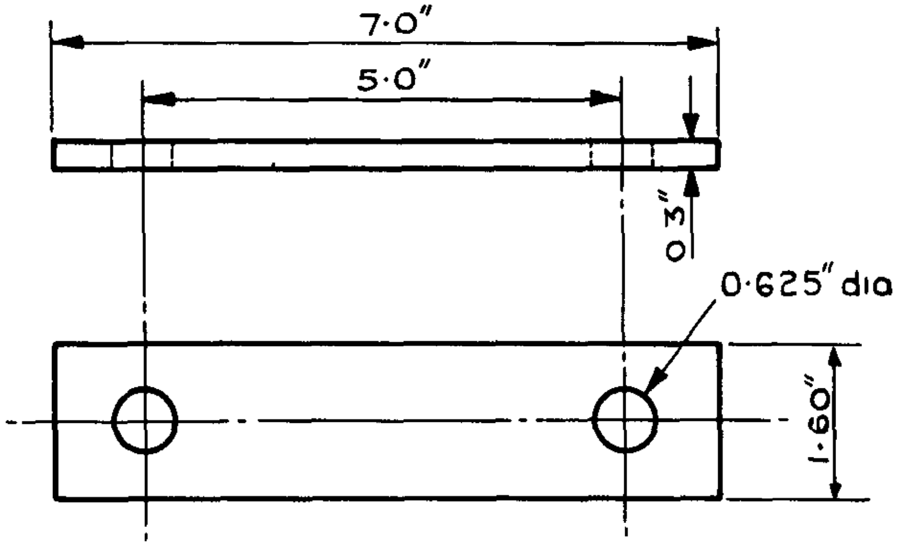
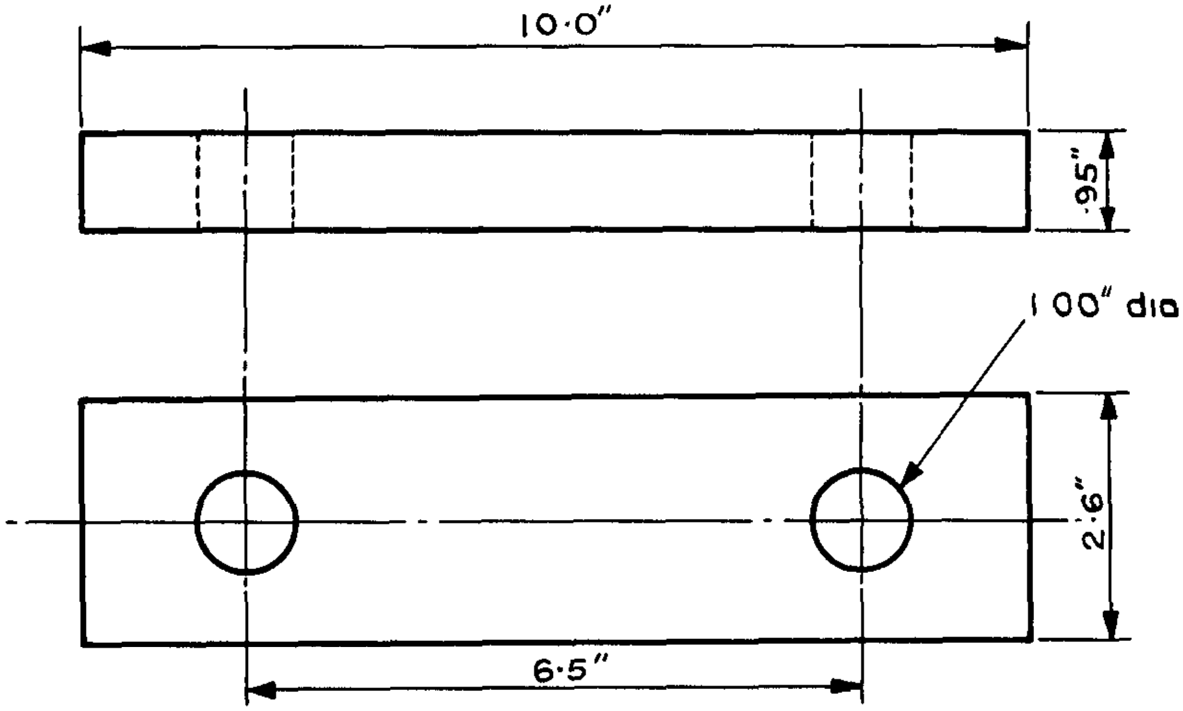
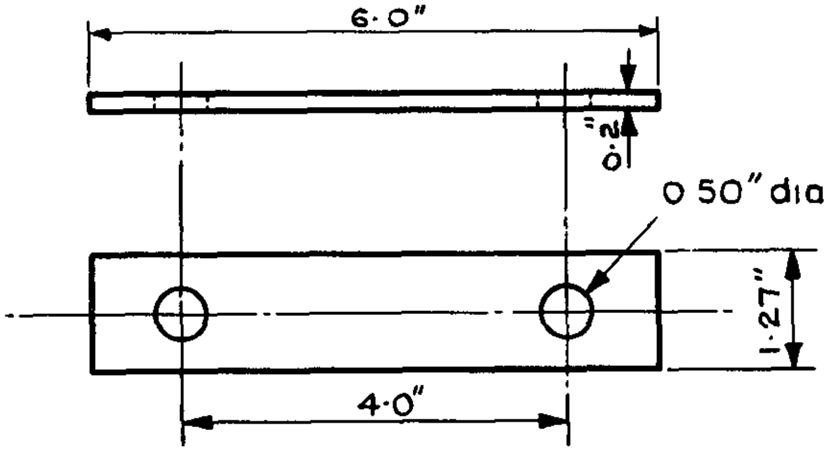


a Material BS 2 L.65 or Al Mg Zn aluminiom alloy



b Material BS 2 L.65 aluminium alloy



c Material D.T.D 5014 aluminium alloy

Scale 1/2

Fig.1 a-c Lug specimens

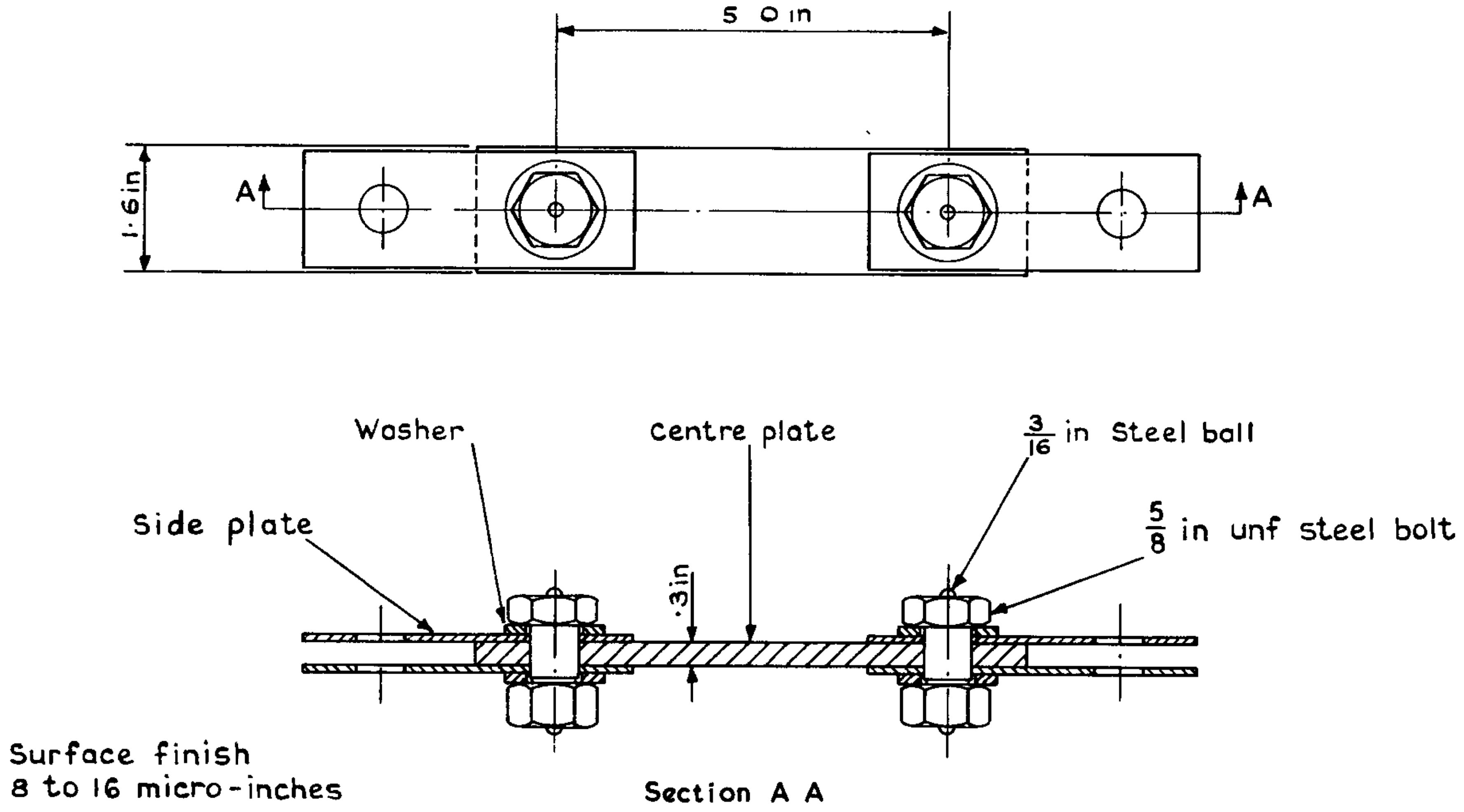


Fig. 2 Clamped lug specimen

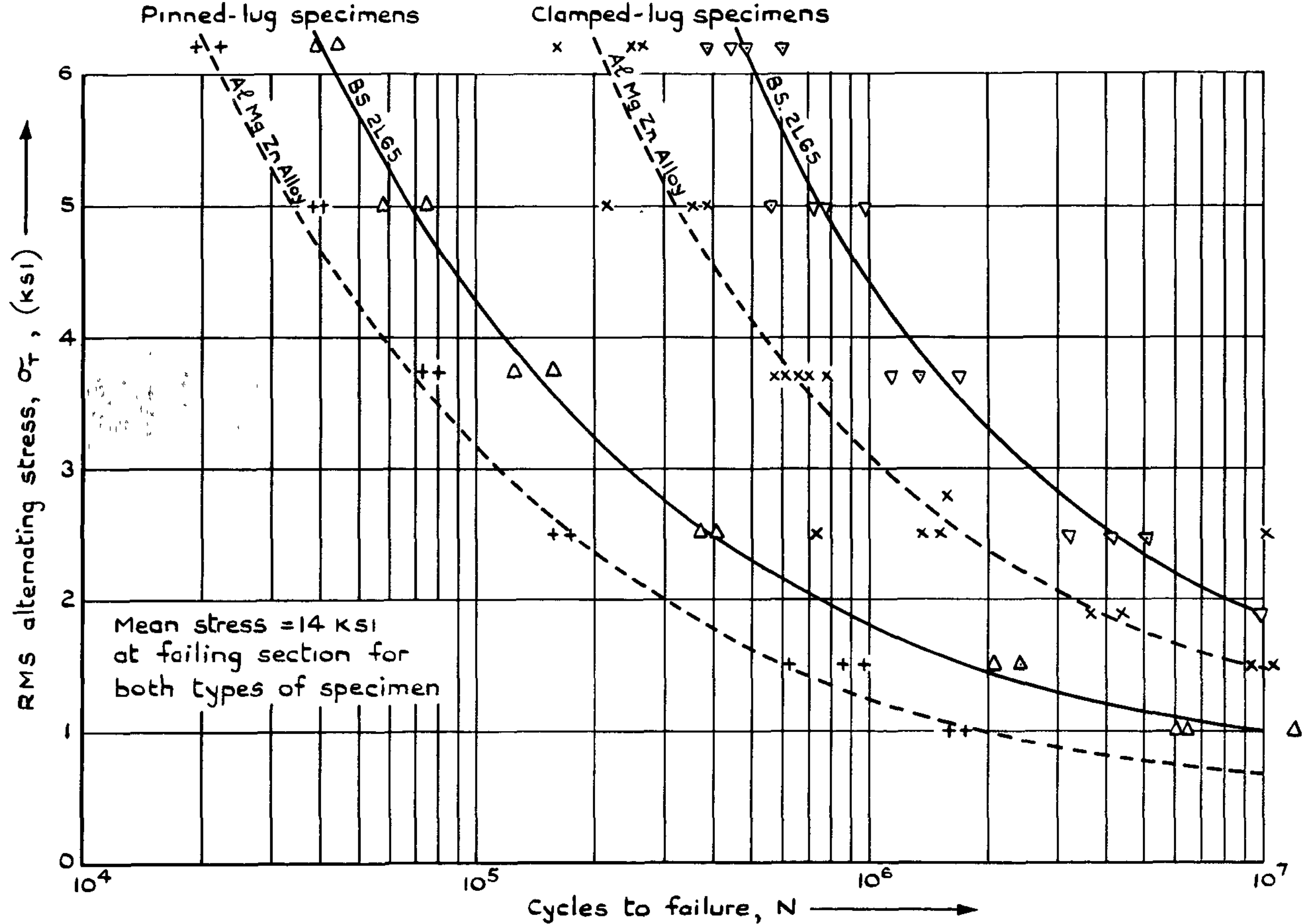


Fig.3 Comparison of pinned-lug and clamped-lug results under constant amplitude loading

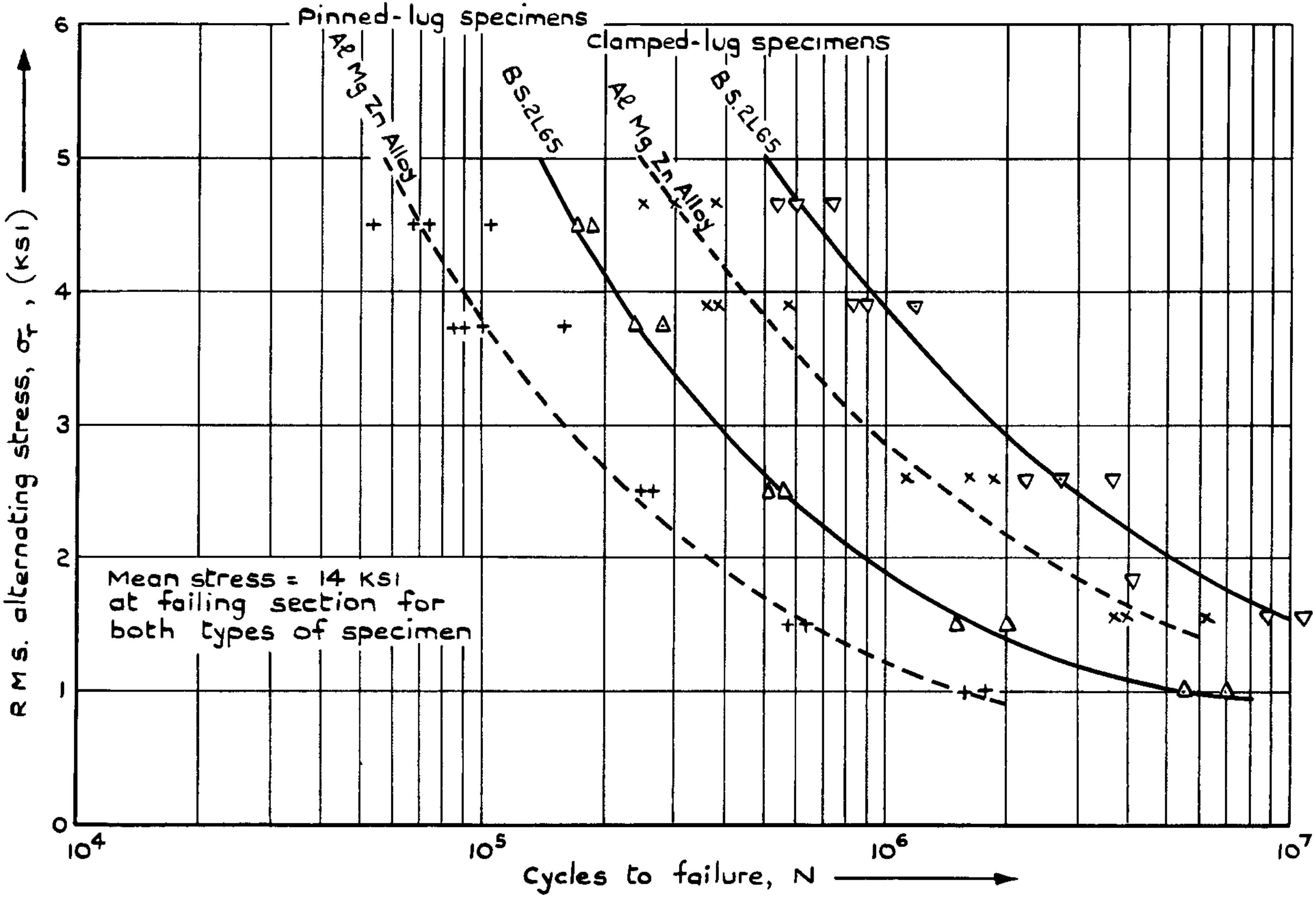
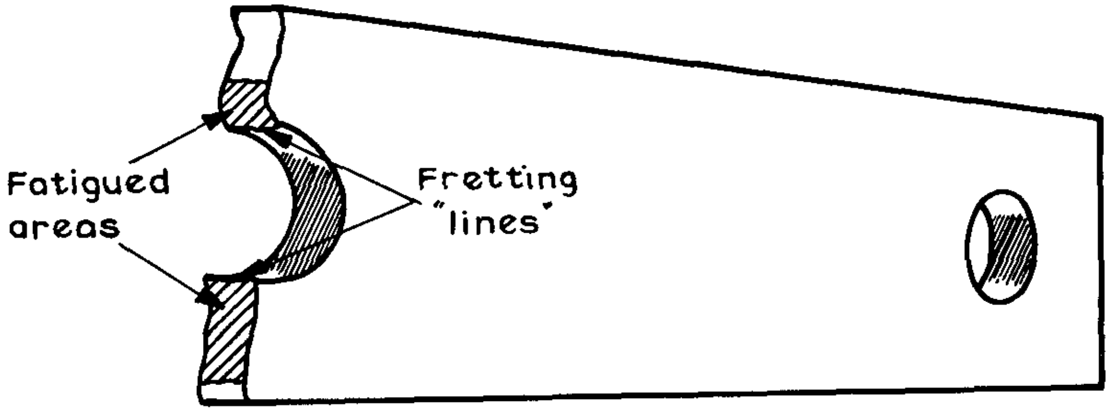
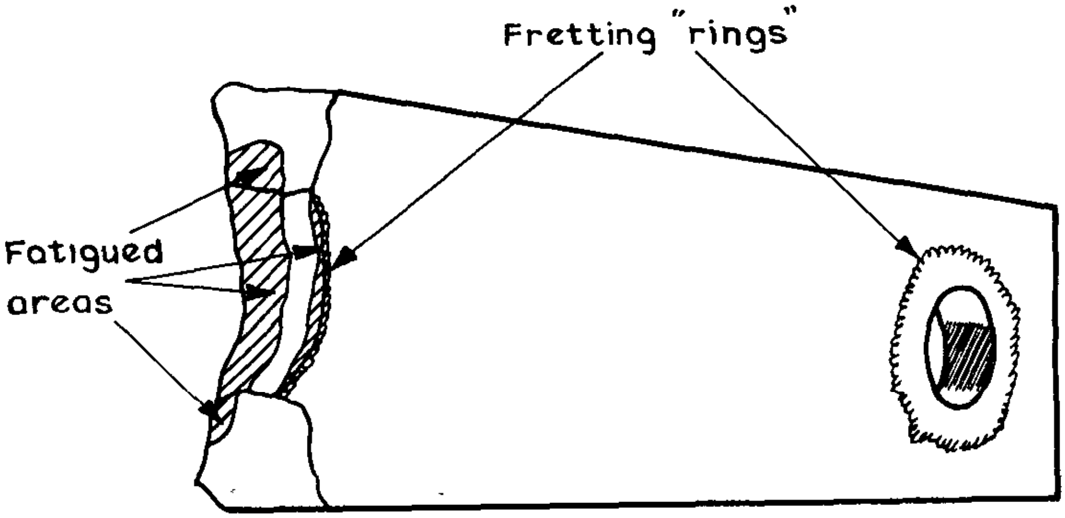


Fig.4 Comparison of pinned-lug and clamped-lug results under random loading

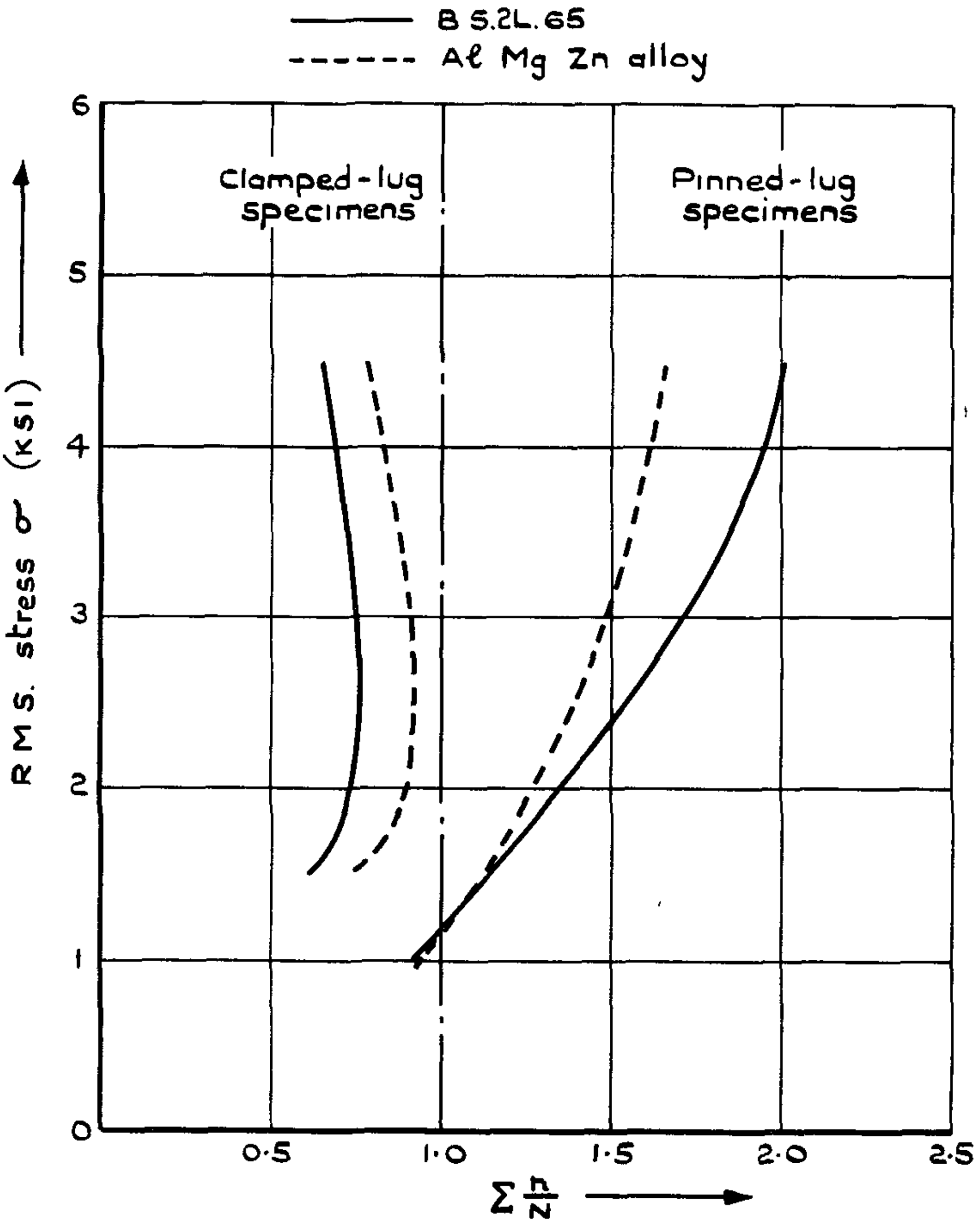


a. Pinned lug specimens – failure through hole



b. Clamped lug- failure away from hole

Fig. 5a & b Typical fractures on pinned lug and clamped lug specimens



Stationary gaussian random loading
mean stress = 14 ksi at failing section

Fig.6 Cumulative damage ratio (miner) vs σ derived from S/N and σ/N curves for pinned lug and clamped lug specimens in B.S2L65 and Al Mg Zn alloy

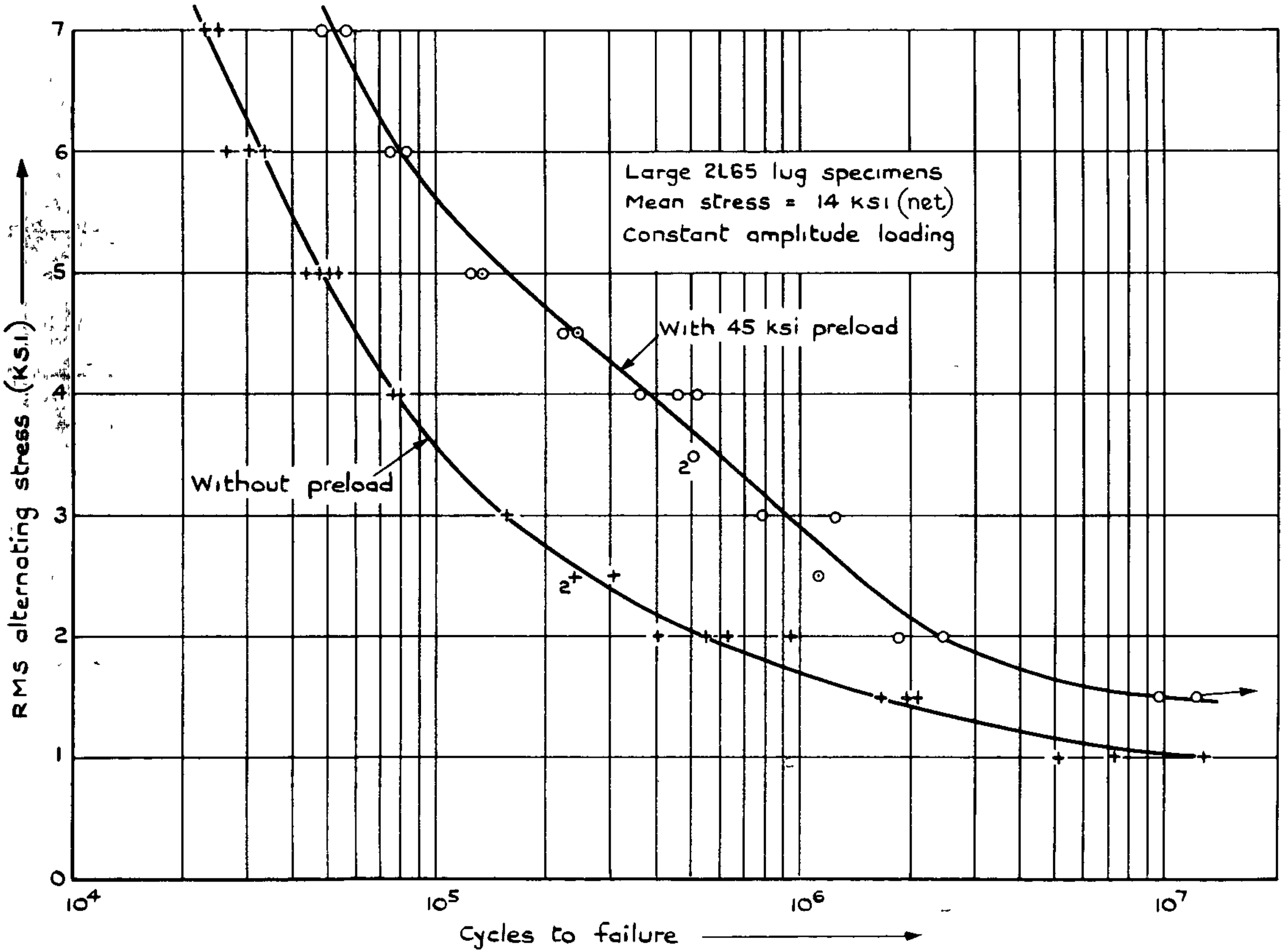


Fig.7 S-N curves for 2L65 lug specimens with and without preload

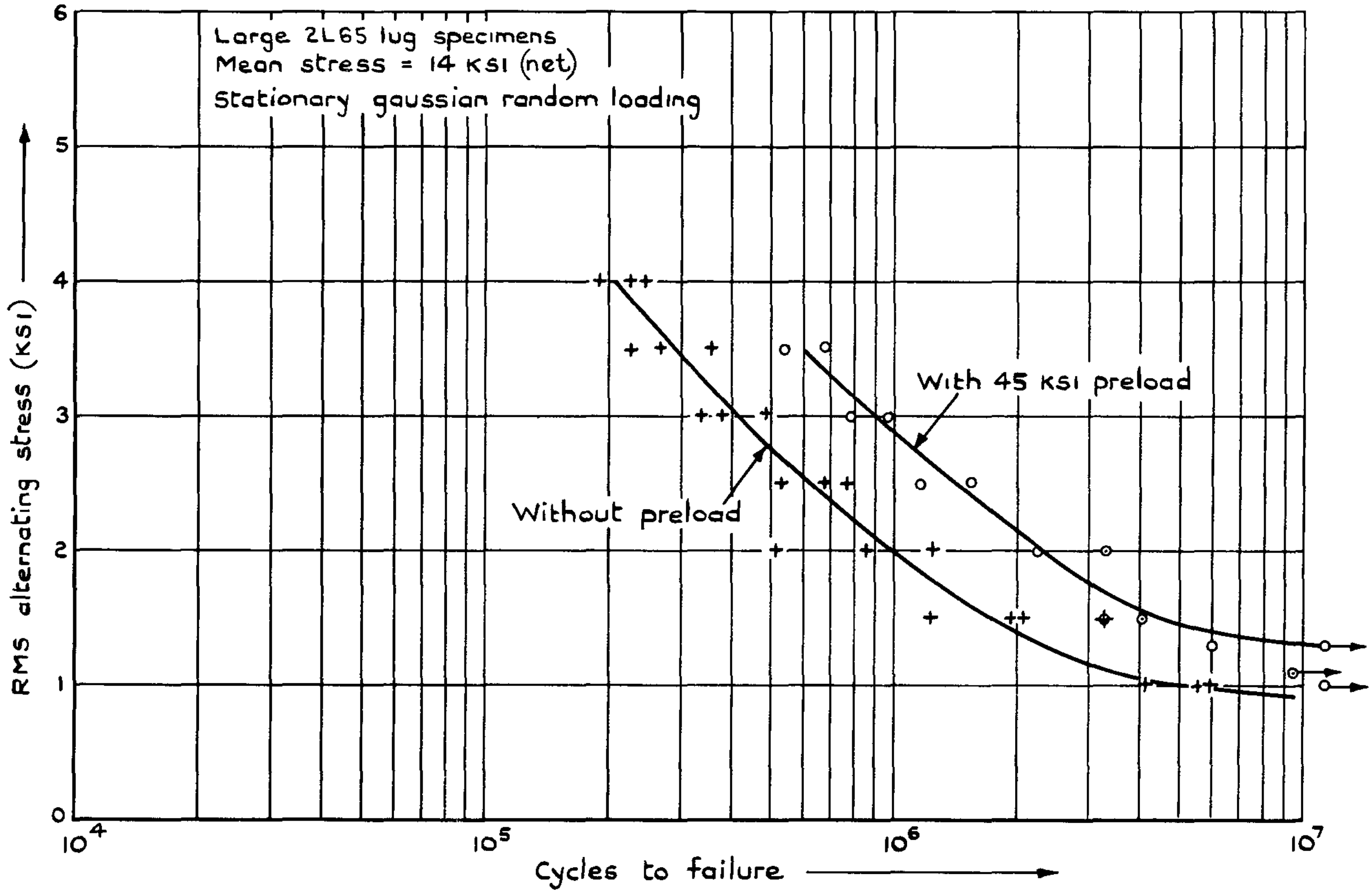


Fig. 8 σ–N curves for 2L65 lug specimens with and without preload

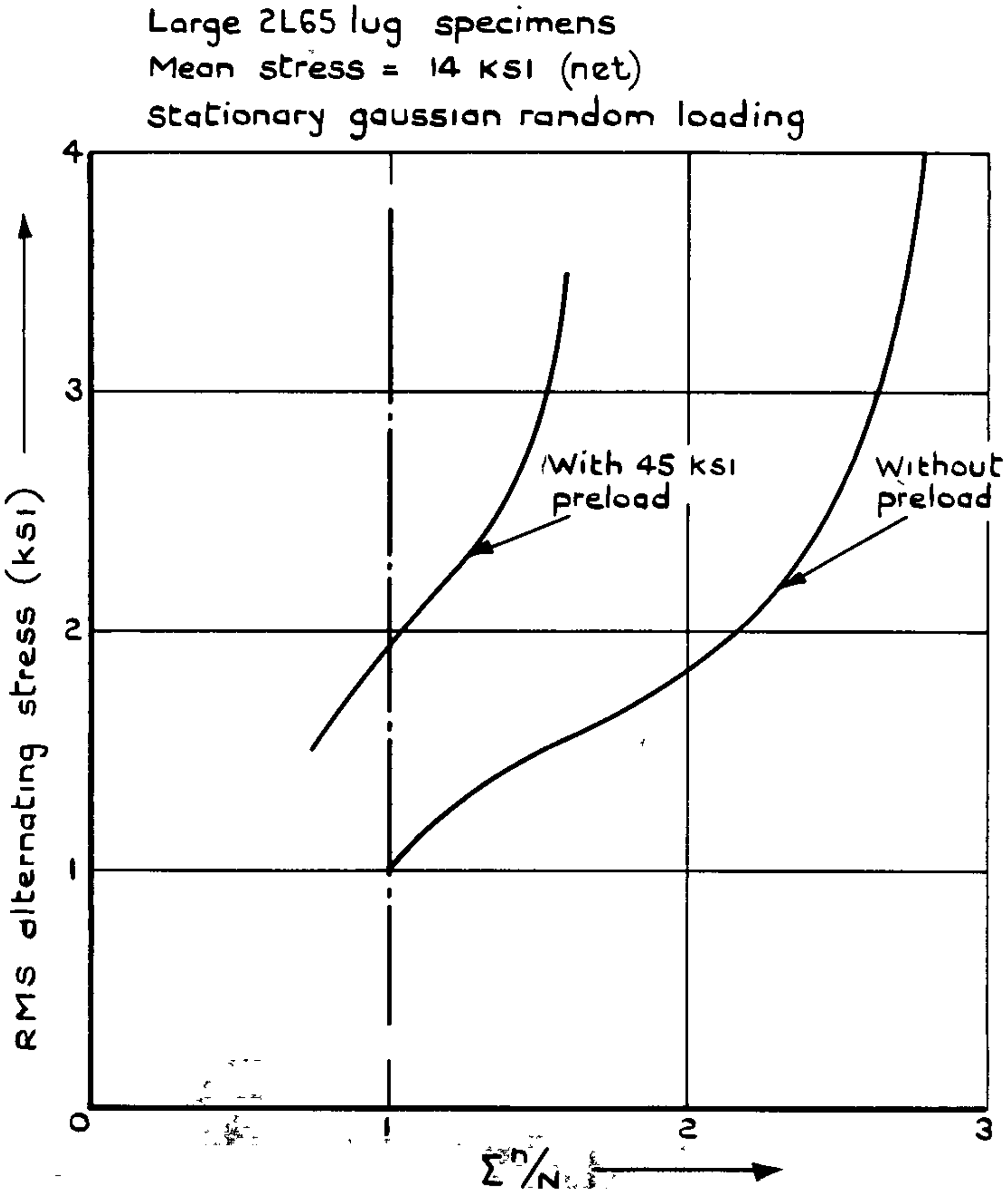
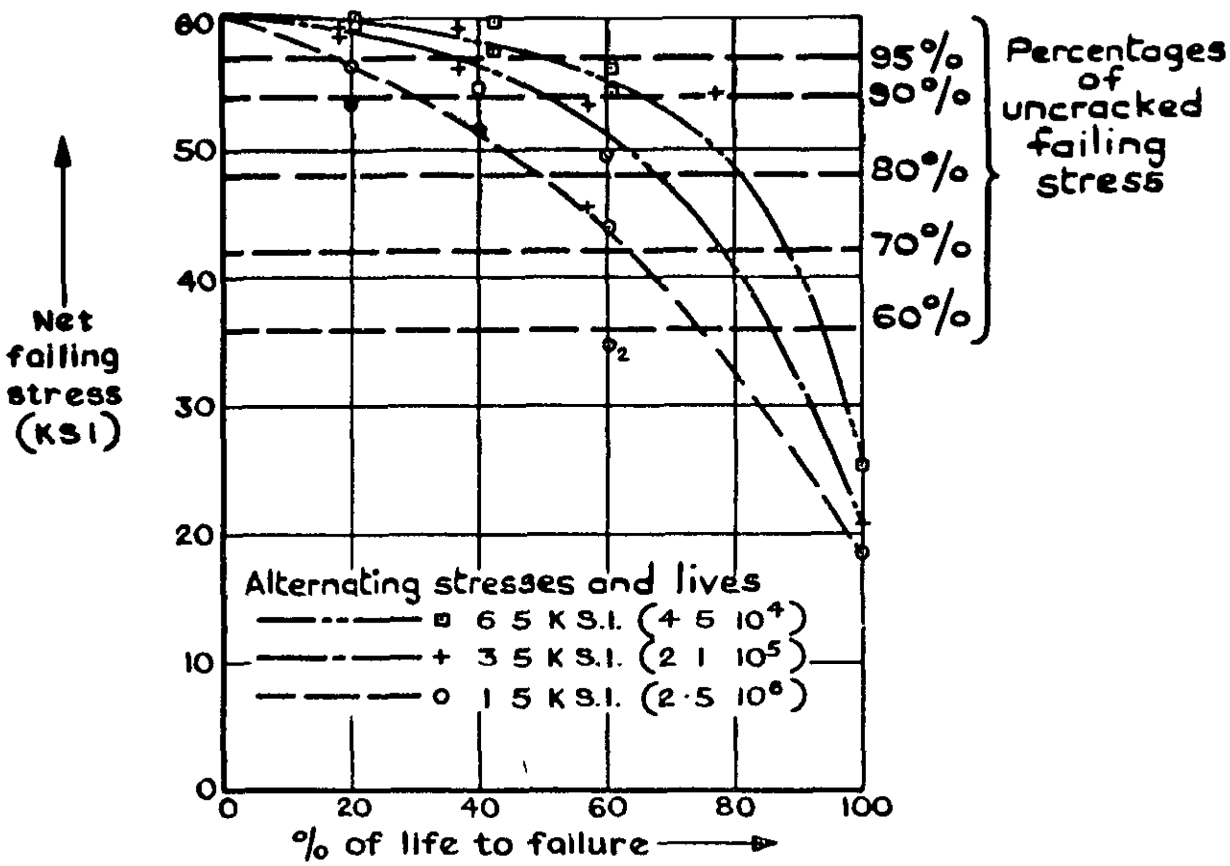
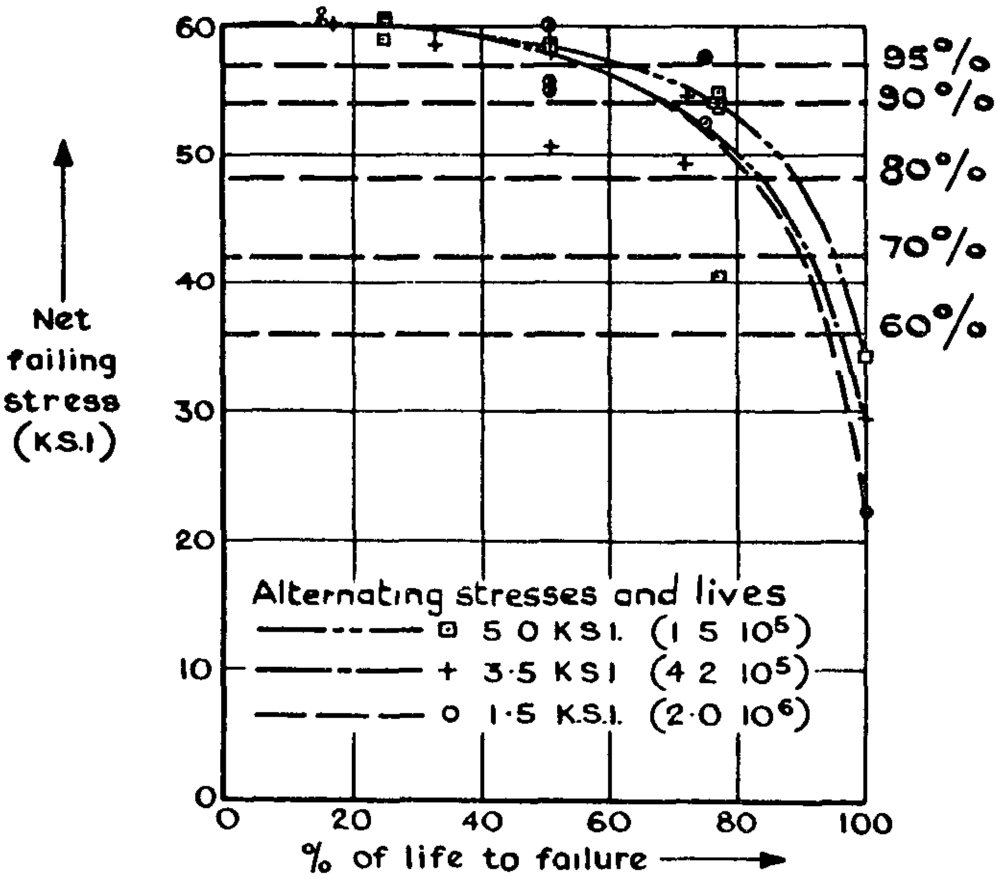


Fig. 9 $\Sigma n/N$ values for lug specimens with and without preload

All alternating stresses are rms



a Constant amplitude loading



b Stationary random loading

Fig. 10a&b Partial damage tests–16 K.S.I. mean small D.T.D 5014 lugs

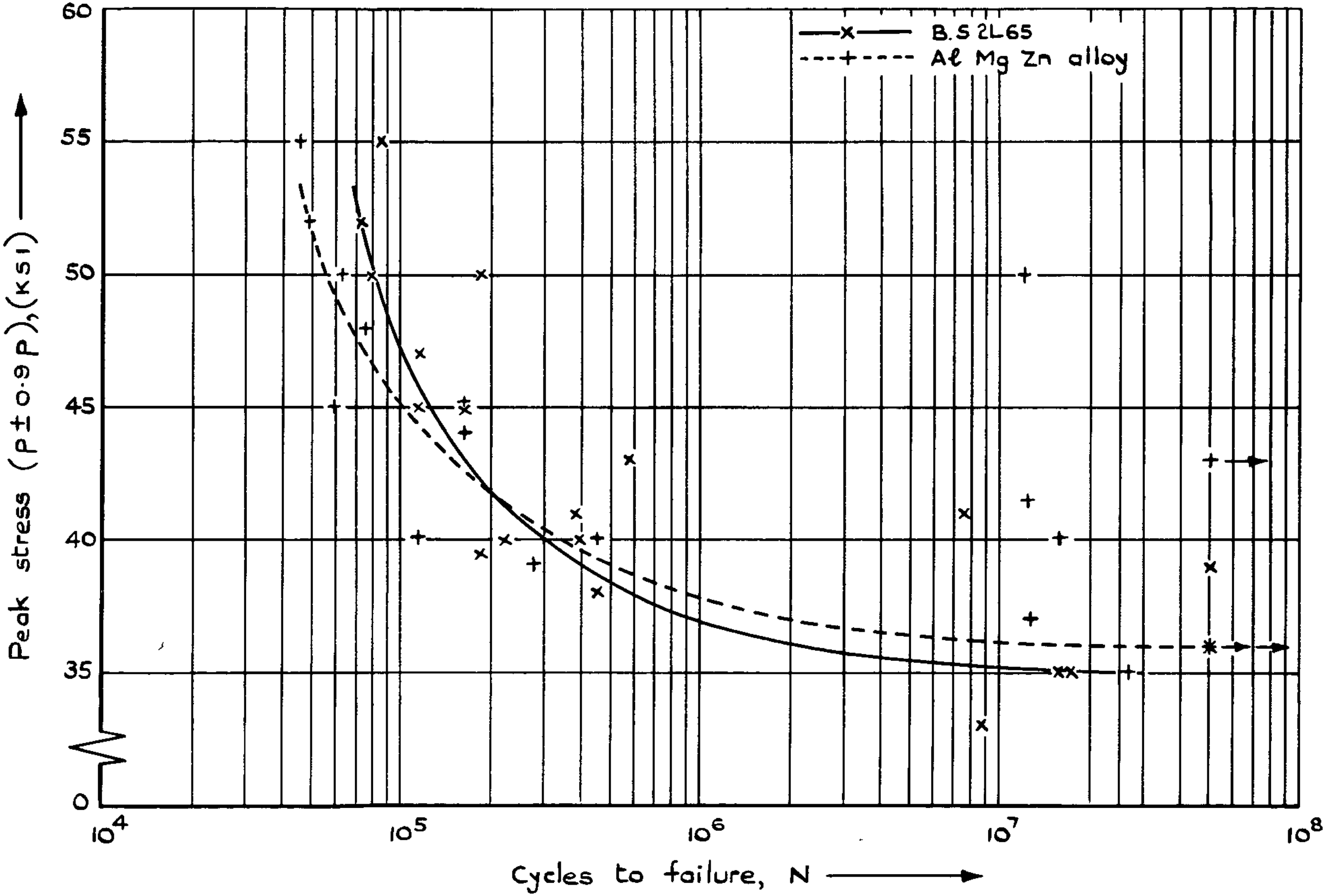


Fig. 11 Comparison of plain specimen results under constant amplitude loading

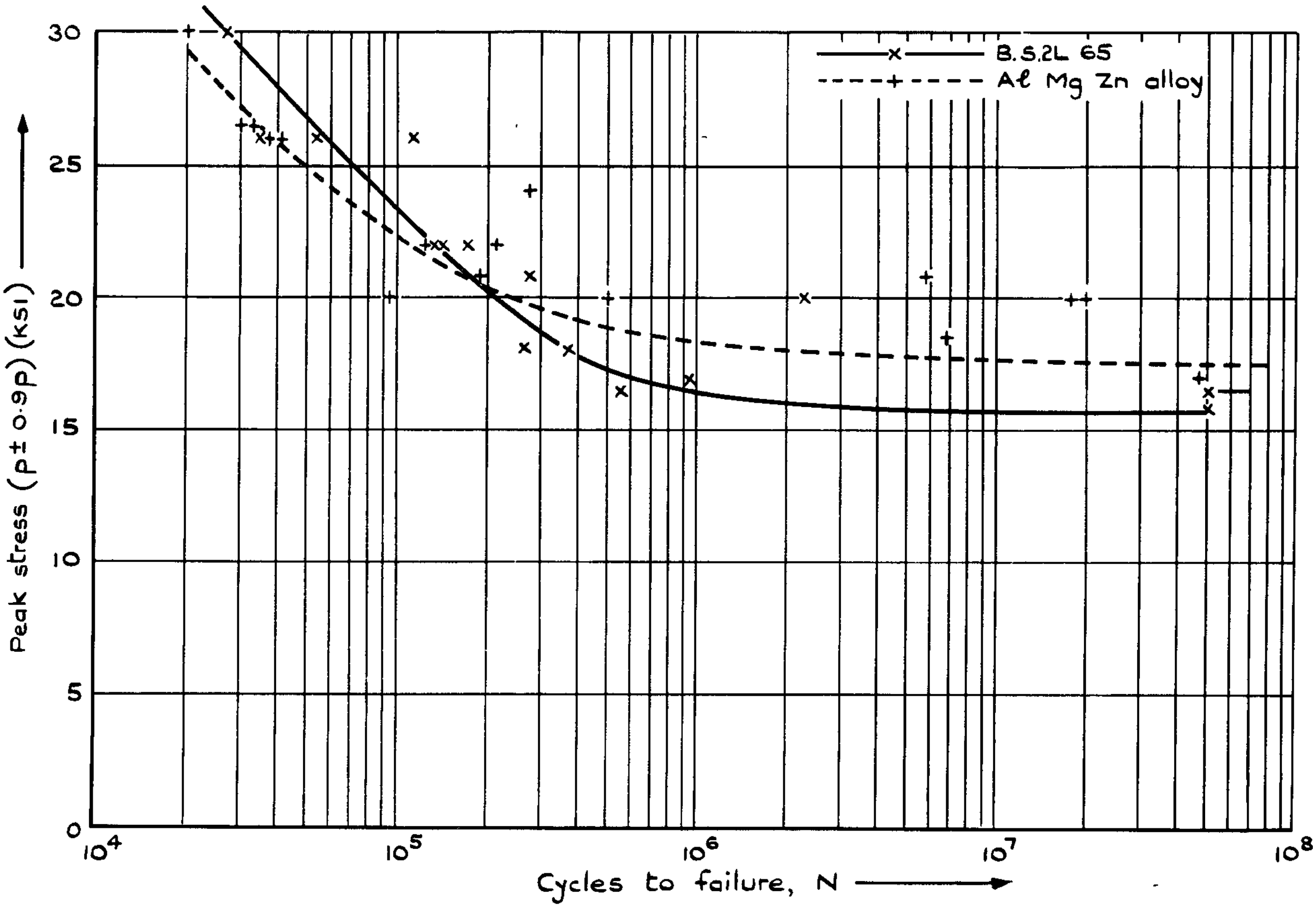


Fig.12 Comparison of 3·1 k_t notched specimen results under constant amplitude loading

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DETACHABLE ABSTRACT CARDS

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