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A DESCRIPTION OF HELIX AND FELIX, STANDARD FATIGUE LOADING SEQUENCES FOR HELICOPTERS, AND OF RELATED FATIGUE TESTS USED TO ASSESS THEM

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ABSTRACT

Helix and Felix are standard loading sequences which relate to the main rotors helicopters with articulated and semi-rigid rotors respectively. The purpose of the ading standards is, first, to provide a convenient tool for providing fatigue data der realistic loading, which can immediately be compared with data obtained by other ganisations. Second, loading standards can be used to provide design data. This per outlines the form of Helix and Felix, summarises their statistical content accord-g to different counting methods and gives results of fatigue tests used to assess eir usefulness.

INTRODUCTION

A standard loading sequence is a variable amplitude repeated sequence of peak and ough loads to be applied in fatigue and crack propagation tests. Each standard presents loading on a particular class of engineering structure. Two such existing andards are FALSTAFF [Ref 1] (Fighter Aircraft Loading STAndard For Fatigue evaluation) d TWIST [Ref 2] (Transport WIng STandard) which represent loading on fighter and ansport aircraft wings respectively. Typical sections of FALSTAFF and TWIST can be en in Figs 1 and 2. Their development has arisen from the fact that, often, life pre-ction methods are not accurate enough to predict fatigue lives or crack rates equately under service (variable amplitude) loading conditions. Therefore when making fatigue assessment of, for instance, a new detail, fastening system or method of life provement, variable amplitude loading has to be used. Often such tests are not tied ecifically to any particular project, but are for more general application. In this se a standard sequence, provided a relevant one exists, is often the best choice for e test loading.

The use of standard sequences is very simple, once facilities exist for generating em. A fatigue or crack propagation test is carried out under the standard loading quence, and the fatigue life or crack rate can then be compared directly with any others tained using the same standard. This enables an immediate estimate to be made as to e fatigue performance of the component or material under consideration for the parti-lar use for which it is intended (eg fighter aircraft wing in the case of using the LSTAFF standard). The test results can then be compared with any others for which tests ve been carried out under the same standard loading. Had the tests been carried out der constant amplitude loading the comparison would not have been valid until the nstant amplitude data had been used with a cumulative damage rule, such as Miner's Rule predict life under typical service loading. The comparison would have been made then the basis of predicted lives or crack rates and would have been subject to the con-derable errors that can apply to such cumulative damage predictions [Ref 3].

Experience has shown that, following the definition of a standard sequence, a alth of relevant data accumulates quickly, negating the need for some tests and giving tensive comparative data for others. This can greatly increase the technical value of dividual test results and reduce the amount of expensive fatigue testing. Large aluation programmes using standard sequences can be shared more readily between fferent organisations and countries because the test results of the programme will be mpatible with each organisation's own standard data. Such data can also be used for tigue life prediction in design instead of constant amplitude data. In this the elative Miner" approach is used [Refs 4&5], which normally gives more accurate pre-ctions than Miner's Rule.

This Report describes the derivation and fatigue assessment of two loading standards for the fatigue evaluation of helicopter rotor materials and components. The standards were developed as a collaborative study between West Germany, the Netherlands and UK.

As has become the practice the new loading standards have been given identifying names. For these the origin of the word helicopter (helix-spiral, pteron-wing from the Greek) has provided a convenient basis. The new standards are called:

Helix - Loading standard for 'hinged' or articulated rotors

Felix - Loading standard for 'fixed' or semi-rigid rotors.

The second of the names proves to be particularly appropriate as an early pioneer in helicopter development was Felix Tournachon. The lower case lettering is because the names Helix and Felix are not acronyms.

This Paper summarises the form and statistics of Helix and Felix and the results of the fatigue tests used to assess them. Full details can be found in the two final project reports. The first of these [Ref 6] covers the background to their definition, statistical content according to different counting methods, and results of the fatigue tests. A full description of the form of the standards, including details required for their generation is given in Ref 7.

2 SUMMARY OF THE FORM OF HELIX AND FELIX

Helicopters are multi-role vehicles and in different roles can experience greatly differing sequences of blade loads. For the purpose of this study a sortie was defined as a flight fulfilling a particular role, and a flight as the period between take-off and subsequent landing. Helix and Felix consist of the same sequence of 140 sorties representing 190.5 h of flight. Each sortie in the sequence represents one of either Training, Transport, Anti-submarine Warfare (ASW), or Search and Rescue (SAR). Each of these appear in the sequence in three different lengths.

Each sortie consists of a sequence of manoeuvres, which is the same every time a particular type of sortie with the same length is applied. Helix and Felix each have their own set of manoeuvres which are placed in sequence in order to define the sorties. The manoeuvres are similar for Helix and Felix, but are not always directly equivalent. For this reason the sequences of manoeuvres making up any sortie are similar but not identical for Helix and Felix. When any manoeuvre is applied on different occasions the sequence of loads is always the same.

The following sections 2.1 to 2.3 describe the component parts of Helix and Felix in detail. Full details of their derivation can be found in Ref 6, and a full definition in Ref 7.

2.1 Sequence of sorties

The 140 flight sequence of sorties applying to both Helix and Felix is shown in Table 1 and was chosen on the basis of a once and for all random draw. As can be seen each sortie is defined in three lengths, 0.75 h, 2.25 h and 3.75 h. Table 2 shows the numbers of sorties of each length in the sequence.

2.2 Definition of manoeuvres

As described in Ref 6, before the sequence of manoeuvres for each sortie could be defined it was necessary to define individual manoeuvres for each class of helicopter. Helix was based on data obtained from the Sea King and Felix on data from the BO-105.

Data available for the Sea King and BO-105 identified 24 and 22 manoeuvres respectively, which were to be placed in sequence in the subsequent definition of the sorties. These were all non-dimensionalised to express the loads or strains on a scale up to 100 in intervals of 4. This scale was deemed to be in "Helix Units" or "Felix Units". As originally defined Helix [Ref 8] and Felix units were on scales up to 74 and had a greater number of defined levels than in the final versions. The differences between the original and, as described here, final versions of the standards are described in Ref 6.

Tables 3 and 4 list the defined manoeuvres in Helix and Felix, respectively. Shown .so is the loading content of each manoeuvre expressed in Helix/Felix units. Each ınoeuvre is applied at its own characteristic mean stress value, with each cycle applied ; a full cycle, as described in section 2.3 below. As can be seen the definitions of the ınoeuvres are similar, but not identical, for the two classes of helicopter. For instance ·lix has two manoeuvres, 8 and 9, describing approach to hover, whereas Felix has only ıe. These differences reflect the different sources of data and different definitions of ıat at first sight may appear to be the same manoeuvre. These inconsistencies between the ɪo sets of data led, as shown below, to manoeuvre sequences in each sortie which differed ı the two standards.

For both standards, as for virtually all laboratory loading sequences, an alter-ıting level was selected below which cycles were not included. As can be seen from ıbles 3 and 4, the lowest amplitudes included were 20 and 16 for Helix and Felix res-ɜctively. It can be seen from Tables 3 and 4 that the omission of the low level cycles ɜsulted in some manoeuvres having no significant loads. For completeness these manoeuvres ɜre included in the standards but no loads or dwells are applied. Omission of levels from ɜlix and Felix is discussed further in section 2.7.

.3 Sequence of loads in a manoeuvre

The sequence of loads in any manoeuvre was chosen for both standards on the basis : a once and for all random draw. Therefore, every time a particular manoeuvre is per-ɔrmed the sequence of loads is the same. As an example Table 5 shows the sequence for ıe first three out of the 24 defined manoeuvres in Helix. The numbers are all in Helix/ ɜlix units. In each case the first number is the mean stress. The subsequent numbers ɜpresent complete alternating cycles going positive first. Many of the cycles have to be ɜpeated several times in order to carry out their function fully, or to account fully ɔr the time spent in that manoeuvre (eg forward flight).

.4 Sequence and mix of manoeuvres in a sortie

The lack of operational statistics describing manoeuvre sequences led to their ynthesis by common sense consideration of the flight profile and the objective of the ɔrtie. In the simplest case the above approach says, for instance, that a helicopter annot perform a bank turn without first taking off. As an example, Table 6 shows the irst six manoeuvres of the Helix training sequence. The original intention was to use ıe same sequence of manoeuvres for Helix as Felix. However, in practice, it was found ıat the defined manoeuvres were not always directly equivalent between Helix and Felix, ıd so could not always be sequenced in the same way. Therefore the sequences for Helix ɜre derived first, and those for Felix formulated to be as similar as possible. The ɔnsiderations taken into account when synthesising the four sortie sequences were as ɔllows.

(a) Training - this was the most difficult sortie to define because of the wide ɜnging operations that are flown. The assumption was made, however, that this sortie ıould simulate the essential aspects of flight needed to perform other sorties. In ıdition, a pure training exercise was simulated, in which the helicopter performs ɜnoeuvres to demonstrate handling characteristics. Fig 3 shows a trace of the first six ɜnoeuvres of those for the Training sortie for Helix corresponding to Table 6. Note that ı Table 6 the column 'Matrix applications' refers to the number of times that the defined ɜquence of loads has to be repeated in order to describe fully the manoeuvre.

(b) Transport - this sortie represents take-off and low-speed manoeuvres away from he terminal area, flight at cruising speed whilst manoeuvring to take into account errain and air traffic control restrictions, and finally landing in the terminal area.

(c) ASW - in this sortie, apart from the requirement to move to and from the base rea, the helicopter repeatedly decelerates to allow deployment of a sonar buoy, and ccelerates to move to a new search area.

(d) SAR - the essential part of this sortie is the flying of low speed manoeuvres n order to execute a rescue.

2.5 Variation in lengths of sortie

The 0.75 h and 2.25 h flights were defined as fractions of the full 3.75 h sorties. Thus only one sequence of manoeuvres was defined for each sortie, the whole of which is used for the 3.75 h flight. For the flights of 0.75 h and 2.25 h take-off and landing are applied as for the complete sortie, but a selected part or parts is cut out from the rest of the flight. Full details are given in Refs 6 and 7.

2.6 Ground loads

The measured values used for the ground load transitions are -20 for Helix and -28 for Felix, both values being in Helix/Felix units. It is assumed for both Helix and Felix that this ground load transition value is reached at the end of each flight. Thus it is assumed that the rotor comes to a standstill at the end of each flight, so that each air-ground-air transition is a start-stop-start transition.

2.7 Shortened versions of Helix and Felix

In section 7.3 it is suggested that Helix and Felix can be used in shortened forms in order to reduce testing times when testing at long lives close to the fatigue limit. The full sequences were recommended for use in supplementary tests at higher stress levels. This section describes the method of omission of low level cycles in order to obtain the shortened sequences. Section 3.1 describes rainflow analyses of the shortened sequences.

The method of omission of cycles is to choose a manoeuvre alternating stress level at and below which cycles are omitted. However if this is applied rigorously some manoeuvres disappear altogether. In order to retain the identity of such manoeuvres one alternating cycle is applied at the highest level contained in that manoeuvre. This level is, of course, at or below the nominal level of omission.

The levels of omission chosen for normal use were 32 for Helix and 28 for Felix, giving defined sequences known as Helix/32 and Felix/28. The sequences are generated in exactly the same way as for the full versions except that the defined loads for each manoeuvre are modified. Table 7 gives the modified and unmodified load sequences for two of the Helix manoeuvres. Lengths of the full and modified sequences are given in Table 8.

3 STATISTICS OF HELIX AND FELIX

In this section are presented the most important statistics, from the point of view of fatigue, of the two standards. Additionally the spectra of Helix and Felix are compared with each other and also with operational data.

3.1 Comparison of Helix and Felix spectra

Helix and Felix were analysed by more than one counting method, and the results of these are shown in Tables 9 to 12. Tables 9 and 11 give the results of the rainflow analyses, and Tables 10 and 12 give analyses of peak, trough and levels crossed distributions.

Fig 4 shows a comparison of Helix and Felix spectra using the data obtained from rainflow counting. In Fig 4 mean stresses have been ignored to ease the comparison. Large steps can be seen in both Helix and Felix, at the top end of the spectra, due to the air-ground-air transitions, which are associated with extra loads on the negative side only. This tends to mask the marked difference in the shapes of the spectra for the flight loads, with the spectrum for Helix being generally flatter than that for Felix outside the region affected by the start-stop-start transitions. Fig 4 shows also the spectra for the shortened sequences Helix/32 and Felix/28, which appear also in Tables 13 and 14.

The differences between the flight load spectra for Helix and Felix are significant in that they are most apparent at the high tensile stresses, a region of particular importance to fatigue. This can be seen in Fig 5 which compares the two on the basis of positive-going levels crossed. Here the differences are more obvious at the high stress end than in the previous Figure, because the start-stop-start transitions only affect this ot at the negative stresses. At stresses above 60 Helix/Felix units a much sharper uncation on Helix than Felix can be seen. Also evident from Fig 5 is that both the top d bottom lines of the Felix spectrum are generally below those for Helix, although the ximum loads have been scaled to be the same in both cases. This indicates a generally wer relative level of mean load for Felix than Helix.

2 Comparison of Helix and Felix spectra with operational data

It should be appreciated that Helix and Felix were derived for a particular mix of noeuvres and sorties for which there is no complete comparative set of data. Conse-ently all the comparisons in this section are for Helix and Felix, representing a wide nging mixture of roles, with data for particular helicopters carrying out particular les. It follows, therefore, that a close similarity between the standards and the erational data would not necessarily be expected. Fig 6 shows a Sea King transport ectrum, compiled as part of the Helix/Felix project [Ref 6], compared with Helix. The a King data was factored so that it represented the same number of flying hours as lix, and the stresses were multiplied by the same factor as was used to derive Helix its in formulating the standard. As can be seen from Fig 6 there is very good agree-nt between the two spectra at the low stress end. At the high stress end Helix exhibits e step arising from the air-ground-air transitions which were not included in the Sea ng data, so similarity would not be expected in this region.

Fig 7 shows spectra for the BO-105 and Lynx compared with that for Felix. The Lynx d BO-105 spectra were to a design mix of manoeuvres, as described in Ref 6. For the rpose of the comparison the stresses and numbers of cycle were factored in the same way was described above for the Sea King. It can be seen from Fig 7 that agreement between lix and the Lynx and BO-105 spectra is quite good, except at the upper end where, as in e case of Helix, the Felix spectrum exhibits a step associated with the air-ground-air ansitions. Thus as in the case of the Sea King the Lynx flight spectrum compares well th that of the standard.

It was concluded that spectra for Helix and Felix compared well to measured data, spite differences in the mix of manoeuvres.

OUTLINE AND AIMS OF FATIGUE TEST PROGRAMME

Standard loading sequences, are used for two reasons. First they are a tool for ving an immediate comparison of one set of fatigue data with another. Second they may used to provide design data. In considering the first point it is clearly an advantage, st from the point of view of convenience, that any test result using a standard loading n immediately be compared with a library of fatigue data without resort to a cumulative mage rule. However a further consideration is whether the use of standard sequences at are as realistic as possible give more valid comparisons than with more simple quences such as the commonly employed block programme. Thus the question may be asked to whether the objective of easy comparison can be met by the adoption of a standard in e form of a block programme. Also, if standard block programmes were adopted, would the ta generated be better or worse for use in life prediction than the more complex lix and Felix?

The fatigue test programme, designed to investigate the above questions, consisted inly of tests under constant amplitude loading, Helix, Felix and block programmes signed to give fatigue lives similar to those of the two standards. Since Helix and lix were the most representative of all the loading sequences used, the assumption was de that comparisons using the two standards were the most valid, and assessments were de as to how closely comparisons made under other loadings could repeat them or be used predict them accurately. The assessment of Helix and Felix as design data was limited seeing how well other loading actions could be used to predict lives under the two andards (as distinct from comparative lives or comparative fatigue strengths in the rlier assessment). This analysis could at best only identify possible inadequacies in fe predictions using the other loading sequences which could possibly be redressed ing the more representative Helix and Felix. A full assessment of this would require re fatigue tests under loading spectra for specific design cases on specific helicopters, d is a topic for further study.

The final aim of the test programme was to assess the possibility of using Helix and Felix in a shortened form by omitting some low level cycles. Thus tests were carried out as described in section 7 with a shortened version of one standard, Helix.

The joint test programme consisted of 290 fatigue tests carried out at four different Establishments in three countries, and is summarised in Table 15. Details of the testing are given below and in supplementary reports issued by participating countries [Refs 9 and 10].

4.1 Loading sequences used in the tests

The test programme included tests under constant amplitude loading, Helix and Felix, Helix with some low levels omitted and three-level block programmes. Helix and Felix were always applied in their original form with the old number of defined stress levels. The essential difference between the old and new versions of Helix and Felix is small, and it is considered that the results of the test programme would not be significantly different if the new versions of the standards were used [Ref 6].

The three-level block programmes representing Helix and Felix were derived as shown in Fig 8. Tests were also carried out [Ref 6] under other block programmes which were not regarded as being as representative as those in Fig 8, and the results of these tests are not reported here.

4.2 Fatigue test specimens and materials

The fatigue test specimens are shown in Fig 9. Three basic types of specimen were tested. The first of these was a notched (open holed) specimen having a stress concentration factor based on net section of 2.5. The aluminium alloy specimens tested at LBF and IABG were virtually identical to the titanium alloy specimens tested at NLR. The titanium specimens tested at RAE in the programme investigating omission of low level cycles were smaller and thinner, but had the same stress concentration factor.

The second type of specimen was a lug, manufactured by MBB-UD, and made out of multidirectional GRP.

The third and final specimen was a shear stress specimen, tested in bending, and designed to test interlaminar shear strength in fatigue. The form was to a standard MBB-UD specimen and manufacture was out of unidirectional GRP material taken from a BO-105 helicopter main rotor.

5 FATIGUE TEST RESULTS AND CUMULATIVE DAMAGE CALCULATIONS

Sections 5.1 to 5.4 summarise the most important fatigue test results from the joint test programme. The results presented are the majority of the variable amplitude tests, these being under Helix, Felix and the corresponding block programmes. The tests investigating omission of low level cycles are reported separately in section 7. Sections 5.1 to 5.4 also discuss the cumulative damage behaviour of the respective specimens. Section 6 further discusses the results of section 5 as pertaining to the projected applications of Helix and Felix.

On the grounds that no cumulative damage rule has found acceptance as being generally superior to Miner's Rule, only predictions using this Rule are presented here as a basis for the assessment of Helix and Felix. The Rule was applied taking the fatigue limit into account. Variation in calculated damage of individual cycles due to their mean stress being other than that at which constant amplitude tests were carried out was accounted for by interpolating or extrapolating from tests at more than one value of R. This data was either in the form of a set of S-N curves or a Haigh Diagram.

Some assessments were made considering the Relative Miner approach [Refs 4 and 5], which is the most likely way that data obtained under Helix and Felix would be used to predict life for a component subjected to a loading action in the same class as Helix or Felix. There are a number of variants of this approach, but, as considered here, results of tests under a loading standard are used to adjust stresses and/or lives on relevant existing S-N data, such that application of Miner's Rule to that data would predict accurately the lives obtained under the standard. Miner's Rule is then applied to e adjusted data to predict lives under the required loading action. Clearly there is no vantage to this approach if lives under the standard can be predicted accurately by ner's Rule because the Relative Miner method would give the same answer as Miner's Rule. wever if Miner's Rule predicts lives that are too long or short for the standard, the lative Miner Rule compensates for this, assuming in effect that errors in using Miner's le directly would be similar for the loading action in question and for the standard.

1 Notched specimens of 3.1354-T3 aluminium alloy

Fatigue test results relating to Helix, together with the predictions using ner's Rule are plotted on Fig 10. The corresponding data for Felix is plotted on g 11.

Considering first the relative lives under the different loadings on Fig 10 it n be seen that the fatigue strength at 1000 flights to failure under Helix block ogrammed loading was similar to that for Helix but there were indications that at gher stresses fatigue lives under block loading would be longer than for Helix. wever this behaviour was not predicted by Miner's Rule. Whereas the Miner predictions r block programmed loading were good, at least at the lower stress levels, those for lix predicted a fatigue strength 20 per cent above that realised in practice (ie unsafe).

Turning now to Felix, it can be seen from Fig 11 that, as for Helix, the block ogramme fatigue lives were predicted well by Miner's Rule and the lives under the andard, in this case Felix, were over-estimated by the Rule. However this over-timate was not as great as for Helix, the largest over-estimate of fatigue strength ing about 10 per cent in this case compared with 20 per cent for Helix.

It follows from the above results that an assessment of aluminium alloy notched ecimens for articulated and semi-rigid rotors using block programmed loading represent-g either Helix or Felix would have given lives similar to those predicted by Miner's le directly. This means that any predictions using this data and a Relative Miner proach would have predicted lives for Helix and Felix also similar to those of Miner's le applied directly. For lives greater than 50 flights to failure this would lead to over-estimate of the fatigue strength under Helix, and presumably similar under rvice loading, of about 20 per cent, as shown in Fig 10. The corresponding over-stimate for Felix would be about 10 per cent.

.2 Lug specimens of multidirectional GRP

Fatigue test results under Felix, together with predictions using Miner's Rule, re plotted on Fig 12. A comparison with Fig 11 shows that the cumulative damage haviour of the multidirectional GRP lug specimens was very similar to that for the luminium alloy specimens. Miner's Rule always gave unsafe predictions in both cases, redicting fatigue strengths that were too high by up to 15 per cent for the lugs and up 10 per cent for the aluminium alloy specimens. No fatigue tests were carried out under he representative block programmed loading (see section 4.1) for the lug specimens.

.3 Shear stress specimens of unidirectional GRP

Fatigue test results for the shear stress GRP specimens under Felix and Felix block rogrammed loading are given in Fig 13. It can be seen that Felix and the block pro-rammed loading gave similar lives, the most noteworthy point being that Miner's Rule redicted lives that were too long by a large margin, the difference in predicted and chieved fatigue strength for Felix being more than 20 per cent over the range of test ives. The accuracy of Miner's rule appeared similar for the two loading actions but the ata were sparse, and although there was no evidence suggesting that Relative Miner rediction cases on block programmed datas would be substantially in error, firm conclu-ions cannot be drawn.

.4 Notched specimens on titanium alloy 6Al-4V

Fatigue test results for Felix and the corresponding block programmed loading are lotted, together with the relevant Miner's Rule predictions, in Fig 14.

Fig 14 presents a picture not dissimilar to that of Fig 11, which shows a corres-onding set of results for aluminium alloy. In both cases the predictions for tests under Felix gave lives that were generally too long (unsafe), with the predictions corresponding approximately to the limit of the achieved scatter band on the long life side. In both cases too, Miner's Rule predicted that life under block programmed loading would be shorter than under Felix. However whereas the Miner's Rule predictions were reasonably good for aluminium alloy under block loading, for titanium alloy, where the scatter was considerably greater, and the lives were similar to those under Felix, the predictions followed the low life side of the scatter band. It follows therefore that a Relative Miner prediction of Felix lives from the results of the tests on titanium specimens under block loading would predict lives longer than those of Miner's Rule applied direct. In fact, Fig 14 shows that the achieved lives were shorter than predicted by Miner's Rule direct. Therefore the Relative Miner prediction would be more in error than Miner's Rule applied direct and, in fact, more unsafe. The amount of extra error would be governed by the difference between the direct Miner predictions for block loading and the test results for that loading. This is not easy to assess accurately because of the large scatter, but the results suggest an extra error of 10 per cent on fatigue strength.

Thus it can be concluded that in this case, although the Felix block tests gave lives similar to those under Felix, the block sequence did not represent Felix well with regard to cumulative damage behaviour, and Relative Miner predictions of Felix from the block tests would be more in error and more unsafe than Miner's Rule applied direct.

6 ASSESSMENT OF THE TEST RESULTS IN TERMS OF THE PROJECTED USES OF HELIX AND FELIX

In sections 5.1 to 5.4 the cumulative damage behaviour of four types of specimen was examined. This assessment was in terms of, first, the accuracy of Miner's Rule applied directly to predict lives under Helix, Felix and the corresponding block programmes. Second was considered the use of a Relative Miner approach to predict lives under the Standards from the block programme data. The discussion continues now to relate this to the projected uses of Helix and Felix.

6.1 Use as tools to obtain comparative fatigue data

The convenience of being able to make a reliable comparison of two sets of fatigue data without resort to cumulative damage rules has already been remarked upon. However it is instructive to examine whether comparisons based on predictions using Miner's Rule would give results significantly different from those using Helix and Felix. Examination of Figs 10 to 14 show that for both Helix and Felix Miner's Rule virtually always predicted lives that were too long. In cases where Miner's Rule over-predicted by the similar amounts, for instance in Figs 11 and 12 for Felix applied to aluminium alloy and GRP lugs respectively, comparisons based on Miner's Rule were similar to those using Helix and/or Felix. However there were significant differences in other cases. The largest difference between the two methods of comparison was when comparing aluminium alloy (Fig 11) with unidirectional GRP (Fig 13) for semi-rigid rotor helicopters. Fig 11 shows that the mean fatigue strength under Felix of aluminium alloy specimens was between 0 and 10 per cent less than predicted by the Rule. However in Fig 13 the corresponding factor was between 25 and 30 per cent. Therefore an assessment of the comparative fatigue strength of the two materials based on constant amplitude data would be generally more than 15 per cent in error, assuming of course that the assessment using the more representative Felix was correct.

Consider now the use of block programmed loading for the comparison of fatigue strengths. Felix block programmed loading was assessed against Felix in three cases. For aluminium alloys it gave fatigue strengths about 10 per cent below Felix (Fig 11), for unidirectional GRP it gave fatigue strengths similar to Felix (Fig 13), and for titanium alloy specimens (Fig 14), it appeared to give fatigue strengths lower than Felix at the higher stresses, and higher than Felix at the lower stresses. Therefore errors in comparative fatigue strengths would be about 10 per cent comparing aluminium alloys with unidirectional GRP, with perhaps greater errors than that at some stress levels comparing aluminium and titanium alloy. It was concluded that there was no reason to suppose from the test results that the results of block programmed tests would give comparisons more valid than Miner's Rule.

.2 Use as design data

As shown in section 5 the use of Miner's Rule to predict fatigue lives under Helix nd Felix gave some considerable errors, particularly for aluminium alloy under Helix Fig 10) and unidirectional GRP under Felix (Fig 13) where the fatigue strength was someimes over-estimated by 20 per cent and more. In all cases the Rule predicted lives that ere too long. Although these errors can be accounted for in some cases by alternative umulative damage rules the hope is that Helix and Felix used in conjunction with a elative Miner approach would give the most reliable predictions.

The most notable outcome of the test programme was the conclusion that the block rogrammes did not show the same cumulative damage behaviour as *Helix* and *Felix*. *However* he Relative Miner approach seeks to minimise errors in Miner's Rule by assuming that umulative damage behaviour under the waveform for which life is predicted is the same as hat under the waveform used to obtain the basic fatigue data. Therefore the use of block rogrammed loading as the source of basic fatigue data was assessed in section 9 as preicting lives either no more accurate than Miner's Rule or more inaccurate. In no case as the use of block programmed data likely to predict lives substantially more accurate han Miner's Rule, and for the case of titanium alloy (section 5.4) would predict lives ore unsafe as well as less accurate than Miner's Rule. It was concluded from the above hat if life prediction more reliable than that provided by Miner's Rule was required it as unlikely to be achieved or substantiated reliably using block programmes.

It is considered that the above findings give the strongest possible reasons for dopting more realistic loading in helicopter substantiation procedures, with Helix and elix playing an important part in this.

TESTING WITH SHORTENED VERSIONS OF THE STANDARDS

In their full form Helix and Felix both consist of over two million cycles, each equence representing 140 flights only. Thus a typical test in a servohydraulic machine t 15 Hz to 1500 flights would take about 18 days. There is considerable scope for peeding up tests by using high speed servohydraulic machines; for instance the RAE tests ere carried out at 45 Hz, which is three times faster than the example given above. owever it was felt that testing times were still formidable and tests were carried out nder sequences with some low level cycles omitted to look at the possibility of further hortening testing times. The tests were on Helix and Helix with levels omitted, on pecimens of titanium alloy (section 4.2).

.1 Test sequences

Helix was used as one test sequence. The shortened version was derived simply by mitting alternating level 20 (old units) and below. This procedure led to 13 out of the 4 manoeuvres in Table 3 disappearing altogether and these were omitted from the sequence. he result was to give a reduction in length of the sequence of 88 per cent. This was he version of the reduced sequence which was used exclusively in the fatigue tests and n this paper is termed Short Helix.

.2 Fatigue test results

Test results under Helix and Short Helix are plotted in Fig 15. Two peak stress evels only were used in the tests and in both cases the mean life under short Helix was onger, in terms of number of flights, than under Helix. At the high level the ratio of ives under Short Helix to Helix was 4:1 and at the lower level was 1.8:1. Assuming that elix gave ideal assessments this represented errors in using Short Helix to assess the atigue strength of about 4 per cent at the lower stress level and 8 per cent at the igher stress level.

.3 *Recommendations for the use of the shortened sequences*

In order to reduce testing time in determining fatigue strengths at long lives hree approaches can be used. First, the testing frequency can be raised to the limits f valid testing or the limit of the machine, whichever is less. Second, tests can be arried out at a high stress level and the results extrapolated downwards. Third, testing an be carried out using sequences with low levels omitted. The second and third possiilities are the concern of this paper.

The actual results in Fig 15, suggest an error of 4 per cent in using Short Helix to determine the fatigue limit. This is not a particularly large error, and, if validated as a generally applicable result, might well be an acceptable penalty to pay for test lives about one quarter of those for the full standard sequence. A factor based on the results of research work could be used to reduce the errors still further. Alternatively or additionally the results of tests under the full sequence at higher stress levels might be used to deduce the error factor at the fatigue limit, for instance as represented by the tests at the higher stress level in Fig 15, and which gave lives under Helix about one tenth of those at the lower stress level.

When low level cycles are removed from a variable amplitude sequence Miner's Rule predicts that, if the S-N curve for the component is a straight line on a log-log plot, then the resulting percentage change in life is independent of the overall stress level of the variable amplitude sequence. However S-N curves tend at the bottom to bend towards the long life direction, perhaps forming a fatigue limit, and as a result Miner's Rule predicts that the lowest bank of cycles in, for instance, Helix do some damage at high overall stresses, and none, or virtually none at low overall stress levels. Thus Miner's Rule predicts that the omission of a bank of lowest level cycles will affect life under variable amplitude loading by a larger percentage at high overall stress levels than at low. Although it is generally accepted that cycles below the fatigue limit are more damaging than predicted by Miner's Rule the above trend is likely still to hold on the grounds that there is still likely to be a damage threshold for small cycles in variable amplitude loading sequences, even if it is somewhat below the constant amplitude fatigue limit. This is supported by the results in Fig 15, where inclusion of low level cycles appeared to be twice as damaging at the higher overall stress level than at the lower.

Nevertheless at present the magnitudes of the errors in using the shortened sequences Helix/32 and Felix/28 are not established and the above results must be regarded as provisional. It is recommended therefore that the shortened sequences should be used with extreme caution. They should be used only at the lower stress levels, close to the fatigue limit where the errors in using them are liable to be less severe as indicated above. Such tests should be supplemented by further tests under the full standard loadings at higher stress levels. Further research is necessary, however, to quantify better the errors in following this procedure, particularly since the data available so far has used Short Helix only.

8 CONCLUSIONS

(1) Two loading standards, Helix and Felix, applying to the main rotors of articulated and semi-rigid rotor helicopters respectively, were defined in both full and shortened forms. The shortened forms of the standards are known as Helix/32 and Felix/28.

(2) In a fatigue test programme, which included tests on aluminium alloy, titanium alloy and GRP specimens, the use of Helix and Felix was assessed, both from the point of view of tools to provide comparative fatigue data, and as a source of design data. It was found that Helix and Felix gave comparative fatigue strengths that varied significantly in some cases from those obtained using three-level block programmes, and from those predicted from constant amplitude loading.

It was found also that block programmes designed to be equivalent to Helix and Felix did not represent them well in terms of the accuracy of Miner's Rule in predicting lives under them. The use of data obtained under block programmes and a relative Miner approach would have led to predictions generally less accurate than those using Miner's Rule applied direct.

(3) It was concluded that the failure of the block programmes to represent the cumulative damage behaviour of the more representative loadings gave the strongest possible reasons for adopting more realistic loading in helicopter substantiation procedures, with Helix and Felix playing an important role in this.

(4) Following tests assessing the effect of omitting low level cycles from Helix, it was recommended provisionally that the shortened versions of the standards should be used with extreme caution, and then only for long life tests to determine the fatigue limit. These tests should be supplemented by tests under the full standards at higher levels.

) More research is required into the effect of omitting low level cycles from Helix d Felix, and into the accuracy of the relative Miner approach using Helix and Felix data a basis.

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In: "Helicopter fatigue life assessment", AGARD CP-297, 1980

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Table 1

SEQUENCE OF SORTIES FOR 140 FLIGHT SEQUENCES OF HELIX AND FELIX

21, 11, 43, 11, 21, 12, 22, 11, 11, 21, 21, 21, 23, 42, 23, 21, 12, 11, 21, 22, 11,
42, 22, 21, 32, 21, 11, 22, 32, 22, 11, 31, 21, 22, 11, 11, 42, 42, 21, 21, 33, 12,
31, 22, 22, 11, 11, 11, 11, 11, 21, 21, 11, 41, 11, 12, 22, 22, 22, 11, 21, 11, 21,
11, 21, 21, 21, 21, 11, 11, 22, 21, 21, 21, 11, 21, 11, 12, 12, 21, 11, 11, 22, 11,
41, 21, 11, 11, 11, 23, 11, 21, 11, 21, 11, 21, 11, 22, 32, 23, 11, 12, 22, 22, 23,
12, 21, 11, 22, 11, 11, 41, 33, 22, 32, 21, 11, 21, 21, 22, 21, 21, 12, 21, 11, 21,
21, 13, 11, 11, 12, 11, 11, 11, 41, 11, 22, 11, 41, 12.

Key:

Training - 10
Transport - 20
ASW - 30
SAR - 40

Shortest flight duration - 1 (0.75 hour)
Middle flight duration - 2 (2.25 hours)
Longest flight duration - 3 (3.75 hours)

therefore 23 is a transport flight of the longest duration

Table 2

NUMBER OF FLIGHTS OF EACH SORTIE FOR THE THREE FLIGHT DURATIONS IN HELIX AND FELIX

Flight duration (h)	Number of flights			
	Training	Transport	ASW	SAR
0.75	47	38	2	5
2.25	11	20	4	4
3.75	1	5	2	1

Table 3

LOAD MATRIX FOR HELIX

Alternating stress			20	24	28	32	36	40
No.	Manoeuvre	Mean stress	No. of cycles					
1	Take-off	44	2	-	-	-	-	-
2	Forward flight 20 kn	72	13	-	-	-	-	-
3	Forward flight 30 kn	68	-	12	2	-	-	-
4	Forward flight 40 kn	60	4	9	1	-	-	-
5	Forward flight 60 kn	60	11	2	-	-	-	-
6	Forward flight 103 kn	64	2	4	12	-	-	-
7	Maximum power climb 70 kn	68	1	-	-	-	-	-
8	Shallow approach to hover	56	12	5	6	8	4	-
9	Normal approach to hover	60	11	2	4	3	5	1
10	Hover	-	-	-	-	-	-	-
11	Bank turn port	68	-	1	20	1	-	-
12	Bank turn starboard	68	-	1	16	1	-	-
13	Sideways flight port, 30 kn	56	3	-	-	-	-	-
14	Recovery from 13	52	11	5	9	1	2	-
15	Sideways flight starboard	60	3	3	3	-	-	-
16	Recovery from 15	52	11	2	3	2	4	1
17	Rearwards flight 20 kn	68	1	-	-	-	-	-
18	Recovery from 17	60	4	-	9	10	1	-
19	Spot turn port	64	30	8	2	-	-	-
20	Spot turn starboard	68	3	-	-	-	-	-
21	Autorotation	60	19	-	-	-	-	-
22	Recovery from 21	60	-	2	10	4	1	-
23	Descent	60	11	2	-	-	-	-
24	Landing	72	1	3	1	-	-	-

All stresses are expressed in Helix units.

Table 4

LOAD MATRIX FOR FELIX

Alternating stress			16	24	28	32	36	44	48	52	60
No.	Manoeuvre	Mean stress	No. of cycles								
1	Take-off	32	7	13	11	1	-	-	-	-	-
2	Forward flight 0.2 VNE	48	11	2	-	-	-	-	-	-	-
3	Forward flight 0.4 VNE	-	-	-	-	-	-	-	-	-	-
4	Forward flight 0.6 VNE	48	2	-	-	-	-	-	-	-	-
5	Forward flight 0.8 VNE	-	-	-	-	-	-	-	-	-	-
6	Forward flight 0.9 - 1.1 VNE	48	24	1	-	-	-	-	-	-	-
7	Maximum power climb 70 kn	-	-	-	-	-	-	-	-	-	-
8	Transition to hover	40	10	1	-	-	-	-	-	-	-
9	Hover	36	10	1	-	-	-	-	-	-	-
10	Cruise turns 0.4 - 0.8 VNE	60	20	4	-	-	-	-	-	-	-
11	Cruise turns 0.8 - 1.0 VNE	64	14	13	1	-	-	-	-	-	-
12	Sideways flight port	36	11	3	-	-	-	-	-	-	-
13	Sideways flight starboard	36	10	19	13	1	-	-	-	-	-
14	Rearwards	36	10	9	1	-	-	-	-	-	-
15	Spot turns	36	16	2	-	-	-	-	-	-	-
16	Autorotation (AR)	40	32	21	9	3	1	1	-	-	-
17	AR incl large amplitude	40	32	21	9	3	1	1	3	1	3
18	Recoveries from AR	36	32	2	-	-	-	-	-	-	-
19	Control reversals 0.4 VNE	36	32	12	5	3	1	-	-	-	-
20	Control reversals 0.7 VNE	44	36	13	5	3	2	-	-	-	-
21	Descent	36	-	1	26	2	-	-	-	-	-
22	Landing	3	-	-	-	-	2	-	-	-	-

All stresses are expressed as Felix units.

Table 5

SEQUENCE OF LOADS FOR FIRST THREE OF THE HELIX MANOEUVRES

1 Take off
44, 20, 20

2 Forward flight 20 kn
72, 20, 20, 20, 20, 20, 20, 20, 20, 20, 20, 20, 20, 20,

3 Forward flight 30 kn
68, 24, 24, 24, 24, 24, 24, 24, 24, 24, 24, 24, 24, 24, 24
etc.

Table 6

FIRST SIX MANOEUVRES IN TRAINING SORTIE

Position No.	Manoeuvre	Manoeuvre No.	Time in manoeuvre	Matrix applications
1	Take off	1	36	6
2	Forward flight 20 km	2	12	3
3	Forward flight 30 km	3	12	2
4	Forward flight 40 km	4	12	3
5	Forward flight 30 km	3	18	3
6	Forward flight 20 km	2	20	5

Table 7

CORRESPONDING SEQUENCES OF LOADS FOR TWO MANOEUVRES IN HELIX AND HELIX/32

13 Sideways flight port

Helix

56, 20, 20

Helix/32

56, 20

16 Recovery from sideways flight to starboard

Helix

52, 36, 20, 36, 32, 20, 28, 40, 36, 36, 20, 20
24, 20, 24, 20, 20, 28, 20, 28, 20, 20, 32
20

Helix/32

52, 36, 36, 32, 40, 36, 36

Table 8

NUMBERS OF FULL CYCLES IN HELIX AND FELIX BOTH IN FULL AND SHORTENED FORM

Sequence	No. of whole cycles
Helix	2132024
Helix/32	145862
Felix	2285072
Felix/28	161034

Table 9

HELIX RAINFLOW ANALYSIS

Distribution of the ranges

Range size (Helix units)	No. of ranges	Cumul.. No.
4	5988	4264048
8	1312	4258060
12	554	4256748
16	138	4256194
20	280	4256056
24	0	4255776
28	554	4255776
32	0	4255222
36	464	4255222
40	959084	4254758
44	738	3295674
48	910654	3294936
52	7176	2384282
56	2336362	2377106
60	4452	40744
64	20658	36292
68	542	15634
72	11796	15092
76	830	3296
80	1884	2466
84	20	582
88	282	562
92	0	280
96	0	280
100	0	280
104	0	280
108	0	280
112	0	280
116	0	280
120	280	280

Table 10

HELIX ANALYSIS OF PEAKS/TROUGHS AND OF POSITIVE LEVEL CROSSINGS

Level (Helix units)	No. of peaks	No. of troughs	Positive levelcr.
-20	0	140	140
-16	0	0	140
-12	0	0	140
-8	0	0	140
-4	0	0	140
0	0	0	140
4	0	0	140
8	0	0	140
12	0	281	421
16	0	1688	2109
20	0	2233	4342
24	0	10412	14754
28	0	7093	21847
32	0	16898	38745
36	0	1163994	1202739
40	0	676930	1879669
44	0	210951	2090620
48	0	5651	2096271
52	0	32039	2128310
56	141	88	2128257
60	160	1010	2129107
64	1834	2283	2129556
68	2798	333	2127091
72	7012	0	2120079
76	6346	0	2113733
80	248246	0	1865487
84	253998	0	1611489
88	382222	0	1229267
92	1150931	0	78336
96	73302	0	5034
100	5034	0	0

Value refers to interval between the defined level and the one below it.

Table 11

FELIX RAINFLOW ANALYSIS

Distribution of the ranges

Range size (Felix units)	No. of ranges	Cumul. No.
4	1374	4570144
8	832	4568770
12	3682	4567938
16	2072	4564256
20	3376	4562184
24	2462	4558808
28	1681	4556346
32	4055804	4554665
36	1795	498861
40	10516	497066
44	960	486550
48	342776	485590
52	3184	142814
56	105036	139630
60	3930	34594
64	20528	30664
68	2158	10136
72	6756	7978
76	234	1222
80	312	988
84	68	676
88	50	608
92	180	558
96	18	378
100	16	360
104	16	344
108	14	328
112	13	314
116	0	301
120	285	301
124	0	16
128	16	16

Table 12

FELIX ANALYSIS OF PEAKS/TROUGHS AND OF POSITIVE LEVEL CROSSINGS

Level (Felix units)	No. of peaks	No. of troughs	Positive levelcr.
-28	0	546	546
-24	0	0	546
-20	0	24	570
-16	0	0	570
-12	0	8	578
-8	0	24	602
-4	0	40	642
0	0	1472	2114
4	0	9442	11556
8	140	49938	61354
12	0	55619	116973
16	0	9146	126119
20	0	157152	283271
24	0	81595	364866
28	0	43200	408066
32	0	1750246	2158312
36	140	17641	2175813
40	354	14290	2189749
44	470	77633	2266912
48	3196	17056	2280772
52	141552	0	2139220
56	8836	0	2130384
60	99165	0	2031219
64	1796322	0	234897
68	22370	0	212527
72	83615	0	128912
76	80940	0	47972
80	17408	0	30564
84	15500	0	15064
88	13960	0	1104
92	1080	0	24
96	0	0	24
100	24	0	0

Value refers to interval between the defined level and the one below it.

Table 13

HELIX/32 RAINFLOW ANALYSIS

(Helix with omission level 32 and below)

Range size (Helix units)	No. of ranges	Cumul. No.
4	5988	291724
8	1312	285736
12	554	284424
16	138	283870
20	0	283732
24	0	283732
28	280	283732
32	0	283452
36	138	283452
40	15270	283314
44	0	268044
48	40882	268044
52	732	227162
56	190524	226430
60	142	35906
64	20130	35764
68	542	15634
72	11796	15092
76	830	3296
80	1884	2466
84	20	582
88	282	562
92	0	280
96	0	280
100	0	280
104	0	280
108	0	280
112	0	280
116	0	280
120	280	280
124	0	0
128	0	0
132	0	0

Table 14

FELIX/28 RAINFLOW ANALYSIS

(Felix with omission level 28 and below)

Range size (Felix units)	No. of ranges	Cumul. No.
4	1374	322068
8	832	320694
12	3682	319862
16	1628	316180
20	4	314552
24	436	314548
28	459	314112
32	4118	313653
36	4381	309535
40	1664	305154
44	692	303490
48	162666	302798
52	872	140132
56	104666	139260
60	3930	34594
64	20528	30664
68	2158	10136
72	6756	7978
76	234	1222
80	312	988
84	68	676
88	50	608
92	180	558
96	18	378
100	16	360
104	16	344
108	14	328
112	13	314
116	0	301
120	285	301
124	0	16
128	16	16
132	0	0

Table 15

SURVEY OF THE JOINT TEST PROGRAMME

Material	Ti 6 Al 4 V		Al Cu Mg 2 (eq 2024)		Unidir. GRP		Multidirectional GRP	
Specimen type	Open hole, $K_t = 2.5$		Open hole, $K_t = 2.5$		Unnotched		Lugs, 10 mm hole dia	
Thickness	2.2 mm	5.5 mm	5 mm		10 mm		10 (2nd delivery: 8)	
Loading type	Axial		Axial		4-point bending		Axial	
Laboratory	RAE	NLR	IABG	LBF	RAE	IABG	IABG	LBF
Testing type		No. of tests						
Constant amplitude	5	15	5	25		38	45	2
Helix standard	14			21		1		
Helix reduced	14							
Helix block			5	11		9		
Felix standard		11	17			7		18
Felix block		8	5			3		11

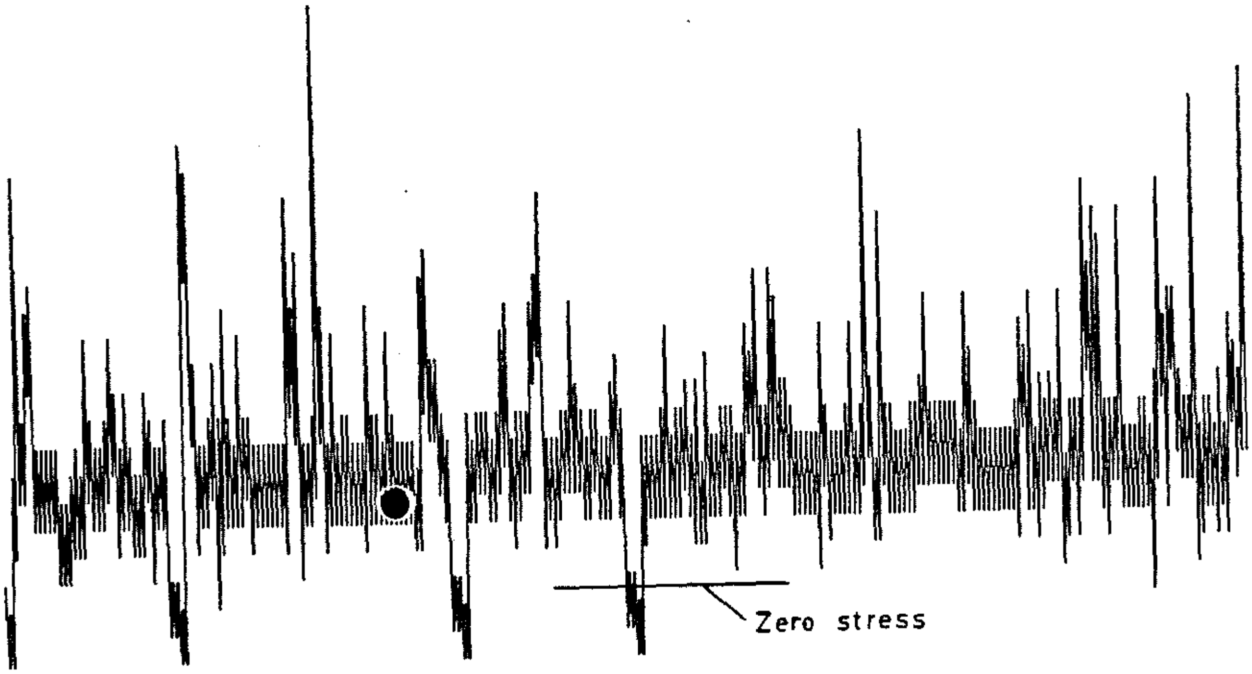


Fig 1 Section of generated waveforms in FALSTAFF

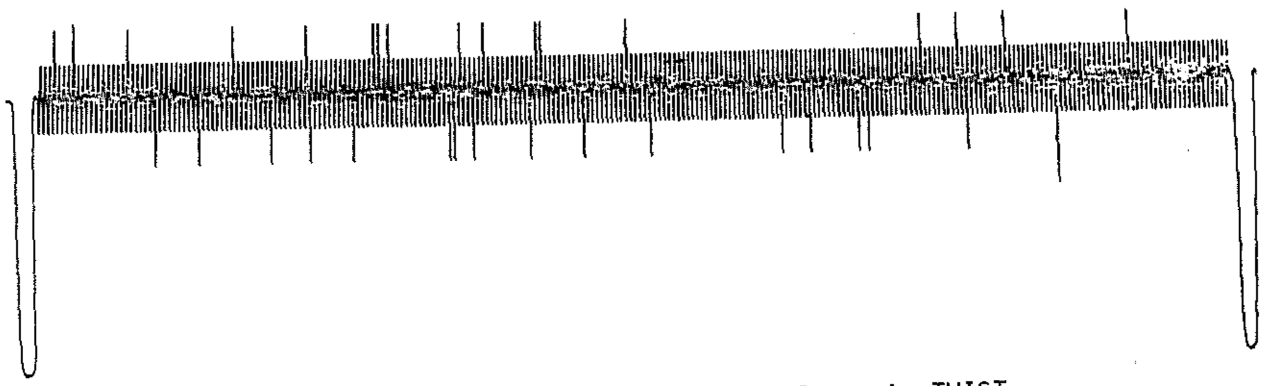


Fig 2 Section of generated waveforms in TWIST

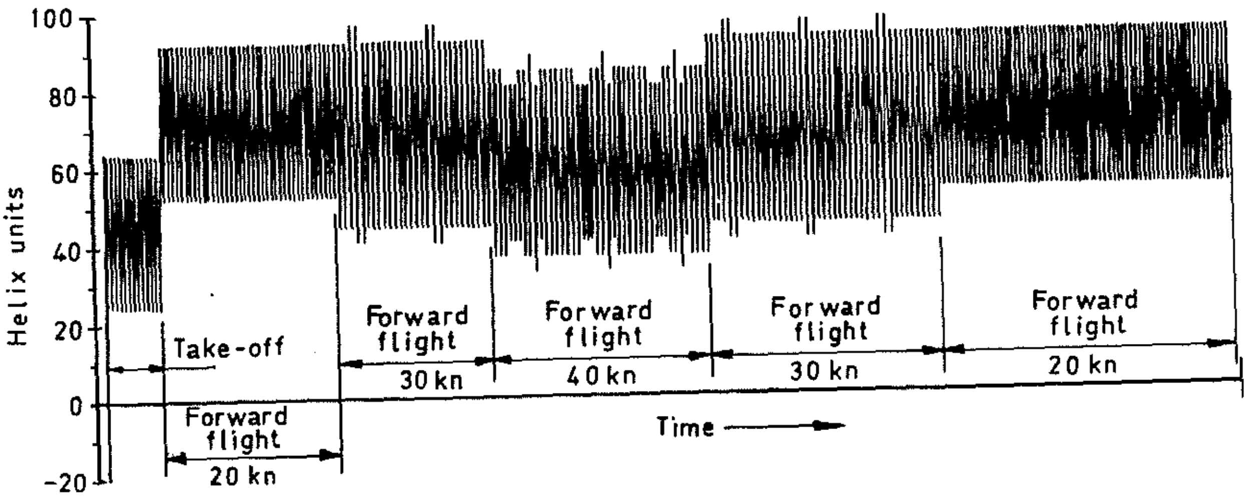


Fig 3 Example of the load time history for the first phase of a training flight in Helix

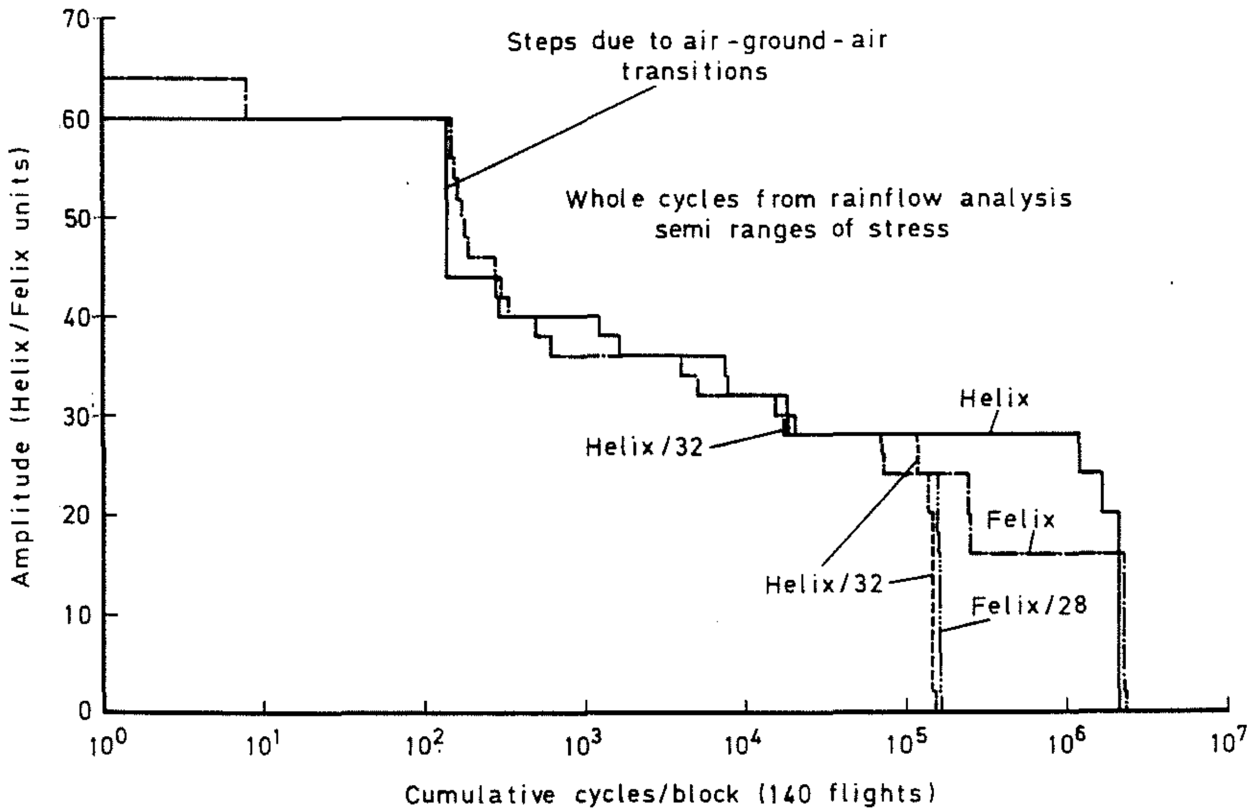


Fig 4 Comparison of Helix and Felix - whole cycles from rainflow analysis

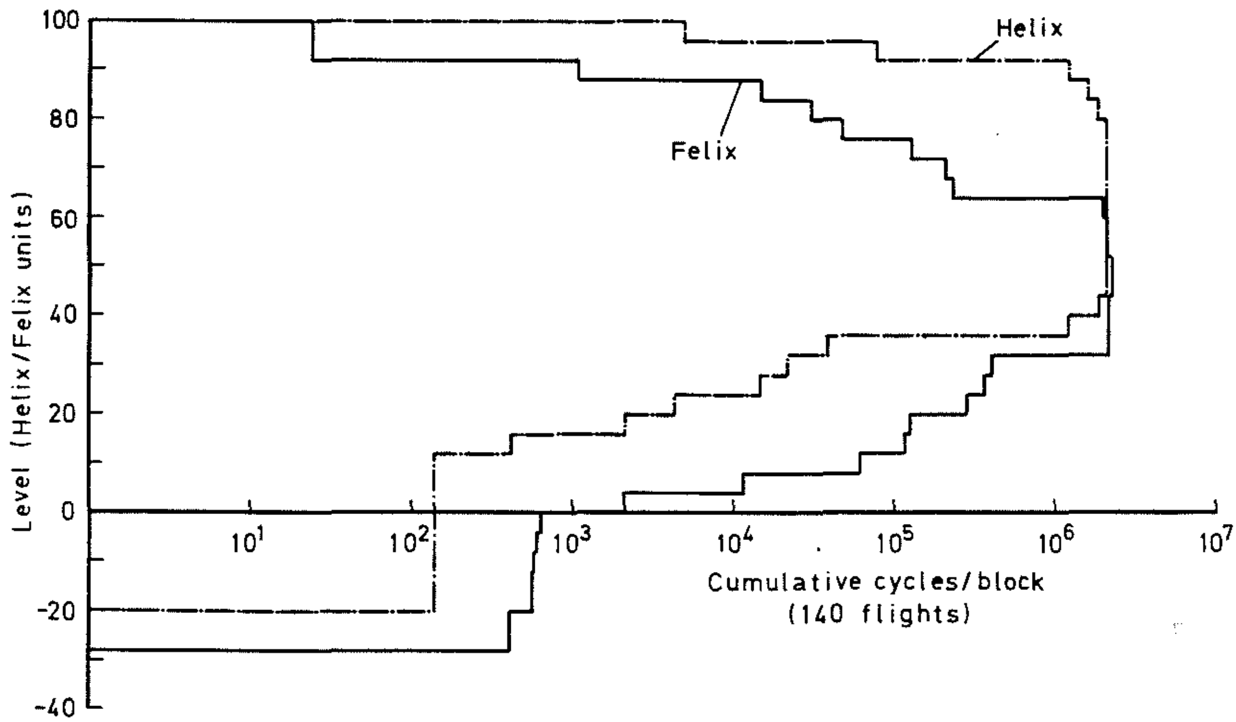


Fig 5 Comparison of Helix and Felix spectra - positive - going levels crossed

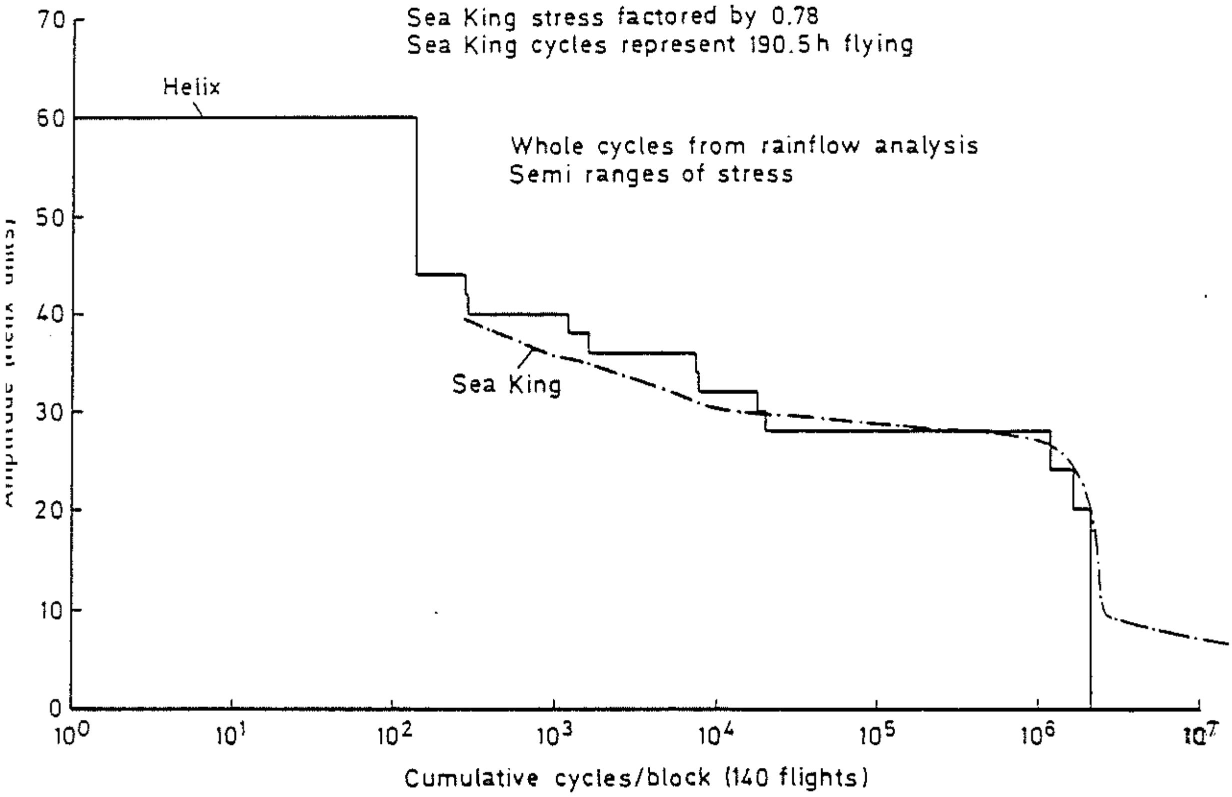


Fig 6 Comparison of Sea King transport spectrum with Helix

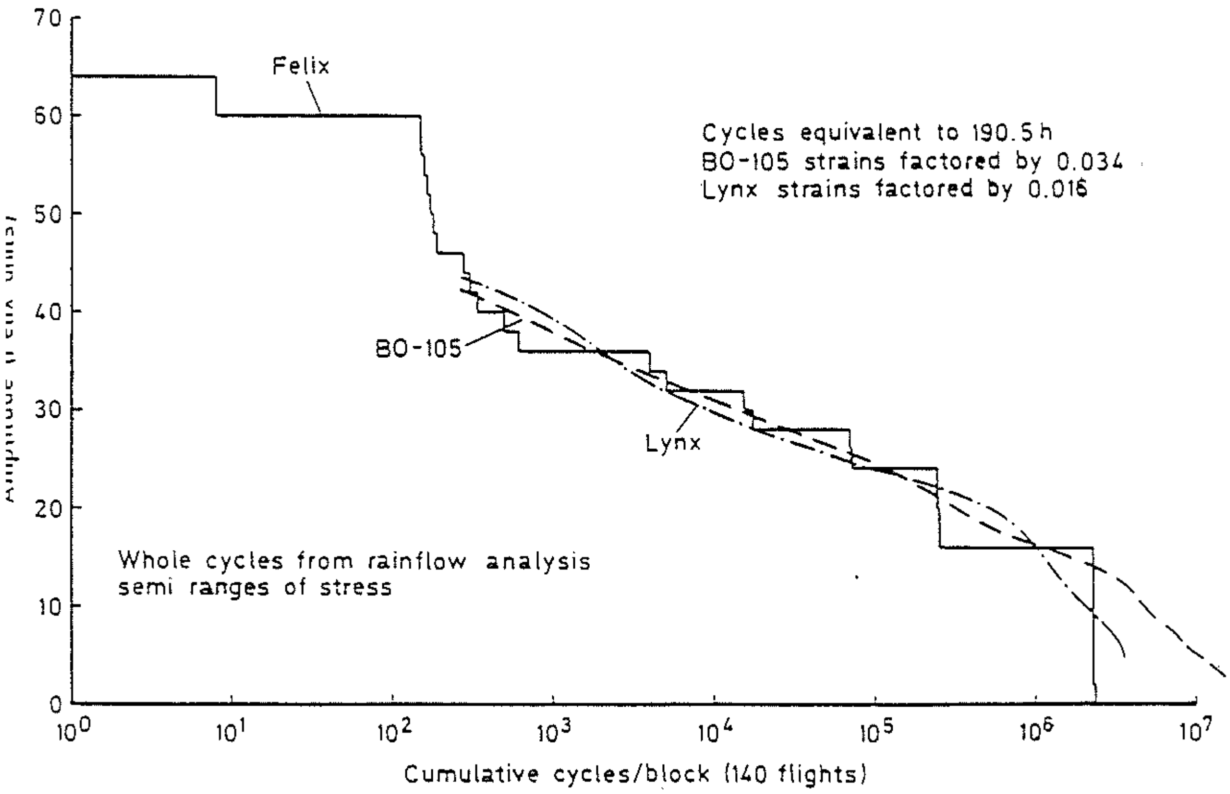
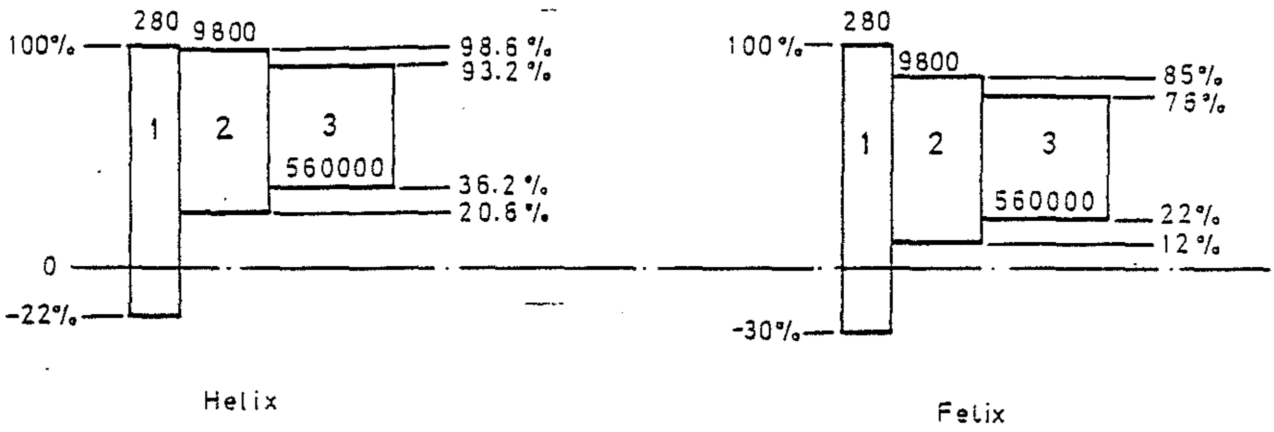


Fig 7 Comparison of Felix spectrum with those for BO-105 and Lynx



Sequence 1-2-3-3-2-1-1-2--etc

Fig 8 Three level block - programmes - 140 flights each

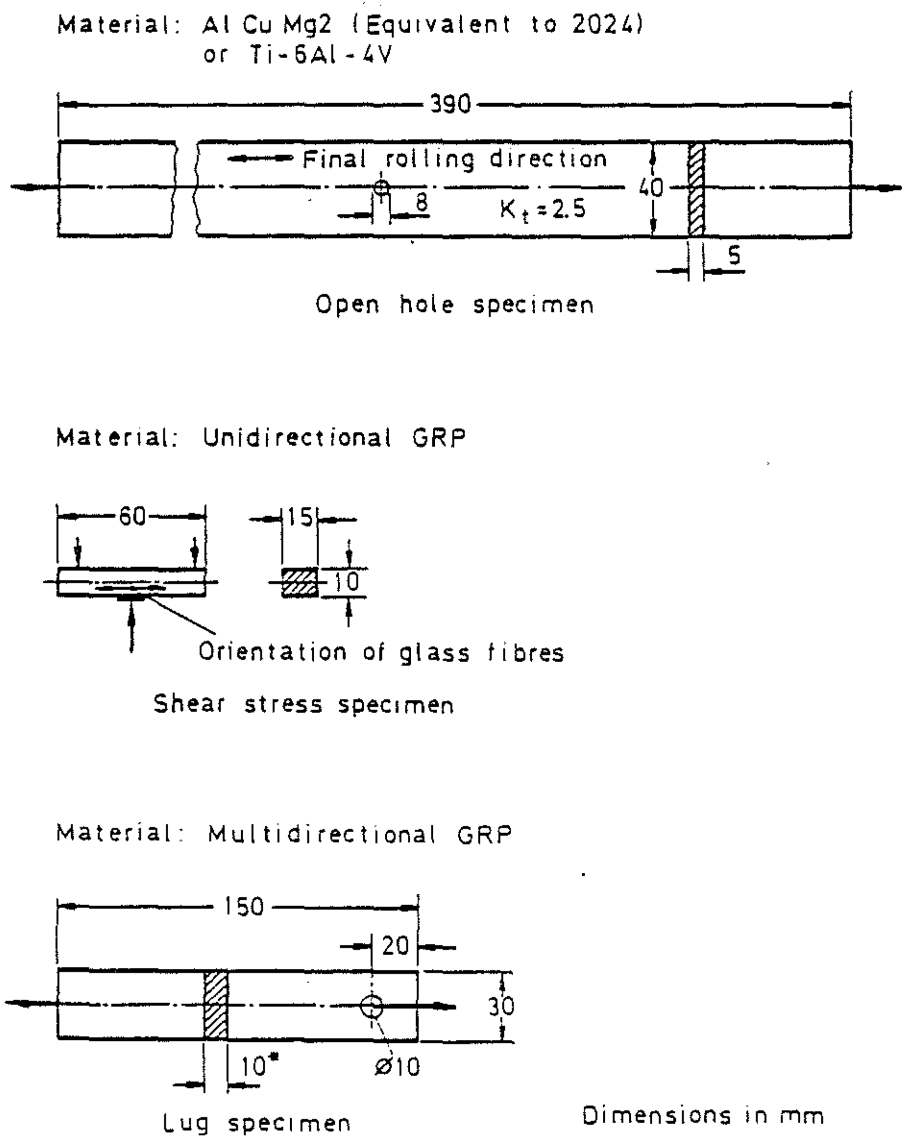


Fig 9 Test specimens

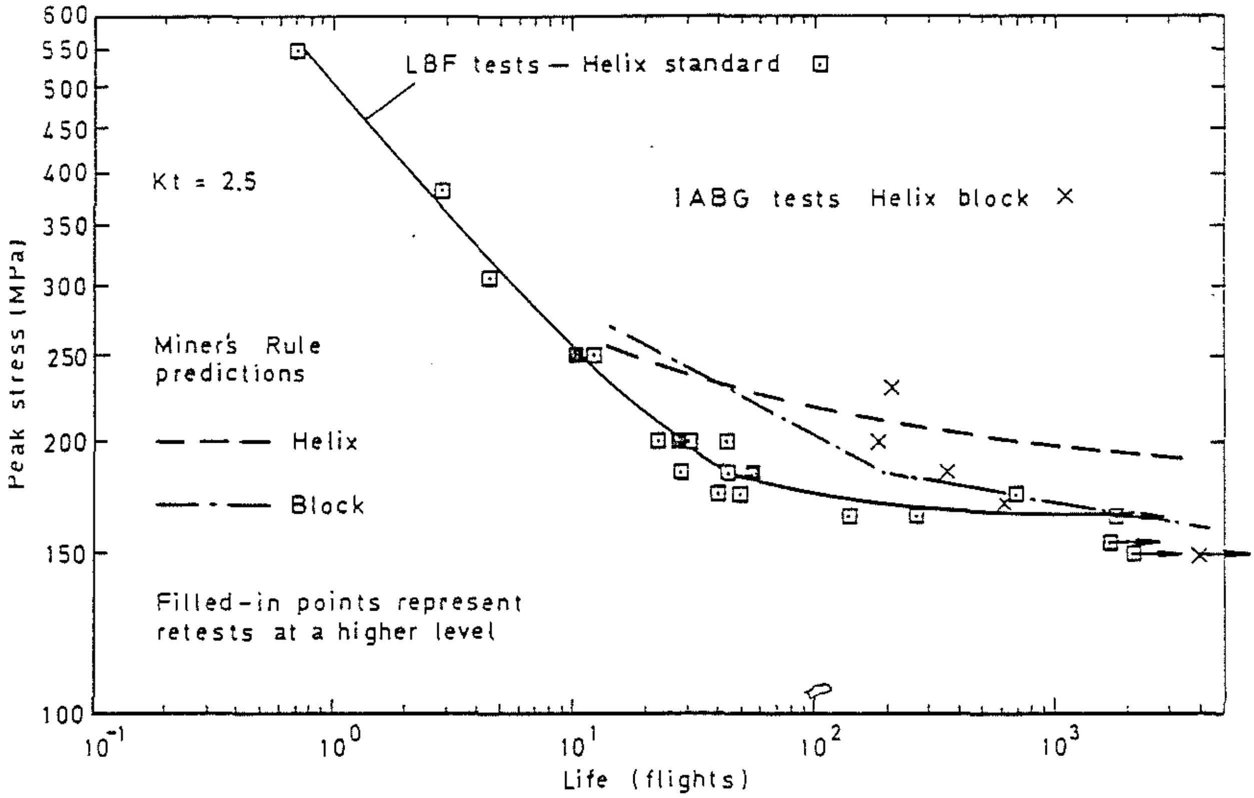


Fig 10 Helix and Helix block tests on 3.1354-T3 aluminium alloy notched specimens

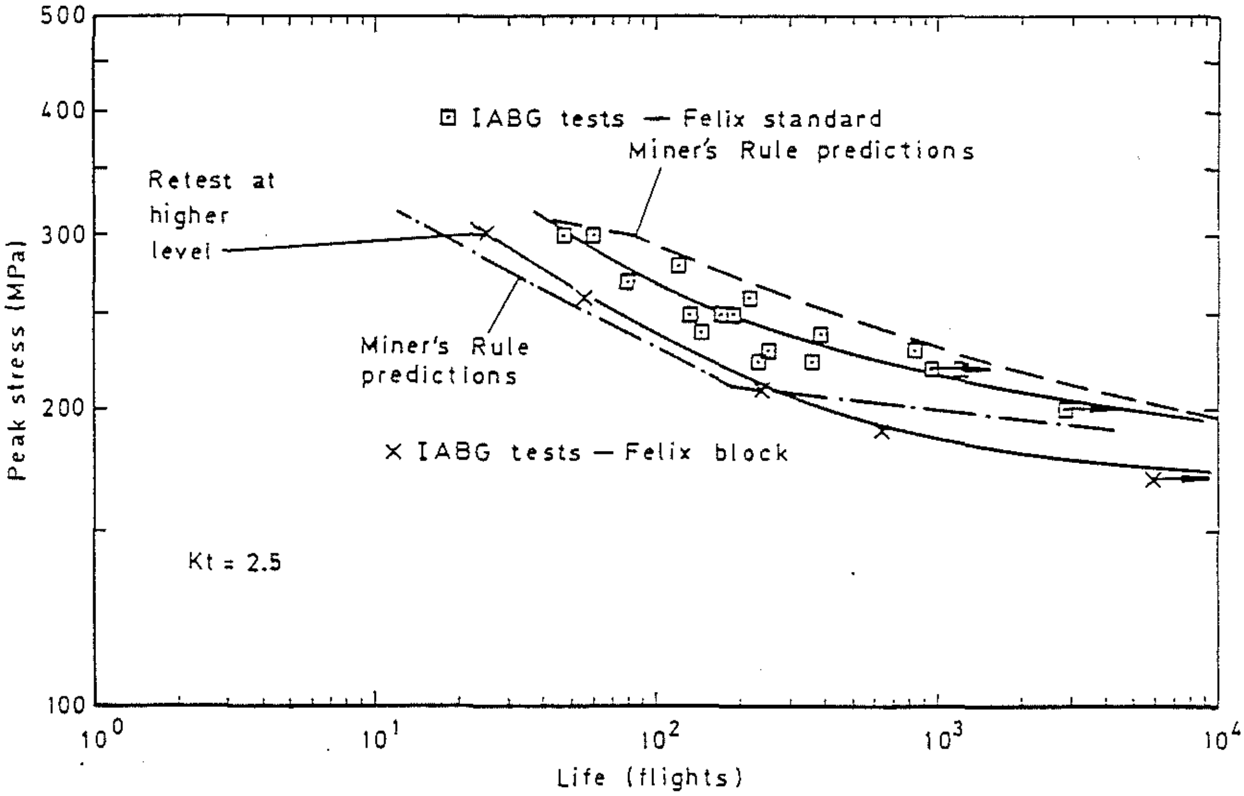


Fig 11 Felix and Felix block tests on 3.1354-T3 aluminium alloy notched specimens

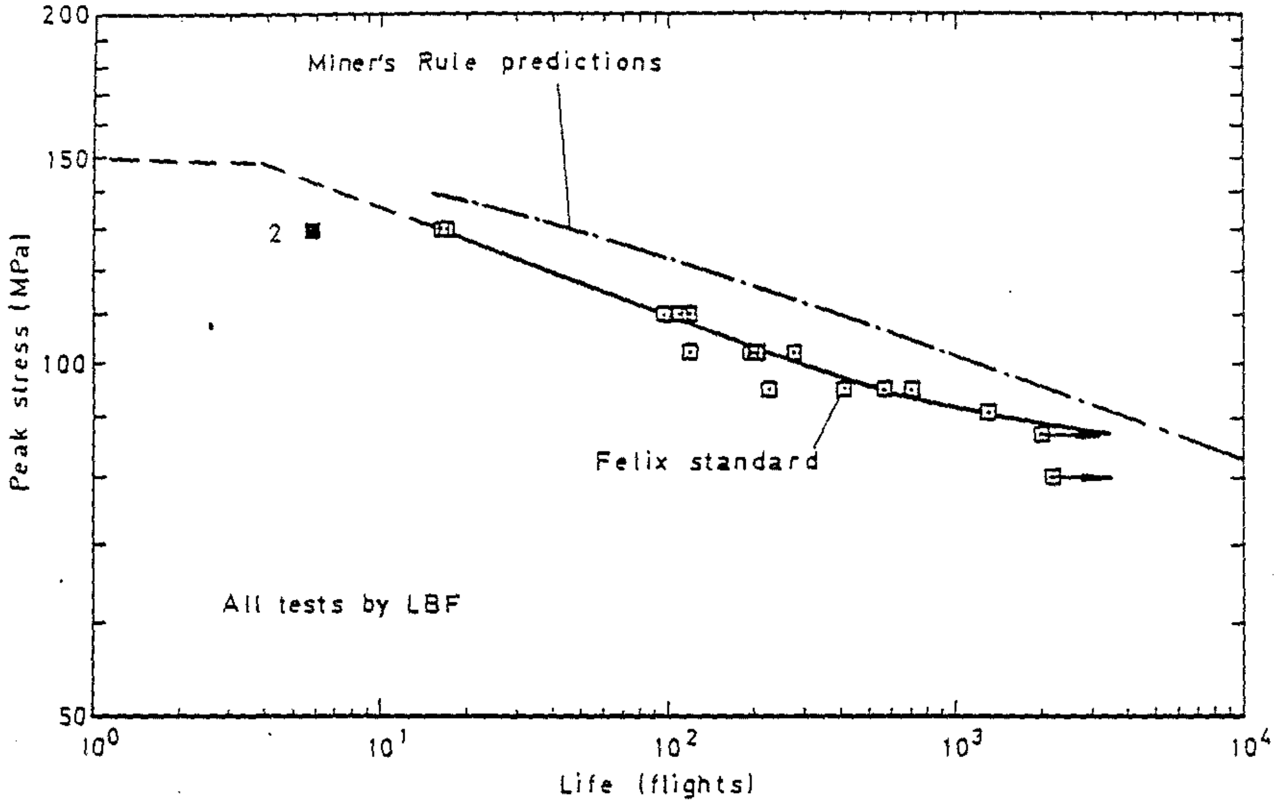


Fig 12 Felix and Felix block tests on multidirectional GRP lug specimens

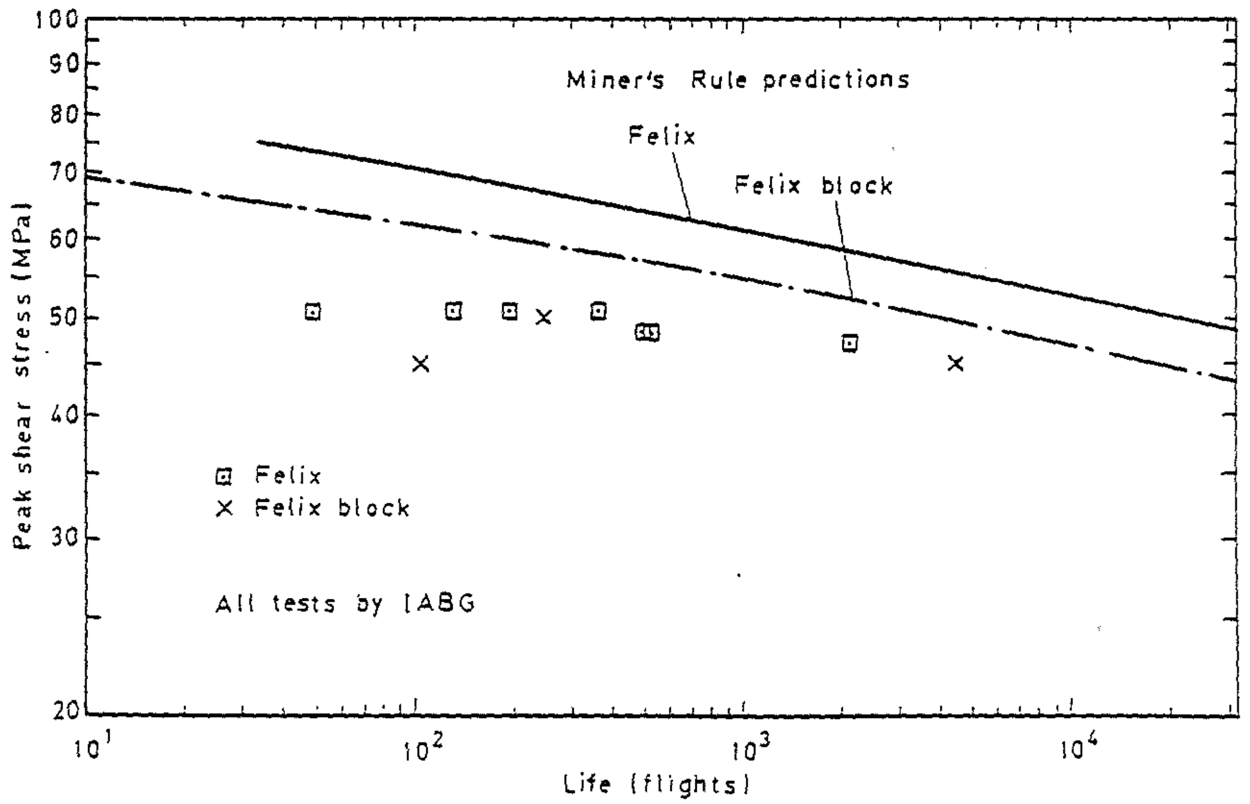


Fig 13 Felix and Felix block tests on unidirectional GRP bend specimens

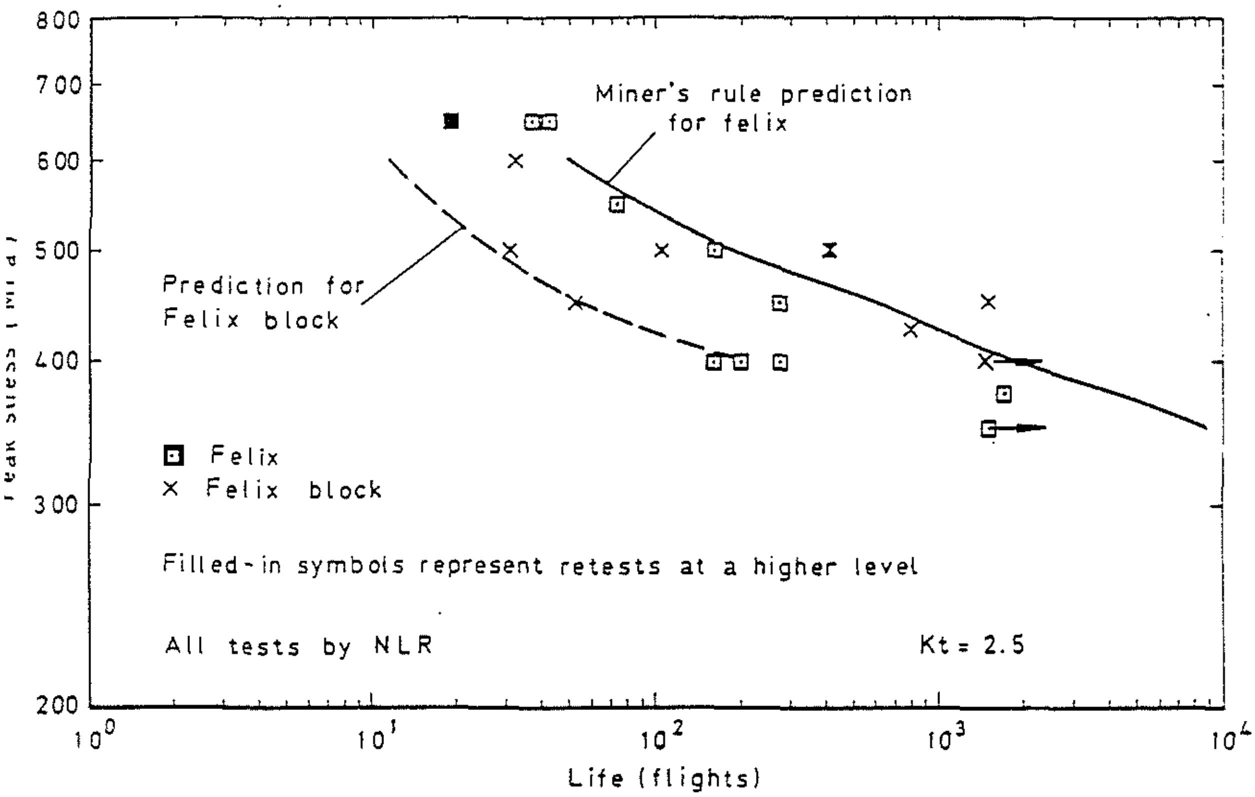


Fig 14 Felix and Felix block tests on notched specimens of titanium alloy

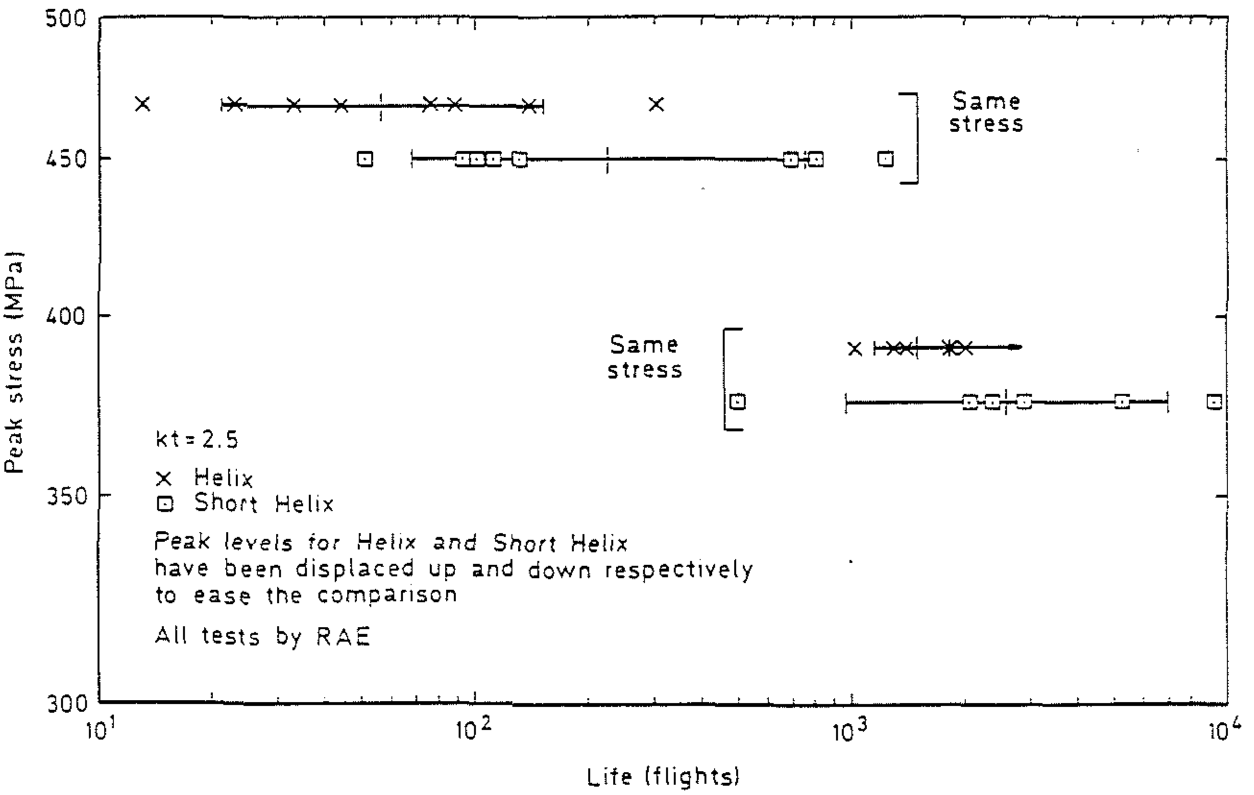


Fig 15 Helix and Short Helix tests on titanium alloy notched specimens