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A METHOD OF CALCULATING THE SAFE FATIGUE LIFE OF COMPACT, HIGHLY-STRESSED COMPONENTS

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SUMMARY

This paper describes a method which has been developed for estimating the safe fatigue life of compact, highly-stressed and inaccessible components for aeroplanes and helicopters of the Royal Air Force. It is explained why the Design Requirements for British Military Aircraft do not favour the use of a damage-tolerance approach in these circumstances.

INTRODUCTION

Performance considerations dictate that the structures of many types of military aircraft are compact and highly stressed. In consequence, many components are relatively inaccessible for inspection and stresses are often so high that cracks which are only just perceptible can cause appreciable reductions in strength.

Good practice dictates that the materials used for these inaccessible components must be of consistently high quality with high toughness and good corrosion resistance as well as good fatigue performance. Additionally, the design of the components must be such that the desired fatigue performance can be achieved using standard manufacturing processes which do not themselves leave room for inconsistencies. The consistency that is inherent in a good design is achieved in service by providing protection against corrosion and accidental damage and ensuring that this protection is maintained throughout the life.

The Airworthiness Division of DRA, formerly RAE, Farnborough is the principal architect of the Fatigue Design Requirements for British Military Aircraft (1) and so we begin by explaining why we have retained a safe-life [S-N] procedure for estimating the fatigue performance of compact, highly-stressed and inaccessible components rather than moving to a damage-tolerance approach. We then outline an advanced method of life estimation [providing a best estimate of the mean/typical life] that has been developed for application under the wide range of conditions that must be considered in design (2). Returning to our Design Requirements role, we outline the basis of the factor of 3 1/3 that has been used for major fatigue tests [to allow for the intrinsic scatter in fatigue performance between one airframe and another] and describe the Safe S-N procedure that has been developed to allow for the changes in scatter that accompany changes in the slope of the S-N curve (3). It is explained how this procedure is used to adjust the test factor of 3 1/3 when the service loading severity differs appreciably from that used for the major fatigue test and how it is also used to assess the effectiveness of the test in proving the safe life of all fatigue-sensitive features of the structure.

WHY WE HAVE RETAINED A SAFE-LIFE APPROACH FOR ESTIMATING THE LIFE OF COMPACT, HIGHLY-STRESSED COMPONENTS

The safe-life procedure that is used for estimating the fatigue performance of *compact, highly-stressed and inaccessible components* for British military aeroplanes and helicopters has its roots in an approach introduced in the mid fifties to provide a disciplined basis for demonstrating compliance with the increasing fatigue life requirements that were then being specified. The need for loads monitoring has always featured in British safe-life requirements and it is perhaps largely for this reason that we have not suffered the shortcomings which caused the USAF to become dissatisfied with the approach in the mid sixties (4). Indeed, we believe the balance between performance and safety is about right - the chance of losing a British combat aircraft due to a fatigue failure is about as low as the chance of death due to a road accident when driving a car (5), Figure 1 . Like other airworthiness authorities, we accept the use of a damage-tolerance approach for those components which are relatively accessible for inspection and have crack growth characteristics which enable damage to be detected, reliably, before the safety of the structure is seriously impaired.

When, in 1969, an F-111 aircraft was lost from a serious manufacturing defect in a compact, highly-stressed and inaccessible component after only 100 flying hours, the USAF introduced the 'initial flaw' concept and thereby grasped the nettle of applying the damage-tolerance approach to uninspectable structure. [The slow-crack-growth option which forms the basis of this step has always been available in the British Military Requirements, but we have always insisted that there must be an appreciable period during which the crack growth is *inspectable*]. Even today, however, there remain appreciable uncertainties in applying the concept to compact, highly-stressed components in which the period of detectable crack growth is insufficient to provide confidence in the analysis.

Like the USAF, we were concerned at the gap in the safe-life requirements which was exposed so vividly by the loss of the F-111, but in our case (6) we chose to address the problem by making the good practice outlined in the previous section a condition of compliance viz.,

(i) the materials used must be of consistently high quality with high toughness and good corrosion resistance as well as good fatigue performance,

(ii) the design of the components must be such that the desired fatigue performance can be achieved using standard manufacturing processes which do not themselves leave room for inconsistencies, and

(iii) the components must be protected against corrosion and accidental damage throughout their service lives.

Where a compact and highly-stressed component is susceptible to accidental damage, an initial-flaw approach may provide an alternative to re-design, but the validity of the inspection periodicity would need to be demonstrated by test and any inspection penalty would need to be acceptable to the operator.

AN ADVANCED METHOD OF FATIGUE LIFE ESTIMATION

The literature on methods of fatigue life estimation is strewn with good intentions - methods which have worked well for the special conditions under which they were developed, but which have been found wanting when applied over the wide range of conditions which must be considered in design. For this reason, Miner's Rule is still widely used in design and certification - although it is normally used only as a transfer function between a test under realistic loading and the actual loading applied in service.

For some years there has been a realisation that in the absence of realistic test data upon which to adjust the Miner calculation, it is possible to improve the estimate for metal components by taking account of local residual stresses that may be generated by local plastic deformation under extreme cycles in the loading spectrum. It has also been recognised that when most of the fatigue life is occupied by the formation of microcracks, rather than by their propagation, a further 'elastic' interaction may need to be taken into account (7). It is noteworthy that an alternative method of allowing for the interaction effects associated with local plasticity is favoured by the US Navy. This uses the local strain theory due to Neuber together with special test data obtained under constant *strain* amplitude (8). The method makes no specific allowance for elastic interaction, but, as with our own approach, there is provision for calibration factors to be built-in as experience is gained over the wide range of conditions which are encountered in design.

The method of life estimation developed by the authors (2) uses conventional constant [load] amplitude S-N data as a basic building block and this is adjusted to allow for the effects of residual stresses and elastic interaction.

In developing the method, the range of structural features which must be considered in design was represented by lug specimens (high stress concentration and fretting - life occupied largely by *propagation* of microcracks) and open-hole specimens (moderate stress concentration, no fretting - life occupied largely by *initiation* of microcracks), with the addition of double-dog-bone specimens assembled using interference-fit fasteners and interfay. Most of the lugs and all of the open-hole specimens were manufactured from aluminium alloys, titanium alloy (annealed), NiCrMo steel and maraging steel. The specimens were tested to failure, under constant amplitude loading and spectra representing aeroplane and helicopter applications (9). In total, the lives estimated were evaluated against 30 different test conditions, representing data from more than 300 fatigue tests.

For lug specimens (representing fastened joints with high load transfer through the fasteners), the method provided a good estimate of the life in most cases; (achieved life)/(estimated life) = 1.0 on average compared with a figure of 3.6 (conservative) for Miner's Rule. However, for the NiCrMo steel specimens the life was *overestimated* (unconservative) by a factor of between 1.5 and 10.

For all the types of specimen taken together (representing fastened joints, fillets and open holes), the method was equally applicable; (achieved life)/(estimated life) = 1.1 on average compared with a figure of 2.8 (conservative) for Miner's Rule. The life was *overestimated* (unconservative) by a factor of 1.5 or more on only 5% of occasions if the NiCrMo steel lug specimens were excluded.

The main feature of the method is that, without the need for special data, it does seem to provide a more consistent estimate of fatigue performance than Miner's Rule when applied across the range of structural features and loading spectra that must be considered in design. However, in any application we always try to find *some* test data upon which to build confidence in the validity of the estimates.

OBTAINING A SAFE LIFE USING THE SAFE S-N PROCEDURE

In the mid fifties, when most structures were made from aluminium alloys, large numbers of structural components, such as wings and tailplanes, were tested to failure under various fatigue loadings. The results of these tests formed the basis of the our safe-life requirements. Most fatigue failures were found to occur in joints where the effects of fretting were combined with high shear transfer through the fasteners - these features having the lowest ratio of fatigue to static strength. On the basis of this evidence, our predecessors recommended that the test life of an airframe [under realistic loading] should be reduced by a factor of 3 1/3 to allow for the scatter between one airframe and another. The factor was believed to correspond to the ubiquitous 'three standard deviations down' on the mean fatigue life and also included an allowance for the uncertainty in using only one specimen to estimate the mean. An additional factor of 1.5 was specified for use in cases where loads were unmonitored. Thus, the design of safe-life components for British military aircraft has been driven by the need to satisfy this test requirement.

It is well known that the scatter in fatigue life is lowest at the highest severities of loading, where the S-N curve is steep, and that scatter increases progressively as the loading severity is reduced - eventually becoming so large that it must be handled using a factor on stress. The Safe S-N approach (3) makes an allowance for this variation in scatter and enables the life factor that is applied in interpreting the test loading to be adjusted from 3 1/3 to a more appropriate value in those cases where the severity of loading in service differs appreciably from that applied on test.

Additionally, the Safe S-N procedure is used to assess the adequacy of the test factor of 3 1/3 for other components. Where a shortfall is apparent, a supplementary compliance is required.

Derivation of Safe S-N Curves

The factors on life and stress which are specified for the construction of Safe S-N curves are based upon a statistical analysis of the scatter of large numbers of specimens representing structural components made from aluminium alloys, titanium alloy and steels. These specimens were tested to failure under spectra representing aeroplane and helicopter applications (9). Each sample of tests was used to construct an S-N curve of [four-parameter] Weibull form viz.,

$$S = S_{inf}(1 + A/(N+G)^{m})$$

where S_{inf} = stress severity at fatigue limit

A = numerical constant

G = numerical constant governing low endurances

m = numerical exponent

For loading severities, S, typical of the lower surface of combat aeroplane wings, the scatter was found to differ appreciably between features and materials, but these large differences tended to disappear when the comparison was based on the local *slope* of the S-N curve. At the fatigue limit the scatter [coefficient of variation in S_{inf}] was not considered to be sufficiently dissimilar for a distinction to be made between the different features and materials.

For aluminium alloy lugs [representing the joints with high shear transfer through the fasteners which featured so prominently in the tests done in the fifties], our tests showed that the customary life factor of 3 1/3 corresponds to a probability of failure of about 1 in 1,000 for a loading severity corresponding to a safe life of between about 6,000 and 9,000 flying hours. At the fatigue limit, this probability of 1 in 1,000 corresponds to factor on stress of about 1.5 [scatter at S_{inf} assumed to be the same in all cases]. Thus, by analysing the scatter observed for aluminium alloy lugs at various loading severities, we were able to construct a continuous 'Safe S-N curve' that corresponds to a probability of failure of 1 in 1,000 and is consistent with the practice of using a factor of 3 1/3 for major tests. By applying the life factor from the steepest part of the curve [2.8] to the steepest part of the curves for the other features and materials, together with the stress factor of 1.5 at the fatigue limit, we were able to construct Safe S-N curves that produced a working approximation to the scatter which had been observed in each case.

In order to use the test factors on life and stress in estimating a safe life, or generating a test spectrum, it is necessary to apply them to an estimated mean S-N curve for *constant amplitude* loading and blend them together to form a continuous curve. The need to blend the curves arises when the shape of the S-N curve for constant amplitude loading differs from that under the spectrum loading from which the scatter data was derived. For S-N curves of Weibull form, as are commonly used in aerospace applications, a numerical method is available to eliminate any inconsistencies in this blending process (10). A Safe S-N curve drawn using this procedure is illustrated in Figures 2 and 3.

The factors specified for the construction of Safe S-N curves (1) enable account to be taken of the number of tests used to estimate the mean fatigue performance and the number of components on the aircraft [normally two nominally identical tests/components per airframe and 6 tests/4 components for helicopter dynamic components]. Corresponding procedures can be used to derive Safe S-N curves for any desired probability of failure.

Applications of the Safe S-N Procedure

The introduction of the Safe S-N approach into the Fatigue Design Requirements for British Military Aircraft has been accompanied by a number of other changes which are designed to enable the most effective balance to be achieved between the often conflicting requirements of performance, durability and safety (11). Notably, all components must now be shown to have a certain minimum fatigue life under the increases in loading severity that are likely to occur in service. In addition, airframe structures - with the exception of those of helicopters - must be subjected to an additional - termed 'preliminary' - fatigue test that will identify any major shortcomings so that these can be corrected before production is established.

Applications to Combat Aeroplanes

The British Aerospace Hawk, Figure 4, is used by the Royal Air Force for flying training of a general nature and for training in the use of tactical weapons (12). The loading spectrum experienced in the tactical weapons role is markedly more severe than the loading applied in the major fatigue test. When life factors for aluminium alloy lugs are derived for the two loadings, we find that the factor for the more severe loading is lower by about 10%. It is noteworthy that in this computation we have used the method of life estimation described earlier in order also to take into account the beneficial effects of the residual stresses generated under the higher loads. Thus, we have recommended that the factor of 3 1/3 should be reduced to 3 in computing the fatigue life consumed in the tactical weapons role. We estimate that the increase in life resulting from this reduced factor will save the Royal Air Force in the region of £50M.

By contrast, the Panavia Tornado, Figure 5, has been tested to a spectrum that is *more* severe than that encountered in service. When the life factors for aluminium alloy lugs are derived for the two severities of loading we find that the factor for the less severe loading is higher by about 20%. If this increase is applied to the usual factor of 3 1/3, the factor becomes 4 for Royal Air Force aircraft. However, the increase in mean life at this lower severity is more than sufficient to compensate for the increase in factor.

Applications to Transport Aeroplanes

The structures of transport aeroplanes are relatively accessible for inspection and critical crack sizes are usually such that regular inspections of a general nature can be relied upon to detect damage before the safety of the structure is seriously impaired. However, as fleets of transport aeroplanes have become older there has been an increasing awareness that the damage tolerance of some components can be undermined and so there has been a return to the safe-life concept to provide a guide to the finite life that must be imposed in such cases.

We have calculated that for older aircraft, which were designed for a service life of about 30,000 flights [and for a test life of between about 100,000 and 150,000 flights], the effect of interpreting the major test using the Safe S-N procedure rather than a factor of 3 1/3 would be to increase slightly the life of the pressure cabin and to decrease slightly the life of joints with high shear transfer through the fasteners. It is emphasised, however, that the life of the pressure cabin would not be extended unless an exhaustive test had been done and the necessary standard of 'good practice' could be demonstrated. Other features, such as joints with relatively low shear transfer through the fasteners and sculptured fillets would have their safe lives approximately halved. In extreme cases, it is possible that the probability of occurrence of damage of a critical size could rise from about 1 in 1,000 at the reduced safe life to nearer 1 in 20 at the end of the life obtained using a factor of 3 1/3; items for which an insufficient safe life had been demonstrated would be the subject of a supplementary compliance.

Applications to Helicopters

The usage of helicopters is not monitored as closely as that of military aeroplanes and so the fatigue spectrum used for design is necessarily rather conservative.

Wherever practicable, components are designed so that the stress amplitudes associated with normal usage are below the flat portion of the Safe S-N curve. The stress factor of about 1.5 used in the derivation of the Safe S-N curve is somewhat lower than the factor customarily used for the aluminium alloy components of British military helicopters, but slightly higher than the factors used for components manufactured from steels, titanium alloys and fibre composites. Nevertheless, the influence of introducing the Safe S-N approach in this relatively flat region of the S-N curve is likely to be fairly minor in relation to the influence of the various conservatisms that must necessarily be associated with design.

Those components which, exceptionally, experience most damage on the relatively steep part of the S-N curve, are known to have unnecessarily conservative lives if the stress factor is retained in this region. Therefore, in circumstances where the life is found to be too low, it has been usual to adopt the fixed life factors used for aeroplanes. In such circumstances, the effects of introducing the Safe S-N approach will be much the same as those already described.

CONCLUDING REMARKS

Good practice dictates that the materials used for compact, highly-stressed and inaccessible components must be of consistently high quality with high toughness and good corrosion resistance as well as good fatigue performance. Additionally, the design of the components must be such that the desired fatigue performance can be achieved using standard manufacturing processes which do not themselves leave room for inconsistencies. In order to achieve the consistency that is inherent in good design it is, of course, essential to provide protection against corrosion and accidental damage and to maintain this protection throughout the life.

When this good practice is followed, the safe-life [S-N] procedure is considered to provide a satisfactory method of substantiating fatigue life. Indeed, for compact, highly-stressed and inaccessible components we specify that the safe-life procedure *must* be used. Where a compact and highly-stressed component is susceptible to accidental damage, an initial-flaw approach may provide an alternative to re-design, but the validity of the inspection periodicity would need to be demonstrated by test and any inspection penalty would need to be acceptable to the operator.

Given the good practice outlined above and an acceptable procedure for monitoring the service loading, the validity of the safe-life approach centres on the method of life estimation and the procedure used for allowing for the intrinsic scatter between one component and another.

An advanced method of life estimation has been outlined and this is shown to be more consistent than Miner's Rule when applied to a range of conditions that must be considered in design.

Returning to our Design Requirements role, we have outlined the basis of the factor of 3 1/3 that has been used for major fatigue tests [to allow for the intrinsic scatter in fatigue performance between one component and another] and have described the Safe S-N procedure that has been developed to allow for the changes in scatter that accompany changes in the slope of the S-N curve. It has been explained how this procedure is used to adjust the test factor of 3 1/3 [on the basis of data for aluminium alloy lugs tested under realistic loading] when the service loading severity differs appreciably from that used for the major fatigue test and how it is also used to assess the effectiveness of the test in proving the safe life of all fatigue-sensitive features of the structure.

As something of an anecdote, we refer to a problem in fatigue life estimation set by the US Army some years ago (13). The principal helicopter manufacturers were invited to estimate the safe fatigue life of a pitch link - for those unfamiliar with helicopters, this is an axially-loaded item looking rather like a turnbuckle. Details were provided of the design and of the fatigue performance of the component under constant amplitude loading. It was left to the individual manufacturers to choose an appropriate S-N curve, make an allowance for the intrinsic scatter in fatigue performance and estimate the safe life. Before disclosing his estimate of the life, Charles Hardersen of Kaman Aerospace Corporation observed that as fatigue lives were important to both safety and economics, if engineers didn't calculate them then accountants would probably get the job. He also observed that when confronted with a common body of data, accountants generally arrived at the same answer. *The safe lives estimated by the various manufacturers were 58, 191, 470, 6450, 22523 and 24570 hours!* For the record, using the method we have described here, we obtained a safe life of 590 hours.

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Figure 1. The chance of losing a British combat aircraft due to a fatigue failure is about as low as the chance of death due to a road accident when driving a car.

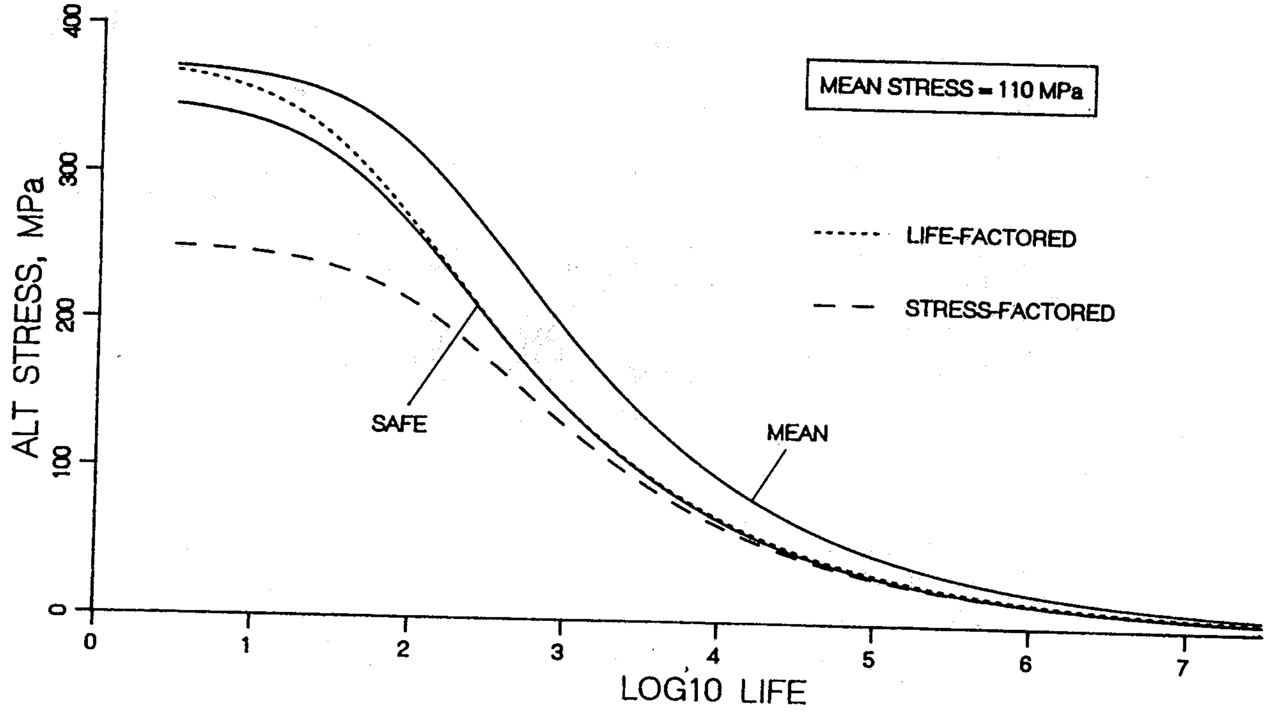

Figure 2. Safe S-N curve of Weibull form - showing compatibility with a safe value of static strength (B value: 460 MPa) - drawn using a numerical method (10).

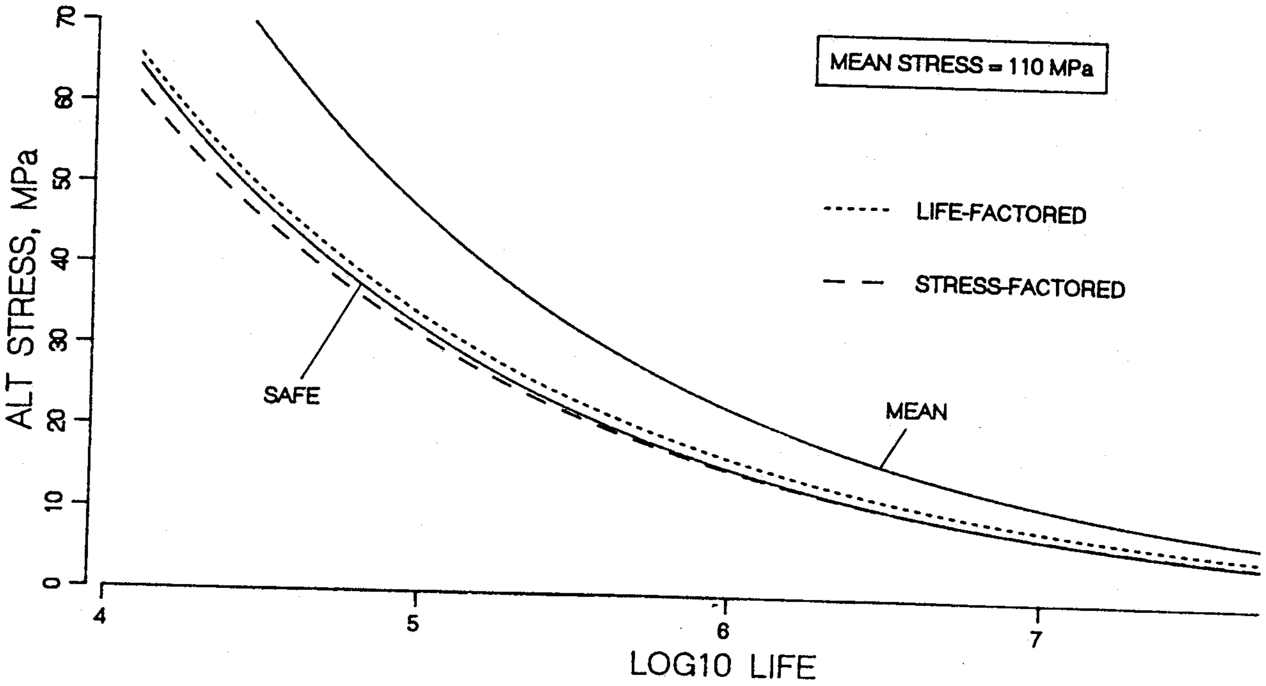

Figure 3. Safe S-N curve of Weibull form - showing transition between life and stress factors in region of most interest - drawn using a numerical method (10).

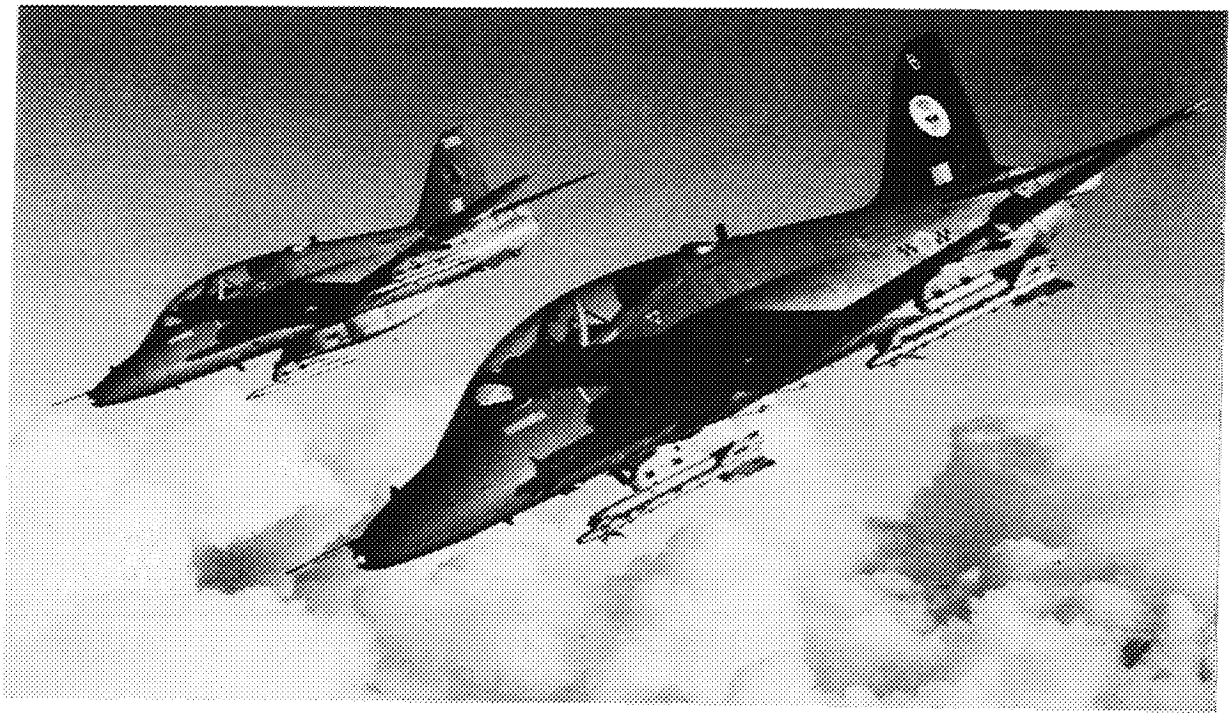

Figure 4. The loading spectrum experienced by the British Aerospace Hawk in the Tactical Weapons role is markedly more severe than that applied in the fatigue test and so a lower scatter factor is needed.

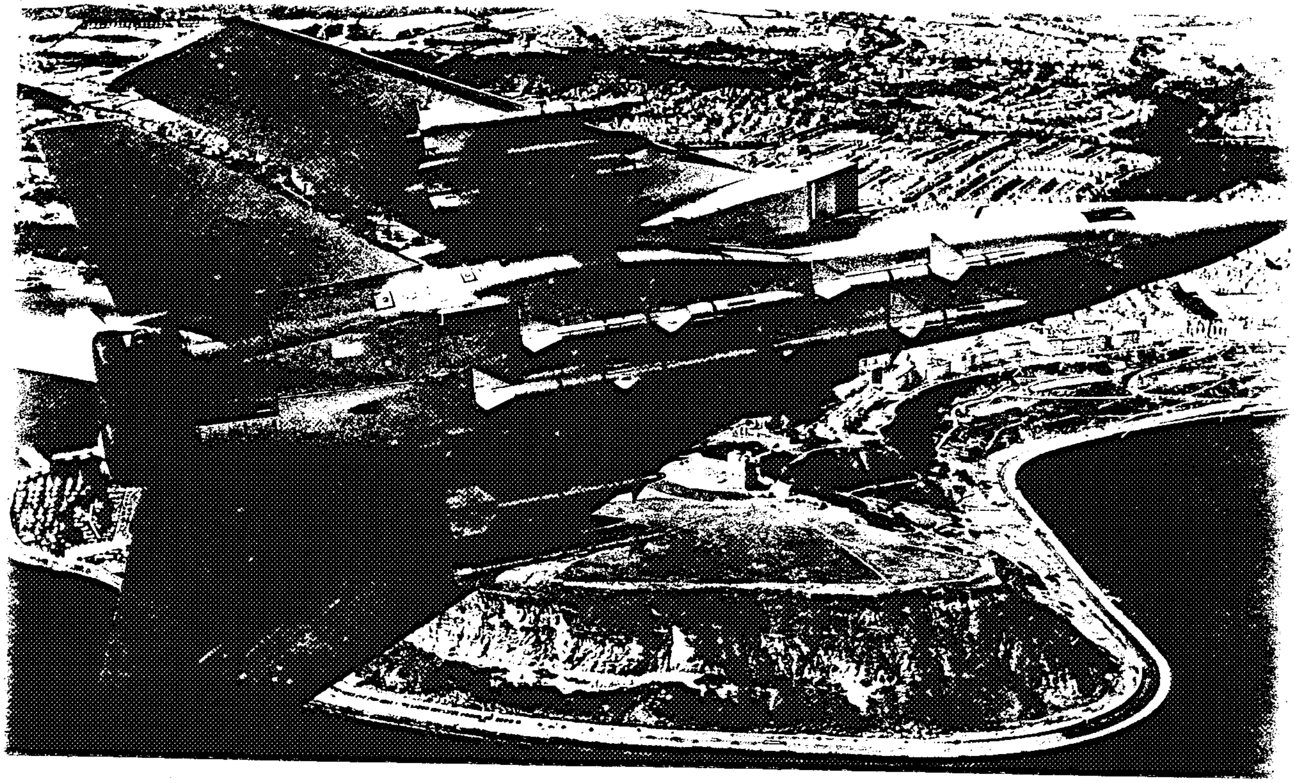

Figure 5. The loading spectrum experienced by the Panavia Tornado is markedly less severe than that applied in the fatigue test and so a higher scatter factor is needed - this is more than compensated for by the higher mean life.