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DAMAGE TOLERANT DESIGN FOR HELICOPTER STRUCTURAL INTEGRITY

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INTRODUCTION

1. The Royal Air Force is not a research organisation, neither is it a manufacturer of aircraft, and yet it has a considerable interest in the design of aircraft and in the direction of aircraft research. When all the major European helicopter agencies meet together like this, the Royal Air Force is very grateful to have an opportunity to speak to them as a customer whose operating experience and requirements must be understood by the manufacturer, if new equipment is to be as operationally effective as is possible.

2. The era of the cheap aircraft is over. We think nowadays in terms of millions of pounds sterling for a combat aircraft, and three quarters of a million for a new helicopter. This, of course, is due to the complexity of such aircraft, and to financial inflation, but whatever the reason, we now have smaller fleets of aircraft which have to perform a wider range of roles, and have to last much longer than heretofore. Consequently, the Royal Air Force is taking a greater interest in influencing research with the objective of a redirection towards reducing life cycle costs, not only in initial cost but in operating and maintenance costs. High performance, and lightness in weight are no longer the prime requirements, desirable though they be; now we require long life, ease of repair, reliability and damage tolerance. Advances in rotor blade aerofoil shapes giving greater lift, or in gearbox technology, are of little benefit to a military operator if they are not accompanied by an assurance of tolerance to impact or fatigue damage and an acceptably long life.

3. Structural degradation due to fatigue, corrosion and general wear has assumed greater importance during the last decade as a result of the increasingly long lives required from our helicopters. A satisfactory standard of structural integrity can only be achieved by a combination of suitable design requirements and a related maintenance policy. Royal Air Force experience, and international developments in the structural integrity field, suggest that current United Kingdom design requirements give neither an adequate assurance of structural integrity nor provide the most economical design for long life and operational effectiveness.

4. At present the United Kingdom design requirements for military helicopters deal separately with fatigue and corrosion. The fatigue requirement specified that the structure, and by structure I include rotor blades, transmissions, and controls, shall be designed to have a safe fatigue life, derived by calculation or tests, at least equal to the life required by the helicopter specification. That requirement was issued in 1958 and has not been altered since, although techniques of achieving these requirements have improved considerably since that time. Consequently, all United Kingdom helicopters are designed to a safe life philosophy. The requirements for corrosion protection have very recently been re-written and reflect the latest state of knowledge. As a result we can be reasonably satisfied that new helicopters will not contain materials known to be susceptible to stress corrosion, and that manufacture and assembly will be to a standard that affords the best available anti-corrosion techniques. However, we are no longer satisfied that the safe life philosophy is the correct one, even though the helicopter enjoys an enviable safety record, and the number of fatal accidents due to fatigue failures have been so few as to suggest that the design philosophy is the correct one. However, because of scatter in fatigue strength, and the uncertainty of the helicopter operating spectrum, large factors are used in the safe life

derivation process. Consequently, critical components are given a conservative safe life, and are withdrawn from use well in advance of their actual fatigue life. This is clearly uneconomic. Another point which must be made is that many of the fatal accidents which have occurred as the result of fatigue failure have arisen from stress raisers caused by maintenance or manufacturing errors. Thus the reserves of fatigue strength can be drastically reduced by small human errors, and an acceptable standard of integrity of the structure can never be taken for granted no matter how excellent the standard of maintenance or the number of flying hours flown by the helicopter.

5. In addition to the uncertainty of the integrity of the structure at any particular time throughout the life of the helicopter, there is another major criticism of the safe life design philosophy. That is, that the designer has to apply a programme of loads on his fatigue tests which are obtained realistically enough from instrumented flight trials, but the frequency of application of those loads are obtained by reference to an arbitrary flight manoeuvre spectrum specified in the design requirements. Results from random flight spectrum trials by in-service helicopters tend to vary widely from the design spectrum. Individual problem areas on helicopters which have resulted in flight measurement programmes to determine a "true" spectrum, have also revealed discrepancies with the design spectrum. It is widely recognised that the design spectrum bears little relation to the truth, and attention is now being directed towards the establishment of more realistic operational flight spectra. Consequently, all our safe fatigue life recommendations are little more than educated guesses, and have resulted in the high degree of conservatism introduced as a safeguard.

6. It is very easy to criticise a system, but another matter to implement an alternative system. I think that everyone here is aware of the shortcomings of the safe life approach to helicopter design, so I will not continue along this line any further. My main purpose in speaking at this Forum is to present to you the Royal Air Force view on the need to implement the damage tolerant design philosophy wherever possible, and to suggest various research activities which would be of direct relevance to achieving a higher assurance of structural integrity for the whole of the required life of the aircraft structure.

THE ALTERNATIVE - DAMAGE TOLERANT DESIGN

7. The alternative to the safe life design philosophy is to design the structure in such a way that any damage arising from the unavoidable errors associated with the normal day to day operations of the helicopter is detected before the strength of the structure falls to an unacceptable level. The types of damage meant are those which arise from design, manufacturing or maintenance errors, exceptional manoeuvre loads, corrosion, and accidental impact. It may even eventually be required to cater for battle damage and bird strikes. This philosophy is now called damage tolerant design, although it was once known as fail safe design. Thus the design requirements must be re-written to ensure that any damage, which may occur at any time, and anywhere on the helicopter, shall not propagate to an unacceptable level without being discovered by some failure warning system of some routine inspection method. To implement such a design philosophy certain fundamental criteria must be defined. For example, the initial crack length, that is the largest crack that cannot be detected by the method of inspection to be used,

and the time lapse between inspections, that is the period during which the crack can propagate before being found. Also, the maximum load which the cracked structure must withstand during the crack propagation period. These three criteria are inter-dependent, the minimum crack length that can be detected can be specified by service experience of cracks found by the selected inspection methods. This must be the smallest crack that can be guaranteed to be found every time. There will be smaller cracks found occasionally, but this is not the meaning of initial crack length. The crack propagation period can be defined by the operator to meet the desired operational requirement. It would then be up to the helicopter design authority to meet the requirement or to seek concessions. Residual strengths are not usually defined in the helicopter specification, but deduced by the designer from the specified roles and performance of the helicopter. For example, the US UTTAS specification required a design objective to have no structural component with less than 30 flight hours remaining from time of detection of damage by a failure warning system to complete failure, and to consider as safe life those components which cannot be provided with failure warning systems and which are impractical to inspect visually. The number of such components should be kept to a minimum. From such a specification the designer has to deduce the residual strengths required by each component.

8. Consequently, the helicopter operator who requires a damage tolerant structure must define the preferred inspection periodicity, the type of inspection to be carried out, and the initial crack length for each item of the structure. From that point onwards the designer must make his own decisions on how best to achieve the requirement.

THE DESIGNERS PROBLEMS

9. There are several methods of achieving a damage tolerant structure. The techniques include making provision for duplicated load paths, crack stopper patterns, ease of structural inspection, and in flight failure detection systems, and by the application of fracture mechanics to the selection of appropriate materials. Each method has its merits and limitations. Duplication is already a common practice, for example, in the provision of twin engines, hydraulic systems, lubricating systems, fuel control systems and so on. In some cases, not only is there a stand by hydraulic system but a reversion to manual capability providing a third alternative. Until quite recently, duplication of the major load paths represented by the rotor blades, control linkages, and transmission shafts have been considered to be impractical from an economic point of view. However, the application of the multiple load path principle can be seen in both the Hughes and Bell Advanced Attack Helicopter rotor blade designs, with the Hughes rotor blade having no less than 5 spars. These blades are secured to the rotor hub by 18 metal straps which can absorb pitch, flap and lead lag movements. Tests have shown that the rotor integrity can be retained with up to 9 of the 18 straps damaged. Duplication of controls is also achieved in the Hughes which has hydraulic actuators for cyclic and collective pitch controlled by mechanical linkages from the cockpit control columns and pedals, with the provision of a parallel electric signalling circuit which takes over in the event of a mechanical failure.

10. Damage tolerant design of stressed skin structure is usually achieved by the provision of crack stopper patterns, but it is very difficult to determine crack propagation rates in such built up structures. A crack approaching a riveted stiffener or frame may be temporarily stopped by a rivet hole, or it may propagate between a pair of rivets and not stop at all. This, naturally, will have an influence on the inspection period to be allocated to the area, and testing to ensure the worst case is represented is not always practical. Also, while jointed structures have a better crack retarding capability than integral structures, they have a greater risk of fatigue damage. Hence the designers choice of integral or built up structure must be a careful compromise of characteristics.

11. Damage tolerant design criteria can also be achieved by ensuring that all areas of the helicopter are accessible for inspection at intervals related to crack propagation rates determined by tests. Inspection for cracks or corrosion can be visual or by a suitable non destructive inspection method. A suitable method is one which can be easily applied by a military operator, operating out of the field if necessary. Examples are the established magnetic plug and spectrographic oil analysis used on engines and gearboxes. It is now Royal Air Force policy that all aircraft structure shall be inspectable, and the provision of access holes for endoprobes to inspect areas previously not inspectable by the eyeball is being applied retrospectively to in service aircraft. Where suspect areas are found, more sophisticated techniques can be applied by specialist tradesmen, but the policy is for 100% structural inspection by visual methods. However, although cracks can be tolerated in structure, the design must still aim for a good fatigue life, because if a damage tolerant structure requires frequent repair or replacement it can be more expensive than one having a longer crack free life. The aim must be to produce a structure with a crack free life of at least half of the specification life, hence it is still necessary to be able to predict structure life with some accuracy.

12. The provision of in flight failure detection systems is a proven application of a damage tolerant design technique. The Sikorsky Blade Inspection Method has been in service on Royal Air Force helicopters for the past five years and has proven itself to be sufficiently reliable to justify the lifeing of blades on condition only. The technique is to pressurise the spar cavity with an inert gas so that, in the event of a fatigue failure, the propagating crack will provide a leak path which causes a loss of pressure to be shown by an indicator located either on the blade root or in the cockpit. Recent blade spar failures on the Puma helicopter have been very successfully shown up by the BIM system, which has undoubtedly shown its flight safety value, not only to engineers, who perhaps did not need to be convinced, but to the helicopter aircrew, who were more sceptical about its usefulness. The pressurised cavity principle has been extended by the Boeing company for application on its UTTAS and Heavy Lift Helicopter Advanced Technology Component Programme. The Boeing UTTAS has a pneumatic pressure loss detection system on its main rotor shaft, the swashplate and the blade retention pin, with in each case a 'safe' and 'Unsafe' indicator positioned in a readily visible location. The HLH has pressurised rotor blade spars and swashplate, but uses fluid filled failure detection systems on the rotor head assembly and in hollow attachment bolts. The UTTAS uses oil filled failure warning on the main rotor hub and pitch shaft. Other variations in use on the HLH include condition monitoring by temperature and sonic signatures of the swashplate bearing, and by vibration signatures on the drive system.

13. The need to estimate crack propagation rates and residual strength in the presence of a crack is very important both in the design and testing of new structures to meet damage tolerant design requirements, and to aid decisions on the safety of existing structure found to be cracked. These needs are being met by the application of fracture mechanics techniques. On new designs, fracture mechanics can be used to influence the choice of material to be used, and to provide the analytical techniques required to size damage tolerant components to sustain operational loads with specified amounts of damage for a specified flight time. Fracture mechanics also contributes to the development of rig test procedures for substantiating that damage tolerant criteria have been met.

14. These are but a few of the techniques available to the designer for the achievement of a damage tolerant design. All are comparatively new and capable of considerable development. But the designers reponsibilities do not end at the design stage. Having been given a design requirement, and having selected the best design technique to meet that requirement, the designer then has to demonstrate that the requirements have been met. Although this can be shown by calculation, experimental demonstration is usually required in all but the simplest cases. This involves decisions on how to simulate the initial crack, where to put the crack on the test specimen, and if more than one crack location is considered probable, how many simulated cracks can be made at the same time. Then there are the decisions on how to allow for scatter and how to represent the service load spectrum on test, and once the test specimen has achieved its inspection period requirement, how then to demonstrate that the residual strength requirement has been met. This is a very complicated area requiring an individual approach for each individual component. The most disturbing aspect is that in the design and testing processes, assumptions have to be made in calculating fatigue crack growth. The fatigue - stress spectrum and the material crack propagation rate characteristics are calculations based on informed guesses deduced from the helicopter operating spectrum and operating environment. Testing of complex components has to be based on flight profiles which state the number of landings, turns, auto-rotations, max power climbs and so on. Instrumented flight trials can provide details of the loading on the various critical components but the frequency of application of such loading can only be taken from the specified operating spectrum. Consequently it is a matter of some importance that the specified manoeuvre spectrum should be as close a representation of actual operational flying as possible, in order to have any confidence in the results of rig and bench testing. Since this confidence does not exist at the design stage of a new helicopter, the designer has to make fairly substantial factors on strength with their consequent effect on the sizing and weight of the component being designed. Nevertheless, even if there is some doubt on the validity of bench tests to demonstrate that damage tolerant criteria have been met, the achievement of a structure which can be permitted to fail in the knowledge that the failure will have a high probability of being revealed by some routine inspection task carried out at some routine interval, is greatly to be preferred to a fatigue sensitive structure likely to fail catastrophically without warning. Although the determination of the inspection period can be a precise theoretical calculation, however, in service, allowance has to be made for the age and state of maintenance of the helicopter, and its variety of roles, some of which cannot be anticipated at the design stage, and the relative severity of manoeuvres resulting from variations in pilot techniques. These variables introduce the need for a factor on the theoretical inspection period or for a reliable load monitoring device and it must be remembered that cracks can appear at any time in the life of the helicopter, and so regular inspections must start from the time of entry into service.

RESEARCH NEEDS

15. Up to now, this presentation has merely summarised the techniques and applications of damage tolerant design requirements for helicopters. The desirability of a change over to damage tolerant design is not questioned. The techniques are fairly new but have been successfully applied in helicopters which are emerging now. Succeeding generations of helicopters will have more and more critical components designed to damage tolerant criteria. Like an evolutionary process, it is bound to happen in the long run. Why then, is the Royal Air Force making this presentation? As I said at the beginning, the Royal Air Force is not a research organisation, but it does all it can to influence the direction of research, and it sees the research required to attain the goals of damage tolerant design as being of primary importance for the future, not only because it affords a greater measure of airworthiness but because it is hoped that it will reduce the operating and maintenance costs of aircraft. By making it known that the United Kingdom Ministry of Defence is intending to redraft its design requirements to adopt a damage tolerant design concept as a basis for all future military aircraft, it is hoped that design authorities and research organisations will direct their expertise at the research required to achieve this policy.

16. In particular, research is required on the establishment of a more realistic helicopter operating spectrum; on the development of improved non destructive inspection techniques, and in failure warning devices, and on the theoretical solutions to the determination of crack propagation rates and residual strengths of complex structures. The establishment of realistic operating spectra is very important because it is the datum from which the designer must work to achieve the requirement life of the helicopter. All fatigue tests and crack propagation tests are dependent upon a programme of loads derived from the operating spectrum, consequently any errors or omissions from the spectrum will be reflected in the tests. This clearly unsatisfactory foundation for all that emerges from the design and test processes must be eliminated as a matter of priority. This is recognised, and work has begun. Two years ago, the Ministry of Defence and Westland Helicopters carried out a manual recording exercise on every sortie flown by military helicopters in the United Kingdom for a period of one year. While the limitations of manual recording are recognised, the results did high-light areas where the design spectrum was totally unrealistic. However, manually recorded data is unacceptable, mainly due to its inherent inaccuracy. There have been several service trials using instrumented helicopters, but these have been small samples and, in the main, directed towards localised areas, such as the tail rotor, or torquemeter. A programme of work has now been started at the Royal Aircraft Establishment at Farnborough on a system for recording and analysing selected parameters on helicopters with the overall aim of developing an instrumentation package which will be capable of fitment to service helicopters without inconvenience to the operators. The data to be recorded will be translated into an operating spectrum. This of course is a very long term exercise, but at least a start has been made. However, obtaining service loads is only half the story. Research is needed on how to convert any sequence of loads into an account of damage accumulation in specific structures. Once service loading can be reliably reproduced on rig tests, the problems associated with proving that damage tolerant criteria have been achieved will be greatly simplified.

17. Another major need in the field of research is in the development of improved non-destructive inspection techniques, and in failure warning devices. The essential requirement of any non-destructive inspection is that it must be simple to operate in dispersed locations, and it must have a very high probability of detection. It is to be preferred to be assured that a larger crack will be found every time rather than a smaller crack be revealed occasionally. We can see a requirement for a technique which will show up the onset of corrosion in inaccessible areas, and then monitor the subsequent growth. The main objective being to minimise the possibility of cracks remaining undiscovered. Research into failure warning systems is slso essential to safeguard those areas which have a limited damage growth design concept, such as rotor head components and drive shafts. If these components are to achieve a criteria, such as the UTTAS 30 hours after failure, it is esesntial that the crack initiation be known. Condition monitoring by vibration or acoustic signature or by monitoring the changes in magnetic properties with stress, may be adapted for components which do not permit monitoring by the pressure differential method.

18. The field of fracture mechanics is also a high priority research area. Theoretical solutions to the determination of crack propagation rates and residual strengths of complex structures are required to assist in the determination of safe inspection periods, and in the interpretation of the importance of cracks found on fatigue tests to the safety of the helicopter in service. Practical research is required into the behaviour of cracked structures subjected to variable loading, including establishing the extent of scatter in crack propagation rates.

19. While doing all it can to encourage research in the fields I've mentioned, the Royal Air Force is forced by economic necessity to regard the fruits of all such research from the standpoint of cost effectiveness. The end product must result in a more economic way of operating or maintaining the helicopter. Improvements in performance are no longer enough in themselves to justify the expenditure of large sums of money. Consequently, in attempting to sell any product, the manufacturer must demonstrate a very convincing cost effectiveness case before his product will be considered.

CONCLUSION

20. This presentation has been made because the Royal Air Force considers that a change of emphasis from safe life design to damage tolerant design is inevitable and seeks to encourage the necessary research directed toward achieving that design philosophy. However, the helicopter being the complex machine it is, it is more likely that a comprise mixture of safe life and damage tolerant philosophies may produce the ideal construction. The overall objective being that we should have a fatigue resistant structure with a good economic life before repairs become necessary, and that the structure should be damage tolerant, so that any fault, however caused, and occurring at any time in the life of the helicopter, will be found by routine inspection before the strength of the structure falls to an unacceptable level.

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