CURRENT AIRFRAME FATIGUE PROBLEMS

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Current airframe fatigue problems concerning crack growth prediction, multiple site damage, corrosion fatigue, life extension and bonded patch repair are reviewed. Various aspects of each of these five topics are considered and associated research requirements are identified. In general, the research requirements apply to both civil and military aircraft structures; most are relevant to both helicopters and fixed wing aircraft.

INTRODUCTION

The increasing pressure to keep aircraft in service longer, ie well beyond their original design lives, means that airframe fatigue problems are becoming increasingly important for ageing aircraft. It is apparent from recent literature and conferences (1-4) that important ageing aircraft fatigue problems include those associated with crack growth prediction, multiple site damage, corrosion fatigue, life enhancement and bonded composite patch repair. However, with the exception of bonded patch repair, these topics are also relevant to the design of new aircraft. The main aims of this paper are to review current problems concerning each of these five topics and to identify associated research requirements. It is recognised that other important airframe fatigue problems exist, such as those involving NDE, HUMS, OLM and composite structures, but these are beyond the scope of the present paper.

FATIGUE CRACK GROWTH PREDICTION

A key requirement for the efficient application of damage tolerance principles is the ability to predict accurately the growth of fatigue cracks in components which are subjected to complex loading spectra and hostile environments. Many collaborative projects have been undertaken in recent years to develop and assess crack growth prediction procedures; most have focused on load interaction effects using computer models to account for plasticity, residual stresses or crack closure. However, there is still little agreement on the most appropriate models for predicting crack growth under spectrum loading, and damage tolerance calculations are often conducted using a linear summation method, based on the assumption that crack retardation effects will result in conservative predictions. Unfortunately, whilst the load interaction model will in general yield a conservative prediction, the overall model prediction may be non-conservative as a result of other modelling assumptions and procedures, such as fitting polynomial distributions to constant amplitude crack growth data or describing them by Paris, Forman and Walker equations. Research is required to determine which modelling parameters have the most significant

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effects on crack growth predictions and hence to develop more accurate models. Work is also required to establish the range of crack configurations and load spectra to which various load interaction models may be applied successfully, and to develop a model for predicting crack growth under combined manoeuvre loading and high frequency buffet loading.

The application of damage tolerance to helicopter structures is receiving increased attention, mainly as a result of proposed changes to airworthiness regulations (1). The loading experienced by rotating components and load frames consists of large numbers of relatively small loads at high stress ratios. Thus, crack tip stress intensity factors for these components are generally in the near threshold regime where test data are sparse and fits to the data are generally poor. In addition, existing load interaction models were developed primarily for fixed wing aircraft applications where stress ratios are relatively low and significant gust or manoeuvre induced loads are superimposed on the in-flight cruise loads. These models may not be appropriate for the very different helicopter loading spectra. Collaborative programmes have been initiated to address these problems and early indications are that predictions are extremely sensitive to the data fits assumed in the near threshold region and that load interaction effects are less important. It is evident that additional work is required to develop improved models to describe constant amplitude data in the near threshold region and to predict load interaction effects under the types of loading spectra experienced by rotorcraft structures.

Damage tolerance analyses based on initial flaw concepts require accurate descriptions of the growth of short fatigue cracks. Although extensive research has been carried out, there appears to be no general agreement on the mechanisms controlling the growth of short cracks, and hence on the type of model that should be used. The wide variability in measured crack growth data reported for some materials may be accounted for by variations in microstructure, particularly grain size and orientation. In view of this variability, some modellers have utilised probabilistic approaches to predict crack growth rates but, in general, deterministic models are still used to predict mean crack growth rates or upper and lower bounds which bracket the test data. Further research appears to be required to develop and assess the potential of fully probabilistic models.

Owing to material and manufacturing technology developments, various novel structures, such as those involving new materials, castings, welded aluminium or titanium alloys, or superplastically formed diffusion bonded titanium alloys, are being considered for future airframe applications. Research is required to characterise and model the damage tolerance behaviour of such structures.

MULTIPLE SITE DAMAGE

The failure in 1988 of a fuselage section on a Boeing 737 operated by Aloha Airlines initiated widespread interest in the occurrence of multiple site damage (MSD). The main concern following this incident was that the residual strength of a structure containing a discrete damage source could be severely reduced by the presence of relatively small fatigue cracks at fastener holes adjacent to the discrete damage source. This resulted in major inspection and repair programmes for ageing aircraft fleets to ensure structural integrity. In addition, numerous research projects (1-4) were initiated where the main objectives were to improve our understanding of the MSD phenomenon, to enable current aircraft designs to be evaluated and their susceptibility to MSD assessed, and to ensure that future aircraft designs avoided or were resistant to MSD.

The key questions to be answered are how and where will MSD form, how fast will it develop and what effect will it have on the residual strength of aircraft structures. Although much of the work on MSD is being undertaken in the USA, many studies are also being conducted in Europe. Work in the USA is concentrating on the development of methods to predict crack growth and residual strength of structures containing MSD, which reflects the widespread use of damage tolerance in aircraft design and certification. In Europe, the use of safe life design philosophies has led to interest in the formation of MSD in addition to its growth and effect on residual strength.

Amongst the many research programmes which have been initiated in Europe, two investigations have been undertaken in the past five years by consortia of industrial and academic partners. The first commenced in 1993 under the auspices of GARTEUR (1) and aimed to develop methods for predicting the initiation and growth of MSD and its effect on residual strength. Probabilistic models were developed to predict damage patterns which might form in rows of fastener holes and deterministic methods such as compounding, stress functions and finite and boundary element analyses were developed and utilised for deterministic calculations of crack growth. The results were compared and where possible validated against experimental data. It was clear at the conclusion of this programme that insufficient suitable experimental data existed for model validation and that considerable development was required in order to apply the models to realistic structural configurations. This resulted in a Brite-Euram sponsored programme to build on the research which had already been carried out.

The Brite-Euram project commenced with a study to determine how widespread were occurrences of MSD, and in what typical locations they were found. This was achieved by examination of in-service records, tear-down inspections of major fatigue tests, and fractographic examination of sections of riveted joints cut from retired aircraft components. Having established typical locations and determined local geometric and material conditions, an extensive programme of tests was defined to simulate these regions. These tests ranged from simple crack growth tests to determine material properties to full scale residual strength tests on pressurised fuselage panels. Models were further developed in order to predict crack initiation periods and patterns, crack growth under MSD conditions and residual strength of structures with both discrete and multiple site damage. This programme is due to be completed in December 1998. However, further work is required to derive simple engineering tools for designers (from the results of the complex stress analyses), to develop design rules for structures where MSD may occur, and to determine accurately the residual strength of complex structures.

CORROSION FATIGUE

The influence of corrosion on fatigue performance is becoming increasingly important as the service lives of aircraft are extended. It is well known that small amounts of prior corrosion damage, eg pitting, can dramatically accelerate the initiation of fatigue cracks and reduce fatigue lives. For relatively simple structures or test pieces, reductions in fatigue performance have, in general, been accounted for by material thinning or stress concentration effects. However, for some airframe structures the effect of prior corrosion damage on fatigue may be complicated by the formation of corrosion products at faying surfaces. For example, corrosion pillowing can induce high stresses in aluminium alloy fuselage skin joints and lead to high aspect ratio, non-surface breaking cracks (1) which are difficult to detect and may undermine structural integrity. It is evident that further research is required to understand and predict the effects of corrosion products on the fatigue performance of joints. In addition, recent work at DERA has shown that if corrosion pits exist in the vicinity of cold expanded fastener holes, then crack initiation may occur in regions of tensile residual stress several millimeters from the holes and fatigue life may be adversely affected. Further research is required to study the effects of hole cold expansion and interference fit on corrosion fatigue of joints. In addition, research is required to develop improved models for predicting the initiation of fatigue cracks in the presence of a corrosive environment; probabilistic approaches appear to be promising (1).

Corrosion of aluminium alloy airframes depends on the surface protection scheme used and the breakdown of such protection schemes, which may occur for a variety of reasons, such as in-service damage, cracking of paint films around fastener heads or sub-standard/defective protective schemes. Paint primers and sealants containing chromate corrosion inhibitors are widely used on airframes, and it is well known that the chromates are extremely effective in inhibiting corrosion, particularly when a paint film is damaged (eg scratched) and metal is exposed to the environment. Unfortunately, the use of chromates is likely to be severely restricted in the future, due to environmental issues, and there is an urgent requirement to develop alternative inhibitors for incorporation in paint schemes, and to assess their influence on corrosion and corrosion fatigue of airframes. Chromates are also used extensively in etching, chromic acid anodising and chromate conversion coating surface pretreatments for aluminium alloys and, thus, alternative chromate-free surface pretreatments are being developed. It is well known that etching and anodising can adversely affect fatigue performance and, therefore, it is essential that the effects of new surface pretreatments on fatigue and corrosion fatigue performance are assessed. Cadmium coatings are used extensively to protect steel fasteners and other steel airframe components, but again serious environmental problems exist and it is likely that the use of cadmium on new equipment will be banned in the near future. Alternative metallic coatings, such as aluminium-magnesium, zinc-nickel and zinc-cobalt alloys, are being developed and it is again essential that the effects of such coatings on fatigue and corrosion fatigue performance are assessed.

Although the effect of environment on fatigue crack growth has been studied widely, additional research is required to develop improved models/methodology for predicting crack growth for in-service environments and loading spectra. For example, research is required to establish the extent to which environmental acceleration of fatigue crack growth depends on the loading spectrum (4), and to assess and develop models for predicting the effect of environment on crack growth under variable amplitude loading. In addition, work is required to investigate the relationship between resistance to stress corrosion cracking (SCC) and environmental acceleration of crack growth for loading conditions and alloys where the threshold stress intensity for SCC is not exceeded. This work should facilitate an assessment of the feasibility of accounting for the effects of environment on fatigue crack growth by using data obtained for ambient laboratory conditions and applying factors related to resistance to SCC for the alloy/environment in question.

Research is also required to investigate and model the corrosion fatigue behaviour of welded aluminium alloy structures, and to assess the corrosion fatigue performance of new aluminium alloys, including novel aluminium-lithium alloys.

FATIGUE LIFE ENHANCEMENT

The financial drive to retain aircraft in service for longer periods has led to the use of fatigue life enhancement techniques both in the construction of new aircraft and in repair and refurbishment procedures (1,4). These techniques are aimed principally at mechanically fastened joints as they are the most common site of fatigue damage. The techniques include hole cold expansion, interference fit fasteners and interference fit bushes. The use of interference fit fasteners has been widespread for many years, with life enhancement being demonstrated by laboratory tests and resultant data being used for certification of safe life structures. The growth of cracks from holes containing interference fit fasteners and bushes is less well understood and modelling is clearly required in this area to enable damage tolerance approaches to be adopted. Most of the research carried out in recent years has been aimed at the use of hole cold expansion, which is now achieving widespread use, particularly by the civil aircraft industry.

Hole cold expansion can be achieved by various methods, but the most usual approach utilises lubricated sleeves through which a mandrel is drawn. The sleeve protects the surface of the hole and the mandrel and reduces the load required to draw the mandrel through the component. The lubricated sleeves may be solid and remain in the hole after cold expansion, or split which are discarded after cold expansion. The split sleeve method is the most widely used, and research has been directed primarily at this approach. Initial work has been aimed at optimising the process by defining appropriate expansion levels, sleeve orientations and direction of operation. Most of this work was experimental but some analytical work has been carried out. The process has been modelled by several researchers; most have used finite element approaches, but usually many simplifying assumptions have been made. As a result, there is no clear definition of the residual stresses induced by the process and no simple method to determine their variation with different process parameters. Further research is clearly required in this area.

Recent research has been aimed mainly at determining the benefits and limitations of the cold expansion process. The main benefit is an increase in fatigue endurance resulting from the compressive residual stresses induced around the hole. The benefits in fatigue endurance will depend on the loading experienced by the structure. Smaller benefits will be achieved at higher applied loads as the mean contribution of the residual stresses becomes less effective. Elevated loading conditions may also result in smaller benefits in fatigue endurance if the loads are large enough to cause redistribution of the residual stresses. Other factors which could cause residual stress redistribution, such as elevated temperatures, also need to be examined. Elevated loading may not be limited to highly loaded structures, but may also occur in moderately loaded structures where stress concentrating features (eg high-load-transfer joints) or secondary bending are present. Whilst the importance of several of the above factors has been demonstrated in fatigue test programmes for specific applications, no rigorous methods are available to predict their influence on fatigue endurance.

Attempts to predict fatigue endurances of cold expanded components have been based mainly on fracture mechanics approaches. The problems encountered in these approaches include inadequate definition of the residual stresses formed (see above), the determination of residual stress redistribution (caused by loading and crack growth) and accounting for crack flank closure due to the compressive residual stress distribution. Additional work on these aspects is required in order to develop engineering models for predicting fatigue crack growth. These must not be limited to cold expansion of open holes but need to be integrated with models of crack growth in joints before they can be used in the design of aircraft structures. However, satisfactory models for predicting the fatigue performance of mechanically fastened joints are not yet available; the development of such models is complicated by the need to take account of contact loads and fretting fatigue.

BONDED COMPOSITE PATCH REPAIR

The repair of fatigue cracks in metallic aircraft structures has received much attention in recent years (1-4), due mainly to increased pressure to extend the lives of both military and civil aircraft. The use of adhesively bonded boron fibre reinforced plastic (BFRP) patches to repair cracked aircraft structures was pioneered by Australian workers. They have used the technique to repair or reinforce a wide range of structures and reported that experience with these repairs has been excellent, in terms of both performance and cost effectiveness. In the USA, various cracked structures have been repaired using bonded BFRP patches, while in the UK, a relatively small number of aircraft have been repaired using adhesively bonded carbon fibre reinforced plastic (CFRP) patches.

Although extensive theoretical and experimental research on bonded composite patch repairs has been carried out, and service experience with such repairs has been good, it is evident that further work is required to assess the full potential and limitations of this method of repair, and to develop optimum repair schemes for a wide range of applications. For example, further research is required to establish the effects of impact damage, service temperature and long term exposure to hot-wet environments on the efficiency and durability of repairs carried out with various types of patch, including BFRP, CFRP and GLARE. In addition, research is required to develop bonded patch repair schemes for structural locations which experience relatively high temperatures associated with engine or aerodynamic heating.

Various models have been developed for predicting the efficiency of bonded patches in retarding the growth of fatigue cracks. In general, the efficiency of repairs to thin flat sheet can be predicted accurately using analytical closed form expressions, but for complex or thick section repairs three-dimensional analyses are necessary. The effects of residual thermal stresses (arising from differential thermal contraction of patch and metal on cooling from the adhesive cure temperature), and debonding during fatigue loading, must be taken into account if the reduction in fatigue crack growth rate due to patching is to be predicted accurately. Unfortunately, a suitable model is not yet available for predicting the development of debonding, and therefore measured or assumed levels of debonding have to be used in patch efficiency predictions. There is a clear requirement for a model to predict patch debonding, and for incorporation of this in a general model for predicting the effect of patching on fatigue crack growth for a wide range of loading spectra.

Research is also required to investigate the full potential of bonded patches for the repair of corrosion damage or battle damage, which would otherwise lead to serious structural fatigue problems. Furthermore, work is required to establish the procedures, and prepare specifications, for the certification of bonded patch repairs. It is well known that slightly substandard surface pretreatment may adversely affect the long term environmental durabilty of adhesively bonded joints, even though initial static properties may be satisfactory. Unfortunately, the detection of such substandard joints by NDE techniques is not possible, and is unlikely to become so in the foreseable future. It follows that certification of bonded patch repairs will depend on process control, and it is important that work is undertaken to ensure that the effects of all process variables are understood and carefully specified. The future development of "Smart" patches may offer an attractive alternative to conventional NDE techniques for monitoring the growth of cracks under patches and the development of debonds.

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