ME541 Fatigue of Materials
(Project-4)

Assuming that you are a structural integrity manager in an aerospace industry. You are invited to give a lecture on “fatigue management practices” for an hour. Prepare the lecture slides what you are going to use in your presententation. (Submit this assignment in digital form).

Review of fatigue monitoring of agile military aircraft

L. MOLENT and B. AKTEPE[1]

Aeronautical and Maritime Research Laboratory, Defence Science and Technology Organisation, 506 Lorimer Street, Fishermans Bend, Victoria, 3207, Australia. [1]*Centre of Expertise in Aerodynamic Loading, RMIT University, GPO Box 2476V, Melbourne VIC 3001, Australia*

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ABSTRACT Fatigue monitoring of airframes has developed over the decades to the stage where it is now incumbent for all fighter type aircraft to be fitted with an airborne fatigue monitoring system. These systems typically collect operational data for the calculation of the safe-life or the inspection interval of the airframe.

This paper presents a state-of-the-art review of fatigue monitoring systems of agile military aircraft. It reviews and comprehensively examines the techniques used in individual aircraft fatigue monitoring programs, and examines current systems and practises. Based on experience from Australian fatigue monitoring programs, it highlights some of the potential pitfalls in the systems and techniques. It also investigates the issues of strain gauge utilization and calibration, collection of flight parameter data, data integrity, comparisons with fatigue test results and fatigue damage models. Some of the problems with current systems are highlighted and requirements for future fatigue monitoring systems are suggested.

This review has determined that there is little uniformity in the fatigue management practices of operators and that many aspects of the fatigue management process have been overlooked by some structural integrity managers. Also, very few of the papers reviewed specified the philosophy or aims of their monitoring systems.

Keywords Fatigue management; Aircraft structural integrity; Fatigue monitoring; Life estimation; Fighter aircraft; Fatigue models.

NOMENCLATURE

h = altitude
IAT = individual aircraft tracking
M = Mach number
N_y = lateral acceleration
N_z = normal acceleration
OLM = operational loads monitoring
p = roll rate
$\dot{p}$ = roll acceleration
PITS = point in the sky
q = pitch rate
Q = dynamic pressure
r = yaw rate
TAS = true airspeed
V = airspeed
W = aircraft weight
α = angle of attack
β = angle of sideslip
δ_{rud} = rudder deflection
δ_{flap} = flap deflection

Correspondence: L. Molent

δ_{elev} = elevator or elevon deflection
δ_{ail} = aileron deflection
Λ = sweep angle

INTRODUCTION

One application where the science of fatigue prediction reaches fruition is in the management of airframe structural fatigue. Fatigue management is now critical in aircraft operations due to the increased production costs of many newer models exerting pressure on operators to extract as much life out of their aircraft as possible. Furthermore, inspections, modifications, repair and aircraft replacements are all expensive activities that are often a direct result of fatigue problems. Consequently, there is much incentive for operators to have efficient structural integrity management programs in place.

The fatigue management of an aircraft starts in the design process with the application of a design philosophy, stress spectra, material data and a damage theory to estimate the fatigue life. This estimate is then certified through a structural fatigue test, following which (or sometimes before) the aircraft operator collects service load data[1] and puts together a management policy.[2] The process of collecting service load data is termed fatigue monitoring, and airworthiness regulations require all fighter type aircraft to be fitted with an on-board usage monitoring system.[3]

Fatigue monitoring serves a number of purposes.

- To fulfil airworthiness requirements to ensure aircraft are not operated beyond an acceptable level of risk.
- To determine the fatigue life status of a fleet of aircraft throughout its life based on an operational spectrum.
- To determine the actual service load history (many operators have found that operational usage of an aircraft is significantly more severe than the design spectrum) to ensure that aircraft are not operated beyond the fatigue damage accumulation threshold for various components as demonstrated through full-scale testing.
- To improve or to optimize the structural integrity management of the fleet (when done in conjunction with a program based on tracking each aircraft in the fleet). The assertion here is that the utilization of each aircraft is different and that using an average value is inaccurate when monitoring the whole fleet.
- To detect occurrences of structural overloads in a timely fashion, thus enhancing fleet safety.
- To assist in the definition of a flight load spectra for new aircraft of the same type.

This paper presents a summary of a literature review[1–120] on fatigue monitoring philosophies, systems, fatigue models and practises. Current processes are presented and comprehensively examined, and where appropriate the benefits and drawbacks of the respective methods are stated. The history of fatigue management is presented as an introduction followed by an outline of usage monitoring programs currently used by operators. It examines the issues of strain gauge utilization and calibration, collection of flight parameter data, data integrity, data handling, comparisons with fatigue test results and fatigue damage models. The paper also includes a discussion on the problems that have arisen in the last decade due to high angle of attack capabilities and redundant structures of fighter aircraft. Discussion in this paper is delineated to fatigue usage monitoring of fixed wing fighter type aircraft. Other similar sciences such as health monitoring and probabilistic approaches to fatigue damage estimation are not directly examined.

HISTORY OF FATIGUE MANAGEMENT OF AGILE AIRCRAFT

Many air forces have experienced their share of fatigue problems. For example, in the Royal Australian Air Force (RAAF), an MB326H suffered a wing fatigue failure that led to the loss of that aircraft,[4] while two Royal Air Force (RAF) Buccaneers[5] and a United States Air Force (USAF) F-111 experienced catastrophic fatigue failure (in 1969 after only 100 h of flying).[6] More recently, wings on the RAF Hawks were replaced at about two-thirds of their design life.[5]

The USAF experience in 1958 with B-47 fatigue failures[7] initiated the development of an Aircraft Structural Integrity Program (ASIP),[6] AF Regulation 80-13 in 1976[8] incorporating damage tolerance requirements as per Mil-A-83444.[9] The ASIP was intended to ensure that structural integrity is a consideration throughout the service life of each new aircraft entering service with the USAF. This led to the mandatory utilization of usage monitoring systems.

In the early days of fatigue management of fighter aircraft, the only means of managing the fleet was through documenting the number of flight hours or landing cycles. When the aircraft reached a certified number of hours, they would be retired. Later, advances in the science of fatigue were being made and cycle counting methods were developed[10] that related loads and stresses to fatigue damage. Subsequently, the peak-count method (of both maxima and minima) led to the

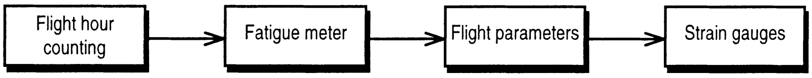

Fig. 1 Evolution in fatigue monitoring tools.

concept of the fatigue meter. Fatigue meters (also called g-meters) compile a count of exceedances of preset positive and negative g-levels during service. In the process, low-amplitude cycles that fall between two discrete levels are not counted. This method was extended to range-pair or hysteresis loop counting, that considered both the amplitude and the mean of the load.[11] The process pairs turning points into cycles that relate to closed stress–strain hysteresis loops.

Velocity–normal acceleration (*V–g*) 'slides' were used to generate gust statistics used in aircraft fatigue design. Australian scientific archives reveal that these continuous trace recorders were used as early as the late 1940s on transport aircraft.[12,13] Here a stylus inscribes a trace, on a smoked glass slide, in one direction by changes in acceleration and in a direction at right angles by changes in airspeed.[14] In the early 1950s velocity–normal acceleration and altitude (*V–g–h*) recorders began use in the USA.[15–17] Later, swing-wing aircraft identified the need for more sophisticated recording systems than the *V–g–h* recorder.[18]

Fatigue meters (or counting accelerometers) and strain range counters were developed in 1952[19–22] and received widespread use on UK military aircraft post-1954.[23,24] Later, a fatigue consumption indicator, consisting of a resettable counter and moving coil meter connected to a modified fatigue meter, were also fitted to some aircraft. It measured the average amplitude of the normal load factor in the previous 20 s and thus enabled the aircrew to assess the economic penalties of continuing the mission or changing the airspeed or the control technique.[17] The first range-pair counter was developed in Australia in the early 1970s.[25–30]

'Fatigue gauges' were proposed in the late 1960s,[31,32] although no record of their implementation was found. These gauges consisted of a 'work-hardenable' foil and were predicated on the theory that correlation factors can be established which related a change in resistance to the fatigue condition of the structure to which it was bonded.[33] 'Scratch strain gauges' were developed in the early 1970s[34,35] as self-contained mechanical extensometers capable of measuring and recording total deformation (and thus average strain) over the effective gauge length of the member to which it is attached.

Fatigue meters are still in widespread use with many aircraft types, however, they are being superseded by modern computers and recording systems. Direct derivation of stress using strain gauges and mechanical strain recorders (MSR) as used on the F-16 has also developed in recent times, as too have the computer-based multi-channel recorder systems, which are discussed further in the section entitled 'Fatigue Monitoring Systems'.

The evolution of fatigue monitoring tools may be summarized as shown in Fig. 1.

Recently, fibre-optic strain gauges have also been applied to fatigue monitoring,[36] however, not at a military fighter aircraft level.

Current fatigue usage monitoring tools are summarized in Table 1, along with their advantages and disadvantages.

Today, manufacturers continue to develop digital systems and sensors that record more flight parameters at higher frequencies than ever before. However, the literature review indicates that during the operational phase, it becomes evident that insufficient thought may have been given to using the systems for fatigue monitoring purposes (aims poorly defined, many parameters are not recorded, reliability and data validity not addressed, etc.). These are detailed in 'Fatigue Monitoring Systems' section.

Operators do not follow one standard method of fatigue management as no detail specifications exist. Design philosophies[37] that feed into fatigue management programs are varied, fatigue tests results are interpreted in different ways and different scatter factors are applied to the fatigue test spectra and fatigue test result. Operators continue to 'experiment' with a number of fatigue monitoring tools as the technology rapidly changes. Some collect raw data while others process the data on-board the aircraft. Others calibrate the data and the fatigue damage model to determine the crack lengths or fatigue indices, and few operators use the same fatigue damage model.

The remainder of this paper critically reviews these philosophies, tools, data processing procedures, damage models and the interpretation of fatigue test results and their application to fleet management.

FATIGUE MANAGEMENT PHILOSOPHIES

An object of fatigue or structural integrity management is to ensure that the life of type of an aircraft at least meets the operator's planned withdrawal date,[4] under normal operating loads and within approved flight limitations without collapse or unacceptable deformation.[38] The philosophy to be followed to achieve this depends in part on a number of factors, e.g. the ability to inspect and repair or replace the component, and the result of complete failure of a component.

Table 1 Monitoring tools

Tools	Advantages	Disadvantages
Flight hour, flight/landing cycle counting	● no equipment needed ● simple and cheap	● assumes each aircraft flies identical spectrum (no mission variability) ● cycle counting is only applicable to landing and pressurized structure
Faigue meter (N_z based counting accelerometer—normally augmented by pilot flight time, mission type and stores information. Weight is assumed to be constant for entire flight)	● simple and cheap ● lightweight ● robust ● minimal post-processing required	● relatively low accuracy ● only components affected by N_z can be monitored ● N_z normally recorded at a fixed nominal centre of gravity (CG) ● difficult to validate data ● difficult to account for missing data ● asymmetric loads not considered ● fixed N_z 'trigger' levels ● time history is lost, hence sequence effects cannot be accounted for ● weight and PITS must be assumed (conservative) ● transfer function between N_z and stress at critical location required
Range pair counters	● relatively cheap ● some data processing conducted on-board	● time history lost ● PITS must be assumed ● difficult to validate data ● difficult to account for missing data ● sensor calibration difficult due to data format
Multi-channel recorders (parametric systems)	● can monitor many flight parameters ● time history retained ● can be used for other investigations (incidents, over-stressing) ● may record data from other sensors like strain gauges ● allows automation of health checks ● can potentially be used to tailor flying operations to minimize damage	● large loads development program required (numerous flight conditions required and equation development is time intensive and intricate) ● accuracy of loads estimated outside original data set is questionable ● abrupt manoeuvres, gust and buffet loads not accounted for ● expensive and normally production interfaced with flight computer ● software and post-processing intensive ● data validation needed
Strain gauges	● directly monitors principal load component (e.g. wing root bending moment) ● responsive to abrupt manoeuvres, gust and buffet loads ● directly comparable to fatigue test ● accounts for weight changes during flight Fibre-optic gauges, e.g. Ref. [36] ● insensitive to electro-magnetic interference ● higher reliability than electrical resistance strain gauges ● high strain resolution	● difficult to determine gauge locations ● gauge installation and maintenance is difficult ● gauges require calibration ● reliability of strain gauge and amplifiers can be poor ● software and post-processing intensive ● electrical resistance strain gauges are sensitive to electro-magnetic interference ● fibre-optic gauges need further development

The fatigue management process starts with a design philosophy that incorporates these factors. Table 2 lists the two design philosophies used by some of the world's air forces (AF) which are integrated into the overall fatigue management program for agile aircraft. It shows that there is an even distribution between the safe-life and damage-tolerant design philosophies, and that new aircraft are still designed and thus managed differently from other aircraft of the same type.

RAAF Aircraft Structural Integrity (ASI) management

Table 2 Design philosophies used for fatigue management by various operators

Aircraft	Operator	Safe-life design limit	Damage tolerance	Year
A-3	United States Navy (USN)	18 000 h[1]		1988[39]
A-7	Portuguese AF		Yes	1991[40]
Alphajet	French AF		Yes[2]	1997[41]
Eurofighter 2000	Royal AF	Yes		1997[42]
F-14	USN	Yes		1996[43]
F-15	USAF		Yes	1984[44]
F-16	USAF, Royal Netherlands AF		Yes[3]	1996[45]
F/A-18	USN	6000 h		1997[46]
F/A-18	RAAF, Canadian Forces[4]	Yes		1998[47]
F-111	RAAF		Yes[5]	1996[48]
Hawk T.Mk.1	RAF, RAAF	6000 h		1993[49]
Kfir	Israel AF		Yes[6]	1988[50]
MB339 CB	Royal New Zealand AF	Yes		1995[51]
Mirage 2000	French AF		Yes	1995[52]
JAS-37 Viggen	Swedish AF		Yes[7]	1993[53]
JAS-39 Gripen	Swedish AF		Yes	1993[53]
Tornado	German AF and Navy	4000 h		1991[54]

[1] Extended from 3000 h to 18 000 h. [2] Safe-life for 10 000 h in the original design. Mods cleared it to 18 000 h. Life extension program based on damage tolerance approaches is now to be used. [3] Designed for a service life of 8000 h. [4] Reference [55] in 1981 states that the Canadian Forces considered a durability and damage-tolerance approach, however, operate the CF-18 as a safe-life aircraft. [5] Originally safe-life of 4000 h. Changed in late 1980s to 'Safety-by-inspection', i.e. damage-tolerance philosophy. [6] Designed for a safe-life of 4000 h. [7] Designed to a safe-life philosophy. However, the aircraft was re-assessed for damage tolerance.

incorporates a combination of safe-life and damage-tolerance philosophies for the various aircraft. In the case of the F/A-18, a safe-life philosophy is used. The F-111, which began service in Australia in 1973, was initially managed on a safe-life basis, but later, a safety-by-inspection approach was justified through analytical calculations, a durability and damage-tolerance analysis, and proof load testing.[4] (The safety-by-inspection philosophy is equivalent to a damage tolerance philosophy.) With the USAF now no longer operating F-111 aircraft, a full Australian review of the durability and damage tolerance analysis of each of the critical points identified by the original equipment manufacturer is being undertaken.

The aircraft design philosophy, however is but one aspect of the overall fatigue management process. The fatigue management process should also:

- consider that fleet aircraft cannot be operated beyond the equivalent damage accrual demonstrated in a fatigue test and any life extension must be substantiated by further fatigue tests to determine the next critical location (appropriate repairs followed by testing to failure is required);
- seek to manage fleet structural integrity based on fatigue test results;
- incorporate a loads monitoring program on each aircraft to routinely measure load cycles in primary structure (as opposed to 'hot-spots');[47]
- employ an economic and reliable fatigue monitoring system;
- ensure data integrity;
- include the calibration of operational data with fatigue test data;
- consider the method of processing fleet data (i.e. either raw data collection for ground-based processing or on-board processing);
- include a damage model that provides an accurate estimation of fatigue accrual on a scientifically robust basis; and
- provide the operator with regular feedback.

These elements are considered in the following sections.

INDIVIDUAL AIRCRAFT MONITORING PROGRAMS

Among other factors, the variation in the operational loading experienced by a fighter type aircraft throughout its life and the need to identify operational overloads make individual aircraft tracking (IAT) programs necessary. Furthermore, to assess the consumed fatigue life of an aircraft structure, knowledge of the actual load experienced by that structure is essential.[56] And even where a safe-life may be stipulated, some aircraft are retired at a different number of flight hours due to their calculated rate of fatigue damage accumulation being higher or lower than the target rate because of operational variations.

Prime factors driving IAT are the unique combination of loads experienced by different aircraft in the fleet and the availability of a good on-board monitoring computer.[57] Traditionally, it was assumed that if the fleet average load factor (N_z) exceedance curves matched that of the design spectrum, the aircraft could safely be operated until the design life. Today, however, each operator of modern aircraft is likely to have a different usage spectrum to the design spectrum. The root bending moment of the component is the primary factor to monitor instead of N_z (due to non-linear aerodynamic and adaptive controls) and a fleet-wide average load spectrum is not viewed as being accurate enough for agile combat aircraft.[58,59]

While heavy military transport aircraft have very strict mission profiles, agile fighter, trainer or attack type aircraft are well known to experience substantial variability in their missions (see Ref. [60] and next section). Therefore, they cannot be tracked based on mission hours alone, and it is the authors' view that an IAT program is necessary for agile combat type aircraft. For the RAAF F/A-18 fleet, IAT is conducted with every F/A-18 in the fleet instrumented with the same basic system, this being the maintenance signal data recording system (MSDRS).[38]

One of the greatest benefits of an IAT program is that loads monitoring can take place without a prior knowledge of the exact critical location. Ideally, provided that a sufficient number of primary load carrying structures are routinely monitored, stresses at all critical locations could be determined from fatigue tests, with a transfer function relating the monitored load to the critical location stresses. Therefore, a change in the critical location can be accommodated through the development of a new transfer function to the new critical location.

Some of the benefits gained from the RAAF IAT program include:

- drawing comparison between design and usage spectra for each aircraft;
- estimation of the fatigue life or damage status of major components on each aircraft based on loads monitoring in the primary structure of that aircraft and related to fatigue test results;
- planning of maintenance action according to fatigue life estimates;
- modification of operations to stabilize the rate of fatigue life consumption;
- building an operational load database in conjunction with flight trials for application to a fatigue test and to compare with early fatigue test data;[61]
- identifying the variability in response between aircraft in the fleet under the same flight conditions (through assessment of mission severity, effects of stores and point-in-the-sky affects);
- gaining a better understanding of the loading environment (in conjunction with flight trials data); and
- observation of the difficulties introduced by buffet and structural redundancy at vertical tails.[47]

Data obtained from IAT programs can also be used:

- to better design future aircraft or be smart buyers in the acquisition of new aircraft for the same role; and
- to define (in conjunction with flight trials data) which parameters might be measured on new aircraft or new systems for the same aircraft to allow the more accurate calculation of the life of critical structural components.

Fleet usage variability

Once critical locations are identified in the design stage and in fatigue tests, IAT programs are used to accumulate and analyse load data from each aircraft in the fleet to predict the damage status at the critical locations. Hence, the fatigue life status of each aircraft throughout its life, based on its own operational load spectrum is determined. From this information, the amount of fatigue life consumed and the remaining life for each aircraft in the fleet may be calculated independently of other aircraft in the fleet.

Calculating a life based on individual spectra reveals a wide spread in the rate of fatigue usage, as shown in Fig. 2 for RAAF data collected over 135 000 operational hours on over 70 F/A-18 aircraft. The fatigue accumulation rate is the individual aircraft fatigue damage value, calculated using the standard RAAF F/A-18 method, and

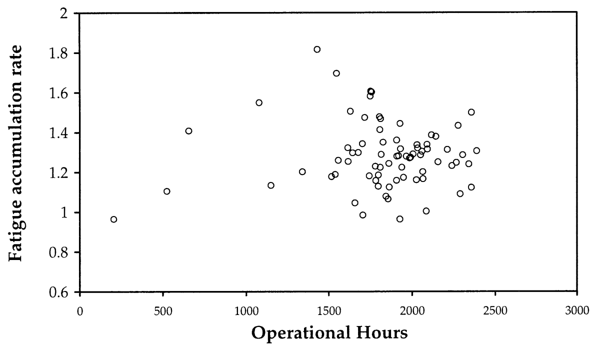

Fig. 2 Rate of fatigue damage accumulation for a fleet of aircraft.

then normalized by the aircraft's operational hours. It can be seen that using a fleet average would be unwise because some aircraft accrue fatigue damage at almost twice the rate of others. The figure also shows that left unchecked, this trend does not 'average out' over the life of the fleet.

Comparison between design and usage spectra

It has previously been stated that 'if differences in mission mixture between aircraft remain systemic and significant, there is a case for individual airplane tracking'.[60] This systemic difference is now common and very significant in agile fighter aircraft. In fact, it is rare for two agile aircraft of the same type to experience identical loads for the same type of mission; hence, the need for IAT to examine usage spectra is justified.

New aircraft are serving multiple roles and expectations of enhanced performance are leading to higher operational demands being placed on them. Hence, the operational spectrum of a new aircraft type may be expected to be more severe than the same aircraft type just retired from the fleet. The experience of many operators is that the average usage spectrum is more severe than the design spectrum[60] as was the case in early RAAF flying for a fleet average, as indicated in Fig. 3.

Operational loads spectra may be more severe than the assumed design spectra due to variations in the way the aircraft is operated (mission variability and pilot technique) or due to more severe manoeuvres being experienced for the same given mission. Their definition can be useful in identifying trends in aircraft usage, to determine whether the flying has become more benign or more severe and to schedule operations accordingly.

Maintenance action

IAT programs can further be used to establish the inspection and modification requirements and schedules for fleet management, to reduce the cost of unscheduled repairs.

Because IAT allows individual rates of fatigue usage or crack growth rates to be estimated, inspections, repairs or any other maintenance action can be carried out based on accumulated fatigue values or crack lengths instead of flight hours or other simplified usage monitoring. If operational usage is found to be less severe than design estimates, the incorporation of structural modifications and repairs based on design certification testing can be delayed.

IAT programs can also highlight when operational limits are exceeded and identify the need for maintenance action.

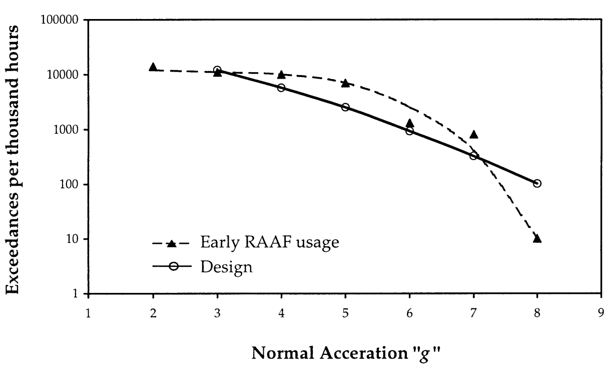

Fig. 3 Comparison of design and operational usage for RAAF early flying on a combat aircraft (from Ref. [55]).

Modify operations

IAT is particularly useful if large variability exists between squadron operations, between missions and perhaps between pilots. With agile fighter aircraft, missions of the same type will lead to the accumulation of different amounts of damage.[60]

Currently, RAAF F/A-18 operations are broken down into 44 different types of missions. A breakdown into mission type has revealed that the variation in fatigue damage accrual rate within a mission type is substantial (at least one order of magnitude). In fact, the variation seen within one mission type can be as large as that between missions.[60] Hence, it cannot be assumed that a change in mission from one type to another will necessarily result in less fatigue damage for fighter aircraft.

IAT can be used to determine how the structural life of an aircraft varies with aircraft operations. These can be customized (by varying the point-in-the sky flown: PITS) to meet operational and maintenance needs, or to determine the cost of specific operations. Particularly damaging flight regimes may be identified and their occurrences may be reduced.

IAT programs also allow for identification of usage trends over time at fleet, squadron, mission or pilot level. The effect of changes in roles, mission types and mission content on the fatigue life can all be examined and appropriate changes to aircraft operations can be made if warranted.

Operational loads monitoring

While the IAT program means that all aircraft are fitted with the same standard equipment, it is also beneficial to have at least one aircraft in the fleet equipped to preform a loads development or strain survey program. In the RAAF, the F/A-18 and F-111 fleet have one aircraft each fitted with the standard IAT equipment as well as additional strain gauges, accelerometers and sophisticated data acquisition system for loads development work.[62] Another example of this is the Swedish JAS-39 program, where one aircraft is dedicated to the loads survey program, to which 500 strain gauges were fitted.[53] Further examples of loads survey programs may be found in Refs [63–65].

Often in redundant structures loads experienced in flight may be distributed differently from those of the fatigue test article, and components with the highest in-flight load may not be the most critical. In the case of the F/A-18, three centre fuselage bulkheads absorb the wing bending loads. Considering that the most fatigue critical locations on the F/A-18 structure are thought to be the bulkheads, it is worthwhile collecting flight data at these to verify the loads used on the fatigue test.

Aerodynamic buffet

A major performance improvement to fighter aircraft over the last two decades has been the increased angles of attack that they have been able to achieve. This improvement has given rise to unsteady aerodynamic buffet loads that excite the flexible modes of the wing and empennage. This has led to structural problems with the F-111 TACT,[66] F/A-18,[67] F-15,[65,68] Jaguar,[69] Hawk,[49] T-45[70] and numerous other aircraft. IAT and flight test programs can also be used to examine phenomena such as outer wing and empennage buffet and their effects on the fatigue life of critical structure. With sophisticated fatigue monitoring systems such as that on the F/A-18, an extensive database was developed to identify the conditions at which these phenomena occur and to further investigate the problem.

Fatigue monitoring of the vertical tail can be difficult due to complexities such as buffeting, a redundant structure and non-linear relationship with the normal acceleration at the aircraft's centre of gravity. Strain gauges have been fitted to the F/A-18 empennage for the purposes of fatigue monitoring. However, this IAT has demonstrated that difficulty in calibration and relating fleet measured strains to fatigue test results for the vertical tail have made their use impractical.[71]

Time spent in certain dynamically fatigue-damaging angle of attack and dynamic pressure regimes have also been examined[67] to quantify buffet affects. Today, however, a reliable and accurate method is still the subject of studies.[72]

FATIGUE MONITORING SYSTEMS

Historically, substantial effort has gone into system design, manufacture and data collection in fatigue monitoring systems. However, the rapid improvement in the computing power of structural fatigue monitoring systems has also led to a sharp increase in the amount of data collected and thus in the costs involved with data processing, software development and data analysis. Therefore, to minimize the effort required after data are collected, there is an incentive for the operator to choose the right monitoring system at the outset.

In fleet operations, the accuracy of the fatigue life or crack length prediction depends primarily on two factors, viz. the fatigue monitoring tools that are used in the IAT and the accuracy of the model being used for the prediction.

Usage monitoring based solely on recoding 'administrative' parameters, e.g. flight hours, mission type, mission duration, pilot name, configuration, take-off and landing weight have been used in the past. However, the advent of sophisticated data acquisition systems has led to more accurate methods being developed. Flight hour or N_z counting are poor options (Table 1) for modern air forces operating technologically advanced fighter aircraft. Some of the monitoring tools used on modern aircraft are listed in Table 3.

As evident from Table 3, the individual and combinations of tools used varies greatly among aircraft and even among operators of the same aircraft. Fatigue meters alone are still used in four older generation fighters, while only two operators use purely flight parameter-based systems (the 'indirect method'). No operator was found to exclusively use strain gauges (the 'direct method'). The most popular combination found was a strain gauge system supplemented by flight parameters as recommended in Ref. [47].

When considering the tools to be used for fatigue monitoring, aside from the cost, perhaps the most important considerations are the volume and accuracy of the data. Other factors, e.g. maintenance of the system, data compression, data integrity, data retrieval, upgrade cost, size and weight must all be considered. Modularity of the system, the number of channels, memory, programming and data sampling frequency must also be given consideration.[82]

Many aircraft today are undergoing avionics upgrades and fatigue monitoring systems are being reviewed with these upgrades. Sampling rates of the systems are increasing and 'megasamples per second' may soon be common. Parameters should be sampled at sufficiently high rates and account for dynamic loading. Sampling rates as high as 70 and 140 samples per second were used on the Nimrod aircraft in 1984, when systems were much larger and heavier[91] than today's modern systems. Today, sampling rates over 500 Hz may be easily achieved on data acquisition systems, but are yet to be installed on any aircraft studied in this review.

Fleet structural integrity managers must take into consideration possible upgrades in computer systems and

Table 3 Service load monitoring systems on modern aircraft

Aircraft (operator)	Dedicated fatigue meter	No. of strain gauges	Flight parameter	% of service aircraft fitted
A-3 (US Navy)	√	1	×	100% [39]
Alphajet (French AF)	√	0	×	100% [41]
AMX (Italian AF)	×	12	√	100% [73]
B-1B (US AF[1])	√	6	√	100% [74]
EF200 (Partner nations)[2]	×	√	√	TBD[42]
F-14 (US Navy)	×	0	√	[43]
F-15 (US AF)	√ [3]	0	√	20% [74]
F-16 (Royal Nedl. AF)	×	5	√	100% [75]
F-16 (US AF)[4]	×	1	√	100% [45]
F/A-18 (RAAF)	×	17 [5]	√	100% [76]
F/A-18 (US Navy)	×	6	√	100% [46]
(R)F-104 (Royal Nedl. AF)	√	0	×	15% [58]
F-111 (RAAF)[6]	√	11	×	4% [48]
Hawk (RAF)	√	0	×	100% [49]
Hawk (RAAF—specification)	√	6	×	100% [77]
JAS-39 (Swedish AF)	√	5 [8]	×	100% [53]
JAS-37 (Swedish AF)	√	0	×	[53]
Kfir (Israel)	√	0	×	100% [50]
MB339CB (Royal NZAF)	√	8	×	100% [51]
Mirage 2000 (French AF)	√	0	√	100% [52]
Tornado (Italian AF)	×	0	√	100% [78]
Tornado (Royal AF)	√	√	×	100% [5]
Tornado (German AF)[7]	×	2	√	10% [54,79]

(√ = yes; × = no).
[1]The B-1B is included here because it was the first aircraft in the USAF to incorporate as a design requirement, a dedicated Structural Data Collector to record structural loads on every aircraft.[74] It was the first USAF aircraft to be equipped with a load monitoring device capable of recording flight parameters on every aircraft in the fleet. [2]Both the strain gauge and flight parameter-based systems have been accommodated in the design. Individual operators will select one or both of these systems. [3]All F-15s in the USAF are equipped with fatigue meters. [4]The Crash Survivable Flight Data Recorder is fitted to every aeroplane but is not used for fatigue monitoring at present. [5]RAAF F/A-18s are fitted with the additional strain-based Aircraft Fatigue Data Analysis System (AFDAS).[81] [6]Only four F-111s in the RAAF are equipped with AFDAS, however all F-111C have fatigue meters. [7]1987 figure quoted from Ref. [80]. [8]These gauges are calibrated in flight.

collect data that are transferable from one system to the next. When data are not transferable from one system to the next, it becomes difficult or impossible to accurately account for data from early periods of flying. This difficulty in filling in missing data and other problems associated with mid-life upgrades highlights the importance of getting it right at the time the aircraft is introduced into service.

The direct method of loads monitoring using strain gauges is the method advocated by the authors. However, these should be complemented by the indirect or flight parameter-based method to 'fill in' for missing or corrupt data, and to validate and calibrate strain gauge data.[47] Other advantages of this combination include the ability to analyse flying on a PITS basis and the option of using a parameter-based secondary system to validate data from the primary system.[59]

Commonality in the ground-based processing across all aircraft types for each AF is highly desirable, albeit probably uneconomical and impractical. While it may not be necessary for all the systems to be identical, similarity in the systems can lead to cost savings through commonality in ground-based software.

Strain gauges

Historically, concerns with the inability to monitor stress activity near the wing root by a fatigue meter alone led to the development of strain-measuring devices capable of responding primarily to the wing root bending moment (WRBM). Strain gauges located near the wing root were installed to enable the effects of weight changes with fuel burn and weapons release during flight to be accounted for.

Today, judicious placement of the strain gauges can account for these effects at various PITS constituting the flight envelope. The location of the strain gauge must be such that its response is predominantly influenced by the principal loading inducing the fatigue damage at the critical locations considered. In particular, care must be taken to ensure that the location of the strain gauge:

- can be calibrated to the damage-inducing load;
- is dominated by the principal load (e.g. WRBM) and insensitive to other loading actions;
- is in an area of low stress gradient;
- can be directly related to the stress at critical structural locations (preferably by a linear relationship for both positive and negative loads);
- is not prone to gauge 'drift' (varying response to a nominal load over time. F/A-18 wing root lugs are an example of this);
- is not subject to load redistribution due to redundant load paths;
- is accessible for easy replacement;
- is positioned as close to practicable to a backup strain gauge in the advent that the primary strain gauge fails or drifts;
- is replicated at a 'mirrored' location to estimate the asymmetrical component of the loading;
- is replicated on the fatigue test article so that direct comparisons can be made (often overlooked in many IAT programs); and
- is accurately positioned and protected from the environment and service wear.

Strain gauges have the advantage of being sensitive to load, and thus aerodynamic phenomena, and provide an indication of the loads the structure experiences. The magnitude of the effects of phenomena such as buffet and gust loads can only be measured by strain gauges or accelerometers[70] and not by flight parameters or fatigue meters. The installation of a gauge must be performed precisely with a template (location and orientation are critical) and the gauge must not be fragile or erratic. Procedures must be in place to frequently check the condition of the gauges and erroneous gauges must be found and replaced quickly.

Ideally, both sides of the attachment locations (especially the wing root) should be monitored.[59] Operational data have shown that the accumulation of fatigue damage on the two sides of the aircraft may not be even, as demonstrated by left and right F/A-18 wing root strain being different depending on the manoeuvre as shown in Fig. 4.

The number of channels available on the data acquisition system may restrict the number of gauges that can be placed. Currently, about seven gauges appears to be standard (Table 4), but this number may vary in future aircraft.

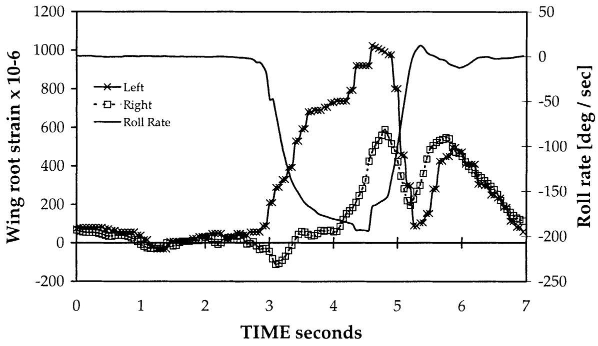

Fig. 4 Right and left wing strains in a roll to the left.

Critical point or 'hot-spot' strain measurement is still common practice, e.g. see Ref. [48], but is not recommended for IAT.[84,85] The major problem with hot-spot gauges is that they are placed in regions of non-uniform strain that make calibration and replacement difficult. A good example of the former problem was with the F-16 MSR where a variation in strain from 85% to 155% was seen over the length of the MSR[75] for a given load case. (The MSR is 203 mm long with a gauge length of about 13 mm and is installed on the lower flange of the centre fuselage wing carry-through bulkhead.) Furthermore, a high strain gradient and the relatively large gauge length implies that the maximum strain is not recorded and uniform strain through the strain gauge is not present.

While the benefits and drawbacks of 'hot-spot' monitoring have been mentioned,[47] the authors' views are that strain gauges used in IAT programs should be for structural load monitoring only. In that application, the loads measured by the strain gauges are related to stresses at a critical point via a transfer function, instead of being used directly for maximum stress measurement. Hence, the aim is not to place gauges to determine their lower or upper limits, but to measure loads in the main paths leading to the critical areas.

Gauges should be sampled at frequencies of about 10 times the natural frequency of the fundamental bending mode of the structure for areas that are suspected to be dynamically affected. This will ensure that the maximum peak and valley of each cycle are captured.

Strain gauge calibration

Because the fatigue usage of a military aircraft is normally calibrated against the damage accumulated on a fatigue test article, calibration of strain gauges located in nominally identical locations to those on the fatigue test article is essential in order to obtain an accurate estimate

Table 4 Service load monitoring locations using strain gauges

Aircraft	Operator	Total	CR	IW	OW	FF	CF	RF	HTR	VTR	Other
A-3	USN	1	—	1							
AMX	Italian AF	12	—	3	1	1	2	1	2	2	
AV-8B	Royal AF[82]	16	—	1	2		6	2	3	1	1
Hawk	Royal AF	14[1]	—	3	4		2		2	3	
B-1B	USAF	5	—	2					3		
EF2000	RAF	16	3	1	1	1	4	1	—	1	4
F-16	RNLAF	5	—	1			1		1	1	1
F-16	USAF	1	—	1							
F/A-18	USN, RAAF-MSDRS	7	—	1	1	1			2	2	
F/A-18	RAAF-AFDAS	11	—	1	1	1	3		2	2	1
F/A-18	Swiss AF-MSDRS[83]	7	—	1	1	1	1	1	1	1	
F-111	RAAF	11	—	6		1	2		1	1	
JAS-39	Swedish AF	5	2	2						1	
Tornado	German AF and Navy	2	—	2							

Unless otherwise stated, reference documents for each aircraft are the same as those shown in Table 3. CR, canard root; FF, forward fuselage; HTR, horizontal tail root; IW, inner wing; CF, centre fuselage; VTR, vertical tail root; OW, outer wing; RF, rear fuselage.

[1] These gauges were only used during the OLM survey program.

of the fatigue life. They must be calibrated so that the loads derived from them can be directly related to loads derived from the equivalent strain gauge on the fatigue test article. To verify the fatigue test loading the test article gauges may also have been calibrated against the response of a loads development aircraft.

Furthermore, two gauges placed at nominally identical locations, but on different airframes, may not respond equally to a nominally equal global load due to slight differences in airframe build quality, strain gauge alignment, adhesive thickness and in the gauge factor or gauge/amplifier sensitivity. Multiple load paths in a redundant structure may also cause varying gauge response arising from differences that are ‘built-in’ before delivery. This variability has been observed to be as much as 50% in vertical tails of the RAAF F/A-18 fleet.[86]

Calibration is also necessary to account for drift in the strain gauge reading. With the F/A-18, the wing root strain gauge is known to drift as a result of the wing pin attachment bushings causing a redistribution of stress near the strain gauge.[87] This strain gauge is calibrated by comparing operational data with that produced by a reference WRBM applied at the appropriate fatigue test article.[47,59,87]

Analytical predictions of the calibration factor should be adopted because it is very costly to physically conduct a ground calibration of each aircraft. While the Australian F/A-18 fleet of ~70 aircraft is relatively small, a major effort would be required to calibrate each aircraft (as was performed in RAF Tornado.[88]) Hence, analytical methods, involving the identification of similar operational PITS and configurations, were developed and validated by ground calibration of 10 fleet aircraft from various squadrons.[86,89,90] The ground calibration involved application of a distributed or point load to the structure in question and the simultaneous recording of the strain experienced by the strain gauge. This procedure was used to identify the strain per root bending moment (from regression analysis) for the wings, vertical tails and horizontal stabilators, to validate the analytical methods.

Alternatively, gauges may be calibrated in flight, under certain configurations and regimes that are flown often. For example, the 1g trimmed condition under a common stores and weight configuration could be used. On the JAS-39, in-flight calibrated strain gauge bridges are used[91] and studies examining this method on the F/A-18 were noted as being operationally expensive.[92] The major advantage of this method is that it can be automated to reduce post-processing efforts.

Flight parameters

Many military aircraft today have a sophisticated computerized control system that relates flight parameters to control surface deflections. These control systems together with fatigue monitoring systems are sometimes integrated into the mission computer.

With flight parameter-based systems, loads in the major load carrying members are calculated from flight parameters using regression techniques.[93] These loads in turn are related to stresses at critical locations via transfer functions. The load equations are often developed for a certain range of strain (i.e. separate equations for tensile and compressive loads) and for symmetrical or asymmetrical flight, supersonic and subsonic conditions. Further studies have shown that separate equations are also required for different stores configurations.[76,94]

Flight parameters should be integral to an IAT system and may be used to:

- calibrate strain gauges;
- validate strains and estimate strains when data are corrupted;
- produce aircraft utilization statistics;
- determine significant loads;[52,95,96] and
- provide an independent check of the damage calculated via the strain gauges, as recommended in Ref. [59].

In order for flight parameters to be used in the first two cases, sufficient synchronously monitored parameters are required to estimate the recorded strains to a desired level of accuracy. For example, it has been shown[76] that for empennage strain gauges, the following parameters (among others) are significant:

- angle of attack, α;
- stabilator deflection, δ_{elev};
- rudder deflection δ_{rud};
- trailing edge flap deflection, δ_{TEF};
- yaw rate, r;
- pitch rate, q; and
- aileron deflection, δ_{ail}.

The parameters listed in Table 5 are indicative of those recommended for inclusion in a flight parameter-based fatigue monitoring system.

Some of the parameters recorded on agile aircraft employing flight parameters are listed in Table 6. As listed in the table, following from the *V–g–h* recorder concept, the four most important parameters (speed, altitude, load factor and weight) are recorded on almost every system. While angle of attack is commonly measured, angle of sideslip is rarely recorded. Angular rates and control surface deflections are generally recorded on the newer systems on fighter aircraft. However, their sampling rates are often too low for meaningful results to be produced.[86]

DATA HANDLING AND PROCESSING

With the growing volume of data being captured by the monitoring systems, data handling procedures that are efficient, inexpensive and simple must be in place. While much of the data handling procedures are being outsourced by operators, it is important for the operator to determine the level of involvement they have in the overall process. The level of involvement feeds back into the decision as to whether an aircraft should have on-board data manipulation and analysis software to produce a final damage value for each flight or only capture data with all processing being executed on-ground by the operator or a contractor.

As technology and the science of fatigue are constantly improving, the monitoring system should be capable of being upgraded. Because upgrades of on-board hardware or software are very expensive and not uncommon within the lifetime of the aircraft, systems should be modular for ease of upgrade or replacement.

On-board versus ground-based processing

The amount of on-board processing may vary. As a minimum raw N_z, strains and flight parameter data may be recorded. A form of on-board data compression is the storage of only peaks and valleys of the signals (where low amplitude or low mean cycles are 'discriminately' omitted). If only peaks and valleys are stored, then it is highly recommended that each peak and valley trigger be 'time-stamped' to enable data checking at a later date.[100] Developing from peak valley recording, numerous operators 'cycle count' the data[101] and/or discretize data into a fixed number of levels (currently about 40 appears common) and a matrix of occurrences is created, as per the JAS39.[102] This is then further processed on-board, to produce a measure of fatigue damage (e.g. fatigue index—FI or damage value), or downloaded after the flight for further processing, similar to the RAAF AFDAS system.

Typical on-board processing today includes data checking routines, a stress calculation for each location, cycle counting, damage calculation and result storage.[52]

Table 5 Flight parameters recommended for monitoring

• absolute time	• normal load factor, N_z	• Mach number, M
• relative time	• fuel weight	• true airspeed, TAS
• roll rate, p	• all up weight, W	• calibrated airspeed
• pitch rate, q	• stores weights	• dynamic pressure, Q
• yaw rate, r	• angle of attack, α	• altitude, h
• roll angle	• angle of sideslip, β	• control surface deflections (canard, flap, aileron, elevator, rudder)
• pitch angle	• wing sweep angle, Λ	
• yaw angle		

Table 6 Flight parameters recorded on some aircraft

Aircraft (operator)	V	N_z	h	W	α	β	δ_{rud}	δ_{flap}	δ_{elev}	δ_{ail}	N_z	p	q	r	$\dot{p}$	Λ	Other	Ref.
B-1B (USAF)	√	√	√	√	×	×	×	√	×	×	×	×	×	×	×	√	×	74
F-14 (US Navy)	√	√	√	√	√	×	√	√	√	×	×	√	√	×	√	√	×	43
F-15 (USAF)	√	√	√	√	√	×	√	×	√	√	√	√	√	√	√	—	√	97
F-16 (USAF)	√	√	√	√	√	×	√	√	√	√	√	√	√	√	√	—	√	98
F/A-18 (RAAF, USN)	√	√	√	√	√	×	√	√	√	√	√	√	√	√	×	—	√	76
F-111 (RAF)	√	√	√	√	√	×	√	√	√	×	√	√	√	√	×	√	√	48
Hawk (RAF)[1]	√	√	√	×	×	×	√	√	√	√	√	×	×	×	×	—	√	49
Mirage 2000 (French AF)	√	√	√	√	×	×	×	×	√	×	×	×	×	×	×	—	×	52
Tornado (Italian AF)	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	×	99
Tornado (German AF)	√	√	√	√	√	×	√	√	—	√	×	√	√	√	×	√	√	54, 79

(√ = yes; × = no).
[1] OLM program only. Operational fatigue monitoring is only carried out with a fatigue meter.

An example of a fighter aircraft where on-board real-time fatigue calculations are conducted is the Eurofighter 2000 (which is known as the structural health monitoring system).[42] With this system, internal loads for various flight conditions and structural locations are predicted from finite element models or obtained from fatigue tests and stored in templates on-board the aircraft. Flight parameters are then recorded on-board and the stress for that condition is obtained from one of the 17 500 on-board templates. So, for each flight or block, a stress spectrum is generated, which is then cycle counted and the incremental crack lengths determined. The B-1B has a similar system containing a database for over 1000 load conditions covering a range of PIS and is used directly to produce a stress spectrum for specific locations.[97]

At the other end of the spectrum, the F/A-18 is an aircraft where minimal processing is carried out on-board and extensive processing is performed on-ground.[46] Although on-board processing appears attractive, it has many significant pitfalls (Table 7). Data that are collected on-board but compressed cannot be easily verified, validated or calibrated after the flight. Therefore, on-board damage calculation cannot be recommended if raw data are not stored with the final damage values.

The frequency of data downloading and the time spent in downloading is a major maintenance consideration, and downloads after every flight are not desirable as this consumes much time. A download frequency of about once every 50 h appears acceptable. However, it still means ~100 downloads over the lifetime of the aircraft.

Fleet reprocessing may sometimes be required to account for errors or improvements in the software. In such cases, it may be necessary to identify the status of the fleet (from the data of acceptance) using the improved software. Australian experience has shown that reprocessing the raw data for a fleet of 70 aircraft can be completed in approximately a fortnight.

In terms of cost, it is somewhat difficult to obtain a breakdown between maintenance times and software development times. However, the USN experience at maintaining the software alone is reported to be in the order of $285 per year per aircraft.[44]

Data integrity and fill-in methods

Recording systems are effected by external factors that lead to a loss of data or to the recording of spurious data. It is common for data losses to be 10–20%.[18] About a decade ago, this figure was in the order of 50%.[44] Hence, it may be expected that the current figure will decline to half its value in another decade.

Data errors may have various sources:

- instrument malfunctions, faulty sensors or unserviceability errors;
- recording system failure leading to no data being recorded for portions of or for complete flights;
- data down-load errors leading to loss of data;
- recording errors in the system that lead to data spikes;
- system input errors that lead to excessive data (e.g. too many turning points in a particular time being captured due to a discriminant being set too low); and
- other reasons that lead to corrupt data (where the data recorded are unrealistic, such as where data are duplicated across various portions of a flight).

Hence, for each parameter or combination of parameters, the following checks should be conducted:

- range operational envelope limit checks;
- maximum rate of change;
- excessive recording;

Table 7 Some of the benefits and drawbacks of on-board and ground-based processing

	Advantages	Disadvantages
On-board (damage or life calculated on-board)	• Low volume of data. • Minimal space is taken up in the aircraft. • Light-weight. • Quick access to data. • Short turn-around times.	• Data compression does not allow access to raw data. • Subsequent analyses cannot trace back the original data. • Software must be accurate because it is expensive to amend (the in-flight damage calculation). • Re-processing of fleet data is not possible or is very difficult. • Only available for pre-determined critical locations. Changes to the critical location may require a software change.
Ground-based (only raw data collected on-board)	• Access to raw data for validation, calibrations and other studies. • Re-analysis of data may be performed (i.e. a whole lifetime may be re-analysed as in the case for the RAAF F/A-18). • Special purpose software packages may be developed and improved without the need for on-board software upgrades. • Only a recording system is needed. • Shared resources (software) between different aircraft types.	• Large data storage equipment required on-board the aircraft. • Long 'down-load' times. • Access to fatigue damage data not immediately available. • Extensive ground-based analysis software required. • Significant logistical effort for data validation and archiving.

- data cutting out in the middle of a flight (continuity);
- spikes;
- data repetition:
- initialization; and
- synchronization between parameters (for time lags).

Spurious data are found on every system, and lost or bad data from a fraction of a second or a whole flight must be accounted for. As an example, with the RAAF F/A-18, single bad points in the wing root strain gauge are accounted for (filled-in) using *V–g–h* parametric methods, while whole flights are filled-in using a method based on the typical damage accumulated by the type of flying conducted.[87] Due to the variability in missions stated earlier, the fill-in method should be conservative in its estimate of the life (i.e. predict a shorter life value) to ensure safety of the aircraft.

DAMAGE MODELS AND FATIGUE TEST RESULTS

A purpose of any fatigue monitoring program is to determine the fatigue life status of a fleet of aircraft based on their operational spectrum. All fleet structural integrity programs are established on the results of analytical studies and full-scale fatigue tests. However, with a difference between operational and design spectra, interpretation of fatigue test data and application to the fleet can be difficult.

Full-scale fatigue tests seek to:[103]

- identify the most critical parts of the overall structure which are susceptible to fatigue damage;
- compare analytical design data with fatigue test data;
- substantiate a life extension program;
- determine the safe-life or damage tolerance limits; and
- determine crack growth characteristics and accordingly formulate inspection and maintenance schedules.

The results of the fatigue test are required in order to implement a fatigue monitoring system. It is then the fatigue behaviour at each critical location that fatigue damage models seek to simulate. Some damage models used for fatigue monitoring are listed in Table 8. It should be noted, as highlighted in this paper, that the 'damage model' is only one component of the overall monitoring system. Each component contributes to the overall accuracy of the monitoring system. Regardless of the basis of the damage model, be it total life or crack growth, the other components should be common.

These fatigue models should be calibrated using the full-scale fatigue test results complemented by material coupon test, component tests and/or from in-service defects.

Table 8 Fatigue damage models used on some of today's aircraft

Aircraft	Method
F/A-18	Local strain approach using cyclic and hysteresis material curves and Neuber's notch stress rule.[104] Data are cycle counted. Empirical equivalent strain equation used to convert cycles for any stress ratio to the equivalent damage for a cycle with stress ratio of -1.
Tornado	Palmgren–Miner cumulative damage rule.[105] Material stress–life curves for various stress ratios, geometric stress intensity factors and manufacturing methods are used to ascertain the number of cycles to failure.
Hawk	Palmgren–Miner cumulative damage rule. Material stress–life curves for various geometric stress intensity factors and manufacturing methods are used to ascertain the number of cycles to failure.[49]
A-7	Forman equation to define crack growth rate curves. EFGRO program contains Wheeler retardation model where growth rates are reduced for cycles after an overload until flaw grows 'through' the yield zone.[40]
Kfir	Crack closure model to describe crack growth and retardation characteristics.[50]
F-15	Contact stress model accounts for residual stresses that arise from peak overloads and crack growth retardation caused by plasticity at the crack tip.[68]
F-16 (RNLAF)	Crack growth model where sequence effects are taken into account and are calibrated to a reference usage period and reference strain. Interactions between large and small load cycles are accounted for. Crack closure and crack growth retardation are accounted for and the minimum crack opening stress is taken into consideration.[106]
F-16 (USAF)	Uses the modified Willenborg model[107] with classical stress intensity solutions. Historically, stress exceedance data and a flaw growth library were used to create cumulative flaw growth curves for each control point on each aircraft.[45]
JAS-37 Viggen	Cycle-by-cycle analysis used without load interaction effects (plasticity ignored). Finite element stress analysis for stress intensity calculations. LIFE program compared with CRACK IV, EFFGRO and ESACRACK programs.[108]
Mirage 2000	ONERA's crack closure model.[109]
B-1B	Utilizes the Walker equation. Routine includes a tensile overload retardation model and a compressive load acceleration model. The load interaction model is a modified Willenborg/Chang model that assumes that the overload retardation effect is caused by variations in the local stress field as the crack grows through the compressive residual stress zones produced by the overload. The Willenborg model predicts that the maximum retardation will occur immediately after the overload and the growth rate will return to its constant amplitude counterpart when the current interaction zone reaches the end of the overload interaction zone.[97]

It must be shown that the damage model can scale between the fatigue test result and the extremes of fleet usage. Therefore, the spectrum applied to a fatigue test must be accurately interpretable using the fatigue damage model chosen for IAT purposes. RAAF F/A-18 fleet management is based on numerous fatigue tests and damage models are calibrated to their results.[59]

Many aims of an operational loads monitoring or an IAT program can only be achieved through the conduct of a fatigue test. These aims include identification of fatigue critical locations, substantiation of analytical test lives and the identification of potential services failures due to high loads. Hence, there is a strong relationship between the full-scale fatigue test result and the IAT program.

CONCLUSIONS

A review of the state of the art in fatigue monitoring has been presented, examining philosophies, systems and tools, fatigue models and fatigue test interpretation. Experience with Australian fatigue monitoring programs has been drawn on to highlight deficiencies in certain practises and forecast future programs.

It has been shown that due consideration in the management of fighter aircraft fatigue must be given to the application of fatigue test results to fleet data, an IAT (International Aircraft Technology) program, a reliable and economical fatigue monitoring system, validation of damage models and data calibration.

It has been shown that IAT has been beneficial in comparing operational and design usage, in the planning of maintenance action, in modifying operations and in the understanding of structural problems.

The various options for fatigue monitoring systems have been presented, and a way forward using a combination of direct and indirect methods has been recommended.

In summary, the Australian F/A-18 fatigue management program has shown that fatigue monitoring should not be an afterthought to the design. Careful consideration must be given to the design philosophy, the monitoring system, the fatigue test and the application of its results to the fleet early in the process.

REFERENCES

1 W. Schütz (1973) *Fatigue Life Prediction for Aircraft Structures and Materials*. AGARD-LS-62, ICAF-Doc-693. Advisory Group for Aerospace Research and Development, France.

2 D. J. Jones, M. J. Duffield and D. M. Holford (1998) *Future Fatigue Monitoring Systems for Fixed Wing Aircraft. Proposals for*

a New Policy and a Strategy for the Way Ahead. DERA/AS/ASD/CR/97600/1.0. Defence Evaluation and Research Agency, UK.

3 Anon (1987) *Fatigue Damage Tolerance Service Monitoring*. Leaflet 201/6 (Royal Air Force) Def Stan 00-970, Vol. 1, Amendment 6, UK.

4 E. S. Wilson (1995) Developments in RAAF aircraft structural integrity management. In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft fatigue Performance* (Edited by J. Grandage and G. Jost). Melbourne.

5 M. E. J. Render and J. E. Stevens (1991) Aircraft fatigue management in the RAF. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.

6 J. W. Lincoln (1991) Life management approach for USAF aircraft. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.

7 G. R. Negaard (1980) *The History of the Aircraft Structural Integrity Program*. Aerospace Structures Information and Analysis Center, R-680.1B, USA.

8 Anon (1976) *Aircraft Structural Integrity Program: Research and Development. AFR* 80-13, Department of the Air Force, Washington, DC, USA.

9 Anon (1974) *Military Specification: Airplane Damage Tolerance Requirement*. MIL-A-83444, Department of the Air Force, Washington, DC, USA.

10 R. A. V. Byron (1981) *Fatigue in Aircraft*. University of New South Wales Report 1981/AM/1, Australia.

11 M. Matsuiski and T. Endo (1958) Fatigue of metals subjected to varying stress. In: *Proc. Kyushu Meeting of Japan Society of Mechanical Engineers*, Japan.

12 F. H. Hooke (1948) *V-G Recorder Results from a Dakota Aircraft Operating Between Australia and Japan*. Aeronautical Research Laboratories, ARL-Struc-Mat-R-111, Australia.

13 F. H. Hooke (1949) *V-G Recorder Results from a DC-3 Aircraft Operating Between Perth and Darwin*. Aeronautical Research Laboratories, ARL-Struc-Mat-R-135, Australia.

14 R. Hain Taylor (1952) *Some Preliminary Results from V-g Recorders Installed in Military and Civil Aircraft*. R&M No. 2610. Aeronautical Research Council, London.

15 I. Taback (1950) *The NACA Oil-Damped V-G Recorder*. NACA-TN-2194, USA.

16 N. R. Richardson (1951) *NACA VGH Recorder*. NACA-TN-2265, USA.

17 J. R. Sturgeon (1971) Flight data acquisition for fatigue load monitoring and conservation. RAE-TM-799. *32nd AGARD Structures and Materials Panel*. Advisory Group for Aerospace Research and Development, France.

18 R. Schütz and R. Neunaber (1984) Operational loads data evaluation for individual aircraft fatigue monitoring. *58th Meeting of the AGARD Structures and Materials Panel*, Sienna, 2–6 Apr 1984, AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.

19 J. Taylor (1952) Accelerometers for determining aircraft flight loads. *Engineering* 473–507.

20 J. Taylor (1954) *Design and Use of Counting Accelerometers*. R&M No. 2812, Aeronautical Research Council, UK.

21 C. E. Scott and W. D. Rowland (1970) A transducer for measuring and recording several levels of strain. *Proc. Society of Experimental Stress Analysis*, UK.

22 J. R. Sturgeon (1972) *Increasing the Operational Effectiveness of Military Aircraft by Flight Data Acquisition*. RAE-TR-72169, UK.

23 J. R. Sturgeon (1966) The use of accelerometers for operational loads measurements in aircraft. In: *Proc. Conf. Stresses in Service*, UK.

24 A. P. Ward (1991) The development of fatigue management requirements and techniques. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.

25 D. G. Ford and A. K. Patterson (1971) *A Range Pair Counter for Monitoring Fatigue*. Aeronautical Research Laboratories, ARL-Struct-Mat-TM-195, Melbourne.

26 Anon (1978) *The Aircraft Fatigue Data Analysis System*. British Aerospace Australia, Salisbury, South Australia.

27 R. C. Fraser (1979) *Fatigue Damage Estimation for the BAeA Aircraft Fatigue Data Analysis System*. Aeronautical Research Laboratories, ARL-Struct-TM-297, Melbourne.

28 M. J. Goodrige and L. E. Woods (1980) AFDAS—an aircraft fatigue data analysis system. *Proc. Conf. of Inst. of Engineers*, Adelaide, Australia.

29 P. J. Howard (1980) *Flight Trail of the Aircraft Fatigue Data Analysis System (AFDAS) MK2 Prototype*. Aeronautical Research Laboratories, ARL-Struct-N-466, Melbourne.

30 J. M. Finney and A. D. Denton (1986) Cycle counting and reconstitution with application to the aircraft fatigue data analysis system. *J. Inst. Mech. Eng.* **1,** 231–240.

31 R. S. Horne (1968) Development of a semiautomatic fatigue evaluation system for transport aircraft. *J. Experimental Mechanic*.

32 E. J. Blackburn (1971) Direct measurement of fatigue damage in aircraft. *J. Strain*.

33 A. D. Graham (1974) *Fatigue Monitoring Devices in Aircraft*. Struc. and Mat.-TM-222, Aeronautical Research Laboratories, Melbourne.

34 T. L. Haglace (1970) *Flight Test Evaluation of a Scratch Strain Gauge*. AFFDL-TR-69-116, Wright Patterson Air Force Base, Ohio, USA.

35 H. A. Wood (1970) In-flight strain measurements using the Prewitt scratch strain gauge. In: *Proc. ASTM Committee E-9*, Toronto, Canada.

36 F. A. Blaha and L. Grenier (1996) A fiber-optic loads monitoring system for the CL-600 challenger aircraft. In: *Proc USAF ASIP Conference* (Edited by T. D. Cooper, J. L. Rudd and J. W. Lincoln), 6–8 Dec. 1994, WL-TR-96-4030, USA.

37 F. H. Hooke (1971) *The Fatigue Life of Safe Life and Fail-Safe Structures: A State-of-the-Art Review*. Aeronautical Research Laboratories, ARL-Struc-Mat-334, Melbourne.

38 E. J. Ward (1995) *Hornet Aircraft Structural Integrity Management Plan*, Issue 1. RAAF Logistics Systems Agency, Melbourne.

39 S. Dore and D. Ginsburg (1988) *A-3 Strain Measured Fatigue Tracking*. Aerostructures Inc., TR88015, Arlington, VA, USA.

40 D. Santos and L. Vasconcelos (1991) Fatigue Management for the A-7P In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.

41 L. Defever, T. Courbe and L. Le Tellier (1997) Alphajet aircraft life extension programme. In: *Proc. 19th Symposium of the*

International Committee on Aeronautical Fatigue: Fatigue in New and Aging Aircraft (Edited by P. Poole), Edinburgh.
42 S. R. Hunt and I. G. Hebden (1997) Eurofighter 2000: an integrated approach to structural health and usage monitoring. In: *Proc. 19th Symposium of the International Committee on Aeronautical Fatigue: Fatigue in New and Aging Aircraft* (Edited by P. Poole), Edinburgh.
43 R. H. Dalrymple and T. M. Fallon (1998) F-14 fatigue tracking methodology and lessons learned. In: *Proc. 1997 USAF ASIP Conference* (Edited by J. W. Lincoln, G. K. Waggoner, J. Rudd and J. Turner), 2–4 Dec., USA.
44 A. H. Johnson and M. J. Dubberly (1984) Navy operational loads data sources and systems. In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, Italy, 2–6 Apr, AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
45 J. W. Morrow and G. T. Herrick (1993) An overview of the F-16 service life approach. In: *Proc. 77th Meeting of the AGARD Structures and Materials Panel*, Bordeaux, France, 29–30 Sept., AGARD-R-797. Advisory Group for Aerospace Research and Development, France.
46 R. Koenigstein (1997) *Structural Appraisal of Fatigue Effects (SAFE) V200 Manual.* McDonnell Douglas Corporation, March 1997 Meeting of the F/A-18 International Fatigue Tracking Working Group.
47 L. Molent (1998) A unified approach to fatigue usage monitoring of fighter aircraft based on F/A-18 experience. In: *Proc. 21st Congress of the International Council of Aeronautical Sciences*, Melbourne, ICAS Paper 98-5.1.3.
48 M. O. Wilkin (1996) *F-111 Aircraft Structural Integrity Management Plan*. RAAF Logistics Systems Agency, Melbourne.
49 J. O'Hara (1993) The evolution of the BAe Hawk and its structural clearance. In: *Proc. 17th Symposium of the International Committee on Aeronautical Fatigue: Durability and Structural Reliability of Airframes* (Edited by A. F. Blom), Stockholm.
50 E. Reinberg and A. Brot (1988) Summary of the Kfir fatigue evaluation program. In: *Proc. 16th Congress of the International Council of Aeronautical Sciences*, Jerusalem, ICAS Paper 88-5.8.2.
51 D. L. M. Keesing (1995) Airborne strain and fatigue life monitoring. In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft Fatigue Performance* (Edited by J. Grandage and G. Jost), Melborune.
52 R. J. Cazes and P. Defosse (1991) Aircraft tracking optimization of parameters selection. In: *Proc. 16th Symposium of the International Committee on Aeronautical Fatigue Symposium: Aeronautical Fatigue in the Electronic Era* (Edited by A. Kobayahsi), Tokyo.
53 A. F. Blom and H. Ansell (1993) *Fatigue Management and Verification of Airframes*. Aeronautical Research Institute of Sweden, FFA-TN-1993-55, ICAF-DOC-1961.
54 P. Fraas and A. Göllner (1991) Tornado structural fatigue life assessment of the German Air Force. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.
55 M. B. Zgela and W. B. Madley (1991) Durability and damage tolerance testing and fatigue life management: a CF-18 experience. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.
56 J. B. de Jonge (1970) The monitoring of fatigue loads. In: *Proc. 7th Congress of the International Council of Aeronautical Sciences*, ICAS Paper 70–31.
57 D. Crocker and M. Oore (1995) Individual aircraft tracking system for the Canadian P-3C (CP-140/A) aircraft structural integrity program. In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft Fatigue Performance* (Edited by J. Grandage and G. Jost), Melbourne.
58 J. B. de Jonge (1989) Load experience variability of fighter aircraft. In: *Proc. 3rd Australian Aeronautical Conference*, Melbourne.
59 L. Molent (1997) A review of a strain and flight parameter data based aircraft fatigue usage monitoring system. In: *Proc. 1996 USAF ASIP Conference* (Edited by T. D. Cooper, J. L. Rudd and J. W. Lincoln), USA.
60 A. D. Graham, D. Symons, D. Sherman and T. Eames (1993) ARL F/A-18 IFOSTP full scale fatigue test. In: *Proc. 5th Australian Aeronautical Confernece*, 13–15 Sept., Melbourne.
61 J. B. de Jonge (1989) Assessment of service load experience. 12th Plantema Memorial Lecture. In: *Proc. 15th Symposium of the International Committee on Aeronautical Fatigue: Aeronautical Fatigue in the Electronic Era* (Edited by A. Berkovits), Jerusalem.
62 A. J. Dietz and C. K. Rider (1993) RAAF Hornet flight test programme to obtain flight loads data. In: *Proc. 5th Australian Aeronautical Conference*, Melbourne, 13–15 Sept.
63 W. L. Price (1995) The Royal New Zealand Air Force Andover C.Mk.1 loads environment spectrum survey (L/ESS). In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft Fatigue Performance* (Edited by J. Grandage and G. Jost), Melbourne.
64 R. Mach (1991) Managing airborne assets through loads monitoring. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.
65 L. J. Huttsell, J. A. Tinapple and R. M. Weyer (1998) *Investigation of Buffet Load Alleviation on a Scaled F-15 Twin Tail Model*. Air Force Research Lab, USA.
66 C. F. Coe and A. M. Cunningham Jr (1987) *Predictions of F-111 TACT Aircraft Buffet Response and Correlations of Fluctuating Pressures Measured on Aluminium and Steel Models of the Aircraft.* COE Engineering, NASA-CR-4069, USA.
67 D. P. Conser and G. L. Keys (1992) *F/A-18 Production ASPJ Vertical Tail Dynamic Fatigue Test FT98 Test Spectra Development*. McDonnell Douglas, MDC 91B0424, St. Louis, USA.
68 J. T. Johnston, R. E. Pinckert and R. A. Melliere (1984) The F-15 flight loads tracking program. In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, Italy, 2–6 Apr 1984, AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
69 D. M. Holford and J. R. Sturgeon (1984) *Operational Loads Measurement—A Philosophy and its Implementation*. RAE-TR-84031, AD-A-149-445, AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
70 J. K. Burnham (1995) Predicted dynamic buffet loads for limited response measurements: T-45A horizontal tail. In: *Proc. 36th AIAA/ASME/ASCE/AHS/ASC, Structures, Structural Dynamics and Materials Conference*, New Orleans, LA, 10–13 Apr., AIAA Paper 95-1338.

71 B. Aktepe, L. Molent, A. D. Graham and D. Conser (1999) Buffet loads and structural redundancy considerations in vertical tail fatigue monitoring programs. In: *Proc. 8th International Aerospace Congress*, Adelaide, 13–15 Sept.
72 P. Chapman, K. Hewitt and L. Molent (1999) *A Critical Review of the F/A-18 Vertical Tail Fatigue Tracking Process*. Defence Science and Technology Organisation, DSTO-TR-0642, Melbourne.
73 P. Amabile and T. Giacobbe (1991) Proposal for the new fatigue management system for the AMX. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.
74 A. G. Denver (1989) Tracking B-1B aircraft with a structural data recorder. In: *Proc. 15th Symposium of the International Committee on Aeronautical Fatigue Symposium: Aeronautical Fatigue in the Electronic Era* (Edited by A. Berkovits), Jerusalem.
75 D. J. Spiekhout (1989) Re-assessing the F-16 damage tolerance and durability life of the RNLAF F-16 aircraft. In: *Proc. 15th Symposium of the International Committee on Aeronautical Fatigue Symposium: Aeronautical Fatigue in the Electronic Era* (Edited by A. Berkovits), Jerusalem.
76 L. Molent, F. Polanco, R. Ogden and Y. G. Ooi (1995) *Development of Parametric Strain Equations for Fatigue Sensors on the RAAF F/A-18*. Defence Science and Technology Organisation, DSTO-TR-140, Melbourne.
77 M. C. Havinga and C. J. Botes (1999) *Health and Usage Monitoring System for the Hawk Aircraft*. Workshop on Helicopter Health and Usage Monitoring Systems, Melbourne, Feb. 1999, Defence Science and Technology Organisation, DSTO-GD-0197, Melbourne.
78 D. J. Spiekhout (1993) *Reduction of Fatigue Load Experience as Part of the Fatigue Management Program for F-16 Aircraft of the RNLAF.* NLR-TP-93423-U, The Netherlands.
79 R. Neunaber (1991) Aircraft tracking for structural fatigue. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.
80 R. Neunaber (1987) Tornado airframe fatigue life monitoring. In: *Proc. 14th Symposium on Aircraft Integrated Monitoring Systems*, Friedrichshasen, 15–17 Sept.
81 L. Molent, B. Aktepe and F. Polanco (1994) *F/A-18 Airframe Data Analysis System Validation*. Defence Science and Technology Organisation, DSTO-TR-54, Melbourne.
82 S. R. Armitage and D. M. Holford (1998) *Future Fatigue Monitoring Systems*. Defence Evaluation and Research Agency, Farnborough, UK.
83 S. Oesch and M. Guillaume (1998) Swiss F/A-18 fatigue tracking system. In: *Proc. 21st Congress of the International Council of Aeronautical Sciences*, Melbourne, ICAS Paper 98-5.1.2.
84 B. Aktepe and L. Molent (1999) Management of airframe fatigue through individual aircraft loads monitoring programs. In: *Proc. 8th International Aerospace Congress*, Adelaide, 13–15 Sept.
85 L. Molent (1998) Proposed specifications for an unified strain and flight parameter based aircraft fatigue usage monitoring system. In: *Proc. 1998 USAF ASIP Conference* (Edited by J. W. Lincoln, G. K. Waggoner, J. M. Manter and C. J. Massey), USA, 1–3 Dec.
86 B. Aktepe, K. Hewitt, R. W. Ogden and L. Molent (1999) *Ground Calibration of RAAF F/A-18 Onboard Fatigue Strain Gauges*. Defence Science and Technology Organisation, DSTO-TR-641, Melbourne.
87 L. Molent and R. Ogden (Eds) (1998) *Review of the RAAF F/A-18 Structural Appraisal of Fatigue Effects (SAFE) Version 112. Volume 1: Detailed Review.* Defence Science and Technology Organisation, DSTO-TR-381/1, Melbourne.
88 A.P. Ward (1984) Tornado—structural usage monitoring system (SUMS). In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, Italy, 2–6 Apr. AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
89 T. H. Skopinsky, W. S. Aikon and W. B. Huston (1954) *Calibration of Strain Gauge Installations in Aircraft Structures for the Measurement of Flight Loads*. NACA-R-1178, USA.
90 L. Molent, R. W. Ogden, and Y. Guan Ooi (1995) *Development of Analytical Techniques for Calibration of F/A-18 Horizontal Stabilator and Wing Fold Strain Gauges*. Defence Science and Technology Organisation, DSTO-TR-0205.
91 A. Walkden (1984) Advanced fatigue monitoring on service aircraft. In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, 2–6 Apr., AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
92 Y. Caron and Y. Richard (1998) *CF-188 Fatigue Life Management Program*. AGARD Paper 4-1.
93 D. M. Holford (1981) *Generation of Loads Equations from Flight Parameters for Use in Fatigue Life Monitoring*. RAE Tech. Rep. 81133, UK.
94 F. Lamarre, S. Major and M. Couture (1994) *IFOSTP Loads Model Documentation*. Bombardier, IFO-0044, Canada.
95 J. D. Yost (1972) Strength and fatigue loads computed with a load–environment model. *J. Aircraft* **9**(3).
96 J. D. Yost (1997) Fatigue and strength loads computed with regression equations empirically derived to convert the load spectra to design values. In: *Proc. 19th Symposium of the Internatoinal Committee on Aeronautical Fatigue: Fatigue in New and Aging Aircraft* (Edited by P. Poole), Edinburgh.
97 A. G. Denyer (1995) B-1B aircraft structural integrity program. In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft Fatigue Performance* (Edited by J. Grandage and G. Jost), Melbourne.
98 R. L. Culp (1984) F-16 force management, yesterday, today and tomorrow. In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, Italy, 2–6 Apr., AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
99 F. Staropoli (1984) Flight parameters recording for structure fatigue life monitoring. In: Proc. 58th Meeting of the AGARD Structures and Materials Panel, Sienna, Italy, 2–6 April, AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.
100 B. Aktepe and R. W. Ogden (1998) *A Comparison of Strain Measurements from the AFDAS and MSDRS Fatigue Monitoring Systems Using RAAF F/A-18 Operational Flight Data*. Defence Science and Technology Organisation, DSTO-TR-640, Melbourne.
101 R. C. Fraser (1979) *A One Pass Method for Counting Range Mean Pair Cycles for Fatigue Analysis*. Aeronautical Research Laboratories, ARL-Struc-Note-454, Melbourne.
102 L. Jarfall (1989) Verification of loads, fatigue performance and damage tolerance of the JAS39 Grippen. In: *Proc. 15th*

Symposium of the International Committee on Aeronautical Fatigue (Edited by A. Berkovits), Jerusalem.

103 J. Y. Mann (1972) *Fatigue Testing—Objectives, Philosophies and Procedures*. Aeronautical Research Laboratories, ARL-Struct-Mat-R-336, Melbourne.

104 H. Neuber (1969) Theory of stress concentration for shear strained prismatic bodies with arbitrary nonlinear stress strain law. *J. Applied Mechanics*, **28,** 554–551.

105 M. A. Miner (1949) Cumulative damage in fatigue. *J. Applied Mechanics, ASME* **12,** 159–164.

106 J. B. de Jonge (1992) Damage severity of monitored fatigue load spectra. In: *Proc. 18th Congress of the International Council of Aeronautical Sciences*, Beijing, ICAS Paper 92-5.4.1, ICAF-Doc-1863.

107 J. Willenborg, R. M. Engle and H. A. Wood (1971) *A Crack Growth Retardation Model Using an Effective Stress Concept*. AFFDL TM-1-1-FBR, USA.

108 B. Palmberg, M. O. Olsson, P. O. Boman and A. F. Blom (1990) Damage tolerance analysis and testing of the fighter aircraft 37 Viggen. In: *Proc. 17th Congress of the International Council of Aeronautical Sciences*, Stockholm, ICAS Paper 90-4.5.2.

109 R. J. Cazes (1995) In-service aircraft fatigue assessment. In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft Fatigue Performance* (Edited by J. Grandage and G. Jost), Melbourne.

110 A.P. Ward (1984) Experiences obtained from service fatigue monitoring exercises. In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, Italy, 2–6 Apr., AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.

111 R. J. Cazes (1993) Assessment of in-service aircraft fatigue monitoring process. In: *Proc. 77th Meeting of the AGARD Structures and Materials Panel*, Bordeaux, France, 29–30 Sept., AGARD-R-797. Advisory Group for Aerospace Research and Development, France.

112 M. G. Pobog-Jaworowski (1995) Structural life management of RNZAF aircraft. In: *Proc. 18th Symposium of the International Committee on Aeronautical Fatigue: Estimation, Enhancement and Control of Aircraft Fatigue Performance* (Edited by J. Grandage and G. Jost), Melbourne.

113 D. J. Spiekhout (1998) New approach for fatigue life monitoring RNLAF F-16 fleet. In: *Proc. 1997 USAF ASIP Conference* (Edited by J. W. Lincoln, G. K. Waggoner, J. Rudd and J. Turner), USA, 2–4 Dec.

114 P. R. Abelkis and J. M. Potter (1997) *Service Fatigue Loads Monitoring, Simulation, and Analysis*. ASTM-STP-671.

115 O. Buxbaum (1972) *A Relationship Between Measured C.G. Vertical Accelerations and the Loads at the T-Tail of a Military Airplane*. AGARD-CP-118. Advisory Group for Aerospace Research and Development, France.

116 V. Ladda and H. J. Meyer (1991) The operational loads monitoring system: OLMS. In: *Proc. 72nd Meeting of the AGARD Structures and Materials Panel*, Bath, 29 Apr–3 May 1991, AGARD-CP-506: Fatigue Management. Advisory Group for Aerospace Research and Development, France.

117 J. Molkenthin (1996) Determination and verification of operational maneuver parameters and time histories. In: *Proc. 83rd Meeting of the AGARD Structures and Materials Panel*, Florence, Italy, 4–5 Sept. 1996, AGARD-R-815: Loads and Requirements for Military Aircraft. Advisory Group for Aerospace Research and Development, France.

118 H. Struck and H. Balke (1984) Evaluation of operational loads to verify structural design. In: *Proc. 58th Meeting of the AGARD Structures and Materials Panel*, Sienna, Italy, 2–6 Apr 1984, AGARD-CP-375: Operational Loads Data. Advisory Group for Aerospace Research and Development, France.

119 H. Struck and C. Perron (1996) Flight loads derived from operational maneuvers. In: *Proc. 83rd Meeting of the AGARD Structures and Materials Panel*, Florence, Italy, 4–5 Sept. 1996, AGARD-R-815: Loads and Requirements for Military Aircraft. Advisory Group for Aerospace Research and Development, France.

120 Z. Wang and Z. W. Chen (1992) The method for developing F-by-F load spectra for fighter aircraft based on manoeuvres. In: *Proc. 18th Congress of the International Council of Aeronautical Sciences*, Beijing, ICAS Paper 92-5.4.2, ICAF-Doc-1863.