DURABILITY ISSUES AND MANAGEMENT OF AGING P-3C AIRCRAFT

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ABSTRACT

This paper presents lessons learnt from the durability analysis of the P-3C aircraft, conducted as part of the on-going international collaborative P-3C service life assessment program (SLAP) effort. The overall SLAP program objective is to reassess the P-3C aircraft life based on a full-scale fatigue test conducted utilizing fleet experience and operational usage data. The paper discusses the traditional life estimation methods for safe-life aircraft structures, and presents its application to the P-3C aircraft. Results and lessons learnt from a series of coupon tests conducted for the purpose of validating and calibrating life estimation methods are also presented with the focus on the do's and don'ts in applying this technique. Total life concepts that include crack growth life are then addressed from the viewpoint of structural maintenance programs that use a top-down approach with a zonal basis. Complementary analysis tools such as crack growth and risk analyses, which are required for ensuring safety for aging fleet aircraft like P-3C, are then discussed. The paper provides details of an emerging fleet management plan from technical standpoint without cost considerations.

1 INTRODUCTION

The United States Navy (USN) and its foreign military sale (FMS) partners initiated a service life assessment program (SLAP) of the P-3C Orion aircraft. This was a comprehensive effort that included finite element modeling of the aircraft structure, flight-tests to collect and validate operational loads, flight and landing usage surveys, development of full-scale fatigue test spectrum, and a full-scale fatigue test of the wing/fuselage structure. Various coupon fatigue and crack growth tests were also conducted as part of the SLAP effort in order assess the complete airframe structure. The objective of the full-scale fatigue test was to substantiate the 15,000-hour design life (one life-time) of the structure with 85th percentile mission profile usage and assess fleet aircraft performance relative to the test. From a fleet safety standpoint, this assessment provides answers to questions such as whether the fleet aircraft is accruing fatigue damage at the design rate, or is the fleet aircraft degrading due to environmental effects at expected rate, or is the fleet aircraft showing unanticipated anomalies.

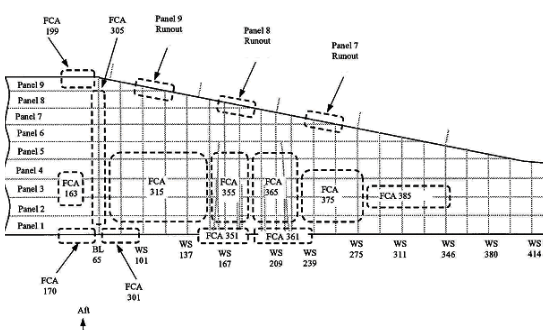
2 FULL-SCALE FATIGUE TEST (FSFT)

The wing/fuselage full-scale test of the P-3C Orion was conducted during Nov 2001-Nov 2002. The full-scale fatigue load test spectrum was developed from the fleet operational usage data collected over during 1991 through 1997, and the environmental criteria from appropriate MIL Specs such as MIL-A-8861 for gust loads and MIL-A-8866 for taxi loads. The operational usage of P-3C aircraft mainly falls under the following missions: anti-submarine warfare (ASW), patrol/search and rescue (SAR), training, and test flights. Individual mission definitions such as mission flight segments and respective segment duration, altitude, speed, and weights were considered in the development of load spectra. For reference, both the mean (50th percentile) and 85th percentile mission spectra were developed. Details of full-scale test and spectrum development are given in References [1] and [2], respectively. The 85th percentile spectrum was applied to the test article in keeping with the USN philosophy of applying severe spectrum. The spectrum also included sets of marker load cycles any premature cracks. The wing/fuselage test article experienced 38,000 hours of 85th percentile spectrum. During the course of the test, enhanced NDI inspections were carried out at fatigue critical areas identified by analysis and previous service findings at certain intervals besides the regularly scheduled 250-hour inspections.

The significant findings of the full-scale fatigue test are indicated in the figure below. The early detection of cracking at domenut hole and spar cap at 11,000 hours near the nacelle region (Fatigue Critical Area, FCA 351) was consistent with the service finding data collected through an airframe bulletin.

SFH	Significant Finding
11,000	Cracks in OWP domenut holes and spar cap, OW lower surface panel cracking at spar cap connection
11,900	Cracks in OW spar web
19,800	Cracks in OW spar web
21,600	OW panel #3 Spanwise Splice crack at MLG rib OW web crack at WS72
25,000	Crack in OW cap in numerous locationsOW Corner Fittings Crack
30,000	Cracks in LHS Web at WS 218
32,500	CW cap and CW spanwise splice
38,000	End of Fatigue Test
Residual Strength Testing	CW weep hole &Empennage failure

The wing fatigue critical areas (FCA) identified by the full-scale fatigue test and analysis are shown in figures below for the lower wing. These FCA's were further grouped under time critical requirement (TCR) zones for enhanced inspection and structural enhancement are also shown below.



TCR1	VS	FCA
Inboard side of inboard nacelle – Dome Nuts	WS 160	351-DN
Inboard side of inboard nacelle – Web	WS 162	351-W
Inboard side of inboard nacelle – spanwise splice to cap	WS 156	351-SS
Outboard side of inboard nacelle – Web	WS 218	361-W
Outboard side of inboard nacelle – dome nuts	WS 217	361-DN
Outboard side of inboard nacelle – spanwise splice to cap	WS 220	361-SS
Outboard side of inboard nacelle – Cap	WS 219	361-C
TCR2		
Inboard side of inboard nacelle – Cap	WS 134	351-C
Outboard side of inboard nacelle – Lower crown spanwise splice	WS 207	365-SK
Center Wing & Outer Wing – Corner fittings	BL 65	301-FT
Outer wing – Web	WS 72	301-W
Center wing - Weep Holes	BL 49	163-WH
TCR3		
Center Wing – spanwise splice to cap	BL 48-65	170-SS/C

3 COUPON TESTS

Coupon tests were conducted to correlate full-scale and coupon test crack initiation lives (at a few significant FCA's) with analysis predictions. These tests helped reveal some of the limitations of analytical models and required corrections, and provided an insight into the fatigue notch factors and mean stress correction methods employed in the local strain logic of fatigue life computations. Although crack initiation was used as the failure criterion of the major wing/fuselage aircraft structure, crack growth tests and analysis were also conducted as part of the overall effort to determine crack growth lives in certain critical locations, help establish inspection intervals, and identify repairs with local structure enhancements. The lessons learnt from both the crack initiation and crack growth tests are presented subsequently.

4 SAFE-LIFE APPROACH TO CALCULATE FLEET DAMAGE STATUS

The traditional USN approach to track fleet damage status is through a 'test and track' philosophy. In this approach, a structural life measurement standard or scale is established from the test-demonstrated life for the applied test loading. Test demonstrated life is usually defined as the time to develop a crack of 0.01 inches. Fleet aircraft are then monitored and measured against this test standard to assess relative fatigue life expenditures (FLEs) using a scatter factor of 2 to account for material fatigue property variability. The fatigue damage accrued on each aircraft is calculated using a sequence accountable local strain approach for the flight-by-flight spectrum (derived from on-board flight data recorders). In general, the test measured standard results in a fatigue notch factor value (or a reference notch stress value) at each FCA. An Individual Aircraft Tracking (IAT) program was then developed using this approach for P-3C aircraft to calculate FLE values at selected critical locations. The flight-by-flight parameter time histories (PTH) were constructed for the aircraft using actual aircraft usage data obtained either through single-channel or multi-channel flight data recorders. Stress to load ratios derived for numerous points in the sky and ground conditions enabled the generation stress time histories (STH) at each FCA from the respective PTH's.

5 IMPACT OF SAFE-LIFE APPROACH

Preliminary set of FLE values for the fleet P-3C aircraft highlighted the problems and concerns of managing aging fleet aircraft. Although the USN tradition is to employ a safe life approach to track and monitor fleet aircraft, a damage tolerance on-condition management of fleet aircraft was inevitable to meet inventory goals and maintain fleet safety. This initiated a fleet management plan described subsequently. In addition, the need for crack growth analysis module in the IAT became more important, since safety by inspections could only be assured by crack growth analysis. This module in the IAT also enables the operators to coordinate inspection activities at appropriate intervals and help in decision-making based on estimated crack sizes. The crack growth module in the IAT has three models: the cumulative, projection and sensitivity models. The purpose of the cumulative model is to provide an indicator of the crack size in the fleet aircraft from the assumed initial crack size. This helps in determining whether immediate inspections are necessary for fleet aircraft. The projection model is used to determine crack lengths and safe inspection intervals for various assumed usage. The sensitivity model helps the user to calculate safe inspection intervals to account for rogue flaws growing in adjacent bays that experience similar stresses, or determine crack growth times for various scenarios.

6 FLEET MANAGEMENT PLAN

After the discovery of cracks during the full-scale fatigue test a set of safety actions were immediately taken to safeguard the fleet. As a first step, fleet inspections and some flight restrictions were imposed until the time teardown inspections, analysis, and fleet management plan were all complete.

Once the preliminary set of FLE values of the fleet aircraft became available, an initial structurally significant inspection (SSI) was initiated to baseline the fleet aircraft from a damage status standpoint. The SSI plan included enhanced NDI inspections of the FCA's in the three TCR zones. The compliance time for the initial SSI plan was defined per previous inspections and TCR thresholds as established by the preliminary set of FLEs at each FCA. The initial compliance time varied from one month for a certain group of aircraft to 18 months for another group. A recurring SSI plan has also been formulated to occur every 27 months and refinements to this plan will be completed after results from teardown and initial SSI data are available. The SSI plan by itself does not guarantee detection of wide spread fatigue damage. This is due to the fact that material degradation over time and discovery of other cracking areas are very likely from on-going teardown and routine fleet inspections. To safeguard the fleet from these likely scenarios, an enhanced structurally significant inspections (ESSI) and component replacements are planned. Also, in some instances, a supplemental kit (SSI-K) is planned to preemptively replace and enhance all known fatigue critical areas in lieu of SSI and ESSI to provide additional flight hours and reduce inspection requirements.

7 RISK ASSESSMENT

To a great extent, the life of P-3C aircraft is determined by the capability, maintenance cost and economic considerations required for the fleet to continue its operational requirements. With the requirement to keep aging aircraft in service, life beyond crack initiation and total life including crack growth has to be considered with the associated risks. For safe-life structures such as P-3C, crack initiation life usually determined the retirement life in line with traditional USN philosophy. Crack size at initiation is subjective, and it is generally assumed that crack sizes at retirement (unfactored safe lives) within the fleet is a normal distribution with a mean crack size of 0.01 inches. For safe-life structures, the risk or probability of failure is typically not calculated prior to crack initiation life. However, to implement safety by inspections or total life concept, a thorough knowledge of crack growth life is required. Crack growth life, in turn depends on the spectrum, material, and material geometry. In addition, extending life beyond crack initiation for safe-life structures requires complete knowledge of damage state (crack sizes and density) of the structure at the end of test or during service. With known damage state of fleet aircraft and crack growth characteristics, lives can be extended beyond crack initiation up to a time within an acceptable level of risk only when inspections are possible. Risk as applied to aircraft structural integrity involves calculating: (a) single flight probability of failure (P_f), i.e., instantaneous probability of a failure event within a single flight, and (b) cumulative level of probability (P_c), i.e., failure rate per aircraft per safe life. In general, risk analysis will provide answers to the question 'what is the probability of failure if an aircraft at a given fatigue life expended value (FLE) flies for certain flight hours without inspection?' The answer is simple if the probability density function of crack sizes at various FLEs is known. When such functions or data are unknown, engineering assumptions have to be made. The shortcomings with risk assessment are not with the mathematical techniques but rather with the inability to accurately characterize the variables. Nonetheless, it is worthwhile to note that the Navy's method for designing, testing and tracking fixed wing aircraft has proven to be capable of preventing in-service, design related, catastrophic failures.

8 LESSONS LEARNT

On FSFT Spectra: Application of the 85th percentile spectrum in the FSFT is consistent with the USN fatigue testing philosophy, whereby the cracks are encouraged to nucleate as quickly as possible using a "severe" spectrum. For this spectrum, the gross weights are higher than average (typically 3 to 7%), there are 47% more missions of shorter duration, 104% more landings, and 81% more pressurization cycles. The spectrum includes "once in a life time" loads, and these loads have a significant effect on the crack initiation and crack growth behavior. The USN employs a scatter factor of 2 on the resulting test life to determine the safe/service life. On the other hand, the USN 50th Percentile spectrum reflects an "average" spectrum. Here, the large "once in a lifetime" loads are usually eliminated, but loads that occur once every 1,000 hours are preserved. This spectrum contains fewer missions; the missions are typically of longer duration; and there are significantly less landings. The importance and applicability of these two types of spectra in ascertaining crack initiation and crack growth characteristics at fatigue critical areas became evident during coupon tests and also in accounting for missing usage data in the fleet aircraft. The crack growth lives were shorter for 50^{th} percentile spectra when compared to the 85^{th} percentile spectra at certain FCA's.

On Marker Cycles: Marker cycles were introduced in the FSFT spectrum per graphic below to ensure traceability of cracks with the applied load spectrum. The fractographic studies always identified marker bands introduced at later in the test life starting at either 10,000, 15000 hours in various fractographs. However, the marker cycles introduced at 3,000 hours could not be identified even after thorough investigations on many fracture surfaces including forward spar web lower front spar attachment. The fracture surface on lower spar web is also shown below to indicate the beach marks at 15,000 hours. The reasons why marker cycle bands introduced early in life could not be identified was attributed to too much smearing in the early phase of crack growth. This indicated that regardless of the block size, marker bands are difficult to detect when the crack lengths are short. Even if the block size of the spectrum is short, say 500 or 1,000-hour spectrum, it may be beneficial to introduce marker cycles after several block applications instead of introducing once in every block.

On Fatigue Notch Factors and Crack Initiation Life Definition: As part of the validating analysis predictions on crack initiation life using local strain approach, we found the following:

The conventional Fatigue notch factor (K_f) to geometrical stress concentration factors (K_t) relationships cannot be used for sharp notches as they are established for mild notch geometries. Using fatigue notch factors calculated in the conventional way, we found that analysis predictions are non-conservative for sharp notch geometries used in the coupon tests. That is, cracks initiate sooner at sharp notches than predicted by crack initiation program based on local-strain logic. In these instances using K_f values close to K_t values improved the crack initiation life predictions. The modified Morrow method for mean stress correction was found to be better suited for tension dominated loading spectrum (FCA 301) than the case where significant compressive loadings (FCA 361) exist. However, the relative lives from analysis correlate well with the test relative lives using the modified Morrow method. Smith-Watson-Topper method of calculating lives for non-zero mean stresses is a better predictor for situations with significant compressive loading and positive mean stresses (FCA 351 and 361). The relative lives correlates well with the test relative lives for the SWT case also. Because of improved life prediction capability with significant compressive loading, the SWT method seems to be better for the studied P-3 spectra in calculating life values for non-zero mean stress cycles.

On Crack Growth Models and Load Spectrum: Crack growth lives, as expected, depend on the sequence of loads and thus crack growth pattern is associated with the position of overload in the spectrum. There is no guarantee that model parameters, such as α's (constraint factors) and rates in strip-yield models, determined for one type of spectrum sequence will hold good on a completely different spectrum. Coupon tests have to be conducted and new parameters have to be established if there is a major spectrum content change in terms of sequence and stress severities. It is particularly important to reestablish model parameters if the load dominance changes from tension to compression. We found that most retardation model options available in crack growth programs made conservative predictions of crack growth lives for the long history loading test cases we studied in P-3C aircraft for several FCA's. In general, we found the strip-yield model (FASTRAN) to be a good predictor for tension-dominated spectrum. With modifications to the constraint factors and rates, strip-yield models provide good correlation to load histories with widely different spectrum contents such as tension dominated and tension-compression histories. We observed from our results that even when strip-yield models correlate well with the coupon tests, they provide conservative predictions at long crack lengths.

On Taxi and Gust Loads: For P-3C Orion type of aircraft, most of the damage contribution comes from ground-air-ground cycles in each flight. Thus, it becomes necessary to accurately capture the flight events as well as ground events. The SLAP experience has demonstrated the importance of taxi and gust loads in the spectrum. For some critical areas around the nacelle region (FCA's 351 and 361), the taxi loads for certain conditions produce peak compressive stresses that are comparable in magnitude to that of peak tensile flight loads. The gust loads were derived using MIL-8861 Specs as reference. Most of the gust loads occur at levels below 2g, however, there are infrequent storm gust incidences between 2-3g that has to be captured for accurate assessment, particularly for fatigue crack growth analysis.

On Flight Data Recorders: P-3C aircraft were originally equipped with single-channel flight data recorders. Only in the mid-1990's USN started to replace these recorders with more sophisticated multi-channel flight data recorders The original single-channel recorders were called Counting Accelerometer Group (CAG) recorders since they recorded vertical load factor exceedances at four preset g levels (1.5, 2.0,2.5 and 3.0g's). It was concluded after a study that these CAG recorders were not capturing gust-induced loads because of the high frequency of gust loading. The multi-channel recorders are called Structural Data Recording Set (SDRS), and these capture aircraft parameters such as airspeed, altitude, and weight in addition to the vertical load factors. The recorders capture data at 64Hz, and thus are able to capture gust induced load factors as well. Comparison of the load factor exceedances captured by CAG and SDRS indicated a significant difference, and proved multi-channel recorder was more efficient and accurate than the CAG recorder. In building the time history of events for each flight (flight-by-flight stress spectrum construction) using CAG data, use was made of the pilot entered flight record data for each flight. Since actual time history of the flight is unknown for CAG data aircraft, some assumptions were inevitable. In a multi-channel recorder system, there is less number of assumptions provided the data quality and data recovery rate is good. The importance of data recovery becomes more prominent when many fleet aircraft are reaching their fatigue life expenditure limits, and have been penalized for poor data recovery by appending higher damage values for the bad data.

REFERENCES

[1] 'The P-3C Service Life Assessment Program - Full Scale Fatigue Test', Jorge Lamas and Michael Edwards, Presented at the International Committee On Aeronautical Fatigue, May 2003, Lucerne, Switzerland.
[2] 'Full-Scale Fatigue Test Repeated Loads Criteria Report', Lockheed Martin Corporation Report, LG99ER0085, November 2002.