LOAD SPECTRUM EVALUATION FOR FAB T-25 DTA PROGRAM

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Abstract *The FAB T-25 "Universal" is the basic training airplane in operation at AFA - The Brazilian Air Force Academy. The T-25 was originally designed under the "safe-life" philosophy, which establishes a finite fatigue life after which the airplane has to be retired from operation. As the T-25 fleet approaches its service life limit, the Brazilian Air Force has started a program to extend the fatigue life of the basic trainer, through an extensive Damage Tolerance Analysis (DTA) program. The DTA design philosophy is aimed at ensuring structural integrity and improving the operational safety of civil and military airplanes. In addition, a DTA program can also be used as a tool for extending the fatigue life of operating fleets previously designed under the safe life approach. This is achieved by defining appropriate inspection intervals, which are determined through crack propagation calculations. One of the most important phases of a DTA program is the evaluation of the actual load spectrum to which the aircraft is submitted during its long-lasting operation. This article presents the procedures and results of the flight load evaluation phase of the T-25 DTA program. Four airplanes were instrumented and flight data was recorded over a period of one year. The installed sensors provided information on vertical and lateral load factors, speed and altitude. The collected data was treated to produce a baseline load sequence, which was used to calculate the sequence of stresses acting on the various fatigue critical locations (FCL) of the aircraft structure. The stress histories are then used as input for cycle-by-cycle crack growth analysis for each FCL. Some results of crack growth calculations using the T-25 spectrum are also discussed..*

Keywords: *damage tolerance analysis, fatigue life extension, crack propagation*

1. Introduction

Until the 1970's, fatigue life design of commercial and military airplanes was based on the so-called "Safe Life" approach, which consists in defining the total time for the safe operation of an airplane using the results from fatigue tests of full-scale prototypes and components, submitted to the expected service loads. Inspection intervals are defined within the safe life, using considerably large safety factors, to account for unexpected early development of structural damage. After the consumption of the pre-determined safe life, the airplane is retired from operation, even when its structure presents no evidence of detectable damage.

Despite the technological developments of experimental procedures used in a typical fatigue test, the safe life approach was found to be insufficient to ensure structural integrity of an airplane. Catastrophic accidents continued to occur, despite the widespread adoption of the Safe Life philosophy in aircraft structural design and maintenance. In 1969, an accident of a USAF F-111 fighter, with only 100 hours of flight, caused the loss of its wing due to a crack-like defect, which had not been detected during the prescribed inspections (Schütz, 1996). The F-111 accident gave a new impulse for the investigations aimed at understanding and solving the aircraft fatigue problem. As a result, a novel structural design philosophy was introduced to the aeronautical community, the Damage Tolerance Requirements (USAF, 1974). This new fatigue design philosophy, based on Fracture Mechanics crack propagation concepts, assumes that any critical point of the structure, also called FCL (Fatigue Critical Location), has to sustain a crack-like damage between two prescribed non-destructive inspections (NDI) without failure.

Besides the improvements in flight safety, the DTA approach presents an additional advantage: the airplane can be safely operated for as long as it is economically viable. Since after the prescribed inspections a structural component proves to be upright, no pre-determined 'retirement age' due to fatigue is defined, so the DTA can also be applied as a tool to extend the operational life of aging fleets. The Brazilian Air Force (FAB) has adopted this approach to extend the operational life of several airplanes in its fleet, such as the F-5 "Tiger" fighter (Wieland et al., 1996) and the AT-25 "Xavante" advanced trainer (Garcia et al., 2001).

This paper presents one of the major phases in the implementation of a DTA program for the T-25 "Universal" basic trainer, which was originally designed using the Safe Life concept. The technical challenges of such a program are described, and the main steps of the adopted solution are presented and discussed. This work was requested and sponsored by the Aeronautical Materiel Directorate (DIRMAB), of the Brazilian Air Force.

2. Overview of the T-25 DTA program

The T-25 (Figure 1) is the basic training airplane made by the Brazilian Aviation Company NEIVA, and used by AFA - The Brazilian Air Force Academy. This airplane was originally designed under the safe-life concept. As the T-25 fleet approaches its service life limit, Brazilian Air Force is questioning whether it can be kept flying safely. The answer is being given through an extensive Damage Tolerance Analysis.

Figure 1. T-25 training airplane.

This airplane came to service in the beginning of the 70's and, to date, no catastrophic structural accident has been reported during its service life. Additionally, the safe-life full scale test was stopped at 7,000 effective flight hours without any reported major damage.

The main goal of the T-25 DTA program is to extend the aircraft service life in 5,000 flight hours, without any degradation of the current levels of structural integrity and reliability. For the complete analysis, five major tasks are devised and implemented. The division proposed follows a general pattern and does not necessarily represent a unique chronological sequence, since some of these tasks are independent from the others. The proposed tasks are:

- Data Review
- Flight Data Recording and Evaluation
- Flight Test Campaign
- Coupon Tests and Model Calibration
- Structural and Fracture Mechanics Analysis

Each one of these main tasks is briefly discussed below.

Data Review - All the original NEIVA T-25 structural reports have been analyzed, providing a solid background for the succeeding tasks. Also, some important information was obtained from the fatigue life full scale test reports. The latter, along with maintenance records, provided the knowledge of the most critical areas to be analyzed, being the key for the fatigue critical location mapping.

Flight Data Recording and Evaluation - Four airplanes from the Brazilian Air Force Academy were equipped with the flight load data recorder - FLDR (Figure 2). For a period of one year, the fatigue flight data was collected by the flight crew personnel and sent to the BAF Research Center for analysis. Each file had the following information: flight time, vertical g (n_z), lateral g (n_y), altitude and speed. Besides the electronic file, for each flight, the crew had to fill out a form with take-off and landing airplane information, such as gross weight, fuel weight, pilot weight(s), aircraft configuration, etc. All this information was put together by the engineers at the Research Center.

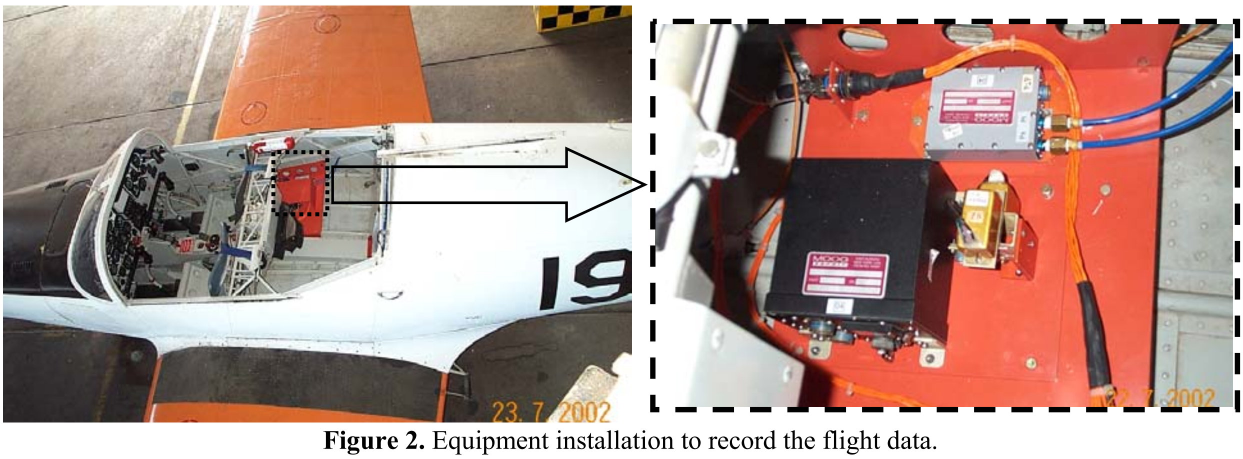

Figure 2. Equipment installation to record the flight data.

Flight Test Campaign - The use of fracture mechanics as a structural tool requires the knowledge of the precise level of stress acting in each FCL as a function of the maneuver loads. This correlation is known as the stress-to-load ratio. Some of the equations can be easily determined by structural analysis and equilibrium. However, for some complex FCL's, local measurements are necessary to backup the calculations. Strain gages were installed in sixteen locations of a BAF Flight Test Division T-25 (Figure 3). The final equations were then adjusted to match the fight test results.

Figure 3. Strain gage installed in a FCL.

Figure 4. Coupon test in the MTS 810 device.

Coupon Tests and Model Calibration - Two FCL's, which were considered to be the most critical, were tested in laboratory. A proper setup was assembled and the specimens were manufactured according to the original design of the FCL structure. The coupon tests were useful to confirm the endurance of the material and also to calibrate the crack growth equation with model interaction (retardation). The tests were performed in a MTS 810 loading device capable of reading cycle-by-cycle spectrum file. The crack growth was observed and measured through a scale travel microscope.
Structural and Fracture Mechanics Analysis - Once all the above parameters are known, the crack growth analyses are performed, and the proper inspection intervals were determined for each FCL. The final result must include a compatibility analysis with the in course maintenance procedures.

A total of 25 fatigue critical locations were considered (Carneiro et al., 2004): 11 in the wing, 10 in the fuselage, 3 in the horizontal stabilizer and 1 in the vertical stabilizer. Over 700 flight hours were collected from the Academy planes, covering all the missions and typical nuances of dissimilar learning pilots.

3. Methodology for Flight Data Collection and Reduction

The importance of flight data recording and evaluation relies on the aircraft's actual employment. To understand this importance, we should go back to the full-scale fatigue test of the T-25, which defined all the Safe Life parameters related to the fatigue life of the aircraft.

A full-scale fatigue testing is normally conducted using a pattern block-sequence load spectrum defined in aircraft certification requirements or, depending on the manufacturer experience, a more close-to-reality block-sequence load spectrum that should represent the expected service loads to which an aircraft is subjected during its real operational life. In fact, the results obtained from full-scale fatigue tests are extremely dependent on the definition of the block sequence load spectrum. A variation in load sequence, applied to any structural component subjected to fatigue loads, may influence significantly its final life due to crack growth retardation effects. If the real sequence load spectrum can be measured during the aircraft typical one-year period of employment, and used to account for retardation effects of crack growth, the damage tolerance analysis results will be much more realistic and reliable than those defined using theoretical block-sequence load spectrum.

The flight data used in the DTA calculations consists of the normal (n_z) and lateral (n_y) accelerations, also called "g" (gravity) loads, altitude and velocity of the aircraft. The n_z and n_y are accelerations applied to the center of gravity of the aircraft. Since this information is not available in this aircraft system, the solution adopted for the T-25 was installing a flight load data recording system model 280E002 from MOOG ESPRIT Inc. This recording system has a micro-processor technology which is able to account for positive and negative accelerations with an accuracy of +/- 0.01g (normal and lateral directions) and also to record information on altitude and velocity when a "trigged" event happens. The FLDR (Flight Load Data Recorder), had n_z and n_y channels trigged so that when, for instance, a n_y event is considered significant, all information related to the other channels was also recorded.

Flight data was collected over one year, taking into account the most severe T-25 operator load spectrum, at AFA - The Air Force Academy. To perform this work, four T-25 were equipped with a flight load recording system in order to obtain at least 500 hours of the aircraft real operational employment. The information recorded at the FLDR was downloaded monthly and sent to analysis at CTA/IAE. The flight data collected is sent in a raw format and had to be converted to engineering units and then analyzed to filter meaningless information. These tasks can be accomplished using dedicated computer programs such as DATAMAN (MOOG ESPRIT, 1997) and EPAD (Santos et al., 2004). Once all the data is converted, it has to be re-evaluated to account for the effective fatigue cycles. The program ProReDa (Mello Jr. et al., 1999a) performs a peak-and-valley counting and reduces the data for n_z and n_y fatigue cycle events, completing the flight data evaluation.

4. Load Spectrum Results

It is important to identify each recorded flight, segment each flight into appropriate phases, and to perform overall validation of each recorded data channel. The validation is required to identify errors introduced by the recording system and errors introduced by wrong data on the supplementary data forms or in the digitalizing process. The recorded data can be graphically displayed as a time history plot using the pre-analysis software. These general features of the edit/pre-analysis program are used to mission and phase mark as well as to resolve any uncertainties of the recorded flight data. These uncertainties may include unreasonable changes in altitude, airspeed, n_z or n_y, indicating evidence of an electrical spike. Unusual n_y reading immediately after takeoff or during pattern activity may indicate extraneous structural vibrations due to the main landing gear operation.

Figure 5 shows a typical example of a T-25 flight. The top plot is altitude profile expressed in meters above the sea level. The bottom plot shows the n_z peaks and valleys expressed in g's. It is also possible to visualize the indicated velocity and the n_y values, to provide additional information about the maneuvering activity during the flight. In most cases, the mission entered on the supplementary data form is accepted as the proper mission identification. Sometimes, the mission identification supplied by the pilot/ground crew may not match the profile of the accepted mission categories. In this case, engineering judgment is necessary and the mission identification has to be changed.

Separation of each flight into appropriate mission phases is required for the calculation of average flight parameters (gross weight, velocity, altitude) for each phase of each mission type. These phases are climb, cruise primary, descent and pattern. With the exception of the primary phase, any number of any phases may be identified for each flight. Only one primary phase is marked for any given flight. Each flight must begin with a climb phase and end with a descent phase. Some missions include pattern activity as the final phase of the flight.

Following successful verification, all the valid recorded data are processed through a series of programs. One of the most important outputs from flight recorded data is the determination of n_z occurrences and the representative flight condition at which they occur. From this information, the external loads and internal FCL stresses for each n_z can be calculated. Random sequencing of theses stresses results in stress sequence files for each fatigue critical location is performed for use in damage tolerance analyses.

In the period of July, 2002 to July, 2003, it was recorded a total of 795 valid flights. This represents 745 flight hours. A total of 9 different T-25 missions were identified on the supplementary data forms for Academy usage. Each flight is classified in one of the nine categories shown in Table 1.

Table 1. Classification of the missions (mission mix).

Group	Mission	Time (h)	Mix (%)
1	Transition stage - two pilots	1,087	20,3
2	First stage - single pilot	0,845	0,5
3	Advanced stage – single pilot – all mission phases	0,957	7,6
4	Acrobatic maneuver – two pilots	0,881	10,7
5	Acrobatic maneuver – single pilot	0,894	4
6	Formation – two pilots	0,923	30
7	Formation – single pilot	0,744	3,6
8	Navigation and instrument	1,170	7,2
9	Others	0,774	16,1

In Table 1, "Time" indicates the average duration, in hours, of each mission type, and "Mix" represents the relative contribution of each mission type to the aircraft total usage. The classification stated in Table 1 is useful to increase the quality of the information about the T-25 aircraft usage. A future change in the flight training profile will easily be accounted for and its influence on fatigue life and aircraft maintenance may be obtained.

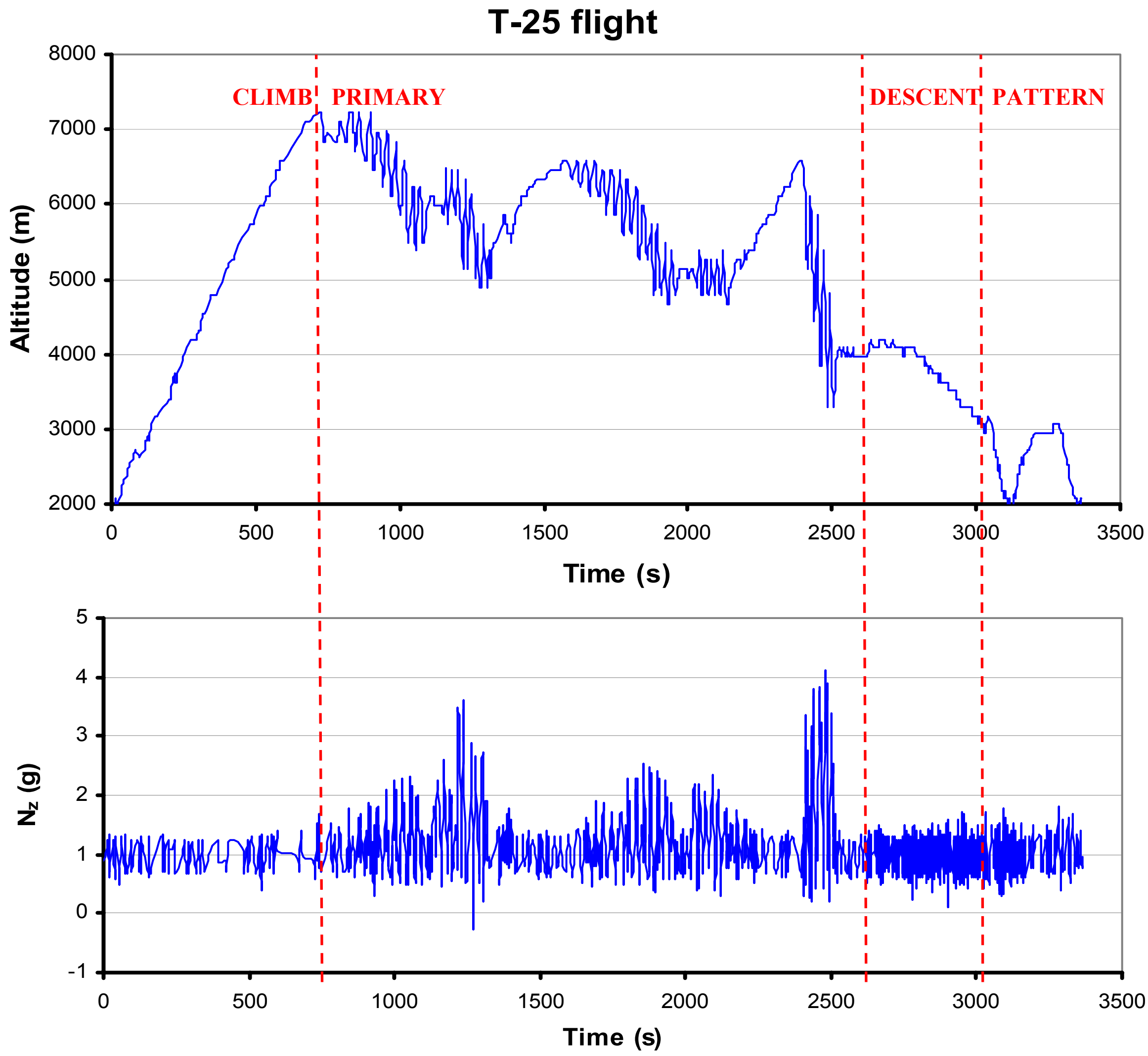

Figure 5. Time history plot of a typical flight.

Figure 6 gives a composite n_y cumulative occurrence spectra for valid T-25 data for each mission per 1,000 mission hours.

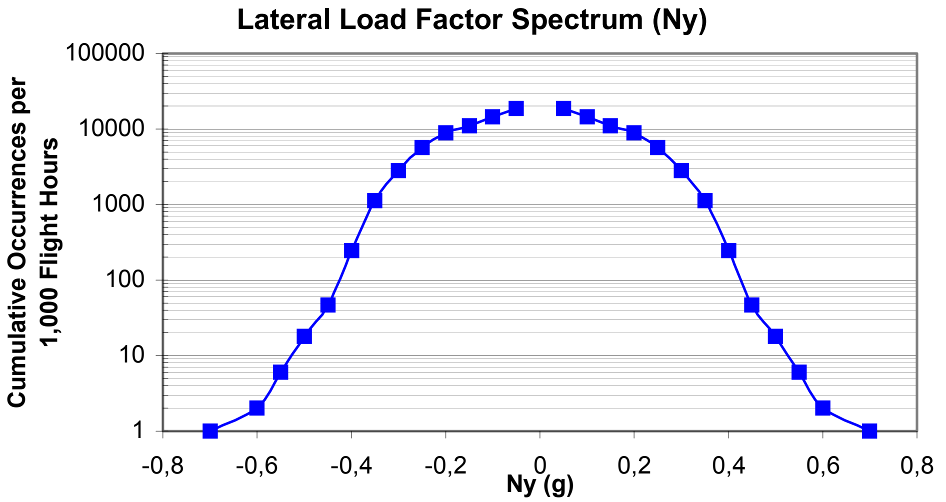

Figure 6. Cumulative n_y (g) occurrences per 1000 flight hours.

Figure 7 gives composite n_z spectra for valid T-25 data for each mission per 1,000 mission hours.

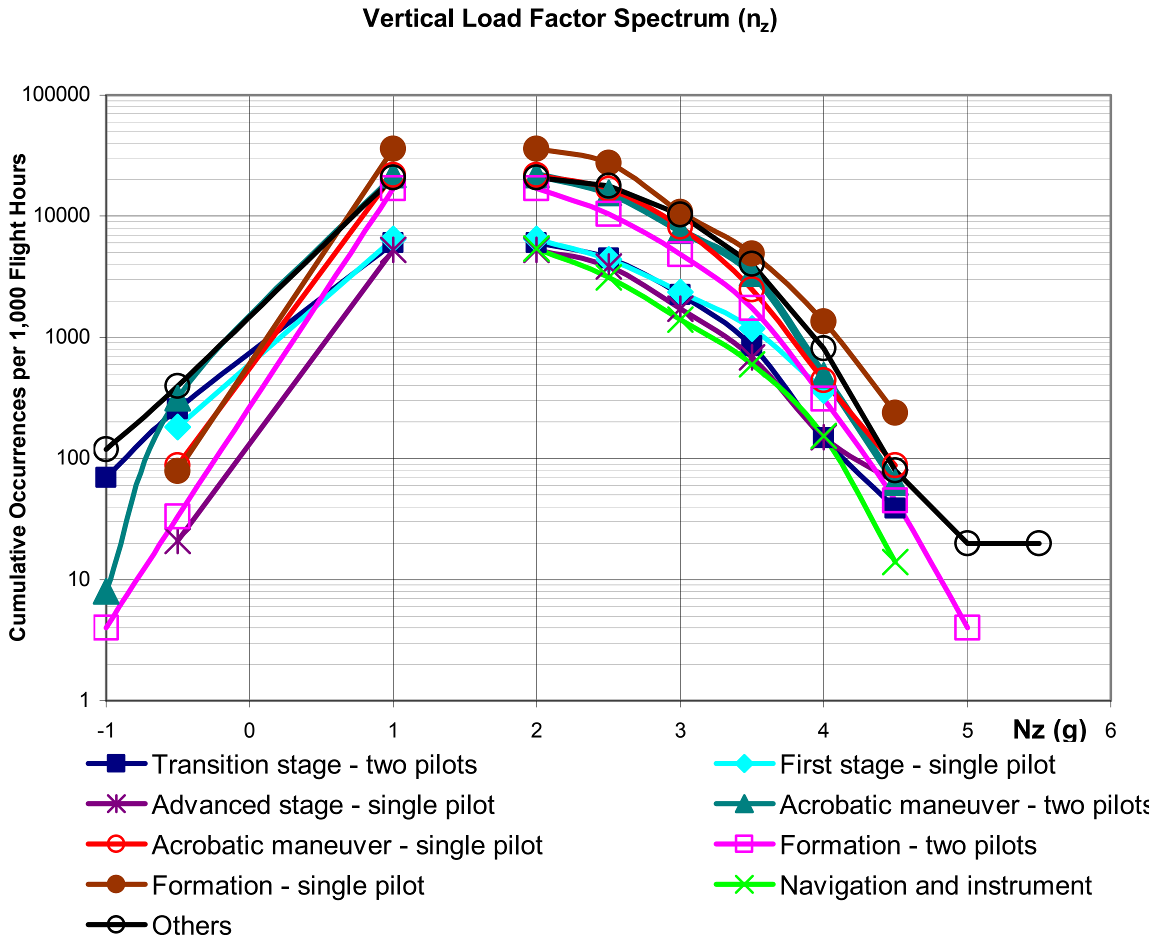

Figure 7. Cumulative n_z (g) occurrences per 1000 flight hours.

5. Preliminary Results of the T-25 DTA Analysis

Despite being a complex, time-consuming task, the flight load spectrum determination is just one step of the DTA process. As already described, a flight test campaign had to be performed for calibration of the stress-to-load ratio equations for the fatigue critical locations. Coupon tests were cycled in laboratory to guarantee the endurance of the material and also to calibrate the crack growth equation with interaction model (retardation). After completion of all these tasks, crack growth simulations were performed for each FCL considering all aspects that can affect the life of the component, such as, proper NDI technique, accessibility of the FCL, and continuing damage. All crack growth simulations were performed using the dedicated software CRACK 2000 (Mello Jr, 1998). This program allows cycle-by-cycle stress spectrum input files, and retardation effects can also be included. The crack growth curves are the basis for the inspection interval determination.

Figure 8 shows an example of a crack growth curve for one fatigue critical location, named W4. This FCL is located in the lower main spar cap (forward) nearby the fuselage-wing attachment. Figure 9 shows a representation of this fatigue critical location.

The chart on Figure 8 shows two curves. The first one (on the left) is the primary crack growth curve. The second one (on the right) is the secondary crack growth. The DTA parameters for this FCL are then defined as follow: The economic life is the total time for a primary crack to grow from an initial flaw to the complete failure of the part, including the growth of the secondary crack. In this case, the economic life of the component was found to exceed 30,000 flight hours. The first inspection is defined as the half time for the primary crack to grow from an as-new detectable crack until it becomes critical (break of the right ligament). For this FCL the initial inspection was found to be 6,400 flight hours. Because the cap is in a sandwich type assembling, the field inspection is considered to be able to detect only if the ligament is broken or not. For this reason, the recurrent inspections are defined by the second crack growth curve. That way, every time the cap is inspected and the ligament is found intact, one can guarantee that at least the structure can sustain the time necessary for the secondary crack to become critical. As defined by the Military standards, the recurring inspection interval is defined as 1,150 flight hours for this FCL. In this particular case, considering the capability of the maintenance personnel, the type of the filed inspection considered was dye penetrant technique.

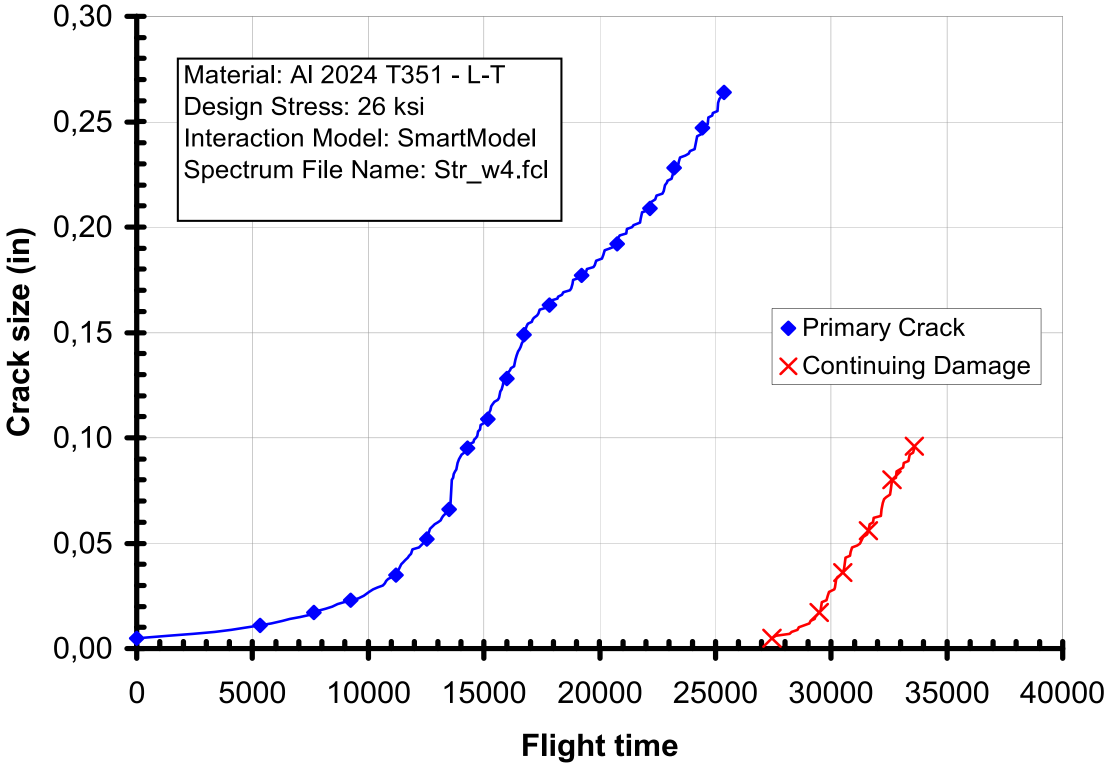

Figure 8. CRACK 2000 analysis output for the W4 FCL.

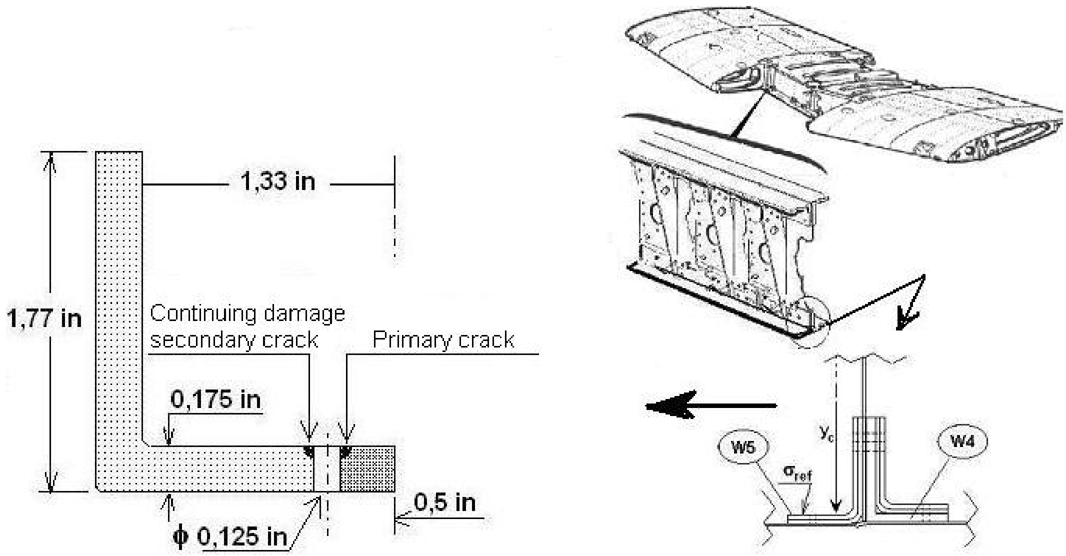

Figure 9. T-25 fatigue critical location W4.

The same analysis is conducted for all fatigue critical locations and then the results are put together for a final analysis and the compatibility of the DTA defined inspection intervals and maintenance procedures.

6. Concluding Remarks

The flight load spectrum evaluation task, which is part of the FAB T-25 DTA program, was presented. The program has the objective of extending the operational service life of the airplane in at least 5000 hours.

Flight data was collected over one-year period, at The Brazilian Air Force Academy, and further analyzed at the Aerospace Technical Center. The results indicate that the mission mix can be divided in 9 types of representative missions. In the future, in case of change of the usage profile, the DTA results can be updated, simply by changing the mission mix in the stress spectrum development.

The resulting fatigue stress spectra were used in the correspondent FCL and a crack growth curve was determined based on all the developed parameters and techniques. The crack growth curves were used to define the three major parameter of the DTA study: The economic life, the initial inspection and the recurring inspection of each component.

The T-25 DTA is now in the interactive phase with the Maintenance Depot and End User. This is considered a key step for the final result, since all the changes and recommendation must be maintainable and operational. Among the suggested changes in maintenance procedure are the new inspections techniques and new access doors for some critical components. Strap reinforcement at some of the critical location may also be proposed to be accomplished during a major Depot overhaul.

7. Acknowledgements

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