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F-5M DTA Program

***Abstract**: The Brazilian F-5 was submitted to avionics and weapons upgrade. This "new" aircraft has proven to be heavier and more capable. A comprehensive damage tolerance analysis is being performed to evaluate how the new mission profiles and weight distribution may affect the airframe structural integrity. Operational data were collected at the Brazilian Air Force Bases where the fighter is flown. Software was developed in order to acquire, filter and analyze flight data. This data was used for comparison between the pre and post modernization mission profiles and to determine the stress level in each of the known aircraft fatigue critical locations (FCL). The results show that the change in aircraft weight and balance and the new operational profile can significantly change the inspection intervals of certain fatigue critical locations of the structure. A preliminary result for the horizontal tail has shown that this component will have a much more restrictive maintenance schedule to assure flight safety.*

***Key words:** Fatigue, Damage tolerance, Structure, F-5, Flight data analysis, Crack growth.*

LIST OF SYMBOLS

BACO	Canoas Air Force Base
BASC	Santa Cruz Air Force Base
FAB	Brazilian Air Force
DTA	Damage Tolerance Analysis
FCL	Fatigue Critical Location
FDR	Flight Data Recorder
IAE	Institute of Aeronautics and Space
N_y	Lateral load factor
N_z	Normal load factor
NDI	Non Destructive Inspection
RFC	Representative Flight Condition
USAF	United States Air Force
SwRI	Southwest Research Institute

INTRODUCTION

The development of new technology and declining governmental budget make it difficult to replace military fleet as it becomes obsolete. Therefore, Air Forces around the world have alternatively decided to update the existing vectors in their inventory. The military aircraft modernization primarily aims at extending mission profiles, but also changes considerably the structure weight and balance. The main effect is the increase in stress levels, which can therefore compromise the structural integrity. To assure flight safety, a comprehensive campaign to collect operational data and to analyze the impact in the structural integrity of the aircraft is necessary.

The aircraft structure is subject to cyclic loads due to maneuvers and gusts that overlap stationary loads of a steady flight. Aircraft fighters, as the F-5, have from the high-g maneuvers the most significant contribution that define their service life.

A structure can lead to catastrophic failure even if it is submitted to loads smaller than its structural design limit. This is a cumulative effect, known as fatigue. Figure 1 illustrates the basic mechanism of how cyclic loads may induce a structural failure.

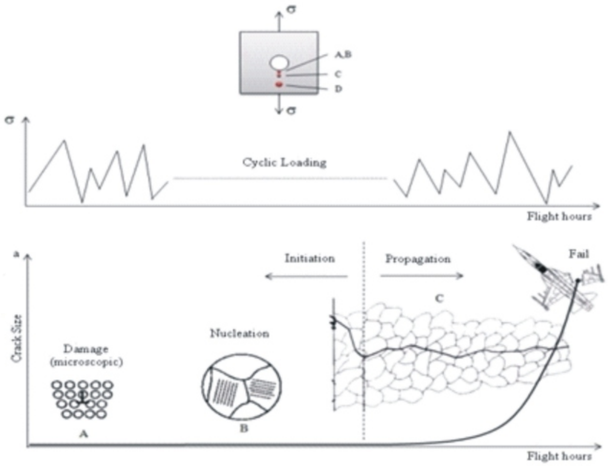

Figure 1: The basic mechanism of fatigue (Mattos, 2008).

As already mentioned, the most compelling reason to extend an aircraft's structural life is the pressure to save money. Figure 2 shows the cost of a combat aircraft in U.S. dollars. As can be seen, the cost has increased exponentially over the years. On the other hand, any weapon system and avionics modernization is also costly. Therefore, modernization usually requires a reassessment of the airframe and further extension of its service life.

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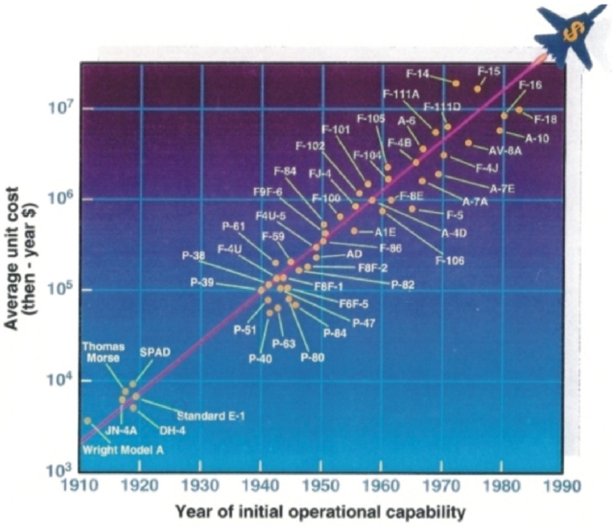


Figure 2: Aircraft average unit cost per year (Burnside, 1993).

The Brazilian Air Force (FAB) is also part of these worldwide budget restrictions. For this reason, until FAB is able to properly acquire new fighters, it is necessary to upgrade and keep the existing ones flying. As part of this, the implementation of airframe life extension and the guarantee of the structural integrity are vitally important.

The F-5 fleet was one of the elected FAB vectors to have its service life extended and the avionics upgraded. In order to fit all new equipment, some structural modification was implemented. With new avionics integration, the F-5 basic weight has increased. Additionally, the F-5 has extended its operational capability, which generates a more severe load spectrum. Figure 3 depicts how an increase in spectrum severity may impact the range of non destructive inspection interval. To properly account all this changes, a comprehensive damage tolerance analysis was necessary, which is described in the next section.

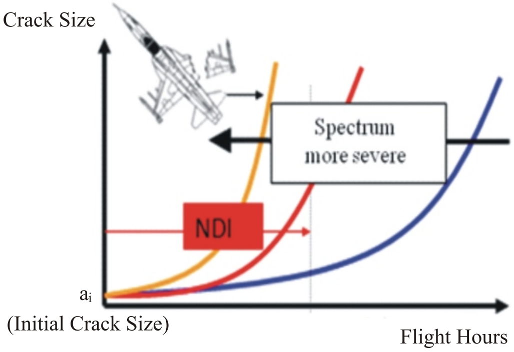


Figure 3: Impact in the range of NDI interval.

THE F-5 DTA PROCESS

The damage tolerance analysis (DTA) comprises several steps. The first step is to determine the way the aircraft is operated in each squadron. This step requires performing the Load/Spectra Environment Survey (L/ESS). This type of survey takes into account not only the load factor, as conducted in traditional analyses, but also addresses the aircraft mission profiles, operational environment, speed, altitude and other time dependent parameters. table 1 illustrates an example of how the same load factor may result in different stress levels depending on the maneuver condition. The example is presented for the F-5 Dorsal Longeron, for the normal load factor (N_z) of 5g's and Mach 0.8. The calculated stress varies up to 47% with changes in weight, flap deflection and altitude.

Table 1: F-5M Dorsal Longeron Stress

Case	Weight (lb)	Fuel Weight (lb)	Flap Def. (°/°)	Alt. (ft)	Stress (ksi)
1	12797	2200	0/0	15000	14.16
2	12797	2200	12/8	15000	19.40
3	11917	1320	12/8	30000	16.14
4	11917	1320	12/8	5000	20.78

Comparing case 1 and case 2, the single change in flap position leads to an increase of 37% in stress, and for cases 3 and 4, changing altitude and keeping fixed all other conditions ensued in a 28.7% difference in stress. Analyzing these cases, we can conclude that not only the load factor, but also other parameters are extremely important to properly determine the structure stress level.

All the major steps of the F-5M DTA Program are represented by the flowchart shown in Figure 4 and are described in sequence.

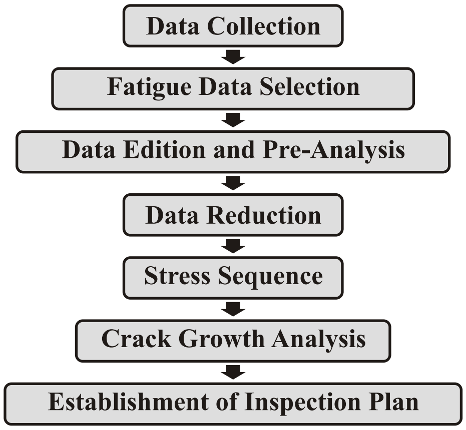
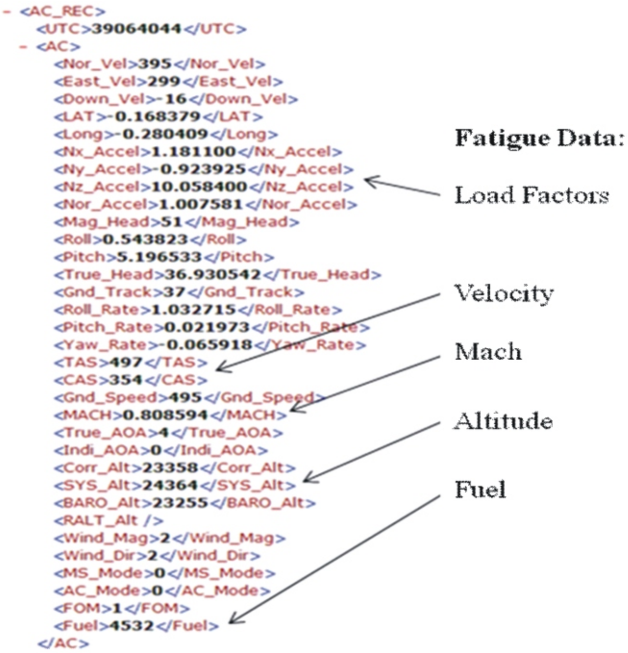


Figure 4: DTA Flowchart.

- **Data Collection:**

The data compilation must satisfy the specification content in section 3.2.2 of the Military Standard MIL-A-8866B. The F-5M Flight Data Recorder (FDR) can store data such as altitude, Mach, speed and load factors. The data is recorded in average frequency of 10Hz and is disposed into XML files. These files are downloaded at the

Air Force Bases and are used during flight debriefing. figure 5 shows an example of the data of a XML flight file. The size of total flight files normally exceeds 100 MB.



```
- <AC_REC>
    <UTC>39064044</UTC>
  - <AC>
      <Nor_Vel>395</Nor_Vel>
      <East_Vel>299</East_Vel>
      <Down_Vel>-16</Down_Vel>
      <LAT>-0.168379</LAT>
      <Long>-0.280409</Long>
      <Nx_Accel>1.181100</Nx_Accel>
      <Ny_Accel>-0.923925</Ny_Accel>
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    </AC>
```

Figure 5: Part of an XML file from F-5M FDR.

Some relevant information of the flights is not registered by the FDR. Therefore, the XML files must be supplemented to make them useful for the next DTA steps. Computer software (F5DACOM) was developed to include this supplementary data for the flight files (Ribeiro, 2008).

This software is used by the Air Force Bases, so that information such as configuration, external stores and events during the flight (weapons launched/released or refueling) are recorded. Figure 6 shows the main screen of the F5DACOM software.

Diretório dos dados do vôo: C:\F5DACOM\134085XX.FC7 - FLY - 4865\

Aeronave: ● F-5EM ○ F-5FM

Matrícula: 4865

Tripulação: 1

Data do vôo: 08/05/2008

Tipo de Missão: ACM - Air Combat Maneuver (10)

Configuração Armada

WINGTIP	OUTBOARD	INBOARD	CENTERLINE	INBOARD	OUTBOARD	WINGTIP
LAUNCHER RAILS	NO PYLON	NO PYLON	150-GAL FUEL TANK	NO PYLON	NO PYLON	LAUNCHER RAILS

Munição na decolagem: 280

Munição no pouso: 280

Pesos

	Takeoff	Landing
Peso Básico	10923	10923
Tripulação	220	220
Munição	197	197
Cargas Externas	416	416

Figure 6: F5DACOM screenshot (Ribeiro, 2008).

F5DACOM creates a new file with all the supplementary data. This new file and the XML flight files are sent to the Institute of Aeronautics and Space (IAE) for analysis. Figure 7 illustrates the main tasks in the collection data process. First, the squadrons download the XML files from the FDR and run the F5DACOM software. Then, the files are sent to IAE by mail (DVD) or through the internet (FTP).

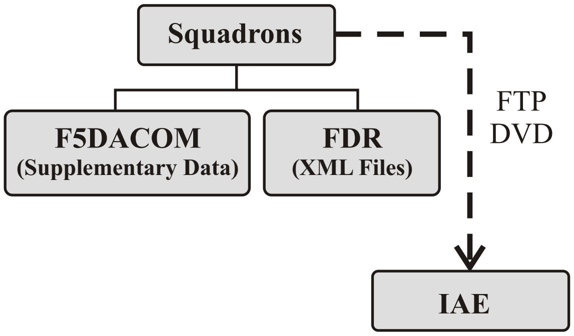

Figure 7: Data collection methods.

- **Fatigue Data Selection**:

The fatigue data pre-selection consists in applying a filtering process to the original data, in order to keep only the events considered significant for the pre-analysis phase and the remaining DTA process.

In order to accomplish this phase, a computer program named SEDAF was developed (Ribeiro, 2009). The SEDAF software performs a filtering process and eliminates unnecessary data by selecting peaks and valleys of the load factors, which are the most important values for the DTA. This procedure reduces the average package of information from 100MB to 300KB through a complex process involving dozens of XML files from the aircraft's data acquisition system. SEDAF uses three triggers to do this: one for normal load factor (N_z), one for lateral load factor (N_y) and another for time. The values of these triggers are 0.5 g, 0.1 g and 30 s for N_z, N_y and time, respectively. These values were based on historical data where it was noticed that variations of N_z smaller than 0.5 g and variations of N_y smaller than 0.1 g did not contribute significantly to the fatigue analysis for this type of aircraft. The software also selects events at every 30 s. Although another filtering will still be performed in the next steps, the amount of remaining data is necessary for flight viewing during the data edition and pre-analysis stages.

Figure 8 shows an example of the filtering performed by SEDAF. Red marks are points kept for further analysis.

SEDAF continues calculating the weight reduction during the flight caused by events related to weapon systems such as launched missiles, released bombs, released chaffs/flares and the ammunition fired.

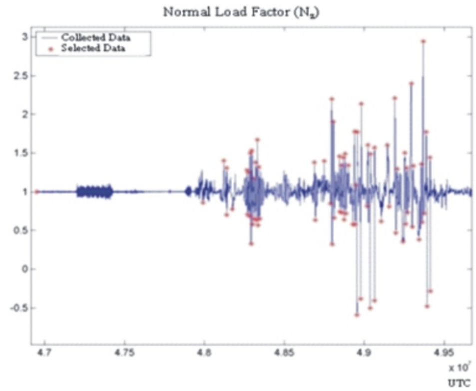

Figure 8: Result from pre-selection for pre-analysis.

- **Data Edition and Pre-Analysis:**

The purpose of pre-analysis is setting the data for the next steps of the DTA program. The data must be collected and pre-analyzed according to Military Standard MIL-STD-1530, section 5.4.4 and AFWAL-TR-8278, section 5.3.2. The software EPAD F-5M was developed specifically to accomplish this task (Mello Jr., 2008). Each flight, previously filtered by SEDAF, must be edited and pre-analyzed by the EPAD F-5M. The information contained in each file can be viewed and edited as a table or graphically. It allows the user to check and fix any discrepancies in all the data.

The first step of pre-analysis is to define the flight phases, such as: climb, cruise, primary, cruise, descent and approach. This marking of the flight phases requires some user's experience due to the nuances of each flight mission. EPAD allows two cruise phases, one before and another after the primary. Figure 9 shows an EPAD chart screen, where the flight phases can be seen in the altitude and N_z plots.

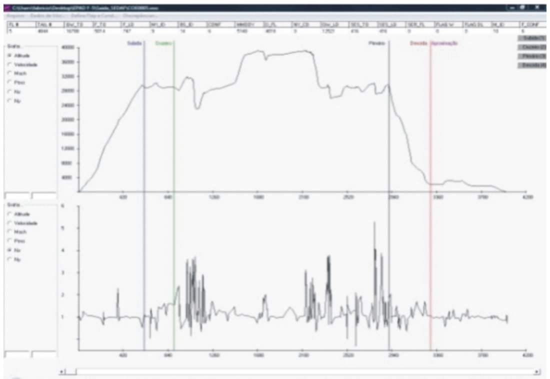

Figure 9: EPAD screenshot.

The flap position is a very important parameter that is not recorded in real time. It is determined by EPAD based on flight conditions for each event (angle of attack and altitude), following the logical procedure described in the aircraft's flight manual. Northrop Corporation, the F-5 manufacturer, performed various tests to determine how the configuration and maneuver types affect the airframe structure.

To properly define the structural impact during a flight event, the maneuvers are divided into three types: symmetrical, roll and abrupt pitch.

- Symmetrical maneuver is characterized by having no significant variation in angles of roll, yaw or pitch. Usually, the lateral load factor (N_y) is very small.

- Roll maneuver is characterized by its significant variation in roll angle along time and its non-zero value for N_y.

- Abrupt pitch maneuver is characterized by a wide variation of pitch angle in a short period of time, with no significant change in yaw or roll movement. Such maneuvers have major importance in DTA due to the high impact on the horizontal tail structure.

During a flight, the aircraft is subjected to different conditions of weight, altitude, Mach, load factors and flap position caused by different maneuvers and events. Based on these conditions, EPAD associates a representative flight condition (RFC) to every point in a flight. These RFCs were previously tested during the Northrop flight tests campaign, when the loads of the aircraft structure were measured.

- **Data Reduction:**

The pre-analyzed data generated by EPAD still represents very large amounts of information and most of these are unnecessary for the fatigue life analysis. Thus, it is necessary to identify the most relevant peaks and valleys of N_z. This data reduction process is performed in accordance with MIL-STD-1530 standards, sections 5.4.4.2 and 5.4.4.3, MIL-A-8866B, Section 3.2.2 and manual AFWAL-TR-823078, Section 5.3.2. These standards define criteria to count cycles, commonly used for fighters and known as conventional counting. The criteria define rules about peaks and valleys, as follows:

A peak needs to be:

- the largest value between two valleys;
- preceded and followed by valleys whose differences between peak (p) and each valley (v_i) are not lower than 50% of peak value less one, i.e.:

$$p - v_i \geq \frac{1}{2} \cdot (p - 1) \tag{1}$$

greater than 2g, unless the following valley is less or equal to zero.

A valley needs to be:

- the lowest value between two peaks;
- at least 1g lower than the previous and next peaks.

Figure 10 shows an example of the counting process for a few events.

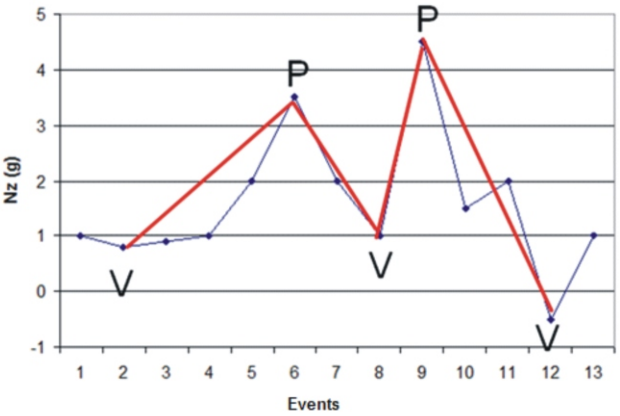

Figure 10: Conventional counting criteria.

Figure 11 shows the real flight spectrum of N_z using data reduction process. The remaining points have been plotted in red. As can be seen, at the beginning of the flight, there is a low N_z level which is related to the climb and cruise phases.

Each flight event that remains at this stage is registered according to the type of mission, the flight phase in which it occurred, the RFC associated and the aircraft weight. After this step, the full discrete spectrum can be generated, normally representing 1,000 flight hours per type of mission.

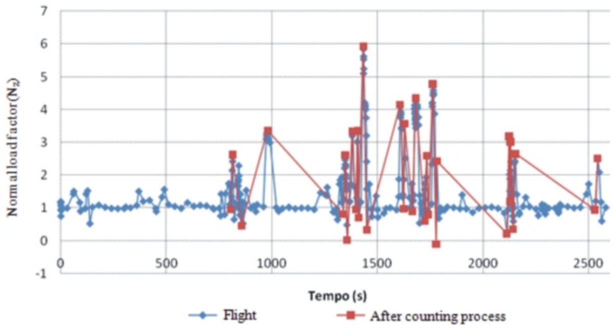

Figure 11: Result from the counting process. (Mattos, 2008).

- **Stress Sequence:**

There are points in a structure where the possibility to develope cracks is higher. They are called Fatigue Critical Location (FCL) and generally occur in regions of stress concentration. F-5M has a total of 41 FCLs: 10 points at the wing, 7 at the fuselage, 2 at the attachment region of the engines, 4 at the vertical tail, 2 at the horizontal tail and 16 at the region called "ziploc".

Each FCL has different stress distributions, because they are at different locations of the aircraft, and also involve different materials and geometry.

The Northrop flight test campaign determined the loads acting on points distributed over 12 stations, taken in relation to a reference datum. Each FCL is associated with one of these stations. The loads are determined based on the type of maneuver as follow:

- Load calculations:
  - Symmetrical

For a given FCL, the associated station has some related symmetrical RFC. Each RFC has 3 listed values of N_z. Each N_z value has the forces and moments measured during flight tests at that station. Thus, the forces and moments for a given N_z referred to that specific FCL and RFC can be calculated through a linear interpolation.

  - Roll

The loads due to roll maneuver are calculated in two steps. The first one determines the symmetric loads and the second one calculates the asymmetric loads, caused by rolling events, which will be added to the symmetrical loads. The additional loading caused by the roll maneuver is extracted directly from a table by searching the closest value of N_z. The roll loads are tabulated for a roll rate of 100°/s. To be properly accounted for, the load must be adjusted for the actual maneuver roll rate.

  - Abrupt Pitch:

Figure 12 shows a typical time history during abrupt pitch maneuver. There are two instants in time that have relevant importance: the entry part where the maximum down tail load is developed and the check part where the most positive tail load occurs. These points are identified as "Entry" and "Check".

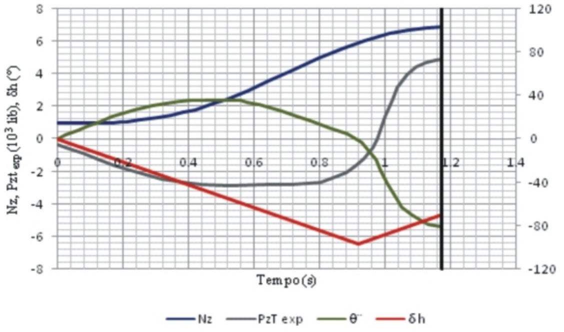

Figure 12: Typical Abrupt Pitch Maneuver (Northrop, 1977).

For each event, N_z “Entry” and “Check” are calculated and compared with N_z valley and peak, respectively. The lower value between N_z “Entry” and valley is chosen and the higher value between N_z “Check” and peak is chosen. Then, the total load is calculated adding abrupt load to the corresponding symmetric load.

- Stress-to-load ratios and stress spectra:

A previous step enabled to know the exact loads acting on a specific region of the airframe, as a maneuver occurs. However, for each FCL it is necessary to know the actual stress the structure is subjected to. These stress-to-load ratios were obtained by static and fatigue tests of instrumented aircrafts and also finite element analysis using the NASTRAN^{TM} software.

A dedicated computer program was created to generate the stress spectra for each FCL, GCTAF F-5M (Mello Jr., 2009). By using the load spectrum from the counting process and all other parameters, such as maneuver conditions, mission mix, and the stress-to-load rations, the GCTAF software generates a stress spectrum for each FCL that is used by the crack growth analysis software.

- **Crack Growth Analysis:**

The next step of a DTA program is to determine how the structure would behave in the presence of cracks. The Crack 2000 software (Mello Jr., 1998) was developed to provide an automated Damage Tolerance Analysis to FAB aircrafts. Its primary capability is to calculate the fatigue life and crack instability of structures subjected to cyclic loading which contain initial flaw defects.

The user has to input a spectrum, geometry and material properties, and choose some options like the retardation effect. The output files have all the necessary information for a complete DTA, such as residual strength and crack growth graphics (Fig. 13). The residual strength is the resistance that the structure withholds in presence of a crack, while the crack growth curve shows the time required for the crack to reach its critical size.

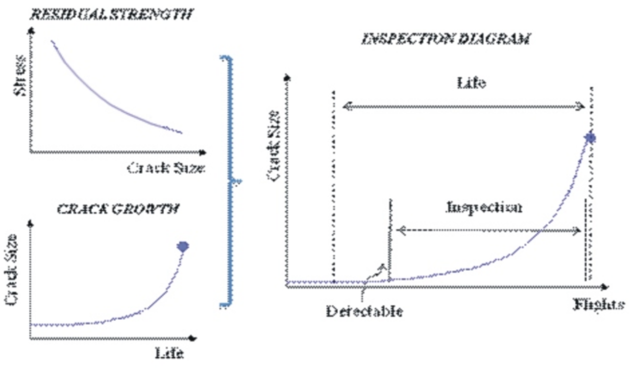

Figure 13: Inspection Diagram.

- **Establishing an Inspection Plan:**

With the information obtained in the residual strength and crack growth curves, the inspection intervals can be established for the referenced FCL, depending on the inspection method chosen. The final work related with DTA is an interactive phase with the Maintenance Depot and End User. The proposed inspection interval may be slightly changed to keep the aircraft maintainable and operational.

RESULTS

The F-5M DTA Program will be completed in August 2009. The following results are preliminary because only a small amount of data was available at this point. However, they show how changes in weight and mission profiles may impact differently in different FCLs of the F-5M. Figures 14, 15 and 16 depict the stress spectra for fuselage, FCL's wing and stabilizer, respectively.

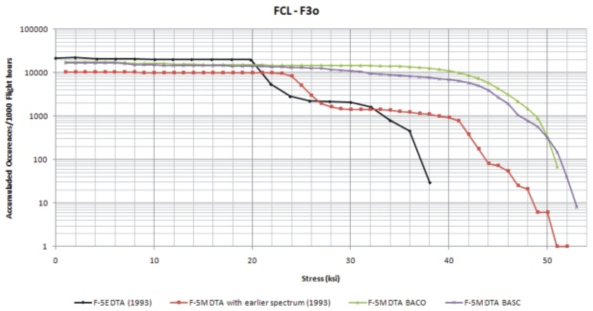

Figure 14: FCL F3o: Edge of Fwd Upper Longeron

The black curves represent the stress spectra for the original F-5E DTA. The red curves were generated by using the new stress-to-load ratios, keeping the original F-5E g-spectrum. The comparison of these two curves shows how the weight and balance changes affect the stress level. The blue and green curves are generated with new stress-to-load ratios and new g-spectrum for the F-5M fleet operating at BACO and BASC, respectively. It can clearly be seen that the “new” aircraft with new operational profile is subjected to higher stress levels, which consequently imply in a more restrictive maintenance schedule. The wing is the component that has minor variation in stress levels, with the new result very close to the original one (fig. 15).

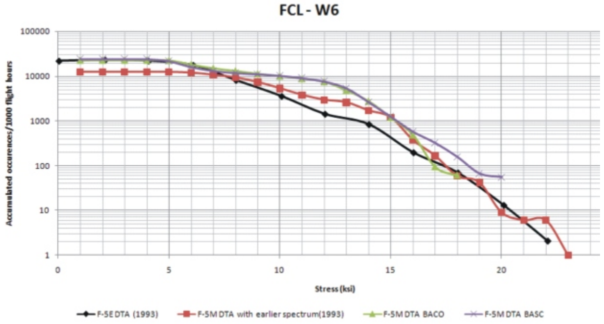

Figure 15: FCL W6: Wing lower skin fastener hole.

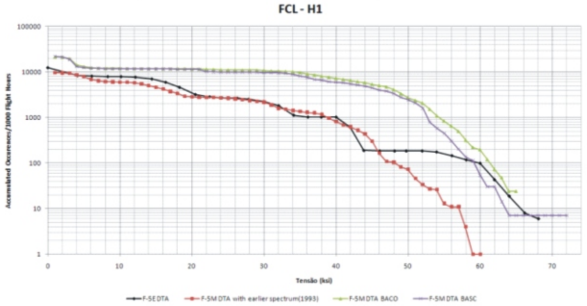

Figure 16: FCL H1: Horizontal Tail.

As an example of the F-5M upgrade impact in structural life, the FCL H1 was analyzed using the Crack 2000 software (Mello Jr. 1998). For the purpose of comparison, the model used was the same as Wieland (1995). The geometry and the other parameters for the analysis are described in the Crack 2000 output file, which is displayed below.

CRACK GROWTH DATA

```
Crack 2000 V. 3.0 (1998)  -  (c) 1995
Alberto W S Mello, Jr.  All rights reserved.
Run date = 11-11-2008     Run Time = 15:42:29
Cycle-by-Cycle Analysis
AISI-SAE 4330V MOD, 180-200 UTS (Plt / Forg)
 Ys = 186    Uts = 190
 Kc = 165.    Kic = 112    Kie = 150
Superposition:
Rten = 1  Rben-W = 0  Rben-t = 0  Rpin = 0
Crack Growth Model:
Forman et al (1990)
Corner Crack at Edge of Plate
Geometry:
W = 2.54       t = 2.13
Two-dimensional - Varying Crack Shape
No retardation Model
```

Figure 17 shows the crack growth curve for the original and the new DTA. It can be seen that the time for a crack to grow from 0.05 in to 0.85 in was reduced in more than 30%. This denotes a change in the inspection interval that will be proposed to the Maintenance Depot.

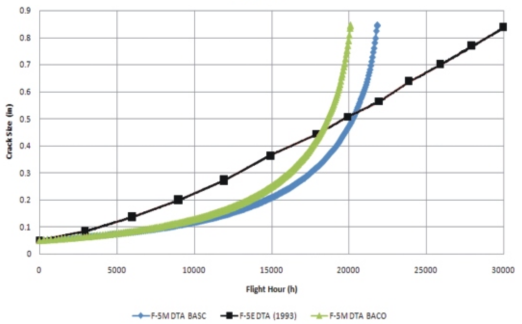

Figure 17: FCL H1 crack growth.

CONCLUSIONS

The implementation of the F-5M DTA Program allows FAB to recognize how the squadrons operate the aircrafts and how modernization can impact its structural life. The results will also help FAB to better use its resources, such as aircraft, spare parts, ground equipment and personnel. The old fighter was upgraded and now the new vector is heavier, but is also capable of performing a wider variety of missions. The only way to guarantee the flight safety is to know how the structure will behave in this new scenario. The tasks of a comprehensive DTA are evolving and are complex. With the available flight data, the assessment of stress spectra for fuselage, wing and horizontal tail FCLs was performed. The preliminary results show that some FCLs can have a major change in stress levels, which lead to different crack growth curves and different inspection intervals. Therefore, it is clear that the evaluation of DTA will contribute directly to the maintenance procedures at the F-5 Depot. The F-5M DTA Program will enable the Brazilian Air Force to accomplish its missions with the certainty that the structural safety is assured.

REFERENCES

AFWAL-TR-82-3073, 1984, “USAF Damage Tolerant Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft Structures”. Wright-Patterson AFB Ohio, Final Report.

Burnside, H., 1993, “Flying Longer: With Confidence”, Technology Today.

Mattos, D.F.V., 2008, “Análise de Dados de Vôo das Aeronaves F-5M Para Cálculo de Vida em Fadiga”, pp.18-74, Graduation Work, ITA, São José dos Campos.

Mello Jr., A.W.S., 1998, “Crack 2000 Program: Software for Practical Fracture Mechanics and Damage Tolerance Analysis”, User's Manual, IAE, São José dos Campos.

Mello Jr., A.W.S. et al., 2008, “Edição e Pré-Análise de Dados Operacionais do Projeto DTA F-5M: Software EPAD F-5M”, IAE, São José dos Campos (RENG ASA-I 03/08).

Mello Jr., A.W.S. et al., 2009, “Geração de Ciclo de Tensões para Análise de Fadiga. Software GCTAF F-5M”, IAE, São José dos Campos (Submitted for approval).

Northtrop Corporation, 1977, “F-5E/F Fatigue Loads for the Damage Tolerance Assessment”, Hawthorne, CA, (NOR 76-164)

RIBEIRO, F. N., 2008, “Procedimentos a respeito da Coleta de Dados de Vôo das Aeronaves F-5EM e F-5FM utilizando o Programa F5DACOM”, IAE, São José dos Campos (RENG ASA-I 02/08).

RIBEIRO, F. N., 2009, “Procedimentos para a Seleção de Dados de Fadiga das Aeronaves F-5EM e F-5FM utilizando o Programa SEDAF”, IAE, São José dos Campos (Submitted for approval).

USAF, 1975,“Aircraft Structural Integrity Program: Airplane Requirements”. Wright-Patterson AFB Ohio, FSG-15GP, (MIL-STD-1530).

USAF, 1974, “Airplane Damage Tolerance Requirements”. Wrigth-Patterson AFB. Ohio, (MIL-A-83444).

USAF, 1975, “Airplane Strength and Rigidity Realibility Requirements, Repeated Loads and Fatigue”, Wrigth-Patterson AFB Ohio, O 45433, (MIL-STD-A-886B).

Wieland, David H. et al., 1995, “ F-5 FMS Durability and Damage Tolerance Update Final DADTA Report F-5”, E. Southwest Research Institute, San Antonio, Texas.