Review of Airframe Inspection Interval for Transport Airplanes Based on Damage Tolerance Analysis

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Abstract

Monitoring the life and managing the airworthiness of the airframes (aircraft structures) is an activity to maintain the aircraft structural integrity, which is part of the Aircraft Structural Integrity Program (ASIP). Airframes of modern transport airplanes are designed based on the Damage Tolerance Analysis (DTA). DTA concept assumes that damages in the form of cracks already exist in structures. In DTA designed structures, inspection is critical in ensuring the safety and integrity. DTA is based on the design spectrum load defined by the Original Equipment Manufacturer (OEM). As the actual operation might result in load spectrum which is different than the OEM design load spectrum, ASIP requires the actual stress spectra monitoring. Inspection review needs to be conducted using DTA, based on the actual stress spectra. The crack propagation scenario needs to be analysed. The time required for a crack to reach its critical length needs to be predicted. This will determine the inspection scenario. This paper introduces the DTA based airframe inspection review, and discusses the methodology to do it.

KEYWORDS: Airframe Inspection Review, Damage Tolerance Analysis, Aircraft Structural Integrity Program, Safety by Inspection.

INTRODUCTION

Modern transport airplanes are designed to operate for a long life, which is often more than 30,000 flight hours. Airframes (aircraft structures) of modern transport airplanes are designed based on the Damage Tolerance. Damage Tolerance concept assumes that damages in the form of cracks already exist in structures. Further, the concept is based on the condition that the existing cracks and their associated lengths should not endanger the structures. The Damage Tolerance concept is applicable for both civil and military transport airplanes. For example, the Lockheed C-130 and IPTN CN-235 transport airplanes, which are operated by the Royal Malaysian Air Force (RMAF), are designed on the Damage Tolerance philosophy. Both use a Safety by Inspection (SBI) management system based on Damage Tolerance Analysis (DTA).

Lockheed C-130 Hercules is a multipurpose heavy/medium size transport airplane. The C-130 Hercules has a straight upper wing configuration combined with pressurised fuselage with big ramp-door and fuselage mounted landing gears. This makes the Hercules an ideal airplane for parachuting (troops and cargo) as well as for quick loading-unloading operations. It can accommodate 92 troops, or 64 paratroops, and also capable of loading in military vehicles. Basically, C-130 airframe is a conventional semi monocoque metal construction, as shown Figure 1. The wing is constructed of metal stiffened panel with two spars. The fuselage is conventional stiffened panel with longerons and frames.

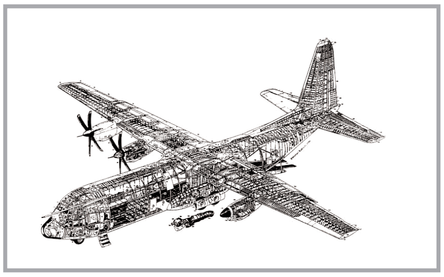

Figure 1: C-130 Hercules airframe [1]

IPTN CN-235 is a two-engine, high wing airplane with big rear ramp-door for easy loading-unloading. It perform similar missions to the Hercules, but smaller in capacity with 35 passengers. CN-235 airframe is a conventional semi monocoque metal construction. The wing is constructed of metal stiffened panel with two spars. The fuselage is conventional stiffened panel with longerons and frames.

Monitoring the life and managing the airworthiness of the airframes is an activity to maintain the aircraft structural integrity, which is part of the Aircraft Structural Integrity Program (ASIP). As the name Safety by Inspection implies, inspection is critical in DTA. DTA is performed to the Primary Structural Elements (PSE) or Fatigue Critical Locations (FCL) of the airframes. DTA of a PSE is based on the spectrum loading of that particular PSE. When the Original Equipment Manufacturer (OEM) designs the PSE, the DTA is based on the design spectrum load defined by the OEM. ASIP requires the actual stress spectra monitoring on the PSE. With cracks assumed to be in existence, the crack propagation scenario has to be analysed. The time required for a crack to reach its critical length needs to be predicted. This will determine the inspection scenario. Optimum inspection interval will :

a. Maximise aircraft availability throughout the defined life type.

b. Minimise operating costs through an optimised inspection program.

Due to the nature of the mission, the need of DTA based ASIP is probably more so in military environment rather than in civil operation. In military operation, it is quite common to have actual operation, which is different than the design requirement and objective which was laid down in the early stage of the design. This results in load spectrum which is different than the design load spectrum. The implication is a different crack propagation scenario, which renders the original inspection interval not appropriate anymore. This situation is not common in civil air transportation. For example, when an airline buys Boeing B747-400, then this airplane is to operate for long distance flight such KL-London, which is indeed a distance that this airplane was designed for. Short distance operation is not economical as this will increase the Direct Operating Cost (DOC) of the airplane.

ASIP is important to monitor the life and manage the airworthiness of the air transport airframes. Conducting ASIP is a standard procedure in major western air forces. For example, the Royal Australian Air Force has a considerable experience on the C-130H [2]. They developed Individual Aircraft Tracking (IAT) system and condition assessment as part of the C-130H life of type study which they undertook. The RAAF conducts the estimation of the structural Life of Type (LOT) of the RAAF C-130H aircraft. They also looked at the proposals of structural refurbishments to achieve Planned Withdrawal Date (PWD) of 2008 and 2030. Their initial conclusions were that the 2008 PWD (30 years old) is likely to be achieved without major structural problems. However, 2030 PWD (52 years old) is possible only with a significant increase in structural maintenance activities including refurbishment.

Canadian Air Force (CF) also has an extensive experience on the CC-130 Hercules ASIP [3]. The main theme of the ASIP program includes the CC-130 usage severity monitoring, managing the in-service damage history, CC-130 maintenance and inspection rationalisation, and corrosion control. The inspection intervals at the critical locations should be based on the actual usage severity. The CF has implemented onboard structural data acquisition systems on all CC-130s. CC-130 in-service history damage management system consists of damage repair and tracking database as well as the program to conduct the damage analysis and mapping. Having this system allows the CF among others to predict fleet damage, to provide quick repair/replace or modification references, to forecast inventory spares, and future maintenance cost. A lot of effort is also spent for corrosion control, as corrosion is always a major problem in aging fleet. Corrosion tracking is conducted by utilising the damage analysis and mapping system.

Airplanes such as C-130 Hercules and CN-235 are main asset and very important element in RMAF air transportation strategy. ASIP is a way to maintain this important asset through maximising aircraft availability throughout the defined life, and minimising operating costs through an optimised inspection program. This paper will discuss the basic concepts of DTA. This paper also describes the aspects need to be looked at and how to approach them, in relation to the damage control through inspection review of the airframe based on DTA.

OVERVIEW OF DAMAGE TOLERANCE ANALYSIS

In Damage Tolerance concept, the structure is allowed to have damages (in the form of cracks), as long as the damage is detectable, inspectable, and the structure remains safe. It is normally assumed that an initial crack already exists. Due to the fatigue loading, the crack will propagate (grow). There will be a critical crack length, which the residual strength will not be able to cope against the stress intensity due to the working load. If the critical length can be found and crack propagation rate can be calculated, the inspection interval can be determined. For conceptual comparison, Damage Tolerance is the opposite of Safe Life. Safe Life is a concept with a fundamental objective of having a structure, which is not going to have cracks during the life it is designed for. Many fighters, including RMAF F/A-18, Hawk, and MiG-29 are designed as Safe Life structures. Even for Safe Life structures, ASIP is important and becoming the standard practices [4].

An important element in fatigue or damage tolerance analysis is the load spectra. While fighter airplanes are more dominated by man-induced maneuver spectrum, transport airplanes are very much affected by gust spectrum (in addition to the maneuver spectrum). Gust spectrum is a load spectrum which

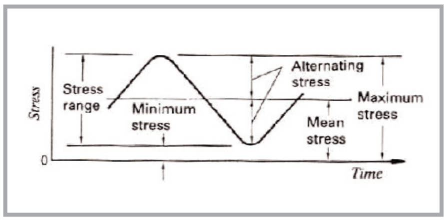

Figure 2: Cyclic stress

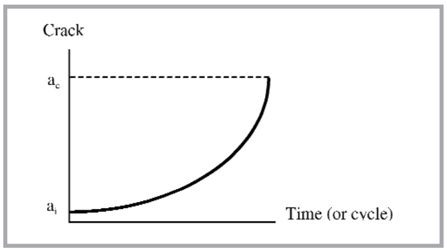

Figure 3: Crack length against time

is caused by air turbulence. By definition, gust is air movement with a velocity component in vertical direction. Vertical movement of air will induce load increment (or decrement) which affects the total loading suffered by the airplane. In turbulence air, the gust spectrum can be very severe and dominates the design load of the airplane.

DTA is based on load spectra in a specific PSE location. The most practical means of having load spectra on a PSE is by attaching a strain gauge on that PSE. Real time strain measurement can be obtained in this way. Transforming the strain spectra into a stress spectra is a straightforward process. Another approach is by recording the g-force (or load factor, Nz) exceedance. However, this approach is not as accurate, as the reading has to be converted into stress spectra through a transfer function.

An important issue is the determination of crack propagation or crack growth rate. The cracks grow due to the application of fatigue load, which basically is a collection of cyclic loads.

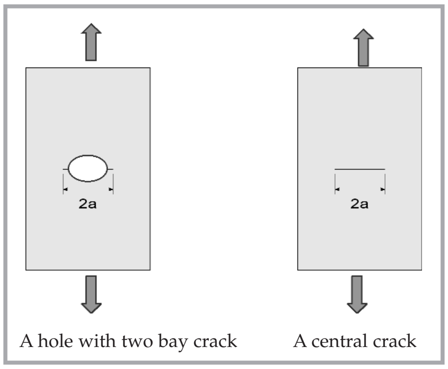

Figure 4: Example of crack geometry

Figure 2 shows a cyclic load diagram with its parameters and terms. Figure 3 shows a typical diagram of crack length against time (or load cycle). It is shown that the crack grows from an initial crack length (a_i) up to the critical crack length (a_c). The rate of crack growth normally is represented as the *da/dN* against ΔK where,

da = the change in crack length
dN = number of load cycle (which yields the change in crack length *da*)
$\Delta K = \beta (\Delta\sigma) \sqrt{(\pi a)}$

The ΔK represents the change (or range) of stress intensity factor, with a represents the crack length, and $\Delta\sigma = \sigma_{max} - \sigma_{min}$ is the stress range value between the maximum and minimum stress. The β factor represents the geometry of the problem. Figure 4 illustrates the crack geometry for two simple cases, a central crack in a plate, and a (two bay) crack in a plate with a central hole. It is common to have the crack length defined as *2a*.

Figure 5 shows the test result of fatigue crack growth for 0.09 inch thick 7075-T6 aluminum alloy under various stress ratio ($\sigma_{max}/\sigma_{min}$) and loading frequency [5]. Crack growth rate can also be simulated using empirical equations with Paris Equation or Forman Equation as among the most popularly used [6].

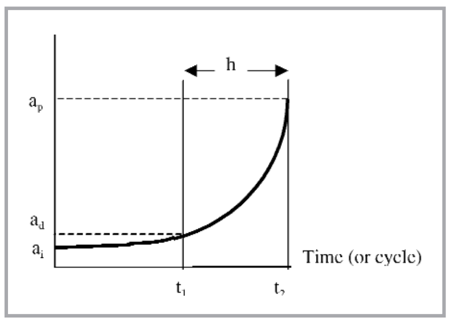

Figure 6: Inspection interval

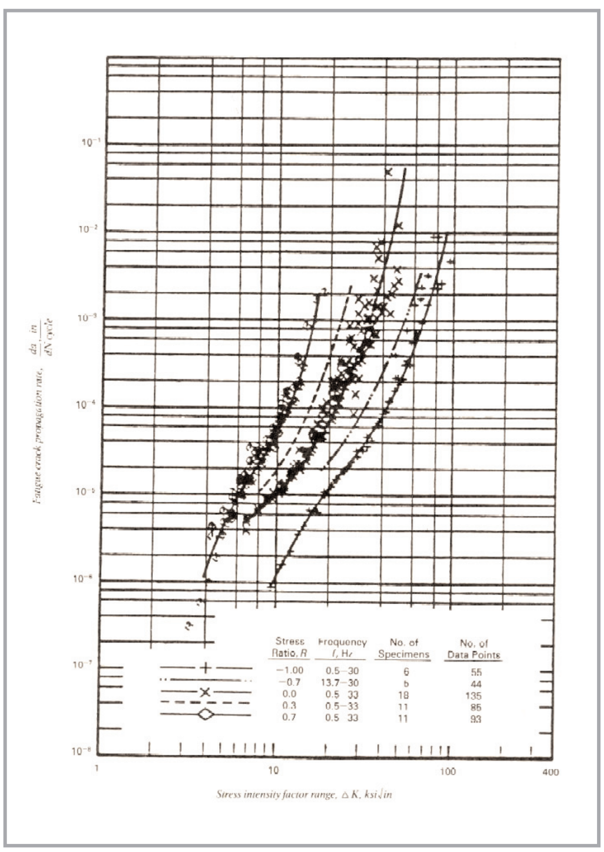

Figure 5: Crack growth rate for 0.09 in thick Al 7075-T6 [5]

INSPECTION REVIEW BASED ON DAMAGE TOLERANCE ANALYSIS

Damage tolerance is the ability of the structure to sustain damage in the form of cracks, without catastrophic consequences, until the economic service life is expired and the airplane or component retired. The Military Requirement also uses the damage tolerance analysis for durability requirement. It states that cracks growing from a presumed initial size must be sustainable throughout the economic service life. The purpose of doing crack growth and fracture analysis is to provide the basis for fracture control. Fracture control by inspection is the most commonly practiced, safety depends upon the timely detection and repair of cracks. It is important to note that beyond the critical crack length the residual strength can not cope with the applied load, and fracture occurs. Hence, it is important to ensure that inspections are conducted before the crack reaches its critical length. The purpose of damage tolerance analysis is then to establish the inspection procedure and the inspection interval.

Structural strength is affected by cracks. The residual strength as a function of crack size can be calculated, using fracture mechanic concepts which relates the fracture toughness to the stress and crack length, $K_{1c} = \beta\sigma\sqrt{\pi a}$. The fracture toughness of the material, K_{1c}, is a material characteristic and can be obtained from material testing. When the acceptable residual strength has been set for a certain stress level σ, the maximum permissible crack size a (now $a = a_p$) can be calculated. Again, β represents the influence of the geometry.

Figure 6 shows again a crack propagation diagram which indicates propagation of a crack from initial length a_i up to the maximum permissible crack size a_p. Crack detection is started with the detectable crack size a_d, which implies that any crack length less than a_d is unlikely to be discovered. From crack propagation diagram shown in Figure 6, it can be seen that any successful inspection will be conducted between t_1 and t_2, in the interval h. To ensure that a crack will be discovered, the inspection interval must be shorter than h. It is often taken that the inspection interval is h/2.

ACTIVITIES TO SUPPORT INSPECTION REVIEW

A comprehensive and reliable Damage Tolerance Analysis is the fundamental basis of any Safety by Inspection (SBI) program to allow the aircraft to be utilised to their maximum structural life potential. Central to the inspection review is availability of the means to do load monitoring in the actual operational environment. To conduct the inspection review, the followings are items which need to be addressed:

Perform DTA on Fatigue Critical Locations.

Firstly, it is necessary to determine fatigue critical locations (FCL or PSE) based on current experience, available in-service damage, or OEM reports. For each FCL, the baseline stress spectrum of the OEM design load has to be obtained. Ideally this should be obtained from the OEM. Otherwise, stress spectrum which is based and derived from TWIST [6] for wings and a combination of TWIST and the design pressurisation schedule for the fuselage, or other published data, can be used. Knowing the material and geometry of the FCL, DTA for each FCL can be conducted. This will include determination of cracking scenarios, crack growth rates and residual strength determination to provide baseline inspection intervals.

Converting and Adjusting OEM Design Baseline Periodic Inspection into Actual Operational Environments.

To determine inspection intervals, a DTA which is based on the actual usage of in-service aircraft fleet must be conducted. Accordingly, the baseline DTA needs to be calibrated based on the relative severities of the usage between the baseline spectrum and the actual flight spectrum. DTA for all FCL will be repeated to modify baseline inspection intervals to account for actual usage.

DTA in Relation to the Inspection Interval for Repaired Aircraft.

Throughout the life of an aircraft, structural configuration of FCL may change as a result of repairs and modifications. If this occurs, the DTA baseline for the given FCL may become invalid and no longer adequate as a basis for maintaining structural airworthiness. Hence, a system must be in place to ensure that repair practices are appropriate for an SBI aircraft and that necessary review of the DTA are triggered by repair and modifications actions in the vicinity of FCL. Defect and repair reporting procedures must ensure that the necessary information is being captured to support DTA. Repair practices have to ensure they are appropriate for a SBI aircraft.

CONCLUSION

Modern transport airplanes are designed to operate for a long life. This is true not only for civilian but also for military transport airplanes. Aircraft structures of modern transport airplanes are designed based on the Damage Tolerance concept. In Damage Tolerance concept, the structure is allowed to have damages (in the form of cracks), as long as the damage is detectable, inspectable, and of course it has to be proved that the structure remains safe. It is normally assumed that an initial crack already exist. Due to the fatigue loading, the crack will propagate. There will be a critical crack length, which the residual strength will not be able to cope against the stress intensity due to the working load. If the critical length can be found and crack propagation rate can be calculated, the inspection interval can be determined.

Military transport airplanes such as Lockheed C-130 and IPTN CN-235, which are operated by the Royal Malaysian Air Force (RMAF), are designed on the Damage Tolerance philosophy. Both use a Safety by Inspection management system based on Damage Tolerance Analysis (DTA). Inspection is critical in DTA. DTA are performed to the Primary Structural Elements (PSE) or Fatigue Critical Locations (FCL) of the airframes. DTA of a PSE is based on the spectrum loading of that particular PSE.

It is important to conduct ASIP to monitor the life and manage the airworthiness of the structures of military transport airplanes. When the Original Equipment Manufacturer (OEM) designs the PSE, the DTA is based on the design spectrum load defined by the OEM. In military operation, it is quite common for airplanes to conduct operation which is different than the design requirement and objective which was laid down in the early stage of the design. This results in load spectrum which is different than the OEM design load spectrum. The implication is a different crack propagation scenario. ASIP requires the actual stress spectra monitoring on the PSE. The crack initiation and propagation scenario has to be analysed. The time required for a crack to reach its critical length need to be predicted. This will determine the inspection scenario. Optimum inspection interval will give:

a. Maximum aircraft availability throughout the defined life type.
b. Minimum operating costs through an optimised inspection program.

To conduct the inspection review for military transport aircrafts, there are items which need to be addressed:

- To perform DTA on Fatigue Critical Locations
- Converting and adjusting OEM design baseline periodic inspection into actual/operator operational environments.
- DTA in relation to the inspection interval for repaired aircraft.

Transport airplanes, such as the C-130 Hercules and CN-235, are a very important element in RMAF air transportation strategy. This is also true for any other Air Forces in the world. ASIP is a way to maintain this important asset and will maximise aircraft availability throughout the defined life, and minimise operating costs through an optimised inspection program. For the DTA designed airplanes, Safety by Inspection is the key to the successful ASIP. This paper has introduced the DTA based airframe inspection review, and has discussed the methodology to do it. ■

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