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STRUCTURAL ANALYTICAL CONTROL PROGRAM FOR C-130 FLEET OF TURKISH AIR FORCE

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ABSTRACT

In an effort to ensure continued airworthiness and flight safety of aging C-130B/E aircraft fleet of the Turkish Air Force (TurAF), 2nd Air Supply and Maintenance Center (ASMC) Command has initiated and implemented an analytical control program to solve structural problems before there any catastrophic structural failures. As the aircraft grow older, the potential for fatigue cracking and corrosion increases. Many of the aging aircraft in the TurAF inventory are experiencing increased maintenance costs because one or more of these problems are present. To varying degrees, all of these older aircraft have encountered, or can be expected to encounter, aging problems such as fatigue cracking, stress corrosion cracking, corrosion, and wear. The critical fatigue component for the C-130 fleet is the center wing box, which is structurally more susceptible to the stresses of mission profile and payload. For center wings with 30,000 or greater equivalent flight hours (EFH), an inspection program to detect generalized cracking and possible onset of Widespread Fatigue Damage (WFD) should be instituted in accordance with 2nd ASMC Time Change Technical Order (TCTO) based on Service Bulletin 82-790, which includes center wing general cracks and common fatigue damage inspections.

INTRODUCTION

Many nations are now keeping aircraft in their inventories longer than ever before. In many cases, aircraft are left in the inventory longer because they are still operationally effective; however, in most cases, they remain in the inventory because the money is not available to replace them. Aircraft, which are seeing the effects of aging through corrosion and fatigue cracking, are causing their operators to bear a significant economic burden to keep them operational with the potential for degradation of flight safety of aging aircraft if they are not maintained properly [1].

Aircraft age is difficult to define. It is often referred to as simply the chronological age of an aircraft, however, this excludes many important factors. In fact, aircraft age is a combination of the chronological age, the number of flight cycles, and the number of flight hours. Determining an aircraft's age is made even more complex by the fact that individual aircraft components will age at different rates. Chronological age is particularly relevant for corrosion, as the effects of corrosion increase over time. The effects of wear on components will also increase over time. Flight cycles will cause fatigue in aircraft wings, pressurized sections, and other structural components. The number of flight hours also cause fatigue and so is another important measure of an aircraft's age.

Given the above influences, it is difficult to directly compare aircraft. However, all these factors need consideration when determining if an aircraft is 'old'. Furthermore, other factors can affect the aging process. These include the maintenance on an aircraft, the type of aircraft operations, and the

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operational environment. Difficulty arises in quantifying the effective increase in age with additional exposure to these factors. Nevertheless, it is known that these factors will increase the pace and effects of the aging process. In common, aging aircraft can be defined as an operational aircraft approaching the end of its design life assumptions.

Aging of an aircraft can be a safety issue, but with adequate maintenance, the consequences of aging can be mitigated. Current and future maintenance programs will act as a preventative measure to reduce the safety risk associated with ageing aircraft, but only if the operators adhere to the programs [2]. Some aging mechanisms such as fatigue occur through repetitive or cyclic loading. While others, such as wear, deterioration, and corrosion occur over time. If not managed, these aging mechanisms can be a significant safety concern.

Around the world, there have been a number of aircraft accidents relating to age. One of the most significant of these accidents was Aloha flight 243. On 28 April 1988, the Boeing 737-200 aircraft sustained an explosive decompression. At the time of the accident, the aircraft had been in service for 19 years and had accumulated a high number of flight cycles, where a flight cycle is one completed takeoff and landing. The combination of fatigue and corrosion affected the fuselage skin and led to the failure of the structure. In addition to the Aloha flight 243 accident, there have been a number of other accidents and incidents related to ageing aircraft. One such age related accident occurred on 12 April 1989, when the rudder of a British Airways Concorde aircraft, fractured and separated in flight. The rudder separation occurred due to ageing of the composite structure. Another accident attributed to ageing was TWA flight 800, on 17 July 1996, where deterioration of the wiring in the wing centre section led to the fuel tank explosion. These accidents and incidents have highlighted the safety implications resulting from aircraft aging and have demonstrated the importance of effective continuing airworthiness programs.

There are two basic approaches for managing the aging process. The first method is to replace the aircraft, while the second method is adequate maintenance of the aircraft. High-capacity regular public transport (RPT) operators have generally controlled aircraft age by investing in the acquisition of new aircraft to replace their older aircraft. The resultant savings in maintenance costs balance the expense of acquiring new aircraft. While the new aircraft still require maintenance, this is generally less demanding and hence less expensive than maintaining ageing aircraft. The second method of controlling aircraft ageing, ongoing additional and specific maintenance, is generally most common for general aviation and low-capacity RPT aircraft. These sectors of the aviation industry operate under tight economic constraints with limited capacity to acquire new aircraft, and in any case, the absence of suitable new production aircraft restricts their options for acquiring new aircraft. When maintenance is chosen as the mechanism to control ageing, the program needs to take into account in-service defects as well as analysis of flight critical components. Manufacturer support is important to ensure the thoroughness of the program.

Aircraft are typically designed to a specific lifespan, known as the design life of the aircraft. This lifespan allows designers to ensure that throughout the specified life, the aircraft’s structure and components operate reliably. Manufacturers test and analyze an aircraft type to ensure that the aircraft can withstand use for the period of the design life. Hence, with regular maintenance, operators can expect reliable service throughout the design life. Exceeding the design life may be possible in some circumstances, but is likely to increase maintenance costs. In some cases, the cost of maintenance may exceed the replacement cost of the aircraft. As such, it may not be economically viable for an aircraft to continue flying at some point during its life. This has led to the design life being known as the ‘economic’ design life. Aircraft owners may continue to invest in maintenance rather than outlay the large sums required to acquire new (or newer) aircraft.

The two key processes that lead to aircraft aging are fatigue and corrosion. These processes generally affect the aircraft structure, but can also affect wiring, flight controls, powerplants, and other components. Fatigue and corrosion can work independently from one another, or they can interact. The interaction between fatigue and corrosion can increase the rate of ageing to a greater extent than that due to either process alone.

Fatigue

Fatigue predominately takes place in metal components, but it can also affect nonmetallic materials. Fatigue occurs through cyclic loading patterns, where a component is repeatedly loaded. Bending a metal paper clip backwards and forwards is an example of fatigue; the paper clip will not break if only bent once, however, if it is repeatedly loaded, it will eventually break. Fatigue failures will often take place at loads much lower than the materials ultimate strength. Generally, the initiation point for fatigue will be a microscopic crack that forms at a location of high stress, such as a hole, notch, or material imperfection. The crack will then grow as loads are repeatedly applied. If not detected and treated, the crack will eventually grow to a critical size and failure will occur at loads well below the original strength of the material. The relationship between repetitive loading and fatigue crack growth creates a link between fatigue related ageing, the number of flight cycles, and the number of flight hours that an aircraft has accumulated. Aircraft components that are susceptible to fatigue include most structural components such as the wings, the fuselage, and the engine(s).

Different types of aircraft operations can influence the rate of fatigue, as they subject the aircraft structure to different structural loads. Operations that have the potential to increase fatigue include those likely to involve high-g maneuvers, such as aerobatics, aerial mustering and aerial agriculture. These operations produce increased and variable amounts of loading due to the high gust and maneuver loads. With this type of loading on the airframe, there will be an increased rate of fatigue. In addition, for pressurized aircraft, the length of a flight sector influences the fatigue rate. As an aircraft climbs, the aircraft structure will expand due to pressurization, conversely as an aircraft depressurizes during the descent the aircraft structure will contract, thus producing fatigue. Hence, the number of pressurization cycles is more important than the length of time an aircraft is pressurized. The effect of fatigue on components can be quantitatively estimated by formal methods of fatigue analysis. Mathematical modeling can predict the rate of crack growth and determine the crack length at which a fracture may occur. This length is known as the critical crack length. This type of fatigue analysis can be used to determine inspection intervals and/or retirement times. To predict the rate of crack growth and the critical crack length, mathematical models take into account the expected loading on the aircraft over its design life and knowledge of the load paths within the structure.

Fatigue was not considered in the design of early aircraft. Instead, the design criterion was maximum strength. Once fatigue was identified as a failure mechanism it was recognized that it needed to be managed, and that management of fatigue should begin in the design phase. The increased understanding of fatigue led to the introduction of design techniques such as safe-life, fail-safe, and damage tolerance. By today’s standards, some earlier methods are no longer considered best design practice. The different design methodologies are discussed below;

Safe-life

Safe-life (also known as safety by retirement) was introduced in the 1940s after fatigue was recognized as a failure mechanism. It specifies a ‘safe’ lifespan within which there is no significant risk of structural failure of a component. The replacement of components must occur before the component reaches its safe-life to ensure flight safety. Today, the safe-life methodology is only used in a few applications such as the design of some general aviation aircraft, and the design of some structures where the critical crack length is too small to be detected prior to a failure.

Fail-safe

The fail-safe design principle was introduced in the 1950s as an improvement to safe-life. A fail-safe structure should be able to sustain the limit load even when one of the elements has failed. To achieve this requirement, a fail-safe design uses backup structures and secondary load paths. This principle relies on the fact that if the main load path fails, there is a secondary load path to ensure the safety of the aircraft until the failure can be detected.

*Damage tolera*nce

Damage tolerance, or safety by inspection, was developed as a design philosophy in the 1970s as an improvement on the fail-safe principle. The damage tolerance approach is based on the principle that while cracks due to fatigue and corrosion will develop in the aircraft structure, the process can be understood and controlled. A key element is the development of a comprehensive program of inspections to detect cracks before they can affect flight safety. That is, damage tolerant structures are designed to sustain cracks without catastrophic failure until the damage is detected in scheduled inspections and the damaged part is repaired or replaced (see Figure 1). In addition, damage tolerance takes into account initial material or manufacturing flaws by assuming an initial crack, which the fail-safe principle does not do.

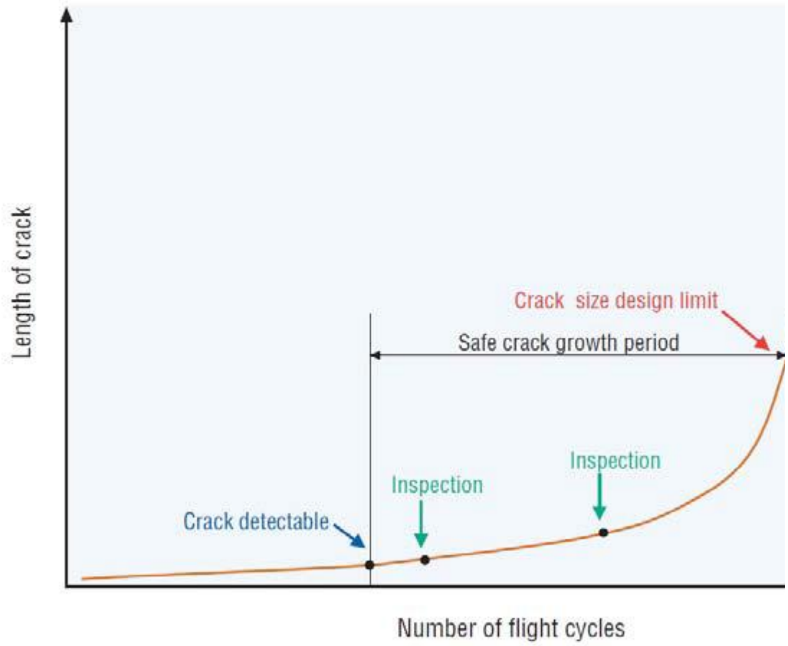

Figure 1: *Theoretical damage tolerance inspection regime to detect cracks before they become critical*

A damage tolerant design should allow cracks to be detected before they reach the critical length that will lead to failure. To ensure that this occurs there should be at least two opportunities to detect the crack prior to it reaching its critical length. The damage tolerance philosophy uses testing and analysis to determine the critical crack length, the residual strength, and the inspection intervals. Tests include flight testing to determine the loads on the structure, and ground testing to determine the fatigue and crack growth characteristics. From the testing and analysis, the critical sites and components susceptible to fatigue can be determined. Fatigue analysis based on flight, ground, and pressurization loads can then be used to determine crack growth performance and residual strength. To increase the likelihood of finding a crack prior to a catastrophic structural failure, the structure should be durable. Durability of an aircraft structure comes from having a slow crack growth characteristic and the ability to contain or restrict the progress of damage.

Corrosion

Corrosion is a time dependent failure mechanism that occurs as a result of chemical or electrochemical degradation of metal. Corrosion generally affects the aircraft structure, however, it can also affect electrical connectors and flight control cables. Corrosion is more prevalent in marine and coastal environments where there is high humidity and salt water. Salt can increase the rate of the chemical reactions that initiate corrosion. This has significant safety implications for the structures of seaplanes, as they are constantly exposed to salt and humidity. To prevent or slow down the rate of corrosion, an aircraft's design will incorporate a number of corrosion control methods. These include material selection, material coatings, joint design, and the use of water drainage. Corrosion cannot be eliminated in design, so regular maintenance and inspections are used as additional control measures.

The processes of fatigue and corrosion can interact, leading to an increased likelihood of structural failure. Corrosion can weaken the material and create locations of stress concentration. These locations of high stress are often initiation points for fatigue, and can lead to the failure of the structure earlier than predicted. The failure can also occur in unexpected locations, making detection prior to failure difficult. While corrosion can be a significant safety concern, the combination of fatigue and corrosion is of greater concern to safety than corrosion alone.

Components that age

The various components that make up an aircraft will age differently depending on their materials and usage. Of particular importance are components that are critical to flight safety. Flight critical components can be categorized into three areas are structures, power plants and other systems. Aircraft structures include the fuselage, wings, empennage, and flight control surfaces. These components are particularly susceptible to fatigue as they often experience cyclic and dynamic loading. Generally, aircraft structures are constructed of metal so they are also at risk of corrosion. Although the majority of aircraft structures are metallic, other materials such as carbon fiber composites, wood, or canvas can be used. These materials will not necessarily be subject to the same ageing processes as traditional metallic structures; however, the aging process will occur in other ways.

The overall strength of an aircraft structure will depend on the individual strengths of the components that make up the structure. The strength of one component can be different to the strength of another component with the same design and manufactured from the same materials. This difference may result from manufacturing variations or the reduction in the strength of the component because of fatigue or corrosion. Because of these differences, there will always be some variability in the failure times of components of the same design.

Whole of aircraft reliability

Reliability is defined as the ability of a component to perform its intended function for a specified time. For an aircraft, reliability is the probability that the aircraft as a whole, or a particular system, subsystem, or component will function as intended for the duration of the flight. The overall reliability of a system or component throughout its life has been described as following a 'bathtub curve'. The lifecycle in the bathtub curve, shown in Figure 2, involves three phases which are infancy, useful life and wear out. During infancy, the failure rate decreases over time, as many failures are due to material flaws or problems in manufacture. This phase is less relevant when considering aging aircraft. In the useful-life phase, failures due to initial flaws gradually decrease while failures due to wear-out gradually increase. Therefore, the average number of failures remains relatively constant throughout the useful-life phase. During the wear-out phase, failures will increase as the product reaches the end of its useful life.

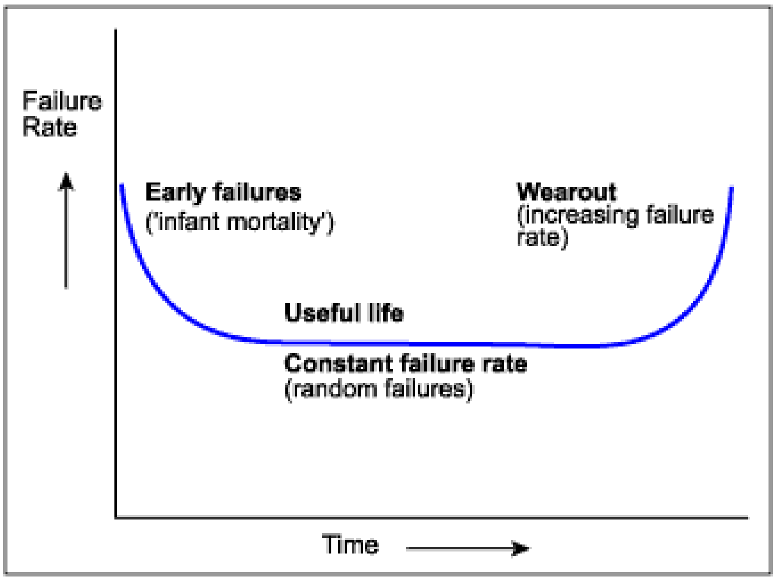

Figure 2: *Bathtub Curve*

The bathtub curve is only a simplified form of reality. For example, the curve does not take into consideration that even while the failure rate is constant, ageing is occurring [2].

METHOD

Influence of maintenance on aging

Aging of equipment and components cannot be prevented but slowed down. It is reasonable to say that if maintenance is poorly or not timely conducted certain aging effects (e.g. wear and tear, contamination, corrosion, etc.) could be accelerated or even started. This means that the physical condition of aged equipment and components in different aircraft can vary due to different quality of maintenance carried out which could result in earlier retirement of components than assigned. Aircraft maintenance programs will always be a compromise as beside others logistic costs and overall fleet management are important issues, which drive their definition.

In view of this and to address aging problems, it is important to include preventive maintenance actions for critical equipment and areas, at shorter intervals in periodic servicing schedules or in special inspections, to ensure that aging problems will be detected in an early state where the effort for repair is still acceptable and an airworthiness critical situation far away [3].

Equivalent Flight Hours

The service life of the C-130s' are determined by equivalent flight hours (EFH). EFH is calculated with following equation:

$$EFH = \text{Severity Factor} \times \text{Actual Flight Hours} \qquad (1)$$

A severity factor accounted for the difference between normal civilian flying and military flying (low level, short-field landings, etc.). Mission profile determined the severity factor, which was averaged over each aircraft's most recent two year history. This calculation translated airframe clock hours into equivalent airframe damage hours which would indicate the higher aging rate of the military airframes. On average, active C-130 aircraft were found to be flying approximately 600 hours per year.

Fatigue cracking of wing primary structure on full scale durability tests conducted by Lockheed Martin Aeronautics Company and also discovered on some aging in-service aircraft has initiated a need to ensure adequate inspection requirements are established to continue safe operation. Analysis of in-service cracking data indicates that rates of fatigue crack propagation vary significantly between individual aircraft and are related to the types of missions flown and operational usage parameters.

The critical fatigue component for the C-130 fleet is the center wing box, which is structurally more susceptible to the stresses of mission profile and payload. The center wing box has a limit of 45,000 EFH. A corrosion limit of 40,000 flight hours was based on historical data and engineering judgment. This data took into account corrosion factors not considered in airframe fatigue analysis. Actual airframe service life depends on which limit, fatigue or corrosion, is reached first.

Initial Usage Assessment

An initial assessment of the wing lower surface severity factors can be made by using the information provided in Table 1. Severity factors are provided for various combinations of average take-off cargo weights and average cruise altitudes. While this is not a comprehensive means to determine severity factors, it will approximate the severity of usage. Average values of take-off cargo weights and cruise altitudes should be computed from available records where possible and/or aircrew interviews. The intent is to obtain reasonably accurate data that describes the average usage of the aircraft. It is likely that a combination of representative missions (cargo weight and average cruise altitude) will be needed to describe the typical usage; in this case, an assessment of the percentage of flight hours accumulated by the fleet with each combination of representative mission is required.

For aircraft that have an Operating weight Empty (OWE) of more than 78,500 lbs, the effective cargo weight must be used in Table 1 and is calculated as follows:

$$\text{Effective Cargo Weight} = \text{Gross Weight} - \text{Fuel Weight} - \text{OWE} \qquad (2)$$

For aircraft that have an OWE of equal to or less than 78,500 lbs, the actual weight of cargo (payload) is to be used. Operating Weight Empty is defined as the empty weight of the aircraft + usable trapped oil + unusable fuel + aircrew + food/water + cargo restraint devices.

It is recognized that current usage data may not be representative of historical usage data, particularly when the aircraft has had more than one operator/owner. In this case, best judgment must be used to evaluate the historical usage. Typical military usage of the C-130 during 1960's through the late 1970's had overall lower surface severity factors of 0.7 to 1,5; however, aircraft that flew in the special operations role consisting of low-level mission were in the range of 3.0 to 6.0.

Table 1: *Initial Assessment of Usage Severity Factors for Wing Lower Surface*

		Average Take-off Cargo Weight (x1000 Pounds)			
		0-<10	**10-<20**	**20-29**	**>29**
Average Cruise Altitude (x1000 Feet)	**>18**	0.5	0.75	1.0	1.5
	12-18	1.0	1.5	2.0	3.0
	5-<12	2.0	3.0	4.0	6.0
	0-<5	3.0 4.5	4.0 6.0	6.0 9.0	9.0 14.0

Actual flight hours accumulated on the center wing and outer wing should be multiplied by the resulting severity factor determined from Table 1. An example of this calculation is provided in Table 2. Typical average usage consists of four basic mission types:

- Short range logistics missions with an average cruise altitude of 11,000 feet and average take-off cargo weight of 17,000 lbs. The Table 1 severity factor is 3.0.
- Long range logistics missions with an average cruise altitude of 21,000 feet and average take-off cargo weight of 12,000 lbs. The Table 1 severity factor is 0.75.
- Pilot training mission with an average cruise altitude of 7,000 feet and average take-off cargo weight of 1,000 lbs. The Table 1 severity factor is 2.0.
- Tactical low-level training mission with an average cruise altitude of 3,000 feet and average take-off cargo weight of 8,000 lbs. The Table 1 severity factor is 4.5.

The percentage of fleet average actual flight hours of each mission (mission utilization) is used to obtain the flight hours accumulated on the component from each mission type. In the above example, assume the actual total flight hours accumulated on the component is 16,000 and the average mission utilization mix is: 25% short range logistics, 50% long range logistics, 12.5% pilot training, and 12.5% tactical low-level training. The flight hours on the component due to each mission type is then calculated as in Table 2. The actual component flight hours accumulated for each mission type are then multiplied by the assessed mission severity factor to obtain EFH. This calculation can be done for each individual aircraft, or for the fleet average aircraft. The resulting total EFH is divided by the actual component flight hours gives the average usage severity factor.

Table 2: *Equivalent Flight Hour Calculation Example*

Mission Type	Utilization %	Component Flight Hours	Severity Factor	EFH
Short Range Logistics	25.0	4.000	3.0	12.000
Long Range Logistics	50.0	8.000	0.75	6.000
Pilot Training	12.5	2.000	2.0	4.000
Tactical Low-Level Training	12.5	2.000	4.5	9.000
TOTAL	**100**	**16,000**	**1.94**	**31,000**

The results of the Initial Usage Assessment should be used by the operator to determine the appropriate course of action. Subsequent action will depend on the results of the initial assessment and are provided in Table 3.

Table 3: *Wing EFH Range - Recommended Actions Based on Initial Usage Assessment*

Category	Center Wing EFH Tables 1 & 2	Outer Wing EFH Tables 1 & 2	Operational Usage Evaluation	WFD Inspection Program	Flight Restrictions	Grounding
A	<30.000	<15.000	X			
B	30.000-39.999	15.000-19.999	X			
C	40.000-45.999	20.000-25.999	X	X		
D	46.000-50.000	26.000-30.000	X	X	X	
E	>50.000	>30.000	X	X		X

Due to the potential safety of flight risk, Lockheed Martin Aeronautics Company strongly recommends that the Table 3 Recommended Actions be implemented as follows:

- Category A – Within 365 days of the Initial Usage Assessment
- Category B – Within 180 days of the Initial Usage Assessment
- Category C – Within 90 days of the Initial Usage Assessment
- Category D – Within 60 days of the Initial Usage Assessment
- Category E – Within 30 days of the Initial Usage Assessment

Flight Restrictions

For center wings with 38,000 or greater EFH, it is recommended that these aircraft be restricted within 60 days of completing the initial usage assessment and the restrictions remain in effect until the full Operational Usage Evaluation is performed and WFD inspection program is completed. Some of the Recommended Flight Restrictions are as follows:

- Maximum gross take-off weight reduced 10%,
- Maximum airspeed reduced,

- Maximum symmetrical and asymmetric (rolling) maneuver load factor +2.0g clean and +1.5g flaps extended,
- Avoid flight in moderate and greater turbulence,
- Avoid abrupt maneuvers. Abrupt maneuvering is defined as rapid input of controls (pitch, roll and yaw) such that maximum control input is achieved in approximately 0.5 seconds or less.

For center wings exceeding 45,000 EFH, it is recommended that the aircraft be grounded within 30 days of performing the initial usage assessment and the aircraft remain grounded [4].

RESULTS

EFH for TurAF C-130 fleet is ranging from 15205 through 30733. In the current situation aircraft have an average EFH of 750 throughout the year, which will cause restrictions by 2022 (38,000 EFH) and aircraft will begin grounded by 2031.

For center wings with 30,000 or greater EFH, an inspection program to detect generalized cracking and possible onset of Widespread Fatigue Damage (WFD) instituted in accordance with 2nd ASMC Time Change Technical Order (TCTO) based on Service Bulletin 82-790, which includes center wing general cracks and common fatigue damage inspections.

TCTO 82-790 applied to two C-130B aircraft to date with tail numbers 61-0963 and 58-0736, which have center wings exceeding 30,000 EFH. Analytical control package included inspection of 53 different structural zones of the aircraft. For aircraft with tail number 61-0963, 2 cracks detected in the "bulkhead cap" located between fuselage stations (FS) 477-617 (Figure 3) and in the "edge of paratroop door opening" located in FS 737 (Figure 4). For aircraft with tail number 58-0736, 1 crack detected in the "front beam" located in the center wing station (WS) 82 (Figure 5). All cracks repaired and the aircraft given to service. Reduced analytical control package applied to another aircraft even center wing EFH not exceeded 30,000, since the outer wings are FY73 type. Reduced analytical control package included inspection of 19 different structural zones and neither cracks nor deficiencies found. Another reduced analytical control package, included inspections of 11 different structural zones, applied to 63-13186 tail number aircraft due to hard landing. 3 cracks detected in the "chine cap" located in fuselage FS 255, right and left main landing gears "self cut-out" radius zones (Figure 6) [5].

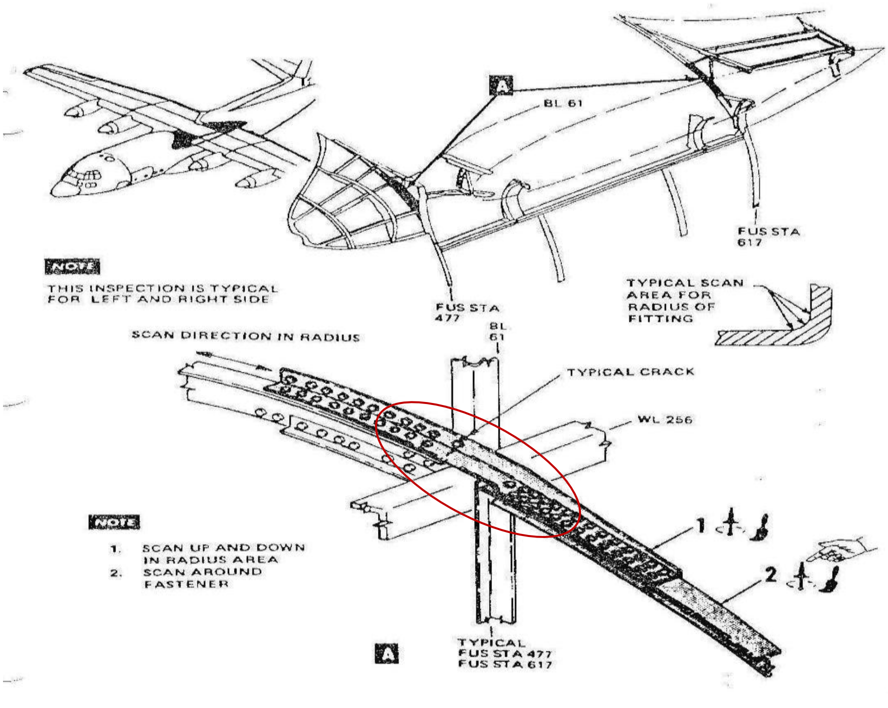

Figure 3: *"Bulkhead cap" located between fuselage stations FS 477-617*

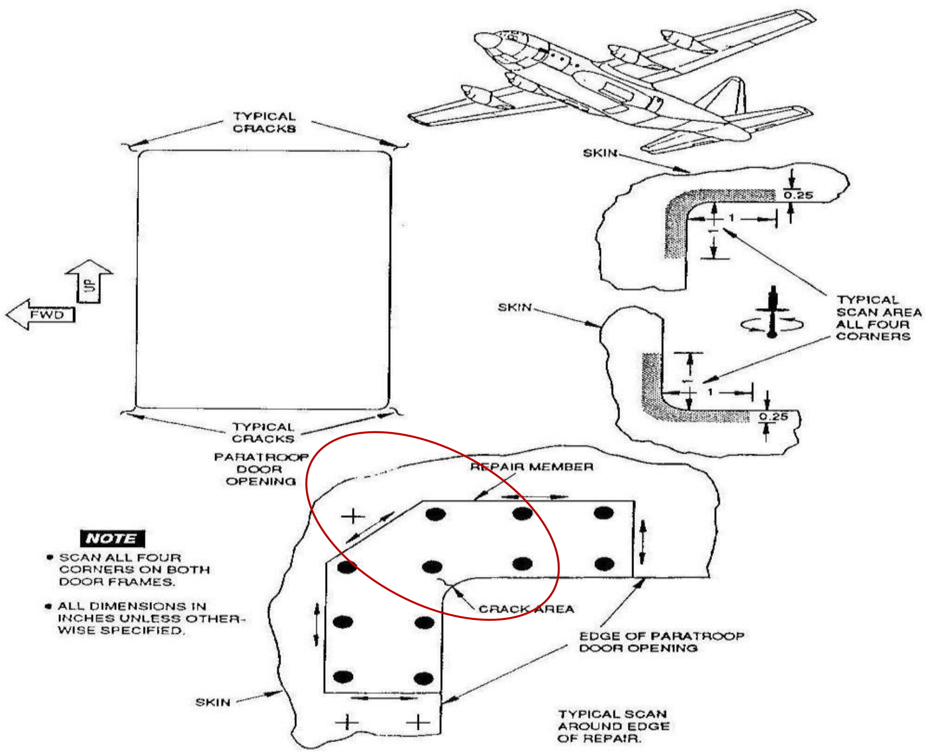

Figure 4: *“Edge of paratroop door opening” located in FS 737*

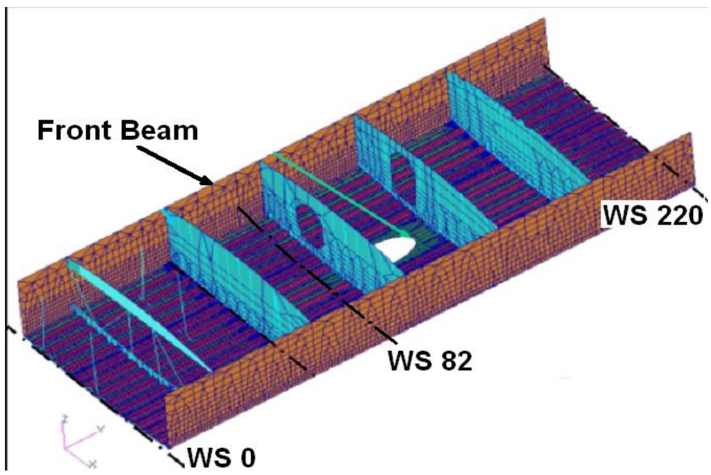

Figure 5: *“Front beam” located in the center wing station WS 82*

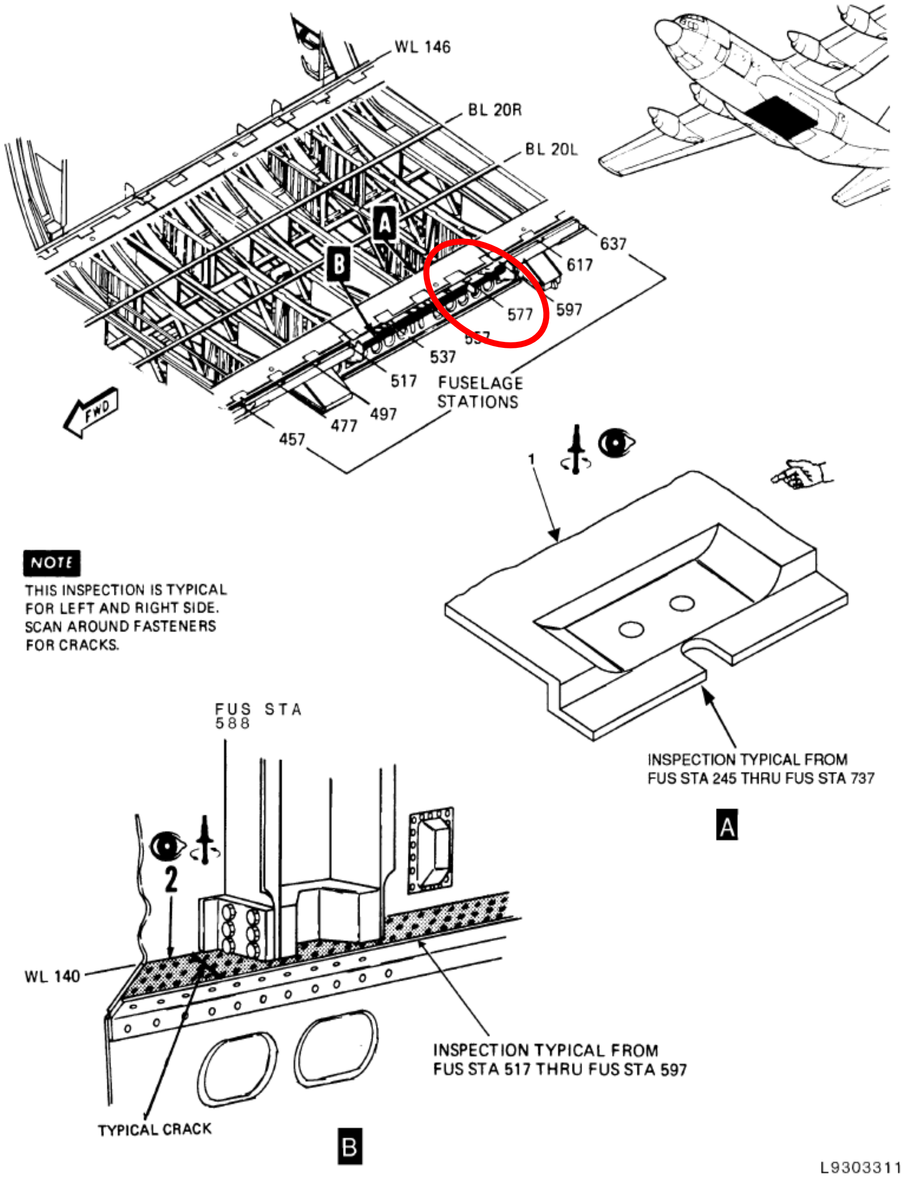

Figure 6: *“Chine cap” located in fuselage FS 255*

CONCLUSIONS

As a result of experience gained during analytical controls, two TCTO’s are prepared and published in order to check all C-130 aircraft in the fleet. TCTO 1C-130-0133 includes inspection of the “bulkhead cap” and the “fitting” located between FS 477-617 where TCTO 1C-130-0134 includes inspection of the “edge of paratroop door opening” located in FS 737. Analytical control program is continuously implemented for aircraft with 30,000 or greater center wings EFH, where reduced analytical control packages are applying to aircraft with center wings EFH less than 30,000 when needed. It is considered that analytical control studies conducted in 2nd ASMC have significant impacts to flight safety for aging C-130 fleet of TurAF.

Acknowledgements

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