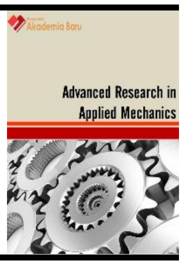
Penerbit Akademia Baru

Journal of Advanced Research in Applied Mechanics

Journal homepage: http://www.akademiabaru.com/submit/index.php/aram/index
ISSN: 2289-7895



Damage Tolerance Assessment Towards Structure Integrity For C-130 Aircrafts Of Royal Malaysian Air Force

Arvinthan Venugopal[1,*], Roslina Mohammad[1], Saardin Abd Aziz[1]

[1] UTM Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

ABSTRACT

Military transport aircraft are vulnerable to the destructive impacts of boundless exhaustion harm caused by cyclic loading and natural conditions in which the aircraft operates. These factors severely affect the aircraft structure's integrity and safety, material performance can be significantly degraded by these factors. The Air Force's aircraft's structural safety is a vital issue affecting aircraft airworthiness in the current era. Due to this alarming issue, the need for a thorough study is critical to determine the impact of structural fatigue on C-130 aircraft in the Royal Malaysian Air Force (RMAF) fleet. This study's methodology uses the correlation of years in service to accumulated fatigue and cyclic loading to study the concept of aircraft aging in military aircraft. The data provided by this C-130 aircraft through an audit is to determine the critical fatigue areas and flight load conditions. Finally, it uses the concept of crack mapping and statistics from the Aircraft Structure Defect Report provided by flying squadrons in the RMAF to evaluate the structural deterioration. This study contributes to a design change review of the current aircraft maintenance plan. Furthermore, this will be the platform to embark on the Aircraft Structure Integrity Program (ASIP) for the RMAF C-130 aircraft.

Keywords:
Royal Malaysian Airforce, C-130, Aircraft Structure Integrity Program, Structure Fatigue

Received: 1 February 2021 **Revised: 30 March 2021** **Accepted: 10 May 2021** **Published: 10 July 2021**

1. Introduction

The Royal Malaysian Air force (RMAF) was formed on the 2nd of June 1958 and was known as the Royal Federation of Malaya Air Force. From the year 1958 till today, the RMAF underwent gradual modernization, and currently, it has 13 bases all over the country that houses radar, training centers, or aircraft. It aims to provide air dominance anywhere in the country, and the RMAF has to have a strong aircraft fleet to achieve its aim and goals.

As it enters the twenty-first century, the RMAF faces challenges in its mission to maintain a capable, state-of-the-art air force. Aircraft in the commercial world or with the military will eventually reach a stage after specific operation years, called structure fatigue. Structure reliability is affected by the two most common factors, which are fatigue and corrosion. It is challenging to determine when an aircraft's structure has reached its critical fatigue life since it is induced by continuous cyclic loading.

* *Corresponding author.*
E-mail address: arvinthanvenugopal@yahoo.com

Many in-service aircraft are required to operate beyond their original design life due to the accelerating costs of the replacement and the ability to upgrade systems in old airframes. As part of the life extension program and aging aircraft audit, RMAF has conducted the structural inspection of several military airframes. This involves dismantling a representative example of older airframes of a particular aircraft type and making a thorough inspection of each component to assess its condition. This teardown of aircraft has enabled the assessment of components that would not commonly be addressed during routine maintenance because of their inaccessibility. Historically, most of the structural failures examined have been in metallic materials, reflecting the predominance of metallic structures in aircraft. The RMAF currently operates aircraft from legacy years, such as the C-130H, S61A-4, MiG-29N, and F/A-18D, which have operated for around 24 to over 50 years [1].

The airframe fatigue design principles are divided into the safe life related to flight hours and the loading spectrum, while damage tolerance allows for damage to growing with repairs included. Throughout any aircraft's service life, its structure is subjected to various complex loads ranging from frequent fluctuating loads with small amplitudes or huge loads that approach the ultimate strength[2].

Fatigue in metallic materials grows in three stages: crack nucleation, crack propagation, and failure. Failures happened due to the material's natural characteristics or damage subject to the material due to the manufacturing or in-service process. Most damages occur due to mechanically or thermally induce loading, environmental effects to component or material characteristics [3].

1.1 Fatigue as a Limiting Structural Life Factor

Fatigue is one of the primary mechanisms causing the deterioration of an aircraft’s structure during its lifetime. Landings, take-offs, and maneuvers subject the structure of an aircraft to repeated stress over its lifetime. This is referred to as cyclic or alternating loading, as shown in Figure 1. Cyclic loading causes fatigue cracks to form in the structure. These cracks grow longer with each stress cycle, degrading the aircraft’s structural strength [4]. A crack initially grows slowly, but the rate accelerates as these cycles accumulate, to the point at which rapid crack growth results in a fracture. Thus, one of the critical design criteria for an aircraft is to endure accumulated fatigue damage over its service life to prevent structural failure [5].

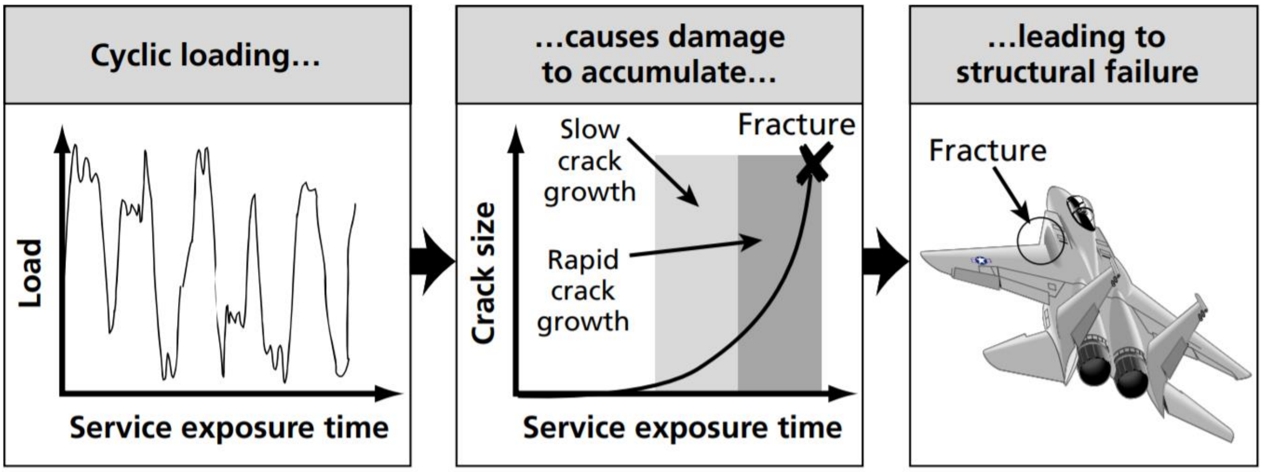


Fig. 1. Fatigue Cracks under cyclic loading and structural failure

1.2 Fatigue Design Concepts: Damage Tolerance Vs. Safe-Life

There are two distinct design approaches for protecting an aircraft's structure from failure due to fatigue damage: safe life and damage tolerance, as shown in Figure 2. These fatigue design approaches differ in how they model damage growth, what they assume about the initial conditions of materials, and the failure criteria they use to establish the aircraft's original design service life [6]. The fundamental difference between these is that the safe-life approach assumes that no fatigue cracks will exist in the structure during the specified lifetime for safe operation; the damage-tolerance approach assumes that potential fatigue cracks may exist in critical locations in fracture-critical parts. For practical purposes, the safe-life approach does assume that tiny fatigue cracks may exist. The damage-tolerance approach requires that the structure tolerate slowly developing cracks safely until they can be detected and repaired [7].

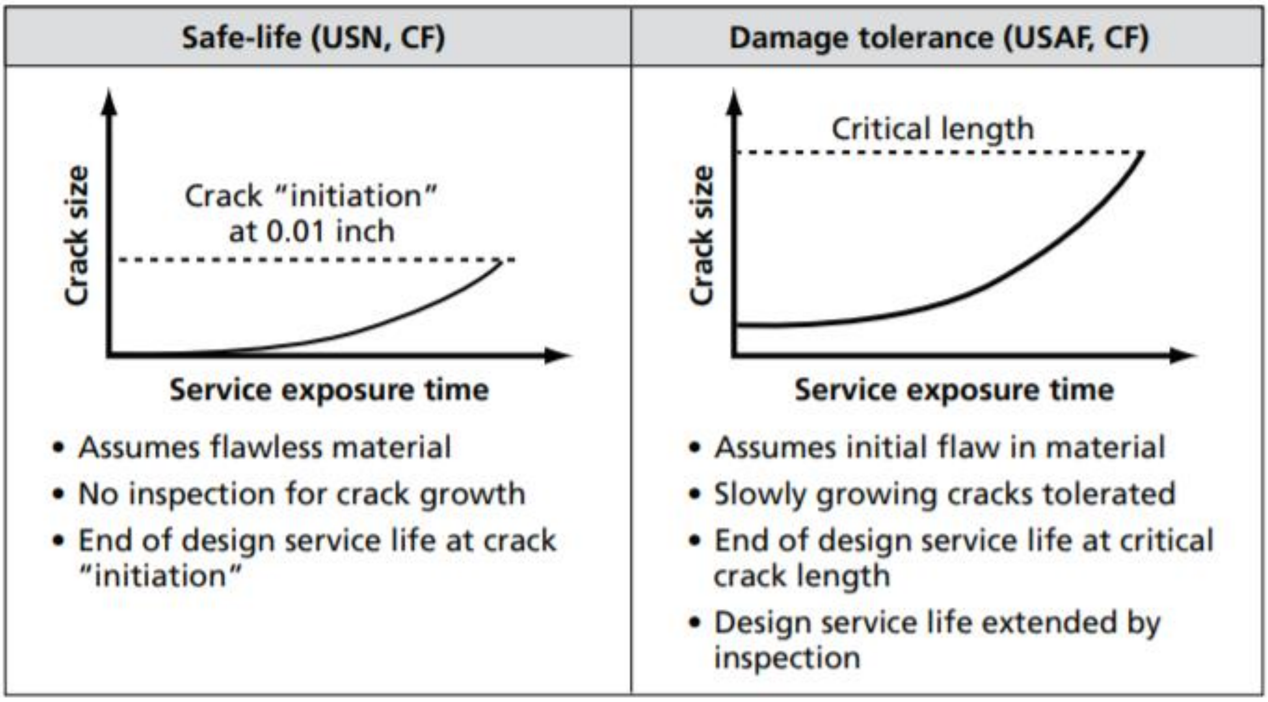


Fig. 2. Comparison of Safe-Life and Damage Tolerance

2. Study Methodology
2.1. Fatigue Testing Method

A fatigue test is carried out to define fatigue life and danger point like the point of failure on a test-piece exposed to a series of stress amplitude, which finally determines the aging factor for the specified aircraft. By idealizing the test settings, it would likely vary one or a few factors affecting fatigue life. However, although these conditions are satisfied, there will always be some unknown and uncontrollable causes that produce a large scatter in fatigue life. The method used for determining the critical fatigue location and its contributing factors, which is the first research objective, is done through the Non-Destructive Test [8].

2.1.1. Non-Destructive Test

Aircraft structures or components are inevitably subjected to fluctuating stress, and hence, irrespective of prone to defect or crack initiation, and leads to the ultimate failure by fatigue fracture. Fatigue failure is a gradual form of local damage determined by many factors, such as the magnitude and frequency of the loads introduced on the element [9].

Figure 3 the C-130 assembly is divided into five primary groups: the fuselage, wing, tail, landing gear, and nacelle group. These areas are then analyzed individually to determine the location for the high-stress concentration area.

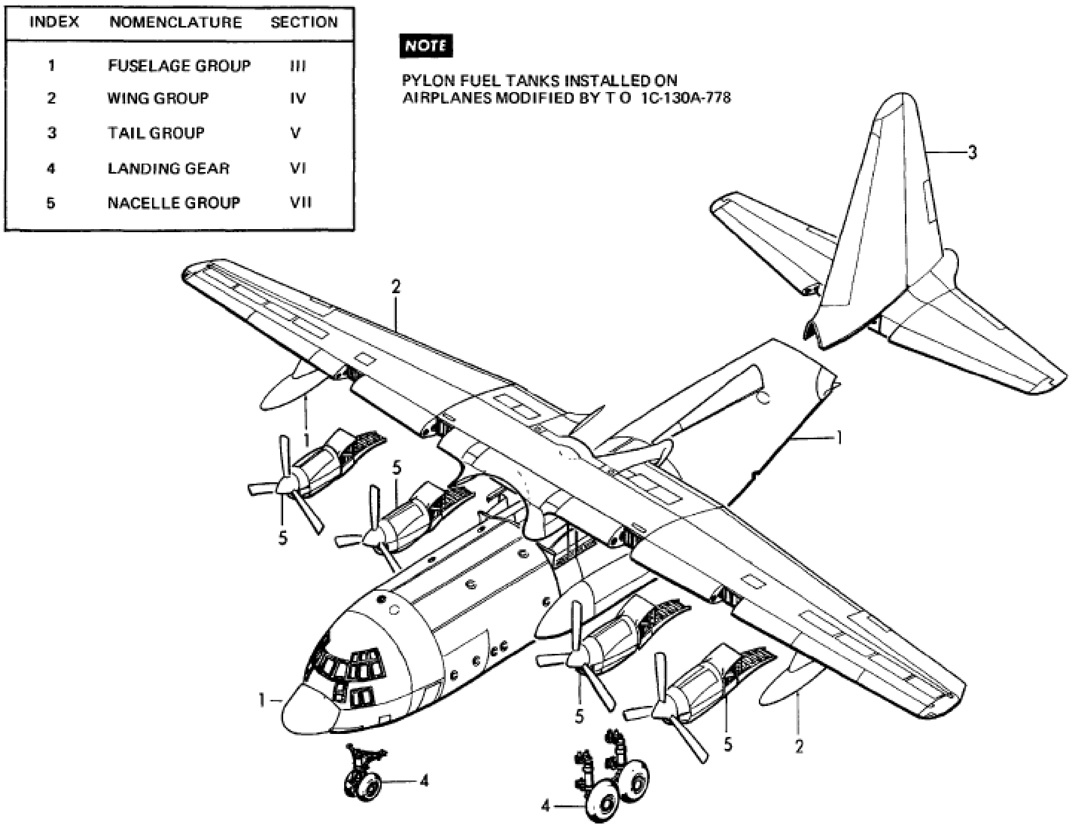


Fig. 3. C-130 Major Group Assembly

Proper maintenance such as scheduled maintenance or inspection of aircraft components in advance will prevent such failures. One of the most appropriate inspections that are widely used currently is the Non-Destructive Test. NDT examines the structure and components of the C-130 series airplane for defects on the surface or inside the material or hidden by other structures without resorting to damaging the part [10].

For the C-130 aircraft that uses the damage tolerant design concept, the user is to inspect its structure periodically for any cracks or deterioration besides replacing them if they are beyond limitation. This inspection approach usually uses NDT technology and requires an accurate prediction of the rate of crack growth or corrosion between inspections [11]. The most commonly used method of NDT is as below [12].

a. Visual Inspection
b. Liquid Penetrant Inspection
c. Radiographic Testing

d. Ultrasonic Testing
e. Eddy Current Testing

The inspection method selected for an area depends on several factors, namely accessibility, portability, type of defect, the material of part, and degree of sensitivity required. Besides that, the discontinuity dimensions can also be determined in the NDT method, such as depth or width [9]. Several types of NDT techniques can be used, such as Ultrasonic inspection, Magnetic particle Inspection, Eddy current inspection, Liquid penetrant inspection, and Visual inspection to inspect the aircraft structure's cracks. Eddy current testing can identify surface cracks and can be used only for conductive components. The magnetic particle inspection method is only applicable for Ferro-magnetic components. The liquid penetrant test can only be used to detect cracks visible to the surface [13]. However, Ultrasonic and X-ray NDT methods can detect surface and subsurface defects with a high degree of sensitivity of any material with minimal surface preparation. These two methods can also be used to inspect assembled components. Therefore, considering these factors, Ultrasonic and Eddy current methods are selected as the most efficient methods used in this research. Using these two NDT methods, the crack sizes in the critical points of the aircraft are identified [14]. These cracks must be found, and crack shape must be measured to analyze fatigue cracks aircraft structures, size.

2.2 Historical Data Review

The critical fatigue location is commonly subjected to various kinds of loads. It is crucial to continually monitor these locations as discrepancies such as cracks, corrosion, and other failures usually occur in these areas. In order to determine the critical fatigue location for the chosen C-130 aircraft, a review on the aircraft structural, historical data such as the Aircraft Structure Defect Report, Organisational and Intermediate Level Maintenance form in *Sistem Pengurusan Komputer Bersepadu (SPKB),* and technical service maintenance data was performed. This data provided by the flying squadron is vital in ensuring the current and historical condition of the aircraft structure.

2.3 Selection of Parameter

The data collection parameters for this study as stated in Table 1. The parameters were fixed based on the available kinds of literature. The parameters will be used on all four aircraft which are the investigated samples. The research was conducted on four C-130 transport aircraft, of which two are from the Subang Air Base and another two aircraft from the Labuan Air Base. Since they have the highest airframe flying hours, these aircraft were chosen, providing vital data from their flying operation.

3. Result and Discussion

The results were grouped based on the structural area and structural location. The structural area consists of the fuselage, wing group, tail group, landing gear, and the nacelle group, while the structural location consists of primary structure, secondary structure, and nacelle. The data are presented based on the aircraft tail number.

Structural crack occurrences on the RMAF C-130 fleet directly affect the fleet's operational availability (Ao). This situation will be even more critical if the RMAF does not have adequate spares or specialists to replace or repair the cracks. Identifying the aircraft's critical fatigue location would be an added advantage to the organization to detect the failures earlier.

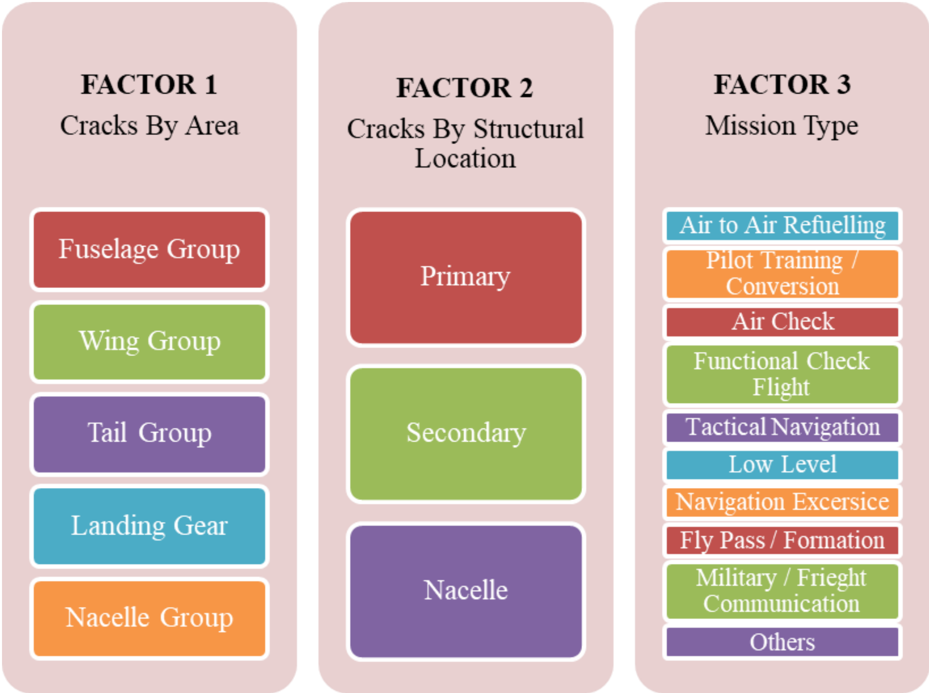


Fig. 4. Research Parameters

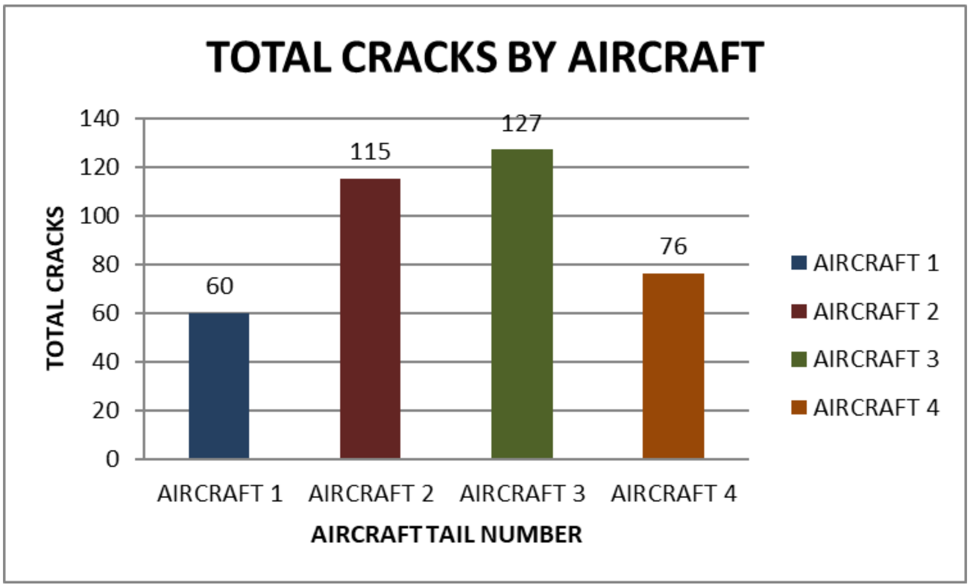


Fig. 5. Total Crack Occurrences from year 1994 to 2018

Figure 5 depicts the total cracks found on the four aircraft which were under study. Based on the data collected, 726 cracks were found on the four aircraft studied from 1994 to 2018. The highest amounts of cracks were on Aircraft 3, with 127 cracks, while the lowest numbers identified were on Aircraft 1, with 60 cracks.

3.1 Crack Analysis by Structural Area

To develop the condition monitoring database, we need to consider the primary factors to be analyzed on each aircraft structure. Based on the factors outlined in this chapter, the C-130 structure will be analyzed based on individual aircraft tracking for cracks by area and cracks by structural location. The crack data are divided into the five main groups of a C-130 aircraft.

The summary of the crack data by structural area for all four aircraft is depicted in Figure 3. The results were attained based on the historical data and current structural assessment from 1994 to 2018.

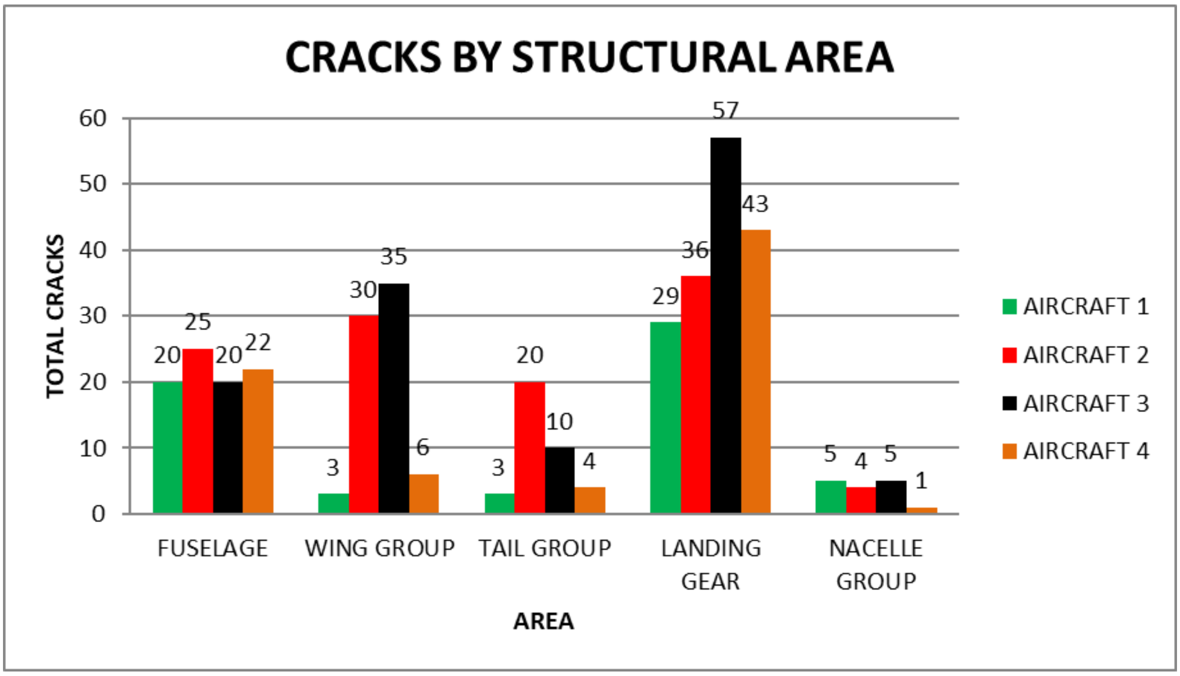


Fig. 6. Cracks by Structural Area

Based on crack frequency analysis performed, 378 cracks were detected on all four structures from 1994 to 2018.

Sixty cracks occurred on the structure of aircraft 1. This aircraft recorded the lowest number of cracks from all four aircraft that were studied. The most critical area for cracks to occur on this aircraft is at the landing gear area, in which 48% of the total cracks occurred at this area.

Aircraft 2 recorded 115 cracks on its five structural areas that were inspected. Based on Figure 3, this aircraft's critical area is highly likely at the landing gear group since that area has recorded the highest number of cracks.

Besides that, there were 127 cracks found on aircraft 3. This aircraft recorded the highest number of cracks amongst all four aircraft. The area prone to damage or recorded a high frequency of cracks in the landing gear has 57 cracks. This aircraft, the C130 – utility aircraft model, was initially built as a short version aircraft. However, the structural modification was performed on this aircraft to extend its airframe length in 2001. The semi-monocoque fuselage design of this aircraft is subjected to various loads. Primary bending loads are taken by the longerons, which usually extend across several points of support. Other longitudinal members, called stringers, supplement the longerons. The vertical structure members, bulkheads, frames, and formers, are located at intervals to carry concentrated loads where fittings are used to attach other units such as wings, power plants, and stabilizers. The high number of tracks recorded at the landing gear area of this aircraft is highly like due to the extensive loads acting on that area, such as bending, shear, and tension loads.

3.2 Crack Analysis by Structural Location vs. Mission Profile, Airframe Hours and Equivalent Based Hours

Lockheed Martin AMS has produced the life limits for the International Military and Commercial C-130 center wing service, incorporating the same methodology. The document related to the inspection is stated in the Service Bulletin (S.B.) 82-788 and released in 2005. The S.B. requires the operators to calculate the EBH hours using the table given besides the subsequent actions given in a series of categories related to the center wing EBH:

a. Lockheed Martin Aeronautics Operational Usage Evaluation, thorough evaluation of aircraft severity factor and determination of EBH.

b. Widespread Fatigue Damage (WFD) inspections are required for center wings with greater than 40,000 EBH.

c. Operational Restrictions required for center wings with greater than 46,000 EBH.

d. Aircraft Grounding required for center wings with greater than 50,000EBH.

e. Successful implementation of WFD inspections and subsequent repair action can relieve operational restrictions and grounding actions.

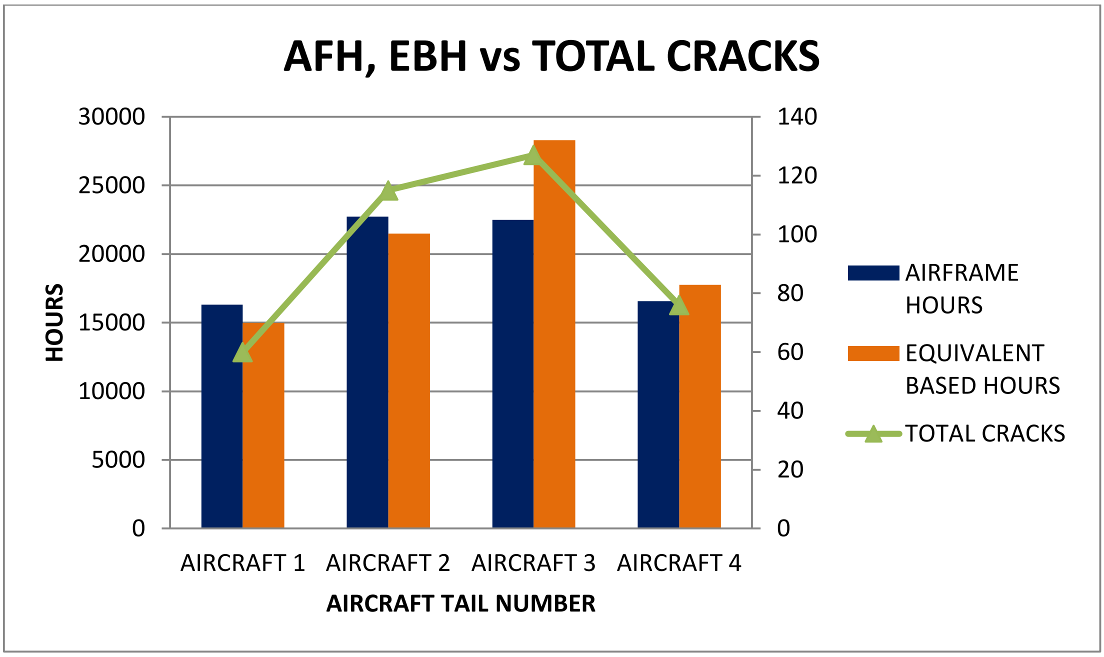


Fig. 7. Airframe Hours, EBH, and Total Cracks

Table 2: Aircraft Mission Profile

MISSION	NO OF MISSION				AVERAGE SEVERITY FACTOR
	AIRCRAFT 1	AIRCRAFT 2	AIRCRAFT 3	AIRCRAFT 4	
AAR	205	0	0	0	3
MCT / CAT / CONV	15	325	280	150	2
AIR CX	20	11	15	10	1
FCF	25	35	30	15	1
TAC NAV	10	20	19	2	3
LOW LVL	15	40	41	0	7
NAVEX	15	56	50	0	2
FLY PASS / FORMATION	5	10	25	30	1
MILITARY / FREIGHT COMM	25	130	210	300	2
OTHERS	20	15	20	20	1
TOTAL	**355**	**642**	**690**	**527**	

Figure 8 shows the relations between the total airframe hours, EBH, and total cracks, while Table 2 shows the aircraft mission profile performed for each aircraft. Total flying hours on an aircraft may affect its structural integrity. Flying hour totals on an airframe contribute to fatigue cracking and can reasonably affect its integrity. Aircraft which fly much more frequently than other aircraft may impose continuous cyclic loading on their structure. Based on the mission profile performed by these aircraft, aircraft three are tasked to perform the Military / Freight Communication and Training / Conversion as its main profile. This aircraft, the C-130 model, is a utility aircraft; besides, this aircraft has also been involved in low-level flying around 70 times. Furthermore, the average severity factor for this mission profile is around seven which can induce a certain number of cracks due to its high take-off weight and low-level operation plus low-level, high-speed maneuver, which can induce a high level of stress.

Both the airbases and mission type affect the aircraft's load spectra are demonstrated by aircraft two and aircraft 3. Both of these aircraft are located at Labuan Air Base, which is on the island of Labuan. The geographic correlation of the airbase location affects the spectra observed. Furthermore, the uneven surface on the base's runway would also significantly contribute to aircraft cracks due to heavy landing. The call sign of tactical workhorse would also indicate that the squadron's main operation focuses on the low-level navigation operation. This mission induces high stress on the aircraft since it accounts for the higher severity factor.

3.3 Crack Mapping

Maintaining the strength, rigidity, damage tolerance, and durability of the RMAF aircraft structure depends on the military airplane's actual usage, and it may differ significantly due to a widely varied pattern of usage severity. A fundamental element of force management is Individual Aircraft Tracking (IAT). This method that used the crack mapping analysis can predict potential flaw growth in critical areas of each airframe based on individual aircraft usage data.

.

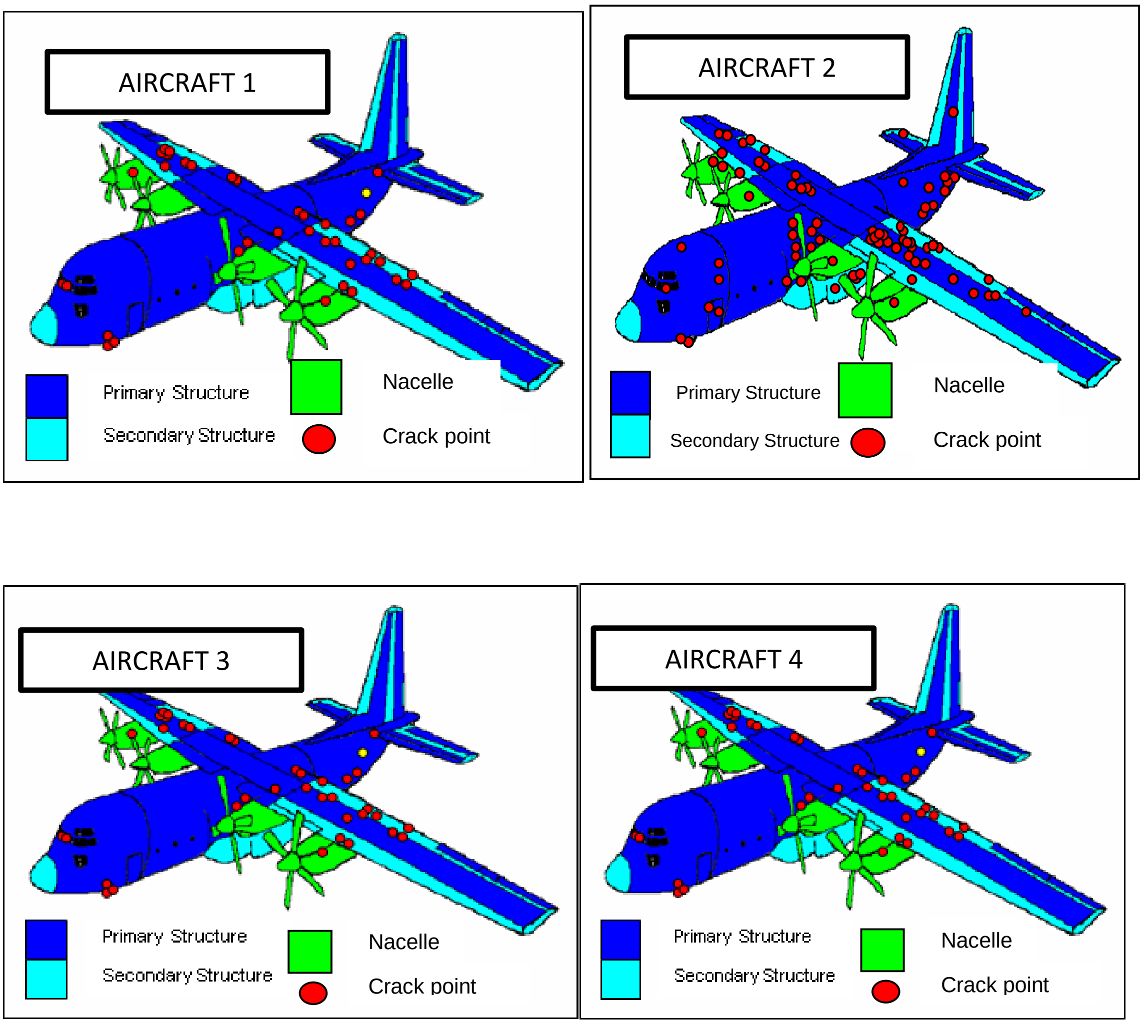


Fig. 8. Crack Mapping

3.4 ASIP Development

Reliable, maintainable, online-line airplane systems are a mandatory requirement for the RMAF. An airplane system's essential item is the airframe structure with the mandatory attendant requirement of structural integrity. The Aircraft Structure Integrity Program (ASIP) is a systematic procedure applied to a particular airplane system to enhance the design, diagnose the potential or impending failure, provide a basis for corrective action, and predict the airframe's operational life expectancy. The ASIP will be a condition monitoring database management for the airframe structure of RMAF C-130 [15].

The RMAF is working together with CAIDMARK Sdn Bhd to carry out the project. Both the office will work on the data management and analysis. As a beginning, the RMAF has agreed to embark on a minor ASIP that includes Task I, IV, and V, the Design Information, Certification, and Force Management Development and Force Management Execution.

4. Recommendation

The C-130 gives the RMAF a significant and viable long-term option for strategic and tactical delivery for joint and multinational operations. Extending the aircraft's service life will result in a better return on investment for the significant design and manufacturing costs associated with developing a specialized, unique airframe. The structural life assessment is the first that consideration has been given to managing fleet health through ASIP. Broadly the service can follow the six broad recommendations to manage its aircraft fleets' capabilities over the next 20 years or so years:

a. Continue the current plan.
b. Replace fleets sooner.
c. Reduce force size.
d. Accelerate modification initiatives.
e. Increase maintenance capacity.
f. Streamline and modernize maintenance.

5. Conclusion

Since the aircraft has moved into the aging phase, the current analysis scope should be expanded to determine the crack growth behavior and the true FCLs for RMAF C-130H aircraft. Damage Tolerance Analysis includes crack growth analysis to predict crack growth life and residual strength analysis to predict critical crack length at each FCL of the structure. In order to obtain fatigue loads from the aircraft's actual usage of aircraft, in-flight load measurement could be performed using strain gauges. Flight Load Monitoring (FLM) is the activity to acquire fatigue loads on operational aircraft [16]. Apart from the safety and economic issues mentioned above, the result of FLM can be used for aircraft rotation to ensure optimal fleet usage. Even though there were 378 cracks over 24 years, all cracks or structural damage have been repaired, referring to the structure repair manual provided by Lockheed Martin. All structure damage is classified as standard repair for the time being. Besides that, the most critical area for RMAF C-130 is located at the center wing box.

Acknowledgment
The project was funded by the Universiti Teknologi Malaysia with "Geran Universiti Penyelidik" (GUP) Tier 2 Scheme, with UTM Vote No: Q.K130000.2656.16J42. The authors would like to express their greatest appreciation and utmost gratitude to the Razak Faculty of Technology and Informatics and Universiti Teknologi Malaysia (UTM).

References
1. Venugopal, A., et al., *The Effect of Tropical Environment on Fatigue Failure in Royal Malaysian Airforce (RMAF) Aircraft Structure and Operational Readiness.* Materials, 2021. **14**(2414).
2. Venugopal, A., et al., *Crack Growth Prediction on Critical Component for Structure Life Extension of Royal Malaysian Air Force (RMAF) Sukhoi Su-30MKM.* Metals, 2021. **11**.
3. Boller, C. and M. Buderath, *Fatigue in aerostructures - where structural health monitoring can contribute to a complex subject.* Philosophical transactions of the royal society, 2006: p. 1-28.
4. Venugopal, A., et al., *Structure Life Extension towards Structural Integrity for Sukhoi Su-30MKM.* Materials. **14**.
5. Kim;, Y., S. Sheehy;, and D. Lenhardt, *A Survey of Aircraft Structural-Life Management Programs in the U.S. Navy, the Canadian Forces, and the U.S. Air Force*. 2006.
6. Aktepe and L. Molent., *Review of Fatigue Monitoring of Agile Military Aircraft.* Fatigue Fracture Engineering Material Structure 2001. **23**: p. 767-785.
7. Jr, A.F., *Fundamentals of Structural Integrity : Damage Tolerence Design and Nondesreuctive Evaluation.* 2004. **Hoboken, New Jersey, US: John Wiley and Sons**.
8. Wahyu Kuntjoro, et al., *Development of Fatigue Life Monitoring of RMAF Fighter Airplanes*, in *ICAF Symposium*. 2009: Rotterdm.

9. Riegert, G., et al., *Modern Methods of NDT for inspection of Aerospace Structures.* ECNDT 4.1.4, 2006.
10. Martin, L., *Nondestructive Inspection Procedure USAF Series C-130 Airplane*. 1984: USA.
11. Ž. Marušić, D. Bartulović, and B. Maković, *Methods to Detect and Prevent Fatigue in Ageing Aircraft Structure.* 2014.
12. Baldev Raj, T. Jayakumar, and B.P.C. Rao, *Non-Destructive Testing and Evaluation for Structural Integrity.* Sadhana, 1995. **20**: p. 34.
13. E1417/E1417M-16, A., *Standard Practice for Liquid Penetrant Testing*.
14. Allan, B., et al., *Emerging Nondestructive Inspection Methods for Aging Aircraft*, R.a.I.T.A. U.S. Department of Transportation, Editor. 1994: New Jersy.
15. USAF, *MIL-STD-1530C Aircraft Structure Integrity Program (ASIP)*. 2004, Department of Defense Standard Practice. p. United State Airforce.
16. Bartelds, G., *Aircraft structural health monitoring, prospects for smart solutions from European viewpoint.* 1997.