Prediction of Early Fatigue Crack Growth in PSE Lower Wing Skin of N-2XX Aircraft using DCRACK

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Abstract. Aircraft structural reliability is strongly influenced by fatigue crack propagation in critical wing components subjected to cyclic loading. This study predicts and compares fatigue crack growth at two Principal Structural Element (PSE) locations on the N-2XX aircraft at PT Dirgantara Indonesia using DCRACK simulation: Skin A containing a 164.86 mm access hole and Skin B without geometric discontinuities. Crack growth behaviour was analysed using exponential regression modelling and interpreted within a fracture mechanics framework based on the stress intensity factor range (ΔK). The results show that Skin A exhibits a two-stage crack growth response. Stable Paris-regime propagation occurs during flight cycles 1–600, followed by accelerated exponential growth due to increased stress concentration around the access hole, with crack growth rate rising from 1.642% to 20.33%. In contrast, Skin B maintains predominantly stable crack propagation up to 1200 cycles with an average growth of 6.566 mm and a low growth rate of 1.18%, indicating greater fatigue tolerance. Overall, the findings confirm that geometric discontinuities amplify local stress intensity and accelerate fatigue damage. These results highlight the importance of geometry-sensitive inspection scheduling and support the application of fracture-mechanics-based damage tolerance principles in aircraft structural maintenance planning.

1 Introduction

The structural integrity of the aircraft is highly dependent on the resistance of the lower skin components of the wing to repeated loads (fatigue), as this area is the part that receives high fluctuating stresses during flight and has the potential to be the starting point for the initiation and propagation of cracks [1]. Stress accumulation due to long-term cyclic loads can lead to progressive crack growth, which, if left undetected, can lead to structural failure [2]. Therefore, understanding the characteristics of crack growth is a crucial aspect in assessing service life and applying the damage tolerance philosophy to aircraft structures [3].

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Previous research has shown that the growth of cracks in aircraft structures is influenced by geometric factors, boundary conditions, and material characteristics [4]. The presence of access holes, rivet holes, and thickness variations causes significant stress concentrations that accelerate the growth of cracks [5].

Recent studies have also shown that holes created through a cold expansion process can alter the residual stress distribution and delay the initiation of cracks; however, if left uncontrolled, they can generate residual stress that accelerates secondary cracking [6]. Neto et al. [7] reported that the presence of holes around the crack plane accelerated growth by up to 25% compared to plates without holes due to an increase in local stress intensity factor (SIF). Fageehi [6] also found that the geometry of small holes in aluminium alloys can alter the crack path and accelerate the transition from linear to exponential growth.

Traditional approaches, using the Paris law and its derivative models, are still widely employed in predicting crack growth rates; however, these models have limitations in capturing nonlinear behaviour in the critical phases leading up to failure [8].

Therefore, exponential regression-based approaches and numerical simulations are increasingly being applied because they can more realistically represent the transition from the stable phase to the crack acceleration phase [9]. In addition, the application of analysis software, such as AFGROW and NASGRO, as well as industrial internal tools, enables more accurate service life predictions based on actual data of the flight load spectrum [10,11].

PT Dirgantara Indonesia has developed DCRACK's in-house software, which is designed to analyse the growth of spectral load cracks in the main components of the aircraft structure. However, further validation and implementation of specific elements, such as Principal Structural Elements (PSE), are still needed to assess their effectiveness. The focus of this study is to predict the characteristics of crack growth in Skin A and Skin B PSE of the N-2XX aircraft using DCRACK-based analysis. This study aims to identify differences in crack growth rates due to geometric factors and stress concentration, and to support the determination of inspection intervals and evaluation of the service life of aircraft wing structures [12–14].

2 Method

This study focuses on the analysis of crack growth due to repetitive loads (fatigue crack growth) in the Principal Structural Element (PSE) of the N-2XX aircraft, produced by PT Dirgantara Indonesia. This component is part of the lower skin of the wing, which functions to withstand the main bending load due to aerodynamic and manoeuvring forces.

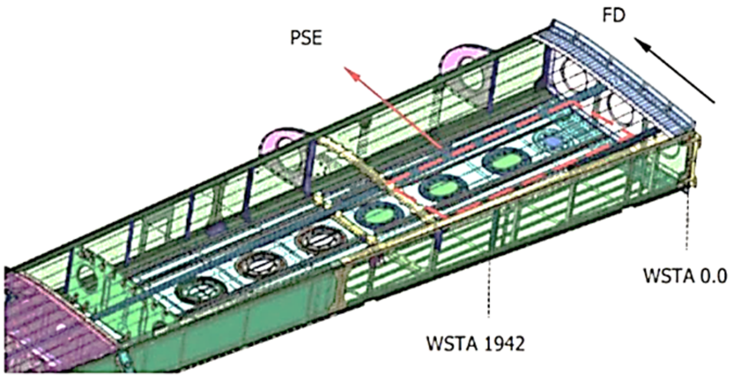

Fig. 1. Outer wing, lower surface, Skin access holes between WSTA 0.0 and WSTA 1942

Fig. 1 illustrates two critical areas that are the focus of the analysis: Skin A and Skin B, both of which have distinct geometric configurations and voltage distributions due to the influence of access holes and local thickness variations [1].

The primary input data used in the simulation include:

1. The initial crack length (a_0) was identified based on the results of the non-destructive inspection at the initial stage of the test.
2. Mechanical properties of materials, including modulus of elasticity, yield stress, and fracture toughness (K_IC). This data was taken from the test results of aluminium alloy material 2024-T351 used in the wing structure [11].
3. The flight load spectrum, obtained from typical operation data of the N-2XX aircraft under various manoeuvre and turbulence conditions, is expressed in flight cycles (FC) units [1].

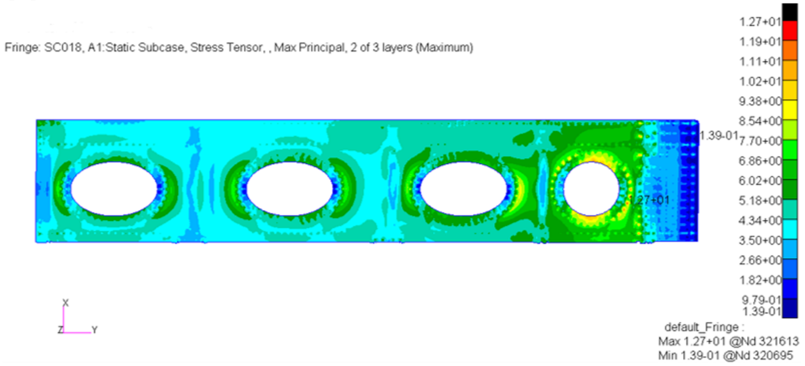

Fig. 2. Distribution of stress on Skin A and Skin B

Fig. 2 shows the voltage distribution in Skin A and Skin B obtained through preliminary numerical analysis using a Finite Element Method (FEM) device to determine the maximum voltage concentration area around the access hole [6]. The stress concentration factor (Kt) and stress intensity factor (ΔK) were then calculated as the basis for the crack growth simulation input using the DCRACK software.

The DCRACK software is one of the applications used in the damage tolerance analysis process. Data, including values such as the number of flights, flight cycles, fractures, Beta factors, and residual strength, are the outcomes of the DRACK program run. These findings are presented in the form of data [14].

The DCRACK software is an internal analysis tool developed by PT Dirgantara Indonesia to predict the rate of crack growth based on the damage tolerance philosophy. The program works by integrating load spectrum data, material mechanical properties, and initial crack length to calculate cumulative crack growth per flight cycle. The validation of this software was carried out through a comparison of the simulation results with those of the Paris' Law-based approach, as well as the results of experimental tests from previous studies [9].

The primary mathematical approach employed in this study is exponential regression, used to describe the relationship between the number of flight cycles (x) and the length of cracks (y) on each skin. The exponential approach was chosen because it is more suitable for representing the growth pattern of non-linear cracks, especially during the acceleration phase after passing the critical crack length threshold [14].

The analysis procedure includes:

1. Data input and pre-processing: The initial crack length (a_0), material parameters, and the load spectrum are fed into the DCRACK module.
2. Crack growth simulation: DCRACK calculates the incremental crack length per flight cycle using actual stress data derived from FEM results.
3. Extraction of output data: The simulation results, in the form of cumulative crack lengths per flight cycle, are exported in numerical format for further processing.
4. Exponential regression modelling: The data from the simulation were processed using a statistical analysis tool to obtain parameters a and b, as well as the R^2 value.
5. Interpretation of results: Crack growth patterns are evaluated to determine linear and exponential phases, as well as identify critical flight numbers at which growth acceleration begins to occur.

Validation was carried out by comparing the crack growth patterns of the simulation results with those of the empirical model and the results of previous studies on aluminium alloys 2024-T3 and 7075-T6 [14]. In addition, the simulation results on Skin A and Skin B were compared to assess the influence of geometry, surface area, and the presence of access holes on stress accumulation and crack growth rate [8].

3 Results and discussion

3.1 Results

The results of the simulation include the stages of crack development *(stage)* from the initial crack to critical condition. The following are *the output* results of the DCRACK program which can be seen in **Table 1** and **Table 2**.

Table 1. PSE Skin A output results

Crack Stage	Crack (mm)	Total flight out
Stage 1	1.270	1
Stage 2	6.015	565
Stage 3	97.994	751
Stage 4	201.323	776
Stage 5	293.066	803
Stage 6	295.606	804

Table 2. PSE Skin B output results

Crack Stage	Crack (mm)	Total flight out
Stage 1	1.270	1
Stage 2	196.284	5684
Stage 3	210.594	1791

3.2 Discussion

The results of the simulation using the DCRACK software showed that Skin A underwent two different crack growth phases (**Fig. 3**).

The crack growth behaviour predicted by the DCRACK simulation reveals distinct fatigue propagation characteristics between Skin A and Skin B, reflecting differences in local structural conditions and crack driving forces. As shown in **Fig. 3**, Skin A exhibits two clearly identifiable crack growth phases. During the initial phase (flight cycles 1–600), crack propagation follows a relatively stable and near-linear trend, corresponding to a controlled fatigue crack growth regime. This behaviour is consistent with the Paris crack growth regime (Region II), where crack propagation is governed primarily by the stress intensity factor range (ΔK) under cyclic loading [2]. The average crack extension in this stage is approximately 4.758 mm, with a modest growth rate increase of 1.642%.

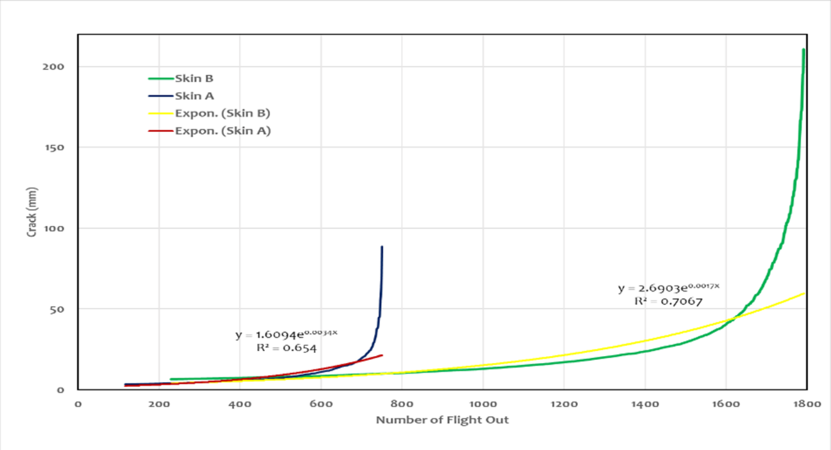

Fig. 3. Crack growth chart between Skin A and Skin B

Beyond approximately 600 flight cycles, Skin A undergoes a transition to an accelerated crack growth phase characterised by an exponential trend. From a fracture mechanics perspective, this transition indicates a significant increase in the effective stress intensity factor as the crack length approaches a critical threshold. Elevated ΔK enhances the crack driving force, promoting unstable crack propagation and reducing the structural load-carrying capacity [5]. Such behaviour aligns with established fatigue crack growth theory, where crack acceleration occurs when structural geometry amplifies local stress intensity near discontinuities.

In contrast, Skin B demonstrates a predominantly linear crack growth pattern up to 1200 flight cycles, indicating that crack propagation remains within the Paris regime throughout the simulated loading history. A lower and more stable stress intensity factor distribution contributes to improved fatigue resistance and delays the onset of unstable propagation [6]. This difference highlights the critical role of structural geometry in controlling crack growth stability.

The pronounced variation between the two skins is strongly influenced by local geometric features. Finite element analysis indicates that Skin A experiences higher stress concentration due to the presence of access holes along the fastener line. These discontinuities elevate the stress concentration factor and directly increase ΔK at the crack tip, accelerating micro-crack initiation and cyclic propagation [9]. Similar findings have been reported in aluminium aircraft structures, where even minor geometric defects significantly alter the crack growth rate and direction [10].

Mathematical modelling of the simulation results results in the following exponential regression equation:

1. Skin A:
   $y=1.6094e0.0034x$, $R^2=0.654y$
2. Skin B:
   $y=2.6903e0.0017x$, $R^2=0.707y$

The exponential coefficients reflect Paris-like crack growth behaviour, where larger coefficients correspond to higher crack propagation sensitivity to cyclic loading [10]. The moderate determination coefficients indicate that while the dominant fatigue trend is captured, additional factors such as residual stresses, crack closure effects, and load variability contribute to non-linear behaviour [14].

The exponential curve observed in Skin A suggests that each increase in flight cycles results in progressively larger crack extension, consistent with accelerated fatigue propagation approaching unstable fracture conditions. The transition around the 600th cycle represents a critical structural state where crack growth becomes highly sensitive to stress redistribution. This threshold has practical implications for inspection scheduling, particularly in regions containing geometric discontinuities or elevated residual stress fields [14].

The transition from linear to exponential phase on *Skin A* around the 600th flight indicates that at this point, the structure has reached a critical crack length, where the rate of crack growth increases dramatically, and the load-holding ability decreases. This condition needs to be used as a reference for stricter structural inspection intervals, especially in areas with *access holes* or high residual voltages [8].

Skin B, meanwhile, maintains a stable crack growth trajectory within the examined cycle range, indicating superior fatigue tolerance. This behaviour supports the principles of damage-tolerant structural design, where predictable crack growth enables maintenance planning based on inspection intervals rather than sudden failure prevention [8].

To validate the simulation results, the predicted crack growth trends were compared with empirical fatigue crack growth models reported for aluminium alloy 2024-T3. The exponential regression behaviour obtained from DCRACK is consistent with Paris–Erdogan crack growth characteristics, where ΔK governs crack propagation rate [2]. Experimental investigations have demonstrated similar acceleration in crack growth when geometric discontinuities elevate local stress intensity, matching the simulated behaviour observed in Skin A [10]. Although the moderate R^2 values indicate the presence of secondary fatigue phenomena not explicitly modelled, the overall agreement confirms that the simulation reliably represents the dominant crack propagation mechanism [6].

Overall, the findings highlight the critical influence of geometric discontinuities and local stress concentration on fatigue crack growth in aircraft skin structures. Access holes redistribute stress fields, increasing crack driving forces and accelerating the transition from stable to unstable propagation [9]. Practical mitigation strategies include geometric optimisation of access holes and residual stress control techniques such as cold expansion or shot peening, which are known to reduce local stress intensity and extend fatigue life [6]. The DCRACK simulation framework demonstrates strong capability in predicting fatigue crack behaviour, supporting its application as a structural reliability assessment tool in aerospace maintenance planning.

4 Conclusion

This study demonstrates that fatigue crack growth behaviour in the Principal Structural Element (PSE) of the N-2XX aircraft can be effectively predicted using DCRACK simulation when interpreted within a fracture mechanics framework. The comparative analysis between Skin A and Skin B confirms that local geometric conditions significantly influence crack propagation stability through variations in the effective stress intensity factor (ΔK).

Skin A exhibits a two-stage crack growth response consisting of an initial stable Paris-regime propagation from flight cycles 1–600, followed by accelerated exponential growth beyond this threshold. The transition corresponds to an increase in crack-driving force due to geometric stress concentration near the access hole, resulting in a crack-growth rate escalation from 1.642% to 20.33% and indicating progression toward a critical structural condition. In contrast, Skin B maintains predominantly stable Paris-regime crack growth up to 1200 cycles, with an average growth of 6.566 mm and a low growth rate of 1.18%, reflecting reduced stress concentration and improved fatigue tolerance.

The exponential regression models capture the dominant crack growth trends and demonstrate Paris-like behaviour consistent with empirical fatigue crack propagation theory. While moderate coefficients of determination indicate the presence of secondary fatigue phenomena not explicitly modelled, the simulation reliably represents the primary mechanism governing crack propagation.

Overall, the findings confirm that geometric discontinuities amplify local stress intensity and accelerate fatigue damage, particularly in Skin A. From an engineering perspective, these results emphasise the importance of geometry-sensitive inspection scheduling, optimisation of access hole design, and implementation of residual stress mitigation strategies to enhance structural durability. The study supports the application of fracture-mechanics-based damage tolerance principles in aircraft maintenance planning and validates the capability of DCRACK as a predictive tool for structural integrity assessment.

Acknowledgement - The authors would like to thank the STT 'Warga' Surakarta Centre for Research and Community Service (PPPM) for its financial support for this publication, and we would also like to thank PT—Indonesian Aerospace.

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