Probabilistic Damage Tolerance Assessment: The Relative Merits of DARWIN, NERF AND PROF

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ABSTRACT

DARWIN is an FAA certified probabilistic fracture mechanics risk assessment software specifically designed for the fatigue life management of titanium aircraft engine rotors disks. This report is a detailed review and discussion of the underlying principles, capabilities and limitations of DARWIN, and also compares the methodology of DARWIN to that of other commonly available probabilistic assessment tools, namely PROF and NERF.

RELEASE LIMITATION

Approved for public release
Probabilistic Damage Tolerance Assessment: The Relative Merits of DARWIN, NERF AND PROF

Executive Summary

This report is a review and discussion of the probabilistic fracture mechanics assessment methodology used by DARWIN (Design Assessment of Reliability With INspection), which is a United States Federal Aviation Administration (FAA) certified probabilistic damage tolerance assessment tool specifically designed for fatigue life management of titanium aircraft engine rotor disks subject to the possible presence of hard alpha defects.

DARWIN utilises a zone-based and Monte Carlo-based probabilistic method for estimating the probability of failure of an entire aircraft engine rotor disk. As for any probabilistic assessment tool, the underlying assumptions that underpin the probabilistic models are one of the key aspects that govern the validity of any risk assessment. This is particularly the case for DARWIN, given that it is FAA certified, and may potentially be applied to future Australian Defence Force (ADF) aircraft engine rotor disks probabilistic assessment related issues.

For this reason, it is considered important that the limitations, underlying principles and assumptions employed by DARWIN be clearly identified and understood prior to application on any real airworthiness issue.

DARWIN utilise a zone-based approach to break down the component into a number of regions. Consequently, the random variables taken into account by DARWIN can be identified at different levels, i.e., location, zone or disk-related. It is unclear, from the available documentation, as to (i) whether variation of the random variables at each of the levels has been correctly accounted for, and (ii) whether the random variables are assumed as truly random for each zone. The latter case can produce an unrealistic, if not totally erroneous probabilistic assessment result.

In DARWIN, the variation in fatigue life is taken into account using a pre-determined fatigue life factor distribution. This assumes that the crack growth rate is constant and independent of load level. However, in reality it is generally found that neither is the case.
Therefore it is uncertain whether the use of a pre-determined fatigue life factor distribution results is a valid probabilistic assessment.

At present, DARWIN is only applicable to axisymmetric components, such as spacers and not to cyclic-symmetric components such as compressor and turbine disks.

Furthermore, the report compares the merits of DARWIN as a probabilistic fracture mechanics assessment tool to those of PROF (Probability of Fracture) and NERF (Numerical Evaluation of Reliability Functions).

In particular three primary aspects of the codes of DARWIN, NERF and PROF have been considered.

1. The limit-state function and the failure criteria that the program utilizes,

2. The random variables that it takes into account, and the assumptions used for taking into account the selected random variables, and

3. The probabilistic methodology used for evaluating the probabilities of failure and, in particular, whether it uses an approximation or a simulation method.

Aspects of these three items of DARWIN are briefly compared with that of PROF and NERF. In summary, DARWIN is a more sophisticated and comprehensive probabilistic fracture mechanics assessment software than either PROF or NERF. It allows a greater number of variables to be taken into account, and the zone-based methodology enables the probability of failure of an entire component, and not just one critical location, to be estimated. However, a number of issues still exist with the underlying principles of the DARWIN methodology. In particular the use of variability at different levels, the pre-determined fatigue life factor distribution and whether the variation in inspection time is disk or zone related remain to be to be resolved.
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1. Introduction

DARWIN (Design Assessment of Reliability With INspection) [1] is a United States Federal Aviation Administration (FAA) certified probabilistic damage tolerance assessment tool developed by the Southwest Research Institute (SwRI). DARWIN is specifically designed for fatigue life management of titanium aircraft engine rotor disks subject to the possibility of catastrophic failure due to the presence of hard alpha defects. As DARWIN is an FAA certified probabilistic assessment code, it is important for DSTO to have a detailed understanding of its underlying principles, capabilities and limitations as a probabilistic assessment tool for addressing future Australian Defence Force (ADF) needs.

In this report, a review of the merits of DARWIN in terms of its probabilistic methodology is presented. As the main focus of this work is on DARWIN as a probabilistic assessment tool, discussion of the fracture mechanics and finite element aspects of DARWIN is limited to those aspects relating to the probabilistic assessment methodology.

2. DARWIN: Design Assessment of Reliability With Inspection

Rare metallurgical anomalies, such as the hard alpha defect in titanium, have been found to be the cause of uncontained engine failures such as the incident at Sioux City in 1989, which resulted in significant loss of life. As a consequence of this incident, the Turbine Rotor Material Design (TRMD) program was founded. The objectives of the program are to conduct research and development to enhance predictive capability, to improve material and anomaly behaviour characterization, and to carry out modelling for better design and management of titanium aero engine rotor disk components. In addition, to prevent an incident such as Sioux City from occurring in future aero engines, the FAA advisory circular AC33.14-1 [2], which specifies that a probabilistic approach be used to account for rare metallurgical anomalies present in titanium rotor disks, has recently been put in place for certification of all titanium rotor disks in aero engines.

2.1 Zone-Based Probabilistic Approach

The difficulty in assessing the probability of failure of titanium rotor components due to fatigue crack initiation from hard alpha rests in the fact that such a defect occurs randomly at any locations within a rotor disk, with the size of these hard alpha defects being also random in nature. Whether a particular defect could cause a disk to fail would depend on its location, the stresses that it experiences, the fatigue crack growth rate at this location and the ability to detect, and remove, cracked rotor disks prior to failure.

A unique feature of DARWIN is the use of a so-called zone-based probabilistic approach [3] to account for random defect location to compute the probability of failure of the entire rotor disk. This zone-based approach allows different areas (or zones) on a disk to have their own defect occurrence rate, material properties, inspection parameters, loads and temperatures.
This feature allows the probability of failure of the entire disk to be more realistically modelled. Further advantages of this approach are that it enables the critical areas (zones) to be identified, providing valuable information for design and inspection planning.

DARWIN achieves this by taking the axisymmetric section of a rotor disk, and subdividing it into $M$ number of zones, as illustrated in Fig. 1, so that a probabilistic assessment is carried out for each zone. The probability of failure of the entire rotor disk can then be computed as the sum of the probability of failure of all the individual zones as presented in [3], or alternatively by following the reliability theory of systems [4] as follows,

$$ P_f = P[F_1 \cup F_2 \cup \ldots \cup F_i \cup \ldots \cup F_M] $$

where $F_i$ is the probability of zone $i$, and $i = 1,2,\ldots,M$.

DARWIN is the first probabilistic fracture mechanics assessment tool that has integrated and allowed a systematic approach for assessing the probability of failure of an entire component. In order to correctly evaluate the probability of failure of the entire disk based on the probability of failure of all the individual zones, it is important that correlations between the variables in individual zones be accounted for representatively. It is uncertain based on the open literature [1, 3, 5] as to whether the correlations of variables between zones have been modelled accurately in DARWIN, but it would appear that an uncorrelated approach has been adopted to provide a conservative result [6].
Given all zones are independent, then the key to computing the probability of failure of an entire rotor disk ‘\( P_f \)’ in DARWIN is in the calculation of the failure probability of each individual zone ‘\( F_i \)’. DARWIN takes into account five random variables; namely stress multiplier, anomaly (defect) distribution, fatigue life factor distribution, inspection time, and the probability of detection (inspection technique), in the evaluation of probability of failure of each zone. In order to allow probabilistic assessment to be representatively carried out, it is important that zones are selected to have a similar stress multipliers, anomaly (defect) distributions, fatigue life factor distributions, inspection times and inspection techniques.

**2.2 Fatigue crack growth model and Failure criterion**

A damage tolerance approach is used in DARWIN to address fatigue life prediction due to fatigue crack initiation from hard alpha defects in titanium rotor components. The fatigue model used in DARWIN assumes that fatigue crack growth begins from the first cycle at the defect of interest, and hence no credit for crack initiation is considered, these defects simply being treated as a crack.

Fatigue crack growth analysis in DARWIN is made using the FLIGHT_LIFE module. The FLIGHT_LIFE module evaluates the fatigue life by summing the crack growth rate ‘\( da/dN \)’, in air for surface or vacuum for embedded initial defects, for each cycle before fracture occurs, and is given by,

\[
L = \int \left[ \frac{da}{dN} \right]^{-1}
\]

Various low cycle fatigue crack growth rate models and geometry factor solutions are available to choose from and in addition a tabular data input option is also available. Details of the available models in DARWIN can be found elsewhere, e.g. Ref [6].

The failure criterion used in DARWIN for characterizing fatigue fracture is,

\[
K_C - K(X) \leq 0
\]

where \( K_C \) is the critical stress intensity factor (or fracture toughness), \( K(X) \) is the stress intensity factor at each fatigue cycle, and \( X \) is a vector of influential random variables.

**2.3 Computational Efficiency in DARWIN**

Any formal probabilistic analysis to compute the probability of failure by fatigue on a cycle-by-cycle basis for a number of different zones, as found in DARWIN, requires a great deal of computational time. The problem here is further complicated by the need to allow the merit of inspections and maintenance to be taken into account during both fatigue life prediction and probabilistic analysis. In addition, to repetitively perform the same procedures for all zones would mean that enormous computational evaluation time is required. For these reasons, the need for computationally fast and efficient probabilistic assessment procedures was recognized as a major objective during the development of DARWIN.

DARWIN uses the Monte Carlo Simulation (MCS) method as the basis of the probabilistic methodology. However, the MCS method is widely recognized as slow and computationally
inefficient, particularly when evaluating low probabilities of failure, such as $10^{-6} \leftrightarrow 10^{-4}$, as required in the aerospace industry. The strategy adopted for improving the overall computational speed of DARWIN is to improve the computational efficiency during both probabilistic and fatigue crack growth analyses. Three major techniques and procedures are currently used in DARWIN to improve computational efficiency:

1. Use of a pre-determined fatigue life distribution function ($X_L$),
2. Use of the Life Approximation function (LAF) and,
3. Use of the so-called Importance Sampling method.

Details about these techniques and procedures are given in later sections.

2.4 User Interface

An attractive feature of DARWIN is that a user-friendly graphical user interface (GUI) is available for handling and viewing input data, conducting fatigue crack growth analysis, setting up the multiple zone probabilistic analysis, and for viewing results. As part of the GUI, an excellent help file is also available, allowing easy troubleshooting and operation of DARWIN to be made.

3. Probabilistic Methods and Random Variables

The important features of the probabilistic methodology used by DARWIN are reviewed in this section. More detail of the methods can be found elsewhere such as in Refs [1, 3, 6].

3.1 Random Variables

The random variables that are claimed to be taken into account during the probabilistic assessment by DARWIN are:

- Defect size ‘$d_0$’
- Stress factor ‘$X_s$’
- Fatigue life factor ‘$X_L$’
- Inspection time ‘$T_i$’
- Probability of detection ‘$POD(a)$’

However, from the point of view of a zone-based probabilistic approach, it is important to note that some of the variables are applicable to the entire disk, some to a number of zones and some to particular zones, the authors have denoted these levels as the three levels of variability. For example, the stress factor ‘$X_s$’ and inspection time ‘$T_i$’ could be applicable to the entire disk (Level I variability), whereas a particular probability of detection ‘$POD(a)$’ (NDI technique) may only be applicable to a group of zones (Level-II variability). Finally, defect size and fatigue life factor may be considered purely random for each defect or zone (Level-III variability). It is unclear whether the methodology used by DARWIN has
differentiated these three levels of variability correctly in its probabilistic assessment, or has it assumed all random variables to be Level-III, i.e. all variables are independent for each zone? In the event of the last case, the probabilistic assessment by DARWIN could become non-representative of the real rotor disk, giving rise to an erroneous assessment result. There is insufficient detail in the open literature of the methodology used by DARWIN for its zone-based probabilistic approach to clearly establish how the variability is treated, consequently it is suggested that SwRI be approached to clarify which approach is employed.

In DARWIN, all of these variables can be taken into consideration when probabilistic fatigue life assessment is made involving inspections, except when the Life Approximation Function (LAF), discussed later in Section 4.2, is employed. In this case, the stress factor random variable, \(X_S\), is neglected. Furthermore, a limitation of DARWIN is that the material fracture toughness \(K_C\), which is inherently a random variable, is presently treated as a deterministic parameter. From a probabilistic assessment point of view, it could be important that the option for these two variables, in particular \(K_C\), is statistically allowed for in order to suit the problem under consideration.

### 3.2 Monte Carlo Simulation

MCS forms the basis of the probabilistic methodology in DARWIN for determining the probability of failure for each zone. Although the procedure used by DARWIN is not mentioned in the open literature [1, 3], the general procedure of the MCS method used by DARWIN for each zone can be summarised as follows.

1. For each simulation, randomly select a value for each random variable, including a defect size \(d_0\), a stress factor \(X_S\), a fatigue life factor \(X_L\) and inspection intervals \((T_i)\). In addition, whenever inspections are involved, a crack detection indicator value \(P_D\) is randomly selected following a uniform distribution for each inspection.

2. Based on the selected values of \(d_0\), \(X_S\) and \(X_L\), the initial defect is grown either to failure in the case of no inspections, or to \(T_i\) in the case of inspections, with the deterministic (Finite Element) stress being elevated by a factor of \(X_S\), and the fatigue crack growth rate being elevated by a factor of \(\frac{1}{X_L}\) (see Section 4.1).

3. In the case with inspections, the crack length \(a(t)\) at \(t = T_i\) is used to select the probability of detecting this crack length \(POD(a(t))\) on the POD function. The crack detection indicator \(P_D\) is used to simulate whether this crack could be missed by NDI at inspection. If \(POD(a(t))\) is greater than \(P_D\), it indicates that the crack will be detected during inspection, and the disk is replaced. Conversely, if the \(POD(a(t))\) is smaller than \(P_D\), it indicates that the crack will be missed during inspection, and the disk is not replaced.

4. When fatigue crack is detected during inspection, the rotor disk will be replaced (unlike in airframes, which can be repaired). Then, the analysis is continued from step 1. If the
fatigue crack is not detected, the crack growth analysis continues as left off at $T_i$. The fatigue crack is then allowed to grow either to failure, as in the case without further inspections, or to the next value of $T_i$, in the case with further inspections.

5. Steps 1-4 are repeated for all $N$ simulations.

The probability of failure $p_f$ at a given time $t$ using the Monte Carlo Simulation method is given by,

$$p_f = \frac{N_f(t)}{N} \tag{4}$$

where $N_f(t)$ is the number of failures prior and at time $t$. It must be noted that the above MCS procedure is for estimating the probability of failure for a single zone on a disk. For the entire disk, however, the above MCS procedure would be somewhat different.

### 3.3 Importance Sampling: A Hybrid Method

The Importance Sampling technique implemented in DARWIN [3] is not the same as the conventional Importance Sampling technique, but better termed as a Conditional Sampling technique. Conventional Importance Sampling is essentially the MCS method, except that random variables are sampled from a biased JPDF with the use of correction (weighting) factors to adjust for sampling of a biased JPDF. The so-called Importance Sampling technique used in DARWIN is a hybrid method, combining the use of a response surface numerical integration method and MCS to improve the sampling efficiency. Further detail on the conventional Importance sampling technique can be found in Reference [4], while the Importance Sampling technique as used in DARWIN is reviewed below.

The basis to achieving an improvement in sampling efficiency by the hybrid Importance Sampling method is in recognizing that fatigue lives greater than the service life are generally not of interest. Therefore, in sampling only the minority population of fatigue lives that causes failure prior to a pre-defined service life $T_s$ would significantly improve the sampling efficiency, and lead to significant savings in computational evaluation time.

To determine, or sample, the combinations of $d_0$, $X_s$ and $X_L$ that will not exceed a defined service life $T_s$ is not a simple task but it is the key the Importance Sampling technique in DARWIN. To do this, the response surface method is employed to ‘map’ the fatigue lives of all combinations of $d_0$, $X_s$ and $X_L$, allowing those combinations that will not exceed the defined $T_s$ to be interpolated for later probabilistic assessment. The essential steps to evaluate the probability of failure using the so-called Importance Sampling method are as follows.

1. Establish the response surfaces, and carry out a numerical integration to obtain the probability of failure for the case of no inspections, denoted by $\overline{p_f}$. 
2. Randomly select a value for $X_S$ and $X_L$ based on each probability distribution function. Using the response surface function, and given the selected values of $X_S$ and $X_L$, $d_0^*$, the conditional value of $d_0$ that will give a fatigue life value equal to $T_L$ can be interpolated.

3. Once $d_0^*$ has been identified, the random value of the initial defect size ‘$d_0$’ would only be made based on its probability distribution function for those initial defect sizes that are greater than $d_0^*$.

4. Then, $d_0$, $X_S$ and $X_L$ (also $T_i$ and $P_D$ if inspection(s) are involved) are cycled through steps 2-4 of the Monte Carlo Simulation.

5. Steps 2-4 are repeated for all $N$ simulations.

The probability of failure ‘$p_f$’ at a given time ‘$t$’ using the Importance Sampling technique is given by,

$$p_f = \overline{p}_f \times \left[ \frac{N_f(t)}{N} \right]$$

(5)

where $\overline{p}_f$ is the probability of failure without inspection at time ‘$t$’, and $N_f(t)$ is the number of failures up to time ‘$t$’.

The Importance Sampling technique could significantly improve the computational efficiency during probabilistic analyses over the plain MCS method, with improvements of as much as 1000 fold being quoted [6]. However, it is uncertain whether the claimed improvement includes the time that is required to establish the response surface function and evaluating $p_f$ for each zone. Furthermore, it should also be noted that at the limit where $T_L$ approaches infinity, $d_0^*$ approaches zero, and the Importance Sampling technique reduces to that of the plain MCS method except that now computational time would significantly increase due to the need to evaluate $\overline{p}_f$ via the response surface function method. Thus, the benefit of the Importance Sampling technique in DARWIN are only realised with small pre-defined service life ‘$T_L$’, and hence the level of improvement in computational efficiency depends primarily on the value of $T_L$.

4. Other Computational Time Reduction Techniques

Minimising computational evaluation time for probabilistic analysis is a major objective in the development of DARWIN. In addition to the Importance Sampling technique discussed above, several other techniques have also been implemented to allow further improvement in computational efficiency and hence to lower the required computational evaluation time. Two of these techniques include a pre-determined fatigue life distribution and the use of a “Life Approximation Function (LAF)”. The assumptions and limitations of these two techniques are profound and are discussed below.
4.1 Fatigue Life Factor Distribution

DARWIN utilises a distribution of fatigue life factor ‘$X_L$’ to characterize the variation in fatigue life due to variation in material properties. In this approach, a deterministic crack length verse fatigue life curve (the master curve) needs to be determined using fatigue crack growth analysis. This master curve is generally based on the mean material property and the mean applied load. Assuming that the applied load is fixed, the variation in fatigue life due to the variation in material fatigue crack growth is taken into account by multiplying the master curve by a fatigue life factor, $X_L$, so that the variation in fatigue life due to variation in material property is given by,

$$L = X_L \bar{L}$$  \hspace{1cm} (6)

where $\bar{L}$ is generally the value of $L$ at $X_L = 1$.

The aim of a probabilistic fracture mechanics analysis is to determine the distribution in fatigue life by taking into account all sources of influencing variables. The fact that the fatigue life distribution in DARWIN is pre-determined limits the validity of the results. DARWIN justifies the use of this assumption as follows:

Consider that fatigue crack growth analysis is carried out using the Paris law (or other variations of the Paris law), and is given by,

$$\frac{da}{dN} = C(\Delta K)^m$$  \hspace{1cm} (7)

where $\Delta K$ is the stress intensity factor range. Assuming that the applied load is deterministic, and that the variation in fatigue crack growth rate ‘$da/dN$’ is characterised purely by the crack growth rate coefficient ‘$C$’, implies that the crack growth rate exponent ‘$m$’ is a constant and hence independent of $C$. Based on these assumptions a probabilistic model for $da/dN$ would be given by,

$$\frac{da}{dN} = X_C \bar{C}(\Delta K)^m$$  \hspace{1cm} (8)

where $X_C$ is the crack growth coefficient factor (a random variable), and $\bar{C}$ is the value of $C$ at $X_C = 1$.

Integrating Equation (8) by separation of variables, the fatigue life ‘$L$’ and variation in fatigue life can be given by,

$$L = \frac{1}{X_C} \left[ \frac{da}{C(\Delta K)^m} \right]^{-1} = \frac{1}{X_C} \times \bar{L}$$  \hspace{1cm} (9)

Equating Equations (6) and (9), gives the fatigue life factor ‘$X_L$’ as equal to $\frac{1}{X_C}$. This shows that, given a deterministic applied loading, the variation in fatigue life due to the variation in material crack growth can be characterised by $X_L$.

Therefore, it is extremely important that the validity of the use of the fatigue life factor is based on an assumption that the variation in $da/dN$ can be characterised by the crack growth rate coefficient ‘$C$’ alone, and that the crack growth rate exponent ‘$m$’ is a constant and is
independent of $C$. Building on this assumption, the Life Approximation Function (LAF) has been introduced to further improve the computational efficiency for fatigue crack growth and probabilistic analyses, and this is discussed in Section 4.2.

### 4.2 Life Approximation Function

An optional technique to improve computational efficiency during probabilistic assessment in DARWIN is the Life Approximation Function (LAF). In analyses where the LAF option is selected, a table of “crack size vs. time curves” for a series of initial defect sizes at $X_L = 1$ and $X_S = 1$ is created using the FLIGHT\_LIFE module. Using this table, a crack size vs. time curve for any initial defect size, the crack size at any time $t$ for any initial defect size can be interpolated, as illustrated in Fig. 2.

The LAF is based on the mean values of $X_L = 1$ and $X_S = 1$. To take into account the variation in the fatigue life factor $X_L$, the LAF simply multiplies the value of $X_L$, as justified by Equation (9), prior to further interpolations for crack size. However, the major limitation in the use of the LAF option at present is that the variation in stress factor $X_S$ is treated as deterministic, and set at $X_S = 1$.

The advantage in setting up the LAF is that a reduction in the frequency that the FLIGHT\_LIFE module is called for when cycle-by-cycle fatigue crack growth analysis is conducted. Consequently the computational evaluation time required for fatigue crack growth analyses in the FLIGHT\_LIFE module can be reduced. The improvement in efficiency by this procedure has been quoted to be approximately tenfold [6].

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![Fig. 2: Interpolation of crack-grown area using the Life Approximation Function](image-url)
In order to take into account the variation in stress factor ‘\( X_s \)’, a cumbersome technique would be to further compute an array of LAFs for a series of \( X_s \), as illustrated in Fig. 3.

![Fig. 3: Method for taking into account the variation in \( X_s \) with the use of LAF.](image)

In this case, interpolation for the crack size needs to be done in a three-dimensional array, and computational efficiency would decrease dramatically due to the need to establish the array of LAFs for a series of \( X_s \). Alternatively, simpler procedure for LAF that take into account both the variations in \( X_L \) and \( X_s \) has been derived proposed as follows.

Consider again that fatigue crack growth analysis is carried out using the Paris law (or other variations) as given by,

\[
\frac{da}{dN} = C(\Delta K)^n = C(\Delta \sigma \beta(a)\sqrt{\pi a})^n
\] (10)

where \( \beta \) is a geometry factor and is a function of the crack length \( a \)

Given that the variations in \( C \) and \( \Delta \sigma \) are given by \( X_C \bar{C} \) and \( X_S \Delta \bar{\sigma} \), respectively, and assuming that the variation in fatigue crack growth rate ‘\( \frac{da}{dN} \)’ is due to the variation in material properties and is characterized solely by the crack growth rate coefficient ‘\( C \)’, the probabilistic fatigue crack growth rate model can be given by,

\[
\frac{da}{dN} = X_C \bar{C}(X_S \Delta \sigma \beta(a)\sqrt{\pi a})^n = X_C X_S^m \bar{C}(\Delta \bar{\sigma} \beta(a)\sqrt{\pi a})^n
\] (11)

Integrating Equation (11) by separation of variables gives,

\[
L = \frac{1}{X_C X_S^m} \left[ \int \frac{da}{\bar{C}(\Delta \bar{\sigma} \beta(a)\sqrt{\pi a})^n} \right]^{-1} = \frac{1}{X_C X_S^m} \bar{L}
\] (12)

This result is important as it shows that the variation in fatigue life due to variations in both \( C \) and \( \Delta \sigma \) can be characterized by a factor \( \frac{1}{X_C X_S^m} \) on the master crack size vs. time curve, where the probability distribution of the factor \( \frac{1}{X_C X_S^m} \) can be easily determined.
Furthermore, this derivation also shows that the variation in $X_S$ can be taken into account during the use of LAF, overcoming the limitation currently experienced in DARWIN.

Even further improvement in computational efficiency, can be achieved since the construction of the LAF, as shown in Fig 1, is actually unnecessary. This is reasoned as follows with the use of Fig. 4.

Assuming that a fatigue crack grows from the initial defect on the first cycle, the crack size for any initial defect size at any time ‘$t$’ can be interpolated identically from a single crack size vs. time curve of the smallest initial defect size, as shown in Fig. 4. This implies that only a single crack size vs. time curve based on the smallest $d_0$ (master crack size vs. time curve) need be constructed to obtain the crack size vs. time curves for all initial defects greater than $d_0$.

Now, given that a master “crack size vs. time curve” based on the smallest initial defect size is available, then based on Equation (12), the crack size vs. time curves for any combination of $d_0$, $X_C$ and $X_S$ can be constructed without the use of the LAF.

Fig. 4: This figure shows that LAF can be obtained from a single crack size vs. time curve computed using the smallest initial defect size.

### 4.3 Validity of the Probabilistic Model used in DARWIN

The use of LAF in DARWIN, and the proposed approach in Section 4.2 is built on the limiting assumption that $da/dN$ can be characterised solely by the crack growth rate coefficient ‘$C$’, while the crack growth rate exponent ‘$m$’ assumed a constant and independent of $C$. In situations where these assumptions are not valid, which is commonly the case, the DARWIN
methodology, its resultant probabilistic assessment, and the proposed approaches become questionable.

Generally, statistical analysis of experimental fatigue crack growth rate data shows that both the crack growth rate coefficient ‘\( C \)’ and the crack growth rate exponent ‘\( m \)’ are variables, and very importantly, \( C \) and \( m \) are strongly correlated variables. This implies that the probabilistic fatigue crack growth rate model needs to be given by,

\[
\frac{da}{dN} = X_C \bar{C} \left( X_S \Delta \bar{\sigma} \beta (a) \sqrt{\pi a} \right)^{X_m \bar{m} (X_C \bar{C})}
\]

(13)

where \( m = X_m \bar{m} (X_C \bar{C}) \) indicates \( m \) is a function of \( C \), and its variation is characterised by a variable \( X_m \). Integrating Equation (13) by separation of variables now shows that,

\[
L = \left[ \frac{da}{X_C \bar{C} \left( X_S \Delta \bar{\sigma} \beta (a) \sqrt{\pi a} \right)^{X_m \bar{m} (X_C \bar{C})}} \right]^{\frac{1}{X_C \bar{C} \left( X_S \Delta \bar{\sigma} \beta (a) \sqrt{\pi a} \right)^{X_m \bar{m} (X_C \bar{C})}}}
\]

(14)

Equation (14) now indicates that a fatigue life factor such as that shown in Equations (6), (9) and (12) could not be validly used, and should be noted that the variation in fatigue life is now dependent on load sequence. This implies that the statistical distribution of \( X_L \) cannot be determined directly from \( X_C \) and \( X_S \) and, in fact, a fully probabilistic assessment involving the basic random variables and cycle-by-cycle fatigue loading would be required to determine the distribution of fatigue lives in a probabilistic assessment.

Since the probabilistic fatigue crack growth rate model of Equation (13) is the more representative model of the actual fatigue crack growth behaviour, then the probabilistic model used by DARWIN, and hence the fatigue life factor in modelling the variation in fatigue crack growth life and the use of LAF is highly questionable. Hence the assumption that the variation in \( da/dN \) is characterised solely by the crack growth rate coefficient ‘\( C \)’ is a major shortcoming of the present DARWIN probabilistic methodology.

5. Fatigue Crack Growth and Fracture Mechanics Analysis

Fatigue crack growth curves are computed in DARWIN using the built-in FLIGHT_LIFE module based on the stresses obtained from the finite element model of the un-cracked component, and it is discussed in more detail in the next section. In addition, the crack growth analyses can also consider whether the fatigue crack is grown in air (surface zones) or in vacuum (embedded zones). This module appears to be very powerful, containing many state-of-the-art fracture mechanics solutions for evaluating fatigue crack growth and the fatigue life for the component at user-defined locations. This is a capability unique to DARWIN and many future improvements to this module are planned. For most other probabilistic fracture mechanics assessment codes, fatigue crack growth modelling and the crack length versus time
curve need to be computed externally using alternative fracture mechanics codes. This capability in DARWIN is a major strength of the code.

The availability of the FLIGHT_LIFE module permits DARWIN to be a crack growth (damage tolerance) analysis tool, similar to that of AFGROW and FASTRAN [7]. However crack growth analysis tools such as AFGROW and FASTRAN do not have the option for probabilistic assessment available. This feature currently makes DARWIN unique amongst both deterministic and probabilistic fatigue crack growth analysis codes.

6. Possible Limitations in the Finite Element Model Processor

DARWIN uses the result files generated in the Finite Element analysis of the component to extract the geometry, element topology and the stress distribution of the un-cracked mesh, in order to perform fatigue crack growth analyses. DARWIN has been specifically designed for engine rotor and disk components but the translator used for importing finite element results is limited to axisymmetric components, such as that for a rotor disk, i.e. modelling just a 2D cross-section of a disk. This limits the application of DARWIN to axisymmetric components, such as spacers, and axisymmetric features on cyclic-symmetric components, such as the bore on fan disks and turbine rotors.

To improve computational efficiency, DARWIN introduces a zone definition for elements with the same material/fracture properties and similar stress levels (differences in stress of less than 5ksi). Therefore costly numerical calculations can be limited only to those zones with initial defects. As the stress gradient at a critical location can often be very steep, the defined zone has to be fine enough in order to capture such steep stress gradients. This can be a problem for defects located within very steep stress gradients, as the variation in stresses may be greater than 5ksi. Although DARWIN has zone refinement capabilities, these are too coarse and further refinement is necessary in order to improve the stress resolution in the region.

As the current version of DARWIN is limited to axisymmetric components, the zone definition, although tedious, can be manually implemented. For a full 3D FE model with complex geometry, this zone definition approach will have to be improved, as it would be no easy task to group elements in 3D models. To this end an automatic zone definition and refinement function is essential for any future practical applications of DARWIN to 3D non-axisymmetric components.

Due to the fact that the risk calculation is based on the zone definition in an FE model of a component, the accuracy of the results can be highly influenced by the density of the defined zones. Although a finer zone definition produces more accurate results, this refinement process has to be implemented manually and repeated several times in order to identify the zones that contribute significantly to overall risk levels. This process can be very time consuming and subjective, and the result depends on the experience of the user. It is therefore highly desirable to implement an adaptive zoning process in DARWIN so that the overall risk level can be calculated iteratively, in order to minimise the effect of zone definition on the
calculated risk accuracy. Although DARWIN is currently the only code that can be used directly for risk assessment of axisymmetric components, it is highly desirable to extend its capabilities to components with full 3D geometry, making DARWIN useful for blades, cyclic symmetric disks and blisks.

7. Comparison of DARWIN with PROF and NERF

Examination of the underlying methodology used by DARWIN has revealed that the basis of its probabilistic fatigue life model is somewhat similar to that used by other available probabilistic fracture mechanics codes such as PROF [8] and NERF [9]. However, DARWIN is considerably more sophisticated and more powerful in several aspects, including the ability to take stress from an FE model for making fatigue crack growth analysis at any location, and the zone-based probabilistic methodology for assessing the probability of failure for an entire rotor disk component. However, when using any commercial computer program such as DARWIN, PROF or NERF to carry out probabilistic assessments, three primary aspects of the code should be considered.

1. The limit-state function and the failure criteria that the program utilises,
2. The random variables that it takes into account, and the assumptions used for taking into account the selected random variables, and
3. The probabilistic methodology used for evaluating the probabilities of failure, in particular whether it uses an approximation method or a simulation method.

Aspects of these three items of DARWIN are briefly compared with that of PROF and NERF in this section.

7.1 Fatigue crack growth model and Failure criteria

DARWIN, PROF and NERF are designed to evaluate the probability of failure due to fatigue based on a damage tolerance fracture mechanics approach. The failure criteria used by DARWIN were discussed previously in Section 2.2, while the failure criteria used by PROF and NERF are as follows.

PROF

PROF utilizes two failure criteria. The first is given by,

\[ K_C - K(X) \leq 0 \quad \text{for} \quad a < a_C \]  \hspace{1cm} (15)

where \( a_C \) is the critical crack length, and is used to limit the range for numerical integration during evaluation of probability in the crack length domain. In order to take into account the probability of failure due to a crack length exceeding the critical crack length on the master crack growth curve, a second criterion,

\[ a_C - a \leq 0 \]  \hspace{1cm} (16)

is used. If the limit for numerical integration in the crack length domain in PROF could be eliminated, the failure criterion reduces to Equation (2), identical to that used in DARWIN. This can be achieved by setting $a_c$ on the master crack growth curve to a very large. This would make the latter failure criterion (Equation (16)) redundant, as failure would then only occur from $K_C$ being exceeded.

NERF

NERF also uses two failure criteria. The first utilises the load-strength interface method, and is given by,

$$\sigma_R - S_{\text{max}} \leq 0$$

(17)

where $\sigma_R$ is the residual strength, $S_{\text{max}}$ is the applied stress, with both $\sigma_R$ and $S_{\text{max}}$ being treated as variables. In NERF, failure due to this criterion is termed static failure. It should be noted that Equation (14) is identical to that of Equations (3) and (12), because they are related by,

$$\left(\sigma_R - S_{\text{max}}\right) \times \beta(a)\sqrt{\pi a} = K_C - K_{\text{max}}$$

(18)

Fatigue cracks that have not failed but have exceeded the allowable crack size, are regarded in NERF as failure by life exhaustion, and this failure criterion in NERF is given by,

$$a_c - a \leq 0$$

(19)

The risk of failure due to both criteria combines to give the total probability of failure at the critical location. In cases where failure due to life exhaustion is not being considered, the failure criteria used by NERF reduces to that used in DARWIN.

7.2 Random Variables

The random variables that are currently taken into account by DARWIN are:

- Defect size ‘$d_0$’
- Stress factor ‘$X_S$’
- Fatigue life factor ‘$X_L$’
- Inspection time ‘$T_I$’
- Probability of detection

Table 1 summarises the random variables that are taken into account by DARWIN and compared with those available in PROF and NERF. The symbol ‘$\Upsilon$’ identifies those variables that are taken into by the code, while variables that are not considered are marked with the symbol ‘$\Omega$’. Variables that are treated deterministically in these codes are also marked with the symbol ‘$\Omega$’ (since they are not treated as random variables). The term ‘deterministic’ is used to indicate that said variables are treated as being deterministic.

Table 1 shows that for probabilistic fatigue life analysis DARWIN is superior to PROF and NERF as it takes three random variables, namely $d_0$, $X_S$ and $X_L$ into account when in
modelling the variation in fatigue life. PROF is the most limited in this sense as it only allows $a_0$ as a random variable, while NERF considers both $a_0$ and $X_L$.

However, an advantage that both PROF and NERF have over DARWIN is that they allow the critical material property (fracture toughness and residual strength, respectively) to be considered as a random variable, while DARWIN treats the fracture toughness as a deterministic parameter for determining fracture. Since the variation in fracture toughness may play an influential role in probabilistic fatigue life assessment, especially in materials that have anisotropic properties, it may be important that DARWIN be modified to allow option for the variation in fracture toughness to be taken into account.

For probabilistic assessment with inspection related to a single aircraft, it may be acceptable to assume that inspection and maintenance is carried out at a fixed time. However, for a fleet of aircraft, due to requirements of availability, operational readiness, limited availability of hangars, maintenance staff and equipment, it is not possible that all aircraft undergo inspection and maintenance at the same time. For this reason, modelling the inspection times as a variable as done by DARWIN is an important attribute for probabilistic (risk) management for a fleet of aircraft. This feature provides DARWIN with a significant advantage over both PROF and NERF, where inspection time(s) are modelled deterministically. However, treating inspection time as random may not truly reflect that of reality, particularly when multiple inspections scheme, as inspection times is intervene by human decision and could be correlated to the previous inspection time.

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<td>Variables</td>
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<td>Defect ‘$d_0$’ or crack ‘$a_0$’ size</td>
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<td>Fatigue life factor ‘$X_L$’</td>
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<td>Inspection time ‘$T_I$’</td>
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<td>Residual strength</td>
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<td>Fracture toughness ‘$K_C$’</td>
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<td>Critical crack size ‘$a_f$’</td>
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### 7.3 Probabilistic Methodology

As discussed in Section 3, DARWIN uses the MCS-based method for evaluating the probability of failure. PROF and NERF on the other hand utilise numerical evaluation methods. The details of the underlying probabilistic methodology, the probabilistic models
and assumptions used by PROF and NERF will not be discussed here, but can be found in [8] and [9], respectively. Although the MCS method is generally significantly slower than the numerical evaluation methods, particularly when small probabilities are involved, in cases where the inspection interval is modelled as a random variable, as in DARWIN, numerical evaluation methods become extremely difficult to implement and consequently the MCS method is currently the most viable and robust method for DARWIN.

8. Discussion

When using computer programs such as DARWIN, PROF and NERF to carry out probabilistic fatigue life assessments, it is very important to ascertain whether the following crucial aspects of the selected code realistically represent the problem under investigation,

1. The limit-state function and failure criteria,
2. The random variables that should be taken into account, and any associated assumptions.
3. The probabilistic method used to evaluate the probabilities of failure, and whether it is an approximation or simulation method.

In this report, the assumptions and limitations of DARWIN, with respect to the three items above have been identified.

The development of DARWIN up to version 4.2 has focused mainly on the creation of an efficient tool for probabilistic fatigue life predictions for axisymmetric components. While a most important aspect, the validation of the probability prediction, has been somewhat overlooked, and it would appear that no investigations have been made or are planned for a validation of the probabilistic modelling assumptions and the probability prediction results. Consequently it is unclear how representative is DARWIN in estimating the failure probabilities of components. This is particularly important as the assumption that the variation in $da/dN$ is characterised solely by the variation in the crack growth rate coefficient $'C'$ is rather inconsistent with reality, and it is not clear whether DARWIN has correctly modelled the various levels of variability of random variables in its zone-based probabilistic approach for estimating the probability of failure of the entire disk.

It is therefore important that the probabilistic modelling assumptions in DARWIN be validated prior to future probabilistic fatigue life assessments of aero-engine rotating components.

The LAF used in DARWIN to improve computational efficiency is based on the assumption that the variation in $da/dN$ is due solely to the variation in the crack growth rate coefficient $'C'$, and that the distribution of fatigue life factor is therefore directly related to $X_C$. At present, the use of this LAF option in DARWIN requires that the stress factor $'X_S'$ be treated as deterministic. This is a sacrifice that the analyst must make in employing the LAF option for probabilistic analysis to speed up computational evaluation. If the assumption currently in
use by DARWIN is valid, the deficiency that $X_s$ needs to be treated deterministically can be overcome using the method presented in Section 4.2. This proposed method might even provide an overall improvement on computational efficiency.

9. Conclusion

DARWIN is an FAA certified probabilistic damage tolerance assessment tool for assessing the risk of failure due to fatigue crack growth from hard alpha particles in titanium aero-engine rotor disk components. The use of a common, FAA certified, package amongst aero-engine designers, engineers and operators for probabilistic assessments to meet certification requirements, allows some level of standardisation and cross-comparison. Consequently it is important that DARWIN, and its future versions, be made available to DSTO for evaluation and assessment, prior to their application on ADF aero engine durability and life management issues.

The validity of probabilistic assessment codes, such as DARWIN, is generally determined by the assumptions that are made and the random variables selected. It is critical therefore that user of a particular probabilistic assessment code is fully aware of the assumptions and limitations of that code. In this report, the main features, assumptions and limitations of DARWIN version 4.2 have been identified, investigated, and discussed.

One of the major uncertainties in DARWIN methodology, as identified in this report, is the zone-based probabilistic approach procedure to assess the probability of failure of the entire rotor disk. In particular, it is uncertain, based on the available literature, as to whether the different levels of variability of random variables, namely whether a variable is applicable to the entire disk, a group of zones or individual zone, have been correctly modelled. In addition, some recommendations to overcome some current limitations have also been presented.

In DARWIN, inspection intervals or time are considered as random variables. However, it is common that a number of critical locations, if not the entire disk, are inspected via non-destructive techniques, and will not be inspected again until the next planned inspection time has elapsed. It is therefore unrealistic to require that each zone on a disk be inspected at different times during any inspection schedule. The limited documentation of DARWIN has not provided sufficient information to clarify whether variation in inspection time is disk-related (or group of zones), or it is treated randomly for each zone, the latter case is clearly unrealistic.

The variation in fatigue life is taken into account in DARWIN using a pre-determined fatigue life factor distribution. This assumes that the rate of crack growth rate is constant and independent of load level. In reality it is generally found that neither is the case. Therefore it is uncertain whether the use of a pre-determined fatigue life factor distribution results is a valid probabilistic assessment.

At present, DARWIN is only applicable to axisymmetric components, such as spacers and not to cyclic-symmetric components such as compressor and turbine disks.
Furthermore a comparison of DARWIN, PROF and NERF has shown DARWIN to be a more powerful and sophisticated package for probabilistic fatigue crack growth life assessment, despite the fact that DARWIN version 4.2 is restricted to axisymmetric engineering components.

**References**


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<td>DARWIN is an FAA certified probabilistic fracture mechanics risk assessment software specifically designed for the fatigue life management of titanium aircraft engine rotors disks. This report is a detailed review and discussion of the underlying principles, capabilities and limitations of DARWIN, and also compares the methodology of DARWIN to that of other commonly available probabilistic assessment tools, namely PROF and NERF.</td>
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