CYIENT

FATIGUE AND DAMAGE TOLERANCE ANALYSIS OF AIRCRAFT STRUCTURAL COMPONENTS

Contents

Executive Summary	01
Ensuring Structural Integrity of Aircraft	01
Complying with Regulations Governing Damage Tolerance	01
Understanding Damages and Inspection Methods	02
F&DT Design Process	04
Evaluating Fatigue and Damage: Our Expertise	06
Providing Comprehensive Support for Challenging Problems - The Cyient Advantage	11
Ensuring Resilient Aircrafts and Passenger Safety	11
Authors	12
About Cyient	13

The primary focus for setting regulatory requirements is to limit structural damage and enhance flight safety during the service life of the aircraft.

Executive Summary

In the early 1970s, the United States Air Force (USAF) developed a damage tolerance philosophy to help eliminate structural failures and cracking issues encountered across various aircraft. The regulatory requirements for the safety of aircraft have drastically evolved and have become more stringent based on significant service and test experience since then. The primary focus is to limit structural damage and enhance flight safety during the service life of the aircraft.

In order to ensure structural integrity, original equipment manufacturers (OEMs) are required to conduct fatigue and damage tolerance (F&DT) studies across design, manufacturing, and in-service stages. These studies entail extensive evaluation, analysis using approved methods, and rigorous reporting that require significant resources, time, and effort. As a result, OEMs are increasingly outsourcing F&DT analysis to experienced vendors in order to reduce the pressure on in-house resources and optimize their utilization for core business processes.

This paper demonstrates the process of performing F&DT analysis with regard to the calculation of fatigue life and determining the crack growth period for an aircraft component, in ensuring the structural safety of an aircraft. It also showcases our extensive capability in performing F&DT analysis studies for both metallic and composite airframe structural parts across pre- and post-manufacturing stages of aircraft life cycle.

Ensuring Structural Integrity of Aircraft

All aircraft operators strive to continue operating their aircraft beyond their intended design life in order to maximize profits. This requires aircraft to be designed using precise material properties and the intended loads likely to be experienced by the aircraft over its lifetime. Therefore, proper structural integrity programs are designed to assure safety and maximize the life of an aircraft.

According to regulatory mandate, OEMs are required to design aircraft that meet a design service goal (DSG) of specified flight cycles with a reliability range of 95% to 100%. Different steps are involved in calculating the life of aircraft components for certification purposes. The certification procedures and guidelines are defined in manufacturers' standard repair documents.

These guidelines/manuals/documents detail procedures for different types of repairs such as structural, avionics, engine, and system. If the repair falls within the purview of guidelines, the damage or non-conformance of the aircraft identified during inspection is cleared. For damages outside the purview of guidelines, the margin of safety for static loads, threshold life, and inspection intervals for the damage are computed.

Typically, OEMs set up an aircraft structural integrity program during pre- and post-manufacturing stages to ensure compliance and aircraft safety. F&DT analysis is an integral part of these programs that help ensure structural stability and reliability of aircraft systems.

Complying with Regulations Governing Damage Tolerance

Regulatory authorities such as the Federal Aviation Administration (FAA) mandate that aircraft need to be repaired and maintained at regular intervals to ensure airworthiness. Similarly, any type of repair in an aircraft requires adherence to certain standards and procedures. These standards are generally set by regulatory authorities including the FAA and

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the European Aviation Safety Agency (EASA) in conjunction with aircraft manufacturers.

In addition, over the years, major airplane accidents have highlighted problems due to aging airplane structures including airframe structural fatigue, and issues related to maintenance, inspection, and repairs. As a result, to ensure continued airworthiness of ageing aircraft, FAA issued AASR 14 CFR Part 26 Subpart E that mandates damage tolerance based inspections for repairs and modifications on airplanes.

According to Federal Airworthiness Regulations FAR25/CS25 requirements, the civil aviation (large aircraft) industry needs to comply with a certain set of standards. These standards include clauses that specify criteria for readily detectable, immediately detectable, and barely visible impact damages (BVID) to help with ultimate load computation. The F&DT calculations need to adhere to clause 25.571. For detailed information on F&DT regulations, please refer to the FAA documentation.

Understanding Damages and Inspection Methods

Damages can occur during manufacturing and post manufacturing stages. Factors include design, manufacturing and assembly errors, environmental conditions, state of the aircraft, fatigue and corrosion of composite structures, etc. In practice, aircraft damages can be classified as shown in Table 1.

Manufacturing Damages are addressed by establishing a damage tolerant design with appropriate safety/knock-down factors	• Oversize hole • Porosities (≤ 2.5%) • Cure and processing tolerances • Incorrect fastener pitch • Alternative fastener type • Part out of tolerance • False cut • Deep countersunk • Alternative material used • Loss of edge landing
Post-Manufacturing Damages are effectively addressed through detailed F&DT calculations	• Corrosion damages • Fatigue cracks • Dents • Gouges • Nicks • Debondings between skin and core (sandwich) • Free edge damages (Delaminations, notches, loose fibers, etc.) • Impact damages • Scratches

Table 1 | Typical damages encountered during manufacturing and post-manufacturing stages

When a damage is identified in an aircraft during inspection, it is either repaired according to procedures and guidelines provided in manufacturers' standard repair documents.

Damage Inspection Intervals

To address these different types of damages and to obtain an economically viable solution for the component, OEMs need to ensure long inspection periods or long replacement intervals.

To achieve long inspection periods, the designer must take the following factors into account:

- Improved inspection procedure
- Using a different material with better mechanical properties and a penalty on the cost
- Redesigning to lower the stresses
- Utilizing redundant systems to prevent catastrophic component failure

Summary of few in-service inspections from Joint Service Specification Guide (JSSG-2006) Appendix is shown in Table 2[1].

Degree of Inspectability	Typical Inspection Interval
In-flight evident inspectable	One flight*
Ground evident inspectable	One day (two flights)*
Walk-around inspectable	Ten flights*
Special visual inspectable	One year
Depot or base level inspection	¼ Design service lifetime
In-service non-inspectable structure	One design service lifetime

* Most damaging mission

Table 2 | Inspection intervals

Inspection Methods

F&DT analysis is performed by considering possible cracking scenarios in the structure. The following inspections are carried out depending on the structure criticality and economic situation of operator.

- General Visual Inspection (GVI)
- High Frequency Eddy Current (HFEC)
- Low Frequency Eddy Current (LFEC) and
- Electro Magnetic Inspection (EMI)

When a damage is identified in an aircraft during inspection, it is either repaired according to procedures and guidelines provided in manufacturers' standard repair documents, or a new repair is approved as shown in Fig. 1.

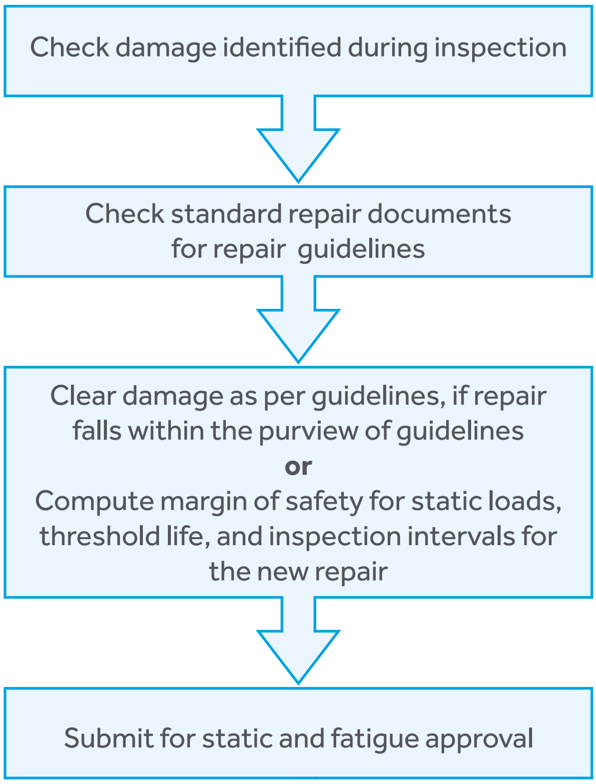

Fig. 1 | General repair guidelines

A structure is said to be damage tolerant if it resists fracture from the already existing cracks for a given period of time.

F&DT Design Process

Damage tolerance is a function of the material property and construction of the structure. An existing crack in the structure may not be potentially dangerous under normal aircraft operating conditions. A structure is said to be damage tolerant if it resists fracture from the already existing cracks for a given period of time.

However, it is assumed that the crack can extend in a sub-critical manner through fatigue and stress corrosion. Therefore, deploying a damage tolerant design process addresses two aspects in a cracked structure.

- Determination of fracture load that can be sustained for a specified crack size
- Prediction of the duration of time required for a 'sub-critical' crack to grow to a proportion that could cause fracture at a given load

Damage tolerant structures can be divided into two major groups:

- **Slow crack growth:** This category includes all types of structures with single and multiple load paths. These are designed in such a way that the initial damage grows at a stable, gradual rate, and does not grow into a size large enough to cause structural failure. Safety is assured through a slow rate of growth.
- **Fail safe:** Usually structures are comprised of multiple elements or load paths. This is to contain damage caused by a failing load path safely, or arrest a rapidly running crack at a tear strap or other deliberate design feature.

Safe Life and Damage Tolerant Design: Two Approaches to Prevent Premature Failure

Conventionally, two approaches – safe life and damage tolerant design are followed to assure that the components don't fail prematurely due to fatigue.

Safe Life: One of the earliest methods to be used, it is based on the premise that once a component reaches a specified number of cycles it is replaced with a new one. This method takes into account only fatigue life issues and has severe economic implications, as a component is replaced irrespective of the number of additional fatigue cycles it can withstand. Nowadays, this approach is only used for critical components of an aircraft such as the landing gear.

In order to obtain a safe and economically viable component, a different approach was needed. As a result, damage tolerance design (DTD) was introduced in the 1970s.

Damage Tolerant Design: As a relatively recent philosophy in structural design, it is defined as "the ability of an aircraft structure to sustain anticipated loads (e.g. limit load) in the presence of fatigue, corrosion, or accidental damage until such damage is detected through inspections (or malfunctions) and repaired". In the DT design philosophy, it is assumed that flaws already exist in the structure as manufactured, and that the structure may be inspectable or non-inspectable in service.

Under this approach, several aspects are taken into consideration during qualification of aircraft components in order to ensure safe structures. These include:

- Obtaining the residual strength as a function of crack dimension
- Determining maximum allowed crack length
- Determining maximum elapsed time for the crack to grow to a critical condition
- Identifying the extent of pre-existing crack permitted in the structure
- Defining inspection interval for replacements of the damaged portion or proof testing the typical process followed for a repair as shown in Fig. 2

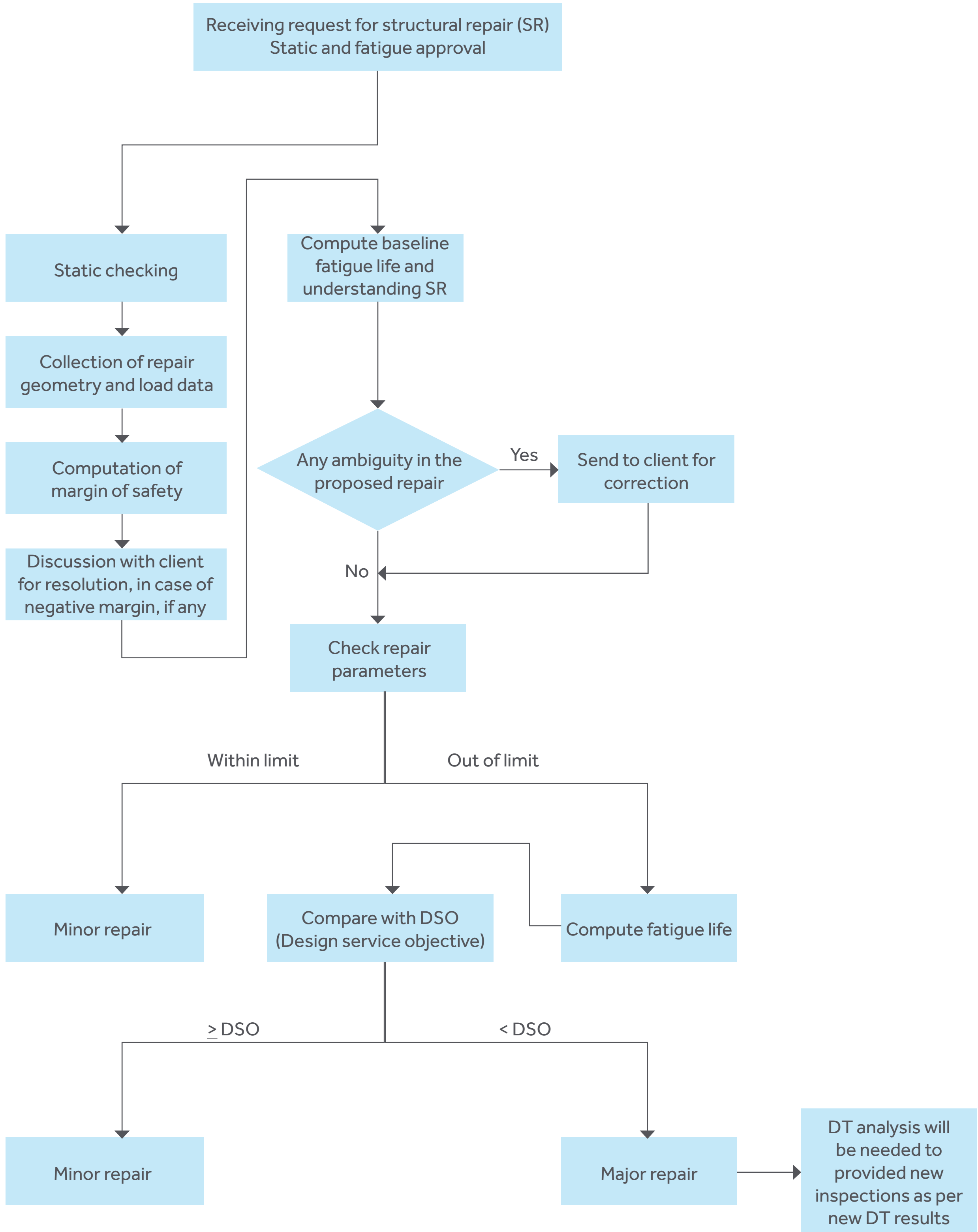

Fig. 2 | F&DT design process

While the fatigue stress survey is used to select the critical stress locations, the fatigue spectrum is used in fatigue and crack propagation analyses.

Evaluating Fatigue and Damage: Our Expertise

We have been providing comprehensive support to Tier 1 OEMs in carrying out F&DT studies for close to a decade. The F&DT process starts with the identification of primary structural element to suggest the appropriate inspection methods. Our in-depth expertise in F&DT in pre-production and in-service phases is summarized as follows:

F&DT Study Across the Aircraft Life Cycle

Following are the steps involved in F&DT study on an aircraft across the life cycle as shown in Fig. 3.

OEMs share Finite Element Model (FEM) to represent the general structural architecture of the component for which the fatigue loads are to be extracted. These fatigue loads are then used in fatigue stress surveys and spectrum generation. While the fatigue stress survey is used to select the critical stress locations, the fatigue spectrum is used in fatigue and crack propagation analyses. Above process is detailed in the section below.

Primary Structural Elements (PSE) Classification

This tabulates the PSE with their respective analysis type. Depending on the type of analysis, fatigue or DT is performed for that sub -component. Typical examples of PSE are fuselage beams, wing spar, pressure bulkhead, frames, fuselage skin, etc.

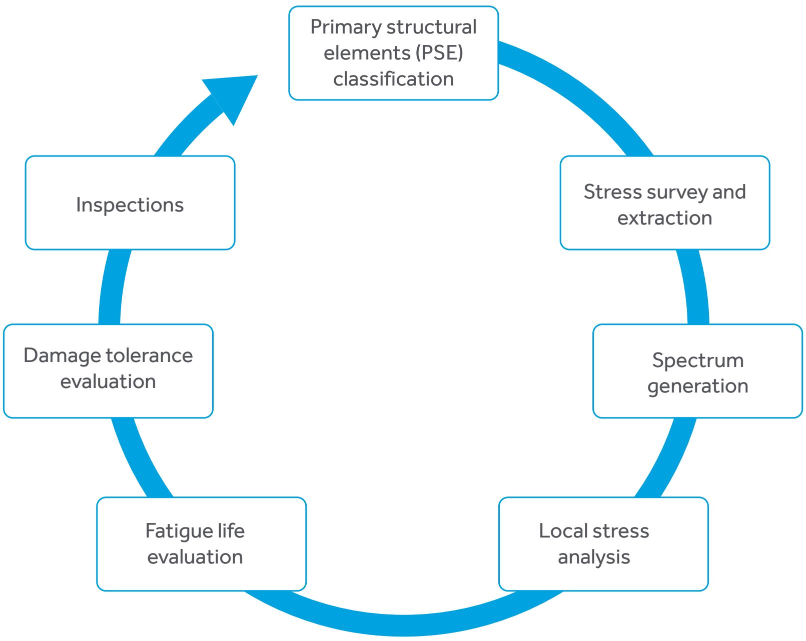

Fig. 3 | Typical F&DT steps in an aircraft life cycle

The necessary stress concentration factors used in fatigue analysis are obtained from the standard design handbooks. When the structure is complex then 2D and 3D FEMs are used.

Stress Survey

This identifies the highest stressed element of the component.

A stress survey of maximum principal/shear stress is carried out on the component to determine the critical location. The stress at the critical location is extracted for further processing.

Spectrum Generation

A component in service is exposed to varied loads through time, which is referred as the spectrum. The spectrum differs in properties and shapes depending on the structural part it belongs to such as wing, tail, or fuselage. For instance, the spectrums for wings and tails are more complex in shape than the ones for fuselage. Before making any fatigue calculations, it is critical to identify this spectrum.

Load spectrum must be identified for the specific part of the aircraft in order to achieve accurate fatigue results. It can be done in two different ways—either from data collected from an actual aircraft or through computer algorithms. A typical process of isolating stress cycles from a spectrum is shown in Fig. 4.

Stress spectrum (using maximum principal/shear stress) is generated by employing the specified number of load cases associated with various flight missions. This process establishes the locations identified for the extraction of fatigue stresses.

During the repair stage, the same spectrum generated during the design phase of the component is used. For the repaired component, a new threshold life is calculated. While prescribing the new inspection intervals, the already exhausted life is deducted from the new threshold life.

Local Stress Analysis

Three-dimensional Finite Element Models (3D FEM) are built to assess the local stress distribution around the locations identified. Maximum principal/shear stress is extracted at these locations for fatigue analyses.

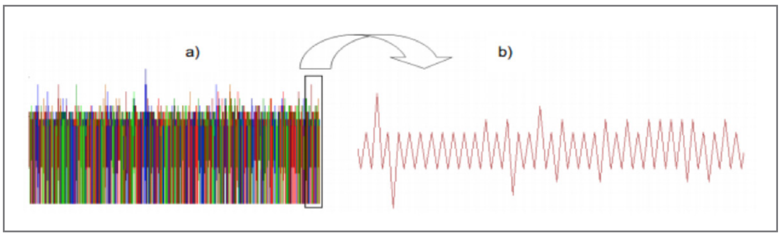

Fig. 4 | Typical isolation of stress cycles

Critical location data, gathered using fracture mechanics principles, forms the basis for carrying out Fatigue life and Damage tolerance analysis.

Fatigue Life Evaluation

The necessary stress concentration factors used in fatigue analysis are obtained from the standard reference sources. However, 2D and 3D FEMs are utilized for generating stress concentration factors when the structure is characterized by complex geometry and loading.

Damage Tolerance evaluation

Damage tolerance evaluation is performed as stipulated in sections CS 25.571 (a) and (b) and is supported by test evidence. The damage tolerant design caters to the damages likely to occur at multiple sites during the design phase. Crack propagation analysis is performed at the location of absolute maximum principal/shear stress by taking into account stress intensity factors. Crack propagation analysis locations are selected based on fatigue life and PSE classification.

Inspections

The development of a maintenance program for every new type of aircraft should include frequency and extent of inspection procedures, before it is introduced into service. The frequency and extent of inspections are determined from the results of the fatigue and damage tolerance analysis studies.
The inspection plan includes:

- Threshold Inspection (TI) - First recommended inspection
- Inspection Interval (II) – Subsequent inspections

The type of inspection (GVI etc.) will depend on the detectable crack length. Typical examples are:

- Large cracks through close visual inspection
- Medium and small cracks using specific NDT

The detectable crack lengths in real life are sufficiently large for all the inspection methods.

F&DT Study in the Post-manufacturing Phase: A Case Study

The post-manufacturing F&DT analysis processes are demonstrated using a case study of aircraft wing skin and frame assembly.

Frame assembly fastener locations are fatigue critical regions as shown in Fig. 5. Skin and frame assembly is analyzed using finite element analysis.

The results are filtered for determining the critical element. Fatigue load spectrum containing different load case combinations is developed to represent fluctuating stress acting on the structure.

Critical location data, gathered using fracture mechanics principles, forms the basis for carrying out Fatigue life and Damage tolerance analysis. Convenient inspections are provided for maintenance depending on the F&DT results and the operator's willingness to invest in inspection methodology.

In Fig. 5, the frame in the skin—frame assembly is subjected to a crack at a diametric location of a hole. When an operator finds this damage, it is repaired using standard repair procedure. The strength of the joint is restored by installing a repair doubler.

The above repair needs static and fatigue approval. Static check is done first and the aircraft is approved to fly.

Within a fixed time frame (as per FAA guidelines) fatigue approval needs to be provided. The F&DT analysis is performed by considering the pre-manufacturing data of that assembly. The joint analysis is performed by taking into account the appropriate configuration. The critical load transferred at the fastener location is identified. The fatigue life is evaluated at the critical location by considering cross sectional area, surface condition, and material properties.

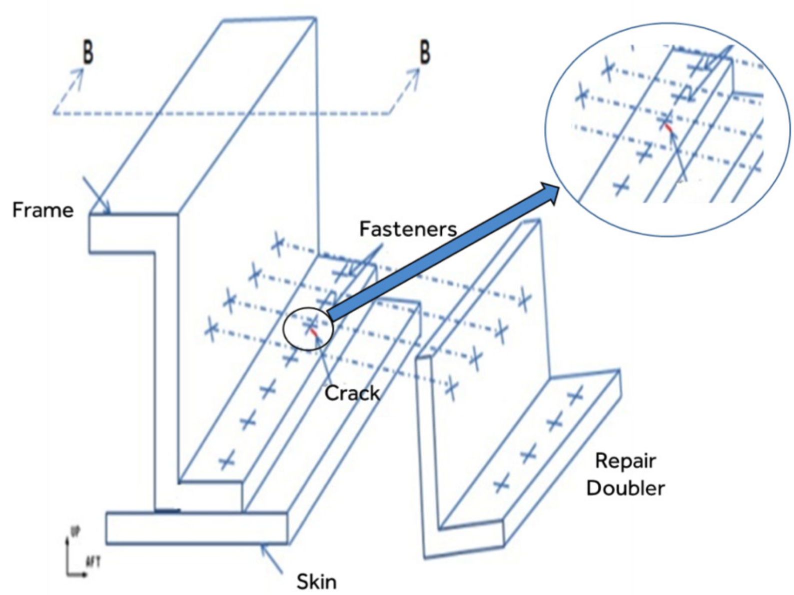

Fig. 5 | Crack on the assembly of skin—frame construction with repair doubler as repair

Finally, the inspection program detailing additional inspections is issued for the repaired structure for its safe maintenance.

A typical process for fatigue life calculation and crack growth analysis is detailed below.

Fatigue Life Calculation
The fatigue life is calculated as demonstrated in Fig. 6.

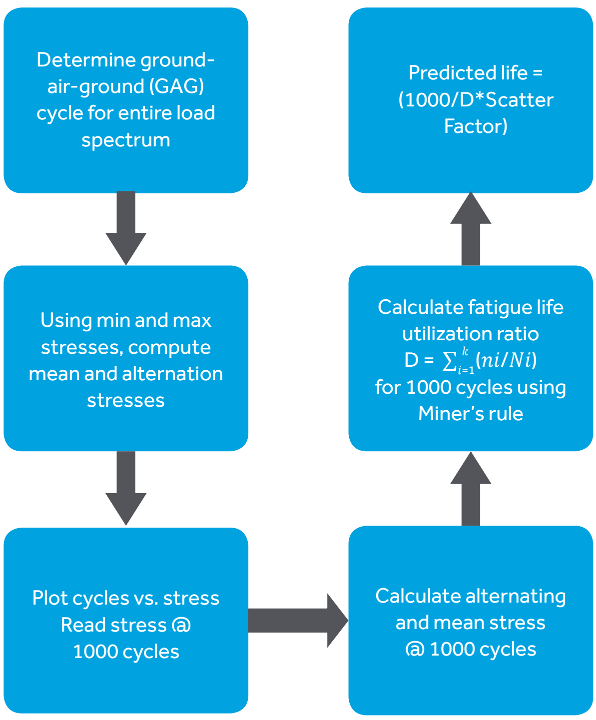

Fig. 6 | Fatigue life calculation

Crack Growth Analysis

Fig. 7 shows the various steps involved in crack growth analysis.

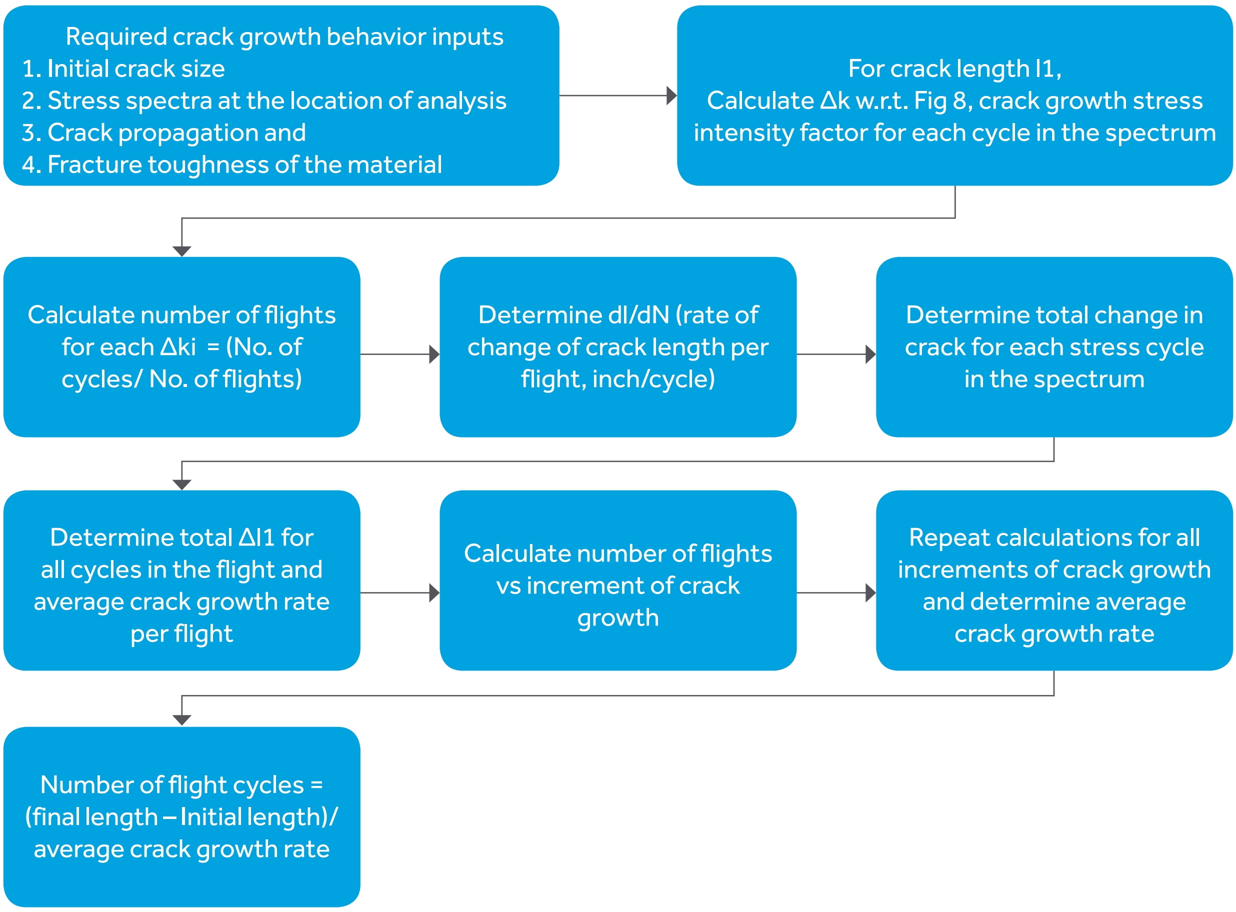

Fig. 7 | Crack growth analysis

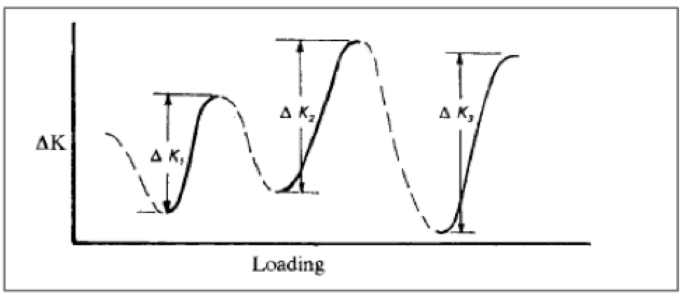

Fig. 8 | Variation ΔK vs. spectrum loading

With our extensive experience and domain expertise, we are capable of providing various alternate solutions for challenging field problems with a quick turnaround time.

Computation of Fatigue Life and Crack Growth Rate

As a certification requirement for the repair carried out on the skin-frame assembly shown above in Fig. 5, a typical repaired assembly is shown in Fig. 9.

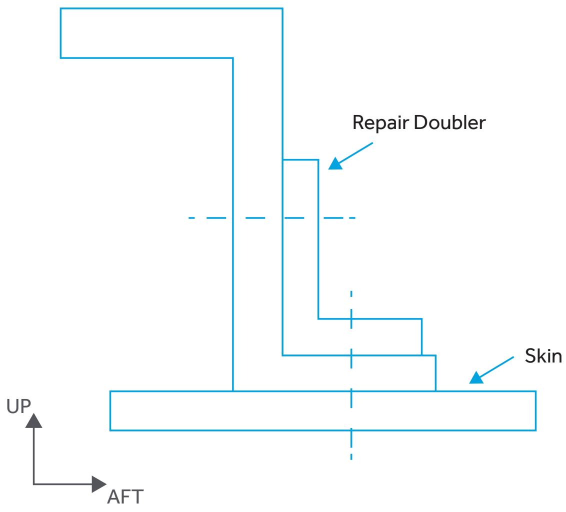

Fig. 9 | Repaired skin-frame

Typical output of F&DT exercise would be

- Predicted life
- Average crack growth rate (inch/flight)
- Number of flights required for the crack to become critical

Providing Comprehensive Support for Challenging Problems - The Cyient Advantage

Drawing upon our extensive experience and domain expertise, we are capable of providing various alternate solutions for challenging field problems with a quick turnaround time. Our extensive experience as the chosen partner for the OEMs and Tier 1 clients enables us to bring unparalleled value to each of our engagements.

Comprehensive services: We provide end-to-end F&DT analysis services across the aircraft life cycle.

Accelerated cycle time: We leverage our in-house productivity improvement tools and re-useable solutions to help reduce data analysis cycle time by 20% to 30% depending on the type of problem.

Optimized cost and operational efficiency: We create standardized processes by combining industry best practices that in turn helps improve operational efficiency and reduce costs.

Ensuring Resilient Aircrafts and Passenger Safety

Aircraft fatigue and fracture can result in accidents and incidents for commercial fleet operators, resulting in high costs involving human life and damage to brand reputation. In fact, structural failures have been attributed to the most fatal and catastrophic accidents in the past. As a result, F&DT has become a critical design consideration and a regulatory requirement to ensure structural optimization and air safety.

However, robust fatigue and damage tolerance design and analysis requires extensive expertise in failure and fracture mechanics, material science, structural mechanics, and analytical work. OEMs that partner with experienced vendors can effectively leverage their expertise to help improve the rigor and efficacy of fatigue analysis, maintain compliance, and enhance passenger safety.

Authors

Padmaja Reddy K is a Team Leader working with the aerospace and defense vertical at Cyient. She is a graduate in Mechatronics, from Hyderabad. She has 7 years of experience in F & DT and stress analysis of metallic and composite airframe structures.

Bhargav Yandra is a Senior Design Engineer working with aerospace and defense vertical at Cyient. He is a graduate in Mechanical Engineering. He has 4 years of experience in F & DT and stress analysis of metallic and composite airframe structures.

S S Subramanya Sastry is Deputy General Manager, Aerospace and Defense at Cyient. A post graduate in Civil Engineering from UVCE Bangalore with specialization in structures, he has 28 years of experience in aerospace engineering. Prior to Cyient, he had served as a Principal Consultant at QGSL and Scientist, National Aerospace Laboratories, Bangalore. He is a Fellow of the Institute of Engineers (India); Fellow of the Indian Institution of Production Engineers (India); member of International Working Group, NAFEMS, UK; Honorary Chairman, NAFEMS India Composite Working Group; Member, NAFEMS India Council; Expert member, NAFEMS Panel on Certification for CAE professionals; Life Member, Aeronautical Society of India; Life Member, Indian Society of Advancement of Material and Process Engineering (ISAMPE), and Life Member, Engineering Design and Analysis Forum, India. He also mentors students at various universities.

About Cyient

Cyient (Estd: 1991, NSE: CYIENT) provides engineering, manufacturing, geospatial, network and operations management services to global industry leaders. We leverage the power of digital technology and advanced analytics capabilities, along with domain knowledge and technical expertise, to solve complex business problems. As a Design, Build and Maintain partner, we take solution ownership across the value chain to help our clients focus on their core, innovate, and stay ahead of the curve.

Relationships lie at the heart of how we work. With nearly 14,000 employees in 21 countries, we partner with clients to operate as part of their extended team, in ways that best suit their organization's culture and requirements. Our industry focus spans aerospace and defense, medical, telecommunications, rail transportation, semiconductor, utilities, industrial, energy and natural resources.

For more information, please visit
www.cyient.com

Contact Us

North America Headquarters

Cyient, Inc.
99 East River Drive
5th Floor
East Hartford CT 06108
USA

T: +1 860 528 5430
F: +1 860 528 5873

Europe, Middle East, and Africa Headquarters

Cyient Europe Ltd.
High Holborn House
52-54 High Holborn
London WC1V 6RL
UK

T: +44 20 7404 0640
F: +44 20 7404 0664

Asia Pacific Headquarters

Cyient Limited
Level 1, 350 Collins Street
Melbourne, Victoria, 3000
Australia

T: +61 3 8605 4815
F: +61 3 8601 1180

Global Headquarters

Cyient Limited
Plot No. 11
Software Units Layout
Infocity, Madhapur
Hyderabad - 500081
India

T: +91 40 6764 1000
F: +91 40 2311 0352

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