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GE Avio Life Management Team
Tech Regulations on LLPs (with case study)

Course on "Mechanical Systems Reliability"
"Structural reliability of aerospace components"
Held by S. Beretta Department of Mechanical Engineering

v1.-

G. Costa / S. Romano

3rd Nov '23

Export Data	
Tagger	*G Costa*
Jurisdiction	Civil
Export Classification/Category	*NECT 008792_20231024*

My **career** – Gianfranco Costa

EMS Advance Lead Engineering
Life Management
Manager – G. Vallillo

TTP Enrolled

Life Management
Advance Lead Engineer – EMS
GE AA

GE Avio Lifing Process Standardization
Focal point for Surface Integrity
Customer / Certifying Agents Exposure (EASA)
PGB & LPT lifing & Fleet Management – Life Counting Algorithm

MRB approver

Typhoon engine & Tornado Engine
LPT Module Hardware Owner
Lead Engineer – GE AA
(2Q 2016 – 4Q 2019)

Manufacturing & Special Processes – Process Validations
Support to Repair Engineering Team
Support to Production and Producibility

Damage Tolerance Focal Point

Life Counting Focal Point

Lifing Cycle Counting Lead
Rotating Parts – Rolls Royce plc
(2Q 2015 – 1Q 2016)

Life Cycle Counting Algorithms deep dive

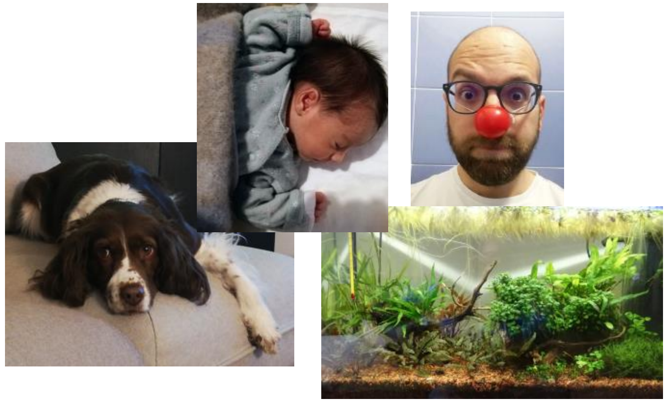
XWB-84k HPT Stress Lead
Rotating Parts – Rolls Royce plc
(2Q 2015 – 1Q 2016)

Lifing Strategy Definition and Management
Team management

Stress & Lifing Engineer
Rotating Parts – Rolls Royce plc
(2Q 2012 ⇒ 1Q 2015)

NPI Execution
Stress & Lifing deep dive
Design & Optimization / DOE / Robust Design for Lifing
Safety Alerts management and resolution
Certification & Technical Life Reviews / FMECA and Failure Analysis

My Life



Education

MS Aerospace Engineering (2012) University of Pisa

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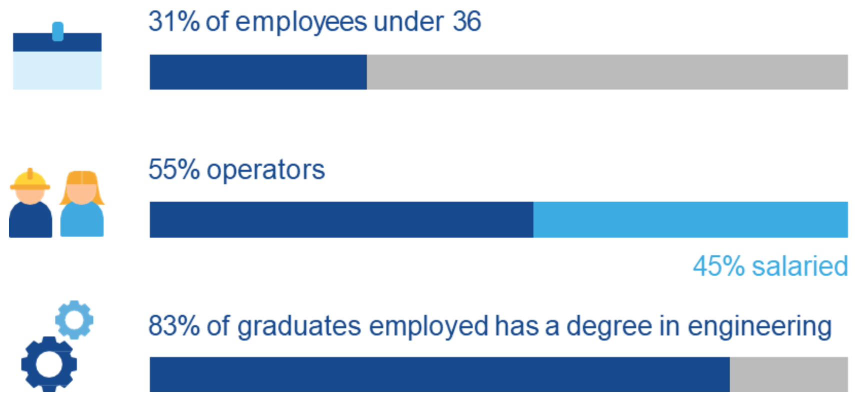
Section #1

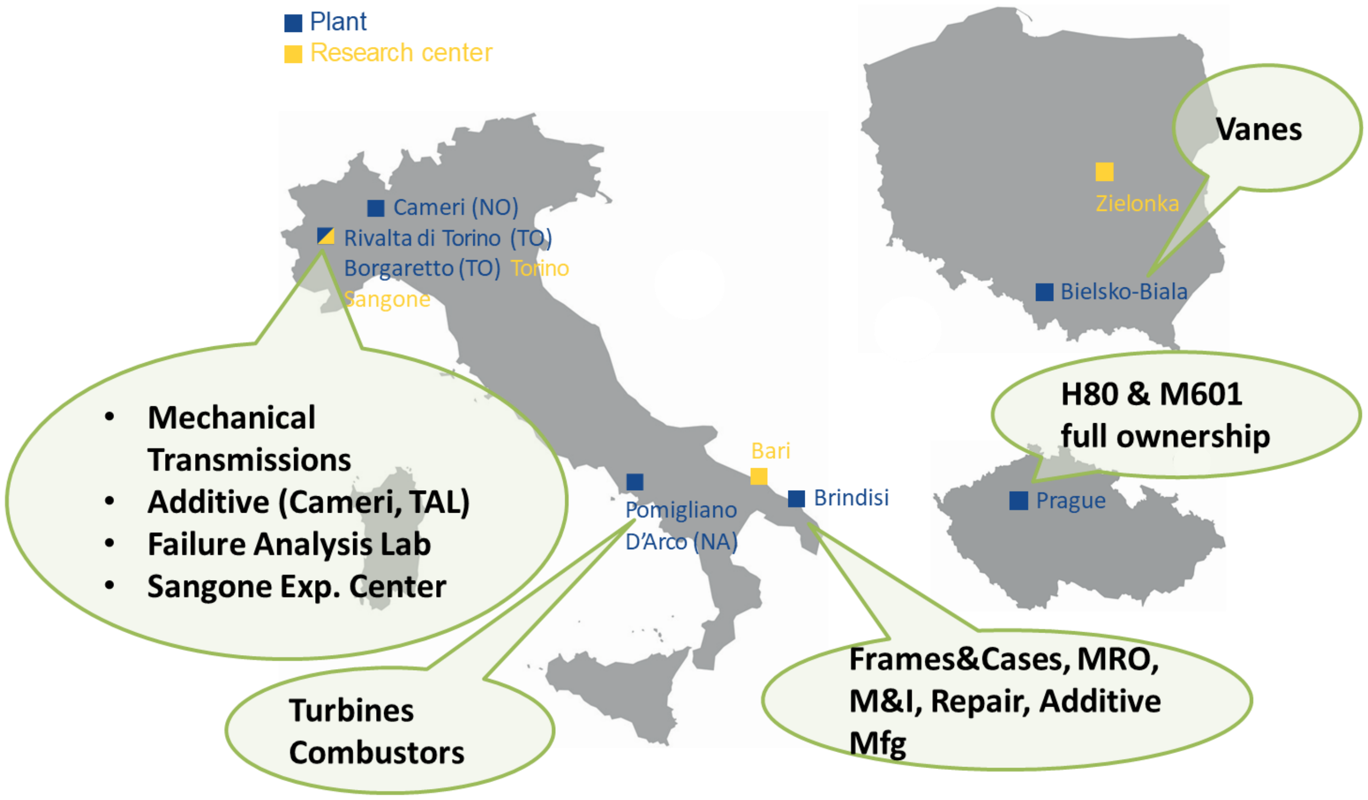
GE Avio Life Management Team

Introduction to GE Avio s.r.l.



5200+ PEOPLE

ACROSS EUROPE



Italy

Poland

Czech Republic

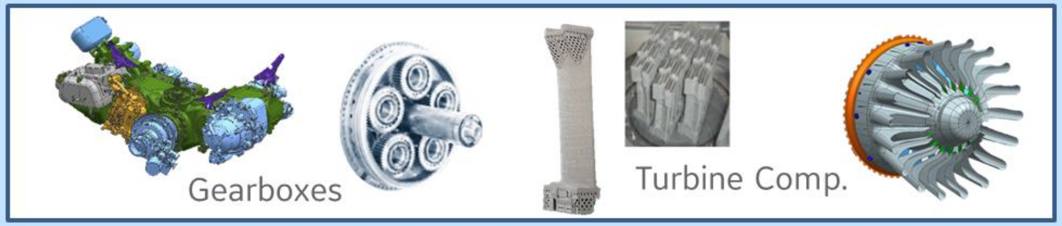
Introduction to GE Avio s.r.l.

Tier #2&1 (*)

Provide GEA with differentiating technology for Next Generation products

Tier #2

Provide Ext OEMs with «value for $» module technology

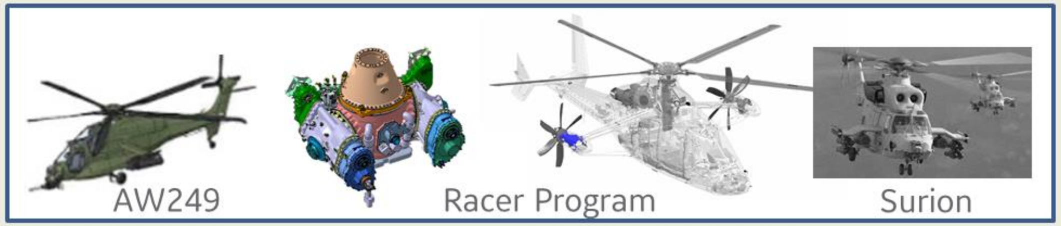


Tier #1&2

Enable EU Military customers to pursue their technology independence strategy

Tier #1

Develop safe & reliable products for Helo OEMs, partner in their electrification pursuit

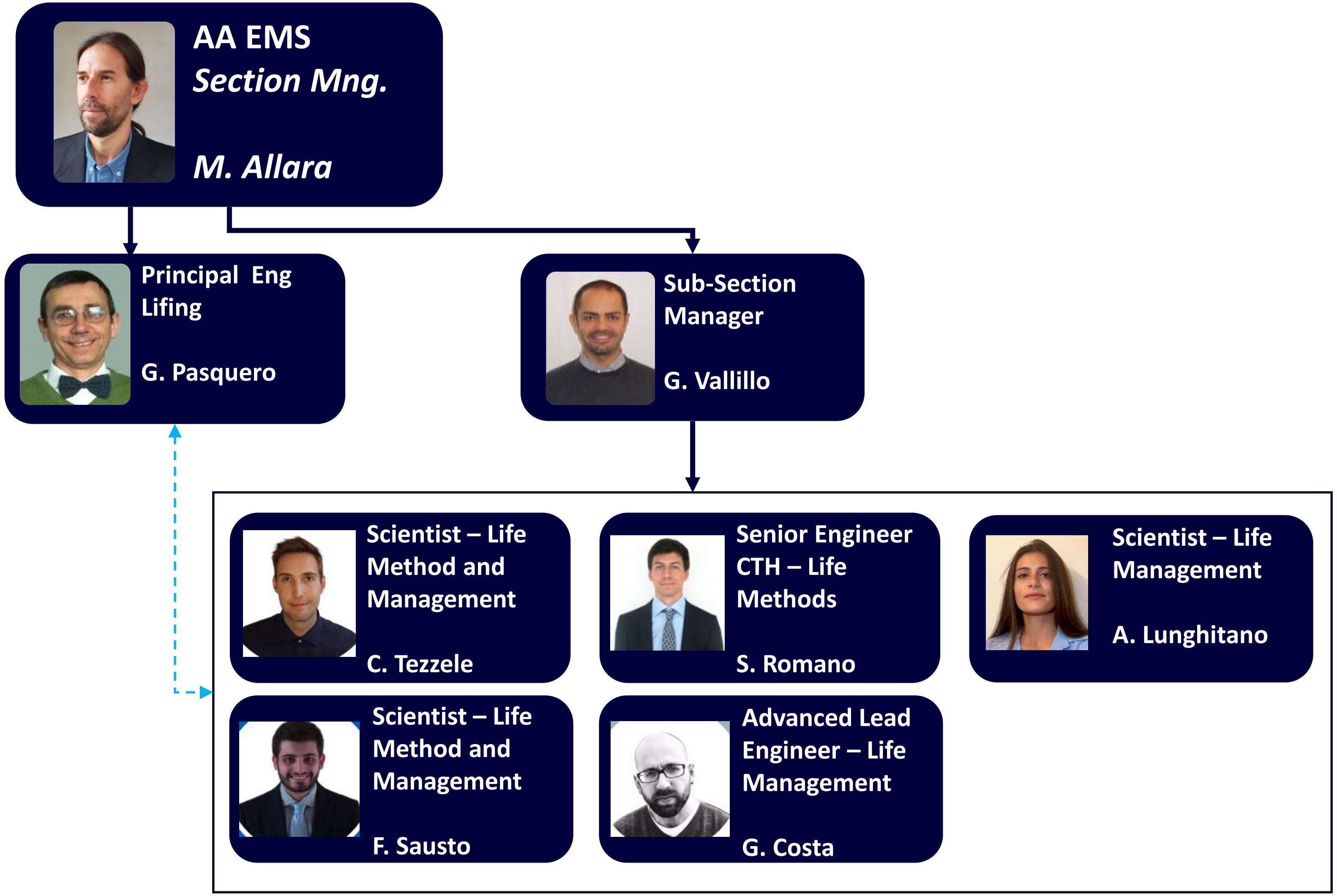


(*) Tier #0: Airframer
Tier #1: Engine integrator
Tier #2: Engine modules

3

Introduction to GE Avio s.r.l.

Introduction to Life Management & Methods Team

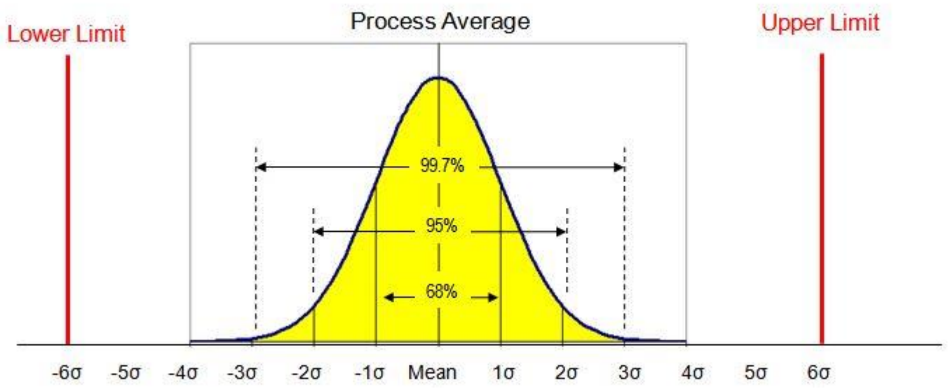


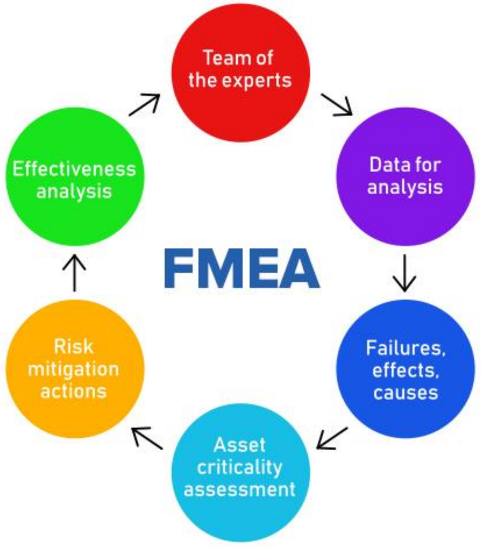
Focus Competencies

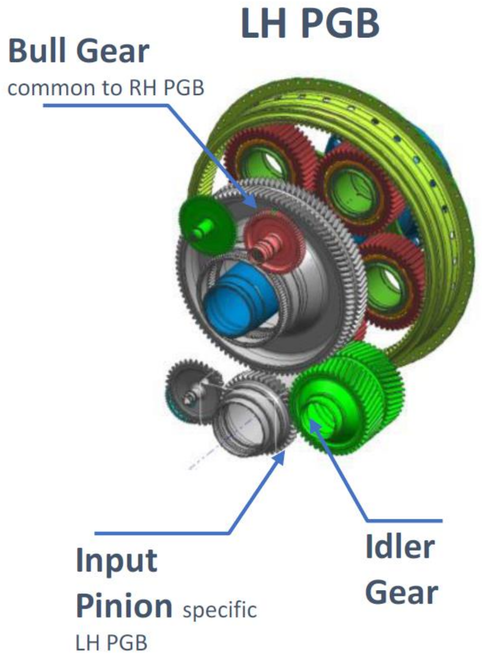
- LCF & HCF
- LEFM
- FCG testing and curve development
- Probabilistic FM
- Surface Integrity & Manufacturing Influence
- Additive Manufacturing
- Usage Based Lifing
- Production & Field Support
- Serviceable and Repairable limits
- Helo & GBX Lifing

Statistical and Reliability Application at GE Avio

- 6-sigma approach to product quality
- Robust Design concepts (gear lifing, anomalies characterization, …)
- Safety & Reliability (FMEA, PFMEA, fault-tree for system)
- Mission Analysis (Monte Carlo)
- Part Certification (PFM for disk lifing, PDT)
- Fleet Risk Assessment







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Section #2

Technical Regulations for Life Limited Parts Lifing

Regulatory Agencies

Federal Aviation Administration

EASA
European Aviation Safety Agency

***Regulate design criteria and verification** to ensure aviation **safety** within a pre-defined **risk target**.*

Technical Regulations for Engine Life Limited Parts

Federal Aviation Administration

Title 14 - Aeronautics and Space

→ Chapter I - Federal Aviation Administration, Department of Transportation

→ Subchapter C - Aircraft

→ Part 33 Airworthiness Standards: Aircraft Engines

→ AC 33.70 Engine life-limited parts.

https://www.faa.gov/regulations_policies/advisory_circulars/

EASA European Aviation Safety Agency

Certification Specifications (CSs) – Initial Airworthiness

→ CS-E Engines

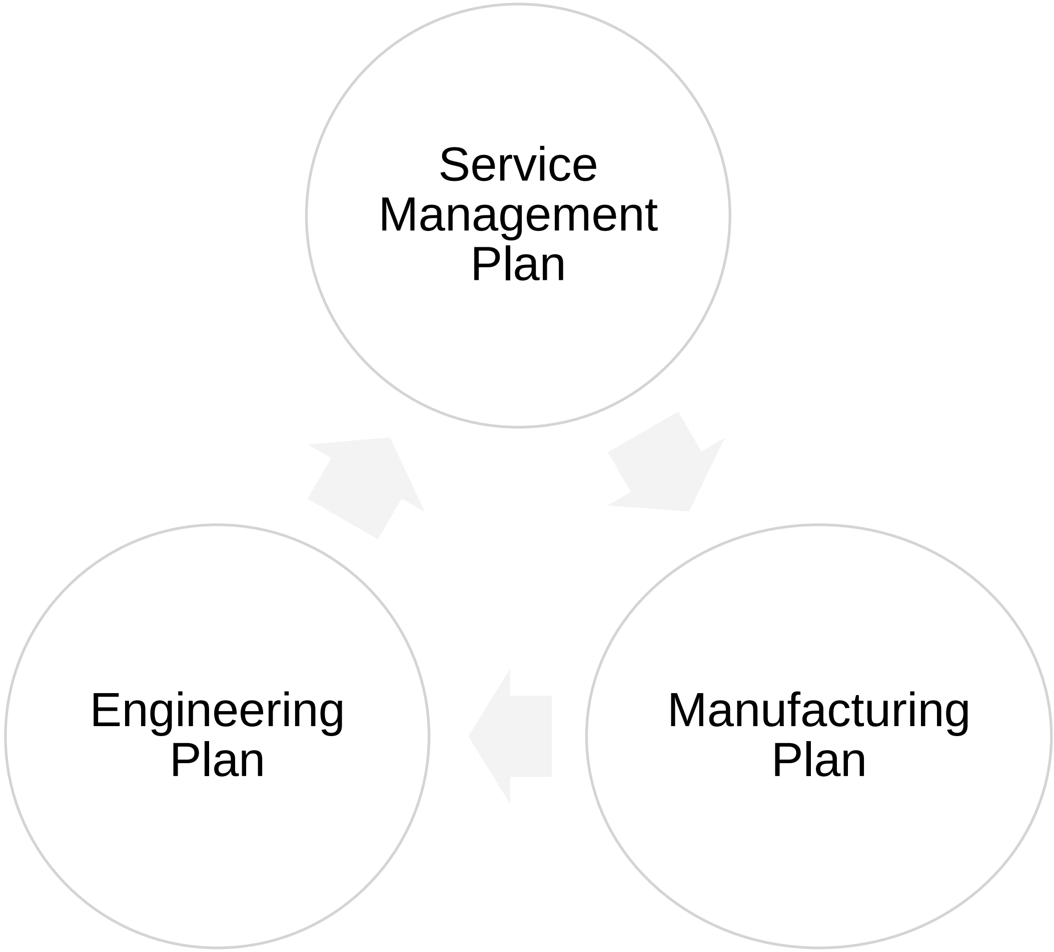
→ CS-E 515

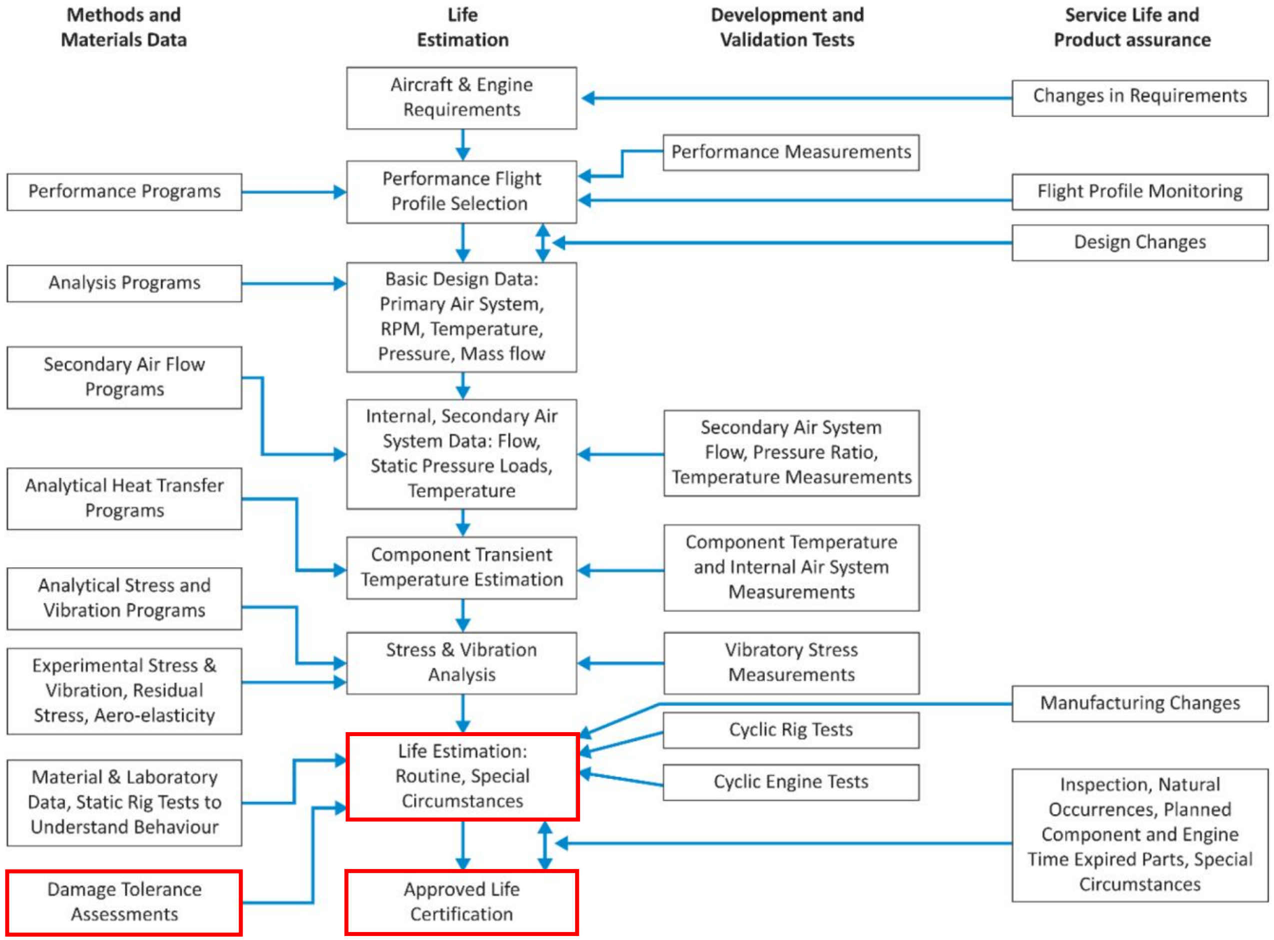
https://www.easa.europa.eu/en/downloads/116287/en

Life Limited Parts – Key Terminology

Life Limited Part / Critical Part *(ref. FAA AC33.70 and EASA CS-E15)*	Rotor and major static structural parts whose **primary failure is likely to result in a hazardous engine effect**. Typically, engine life-limited parts include, but are not limited to disks, spacers, hubs, shafts, high-pressure casings, and non-redundant mount components.
Primary failure *(ref. FAA AC33.70 and EASA CS-E15)*	Failure of a part that is not the result of prior failure of another part or system.
Hazardous Engine Effect *(ref. FAA AC33.75 and EASA CS-E510)*	The following effects must be regarded as Hazardous Engine Effects: i. Non-containment of high-energy debris, ii. Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers, iii. Significant thrust in the opposite direction to that commanded by the pilot, iv. Uncontrolled fire, v. Failure of the Engine mount system leading to inadvertent Engine separation, vi. Release of the propeller by the Engine, if applicable, vii. Complete inability to shut the Engine down. It must be shown that **Hazardous Engine Effects are predicted to occur at a rate not in excess of that defined as Extremely Remote.**
Extremely Remote *(ref. FAA AC33.75 and EASA CS-E15)*	Unlikely to occur when considering the total operational life of a number of aircraft of the type in which the Engine is installed, but nevertheless, has to be regarded as being possible. Where numerical values are used this may normally be **interpreted as a probability in the range 10^{-7} to 10^{-9} per Engine flight hour**.
Life Limit *(ref. FAA AC33.70)*	An operational **service exposure limit** characterized by the application of a finite number of flights or flight cycles. For rotating parts, it is equal to the **minimum number of flight cycles required to initiate a crack equal to approximately 0.030 inches in length by 0.015 inches in depth**.

Life Limited Parts – Lifing High Level Strategy



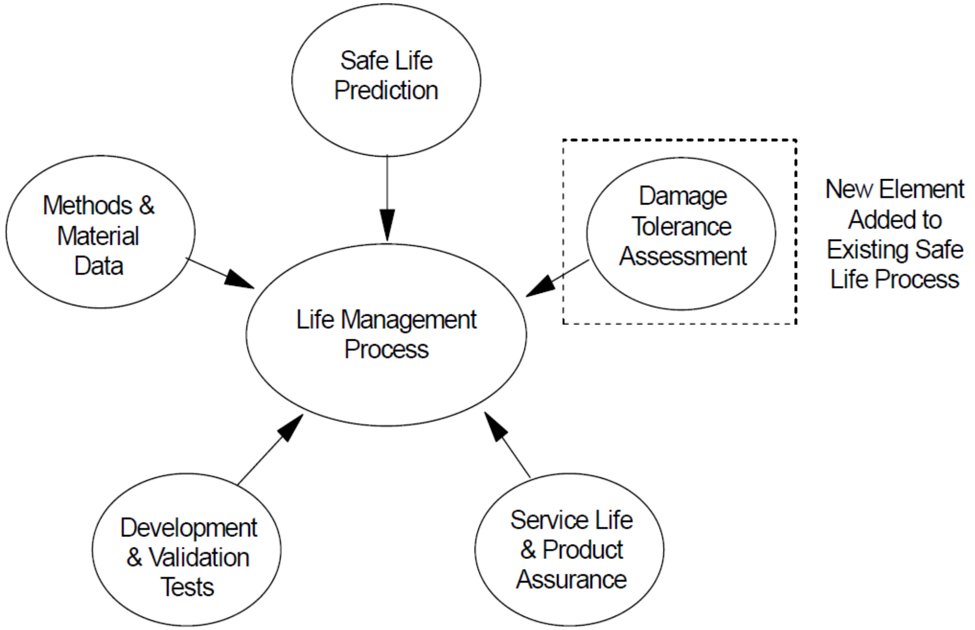


(ref. EASA CS-E515)

Damage Tolerance assessment

"An element of the life management process that recognizes the potential existence of component imperfections, which are the result of inherent material structure, material processing, component design, manufacturing or usage. Damage tolerance addresses this situation through the incorporation of fracture resistant design, fracture mechanics, process control, and nondestructive inspection." *ref.* EASA CS-E15

- Service experience demonstrated that **anomalies do occur** which can potentially degrade the part structural integrity.
- **Historically**, it was assumed nominal material variations and manufacturing conditions with **no explicit addressing of the occurrence of such anomalies** (although some level of tolerance to anomalies is implicitly built-in using design margins, factory and field inspections, etc.).
- A **Damage Tolerance Assessment explicitly addresses the anomalous condition(s)** and complements the fatigue life prediction system.
- The 'Damage Tolerance Assessment' is part of the design process and **not a method for returning cracked parts to service** whilst monitoring crack growth.



Damage Tolerance assessment Deterministic vs Probabilistic

Preferred approach, if all inputs are available and fully validated

Deterministic

Predicts a **crack growth life to rupture** for a **single starting crack size** and **compare the life prediction to** a design **life requirement**

FAA interim approach:

- Residual crack growth life = **3,000 cycles or 50% of the part certified life**, whichever is less.
- IFS = surface crack of **0.030 in x 0.015 in** deep and/or a corner crack of 0.015 x 0.015 inches.
- Cracks placed in the **most unfavorable orientation and location**.

Probabilistic

Risk assessment that involves fracture mechanics-based simulations using **statistical techniques to model the variation in one or more variables and their contribution**.

Variables considered:

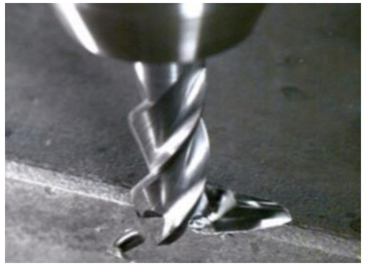
- Anomaly size and frequency distributions.
- Crack growth analysis (stress, temperature, material properties).
- Inspection techniques and intervals.
- Inspection Probability of Detection (POD).

Pictures from:
https://www.cnclathing.com/guide/types-of-cutting-tool-breakage-tool-chipping-forms-causes-solutions
https://www.sansmachining.com/common-tips-for-drilling-machining/
https://www.sandvik.coromant.com/en-gb/knowledge/materials/pages/wear-on-cutting-edges.aspx
https://www.researchgate.net/publication/232399550_Machining_induced_surface_integrity_in_titanium_and_nickel_alloys_A_review/figures?lo=1

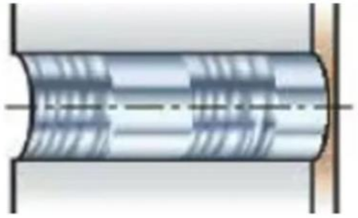
Damage Tolerance assessment
Manufacturing induced defects at holes

FAA Advisory Circular AC33.70-2 “presents a damage tolerance approach which can be used to address manufacturing and operationally-induced anomalies in circular hole features in rotor parts.”

Geometric Anomalies (Visual)



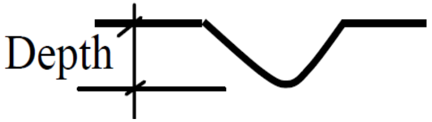
Hole With Good Chip Evacuation

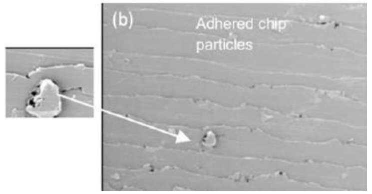


Holes Affected By Plugging Chips

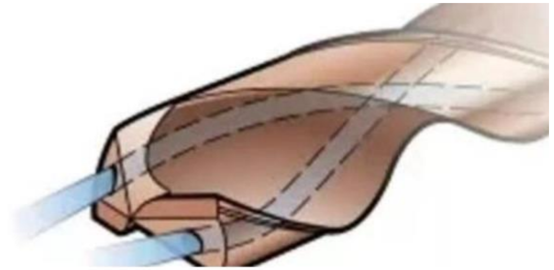
Tool Breakage, Chip Removal

Dents, Nicks, Scratches, Adhered chip particles, Burrs



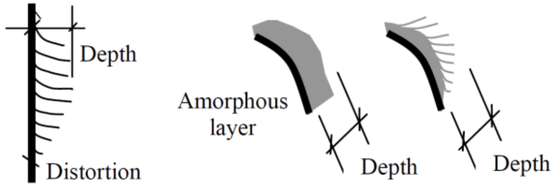


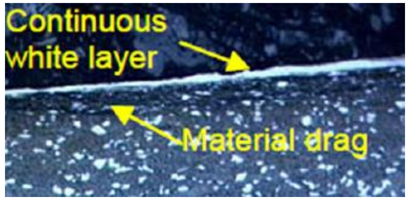
Non-Geometric Anomalies (Surface Integrity)



Lack of Lubrication, Tool Wear, Uncontrolled Machining

Distortion, Amorphous (white) Layer

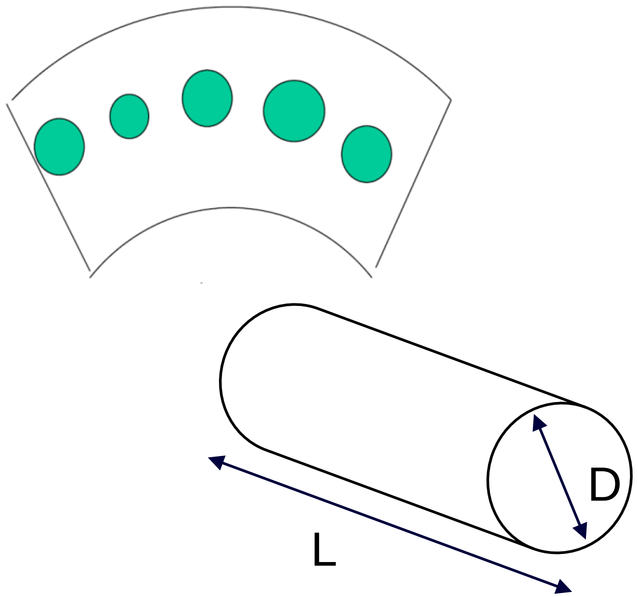




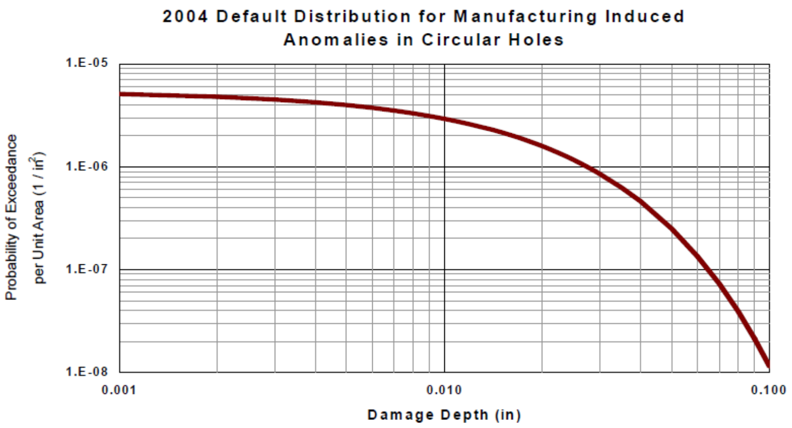
Pictures from:
https://www.cnclathing.com/guide/types-of-cutting-tool-breakage-tool-chipping-forms-causes-solutions
https://www.sansmachining.com/common-tips-for-drilling-machining/
https://www.sandvik.coromant.com/en-gb/knowledge/materials/pages/wear-on-cutting-edges.aspx
https://www.researchgate.net/publication/232399550_Machining_induced_surface_integrity_in_titanium_and_nickel_alloys_A_review/figures?lo=1

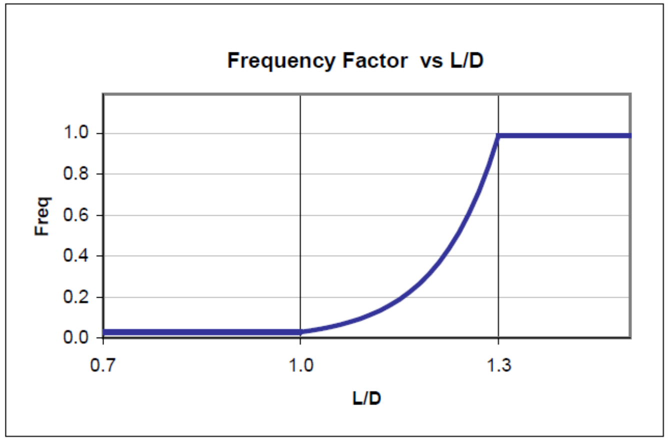
Damage Tolerance assessment
Manufacturing induced defects at holes

- Determine hole set to analyse
- Create FEM and extract analysis data
- Perform LEFM at different defect sizes
- Perform probabilistic assessment
  Add inspections if required
- Calculate final PoF
  Calculate Manufacturing Credits



$$F(x) = \quad \nu * 5.42E\text{-}06 * EXP(- 61.546*(x))$$





(ref. FAA AC33.70-2)

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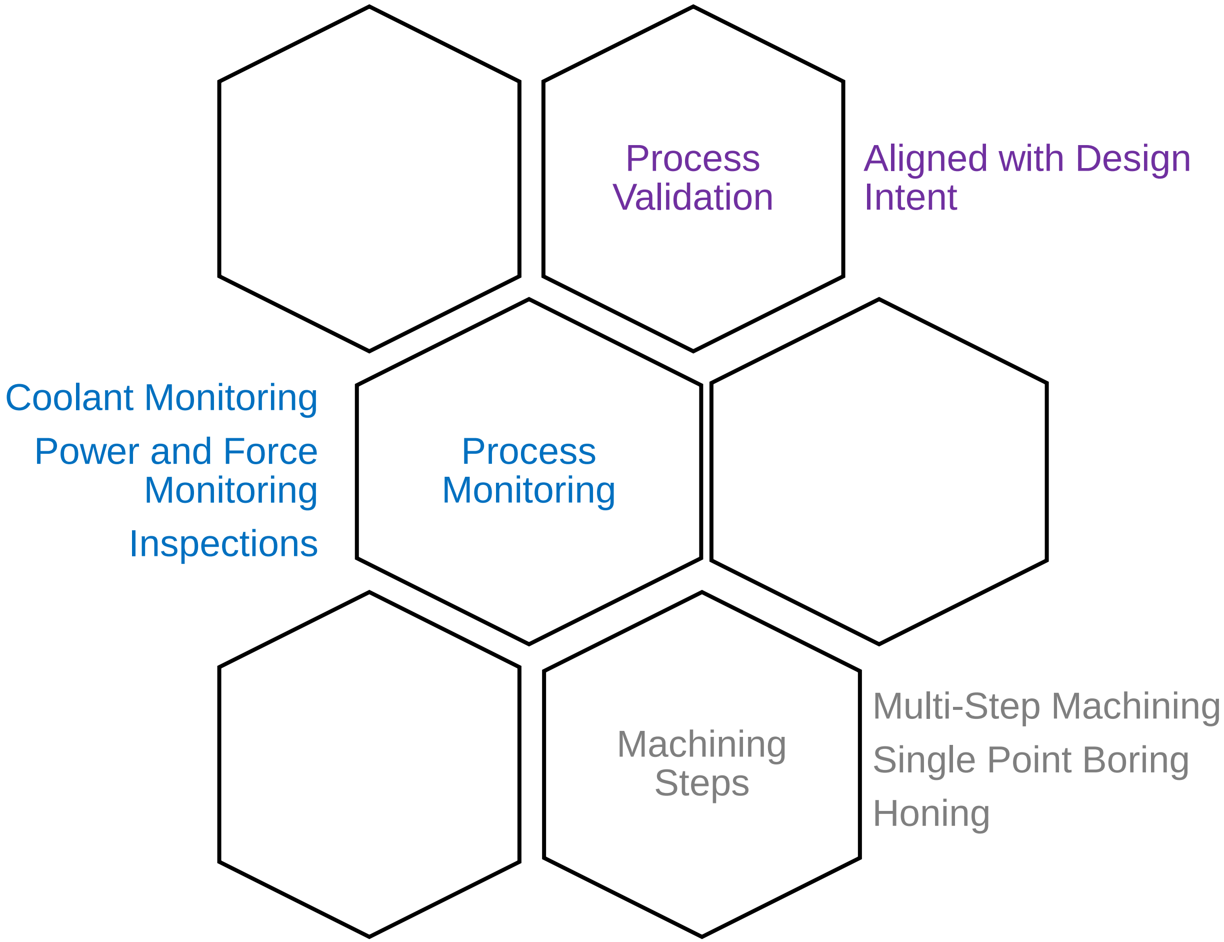
Damage Tolerance assessment
Manufacturing induced defects at holes



Process control	Definition	Credit Factor
Process validation	A procedure in which it is demonstrated that the Manufacturing Process delivers parts consistent with the Design Intent (see FAA Report number DOT/FAA/AR-06/3). Process validation is understood in this AC to include an inspection of the part for geometric anomalies (cracks, scratches, dents, scores, etc.) after manufacture. Such an inspection may be visual, enhanced visual, or semi-automatic such as ECI. In addition, an implicit consideration in assigning credit to the various processes is that secondary operations such as chamfering, edge breaking and finishing are controlled and subject to process validation as described in FAA Report number DOT/FAA/AR-06/3.	5
Single Point Boring	The removal in a finishing operation of a small depth of material, at least 0.004" deep, in the bore of the hole by use of a single point boring tool. This credit is allowed for titanium alloys only.	5
Honing	The removal of a small depth of material, at least 0.002", by a self-centering grinding operation. This credit is allowed for all materials.	5
Coolant Monitor	A device which ensures that there is a continuous flow of coolant with periodic checks on the pressure and the concentration of the coolant supplemented with the training of operators to ensure the direction of the flow towards the cutting edge (see FAA Report number DOT/FAA/AR-06/3). This credit is allowed for all materials.	5
Power Monitor	A device that continuously monitors the power consumed by the machine tool and which must be shown to be sensitive to conditions such as worn tools, loss of coolant, etc., which give rise to anomalies (see FAA Report number DOT/FAA/AR-06/3). This credit is allowed for all materials.	For the use of either a power monitor or a feed force monitor, 20.
Feed Force Monitor	A device that continuously monitors the feed force used by the machine tool and which must be shown to be sensitive to conditions such as worn tools, loss of coolant, etc., which give rise to anomalies (see FAA Report number DOT/FAA/AR-06/3). This credit is allowed for all materials.	For the use of both a power monitor and a feed force monitor, 30.
Inspection	In this context, inspection is confined to the use of inspection techniques specifically aimed at detecting non-geometric anomalies, such as highly distorted material, smeared material, white or amorphous layer (see FAA Report number DOT/FAA/AR-06/3). Generally, this would be an etch inspection specifically targeted at the hole and which must be shown to detect such anomalies. This credit is allowed for all materials.	5

(ref. FAA AC33.70-2)

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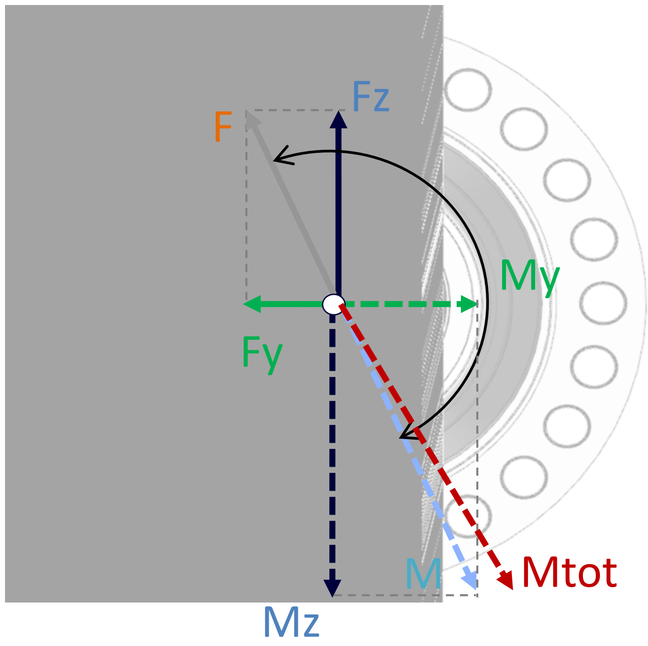
Section #3

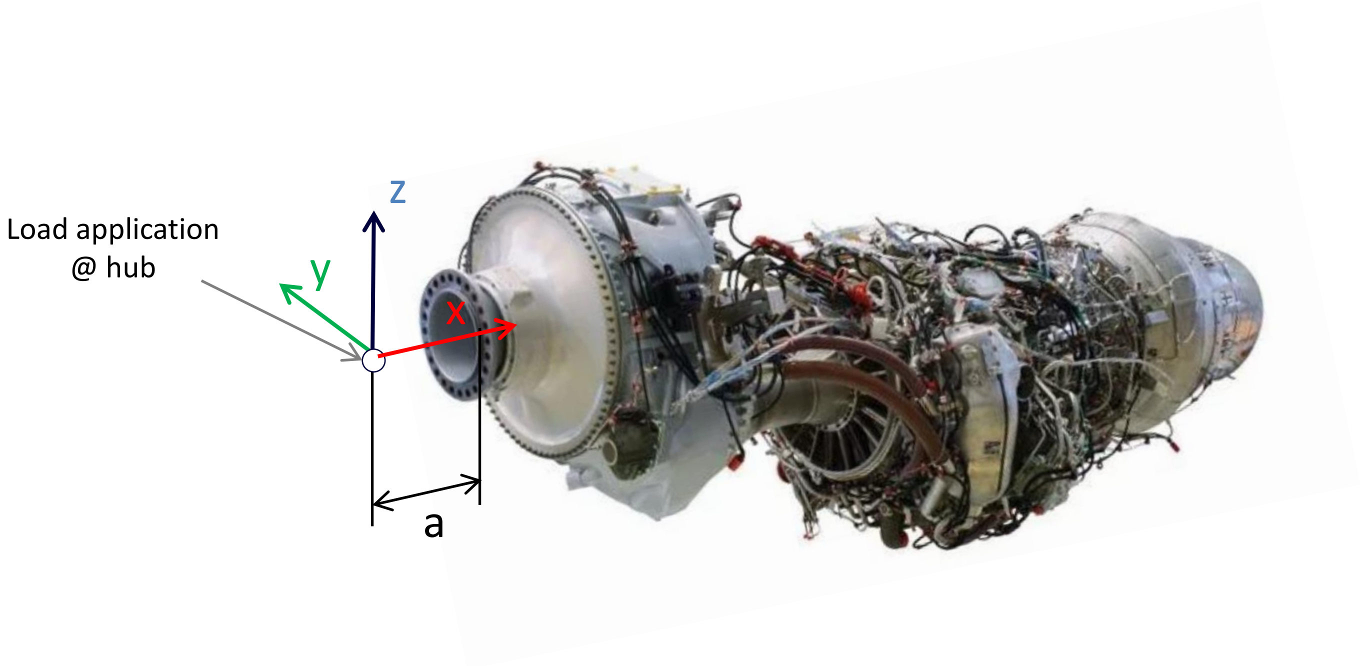
Case Study

Pictures from:
https://www.mtu.de/engines/military-aircraft-engines/transport-aircraft/tp400-d6/

LLP example: Propeller Shaft assessment

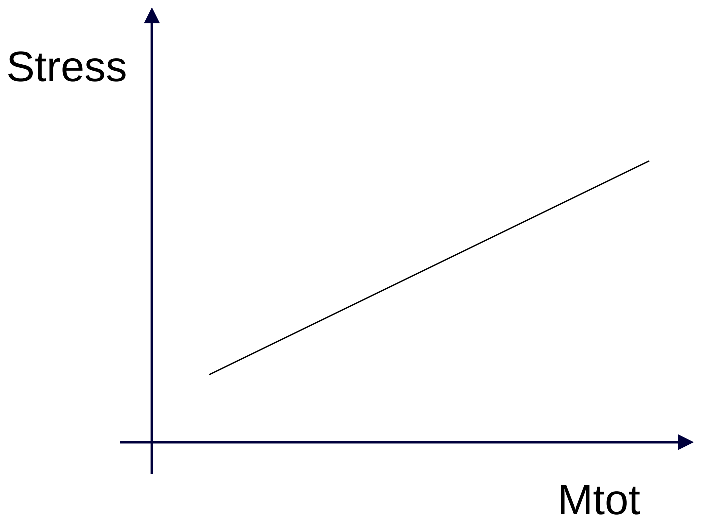


$$Mtot = \sqrt{(My + a * Fz)^2 + (Mz - a * Fy)^2}$$

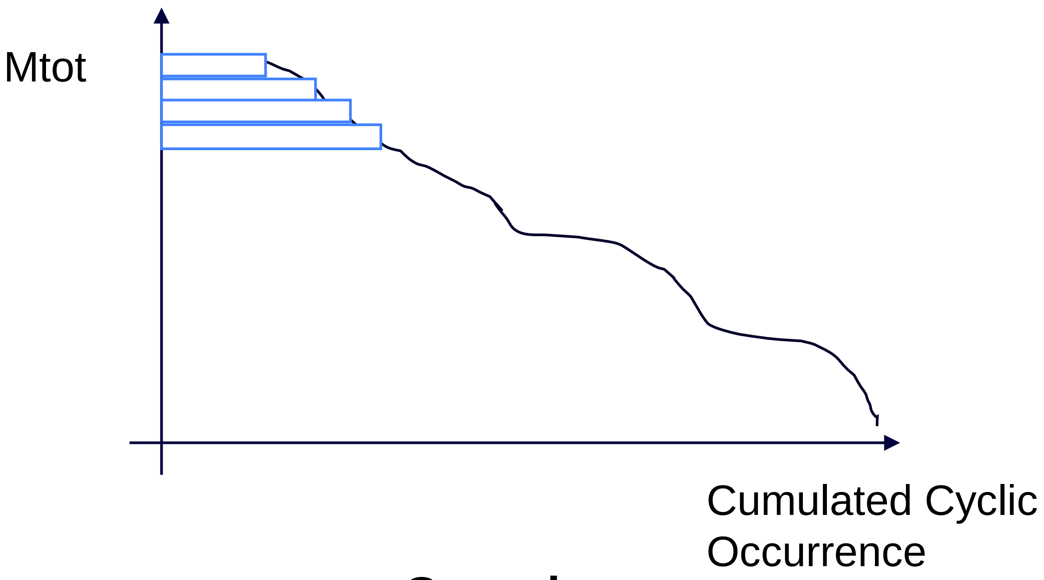


The Propeller Shaft experiences **high-cycle bending loads imposed by the propeller aerodynamic 1P loads** (i.e.: bending moments My and Mz plus shear forces Fy and Fz), in addition to the Propeller torque (i.e.: Mx) and direct and reverse thrust (i.e. Fx) which dominate component stresses.

LLP example: Propeller Shaft assessment



Linear Regressions



Grouping

Propeller Shaft complex loading may be simplified by use of linear regression and load case grouping. Grouping may be applied to all missions defined by the engine specification.

LLP example: Propeller Shaft assessment

Safe Life

Mission A

Mission B

….

Stress Analysis

Loading simplification

Damage computation

Material Data (Lifing curves)

Safe Life verification

Damage Tolerance (deterministic LEFM)

Mission A

Mission B

….

Investigation of Mission Mix variability

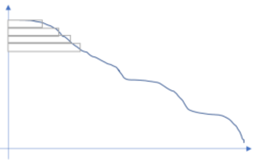
Potential use of Monte Carlo randomization

LEFM on mixes

Potential use of Statistics to support

DT verification

Where each mission is defined as a HCF load spectrum.



Back-Up

Certification Requirements and Mission Analysis

CS-E 515 Engine Critical Parts

(See AMC E 515)

The integrity of the Engine Critical Parts identified under CS-E 510 must be established by:

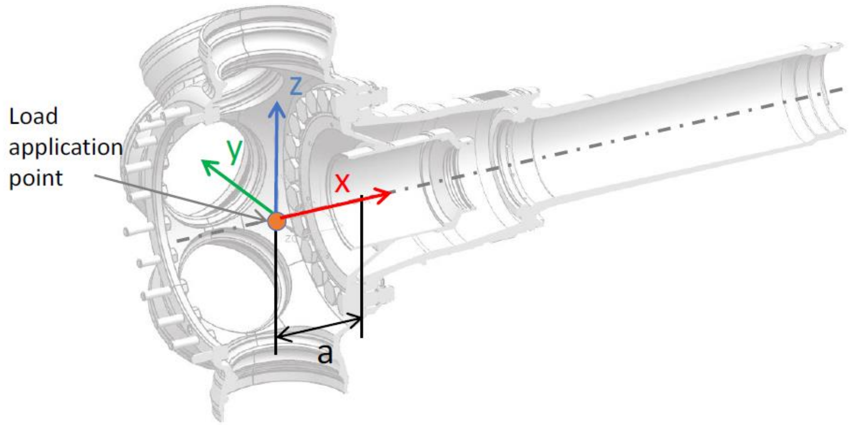
(a) An Engineering Plan, the execution of which establishes and maintains that the combinations of loads, material properties, environmental influences and operating conditions, including the effects of parts influencing these parameters, are sufficiently well known or predictable, by validated analysis, test or service experience, to allow each Engine Critical Part to be withdrawn from service at an Approved Life before Hazardous Engine Effects can occur. Appropriate Damage Tolerance assessments must be performed to address the potential for Failure from material, manufacturing and service-induced anomalies within the Approved Life of the part. The Approved Life must be published as required in CS-E 25(b).

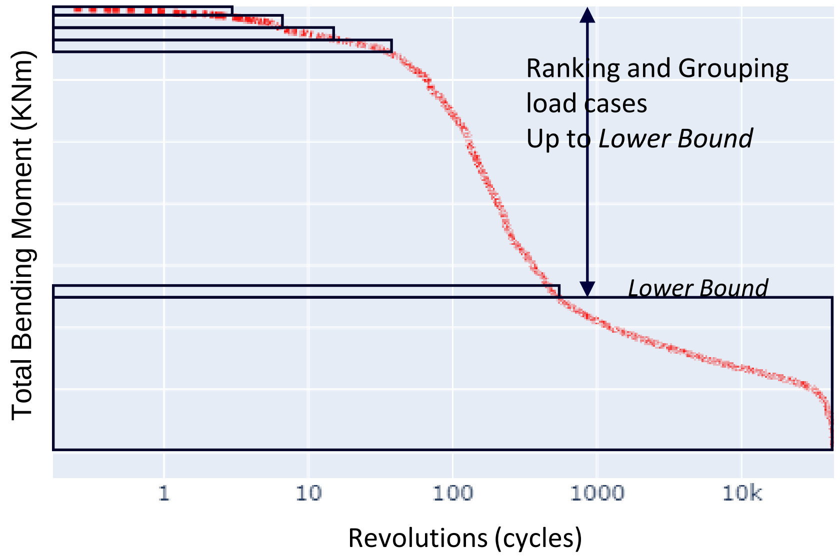
(b) A Manufacturing Plan which identifies the specific manufacturing constraints necessary to consistently produce Engine Critical Parts with the Attributes required by the Engineering Plan.

(c) A Service Management Plan which defines in-service processes for maintenance and repair of Engine Critical Parts which will maintain Attributes consistent with those required by the Engineering Plan. These processes must become part of the instructions for continued airworthiness.

[Amdt No: E/1]

Note CS-27 and CS-29 applicable to Helicopters





Critical Part Life Management (EASA CS-E515)

CS-E 515 Engine Critical Parts

(See AMC E 515)

The integrity of the Engine Critical Parts identified under CS-E 510 must be established by:

(a) An Engineering Plan, the execution of which establishes and maintains that the combinations of loads, material properties, environmental influences and operating conditions, including the effects of parts influencing these parameters, are sufficiently well known or predictable, by validated analysis, test or service experience, to allow each Engine Critical Part to be withdrawn from service at an Approved Life before Hazardous Engine Effects can occur. Appropriate Damage Tolerance assessments must be performed to address the potential for Failure from material, manufacturing and service-induced anomalies within the Approved Life of the part. The Approved Life must be published as required in CS-E 25(b).

(b) A Manufacturing Plan which identifies the specific manufacturing constraints necessary to consistently produce Engine Critical Parts with the Attributes required by the Engineering Plan.

(c) A Service Management Plan which defines in-service processes for maintenance and repair of Engine Critical Parts which will maintain Attributes consistent with those required by the Engineering Plan. These processes must become part of the instructions for continued airworthiness.

[Amdt No: E/1]

The following effects must be regarded as Hazardous Engine Effects:

(i) Non-containment of high-energy debris,

(ii) Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers,

(iii) Significant thrust in the opposite direction to that commanded by the pilot,

(iv) Uncontrolled fire,

(v) Failure of the Engine mount system leading to inadvertent Engine separation,

(vi) Release of the propeller by the Engine, if applicable,

(vii) Complete inability to shut the Engine down.

It must be shown that Hazardous Engine Effects are predicted to occur at a rate not in excess of that defined as Extremely Remote (probability less than 10^{-7} per Engine flight hour). The estimated probability for individual Failures may be insufficiently precise to

Critical Part Life Management (EASA CS-E515)

- **Safe Life:** *A cyclic fatigue-based process in which components are designed, manufactured, substantiated, and maintained to have a specified service life or life limit, which is stated in operating flight cycles, operating hours, or both. The "safe life approach" requires that parts be removed from service prior to the development of an unsafe condition (that is, crack initiation).*

Safe Life Terminology

- **PSCL or Ultimate Life:** *Predicted Safe Cyclic Life, the projected retirement life of the component. It should be aligned with the target in life which defines Project success.*
- **DSCL or Approved Life:** *Declared Safe Cyclic Life, the operating life released for operations, which is generally defined as the PSCL factored by an appropriate scoring.*
- **Initiation Life:** cyclic life to develop a crack equal to the engineering crack size (i.e., 0.015' x 0.030' surface crack).

Min Capability assessed

- **Damage Tolerance:** *an element of the life management process that recognizes the potential existence of component imperfections as the result of inherent material structure, material processing, component design, manufacturing or usage and addresses this situation through the incorporation of fracture resistant design, fracture mechanics, process control, and non-destructive inspection.*

Damage Tolerance Terminology

- Deterministic vs Probabilistic approach

Representative (Avg) Capability assessed

Damage Tolerance Requirements (EASA CS-E515 & CM – PIFS – 007 Is: 01)

A. Deterministic Approach

A.1 Deterministic Damage Tolerance Assessment

Demonstrate that the Surface Fracture Mechanics Life for all critical parts exceeds 3,000 cycles or 50 percent of the part certified life, whichever is less.

Assumptions:

- Analyses performed using Linear Elastic Fracture Mechanics;
- Initial anomaly size is one of the following:
  - 0.762mm x 0.381mm (0.030 inches x 0.015 inches) for an assumed (semicircular)
  - surface anomaly.
  - 0.381mm x 0.381mm (0.015 inches x 0.015 inches) for an assumed (quarter-circular) corner anomaly. […]
- Anomalies should be treated as sharp propagating cracks from the first stress cycle.

A.2 Service Damage Monitoring

The overall objective of Service Damage Monitoring is to review data obtained from field operation of the Type Design engine to determine if there are anomalous conditions which require corrective action.

B. Probabilistic Approach

B1. Probabilistic Damage Tolerance Assessment

The applicant should provide and agree with the Agency […]:

· Anomaly size / frequency distribution
· Fleet utilization
· Maintenance practices
· Anomaly growth characteristics
· Inspection techniques and intervals with POD

The probabilities of Hazardous Engine Effects that must be met are defined in CS-E 510 (a)

B2. Service Damage Monitoring

Same as per Deterministic Approach.

B3. Additional Requirements

Validate the assumptions utilized in the analysis throughout the life of the certified product.