Structural Integrity Substantiation Report: High-Pressure Compressor Casing (HPCC) for the [Engine Program Name] Turboshaft Engine

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Abbreviation	Definition
AMC	Acceptable Means of Compliance
CBO	Core Blade-Out
CS-E	Certification Specifications for Engines
EASA	European Union Aviation Safety Agency

FEA	Finite Element Analysis
FEM	Finite Element Model
HCF	High-Cycle Fatigue
HPCC	High-Pressure Compressor Casing
LCF	Low-Cycle Fatigue
LOoB	Limit Out-of-Balance
MAC	Modal Assurance Criterion
MoC	Means of Compliance
MoS	Margin of Safety
MPC	Multi-Point Constraint
MSUP	Mode Superposition
OOB	Out-of-Balance
P/N	Part Number
RBE	Rigid Body Element
RPM	Revolutions Per Minute
UTS	Ultimate Tensile Strength

1 Objective

The objective of this report is to present the analytical substantiation for the structural integrity of the [Engine Program Name] High-Pressure Compressor Casing (HPCC), Part Number [Part Number], under specified out-of-balance and continuous vibration load conditions. This document demonstrates compliance with the relevant airworthiness requirements of EASA CS-E Amendment 7.

2 Scope

This report documents the structural analysis performed to demonstrate the capability of the HPCC to withstand loads arising from normal engine vibration and from abnormal conditions, including rotor blade failure events. The scope of this analysis is strictly limited to the finite element-based strength and fatigue assessment of the HPCC, P/N [Part Number], Revision.

The analyses herein consume validated dynamic load data, including forces, moments, accelerations, and operational parameters (e.g., rotational speeds, event durations), as defined in the Engine Dynamic Load Analysis Report, Ref.. The derivation and validation of these engine-level dynamic loads, system-level models, and operational limits are certified under the authority of the Engine Dynamics team and are considered outside the scope of this component-level structural report. This partitioned approach is consistent with the principles of AMC E 520(c)(2), which provides for the use of validated data to ascertain the forces that could be imposed on the engine structure.[1]

3 Reference Documents

The following documents form the basis for the analysis and compliance demonstration presented herein.

3.1 Standards

Table 1: Applicable Standards

Document ID	Title	Version/Amendment
CS-E	Certification Specifications for Engines	Amendment 7, 18 Dec 2023 [2]

3.2 Procedures

Table 2: Applicable Procedures

Document ID	Title	Version/Amendment
	Standard Procedure for Finite Element Analysis	
	Standard Procedure for Fatigue Life Assessment	

3.3 Internal Documents

Table 3: Internal Reference Documents

Document ID	Title	Version/Amendment
	Engineering Drawing, High-Pressure Compressor Casing	
	Engine Dynamic Load Analysis Report	
	Approved Material Data	

	Handbook	
	HPCC Component Modal Test Report	
	Engine Ground Vibration Survey (GVS) Report	

3.4 External Documents

Table 4: External Reference Documents

Document ID	Title	Version/Amendment
	Ansys Mechanical User's Guide	[Version]

4 System Description and Architecture

4.1 Engine Description

The [Engine Program Name] is a [e.g., two-spool, free-power turbine] turboshaft engine designed for [e.g., rotary-wing aircraft applications]. The engine architecture consists of a multi-stage Low-Pressure Compressor (LPC) and a multi-stage High-Pressure Compressor (HPC), a reverse-flow combustion chamber, a single-stage High-Pressure Turbine (HPT) driving the HPC, and a multi-stage Low-Pressure Turbine (LPT) driving the LPC. A separate, free-power turbine drives the main rotor gearbox via an output shaft. The engine core, comprising the HPC, combustor, and HPT, operates on the Brayton thermodynamic cycle to generate hot gas energy.[3] The structural casings provide the primary load paths, maintain rotor-stator clearances, and ensure containment of internal pressures and temperatures.

4.2 Compressor Static Parts

4.2.1 High Pressure Compressor Casing (HPCC)

The High-Pressure Compressor Casing (HPCC), P/N [Part Number], is a primary structural component of the engine core. Its principal functions are to:

- Provide the static outer flow path for the high-pressure compressor stages.
- House the HPC stator vanes.
- React to aerodynamic pressure and thermal loads from the gas path.
- Serve as a critical part of the engine's structural backbone, transferring loads between the intermediate case (forward) and the combustor/turbine module (aft).
- Support the main rotor bearing systems via its structural interfaces.
- Ensure radial containment of compressor blades in the event of a failure, as required by CS-E 810.[4]

The HPCC is manufactured from, a high-strength, temperature-resistant nickel-based superalloy. It features precision-machined flanges for interfacing with adjacent modules and mounting bosses for engine accessories and instrumentation. The structural integrity of the HPCC is paramount to the safe operation of the engine, particularly during high-vibration events where it must withstand significant dynamic loads without failure.

5 Compliance and Certification Requirements

5.1 Overview

This report demonstrates that the HPCC meets the structural integrity requirements defined in the EASA Certification Specifications for Engines (CS-E) Amendment 7. The certification basis addresses the engine's ability to operate without harmful vibration and to sustain structural integrity following a failure event, such as a compressor blade loss, without resulting in a Hazardous Engine Effect.[1]

5.2 Compliance Strategy

The compliance strategy for the HPCC is "analysis-led, test-validated." Analysis is the primary Means of Compliance (MoC) for demonstrating structural adequacy under the complex dynamic loading scenarios specified. This approach is necessary because the events, particularly blade-out transients, are difficult and expensive to replicate physically with sufficient instrumentation to capture the detailed stress state of the component.[4]

The credibility of the analytical approach is established through rigorous validation of the Finite Element Model (FEM). The FEM's static and dynamic characteristics (mass and stiffness distribution) are correlated against component-level modal test data and engine-level Ground Vibration Survey (GVS) data. This validation ensures that the analytical model accurately represents the physical hardware's response to dynamic excitation.

A foundational element of this strategy is the consumption of validated loads provided by the Engine Dynamics team, in accordance with AMC E 520(c)(2). This regulation permits the use of validated data from analysis or test to define the forces imposed on the aircraft and engine structure following an out-of-balance event.[1] By using these pre-validated loads, this report can focus exclusively on the structural response and integrity of the HPCC, creating a clear and defensible partition of certification responsibilities.

5.3 Means of Compliance Matrix

The compliance argument is structured to follow the logical sequence of potential in-service events: from normal (but extreme) vibration, to the immediate aftermath of a blade failure, and finally to the continued rotation condition post-shutdown. Table 5 provides a direct mapping of the applicable regulatory requirements to the Means of Compliance and the specific sections within this report where the substantiating evidence is presented.

Table 5: Means of Compliance Matrix

Requirement	Title	Requirement Summary	Means of Compliance (MoC)	Reference in this Report
CS-E 650	Vibration Surveys	The engine must be free from harmful vibration throughout its declared operating envelope.	**Analysis:** Structural integrity is demonstrated by analysis for the limit out-of-balance (LOoB) vibration condition, which represents the most severe permissible vibration in normal service.	§6.4.3
CS-E 810(a)	Blade Failure	It must be demonstrated that any single compressor blade will be contained and that the failure will not lead to a Hazardous Engine Effect before shutdown.	**Analysis:** Structural integrity is demonstrated by analysis for the transient run-down and subsequent stabilized run-on phases immediately following a core blade-out (CBO) event.	§6.4.1, §6.4.2
CS-E 525	Continued	It must be	**Analysis:**	§6.4.4

	Rotation	shown that no hazardous condition arises from continued rotation of the engine's main rotating systems after shutdown in flight.	Structural integrity is demonstrated by analysis for the windmilling condition, which represents continued rotation due to airflow after an in-flight shutdown following a failure event.	
AMC E 520(c)(2)	Validated Data	Validated data must be established to enable the assessment of forces imposed on the structure from out-of-balance running and continued rotation.	**Declaration:** This analysis consumes validated engine-level dynamic loads provided per Ref., satisfying the intent of this AMC.	§2, §6.2.6

6 Analysis

6.1 Analysis Tools

The analyses documented in this report were performed using commercially available and industry-accepted software tools. The versions used are maintained under a rigorous quality assurance program.

Table 6: Analysis Software

Software	Version	Application
Ansys Mechanical	[Version]	Pre-processing, Meshing, Solving (FEA), Post-processing
[Pre/Post-Processor]	[Version]	Finite Element Model Assembly and Results Review
	[Version]	Fatigue Life Assessment (TLIFE)

6.2 Analysis Specifications

6.2.1 Analysis Purpose and Scope

The purpose of the analysis is to calculate the stress, strain, and fatigue damage in the HPCC under the load conditions defined in §6.2.6. The analysis will determine the Margins of Safety (MoS) for strength and fatigue life against certified material allowables and regulatory requirements. The scope is limited to the HPCC structure and its immediate interfaces.

6.2.2 Analysis Methods

Finite Element Model (FEM)
The HPCC is represented by a high-fidelity 3D Finite Element Model (FEM), shown in [Figure 1]. The model was generated from the master geometry defined in Ref.. The mesh consists predominantly of second-order hexahedral (solid) elements to ensure accuracy in stress prediction, with second-order tetrahedral elements used judiciously in areas of high geometric complexity. The mesh density has been refined in critical areas, such as fillet radii and flange bolt holes, based on a mesh convergence study documented in.
Load and Boundary Condition Application
Loads and boundary conditions are applied to the FEM to simulate its interfaces with adjacent engine structures. Flange connections are modeled using appropriate constraints to represent the bolted joints.
A critical aspect of the methodology is the application of dynamic loads from the rotating components. These loads, which include forces and moments at the bearing locations, are transferred to the flexible casing structure using **Remote Point** connections with a **Distributed** formulation in Ansys. This technique is analogous to an RBE3 or distributing element.[7] This formulation is deliberately chosen because it distributes the applied point load to a set of nodes based on a weighting function, without adding any non-physical stiffness to the model. This ensures that the local flexibility of the casing is accurately represented, preventing the artificial stress concentrations and erroneous stiffening that would result from a rigid connection (e.g., a kinematic coupling or RBE2).[9]

Solver and Solution Method
All dynamic analyses (transient and harmonic) are performed using the Mode Superposition (MSUP) method within the Ansys solver.10 This method provides a computationally efficient and validated solution for linear dynamic systems. The response of the structure is calculated by projecting the full system's equations of motion onto a truncated basis of its dominant natural mode shapes, which are pre-calculated in a modal analysis.11 The number of modes included in the solution is sufficient to capture the dynamic response well beyond the highest frequency of interest for each load case, and the contribution of higher-frequency modes is accounted for using the residual vector method (RESVEC) to improve solution accuracy.11
Damping
Structural damping is applied in the model to represent the energy dissipation characteristics of the engine assembly. The damping values and formulation (e.g., Rayleigh damping coefficients α and β, or a modal damping ratio ζ) are consistent with those used and validated in the engine-level dynamic model, as specified in Ref..
Fatigue Life Assessment
A two-tiered fatigue assessment strategy is employed for all cyclic loading scenarios (CBO Run-On, LOoB, Windmilling):

1. **Infinite Life Screening (Goodman):** First, a conservative screening for infinite life (typically defined as >107 cycles) is performed. The calculated alternating and mean stresses at every node are plotted on a Goodman diagram constructed using the

material's endurance limit and ultimate tensile strength.[13] If all points fall within the infinite life boundary, the component is considered to have passed, and no further analysis is required for that load case.
2. **Finite Life Calculation (TLIFE):** If any stress states fall outside the Goodman infinite life boundary, a detailed finite life analysis is conducted. This analysis uses a methodology based on the principles of the NASALIFE code [14], which accounts for mean stress effects using a Walker model. Cumulative damage from different stress levels is summed using **Miner's rule**, where failure is predicted when the cumulative damage fraction reaches 1.0.[14]

6.2.3 Assumptions

- The material is assumed to be homogeneous, isotropic, and linearly elastic.
- Geometric linearity is assumed; stresses and strains are small enough that stiffness changes due to deformation are negligible.
- Temperatures are assumed to be steady-state for each analysis condition and are mapped onto the model from a separate thermal analysis (Ref.). Temperature-dependent material properties are used.

6.2.4 Limitations

- This analysis does not consider non-linear phenomena such as plasticity (except as accounted for in material allowables), large deformations, or contact effects (e.g., blade-casing rub), unless explicitly stated.
- The analysis does not assess the integrity of bolts or other connecting hardware; these are covered in separate reports.
- The analysis assumes the input loads from Ref. are accurate and have been validated.

6.2.5 Conditions

The analyses are performed under a conservative set of operating conditions selected to produce the most adverse effects with respect to the applicable acceptance criteria. For each load case, this involves identifying the combination of parameters (e.g., rotational speed, temperature, pressure) from the engine operating envelope and specific failure scenarios that results in the maximum stress or minimum fatigue life for the HPCC.[5] This approach ensures that the demonstrated margins of safety are representative of the most severe conditions the component is predicted to experience in service.

6.2.6 Analysis Scenarios

Four primary load cases are analyzed to demonstrate the structural integrity of the HPCC. These cases cover the spectrum from limit normal operation to severe failure events and are defined in Table 7. The loads, frequencies, and durations are provided in Ref. and are based on validated engine system models and regulatory requirements for event duration.[16]

Table 7: Analysis Load Case Definitions

Load Case	Description	Analysis Type	Inputs (Ref Doc)	Duration / Frequency	Acceptance Criteria
CBO Run-Down	Transient dynamic event immediately following the loss of a single HPC blade, from max speed to idle.	**Transient Dynamic (MSUP)**	Time-history of OOB forces/moments at bearings	[e.g., 0-5 seconds]	Peak stress must not exceed material ultimate tensile strength (UTS). Positive Margin of Safety on strength.
CBO Run-On	Stabilized running at a post-failure condition (e.g., idle) before shutdown is initiated.	**Harmonic Response (MSUP)**	Frequency-domain OOB forces/moments at bearings	[e.g., 1xN1 sweep over idle range] for a duration of [e.g., 30 seconds]	Peak stress must not exceed material UTS. Calculated fatigue life must exceed

					required life. Positive Margins of Safety on strength and life.
Limit OOB (LOoB)	Highest permissible vibration level during normal engine operation, representing the worst-case balanced rotor condition.	**Harmonic Response (MSUP)**	Frequency-domain OOB forces/moments at bearings	[e.g., 1xN1 sweep over full operating range]	Infinite fatigue life required (stress below material endurance limit).
Windmilling	Continued rotation of the rotor due to aerodynamic forces after an in-flight shutdown.	**Harmonic Response (MSUP)**	Frequency-domain OOB forces/moments at bearings	for a duration of [e.g., 3 hours][16]	Calculated fatigue life must exceed required life. Positive Margin of Safety on life.

6.2.7 Material Data

The mechanical properties for the HPCC material,, are sourced from the approved materials handbook, Ref.. Properties are temperature-dependent, and the analysis uses values interpolated to the specific operating temperature of each load case. Key properties are listed in Table 8.

Table 8: Material Properties for at Temperature

Property	Temperature (°C)	Value	Units
Young's Modulus (E)		[Value]	GPa
Poisson's Ratio (v)		[Value]	-
Density (ρ)		[Value]	kg/m³
Ultimate Tensile Strength (UTS)		[Value]	MPa
0.2% Yield Strength		[Value]	MPa
Endurance Limit (at 107 cycles, R=-1)		[Value]	MPa

6.3 Validation

6.3.1 Validation of Analysis Tools

The Ansys software suite is a widely accepted, commercially available tool for finite element analysis in the aerospace industry. Its solvers and element formulations are extensively verified and validated against a large suite of benchmark problems. Its use for certification analysis is an established industry practice.[17]

In addition to commercial software, TEI utilizes proprietary in-house analysis tools for [e.g., specific post-processing, data mapping, or life-assessment routines]. These tools are developed under TEI's AS9100 certified quality management system.[18] Any in-house tool that automates, reduces, or replaces a process required for certification, and whose output is not independently verified, undergoes a formal tool qualification process. This process is conducted in accordance with the principles outlined in RTCA DO-178C and its supplement, DO-330, "Software Tool Qualification Considerations".[19] The qualification activities include documenting the tool's requirements, performing comprehensive verification and validation, and generating the qualification data package to demonstrate that the tool provides reliable and correct results for its intended use in a certification environment.[19] This dual approach ensures that all software tools used in this analysis, whether commercial or proprietary, meet the rigorous standards required for airworthiness certification.

6.3.2 Validation of Analysis Method

The credibility of the specific FEM used for this analysis is established by demonstrating its ability to predict the known dynamic behavior of the hardware. The model's mass and stiffness distributions are validated by comparing its predicted natural frequencies and mode shapes against empirical data from a component-level modal test (hammer tap test) performed on the HPCC, as documented in Ref..

The primary metrics for correlation are the frequency difference and the Modal Assurance Criterion (MAC). The MAC is a scalar value between 0 and 1 that quantifies the degree of correlation between two mode shapes; a value of 1 indicates a perfect match. A summary of the correlation for the dominant modes in the frequency range of interest is provided in Table 9. The close agreement between the FEA predictions and the test results (frequency error < % and MAC > [0.9]) provides high confidence that the model can accurately predict the component's response to forced dynamic loading.

Table 9: FE Model Modal Correlation Summary

Mode No.	Description	Test Frequency (Hz) (Ref.)	FEA Frequency (Hz)	Difference (%)	Modal Assurance Criterion (MAC)
1		[Value]	[Value]	[Value]	[Value]
2		[Value]	[Value]	[Value]	[Value]
3	[e.g., 1st Ovalization]	[Value]	[Value]	[Value]	[Value]

...	...	...	...	...	...
[N]		[Value]	[Value]	[Value]	[Value]

6.4 Results

This section presents the results of the structural analyses for the four primary load cases. The Margin of Safety (MoS) is calculated as:
MoS=CalculatedLoadAllowableLoad−1 or MoS=RequiredLifeAllowableLife−1
A positive margin of safety indicates that the component meets the requirement.

6.4.1 CBO Run-Down

This analysis simulates the severe, short-duration transient event following a blade loss. The primary risk during this event is a ductile failure due to a single overload excursion as the unbalanced rotor decelerates through critical speeds.[6] The acceptance criterion is therefore based on strength, as the duration is too short for fatigue to be the primary failure mode. The transient dynamic analysis was performed using the input loads from [Figure 2].

The maximum von Mises stress occurs at seconds at [Location on HPCC]. The peak stress and resulting margin of safety against the material's ultimate tensile strength (UTS) are summarized in Table 10. A contour plot of the peak stress is shown in [Figure 3].

Table 10: CBO Run-Down Peak Stress and Margin Summary

Parameter	Value	Units
Maximum von Mises Stress	[Value]	MPa
Material UTS at Temperature	[Value]	MPa
Minimum Margin of Safety (Strength)	**[Value]**	**-**

The minimum margin of safety is positive, demonstrating that the HPCC will not fail due to overload during the CBO run-down transient.

6.4.2 CBO Run-On

This analysis assesses the structural integrity during a period of stabilized running with the large unbalance from the lost blade. This condition is assessed for both strength (peak stress) and high-cycle fatigue (HCF). A harmonic response analysis was performed across the relevant frequency range, with results shown in [Figure 4].

First, a strength check was performed to ensure the peak stresses from the stabilized vibration do not exceed the material's ultimate strength. The results are summarized in Table 11.

Table 11: CBO Run-On Peak Stress and Margin Summary

Parameter	Value	Units
Maximum von Mises Stress	[Value]	MPa
Material UTS at Temperature	[Value]	MPa
Minimum Margin of Safety (Strength)	**[Value]**	**-**

Next, the resulting stresses were assessed using the two-tiered fatigue methodology. The peak alternating and mean stresses at the most critical location, [Location on HPCC], were found to be outside the infinite life boundary of the Goodman diagram. Therefore, a finite life calculation was performed. The results are summarized in Table 12.

Table 12: CBO Run-On Fatigue Life and Margin Summary

Parameter	Value	Units
Required Life	[e.g., 30]	Seconds

Calculated Minimum Life	[Value]	Seconds
Minimum Margin of Safety (Life)	**[Value]**	**-**

The minimum margins of safety for both strength and life are positive, demonstrating that the HPCC can withstand the required duration of CBO run-on without overload or fatigue failure.

6.4.3 Limit Out-of-Balance

This analysis assesses the HPCC's durability under the highest level of vibration permitted during normal operation. The requirement is for infinite life, meaning the component must withstand this vibration level for its entire service life without fatigue damage.

The harmonic response analysis was performed across the full engine operating speed range. The resulting alternating and mean stresses at all locations on the HPCC were plotted on the material's Goodman diagram, as shown in [Figure 5].

Table 13: Limit Out-of-Balance Fatigue Assessment Summary

Parameter	Result
Critical Location	[Location on HPCC]
Assessment	All calculated stress states fall within the infinite life boundary of the Goodman diagram.
Conclusion	**Infinite Life Predicted. Requirement is met.**

The analysis confirms that the HPCC has infinite fatigue life under Limit OOB conditions, satisfying the CS-E 650 requirement for freedom from harmful vibration.

6.4.4 Windmilling

This analysis assesses the fatigue durability of the HPCC during a prolonged period of windmilling after an in-flight shutdown with a blade-out unbalance. This scenario is governed by CS-E 525 and associated guidance, which specifies a conservative duration to cover diversion scenarios.[16] The harmonic response analysis was performed over the windmilling speed range.

The stresses were assessed for fatigue, and a finite life calculation was required. The calculated minimum life and margin against the required duration are summarized in Table 14. A contour plot of the calculated fatigue life is shown in [Figure 6].

Table 14: Windmilling Fatigue Life and Margin Summary

Parameter	Value	Units
Required Life	[e.g., 3]	Hours
Calculated Minimum Life	[Value]	Hours
Minimum Margin of Safety (Life)	**[Value]**	**-**

The minimum margin of safety on life is positive, demonstrating that the HPCC can endure the most demanding regulatory windmilling scenario without fatigue failure.

Table 15: Summary of Minimum Margins of Safety

Load Case	Requirement Type	Minimum Margin of Safety	Conclusion
CBO Run-Down	Strength (vs. UTS)	**[Value]**	**PASS**
CBO Run-On	Strength (vs. UTS)	**[Value]**	**PASS**
CBO Run-On	Fatigue Life	**[Value]**	**PASS**
Limit Out-of-Balance	Fatigue Life (Infinite)	**Infinite Life Predicted**	**PASS**

Windmilling	Fatigue Life	**[Value]**	**PASS**

7 Conclusions and Summary

The structural integrity of the High-Pressure Compressor Casing (HPCC), P/N [Part Number], has been substantiated by analysis for critical out-of-balance and continuous vibration load cases. The Finite Element Model used for the analysis was validated against component modal test data, ensuring its dynamic response accurately represents the physical hardware.

The analyses demonstrate the following:

1. The HPCC maintains a positive margin of safety on **strength** during the severe, short-duration **CBO Run-Down** transient event.
2. The HPCC demonstrates positive margins of safety on both **strength** and **fatigue life** for the required duration of stabilized **CBO Run-On** following a blade failure.
3. The HPCC exhibits **infinite fatigue life** under **Limit Out-of-Balance** (LOoB) vibration conditions, meeting the requirement for freedom from harmful vibration in normal service.
4. The HPCC maintains a positive margin of safety on **fatigue life** for the required duration of post-failure **Windmilling**, satisfying continued rotation requirements.

All calculated margins of safety, summarized in Table 15, are positive. The analysis was conducted in accordance with approved procedures and consumed validated engine-level dynamic loads, consistent with the principles of AMC E 520(c)(2).

Based on the evidence presented, the High-Pressure Compressor Casing, P/N [Part Number], maintains its structural integrity under all specified normal and failure conditions. It is therefore concluded that the HPCC does not contribute to a Hazardous Engine Effect and is compliant with the structural requirements of EASA CS-E Amendment 7.[1]

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