EASA
European Union Aviation Safety Agency

Research project:

Integrity Improvement of Rotorcraft Main Gear Box (MGB)

Webinar: final dissemination event

12/03/24, 15:00-17:00 CET

An Agency of the European Union

This project is funded by the European Union's Horizon 2020 Programme

Disclaimer

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Welcome to this webinar!

This webinar is the final dissemination event of the research project

This project has received funding from the European Union's Horizon 2020 research and innovation Programme.

The EC delegated the contractual and technical management of this research action to EASA.

EASA contracted Airbus Helicopters Technik GmbH (former ZF Luftfahrttechik) for the implementation of the research action following a public tender procedure.

EASA-managed projects are addressing research needs of aviation authorities and are an important pillar of the EASA R&I portfolio.

The agenda

TIME	TITLE, SPEAKER
15:00 – 15:05	**Welcome to the webinar** Willy Sigl, EASA
15:05 – 15:15	**Research scope and objectives** Rodrigo Martin Gomez, EASA
15:15 – 16:15	**Overview of the project implementation and key results** Jörg Litzba, Airbus Helicopter Technik
16:15 – 16:30	**Main takeaways for EASA** Rodrigo Martin Gomez, EASA
16:30 – 16:55	**Questions and answers** Participants, Project Team from EASA and Airbus Helicopters Technik
16:55 – 17:00	**Concluding remarks** Willy Sigl, EASA

Note: this webinar will be recorded and made available at the EASA website after the event.

Question and Answers

→ For sending questions and input, please use the slido app, which is also accessible through WebEx:

- www.slido.com
- event code: 1888564
- passcode: pcw74q

The Research Scope and Objectives

Background

- Research project commissioned following safety recommendations from AIB-Norway following the LN-OJF accident. This accident involved the catastrophic jamming of the MGB due to the rupture of a 2^{nd} stage planet gear due to a crack initiated and propagated in rolling contact fatigue.
- The safety recommendations referred to:
  - Research into crack development in high-loaded case-hardened bearings in aircraft applications
  - Develop MGB certification specifications for large rotorcraft to introduce a design requirement that no failure of internal MGB component should lead to a catastrophic failure.

Stream 1

- → Resilience of the Rotor and Rotor Drive Systems to failure of individual components:
  - → Review a range of state-of-the-art configurations and design options.
  - → Identify design weaknesses*.
  - → Development of alternative configurations and/or component design solutions that could prevent or mitigate such failures.

* This term refers to single points of failure with potential catastrophic consequences.

Stream 2

- Reliability and tolerance to flaws of integrated bearing races subject to rolling contact fatigue:
  - Gather state-of-the-art understanding regarding associated critical design and manufacturing parameters*.
  - Identify:
    - Relevant parameters considering impact on crack initiation and propagation in rolling contact fatigue.
    - Flaws** that need to be considered.

* E.g., operating contact pressure, lubrication film thickness, clearances, surface hardness, case-hardening depth, residual stresses, surface roughness

** E.g., corrosion, scratches, impact, material inclusions, residual stress variability, grinding burns, micro-pitting, spalling

Stream 2 (continued)

- Develop an analysis and testing strategy:
  - Inner and outer race samples.
  - Carburised and nitrided steels to be evaluated.
  - Evaluate the impact of parameters identified within industry applicable ranges.
  - Representative loading conditions, considering body stresses and contributions from residual stresses.
- Perform analyses in support of the definition of the final test plan.
- Conduct tests, collect and analyse data.

Stream 2 (continued)

- Conclusions should, wherever possible, address the following:
  - Characterisation of parameters that help prevent the initiation of cracks in rolling contact fatigue.
  - Identification of flaws for which crack initiation an subsequent propagation may not be precluded.
  - Determine factors that promote crack development back to the surface rather than into the core of the race.

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Overview of the project implementation and key results

This project is funded by the European Union's Horizon 2020 Programme

Agenda

- → Overview
- → Stream 1 – Review of rotorcraft architectures with regards to rotor-drive systems (MGB)
- → Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation
- → Summary of project
- → Conclusion

Agenda

- Overview
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Overview – Project GIFT-MGB (1)

- Project title: Integrity Improvement of Rotorcraft Main Gear Box (MGB)

InteGrity
Improvement
oF
rotorcrafT
Main
Gear
Box

„GIFT-MGB“

- Background: Accident of LN-OJF and related accident investigation findings
- Project duration: 06/2020 – 03/2024 (after public tender)
- Project page incl. deliverables : https://www.easa.europa.eu/en/research-projects/integrity-improvement-rotorcraft-main-gear-box-mgb
- Project team:
  - Project leader: Airbus Helicopters Technik GmbH
  - Project partner: SKF Aerospace, University of Hannover (IMKT), University of Paderborn (WUZ)

Overview – Project GIFT-MGB (2)

Downloads

- MGB – D1.1 - Review of the state-of-the art rotorcraft gearbox configurations and component designs
- MGB – D1.3 - Evaluate and define rotor and rotor drive system design options to prevent single points of catastrophic failure
- MGB – D2.1 - Review of the state-of-art design criteria for reliability and flaw tolerance in integrated bearing races
- MGB – D2.2 - Determination Of Design Parameters: Detailed analysis methodology
- MGB – D2.7 - Test report and conclusions
- MGB – D2.8 - Final report and conclusions
- MGB — Leaflet

Overview – Project GIFT-MGB (3)

- Project is split into 2 (nearly) independent work streams – dealing with separate aspects of the overall project topic

- Stream 1 is dedicated to a global review of rotorcraft architectures with regards to rotor-drive systems (MGB)
  - Review of state-of-the-art rotorcraft gearbox configurations and component design in general
  - Description and supporting evaluation of architecture and individual component design proposal
  - Recommendation for future MGB design to prevent or at least to mitigate catastrophic failure modes

- Stream 2 is dedicated to baseline research with regards to RCF on integrated bearing races
  - Determination of design parameters for component reliability and flaw tolerance under rolling contact fatigue (RCF)
  - Determine factors impacting crack propagation and possible crack-through
  - Activities include analytical analysis, simulation of rolling contact fatigue and crack propagation using FE and testing of representative specimen (also used for FE model validation)

Agenda

- → Overview
- → Stream 1 – Review of rotorcraft architectures with regards to rotor-drive systems (MGB)
- → Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation
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Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design - Overview

→ Analysis with focus on configuration differences (epicyclical vs. collector) using failure flow diagram (FFD) approach based on:
  - potential failure modes and consequences
  - field experience also considering other industries (e.g. automotive, wind energy, …)

→ Failure flow diagram developed using generic methodology:
  - Step 1 - Generic failure flow diagram
  - Step 2 - MGB architecture specific analysis
  - Step 3 - Flow diagram for single component

→ Analysis includes relevant OEM and drive-train architectures using public available data

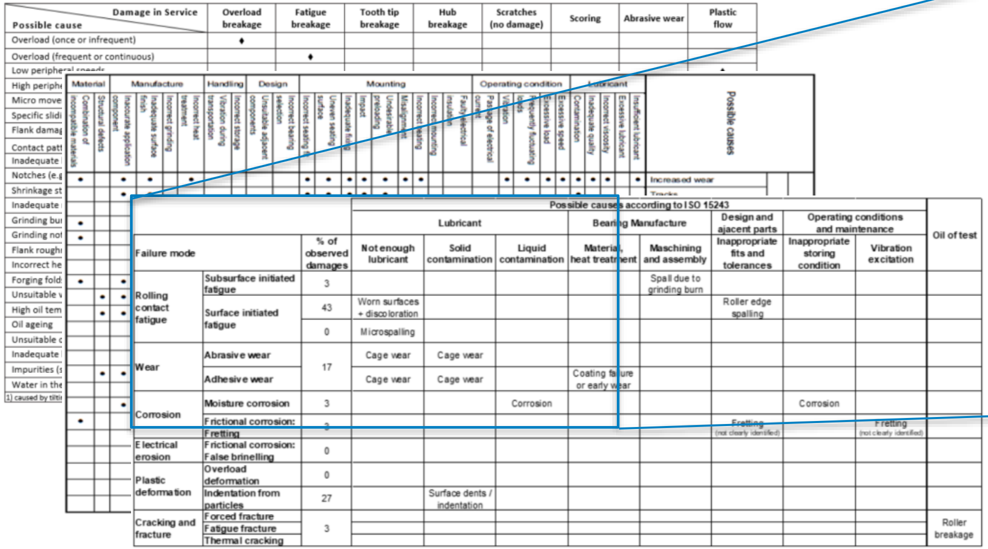
Remark: Analysis is based on public available data. Due to the nature of public data it can not be excluded that OEM internal analysis based on further details may lead to different results e.g., concerning criticality.

→ Recommendation for future MGB design to prevent / mitigate catastrophic failure modes by proposing adequate design solutions / concepts incl. related failure flow diagram analysis

Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – Failure mode analysis

→ Review of accident analysis on relevant helicopter accidents in view of root causes and observed failure modes

→ Failure mode analysis with focus on load path elements, i.e., gears and bearings



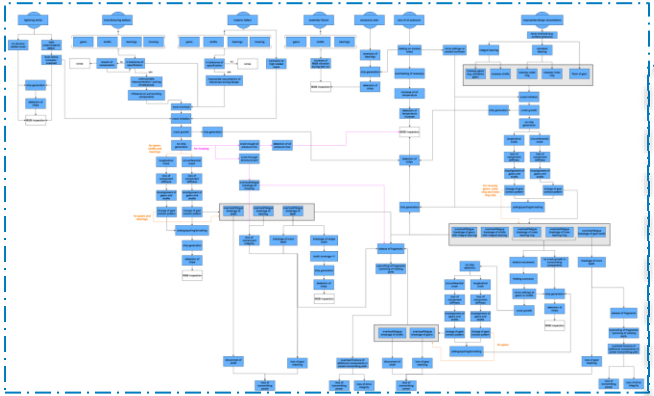
			Possible cau			
			Lubricant			Be
Failure mode		% of observed damages	Not enough lubricant	Solid contamination	Liquid contamination	Mate heat trea
Rolling contact fatigue	Subsurface initiated fatigue	3				
	Surface initiated fatigue	43	Worn surfaces + discoloration			
		0	Microspalling			
Wear	Abrasive wear	17	Cage wear	Cage wear		
	Adhesive wear		Cage wear	Cage wear		Coating or early
Corrosion	Moisture corrosion	3			Corrosion	
	Frictional corrosion:	3				

Planet bearing failure mode analysis

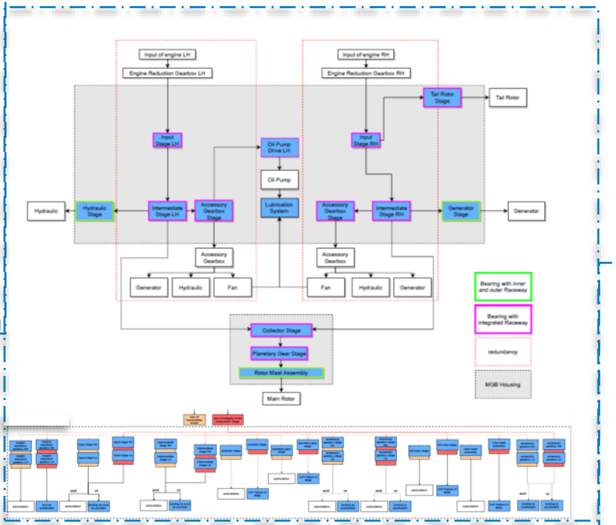
→ Review and analysis of criticality in accordance with AH Tech experience / knowledge, under consideration of standard aviation procedures (e.g., AC29-2C in view of severity classification).

Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – MGB Architecture analysis and FFD (1)

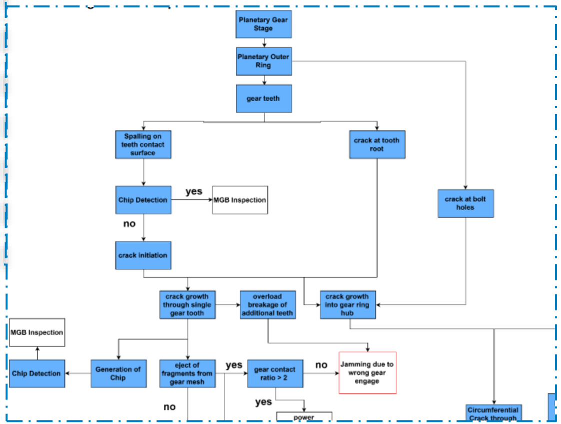
Generic Failure Flow Diagram (FFD)



MGB Architecture FFD



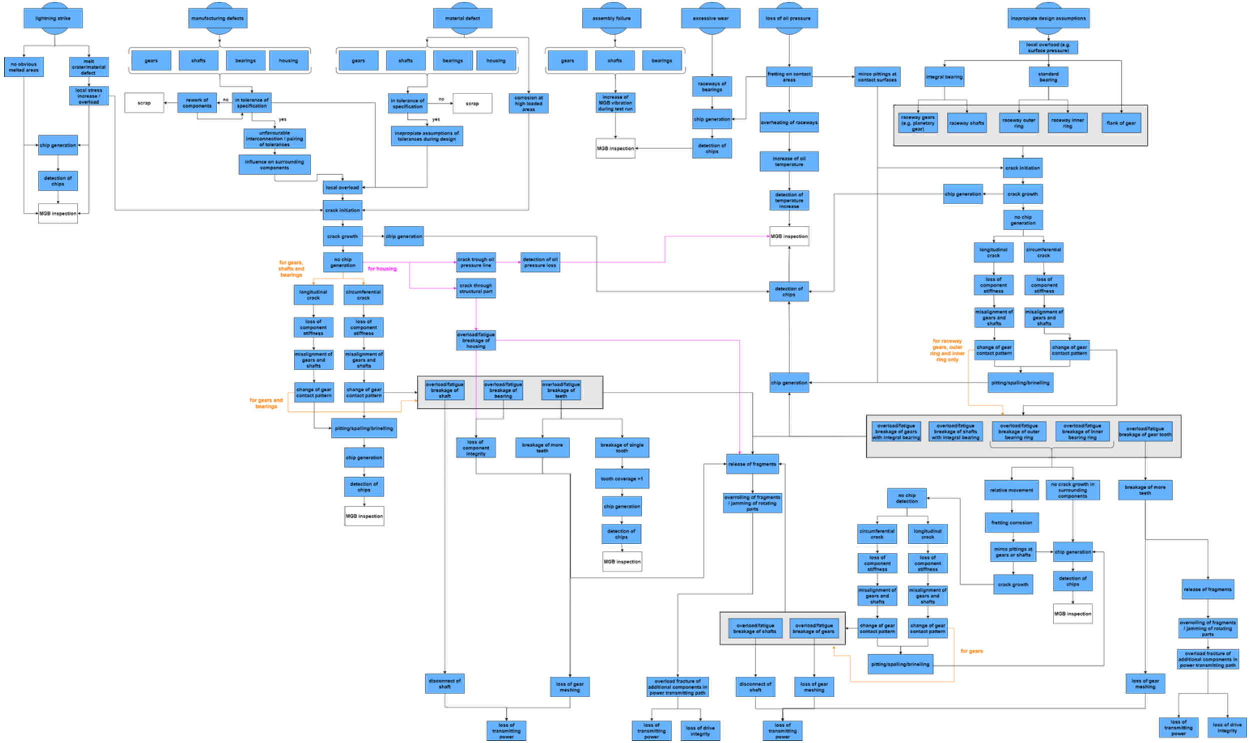
Single Component FFD



Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – MGB Architecture analysis and FFD (2)

→ Relevant failure modes are identified and analysis is performed, considering e.g.:

- Lightning strike
- Manufacturing defects
- Material defect
- Assembly failure
- Excessive wear
- Loss of (oil) pressure
- Inappropriate design assumptions
- Cracks (Worst-Case-Approach)
- …



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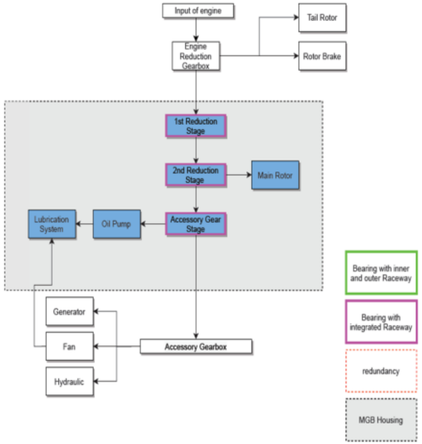
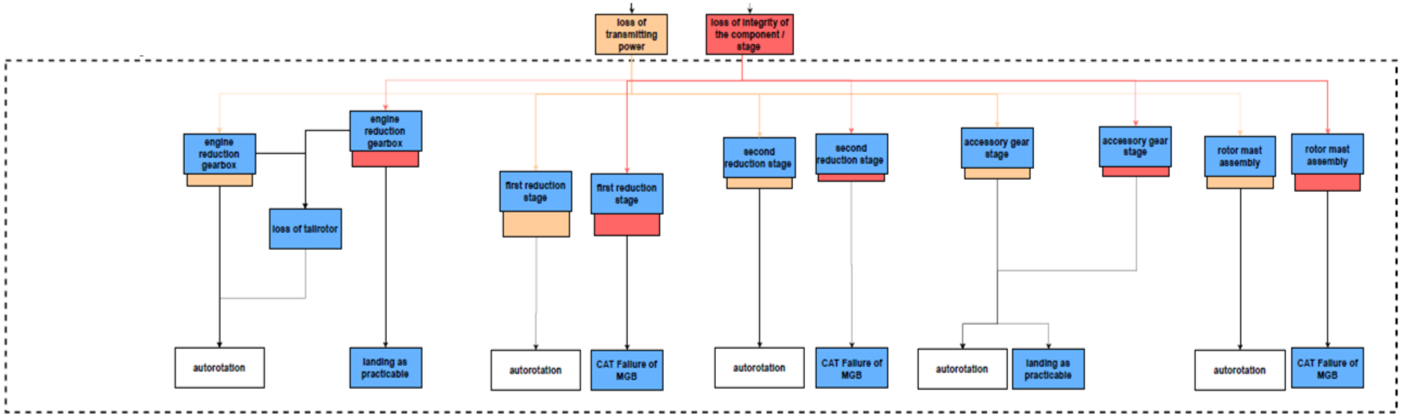
Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – MGB Architecture analysis and FFD (3)

→ Picture shows FFD the example for an epicyclic MGB





loss of transmitting power	disconnect in the load path. No torque can be transmitted, but surrounding components are still free to turn. Rotormast Assembly is mechanically working and able to do autorotation
loss of integrity of the component / stage	jamming and overrolling of fragments lead to breakage of several surrounding components. There is an overload through the whole load path in a way, that integrity of the component is lost and surrounding components are damaged/broken. The autorotation function of the system is lost.

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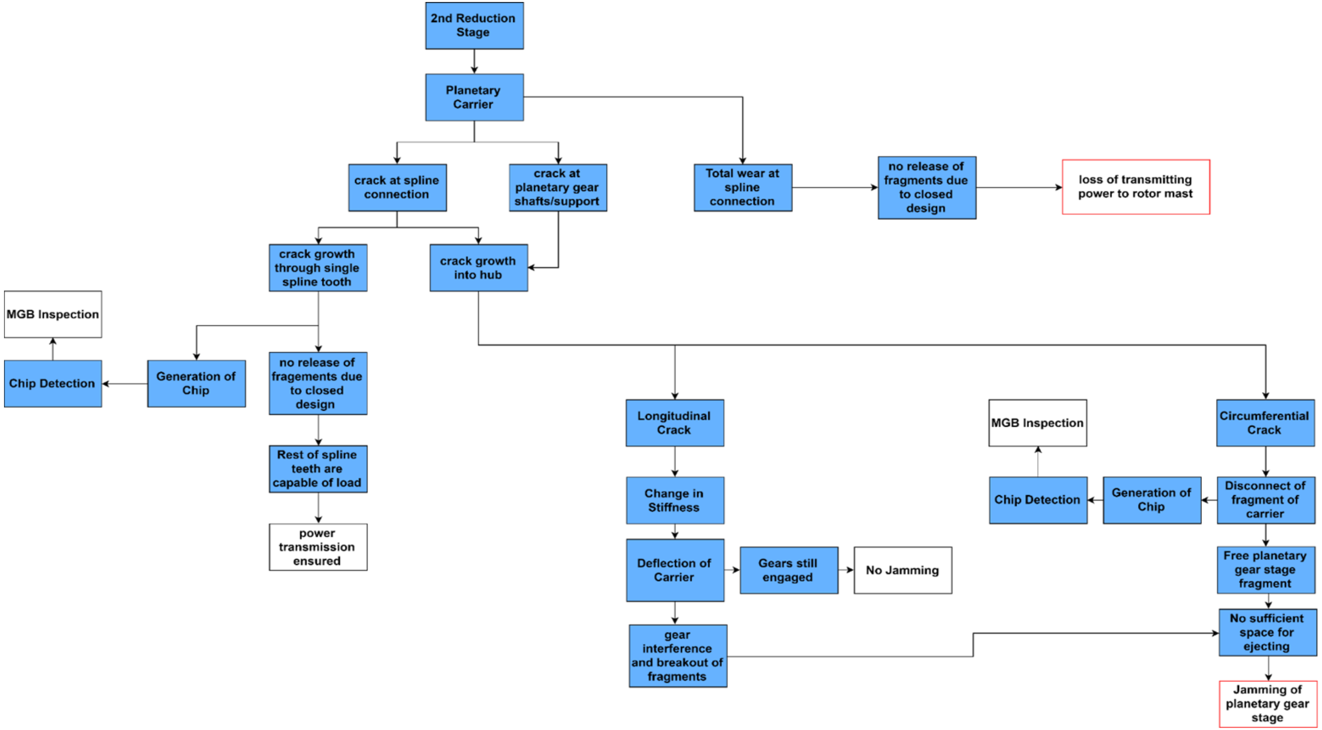
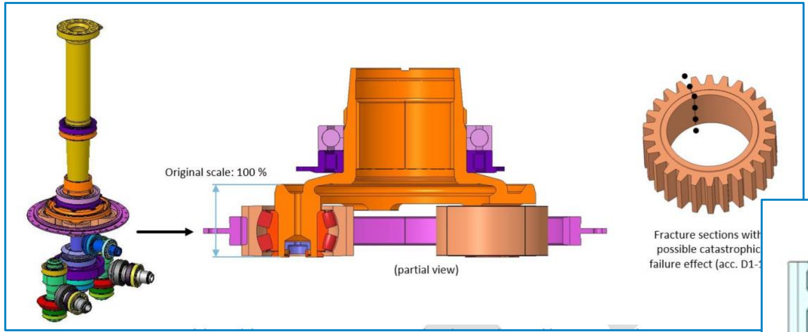
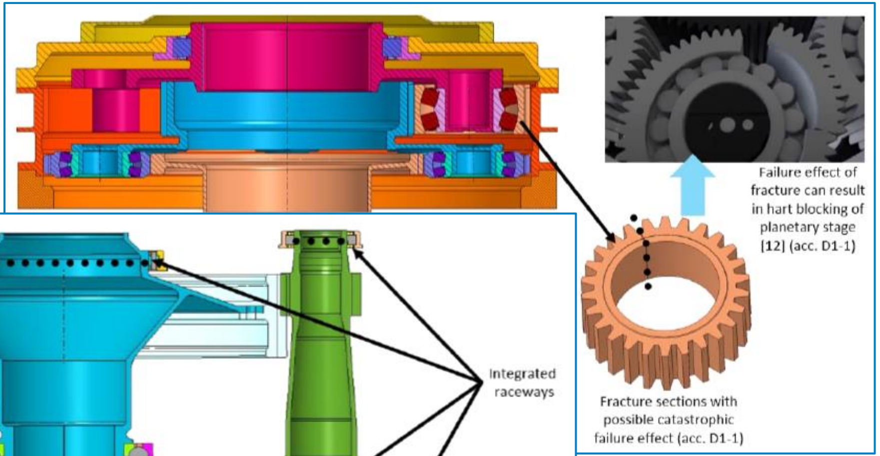
Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – MGB Architecture analysis and FFD (4)

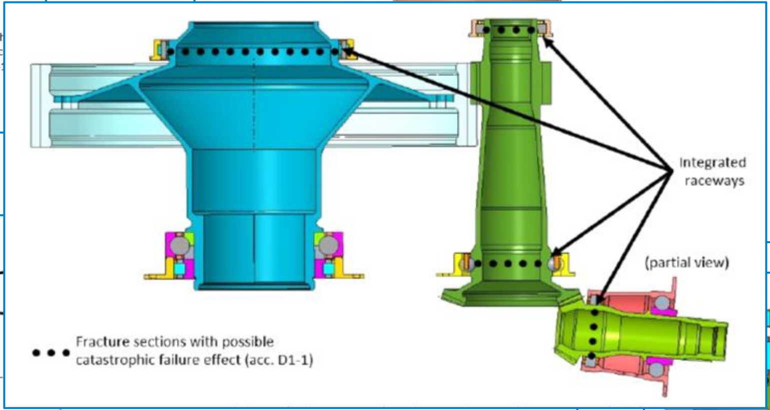
→ Picture shows the FFD example for the analysis of the 2nd reduction gear stage for the MGB

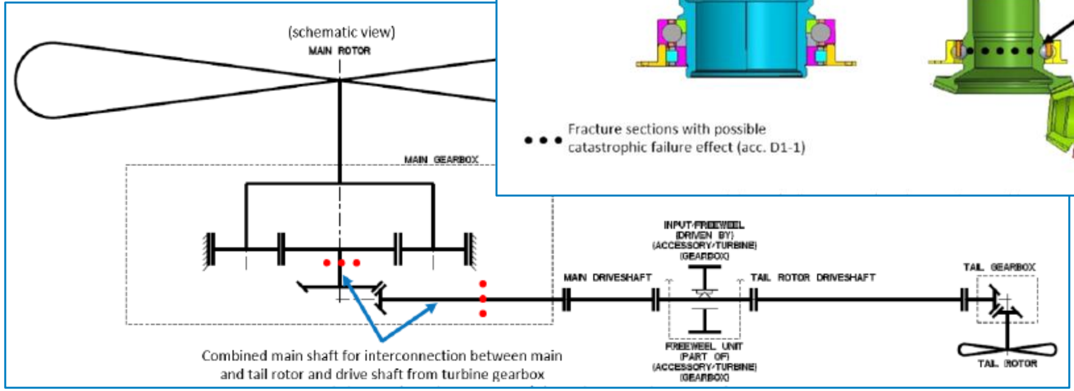


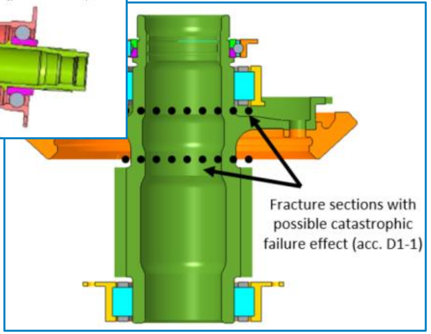
Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – Concepts to prevent SPoCF (1)





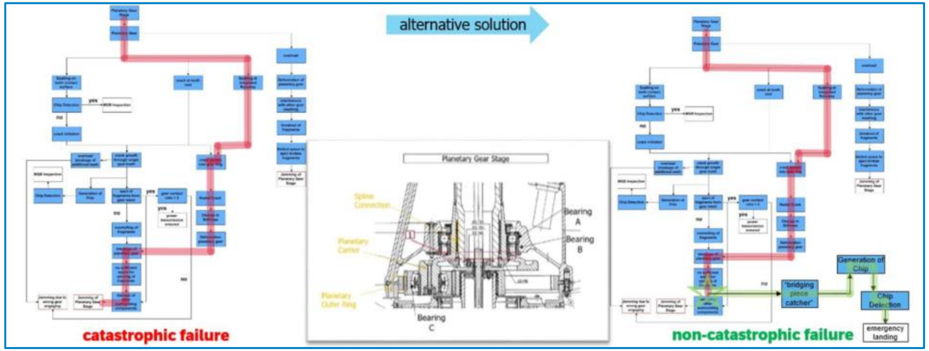






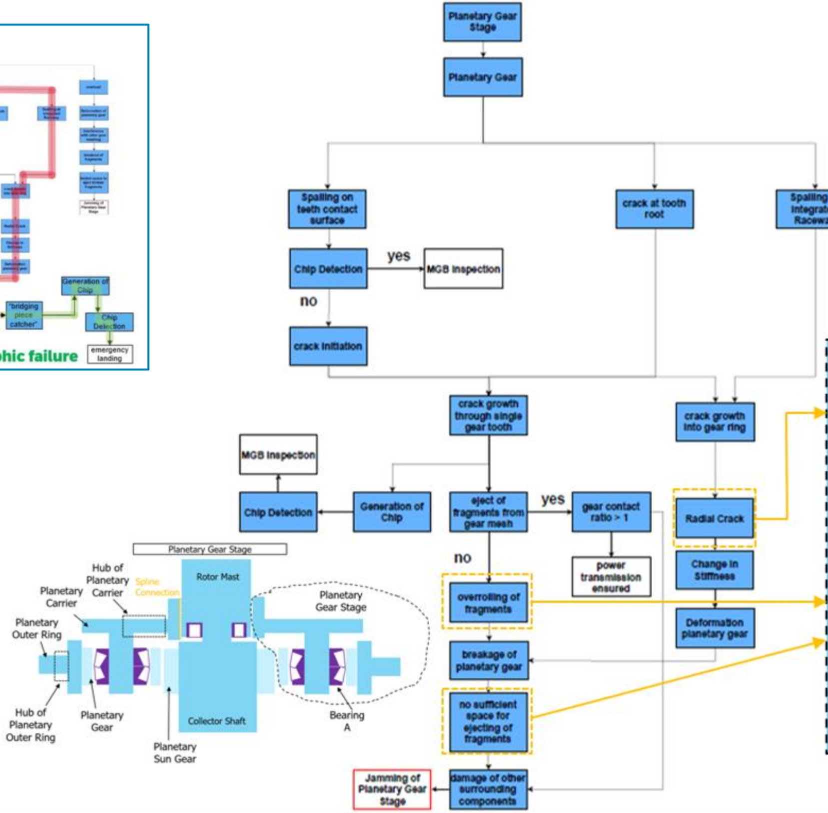
Step 1 – Identification of weaknesses and failure mode – with focus on SPoCF

Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – Concepts to prevent SPoCF (2)



Step 2a – Impact analysis on safety – following EASA agreed FFD approach for this project wrt. catastrophic failure possibility acc. AC29-2C (HAZ, CAT)

Step 2b – Development of safety barriers to prevent / mitigate e.g. jamming and loss of transmitting power on assembly and/or component level



- introduction of non-integrated bearings as safety barrier
- definition of design parameter to avoid crack growth into gear ring

- design implementations to support ejecting of particles from gear mesh and cover of other components

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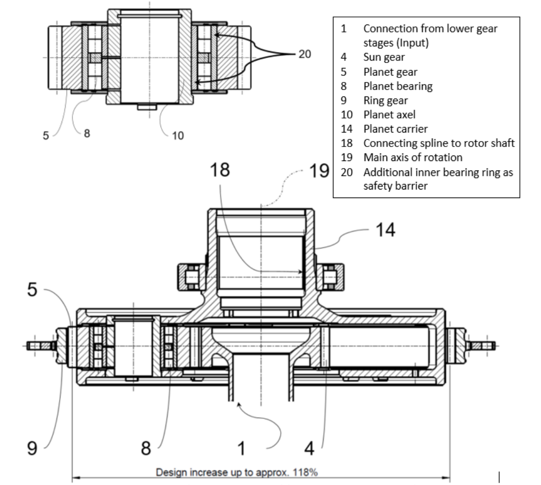
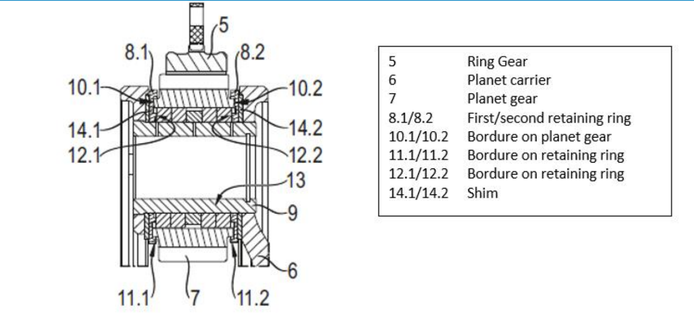
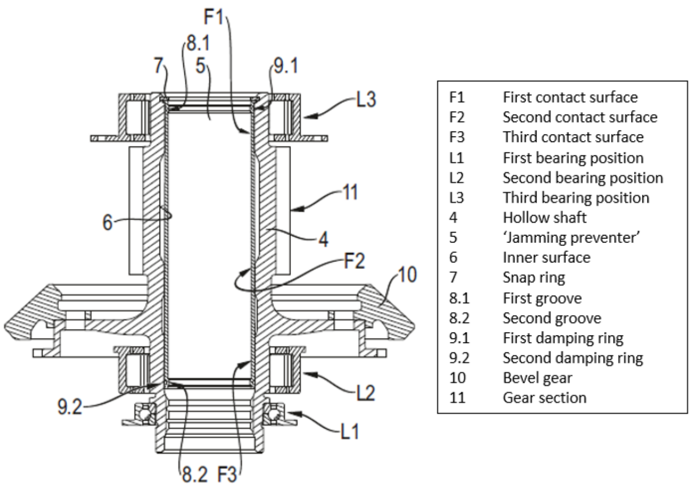
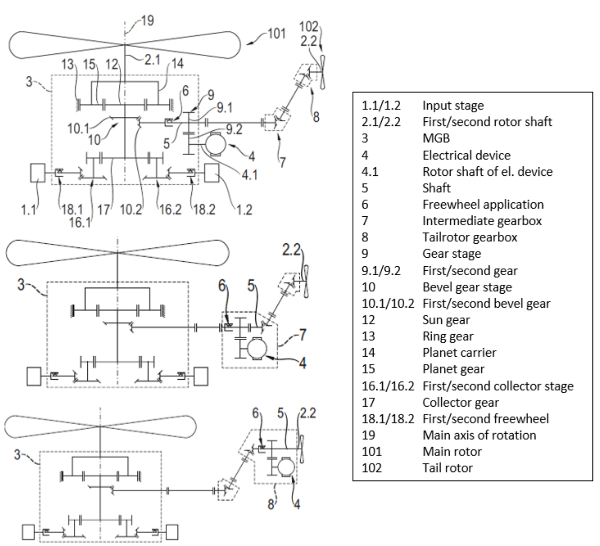
Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – Concepts to prevent SPoCF (3)









Step 3 – pre designing/detailing of developed safety barrier in to existing application to investigate a general feasibility as well as influences on the design

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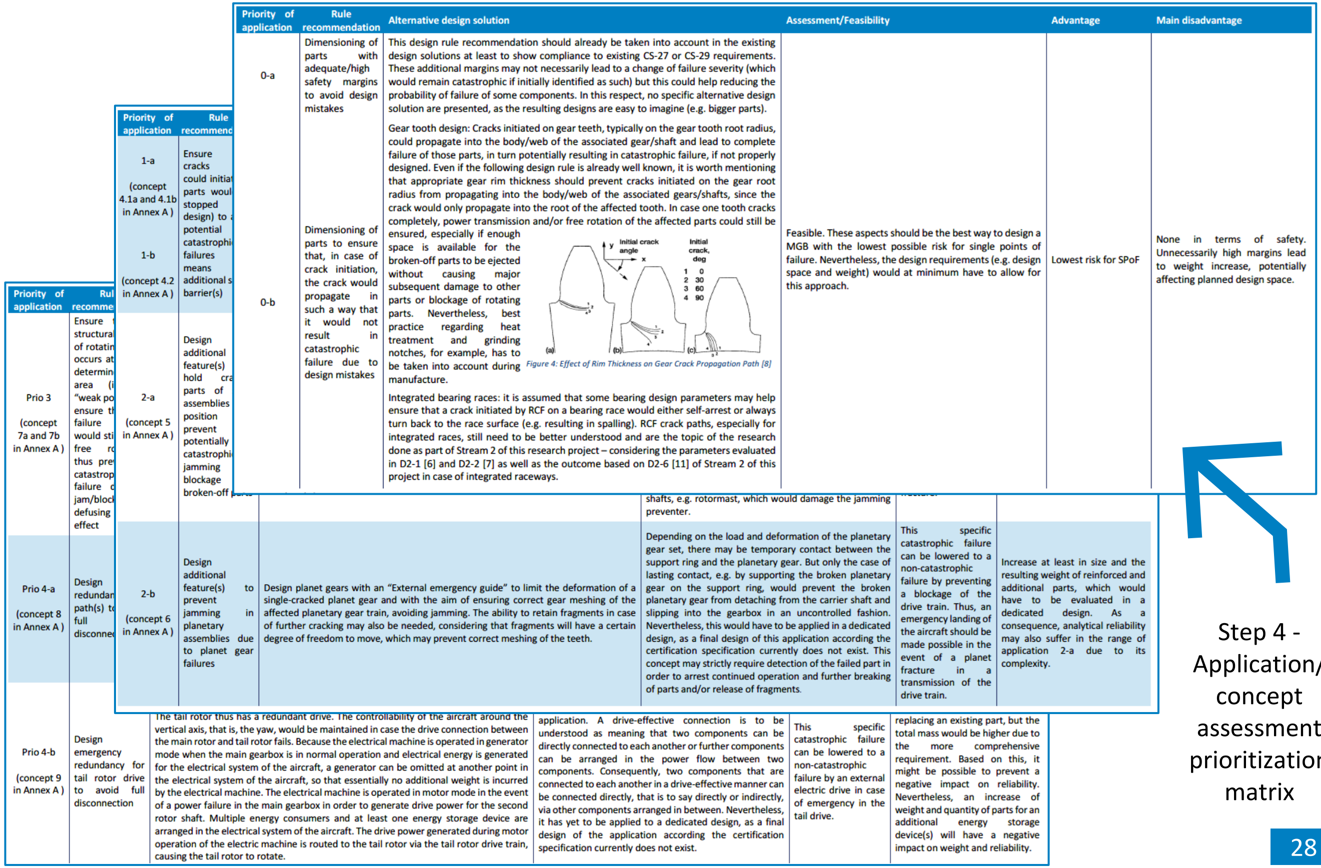
Stream 1 - Review of state-of-the-art rotorcraft gearbox configurations and component design – Concepts to prevent SPoCF (4)

→ Furthermore, detailed analysis of impacts from proposed design solutions and development of design recommendation pointing out e.g.

- Priority of application
  - Most promising
  - Economic aspects
- Feasibility of application
  - Boundary conditions
  - Obstacles
- Dis-/Advantages
  - Influence of level of criticality
  - Influence on e.g. weight, size, quantity of parts



Priority of application	Rule recommendation	Alternative design solution	Assessment/Feasibility	Advantage	Main disadvantage
0-a	Dimensioning of parts with adequate/high safety margins to avoid design mistakes	This design rule recommendation should already be taken into account in the existing design solutions at least to show compliance to existing CS-27 or CS-29 requirements. These additional margins may not necessarily lead to a change of failure severity (which would remain catastrophic if initially identified as such) but this could help reducing the probability of failure of some components. In this respect, no specific alternative design solution are presented, as the resulting designs are easy to imagine (e.g. bigger parts).	Feasible. These aspects should be the best way to design a MGB with the lowest possible risk for single points of failure. Nevertheless, the design requirements (e.g. design space and weight) would at minimum have to allow for this approach.	Lowest risk for SPoF	None in terms of safety. Unnecessarily high margins lead to weight increase, potentially affecting planned design space.
0-b	Dimensioning of parts to ensure that, in case of crack initiation, the crack would propagate in such a way that it would not result in catastrophic failure due to design mistakes	Gear tooth design: Cracks initiated on gear teeth, typically on the gear tooth root radius, could propagate into the body/web of the associated gear/shaft and lead to complete failure of those parts, in turn potentially resulting in catastrophic failure, if not properly designed. Even if the following design rule is already well known, it is worth mentioning that appropriate gear rim thickness should prevent cracks initiated on the gear root radius from propagating into the body/web of the associated gears/shafts, since the crack would only propagate into the root of the affected tooth. In case one tooth cracks completely, power transmission and/or free rotation of the affected parts could still be ensured, especially if enough space is available for the broken-off parts to be ejected without causing major subsequent damage to other parts or blockage of rotating parts. Nevertheless, best practice regarding heat treatment and grinding notches, for example, has to be taken into account during manufacture. *Figure 4: Effect of Rim Thickness on Gear Crack Propagation Path [8]* Integrated bearing races: it is assumed that some bearing design parameters may help ensure that a crack initiated by RCF on a bearing race would either self-arrest or always turn back to the race surface (e.g. resulting in spalling). RCF crack paths, especially for integrated races, still need to be better understood and are the topic of the research done as part of Stream 2 of this research project – considering the parameters evaluated in D2-1 [6] and D2-2 [7] as well as the outcome based on D2-6 [11] of Stream 2 of this project in case of integrated raceways.			

Step 4 - Application/ concept assessment prioritization matrix

Agenda

- Overview
- Stream 1 – Review of rotorcraft architectures with regards to rotor-drive systems (MGB)
- Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation
- Summary of project
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Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation - Overview

- Investigations within stream 2 is focusing on fundamental understanding and potential prediction of crack propagation on integrated raceways under RCF
- Analysis of available literature and field experience coming from relevant applications, incl.:
  - Influencing parameters
  - State-of-the-art design methodologies
  - Lessons learned from accidents
- Test campaign using representative samples for helicopter MGB design (dimensioning, material, manufacturing, loads, …):
  - Specification of test specimen, test conditions and test benches
  - Manufacturing of specimen and testing incl. in depth analysis of results
- FE model definition and validation:
  - Implementation of all relevant parameters into FE model (e.g. residual stress condition, loading due to rolling contact and/or body stress, …) and simulation of crack propagation for various parameter settings
  - FE model validation based on literature (e.g. observed cracks) and performed test campaign
- Definition of recommendations for future design of MGB (influencing parameters, general method)

Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Design criteria and parameters (1)

- Review of experience on design parameters for typical aviation application with focus on relevant type of bearings (SRB / CRB)
- Discussion of known field failures and observed failure modes including cross effects between design parameters
- Fish bone analysis on crack initiation and subsequent crack propagation & damage, taking relevant aspects into consideration
- Evaluation of criticality (low / medium / high) of each parameter

Parameter	criticality for reliability …
Axial clearance and roller length	
Cage pocket clearance	
Osculation	
Inner or outer ring diameter	
Contact angle	
Roller geometrical tolerance	
Roller diameter roughness	
Roller face roughness	
Cage pocket geometry	
Cage guiding diameter and c… landing clearance	
Rings/shaft/gear race… roundness and location	
Rings/shaft/gear raceway profil…	
Rings/shaft/gear race… roughness	

Parameter	criticality for reliability and flaw tolerance of be… (low/…
Parameter…	
Bearing type	low
Tightening – Hoop Stress	low
Roller raceway full contact & truncation	high
Contact Stress	high
Misalignment	high
Slippage and P.V.	high
Lambda ratio lubrication	high
Oil flow	low
Oil cleanliness / pollution	high
Bearing life	low
Internal radial clearance and roller diameter	high

Parameter	criticality for reliability and flaw tolerance of bearing races (low/medium/high)	Rationale
Roughness of cage piloting surface on ring/shaft/gear	low	Complementary to guiding diameter and cage landing clearance
Material and material cleanliness and composition	high	Material has great effect on fatigue limit and fracture toughness but is generally not freely selectable. It is not within the scope of this project to fully characterize the impact of all different characteristics that may be impacted by the material selected with regards to bearing reliability and flaw tolerance. The material cleanliness (melt quality) defines the amount of potential crack initiation locations. The material composition has an influence on the microstructure and potential crack initiation locations.
Hardness	high	Hardness has direct influence on the mechanical properties of the steel and can contribute to cracks or spalling
Case hardening depth	high	Mechanical properties of the steel change at end of hardening zone and can influence the flaw tolerance
Residual Stress	high	Change in stress level could lead to decreased flaw tolerance
Particular parameters for bearings with integrated raceways		
Body stress	high	Generally higher stress level due to superposition of loads at the raceway compared to conventional bearings with non integrated raceways. The higher stress level increases risk of spalling and crack initiation.
Material and surface treatment	high	The selection of the material and the corresponding heat treatment process influences the stress state and the resistance against damages and flaws.
Parameters for planetary gears with integrated raceways		

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Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Design criteria and parameters (2)

→ Based on analysis and in detail literature research three (3) main hypothesis were defined:

1. In the case of a pure rolling contact load, an initiation of a crack with a finite depth may occur.
   I. Crack growth ends at a finite depth
   II. A crack typically leads to spalling damage
   III. Crack growth toward the surface is known for pure RCF. Crack growth into the material is known in combination with a second driver (body stress)

2. Without a complex load situation that is present for example in a planetary gear, there will be no further crack growth into depth under a single load of the rolling contact.

3. Only under the complex load situation (body stress), a crack propagation into the material is possible and has to be considered.

Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Specification of test specimen (1)

→ Test specimen are required in accordance with the three main hypotheses. For clear separation during the test campaign the test phases are named accordingly:

- Phase I.1 = Pure RCF for different contact pressures
- Phase I.2 = RFC + max. contact pressure incl. variation of relevant parameters
- Phase II = Complex load

→ Parameter analysis used as baseline for test specimen with the following target:

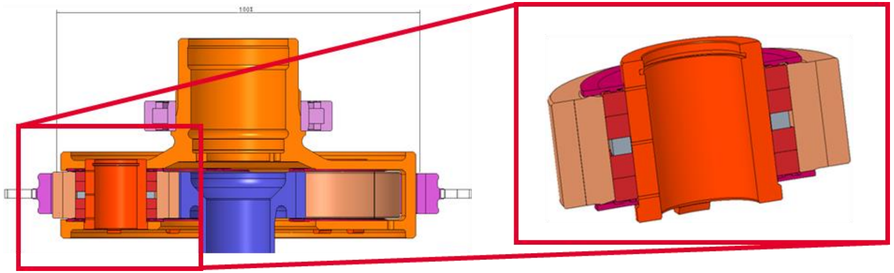
- Ensure representative samples
- Cover widest possible range of parameters still acceptable concerning statistical analysis of test
- Consideration of aviation typical application (e.g. material, loading, …)
- Prioritization of design parameters in view of project target and expected impact

SRB/CRB		Comments
Tightening Hoop Stress	Case hardened steels ~around 250 MPa (function of steel thoughness) Through hardened steels : max 200MPa	
Contact Stress	Below 1600 MPa in nominal condition Below 2200 - 2400 MPa in max conditions	Highly depends on final application and duty cycle partition
Misalignment	Misalignement until full contact / edge contact	
Oil flow	NA	Calculated on the application from the bearing estimated power losses and the oil in-oil out temperature variation
Internal radial clearance	(0.015 to 0.22 mm) ; Internal radial clearance value should guarantee that, with the max ring deformation, the loading zone angle is below 160-180°	
Axial clearance	CRB : linked to roller geometry and skewing risk SRB : depends on radial clearance, contact angle, skewing risk	
Cage pocket clearance	(0.13-0.45 mm) : to avoid fatigue due to roller skewing	
Osculation	(0.50-0.59) : to avoid full contact	
Contact angle	(8 to 18°) : to optimize pressure	
Roller length (typical length to radius ratio)	Length/Diameter superior or equal to 1 Length/Diameter max ~ 1.25	
Roller diameter roughness	0.05 to 0.1 µm	Values could be limited by the manufacturing process
Roller face roughness	0.15 to 0.4 µm (standard 0.2 µm)	
Cage landing clearance	0.05 to 1 mm	
Ring raceway roundness	0.00075 to 0.001 mm	
Ring raceway roughness	0.08 to 0.2 µm	Values could be limited by the manufacturing process
Roughness of cage piloting surface	0.4 µm	
Hardness	Surface hardness : (630) 650HV to 850HV (up to 1100HV for M50NiL nitrided)	
Case-hardening depth	Nitrided steels : from 0.5 to 0.9 mm (HV_{core}+100) Carburized steels : from 0.3 to 1.6 mm at 550HV	
Residual stress	Surface : -400 to -1000 MPa (-1200MPa for M50NiL nitrided) Case-hardened layer : -200 to -400 Mpa	

Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Specification of test specimen (2)

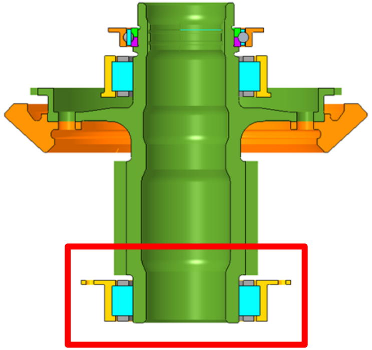
→ Geometry of test specimen is based on MGB analysis concerning typical use of integrated raceways for epicyclic and collector MGB design

Epicyclic design of MGB



Test specimen „ring“ in the version standard ring and ring with notch (complex load situation)

Collector design of MGB



Test specimen „shaft“ in the version non-hollow and hollow (complex load situation)

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Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Specification of test specimen (3)

- → Transformation of necessary design parameters (e.g. material, heat treatment specification, wall thickness, etc.) into number of specimen for the planned tests
- → In addition, 3 specimens were planned per configuration for phase II, selected based on the results of phase I
- → Manufacturing parameters selected in view of processes used for comparable parts. Additional process step required regarding notch for outer ring samples - EDM (electric discharge machining) selected
- → White layer of 32CDV13 inner ring specimen has not been removed (project decision)
- → Analysis after manufacturing showed some acceptable deviation compared to original intention (i.e. variation of hardening depth, hardness, …)

Specimen	Variant	Material	Manufacturing approach	Test Phase
Inner Ring	1	16NCD13	Basic Variant	I.1
Inner Ring	1.1	16NCD13	Basic Variant - hollow shaft	II
Inner Ring	2	32CDV13	Basic Variant	I.1
Inner Ring	2.1	32CDV13	Basic Variant - hollow shaft	II
Inner Ring	3	16NCD13	Adjusted heat treatment	I.2
Inner Ring	4	32CDV13	Adjusted heat treatment	I.2
Inner Ring	5	16NCD13	Adjusted heat treatment	I.2
Inner Ring	6	32CDV13	Adjusted heat treatment	I.2
Inner Ring	10.1	32CDV13	Intermediate heating	I.2
Inner Ring	11	16NCD13	Intermediate heating and surface finish adjustment	I.2
Outer Ring	B	M50Nil	Basic Variant	I.1
Outer Ring	DA	32CDV13	Basic Variant	I.1
Outer Ring	BB	M50Nil	Adjusted heat treatment	I.2
Outer Ring	DC	32CDV13	Adjusted heat treatment	I.2
Outer Ring	BA	M50Nil	Adjusted heat treatment	I.2
Outer Ring	DB	32CDV13	Adjusted heat treatment	I.2
Outer Ring	BC	M50Nil	Adjusted surface finish process	I.2
Outer Ring	DD	32CDV13	Adjusted surface finish process	I.2
Outer Ring	T102	M50Nil	Basic variant - notch severe design	II
Outer Ring	T102	32CDV13	Basic variant - notch severe design	II
Outer Ring	T104	M50Nil	Basic variant - notch less severe design	II
Outer Ring	T104	32CDV13	Basic variant - notch less severe design	II

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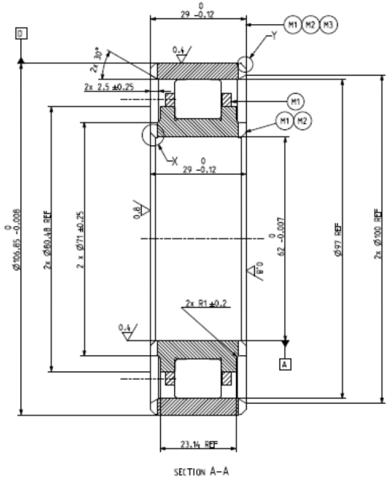
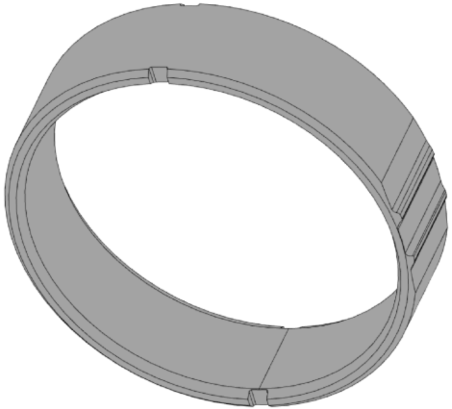
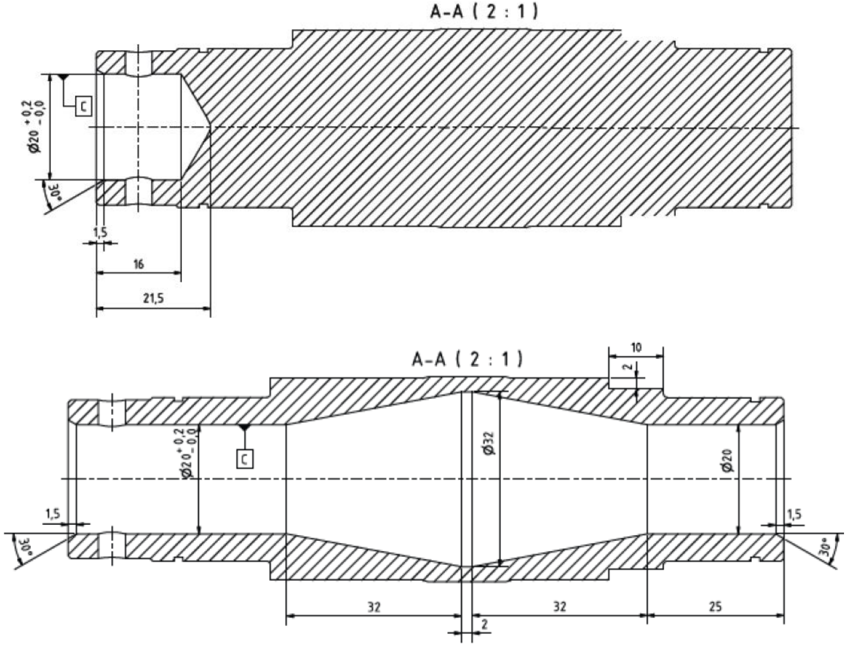
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Specification of test specimen (4)

Baseline specimen „ring“



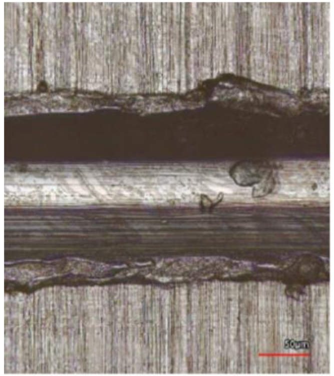


Baseline specimen „shaft“

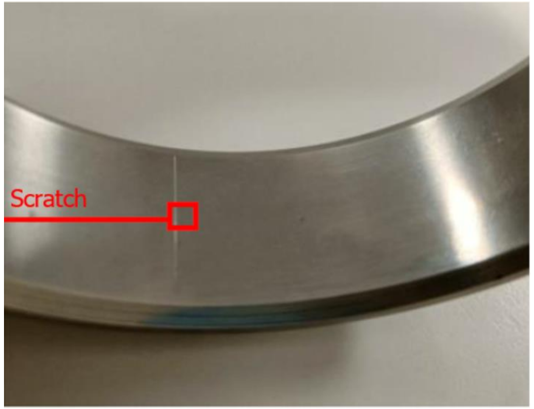


Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Specification of test conditions – Pre-damage

- First evaluation of test conditions revealed need for pre-damage modification to ensure predictable spalling within test campaign
- Pre-damage was done using an indenter (diamond tip, 100 N) with the focus to ensure a classical spalling damage in a short time (to reduce overall testing time) – leading to the starting point for potential cracking



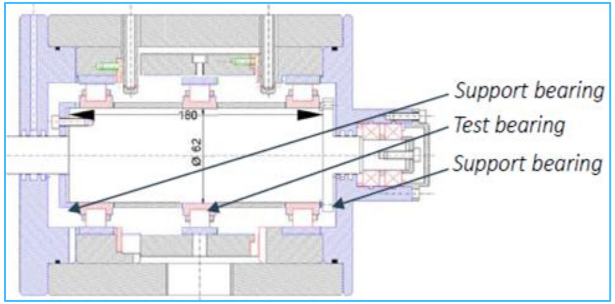
Indenter (right) with scratch on raceway (right)

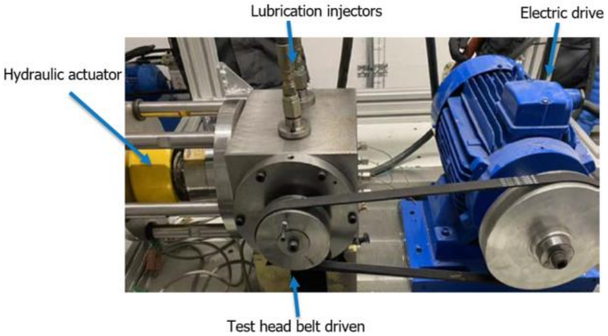


Example: Raceway of outer ring with scratch before start of testing

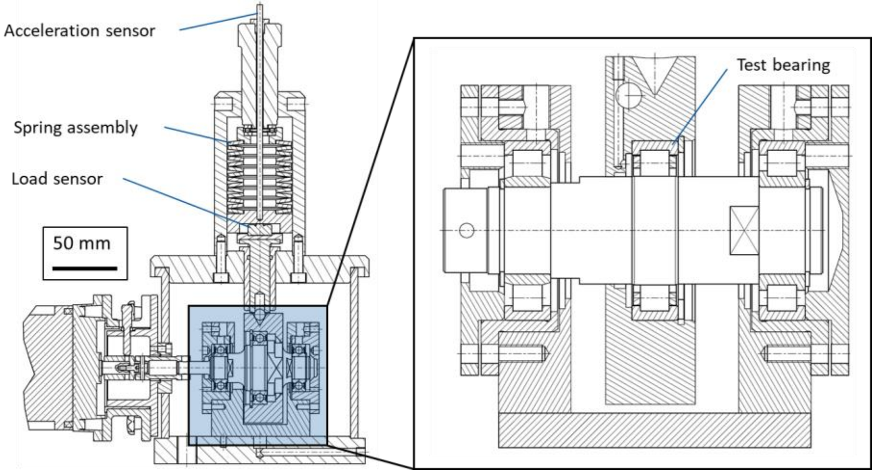
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Test benches

Bench 1: outer raceway





Bench 2: integrated („inner“) raceway

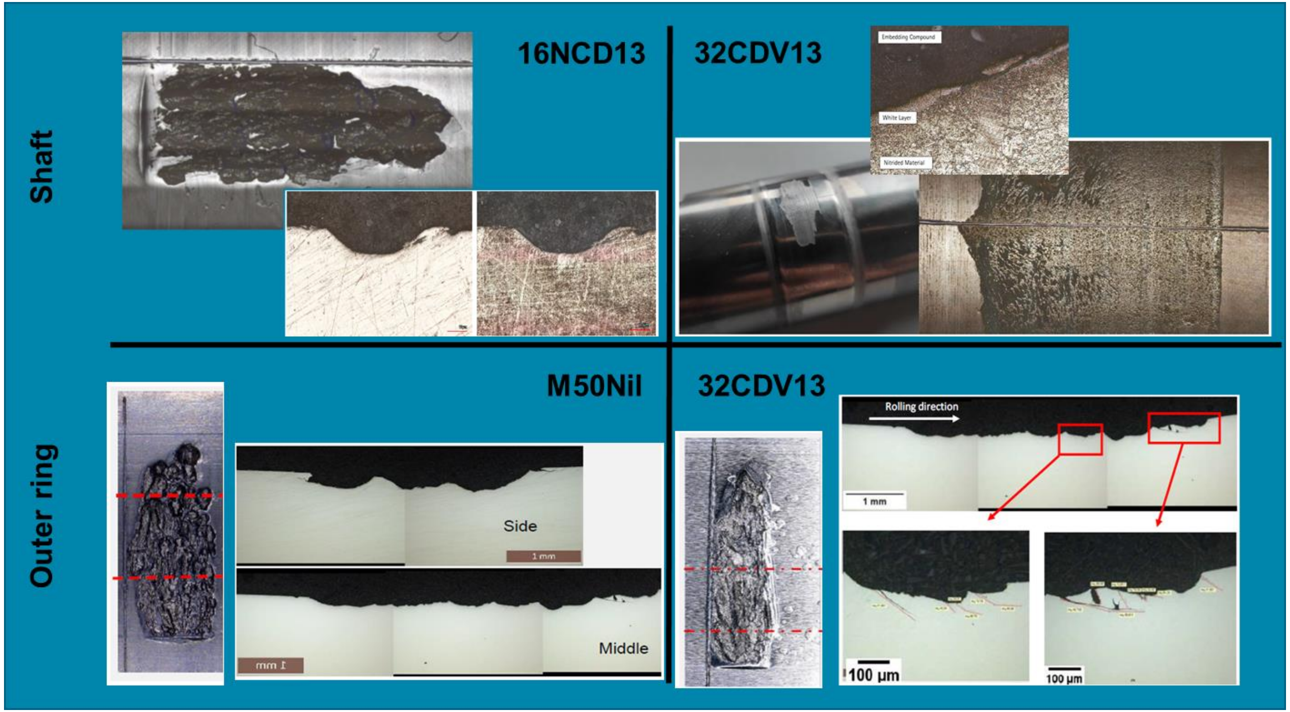


Section view of test bench 2

Test unit – Test bearings RNU 206 ECP and support bearings NU 206 ECP + NUP 206 ECP

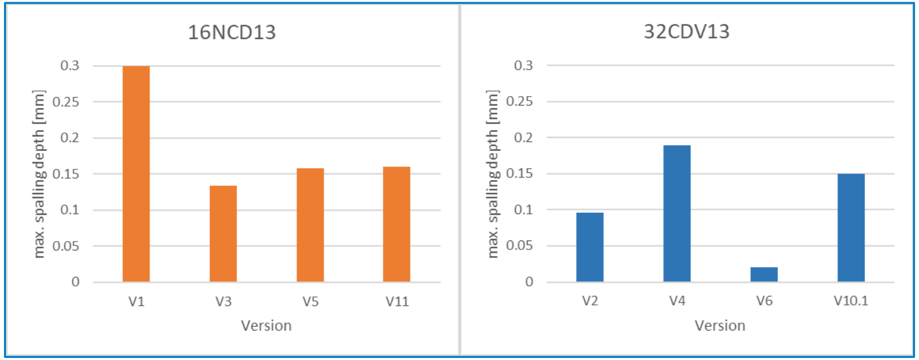
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Test campaign – Phase I.1

- → Typical spalling damage observed for all specimens at 2.4 GPa
- → 32CDV13 shaft specimen with peeling of white layer
- → No spalling at 1.8 GPa and 1.5 GPa detected
- → No crack propagation into depth

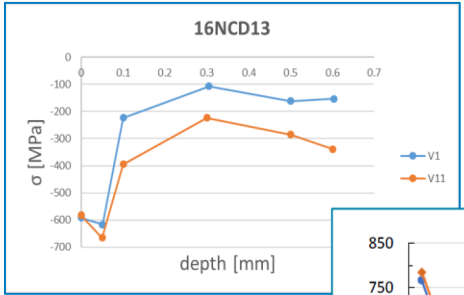


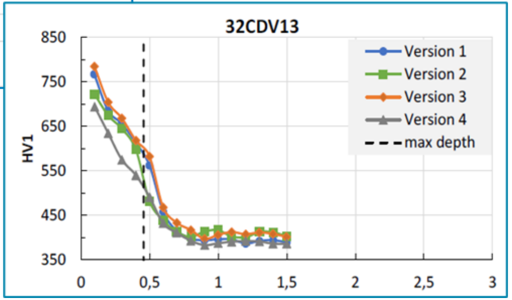
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Test campaign – Phase I.2

- Variation of hardness, hardness depth and residual stress led to variation in spalling depth
- No crack propagation into the material detected
- Results comparable to phase I.1 results
- Crack growth ended at a finite depth

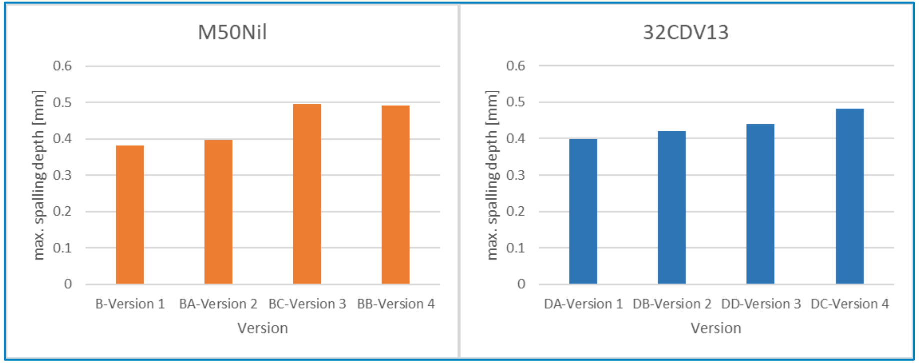


Max. detected spalling depth (16NCD13) and peeling of white layer (32CVD13) – Shaft application





Example of residual stress and hardness measurement results



Max. detected spalling depth – Outer ring application

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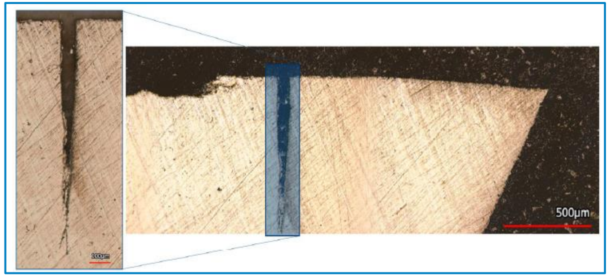
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Test campaign – Phase II - Shaft

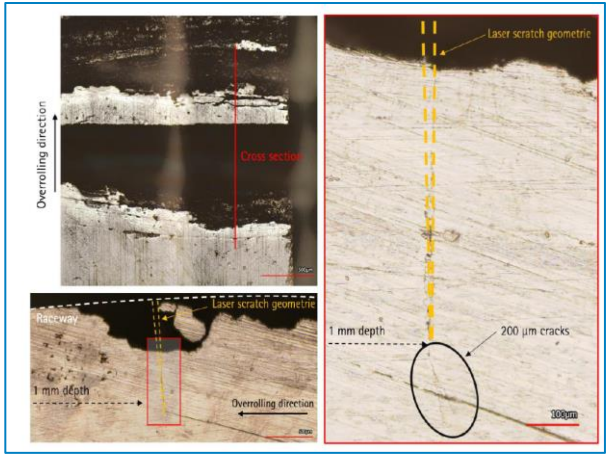
- Crack propagation into depth (not through) found for both materials
- Standard indenter scratch led to same results as for phase I
- Modification of scratch to deeper laser damage to initiate more severe (for crack through propagation promotion) pre-damage



Tested shaft with 16NCD13 at 2.9 GPa with laser scratch

	Material	Version	Quantity	Contact Pressure	Reached cycles	Damage (visual inspected)
Phase II	16NCD13	V1.1	3	2400 MPa	115.6 M. 82.9 M. 39.4 M. 32.4 M.	No spalling / no crack propagation
	16NCD13	V1.1	3	2900 MPa	9.4 M. 13.2 M. 1.2 M.	No spalling / arrested through-crack
	32CDV13	V2.1	3	2400 MPa	35.8 M. 30.1 M. 5.4 M.	arrested through-crack / spalling
	32CDV13	V2.1	3	2900 MPa	1.3 M. 0.6 M. 0.7 M.	arrested through-crack / spalling

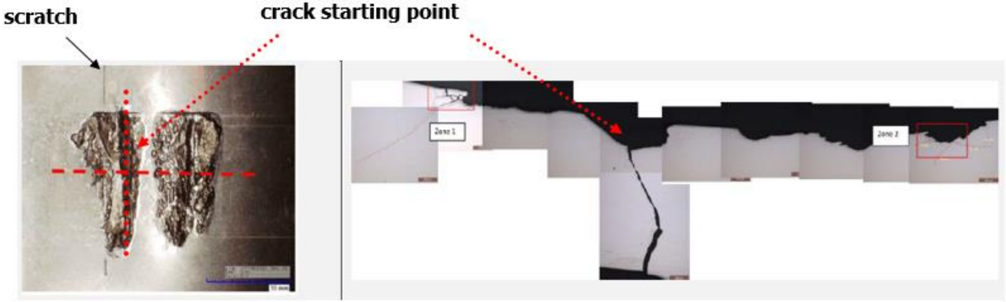
Overview of test results for shaft application with laser scratch specimen – phase II



Tested shaft with 32CDV13 at 2.9 GPa with laser scratch

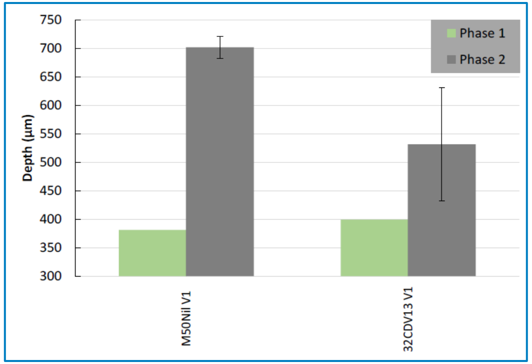
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Test campaign – Phase II (Outer Ring)

- → Crack through detected for M50Nil material at 2.4 GPa
- → 32CDV13 cracked at 2.9 GPa contact pressure
- → Increase of spalling depth due to complex load detected



Tested outer ring (T104) with M50Nil at 2.4 GPa

Tested outer ring (T104) with 32CDV13 at 2.9 GPa



Comparison of measured spalling depth for phase I and phase II

	Material	Version	Quantity	Contact Pressure	Reached cycles	Damage (visual inspected)
Phase II	M50Nil	T104	3	2400 MPa	2.1 M. 2.9 M. 2.2 M.	Spalling with through-crack
	32CDV13	T104	3	2400 MPa	113.3 M. 86.6 M. 115.6 M.	Spalling
	M50Nil	T102	3	1800 MPa	n/a 200 M. 200 M.	Spall with severe cracks / No spall-reaching suspension time
	32CDV13	T102 Pre-test	1	2400 MPa		Spalling with through-crack
	32CDV13	T102	1	1800 MPa	200 M.	No spall-reaching suspension time
	32CDV13	T102	3	2400 MPa	n/a 200 M. 200 M.	Spalling / No spall-reaching suspension time

Overview of test results for outer ring application - phase II

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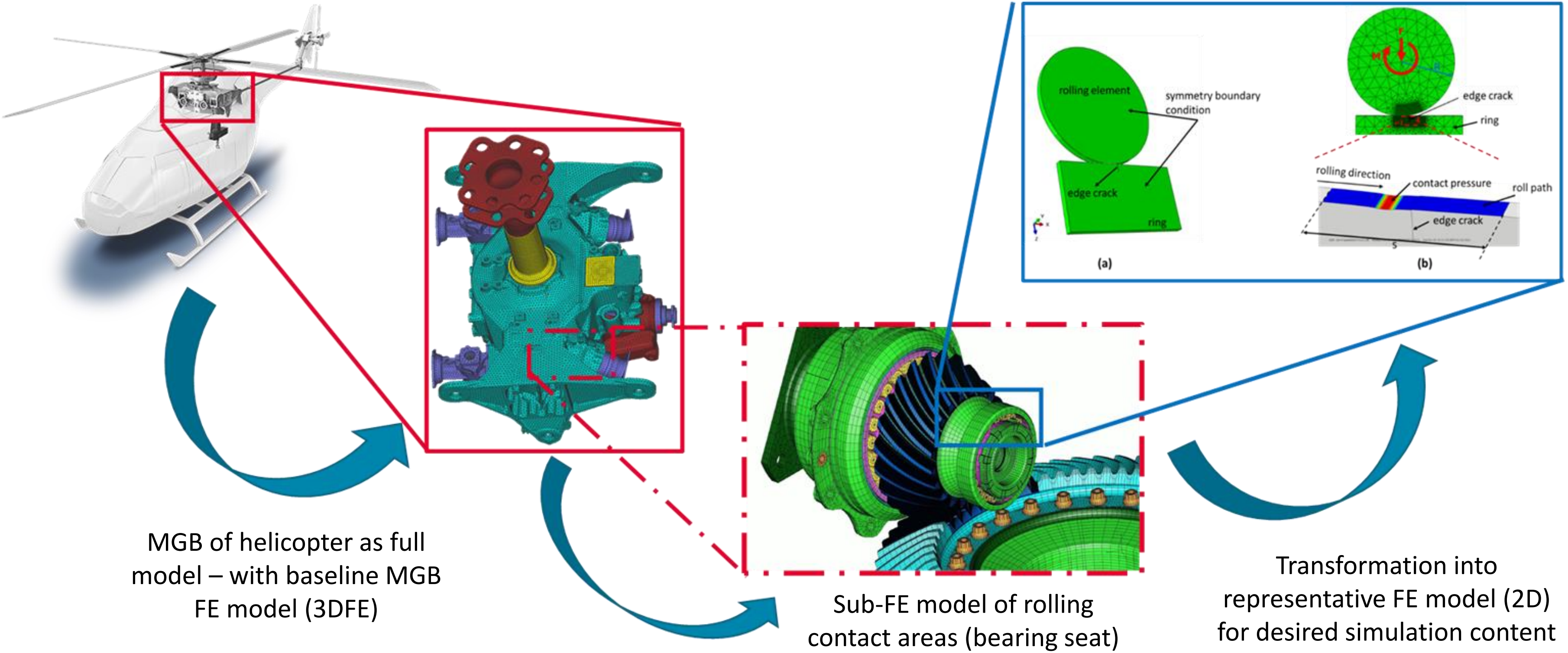
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – FE-model – Model reduction for simulation model



MGB of helicopter as full model – with baseline MGB FE model (3DFE)

Sub-FE model of rolling contact areas (bearing seat)

Transformation into representative FE model (2D) for desired simulation content (RCF + crack propagation)

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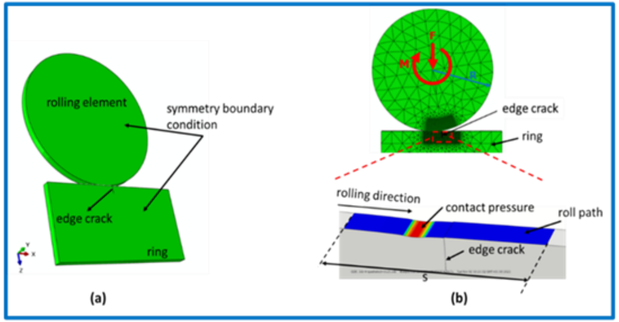
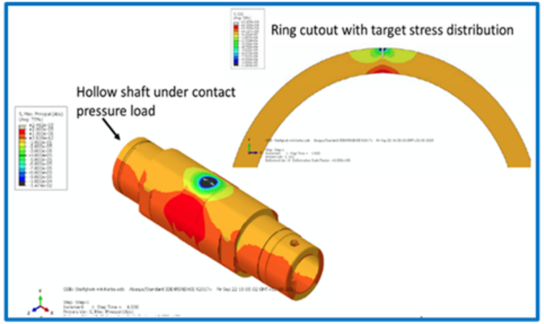
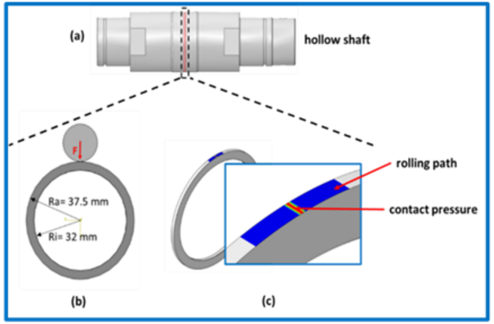
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – FE-model – Crack propagation analysis

→ Example of FE model for complex load situation of inner ring (hollow shaft) and outer ring (ring)

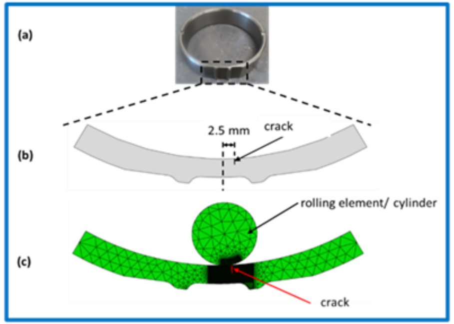


Model used to predict the crack path in hollow shaft





Model used to predict the crack path in outer ring



The shown modelling approach partially applies for phase I simulations (left side), phase II example used for presentation reasons.

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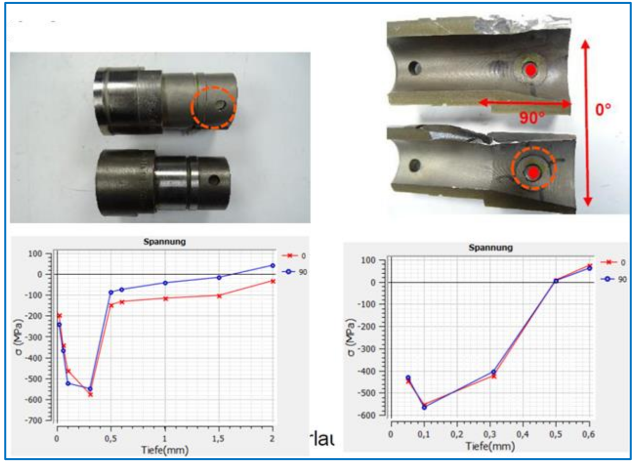
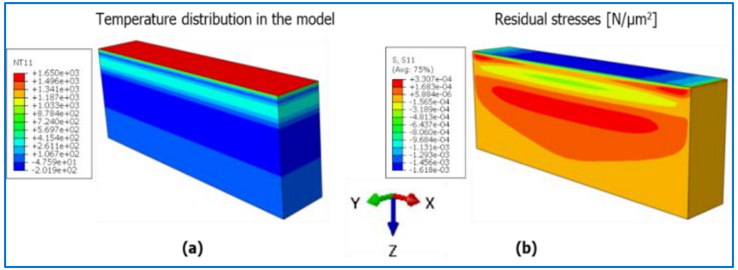
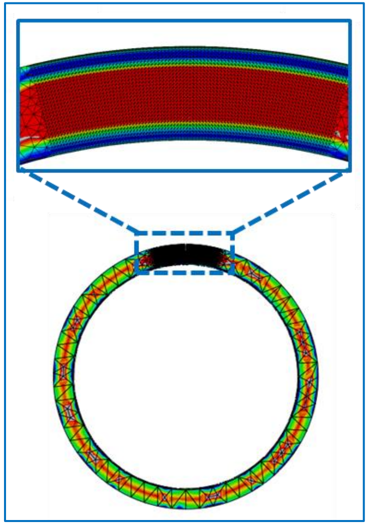
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – FE-model – Residual stress implementation

→ Implementation of residual stress into FE model using thermal stress approach and verification by measurements (shown example: hollow shaft, but also valid for outer ring)

Measurement of the residual stresses from both the inner and outer diameters the raceway → Modeling of residual stresses with thermal stresses → Modeling of the residual stresses in the hollow shaft

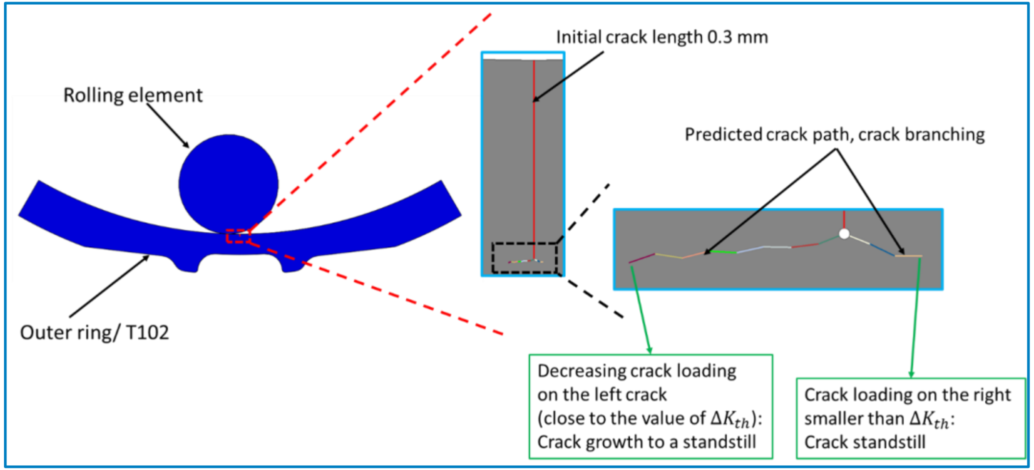


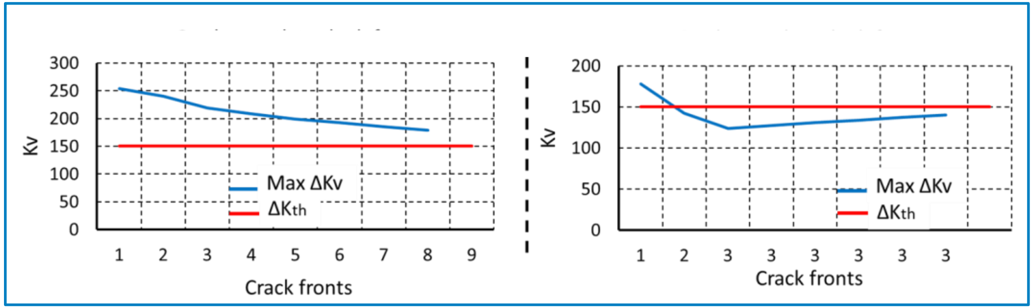




Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – FE-model – Crack propagation simulation

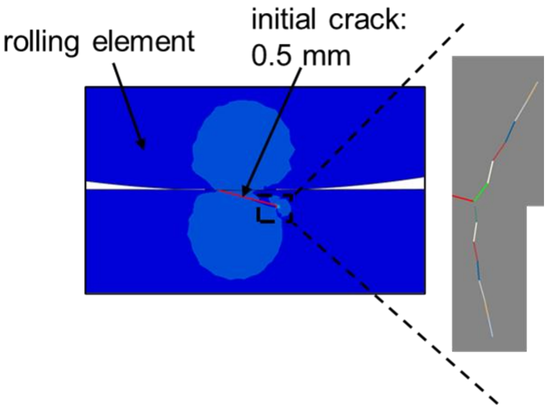
- → Calculation of the stress intensity factors K_I, K_{II} and the equivalent stress intensity factor K_V at the crack front for each simulation step.
- → Crack propagation threshold selected for the purpose of this project according literature / data sheets etc.
- → Crack growth condition: $\Delta K_V > \Delta K_{th}$
- → Calculation of the crack path to the crack stop: $\Delta K_V \leq \Delta K_{th}$
- → Decrease in ΔK_V with crack growth (crack stop is expected)
- → Shown example: Crack growth simulation in the outer ring, showing crack branching and crack growth parallel to the surface in both right and left directions

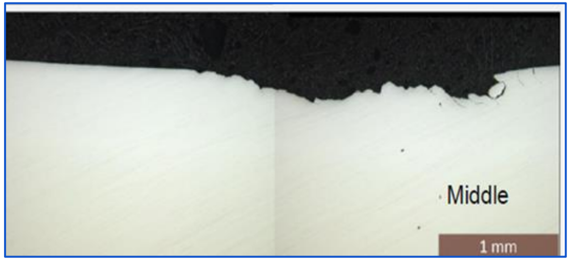




Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Results: Comparison simulation and testing (1)

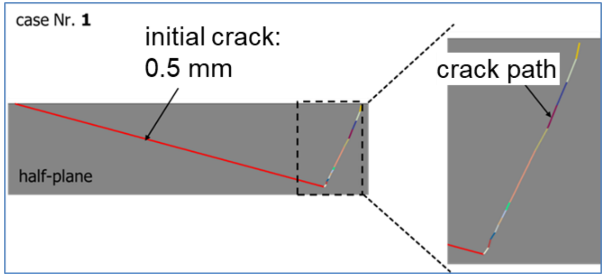
Phase I.1

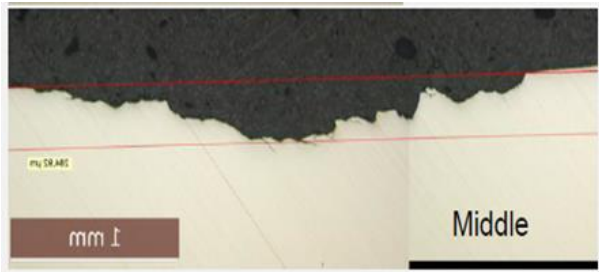




- Comparison for outer ring:
  - Simulation: After the crack branches, the crack stops. No crack through, crack propagation into the depth of the material, only to limited depth.
  - Testing: Spalling observed, no crack growth into depth of the material – good correlation to simulation

Phase I.2





- Comparison for outer ring:
  - Simulation: The crack grows towards the surface - spalling is expected
  - Test: Spalling observed, No crack through, crack propagation into the depth of the material, only to limited depth.

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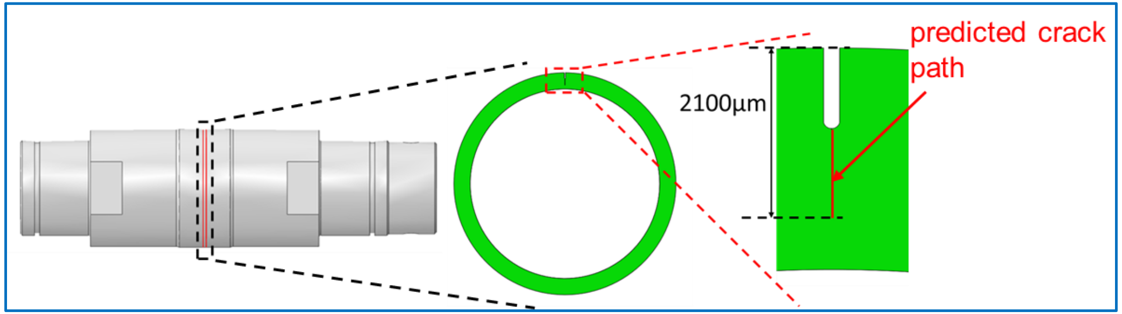
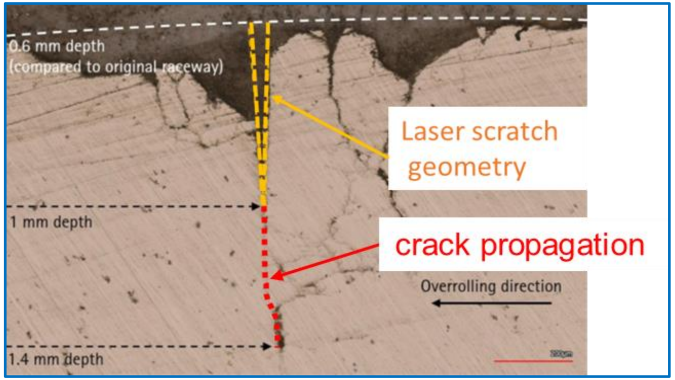
Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Results: Comparison simulation and testing (2)

- Phase II: Results of FE simulation has been compared to the test results for both tested variantes (inner ring and outer ring)

- Results for comparison to the test results for hollow shaft with laser scratch
  - Analysis are based on metallographic analysis of test specimen (crack propagation into the depth)
  - 2D-Crack growth simulation in the ring with the notch (crack propagation into the depth)
  - Qualitative comparison of the predicted crack paths with crack propagation from testing showed good correlation



Prediction of the crack path in the hollow shaft

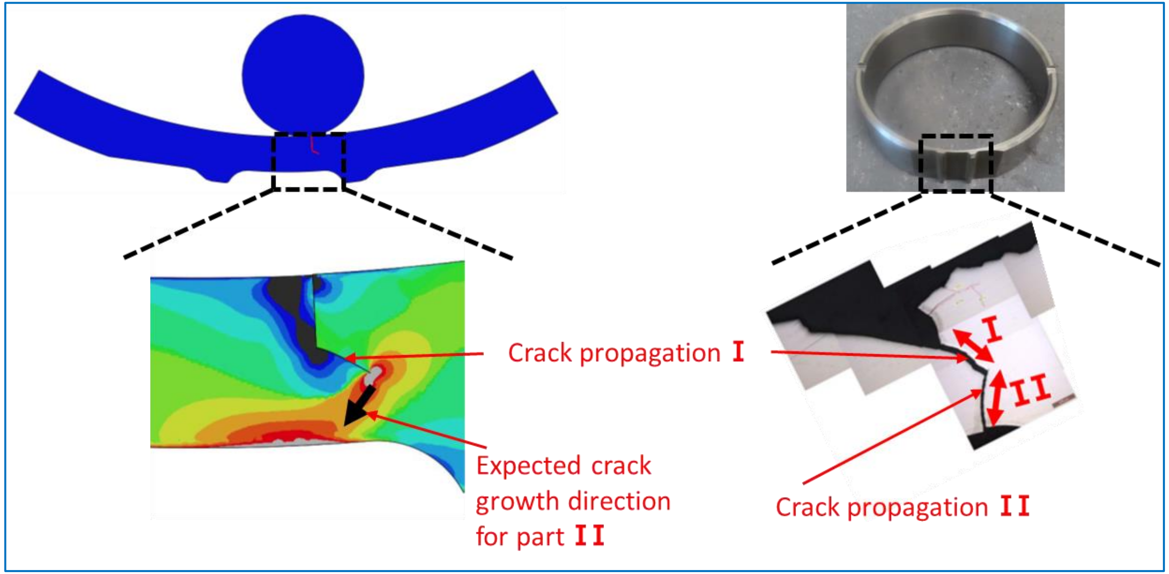


Cross section of shaft for low load level (2.4 GPa) - Crack propagation in the hollow shaft

Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Results: Comparison simulation and testing (3)

- Phase II: Results of FE simulation has been compared to the test results for both tested variants (inner ring and outer ring)

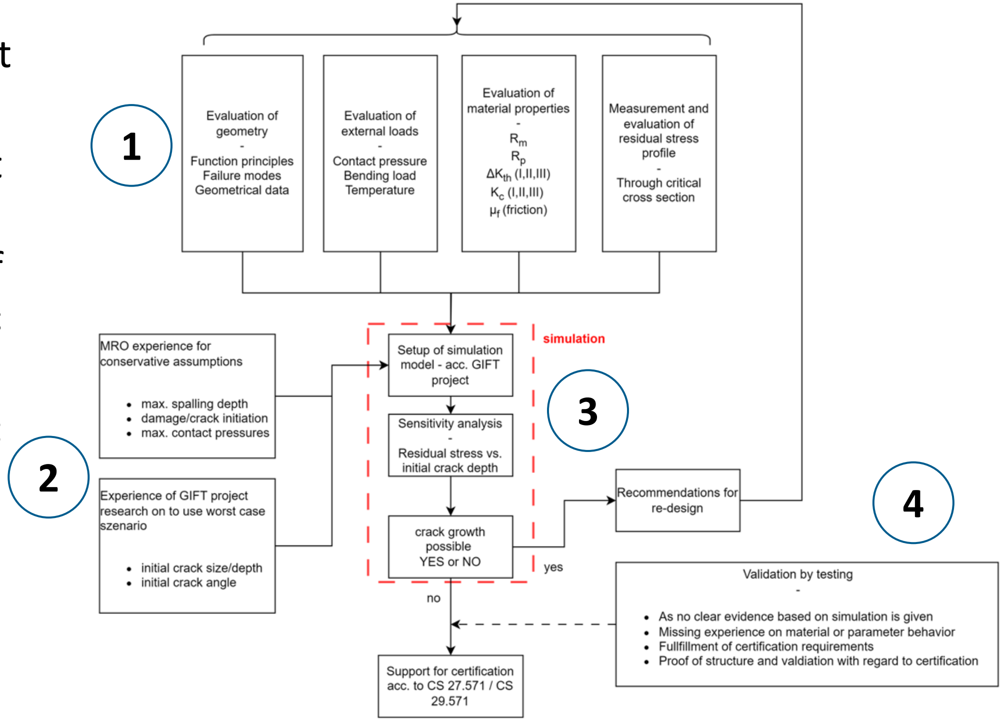
- Results for comparison to the test results for outer ring
  - Analysis are based on metallographic analysis of test specimen
  - Crack growth simulation with the same loads as in the test
  - Comparison of the predicted crack path in section I using FE-simulation with crack propagation in the test ring
  - Crack propagation in section II in the test ring
  - Expected crack growth direction for section II
  - Qualitative comparison of the predicted crack path with results from testing showed good correlation



FE- crack growth simulation (left) and observed crack propagation on test bench (right)

Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation – Results: Methodology for RCF assessment

- Based on the content of GIFT research project a methodology for RCF component assessment was established
- The methodology aims to provide support for compliance demonstration to CS27/29.571 paragraph for certification of integrated bearing races with catastrophic failure mode
- The approach is based on four main steps:
  1. Evaluation of component design values
  2. Collection of additional MRO data and use of experience from GIFT project
  3. Setup of FE simulation and provisions of recommendations for re-design
  4. Validation by testing



Agenda

- Overview
- Stream 1 – Review of rotorcraft architectures with regards to rotor-drive systems (MGB)
- Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation
- Summary of project
- Conclusion

Summary of project

- In depth analysis of current state-of-the-art helicopter MGB architectures were performed based on a failure flow diagram (FFD) approach and design modifications to prevent SPoCF were proposed.

- Damage mechanism and failure modes of bearings using integrated raceways were analysed. Results were used for definition of representative test specimen, test conditions and test benches and a test campaign was performed, analyzing the of impact design and manufacturing parameters on the development of RCF followed by crack initiation and crack propagation.

- The defined main hypotheses concerning RCF and development of crack propagation were confirmed.

- Based on in depth analysis, a FE model for crack propagation was developed and validated within the project scope. Validation was performed using data from literature and the results of the test campaign of this project.

- As a final achievement a methodology supporting CS27/29.571 was developed that allows the designer in an early stage to evaluate a potential risk for crack growth on integrated raceways under RCF.

Agenda

- Overview
- Stream 1 – Review of rotorcraft architectures with regards to rotor-drive systems (MGB)
- Stream 2 – Rolling contact fatigue and influence on crack initiation and crack propagation
- Summary of project
- Conclusion

Conclusion

- Within stream 1 of this project, a representative analysis of current helicopter MGB architectures has been performed, indicating possible SPoCF within each architecture. It can be said that design solutions are available for each of the analyzed architectures (epicycloid, collector) to avoid these SPoCF, however any design solution needs to be analyzed in detail and may have an effect on weight, size, reliability and cost.

- Within stream 2 of the project, a methodology was developed that allows the designer in an early stage to evaluate a potential risk for crack growth on integrated raceways. Due to the nature of the discussed failure mode, each single design has to be analyzed separately. The methodology will contribute to CS27/29.571 and may include test procedures that have been developed during this project.

- Test results have shown that crack propagation through the material, e.g. resulting in a split planetary gear, is only possible under a complex load situation.

- Follow on research is recommended to extend the knowledge gained during this project, since some technical aspects could not be discussed and analyzed in the recommended depth within the defined project scope. Additional work should also include further testing for statistical reasons.

Acknowledgement

→ The project team would like to thank for the support of the involved team at EASA and the project partners SKF Aerospace, IMKT from University of Hannover, University of Paderborn, Central R&D of ZF AG and all colleagues at Airbus Helicopters Technik that participated during the time of the project.

EASA
European Union Aviation Safety Agency

Main takeaways for EASA

Stream 1

- A number of design solutions can be considered to mitigate or minimize the number of catastrophic failures.
- For example:
  - Provide additional support to prevent jamming in the event of rupture of a gear or shaft.
  - Implement shear-section to allow free rotor rotation in case of jamming.
  - Emergency drives.
- However, preventing or mitigating all possible catastrophic failure modes is not feasible/practicable.

Stream 1

- Considerations:
  - (Most likely) effectiveness needs to be shown by test.
  - Impact on weight of the design.
  - Added complexity and potential impact on reliability.

- **Note:** The design solutions presented as part of this activity are EASA's IP and may be freely used.

Stream 2

- High level conclusions:
  - The absence of significant body stresses seems to preclude deep crack propagation in rolling contact fatigue.
  - Thresholds for spalling initiation and propagation in the presence of flaws may be derived. However, these are potentially very application specific.
  - Evaluation of greater range of flaws is needed.
  - Residual stresses play a key role. Accuracy in residual stress measurements may require attention.

Stream 2

- Conclusions on testing:
  - Testing is an effective way of assessing the impact on rolling contact fatigue on an existing design. However, special attention is needed to ensure representativeness.
  - Through-cracking in integrated inner bearing races seems less likely (further testing would be needed to confirm).

Stream 2

- Conclusions on simulations:
  - Further developments are needed to be able to fully rely on simulations.
  - Crack initiation could not be simulated.
  - Accurate in predicting the behaviour of deep cracks (Mode I dominated).
  - Shear dominated crack growth can be explained, however, prediction of crack path is not possible due to kinking or branching.

Stream 2

- Considerations regarding certification:
  - EASA considers the outcome of this research is a step towards developing a valid approach to evaluate the risk of cracking due to rolling contact fatigue.
  - Similar approaches may be proposed in certification to address rolling contact fatigue cracking.
  - The applicability and exact objectives should be discussed on a case-by-case basis.
  - Adequately representative testing should be ensured and any analyses used should be sufficiently correlated.

Questions and answers

Question and Answers

→ For sending questions and input, please use the slido app, which is also accessible through WebEx:

- www.slido.com
- event code: 1888564
- passcode: pcw74q

Concluding Remarks

This project is funded by the European Union's Horizon 2020 Programme

Upcoming EASA research & innovation events

March 12th
Integrity improvement of rotorcraft main gear boxes (**MGB**)
Final dissemination event (webinar)

March 13th
Assessment of environmental impacts – rotorcraft (**NOISE**)
Final dissemination event (webinar, training for users)

March 19th
Market-based Measures – AERO-MS (**MbM**)
Final dissemination event (webinar); Training event on 20 March

April 23rd
New standards for drones and U-Space (**SHEPHERD**)
Final dissemination event (webinar)

April 23-24
Mental Health of Pilots and ATCOs (**MESAFE**)
Final dissemination event during EASA Mental Health Conference

April 25th
Helicopter underwater escape #2 (**HUE2**)
Final dissemination event (webinar)

Research agenda – future research topics

Environment
- New SAF production pathways

Security impacting safety
- AI aspects, conflict zones

Artificial intelligence
- Human factors

Data for Safety
- Research on sfuture uses cases

Health / medical
- Obstructive sleep apnea, high air space operations

Automation
- Impact on responsibilities of flight crews and air traffic controllers

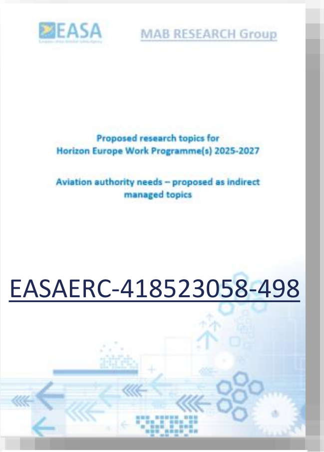
ATM / ANS
- Performance of ground equipment, airspace classifications

Air operations
- Flight time limitations for emCO

Drones
- BVLOS operations

PNT

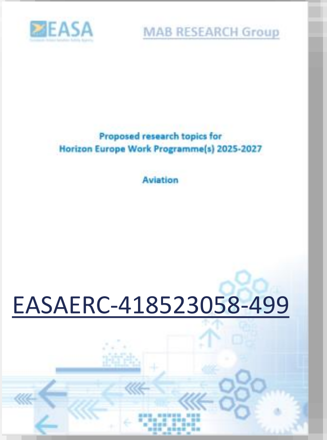
Icing


EASA MAB RESEARCH Group

Proposed research topics for Horizon Europe Work Programme(s) 2025-2027

Aviation authority needs – proposed as indirect managed topics

EASAERC-418523058-498


EASA MAB RESEARCH Group

Proposed research topics for Horizon Europe Work Programme(s) 2025-2027

Aviation

EASAERC-418523058-499

Thank you for joining this webinar!

Integrity Improvement of Rotorcraft Main Gear Box (MGB) | EASA (europa.eu).