Deliverable 3.4: Structural fatigue failure testing for wind turbine components

WP3, Task 3.4

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Author(s):	Haritz Zabala, Leire Lahidalga, Mario Alvarez, Mireia Olave

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Document History

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DoA	In this task, the simplified small-scale testing procedure for ring structural fatigue failure (RSF) mode will be generated and experimentally verified. First, virtual models are going to be used to identify variables (external load type and magnitude, local stress conditions, ...) and conditions (residual stresses, manufacturing effects on surface roughness, ...) that are relevant for the predictions of RSF reliability of component. These variables and conditions will be utilised in the simplified testing procedure. The virtual models developed in WP2 (T2.4.) will be used in order to verify that this test procedure is representative of the real failure mode. After that, an extensive testing campaign is going to performed. With the simple laboratory tests the impact of such variables for the expected reliability and lifetime of the simple specimen will be measured and corroborated. A large amount of experiments (between 12 and 27) is needed. Such extensive and vast experimental campaign will only be possible by the simple experimental testing procedure developed during the task and would never be possible to be carried out in bigger test configurations or in real applications. Expected results/outcomes: Developing the simplified testing procedure for bearing ring fatigue failure testing in laboratory is going to be main result of the task. The results achieved from the simplified tests performed will lead to improved knowledge of the effect loads, material properties and manufacturing processes influencing the reliability of the component regarding this failure mode.	

Date	Version	Author	Comment
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Abbreviations and Acronyms

Acronym	Description
RSF	Ring Structural Fatigue
LAS	Load Application System
WP	Work package

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0. Executive Summary

The aim of this task is to develop and prove a simplified and small-scale testing procedure to reproduce at laboratory conditions the ring structural fatigue failure (RSF) of a pitch bearing. The virtual modes developed in WP2 (T2.4) are used to define and validate the testing campaign, verifying also that the testing procedure is representative of the real failure mode.

First, a simple experimental testing concept is created by means of simulations. Second, the new concept is developed until a real testing configuration is fully defined: test and specimen type and measuring techniques. Third the test bench is designed into detail and constructed. Last, a vast experimental camping is performed in an intermediate scale, between the SN characterization and the real component scale, to assess the effect of the manufacturing process gap between them. Within the project, manufacturing effect is considered simplifying it to a roughness effect, however, the experimental procedure developed can test bolt holes manufactured by different machining techniques, tools and variables.

The task and objectives achieved within this deliverable covering the abovementioned topics are the following:

i. Definition of a simplified testing procedure to reproduce at lab scale the Ring Structural Failure acting on a bolt hole of the a real bearing. The virtual models developed in WP2 (T2.4) were used for this purpose.

ii. Experimental test campaing using the defined procedure. This experimental results will be then used to:

   a. Determine the effect of the manufacturing process (simplified to roughness effect) on the fatigue acting at a bearing bolt hole.

   b. Validate the probabilistic fatigue apporach developed in WP2 (T2.2)

   c. Perform a size effect evaluation, from SN specimen to an intermediate specimen, to make another step and predict the real component in WP4.

During the experimental campaign, the greatest deviation was due to the fracture of the fixing tools (3 months of extension of the deadline). A new configuration had to be defined to solve this problem. Finally, the new fixing system has been used without any problem.

1. Introduction

The society is demanding products with better properties to the industry, being one of the main goals of the near future to reduce our carbon footprint with more environmentally friendly products with an affordable economical cost. To this aim, factories need to certificate products with improved mechanical properties to get more durable, lighter and in fact, better components, with less energy consumption and waste in their manufacturing stage. In this sense, the analysis of failure due to fatigue damage is key to determine the service life of structures and componens subjected to variable loading over time.

Generally, fatigue design criteria are used to define the material properties, dimensions and manufacturing methods of such components. Hence, accurate fatigue estimation methodologies can lead to optimized products, while ensuring fatigue strenth, which clearly represents a matter of interest for the industy. It is necessary to act both on (i) design of new wind turbines and on (ii) extending life of already installed ones.

(i) The current market trend is to develop bigger and more powerful wind turbines with a longer lifetime. To deal with bigger and more reliable wind turbines, there is a need for increasing larger and more expensive test benches. This process implies several relevant disadvantages in terms of testing time, cost, and energy consumption. The development of new concepts and technologies that help on the certification process is hence of utmost importance.
(ii) Installed wind farms are reaching its expected lifetime in the next decade. The possibility of extending the lifetime would be a profitable solution instead of dismantling them.

The simplified tests performed in this task and the data obtained will be used to analyze the RSF in the CS1, for a 20 MW pitch bearing (for evaluating bigger wind turbine designs) and to evaluate the reparation/stiffening solution for the CS3 (extending life of already installed wind turbines). The virtual modes developed in WP2 (T2.2 and T2.4) are used to define and validate the testing campaign, verifying also that the testing procedure is representative of the real failure mode.

First, a simple experimental testing concept is created by means of simulations. Secondly, the new concept is developed until a real testing configuration is fully defined: test and specimen type and measuring techniques. Thirdly the test bench is designed into detail and constructed. Lastly, a vast experimental camping is performed focusing on two effects variable: (i) Manufacturing (roughness) and (ii) Size effect.

1.1. Ring Structural fatigue failure

Pitch bearings are critical components of wind turbines that permit the rotation of the blade with respect to its axis to maximize the power taken from the changing wind. The inner ring, normally attached to the blade, is subjected to a tilting moment that varies in magnitude and direction with wind loads and blade position. The loads are transmitted by the rolling elements through angular contact from the inner to the outer ring that is attached to the hub by bolts, generating important hoop (circumferential) stresses. Under such solicitations, a critical point appears in the outer edge of the holes drilled for mounting the bolts, which is subjected mainly to stress ratios between 0.1 and 0.6 according to a rainflow analysis conducted on realistic stress spectra.

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It is well established that fatigue failure generated by cyclic alternating stresses is commonly divided in three stages: (i) crack initiation, where a crack arises from internal or superficial defects, (ii) crack propagation, where a macro scale (1-2mm) crack propagates until (iii) final fracture of the component is given.

Previous works carried out at IKERLAN have simplified the real component to an open-hole test specimen that was argued to have similar loading conditions and material when compared to the real component. Nevertheless, these simplified tests only have been used to develop and validate crack propagation models (only stage ii) that only represent a small part of the whole RSF failure lifetime. Therefore, a complete analysis of the evolution of the failure is still needed, from the initiation stage until final fracture, what will be performed by this task.

1.2. The need of a simplified test procedure

RSF predictions methods, as common fatigue methods in industry, are based on conservative guidelines and approaches that are supported by years of safe design experiences. Currently, industry is demanding, always within safety, reducing such conservativism to get closer to optimal designs, reducing costs and environmental impact of their products. In this context, fatigue, and more specifically, manufacturing and size effects on fatigue behavior need to be re-assessed to get more accurate and reliable fatigue failure prediction methods. However, these developments, need necessarily experimental validation, something unaffordable by real scale test benches that are developing currently.

RSF predictions to date, are based SN curves, whose obtention is based on standard characterization techniques were a small scale and turned (Figure 1. Left) samples are tested to rupture at different load levels. Such curves, that relate the stress level to number of cycles to rupture of the specimen are then used to predict real components with a great number of conservative assumptions that try to represent relevant changes between both scales that include:

- Geometric and size
- Manufacturing process, from turning specimens to drilling of bearing bolt holes
- Loads and stress components acting, from constant to variable amplitude and stress ratio

Based on the relevant differences detected between both scales, it is evident that defining an intermediate scale test and testing procedure is mandatory in order to define, study and assess such big changes by affordable extensive test campaigns in controlled environments.

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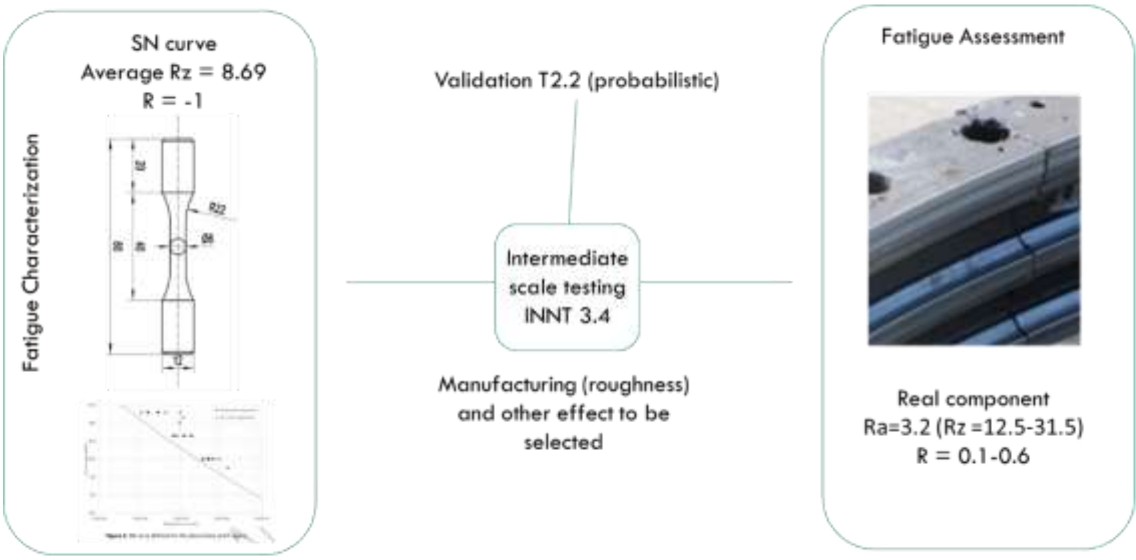

Figure 1 RSF characterization vs. prediction conditions.

2. Simplified test method definition

Test procedure aims to reproduce at lab conditions the Ring Structural Failure of a pitch bearing. Aiming to achieve realistic approximation to the failure mode given in real scale the following requirements are imposed to the testing procedure:

(i) The specimen needs to represent similar wide-to-height ratio of the real component. Thus, a close-to-square cross section is expected, and flat (plate wise) specimens will not be considered.

(ii) RSF will be achieved in a bolt hole, the hole will have dimensions corresponding to the bolt holes defined for CS1, where M36 bolts require Ø 39mm through thickness holes.

(iii) The test will be able to reach, at least, an 800MPa maximum principal stress range with test loading capacity.

(iv) Different bolt hole manufacturing conditions need to be represented

1.3. Test bench selection

The testing procedure to be developed must ensure that, with the maximum load applicable at IKERLAN test machines, a hole (simulating the real hole and its manufacturing conditions) is loaded to a range of stresses that can be enough to achieve its failure by fatigue in different conditions. For this purpose, two test benches can be used in IKERLAN. The characteristics of each test type have been listed in the next table:

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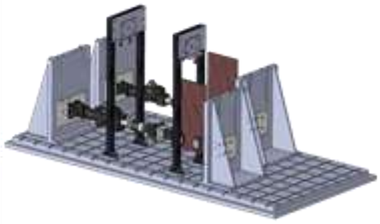
Table 1: Comparison between two test benches

	Servo machine	Hydraulic test bench
Image		
Specimen type	Only flat specimens	Any
Maximum load	150kN	150kN
Tools	Available for flat specimens but only up to 50kN	To be developed
Test frequency	Max. 20Hz (highly specimen dependant)	10-15 Hz
Test control & monitoring	Control in load, displacement and strain if needed	Control in load, displacement control must consider tool compliance

Load and specimen shape limitations of servo-hydraulic testing machine make it less suitable for this testing campaign. Frequency and control boundaries of the hydraulic test bench are not limiting in this case: load control is required and a frequency reduction, if given for the selected specimen, can be overcome by enlarging testing time or increasing test load. The main drawback of using the hydraulic test bench is the need to define and construct tools to lock the specimen. However, it is considered more suitable than the servo machine to avoid flat specimens that wouldn't represent the bearing ring for two main reasons: (i) bearing ring is as tall as wide and (ii) drilling thin plates can result in significantly different surfaces.

1.4. Initial specimen and clamping system definition

In accordance with the design pre-requisites defined in 2, specimens must fulfil at least three important requisites: (i) represent geometrically the outer ring of the bearing being at least as wide as tall, (ii) RSF must start from a bolt hole that could have different manufacturing conditions and (iii) RSF life must represent principally the initiation of a crack more than in its propagation.

Specimen definition was performed in three steps: First, the section (involving the height, wide and bolt hole diameter) of the specimen was defined by analytical expressions. Second, a FE model of the specimen was used to determine the gage length for that section. And finally, a FE study of the specimen and looking for tools was performed to guaranty that (i) the specimen will fail by the bolt hole and (ii) that the tools were able to support such intensive fatigue loads.

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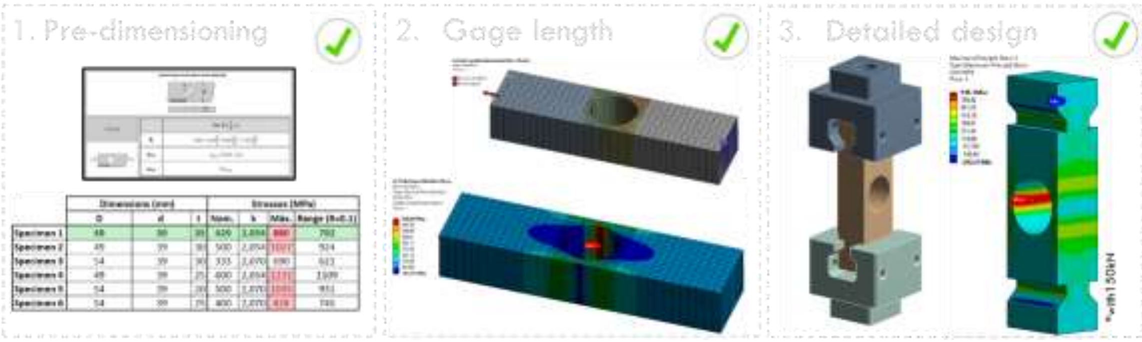
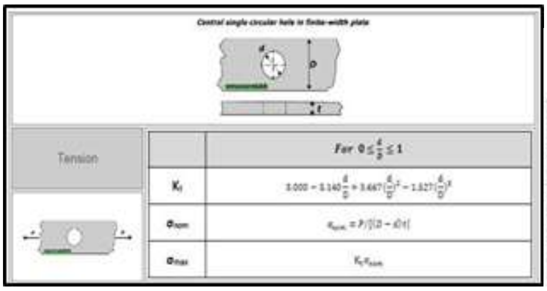


Figure 2: Specimen and tooling definition process

The detail of each step can be is explained below:

1. Pre-dimensioning based on analytical expressions: By means of analytical formulation, the remote stress and the maximum stress achieved over a M36 hole have been obtained for a load of 150kN (maximum load applicable at the hydraulic test bench) and for different specimen heights (t) and widths (D). Based on the results (Figure 3), the dimensions of specimen 1 were selected. They will be the basis to a detailed design of the specimen that must consider the design of the tools and finite element analysis to guaranty that the highest stresses are produced in the hole.



	Dimensions (mm)			Stresses (MPa)			
	D	d	t	Nom.	k	Máx.	Range (R=0.1)
Specimen 1	46	36	40	375	2.057	771	694
Specimen 2	46	36	35	429	2.057	881	793
Specimen 3	50	36	30	357	2.070	739	665
Specimen 4	50	36	25	429	2.070	887	799
Specimen 5	55	36	20	395	2.088	824	742
Specimen 6	55	36	25	316	2.088	659	593

Figure 3. Analytical expressions used and results of specimen pre-dimensioning (in red stresses over 800 MPa).

2. Finite element model to establish the gage length:

A parametric model, where gage length was the main variable, was carried out and solved for different gauge lengths. This study leaded to the conclusion that at least an 80 mm gage length was required to avoid the clamping stresses affect the stress distribution over the hole where RSF may be generated.

3. Finite element model to ensure reliability of the tooling system

After defining specimen section and gage length the way the specimen is going to be clamped to the test bench was conceptually developed and validated by a Finite Element model. Validation was achieved ensuring two conditions: (i) that the highest maximum principal stresses over the specimen, when loaded, are given in the hole, to ensure that specimen will fail at that location. (ii) that the highest maximum principal stresses over the tools area 20% lower than those obtained for the specimen. This way and considered that tools will be constructed with higher quality steel than specimens, tool lifetime will be ensured.

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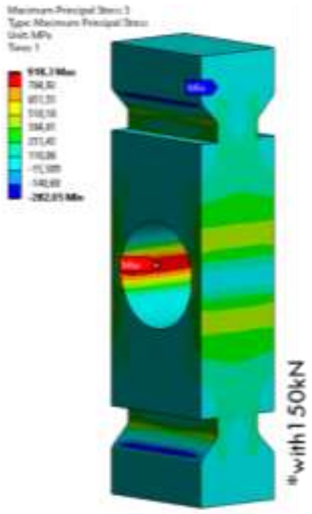

Figure 4 Specimen FEM calculation results considering tools.

Following drawing describes the final specimen geometry to fulfill all the criteria mentioned in this section and the initial clamping system:

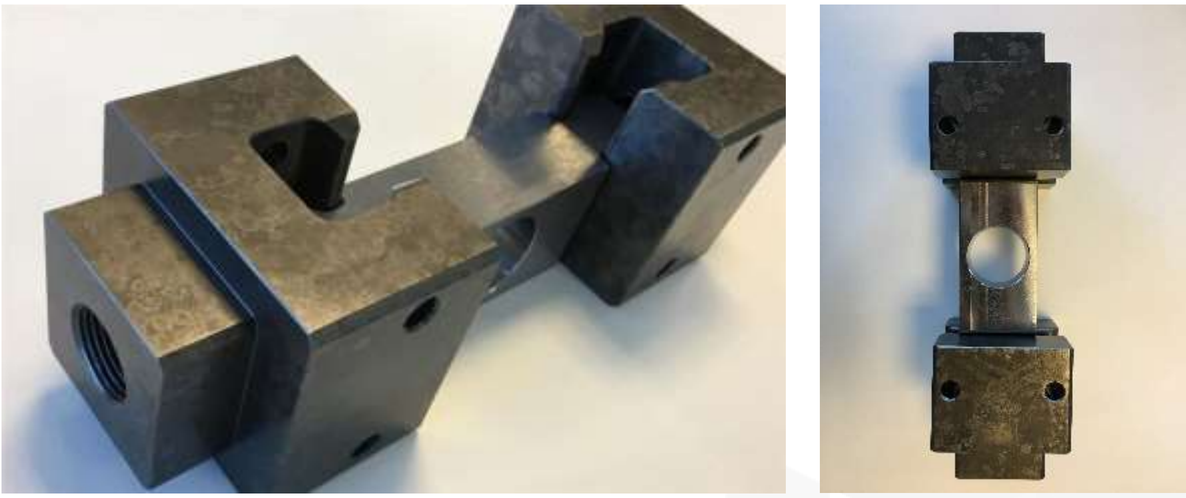

Figure 5: Initial clamping tools and dummy specimen for the testing set up

1.5. Initial trials, unexpected results and time deviations

At a first stage, the design of the specimen and the clamping tool was subjected to some trials to ensure the correct behavior of the system. For that purpose, dummy specimens with the same steel composition, but obtained from a real bearing were manufactured and tested. First trials were satisfactory in terms of control and measurement of the test bench, however first fatigue test finished with unexpected results:

- Fracture of the specimens was expected at 100000 cycles and at 800000 cycles no fracture was found.
- The test stopped due to fixing tool fracture (figure below)

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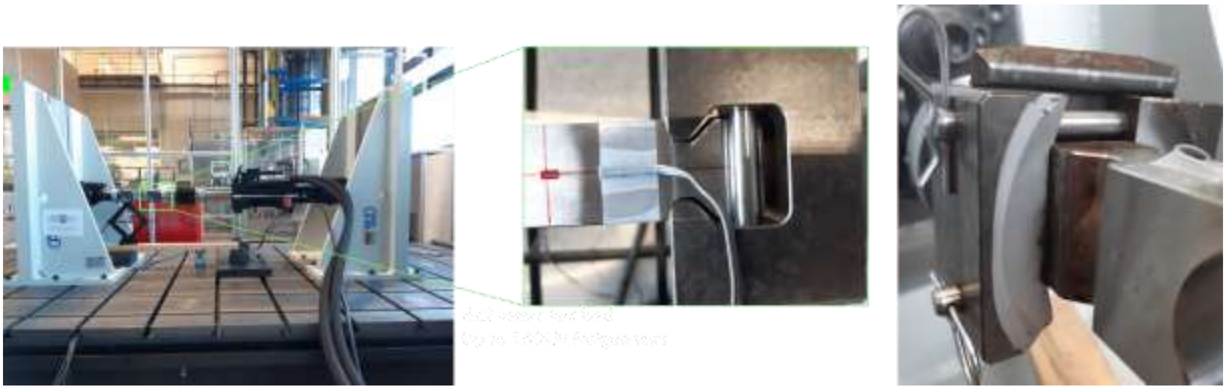

Figure 6: Fixing tool fracture on initial test

The challengue at this point came from overcoming this unexpected results without changing the geometry of the specimens, because due to their delivery times, their manufacturing was already launched before performing this first trials. Two actions were performed at this point to overcome these uneven results:

a. Changing the stress ratio of the tests: Testing loads were changed from being only tractive as in the real component (R=0.1) to traction-compression tests as in SN characterization (R=-1). This decission allows performing higher stress range without yielding locally the specimen and also avoids the need of mean stress correction formulas that could introduce uncertainities in the lifetime predictions of the specimens.

b. Defining a new fixing tool:
The initial test tool, by its desing concept, was not able to perform compresion and in terms of reliablity was proven unreliable to perform all the test planned. A new fixing tool was desinged based on mechanical fixture by a bolting system.

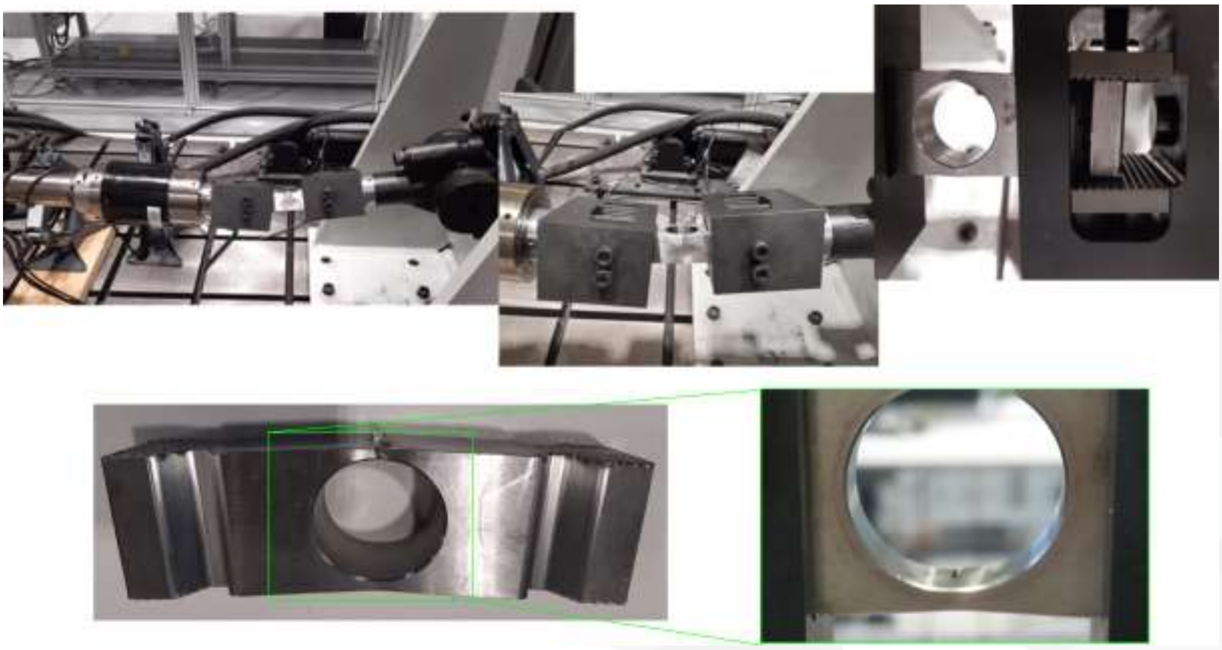

Figure 7: New fixing tool and bending affected failure of the specimen

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After those two actions, an incorrect (bending induced) a second trial was conducted with the new test and fixture configuration leading to an incorrect failure of the specimen. A deeper study showed that this failure was related to the weight the hydraulic actuator, and its misalingnig effect when changing from tractive to compressive loads during a loading cycle, something that was happening in previous test configuration. The accumulative misalingnement introduced lead to an unpredicted bending over the specimen, forcing an undesirable failure of the specimen (Figure above). This effect was neglected hanging the hydraulic actuator, achieving finally a non-bending induced specimen fracture. However, all this unexpected actions impacted to the initial planification and the final deliverable time of the task.

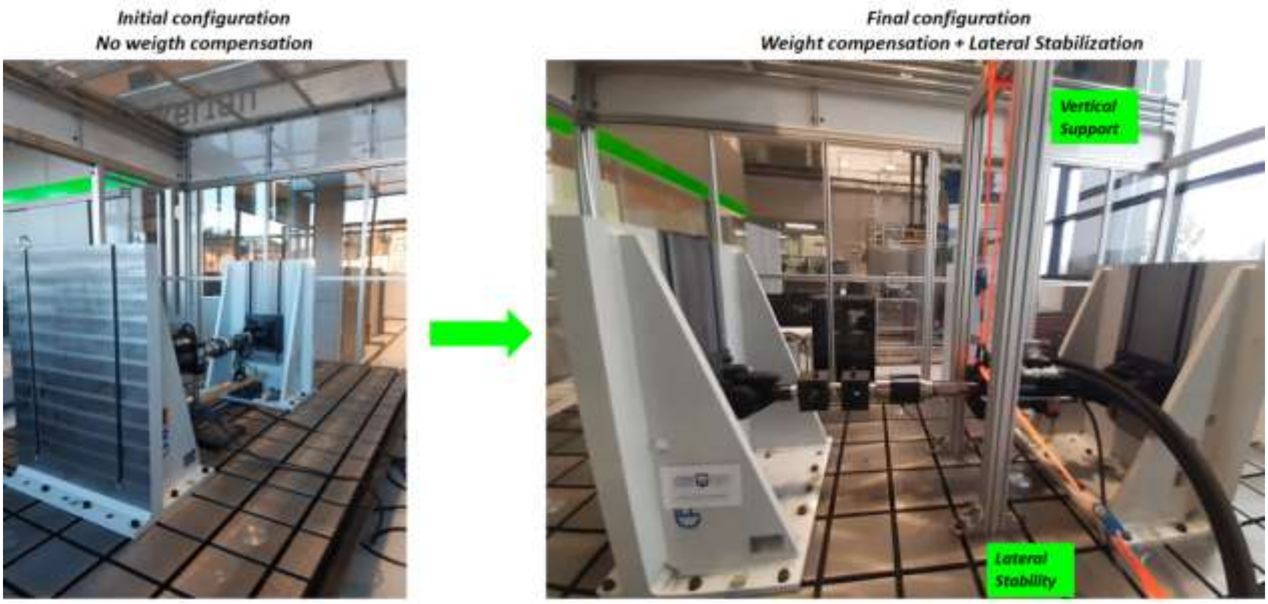

Figure 8: Testing system before and after hanging the hydraulic actuator.

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3. Developed testing procedure

1.1. Test bench set up

The experimental set up is composed by a load application system which consists of a hydraulic cylinder with a maximum load capacity of 150 kN. The components of the experimental set up are shown in **¡Error! No se encuentra el origen de la referencia.** and are explained hereafter.

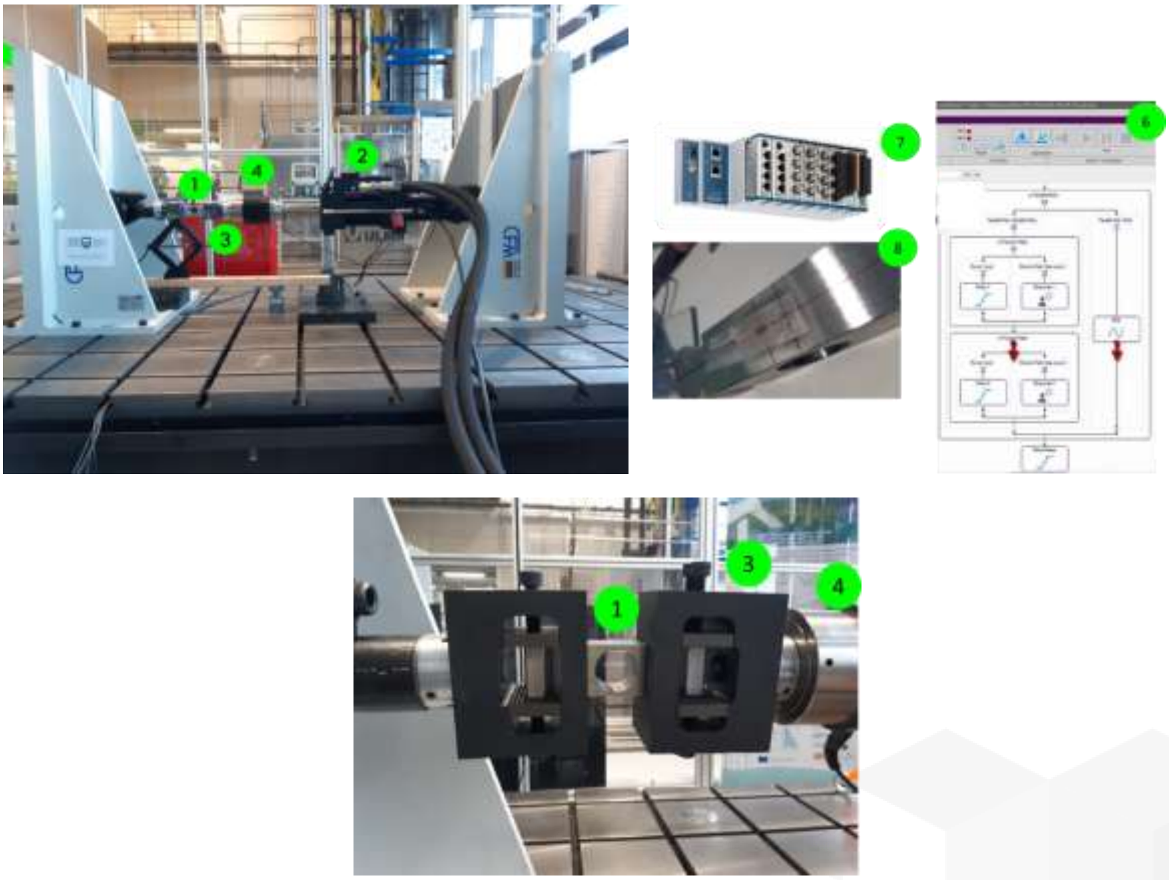

Figure 9 Test bench set up

1. <u>Test specimen (1)</u>: a 42CrMo4 steel open hole piece extracted directly from a real pitch bearing.

2. <u>Load application system (2):</u> Hydraulic cylinder with a load capacity of 150 kN and 150 mm stroke.

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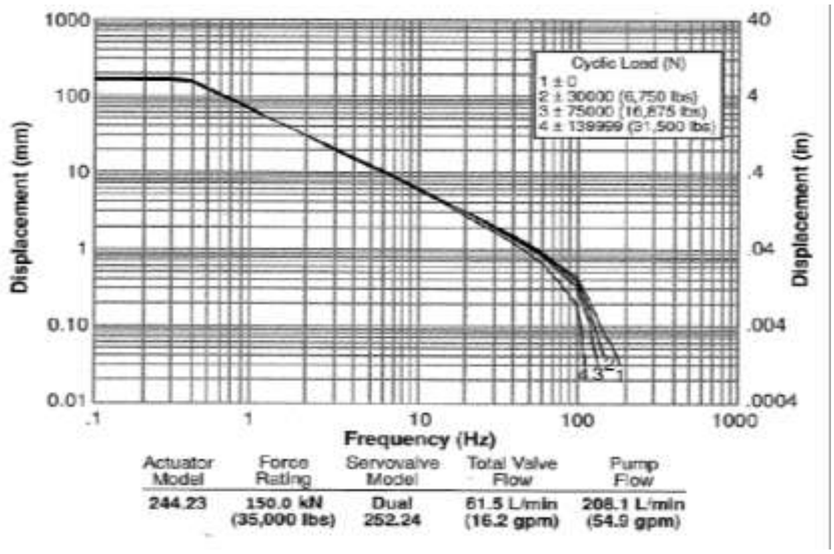

Figure 10 Load application system displacement-frequency relationship

The diagram above shows the displacement-frequency relationship of the LAS. The frequency range of the test is kept below 3 Hz to avoid any dynamic effect that could affect the results.

3. Fixing fixtures (3): Steel clamping system able to transmit the force generated by the LAS to the tested specimen.

4. Load cell (4): 150 kN force transducer able to measure the load produced by the hydraulic cylinder. The test is commanded by load input. Load cell allows the controller to continuously measure the input load of the cylinder.

5. Control and monitoring system (5): Laptop with MTE software is used to monitor the input and output signal recorded by the load cell and the LVDT.

6. Acquisition system (6): a National Instruments (NI9237) acquisition system is connected to the strain gauge (7) for data acquisition.

7. Strain gauge (7): For the first specimen strain gauges were allocated to calibrate the test campaign and to take into consideration the secondary bending moments introduced to the specimen. See Section 1.2 for further information.

1.2. Test calibration

First specimens were subjected to an initial calibration to ensure that no bending effects are introduced and validate the FE model that is used to perform the force to stress conversion. This procedure consisted of carrying out different clamping and loading and unloading cycles to strains gauged specimens. Strain gauge locations were selected based on the FE model, (Figure below) symmetrically both in the top and bottom part of the specimen. Allocating several strain gauges allowed to correlate the force and the strains of the FE model, validating it, but also confirming that the secondary bending moments due to the alignment of the test bench were negligible.

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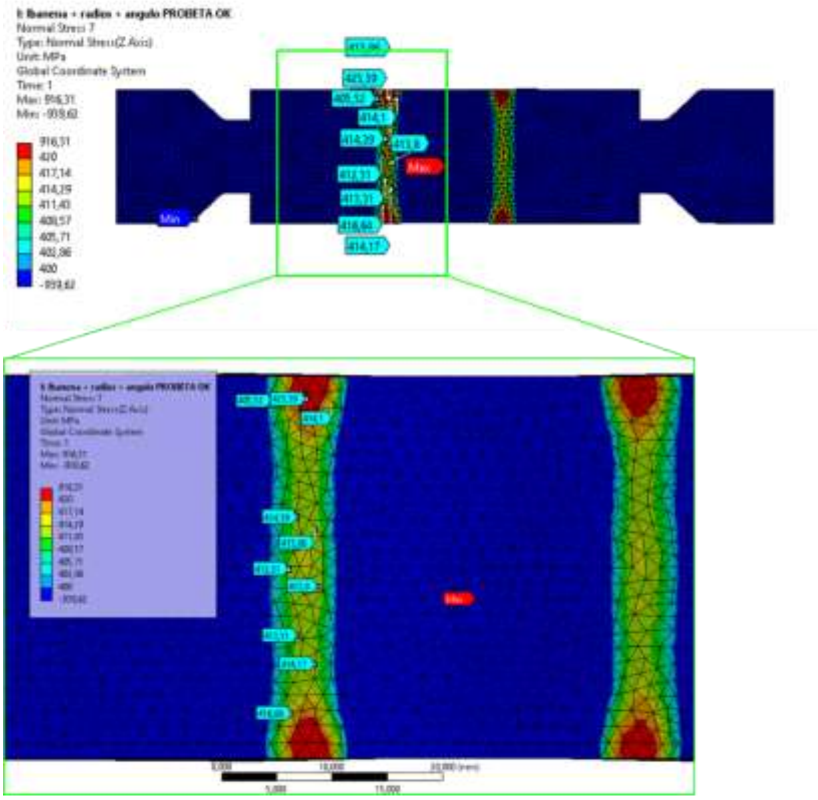

Figure 11 Strain gauge location extracted from FEM

1.3. Measurement process for each specimen

The traceability of each specimen and test is ensured by marking the specimen at first instance while their relevant characteristics are measured:

(i) Geometrical dimensions
- ✓ Height
- ✓ Thickness
- ✓ Bolt hole diameter

(ii) Roughness

Roughness of the specimen is measured in four points inside the bolt hole. 3 repetitions of each location are performed.

1.4. Load level definition

Load level definition was based on the experimental SN curve obtained from the characterization process (these tests are not defined in the INNTERESTING project). For the first test, a stress range objective was defined, being a stress range that achieved a SN test fracture for 10000 cycles. This way, not considered roughness and size effects, would lead to assumable variations in lifetime to fracture and affordable test times. Test control, however, is not commanded by stress range but by load range, so this stress range objective was transformed to load range command via the FE model constructed before.

After this procedure, an initial load level of +/-80 kN was defined for the first test. After first test results, where it was confirmed that good lifetime predictions were made at this load level, load

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was reduced for each test by increments of 2.5 kN to achieve fracture points at higher number of cycles that will be more representative of real bearing fracture.

1.5. Testing procedure

In this section, the steps to be followed to perform every new test are described, additionally an internal document collecting the test bench mounting process to achieve this test configuration was also written for further tests:

1. Identify and prepare the specimen
    a. Geometrical measurement
    b. Roughness measurement

2. Assemble the specimen
    a. Insert a new test specimen
    b. Align the system
    c. Clamp the specimen with the fixing fixture
    d. Turn the actuator on
    e. Ensure the correct preload of the spiral washers

Figure 12 Assembly – Specimen in position –

3. Setup the test:
    a. Close the testing space
    b. Open MPE and set the program with the desired load level (See Concluding remarks

The main conclusions derived from this work are listed below:

- The RSF failure mode of a pitch bearing can be reproduced at lab scale, which will allow a deeper understanding on this failure mode and the variables/physical mechanisms acting on it.

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- The testing procedure developed in this task can be used to perform fast and low-cost experimental campaigns to understand this failure mode and act as intermediate scale between characterization and prediction scales.
- Some experimental aspects as test configuration, clamping conditions actuator position that seem trivial at first time require deeper study when specific failure modes need to be represented.
- Roughness effect is relevant over the component RSF lifetime, demonstrating that the manufacturing process change is relevant when changing from a SN characterization test to a real component prediction.
- A procedure to replicate real manufacturing processes and other effects that may impact on RSF as preload or corrosions is ready to use after this task.

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c. Annex II)
d. Start acquisition system
e. Start the test
f. The test will be provided with limits to end automatically
    i. If load level is exceeded (+ 10% of the commanded load) → Not probable
    ii. If displacement limit is exceeded (± 4 mm) → Fracture
    iii. If 5E06 cycles are reached → Run out

4. Experimental campaign and results

After defining the test and testing procedure an extensive testing campaign was performed to demonstrate that, with the developed testing procedure, it is possible to reproduce the RSF failure mode with reasonable time and cost expenses and under controlled lab conditions. Unfortunately, the unexpected problems during the test procedure definition delayed the deadlines and reduced the usage availability of the test bench for this project, reducing initial test campaign from three (24 specimens) to two (16 specimens) bolt hole manufacturing processes.

Tests performed were manufactured under two different methods, for that the specimen provider was asked to achieve two different roughnesses representing (i) the roughness of a SN specimen (Rz=8) and (ii) the roughness of a real bolt hole (Rz=12 to 32). However, those initial requirements were not fulfilled by the provider, who delivered different roughnesses but not according to those values. First 7 specimens present a roughness close to Rz= 8 µm, which could be considered similar to that obtained for SN specimens, the next 9 specimens present lower roughnesses (Rz=4), that at least could be used to determine a law to correct roughness variations within different scales. That law should be then extrapolated from the results obtained to the real manufacturing process of the pitch bearing (Rz= 12 – 22) in next upscaling tasks.

In this sense, replicating the real manufacturing processes given in a real bearing, and not considered effects of bolt preload, corrosion, coatings will be an interesting topic to work in future research and industrial projects once the testing procedure is closed.

Results for the test specimens tested can be seen in the tables and figures below. Results show how roughness effect is relevant over the component lifetime, demonstrating that the manufacturing process change is relevant when changing from a SN characterization test to a real component prediction.

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Table 2 Results for the experimental campaign roughness 1 (Rz= 4 µm)

Test	Specimen	Roughness	Min Load [kN]	Max Load [kN]	Stress Range	Frequency
1	1	7.42	-80.00	80.00	938.92	2.00
2	2	4.09	-77.50	77.50	909.58	2.50
3	3	5.91	-75.00	75.00	880.24	1,5
4	4	4.47	-72.50	72.50	850.90	1.50
5	5	2.48	-70.00	70.00	821.56	2.50
6	6	6.25	-67.50	67.50	792.22	2.50
7	7	6.92	-77.50	77.50	909.58	2.50
8	8	2.76	-65.00	65.00	762.87	2.50
9	9	3.08	-62.50	62.50	733.53	2.50

Table 3 Results for the experimental campaign roughness 2 (Rz= 8 µm)

Test	Specimen	Roughness	Min Load [kN]	Max Load [kN]	Stress Range	Frequency
1	1	7.87	-77.50	77.50	909.58	2.50
2	2	8.42	-75.00	75.00	880.24	1,5
3	3	10.26	-72.50	72.50	850.90	1.50
4	4	7.88	-70.00	70.00	821.56	2.50
5	5	8.26	-67.50	67.50	792.22	2.50
6	6	6.92	-65.00	65.00	762.87	2.50
7	7	7.99	-65.00	65.00	762.87	2.50

- The resulting Number of cycles are confidential

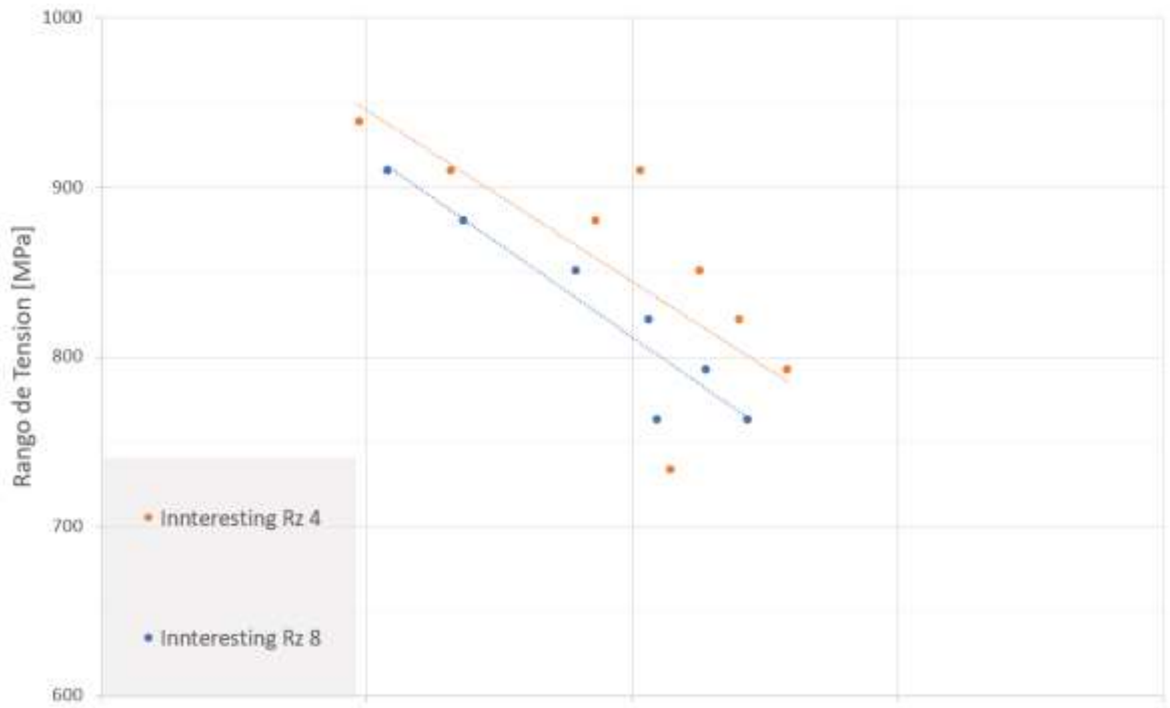

Figure 13 Experimental campaign results for both roughness values.

The specimen crack propagation can be seen in one of the sides of the open hole. Once the crack propagates the rest of the section is weak enough to withstand the load transmitted by the LAS and it breaks suddenly.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851245.

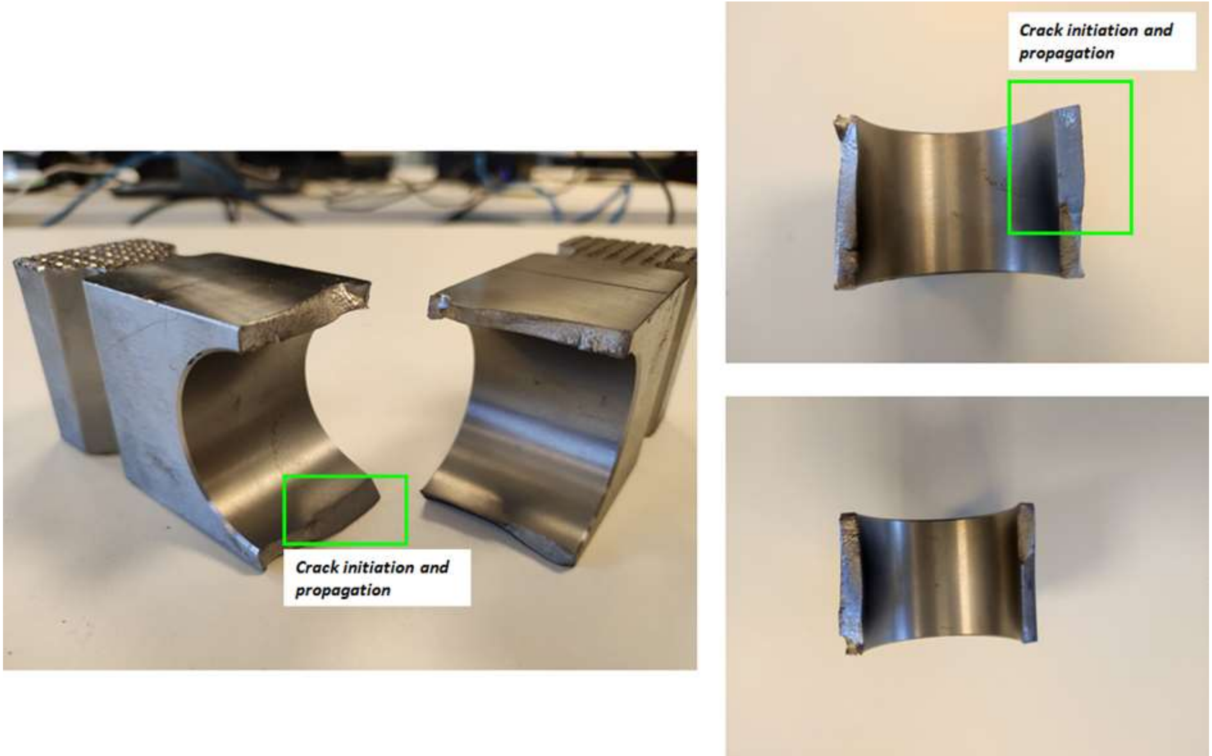

Figure 14 Specimen fracture

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851245.

5. Concluding remarks

The main conclusions derived from this work are listed below:

- The RSF failure mode of a pitch bearing can be reproduced at lab scale, which will allow a deeper understanding on this failure mode and the variables/physical mechanisms acting on it.
- The testing procedure developed in this task can be used to perform fast and low-cost experimental campaigns to understand this failure mode and act as intermediate scale between characterization and prediction scales.
- Some experimental aspects as test configuration, clamping conditions actuator position that seem trivial at first time require deeper study when specific failure modes need to be represented.
- Roughness effect is relevant over the component RSF lifetime, demonstrating that the manufacturing process change is relevant when changing from a SN characterization test to a real component prediction.
- A procedure to replicate real manufacturing processes and other effects that may impact on RSF as preload or corrosions is ready to use after this task.

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Annex II. Testing procedure on test bench

This Annex presents the MPE procedure developed for the test campaign. The flow is composed of (1) 10 kN ramp to get the alignment of the system and remove any clearance that may exist in the system and (2) Sine tapered function with data acquisition tuned to the test load level.

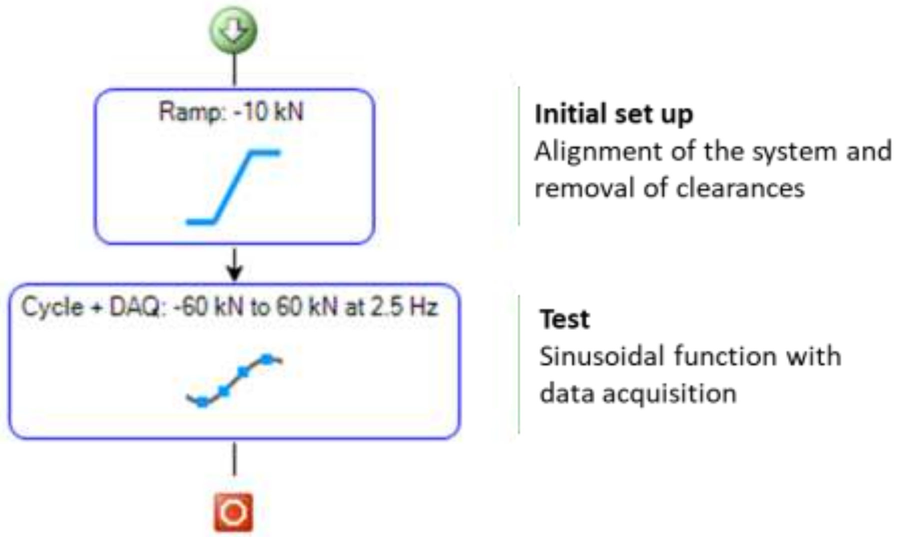

Figure 15 Test procedure

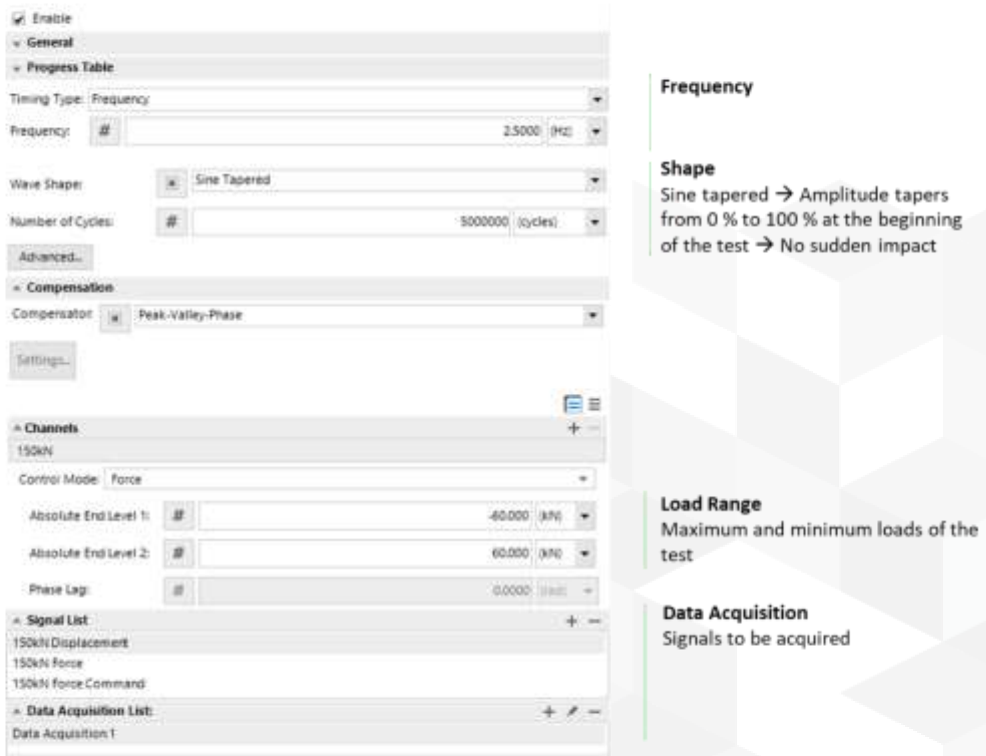

Figure 16 Test definition

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851245.

Annex III. Specimen geometry

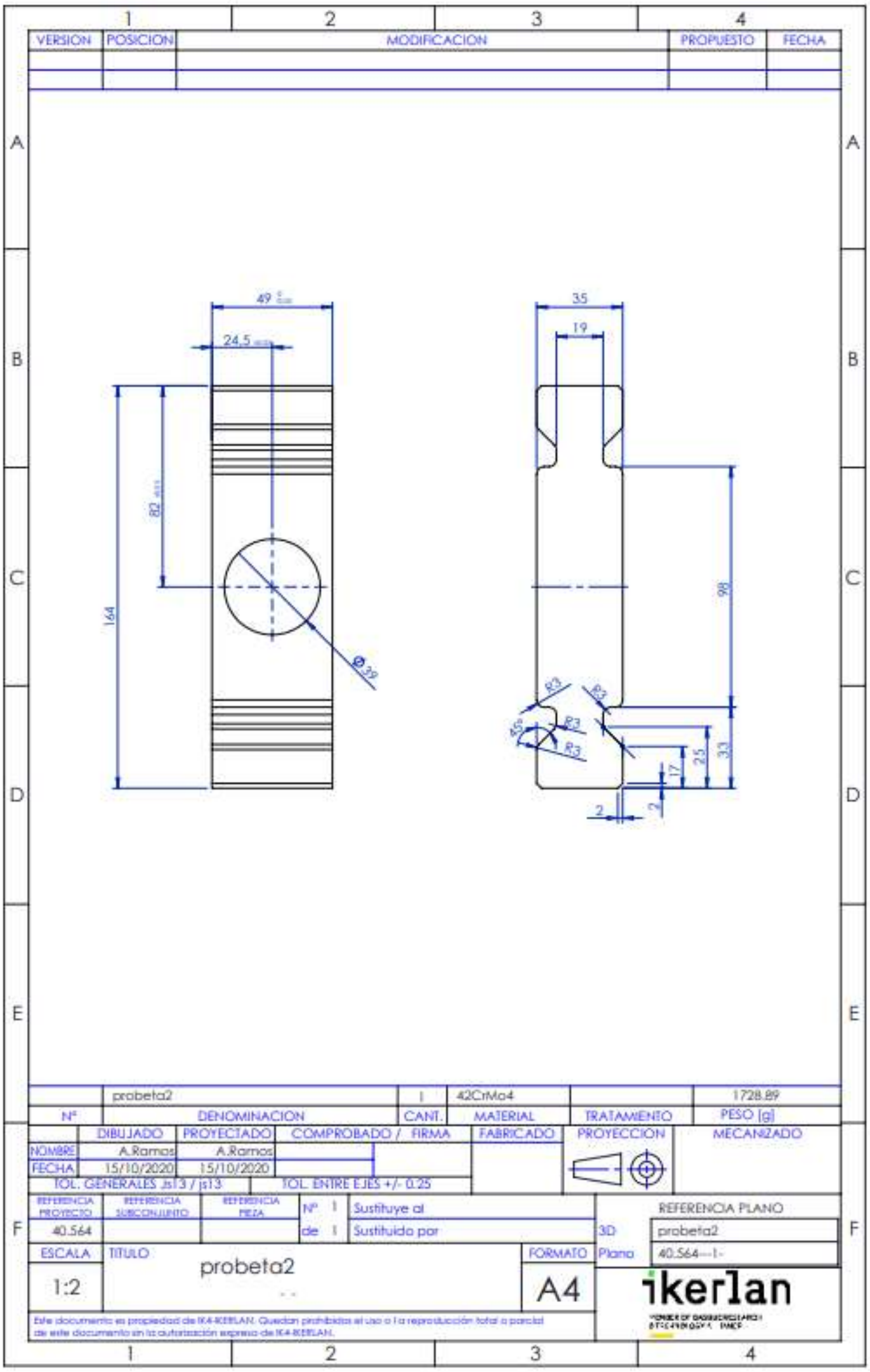

Figure 17 Specimen definition – Manufacturing drawing -

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