Final report

1. Project details

Project title	EUDP 2020-I Demonstration of Future Nacelle Test Bench Foundation
File no.	64020-1098
Name of the funding scheme	EUDP
Project managing company / institution	R&D Test Systems A/S
CVR number (central business register)	37844179
Project partners	Aarhus University
Submission date	3rd February 2023

2. Introduction

Renewable energy is key to a fossil fuel free future. The renewable energy sector is continuously growing, and the energy crisis we are currently experiencing is pushing the need for a renewable energy transition. One of the key elements in this transition is the development and production of wind turbines. In order to reduce the levelized cost of energy (LCoE) the development of wind turbine leads to larger wind turbines, see Figure 1-1, increasing the power per unit in offshore wind turbines.

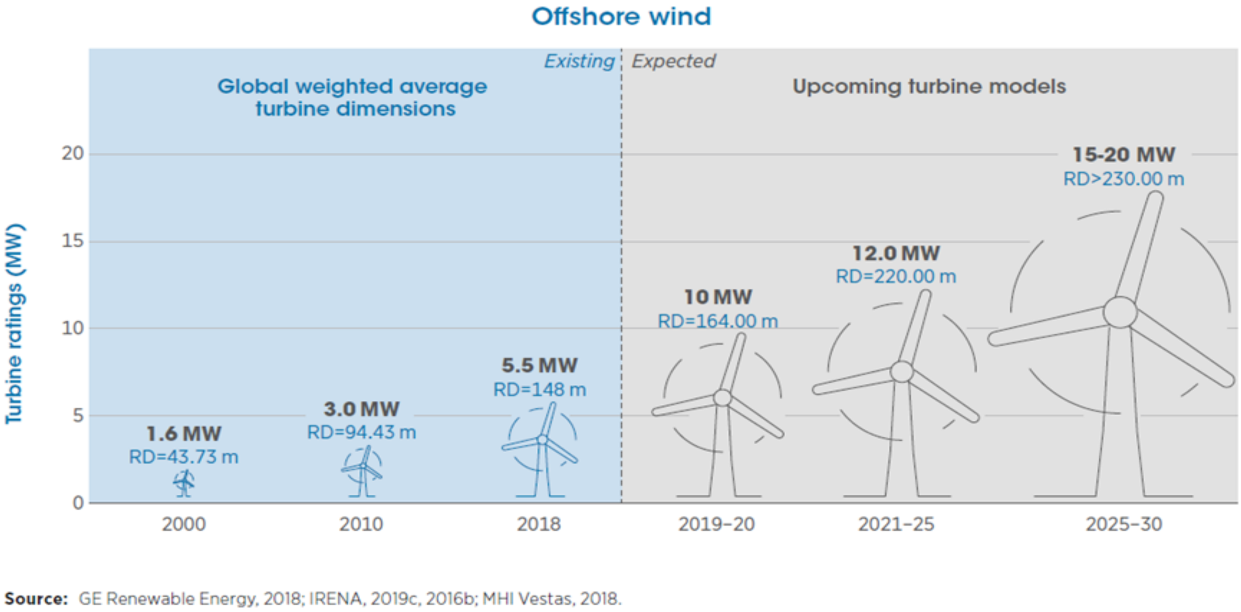

Figure 1-1 Previous and future wind turbines.

The design, performance and safety of a wind turbine is tested before entering full production and service. Testing wind turbine drive trains, sub-systems and main components under realistic conditions are necessary elements of evaluation and optimization of established and future turbine concepts. In addition to full-scale blade testing, the test of a complete wind turbine nacelle (drive train) is one of the most critical in the validation scheme for a new wind turbine. A full-scale test of a nacelle requires a test bench capable of replicating both the drive torque (from the rotation of the blades) and the appertaining wind loads from the fluctuating wind pressure on the blades. Successful testing and demonstration of nacelle design and concepts help shorten innovation time and secure development activities. The increased power per unit results in high requirements to the wind turbine test facilities, which over the recent years has become a more and more significant and essential part of the wind turbine development.

During this project execution R&D Test Systems has designed and built the wind industry's largest and most advanced test bench. The global wind industry will test the future generations of wind turbines on a test bench such as this.

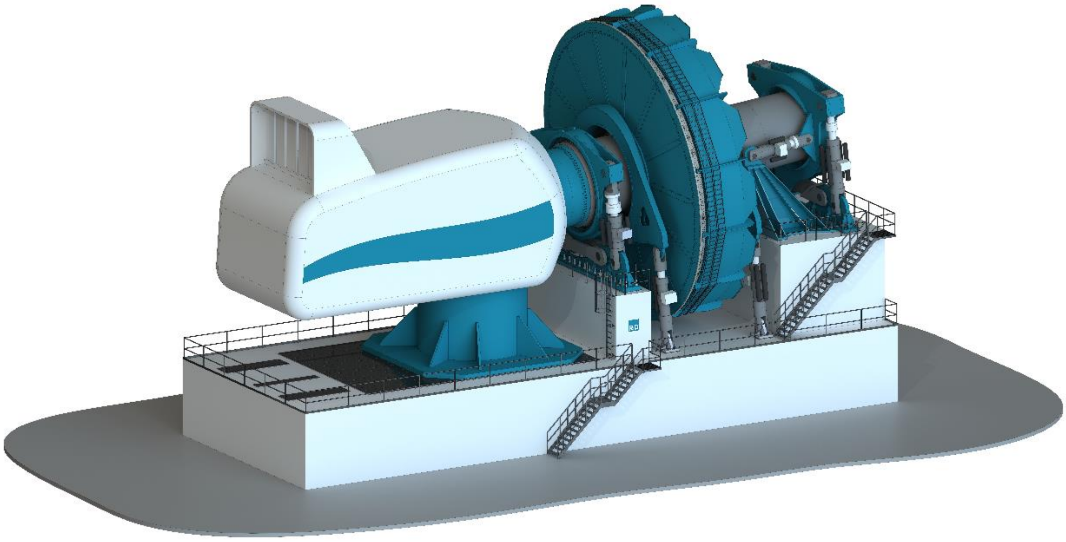

Figure 1-2: The wind industry's largest and most advanced test bench built by R&D Test Systems

One of the most important test scenarios for demonstration and validation of a new wind turbine is "Highly Accelerated Life Test" (HALT), in which the nacelle is put into extreme static and dynamic load conditions. One of the key-components in this test setup is the test bench foundation – a large concrete structure, supporting and encapsulating test loads from the test bench machine components. Enormous forces are transferred from the nacelle test device to the test bench foundation support structure. Looking at the current 8-12 MW offshore wind turbine test benches, they are reaching a physical limit in terms of encapsulating the required test loads in the current commercial test bench foundation concept. This induces a risk that the development and production of future large wind turbines will not be possible. If the test bench foundation structure cannot support the enormous test loads, the test loads must be reduced (not testing at maximum load), which will affect the overall validation of future wind turbines.

2.1 Executive summary (English)

The focus of the project has been to develop, design and demonstrate a foundation solution for use in testing large wind turbines of the future. This is based on R&D Test Systems many years of experience within the development and suppling turn-key test systems for the wind industry and Aarhus University's technological knowledge in concrete design. New methods and concepts for encapsulating the gigantic loads in the foundation structure have been introduced and demonstrated. The execution of this EUDP-project has improved the foundation design methods and provided further understanding of stress behavior and progression in large reinforced concrete structures. The possibility of introducing cavities in the otherwise massive concrete foundation structure has been investigated and analyzed in a FE-model. This enables to integrate some of the test bench auxiliary equipment in the foundation structure. Also, specific sub-systems in the test bench foundation have been developed, tested, and demonstrated, including the anchoring system, the mechanical transitions to the foundation and integration of a concrete post-tensioning system.

The development and demonstration of a future nacelle test bench foundation for 25MW wind turbine drive trains have been conducted in a project group with participants from R&D Test Systems and Aarhus University. Together, the project group have had extensive knowledge both within the wind industry's requirements for test of wind turbines, the design of the overall test system, mechanics, and specifically knowledge on key areas within reinforced concrete design.

The purpose of the foundation structure is to ensure a proper fixation and retention of the large mechanical components that are part of a nacelle test setup. The mechanical components include the specific nacelle

being tested, the test bench drive motor that simulates the rotation/torque applied to the drive train main shaft from the blade hub, and a wind load unit applying forces and bending moments on the nacelle. As the wind turbines increases in size and power, the dynamic forces applied on the nacelle in a test scenario increases. Thus, it requires an exceptionally large and strong concrete structure to ensure that the mechanical components are retained during test execution. It is complex to accurately calculate and simulate the stress progression in these large concrete structures and the design criteria that form the basis of the design are often based on smaller structures. Also, the general knowledge of fatigue design for a concrete structure such as the test bench foundation is relative limited. Improving this understanding of the foundation dynamic behavior and performance leads to better prediction of the lifetime effect a specific test scenario will have on the test bench's foundation.

The project team has looked into the development of a digital damage counter combined with a structural health monitoring system integrated into the future foundation, which is able to log and monitor strain and deformation in concrete, reinforcement, and other key components in the foundation. The purpose of the monitoring system for the digital damage counter is that it collects the strain time history data to define the accumulated damage that occurred in the critical parts of the structure. This leads to defining the residual lifetime of the foundation. The digital damage counter can support the user of the test system to evaluate the remaining lifetime of the foundation during operation. In addition, the integrated structural health monitoring system provides valuable knowledge about stress progression in large reinforced concrete structures and scale effects in relation to the smaller structures that form the basis of the foundation design.

In general, the project is a success, and the project main objectives have been achieved – developing and demonstrating a foundation concept for future nacelle test systems.

2.2 Resumé (Dansk)

Projektets fokus har været at udvikle, designe og demonstrere en fundamentløsning til brug i test af fremtidens store vindmøller. Dette er baseret på R&D Test Systems mange års erfaring med udvikling og levering af testsystemer til vindindustrien samt Aarhus Universitets viden inden for betonteknologi og -design. Nye metoder og koncepter til at indkapsle de meget store belastninger i fundamentet er blevet introduceret og demonstreret. Gennemførelsen af dette EUDP-projekt har forbedret fundamentsdesignet og bidraget til yderligere forståelse af hvorledes spændingerne i store armerede betonkonstruktioner forløber og forplanter sig. Muligheden for at introducere hulrum i den ellers massive betonkonstruktion er blevet undersøgt og analyseret i en FE-model. Dette bl.a. med henblik på at kunne integrere nogle af testbænkens forsyningskomponenter i fundamentsstrukturen. Desuden er specifikke delsystemer i testbænkens fundament blevet udviklet, testet og demonstreret, herunder forankringssystemet, de mekaniske overgange til fundamentet og integration af et efterspændingssystem i betonen.

Udviklingen og demonstrationen af det fremtidige nacelle testbænkfundament til 25MW vindmøller er gennemført i en projektgruppe med deltagere fra R&D Test System og Aarhus Universitet. Tilsammen har projektgruppen besiddet stor viden inden for både vindindustriens krav til test af vindmøller, det overordnede testsystems layout, mekanik og specifik viden inden for design af armerede betonkonstruktioner.

Fundamentets formål er at sikre fiksering og fastholdelse af de store mekaniske komponenter som indgår i en nacelle test, herunder selve nacellen der testes, drivmotor der simulerer rotationen/rotationspåvirkningen fra vingenavet ind på hovedaksen og en vindlastenhed der påfører kræfter og bøjemomenter på nacellen. Idet møllerne bliver større og effekten pr. enhed øges, forøges de dynamiske kraftpåvirkning vindmøllen udsættes for. Det kræver således en meget stor og stærk betonstruktur, at sikre at de mekaniske komponenter fastholdes under test eksekvering. Det er komplekst nøjagtigt at beregne og simulere spændingsforløbet i disse store betonkonstruktioner og de designkriterier der danner grundlag for designet er ofte baseret på langt mindre betonkonstruktioner. Ligeledes er den generelle viden inden for en betonkonstruktion som testbænkfundamentet relativt begrænset. En uddybning af denne forståelse, af fundamentets dynamiske adfærd og ydeevne,

medfører bedre forudsigelse af levetidseffekten som ét specifikt testscenarie vil have på testbænkens fundament og samtidig optimere fundamentsdesignet.

Projektholdet har set ind i udviklingen af en skadetæller kombineret med et strukturelt monitoreringssystem integreret i fundamentet, som er i stand til at logge og overvåge spændinger og deformationer i beton, armering og andre nøglekomponenter i fundamentet. Skadetællerens formål er at indsamle spændingshistorik med henblik på at opsamle den akkumulerede skade, der opstår i de kritiske dele af strukturen. Dette medfører et overblik over fundamentets resterende levetid. Skadetælleren kan således hjælpe brugeren/kunden af testsystemet med at vurdere give mere indsigt i testanlæggets resterende levetid. Desuden giver det integrerede monitoreringssystem værdifuld viden om det aktuelle spændingsforløb i store betonkonstruktioner og skalaeffekter i forhold til de mindre konstruktioner der ligger til grund for designet af fundamentet.

Generelt er projektet gennemført med succes, og projektets mål er nået – at udvikle og demonstrere et fundament for fremtidige fuldskala nacelle testsystemer.

3. Project objectives

The project's primary objective has been to develop and demonstrate a test bench foundation for future nacelle testing and hereby ensure that R&D Test Systems keeps the position as a marked leader in the supply of large-scale test systems for the wind industry. The incentive of the project was to expand market potential for test facility business and lowering the Cost of Energy (LCoE) by facilitating current and future test needs of the wind industry.

This has been done by further developing R&D's current test bench foundations for wind turbine nacelle testing. The objective was to introduce and demonstrate new methods and concepts for incapsulating the large static and dynamic forces applied to the test bench foundation, improving the foundation design, and to obtain further understanding of the stress behaviour and distribution in large reinforced concrete structures. Furthermore, the objective was to develop, test and validate several specific sub-systems in the test bench foundation including the anchor system, vibration damping system, machine interface system etc.

Also, the project objective was to integrate a structural health monitoring system (SHM), being able to monitor strains in the foundation concrete and reinforcement steel. Based on the structural monitoring system the objective was to develop a damage counter system as an add-on product to the test bench turn-key solution. This is something that the costumers are requesting, and increased R&D Test Systems marked potential.

The project results are not only applicable to future nacelle test bench applications but also to other wind turbine test facilities such as blade testing and other test sub-systems.

3.1 Objectives from work packages

3.1.1 Work package 0: Project Management

The objective of WP0 was to ensure a successful execution of the project, with emphasis on achieving the work packages objectives, projected milestones and deliverables within the allocated timeframe and budget. Project management was handled by R&D Test Systems.

3.1.2 Work package 1: Requirement Specifications

The objective of work package 1 was to specify and concretize the general requirements for the future test bench foundation. During the work package test specifications were determined and scaled to cope with the requirements of testing and validating a future 25 MW wind turbine. The objective was to determine and describe the requirement in a requirement specification document, constituting the basis of the modelling, design, and validation for the modeling, design and validation of the future test bench foundation.

3.1.3 Work package 2: Modelling, Design, and Validation

The purpose of work package 2 was to develop and improve the design of the future test bench foundation that meets the requirement specification from WP1. The design concept has focused on improving the technical challenges of the current test bench foundation concept. The intended outcome of work package 2 was a complete design manual describing the future test bench foundation in detail, including sub-systems and focus areas in the construction work of the test bench foundation.

Also, the objective was to create a FE-model of the future test bench foundation for simulation, analysis, and validation of the foundation design.

3.1.4 Work package 3: Experiments on Sub-systems and 3D-modelling

In work package 3 and work package 4 the objective was to develop and test the foundation concept by means of a down-scaled demonstrator including the foundation sub-systems (vibration damping system, anchor system and post-tensioning system).

The intension was to utilize a test load unit developed and produced for a previous EUDP-project. According to the application for this project, the test load unit should have been used for the small-scale testing of the future foundation concept. Looking further into the specification of the test load unit it turned out, that the test load unit did not have sufficient load capacity and that the control system for the test load unit was not applicable with our intensions of demonstrating the future foundation concept. This meant, that the scaled model validation of the foundation concept could not be made small enough to give applicable and valid results as the small-scale demonstrator would not be size equivalent.

Therefore, instead of testing the concept on a small-scale demonstrator the scope of work package 3 was changed to validating the foundation sub-systems by individual experimental tests at Aarhus University laboratory. The objective was then to compare the test results with the design analysis done in work package 2.

Furthermore, the objective was changed to creating a 3D-model of the future foundation concept using a 3D-structure software, Tekla Structures, for animation of the concept. The objective was visualization of the new concept and making the structural challenges in the new design visible. This was to accommodate the conflicts which may occur in the new design concept between the necessary reinforcement layout, the anchor system and post-tensioning systems, with both permanent and replaceable anchor bolts, and all the other components in the foundations. Also, the purpose of creating the 3D-model was to visualize the upscaling of different components in future foundations with larger loads.

3.1.5 Work package 4: Monitoring System and Damage Counter

The current understanding of stress distribution in large reinforced concrete structures such as the future test bench foundation is limiting the possibilities of accurately predicting the fatigue damage to the foundation concrete, anchor system and reinforcement steel. Improving this understanding will led to better prediction on the residual lifetime a certain test case will have on the test bench foundation.

Thus, the project objective in work package 4 was to develop and incorporate a structural health monitoring system in the concrete foundation, capable of monitoring real time stress level in the concrete and reinforcement during a given test scenario. The objective was to investigate different monitoring equipment and systems available on the market, including pros and cons on the products. The best choice of monitoring system for the purpose of investigating dynamically loaded concrete structures has been investigated and a lot of research on the state-of-art market products has been made.

The foundation monitoring system can provide knowledge and insight to the actual condition of the test bench foundation components and monitor what is happening inside the large concrete mass during a given test scenario. This knowledge may also support the general understanding of other large-scale concrete structures subjected to high dynamic loading and thus be transferred to other large concrete structures such as other test bench foundation setups, generic wind turbine foundations, concrete bridges etc.

In addition, in work package 4 the objective was to conduct a foundation damage counter including a description of the design key elements. The purpose of the damage counter was to create a solution that can foresee the residual lifetime of the future test bench foundation, after the test bench has been in operation and the foundation structure has been exposed to dynamic loading. The analytical calculations and FE-simulations conducted in work package 2 are used to determine what foundation components are critical to monitor during operation, location of relevant measurements and hot spots in the foundation structure. The damage counter should collect data on the residual foundation lifetime and help ensure the costumer that new test cases are possible to perform without creating too much damage to the test bench foundation.

3.1.6 Work package 5: Update of Design Methods

The objective of work package 5 was to collect findings from the sub-components experiments conducted in work package 3 and analyse the test data. Also, the objective was to gather inputs to FE-analysis and the foundation design manual and 3D-model and update/modify these based on the test results and latest knowledge. Based on this, inputs to the design manual for future test bench foundation, that was started in work package 2, should be updated and released.

3.1.7 Work package 6: Dissemination

The objective of work package 6 was to disseminate relevant results of the project. A paper on strain measurements in concrete structures by use of optical fibres is planned for publication in Danish Society for Structural Science and Engineering journal “Bygningsstatiske Meddelelser” targeting construction engineers in the construction and energy sector.

4. Project implementation

The EUDP project originally aimed at developing a small-scale demonstrator of the future nacelle test bench. As this was not possible experimental tests were conducted on component level. The reason for that was due to the fact, that the demonstrator, which were to be utilized, did not have the capacity, and therefore would not yield the results expected. The original objective of the project was obtained, thus, in another way. The project scope evolved to become more digital than expected.

5. Project results

In this section the obtained technological and commercial results are described.

5.1 Work package 0: Project management

The results from WP0 should be a successful project execution. From R&D perspective the project has been managed with great care. The activities in the project execution period have been to facilitate meetings within the project organization, plan and execute workshops and to involve external suppliers and partners. In addition, the activities have consisted of coordinating the cooperation between AU and R&D, knowledge sharing and sharing of results between the project organization's participants and reporting status etc. to EUDP.

As a result of WP0 all milestones and deliverables according to the project plan were met as summarized in Table 1. All deliverables within this EUDP project contain confidential information and is therefore not published with this report.

Milestones	**Status**
M1: Future foundation requirement specification completed	Completed
M2: Future foundation design description, initial version completed	Completed
M3: Experiment program completion	Completed
M4: Experiment completion	Completed
M5: Monitoring system guideline and damage counter design description completed	Completed
M6: Future foundation design manual, final version completed	Completed
M7: EUDP report release	Completed
Deliverables	
D1: Future foundation requirement specification	Completed
D2: Future foundation design manual, initial version	Completed
D3: Experimental result report	Completed
D4: Guideline on monitoring system, data processing software and damage counter design description	Completed
D5: Future foundation design manual, final version	Completed
D6: Report on design evaluation and overall project findings	Completed

Table 1: Overview and status on all milestones and deliverables in the project.

5.2 Work package 1: Requirement Specifications

In this work package the overall layout for a future nacelle test bench were developed and requirements towards the foundation determined and documented. The future nacelle test bench shall perform Highly Accelerated Life Test (HALT) by applying test scenarios to the nacelle in which this is put into extreme static and dynamic load conditions. The test bench is designed to test wind turbine nacelles in the size of up to 25 MW. The test bench layout with some of the main components is illustrated in Figure 1-3. *Note that the nacelle being tested is not shown in the illustration.*

The nacelle is fixed to the test bench foundation in the nacelle anchorage area and to the main shaft nacelle interface. The test bench is designed to apply loads in six decoupled degrees of freedom to the nacelle in a predefined load application centre.

Bending moments and forces simulating the fluctuating wind loads on the blades are applied by a wind load unit (WLU) and drive torque simulating the rotation of the blades is provided by a prime mover system. The WLU is a hydraulic actuated mechanism allowing fully decoupled load control of forces and bending moments. The prime mover is mounted directly on the main shaft of the movable WLU and thus transferring the torque to the nacelle through the main shaft.

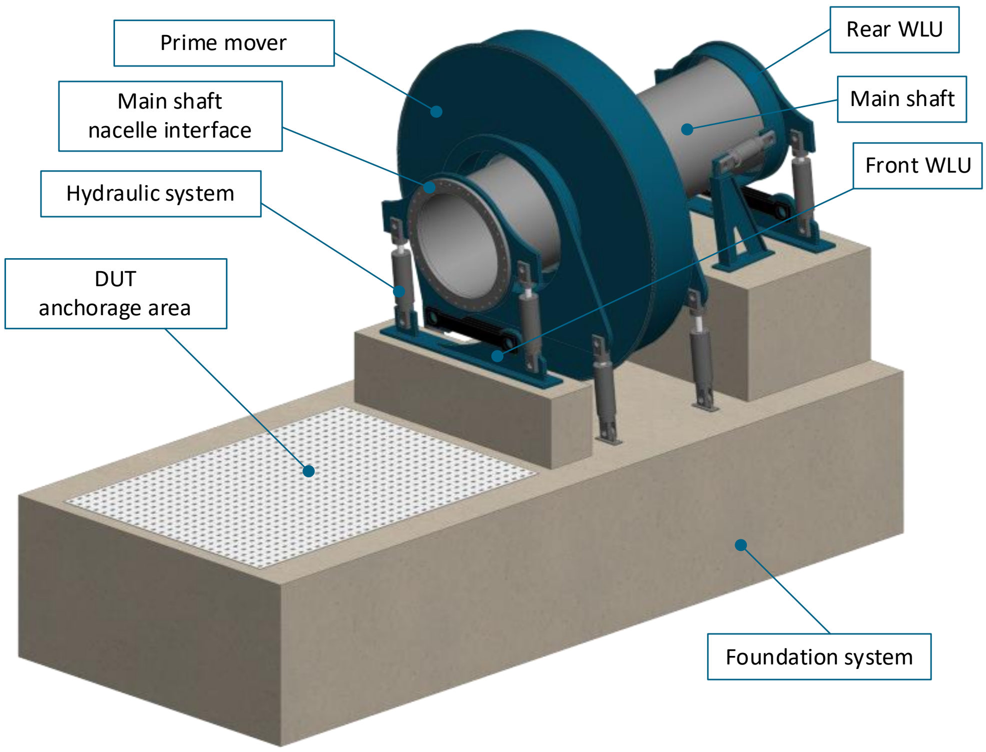

Figure 1-3 Illustration of the Nacelle test bench's main components and systems

Based on R&D Test System's knowledge on current and future wind turbines different types and sizes of nacelles in the range from 16MW to 25MW were sketched in the test bench layout, to set the dimension requirements for the flexible nacelle anchorage area. Also, expected nacelle weights, center of gravity envelope and overall static and dynamic design load cases for the HALT test bench were determined in work package 1. Figure 1-4 illustrates the dimension requirements of the future test bench foundation.

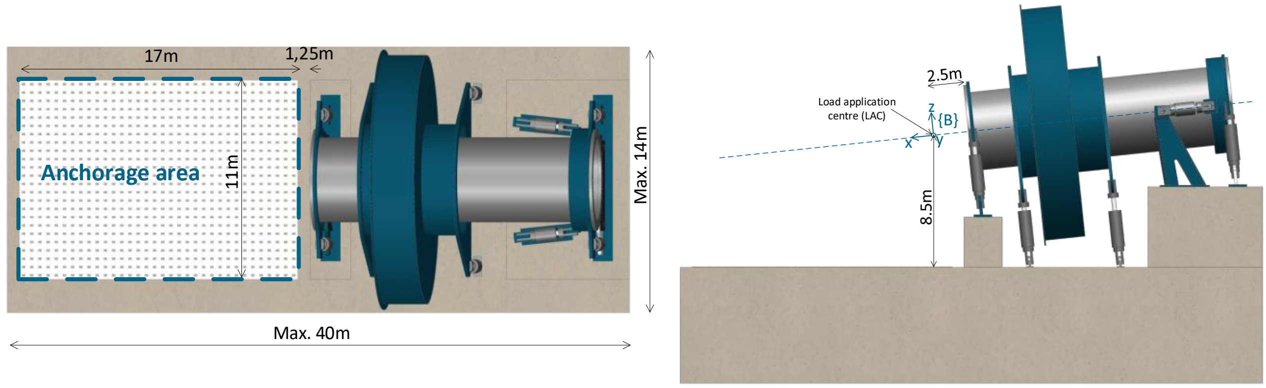

Figure 1-4: Dimensions of future test bench foundation

A requirement specification document was conducted, constituting the basis of the modelling, design, and validation for the future test bench foundation. The requirement specification document includes the test bench performance and design parameters, interfaces to the nacelle, prime mover and wind load unit, safety on loads and deformation and vibration requirements.

Furthermore, the main technical challenges and risks were identified in work package 1, based on the test bench layout, predicted requirements for the future test bench foundation and R&D test systems experience from previous test bench foundation projects. The identified challenges and risks included

- how to handle the heat control of the large concrete mass during the curing process.
- developing a flexible foundation anchor system capable of handling the gigantic loads from the nacelle (e.g., bending moments of up to 200.000kNm in the foundation interface.)
- Ensuring that vibrations are not spread from the test bench to the surrounding environment and vice verses.
- how to encapsulate the large dynamic forces applied on the foundation mass from the test equipment.

5.3 Work package 2: Modelling, Design, and Validation

Based on the requirement specification prepared in work package 1, the future foundation concept has been developed and the design has been continuously improved. The project team has focused on finding a suitable design approach for the complex test bench foundation structure and seeking new solutions for how to fixate the test bench mechanical components and encapsulate the very large dynamic loads in the foundation.

During the project execution, the project organization has continuously developed the concept for the future foundation solution and evaluated the advantages and disadvantages of different solutions and sub-systems. Thus, a structured assessment of the most advantageous solution was conducted considering various parameters such as design advantages, risk, cost, buildability, time, design- and construction experience from similar projects, input from foundation suppliers and contractors. In Figure 1-5 below a matrix illustrating different foundation sub-systems and concepts that has been considered, evaluated, and chosen for the future test bench foundation is shown. The chosen designs are marked with green, and blue are the investigated ideas.

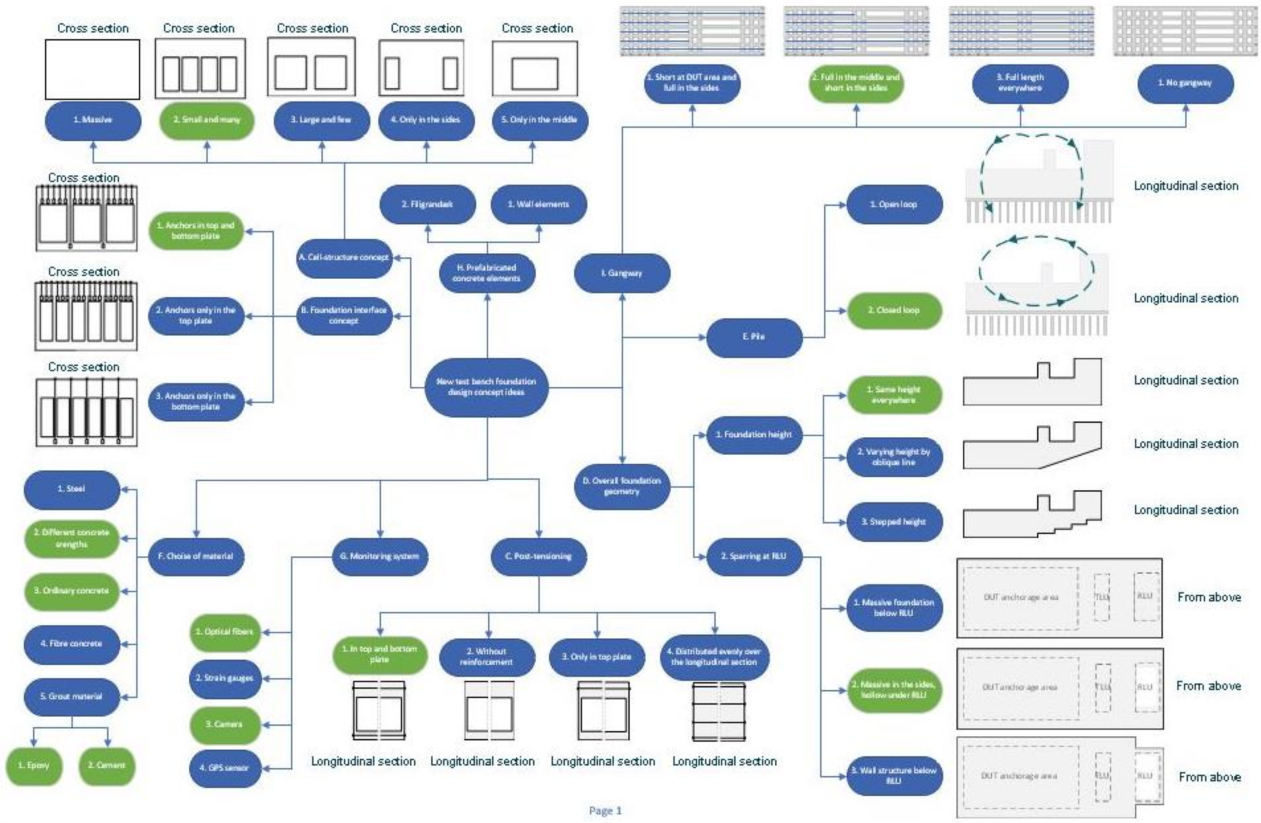

Figure 1-5: Matrix with design concepts. Green boxes are the chosen design and blue are the investigated ideas.

At component level, an assessment has been made of the most optimal solutions for implementation in the overall foundation concept. Meetings with construction contractors have been held to collect their inputs on the buildability of the new design concepts and to harness the contractor's knowledge and experience with the construction of such a complex structure. Furthermore, meetings with suppliers have been held to investigate the possibility of new concepts and to make an estimate of the cost price of the new concept compared to the current concept.

Figure 1-6 illustrates the future foundation design. Below is a description of the overall foundation layout and the foundation structure components developed in work package 2.

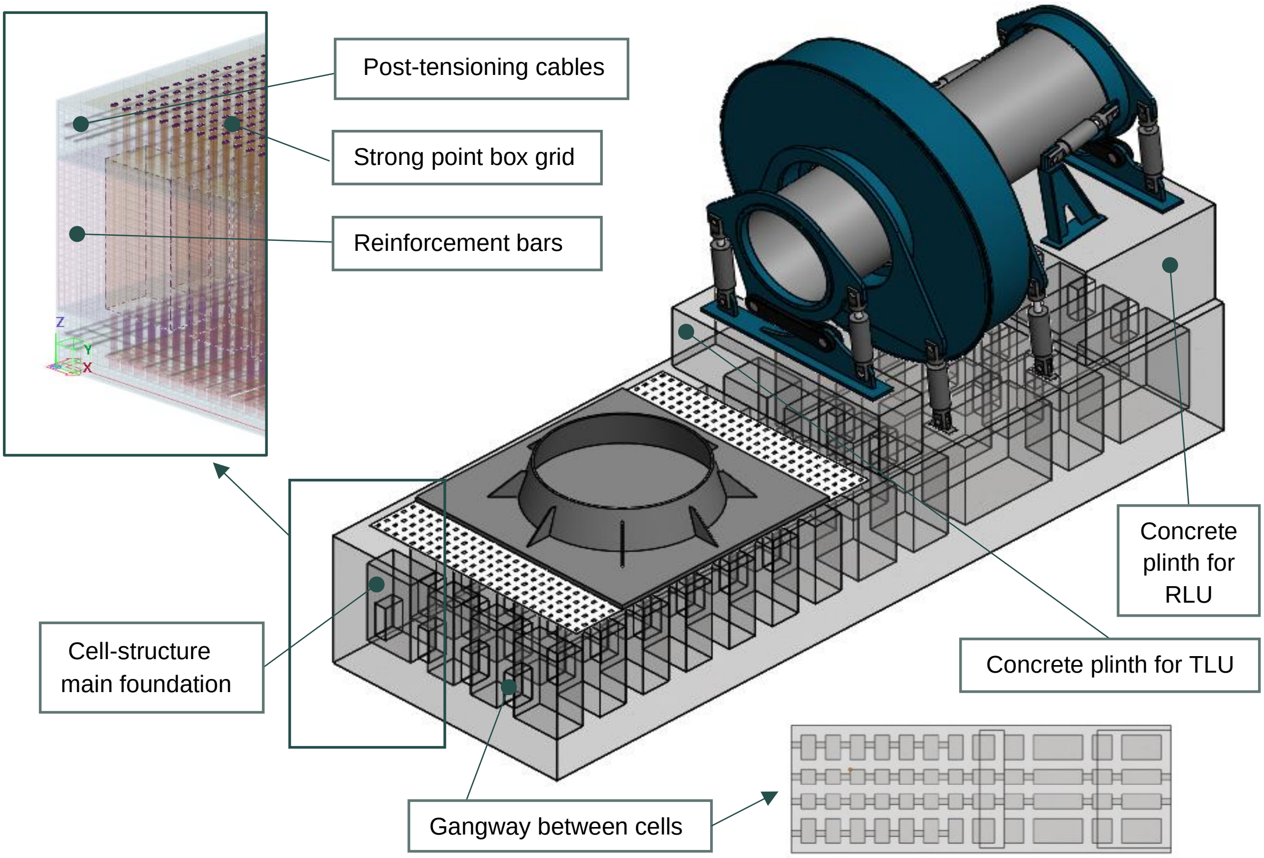

Figure 1-6: Illustration of the future foundation design

Overall foundation layout

The foundation geometry is based on the requirements set out in work package 1 for the overall test system, such as location and size of the mechanical components, where they are placed on the foundation and flexibility in relation to different nacelle sizes etc. In this way, the overall geometry of the foundation is established.

The geotechnical support structure depends on the location of the test bench and soil conditions. Often, the weight of the test setup and the foundation mean that the soil beneath the foundation is not able to directly support the loads. In this way, a deep geotechnical support structure such as a pile foundation must be established. Assessments have been made as to whether loads from the test system's mechanical loads during operation should be carried into the ground by driving the pile structure up into the foundation (an open load course) or keep the mechanical loads in a closed system in the foundation by disconnecting the pile structure from the foundation. Here, it has been found most appropriate to make a closed force flow. The advantages of keeping it in a closed system are that vibrations in the foundation during operation are decoupled from the surroundings and thus do not disturb the surroundings and ambient vibrations do not disturb the test bench. In addition, the closed force system means that the complexity of the flow of forces in the foundation is reduced and it is thus easier to keep track of the impact of cancer in the foundation.

The geotechnical support structure for the foundation depends on the location of the test bench and soil conditions. Often, the weight of the test setup and the foundation mean that the soil beneath the foundation is not able to directly support the loads. Therefore, a deep geotechnical support structure such as a pile foundation shall be established. Assessments have been made as to whether loads from the test system's mechanical loads during operation should be distributed into the soil by integrating the pile structure into the foundation (as an open load loop) or keep the mechanical loads in a closed system in the foundation by disconnecting the pile structure from the foundation. Here, it has been found most appropriate to have a closed foundation load loop by decoupling the foundation from the geotechnical support structure. The advantages of keeping it in a closed system are that vibrations in the foundation during operation are decoupled from the surroundings and thus by integrating a vibration damping system between the foundation and geotechnical support structure it will not disturb the surroundings and surrounding vibrations will not disturb the test bench. In addition, the closed load loop means that the complexity of the load distribution in the foundation is reduced, making it easier to keep track of the impact of the loads in the foundation.

Cell structure

Since the foundation mass contains a large volume of concrete and the requirement to the concrete strength is relatively high, a large energy in the form of heat will develop in the concrete mass during concrete curing. By introducing a cell structure in the foundation, the volume of the concrete is reduced and thus the heat generated during concrete curing is decreased. Also, by introducing the cell structure the load distribution in the foundation becomes more transparent and easier to predict. Furthermore, the amount of concrete used for the foundation structure is reduced, which reduces the resource requirements for future test bench foundation concept. However, it should be noted that there are certain buildable complications with the cell structure, as the otherwise massive concrete mass which can be cast in one casting process must be split into several casting sequences and the cell-structure requires a large amount of formwork work. Thus, the extended execution time and economic aspect must be considered when introducing the cell structure.

Foundation materials

Assessments have been done for the material requirements in foundation structure, including requirements for the vibration material between the geotechnical support structure and the foundation, concrete and reinforcement strength and requirements for the steel and grouting material in the mechanical interfaces. As the foundation is exposed to large loads, the foundation structure contains a large amount of reinforcement. Therefore, it is found difficult to ensure sufficient space for the vibration of the concrete during casting, which is why self-compacting concrete is chosen.

Post tensioning system

To ensure that the concrete is kept in compression (uncracked concrete) in critical sections of the foundation during operation a horizontal post-tensioning system is incorporated in the future test bench foundation. The quantified effects of the post-tensioning system are done through FE-simulation and design calculations. The horizontal post tensioning system will replace some of the reinforcement steel and reduce the stress range in the reinforcement which in the current setup drives the fatigue design. Also, the concrete structure will be stiffer and introducing the post tension system will reduce the overall height of the concrete mass.

Anchor system

The purpose of the anchor system is to fixate and tension the test bench's mechanical components to the foundation. Different solutions for the foundation's anchor systems have been investigated, developed, and designed. Since the nacelle to be tested can have different layouts and positions on the foundation, a flexible anchor system has been chosen in this area of the foundation. The anchor system concept here is replaceable t-bolts that can be immersed in compartments cast into the foundation structure. At the bottom of these compartments an anchor plate is placed on which the anchor head of the t-bolt is clamped to. The other mechanical components included in the test setup do not require the same flexibility. Therefore, this anchor system consists of cast in permanent anchors for fixing and tensioning the motor structure and the wind load unit structure. This permanent anchor system is the same solution that is used in generic wind turbine foundations, known as an unbonded anchor system, where the transmission from tensioning the anchor top is transferred directly down to the embedded anchor plate at the bottom of the anchor.

Foundation construction process

The construction processes for establishing the foundation are that after the geotechnical support structure is established the vibration damping system is installed. Then a thick reinforced base plate is cast on top of the vibration system. Formwork is erected for the foundation walls, including holes, creating free passage from one cell to another through the foundation structure. After casting the foundation walls, the formwork is removed, and a top plate of the foundation is established including the anchor system for the mechanical components. Finally, steel plates are established on top of the concrete foundation structure in the mechanical interface areas of the foundation. The steel plates are adjusted in place and grouted to ensure full bonding between the steel and concrete.

During this work package the foundation concept has been determined and the future foundation design has been optimized. The design optimization is done based on conducted analytical calculations and a FE-model for simulation of force and stress distribution from the machine components to the future test bench foundation structure. Also, the layout of the reinforcement steel in the foundation has been optimization based on the analytical calculations and FEM simulation.

FEM simulations and analytical calculations have been conducted of the concrete structure, anchorages for fixing the mechanical components of the test bench, incorporation of the cell structure into the concrete and post tensioning of the foundation concrete structure. This has led to design validation of the concrete structure. The FE-model is created as a stringer model as illustrated in Figure 1-7

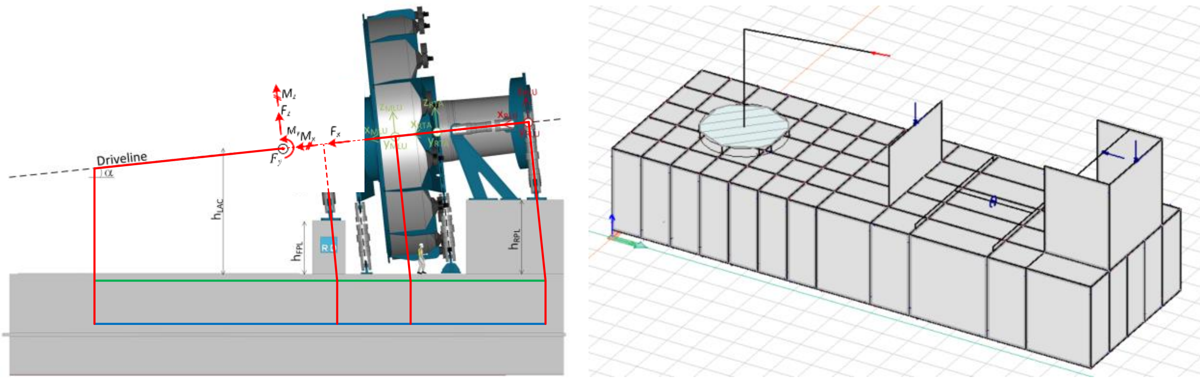

Figure 1-7: Illustration of the FE-model created in FEM-Design software

For the transformation of the test loads in a predefined load application center of the nacelle down to the foundation mechanical interfaces and foundation structure, a calculation tool has been developed. This tool can be used to determine the foundation design loads and thus create input for the verification of the foundation design.

The outcome of work package 2 is a complete design manual describing the future test bench foundation in detail, including the foundation sub-systems and focus areas in the construction work of the test bench foundation

5.4 Work package 3: Experiments on Sub-systems and 3D-modelling

As described in previously the demonstration of the future foundation concept was changed to experiments on a sub-system level in the laboratories at Aarhus University. In WP3 several experiments have been conducted and a 3D-model of the future foundation layout were created. The results of WP3 are described in below sections.

5.4.1 Results of sub-system experiments

Large-scale and time-consuming experiments on some of the uncertainties related to the foundation design were conducted in Aarhus University laboratory throughout this work package to validate future foundation concepts and sub-systems. The experiments are conducted to approach the real behavior and to save materials in future foundations, which will result in a more sustainable foundation design. The experiments will supplement and illuminate some of the challenges in the FE-simulations and analytical calculations and make a more optimal and less conservative design.

Particularly local effects on the foundation in different areas were investigated. These tests will help evaluate on cost, design methods, and fatigue lifetime regarding test bench foundations. Based on comparisons from research in previous studies and experiments, detailed design of test setups was developed and determined. Here, among others, reinforced concrete beams are casted with optical fibers incapsulated in the concrete to investigate if such monitoring system creates valid results. The concrete beams are tested for different load scenarios and data have been analyzed. One type of optical fiber was tested. This fiber type was chosen based on a literature review where previous experimental investigations indicated a proper behavior of the fiber when encapsulated in concrete. The main idea was to investigate the fiber's ability to measure reinforcement strain within proper tolerances for using these measurements as input in a damage-counter. In order to make this evaluation, different ways of attaching the optical fiber to the reinforcement were investigated and the measured response were compared with a conventional model for calculating the reinforcement strain for the given loading conditions. For all the three different ways of attaching the optical fiber, the measured reinforcement strain was within a 10% agreement compared with the model predictions for the level of loads that are expected to be relevant when considering a damage-counter. It is concluded that the idea of applying these type of optical fiber measurements for use as input in a damage-counter is possible as well as it is possible to translate the uncertainty of the measurements into an uncertainty on the estimated life predictions. However, before a practical implementation of such a damage-counter can take place in a reliable way, a way for calibrating the system/measurements is of extreme importance. Results from the experiments are gathered in a report summarizing the outcome and findings.

Experimental tests on the friction coefficient between grout and steel and grout and concrete were conducted for three different values of the contact force. Three different surface treatments were investigated together with steel plates where the surface was sandblasted. Both in the cases of surface treatments and sandblasted surfaces, the experiments indicated higher friction coefficients than expected. As part of the experiments also the initial cohesion were measured. These results show a very high cohesion for all the cases with surface treatments, whereas in the cases of sandblasted surfaces the cohesion is to be considered rather unreliable. This statement is based on the observation that in some of the cases with sandblasted surfaces, the connection between steel plate and grout was already destroyed from just the handling of the test specimens. Among the tested grouts and surface treatments some are to be implemented in current projects and others does not have sufficient data to safely implement yet. However, all experiments imply promising results and new surface treatments, and grouts are therefore something R&D internally is looking more in to.

5.4.2 3D modelling

In the starting phase of the project a generic 3D-model of the overall test bench layout was conducted. This created a basis for the upscaling of the test system to cope with the future 25MW size. Here different setups with a various of nacelles were included in the model to ensure that the future test bench has sufficient flexibility to cope with different wind turbine manufactures requirements. This generic 3D-model was created in SolidWORKS software and the model includes both the overall foundation layout, the foundation machine interfaces and the test bench mechanical components including the nacelle.

During work package 3, a 3D-model of the future foundation concept has been conducted and continuously updated throughout this work package. The model is created based on the design manual and description of the foundation concept created in work package 2. For visualization of the complex foundation concrete structure including the reinforcement layout, anchor system, cell structure and post tensioning system, the software TEKLA Structure was chosen.

Visualization of the foundation concept and making the structural challenges visible has added great value to the project. The 3D-model has illuminated conflicts which may occur in the new design concept between the necessary reinforcement layout, the anchor system and post-tensioning systems, with both permanent and replaceable anchor bolts, and all the other components in the foundations. The model has helped to look at the embedding components built into the foundation, the reinforcement layout in the concrete, the cell structure and form an overview of the places that have needed adjustments so that conflicts and collisions in the foundation sub-systems are eliminated.

3D-modelling is in general a great tool to visualize, detect and handle structural challenges in a large and complex structure such as the test bench foundation. In this project the 3D-model has helped not only determine challenges and conflicts in the structure but also created a basis for considerations regarding the construction work and work procedures in the execution of the foundation, making the execution phase more efficient and cost optimized. In the project execution several meetings were conducted with suppliers and construction contractors having experience with similar construction work as this foundation structure. One of the key elements for these discussions were the 3D-model with to align and ensure on the buildability of the future test bench foundation concept.

In below Figure 1-9 the generic 3D-model of the test bench and the 3D-model of the foundation are illustrated.

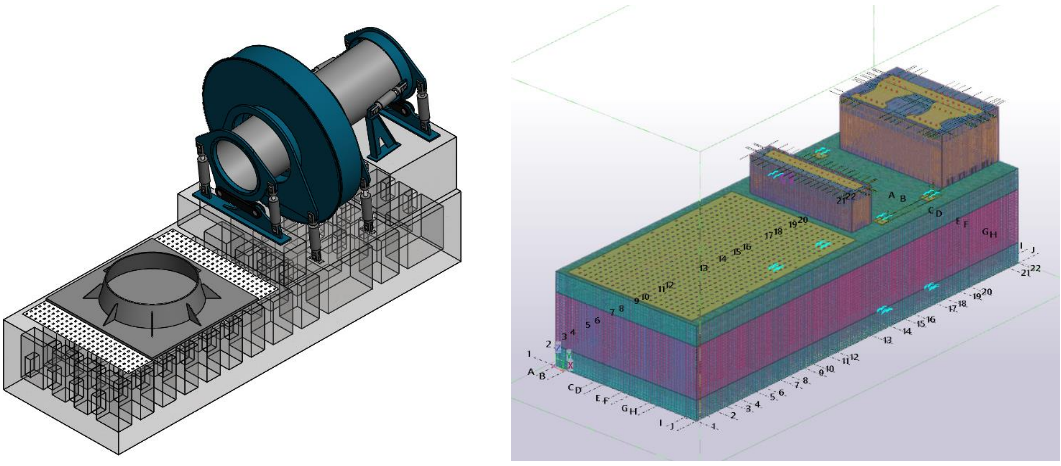

Figure 1-9: Illustration of 3D models conducted in SolidWorks and Tekla Structures respectively.

5.5 Work package 4: Monitoring System and Damage Counter

In this work package different solutions for monitoring the foundation system and sub-components during test operation has been investigated. The purpose of integrating a structural monitoring system in the foundation is to gain knowledge regarding the complex stress distribution within the large concrete foundation during operation. Also, having a monitoring system capable of measuring real-time physical stress level in critical areas of the foundation will support evaluating the fatigue damage and residual lifetime of the foundation after being exposed to a given test load scenario. The intension is that the monitoring system integrated in the foundation will be able to create data-input for a foundation damage counter.

5.5.1 Structural Health Monitoring

A relative new technology and trend in the construction industry is to observe and analysis of a complex structure, such as the test bench foundation system, over time using periodically sampled response measurements to monitor the changes to the material and geometry properties. This system is generally known as a structural health monitoring system (SHM).

The initial activities in this work package have been to find a suitable monitoring system and investigate how this can be implemented into the test bench foundation solution, ensuring that the system can provide valid results in selected and critical areas of the foundation. The process for selecting the SHM system in this project has included selecting the excitation methods, the sensor types, number and location and the data acquisition hardware (including storage and transmittal).

Suppliers of SHM-systems have been engaged to investigate different solutions for the purpose of finding the optimal system for monitoring of dynamically loaded reinforced concrete structures.

Several sensor types have been considered for the SHM system including strain gauges, temperature sensors, accelerometers, and fiber optical sensors. The fiber optical sensor has been considered the most relevant sensor type for this project. Optical fiber is an essential backbone of today's digital world and internet infrastructure, transporting most of the world's data using light instead of electricity. Less known is using fiber optical technology as a sensor for structural health monitoring. Fiber optical sensors embedded within the foundation system can measure variety of parameters, i.e., temperature, vibrations, deformations, accelerations, cracks, and strain. This allows for real time non-destructive evaluation of the concrete, reinforcement steel and anchor system behaviour. Some of the advantages in the fiber optical sensors are:

- They are flexible, small in size and light weighted; thus, they can easily be integrated in tight areas along the foundation rebars and anchors etc.
- They do not have electrical components; thus, they are immune to high voltage that the equipment installed on the foundation requires.
- They are electromagnetically passive and therefore will not influence the equipment installed on the foundation.
- They exhibit multiplexing property and distributed measurements. Therefore, it reduces drastically the cost of wiring installations and allows the monitoring of a large section of the structure contrary to point sensors that require predicting the critical hot spots in the structure before their installation.

To determine the numbers and location of the optical fibers to embed in the foundation the FE-model, conducted in work package 2, were used. Here the most exposed areas of the foundation structure were identified to find the "Hot spots" in the structure relevant for monitoring. The most relevant measurements in the foundation application in order to determine the damage done to the foundation in a given test scenario are

- Strain in the embedded rebars in “hot spot” areas to be able to determine the stress level in the rebar and thus the rebar strength utilization
- Cracks in the foundation to be able to determine if the foundation structure calculation-wise shall be considered cracked or uncracked and to monitor concrete crack widths
- Temperature in the concrete to calibrate the measured strain when converting to stress level in the rebars.

In general, there are three types of fiber optical sensors; single-point sensor that has a single sensing element of the optical fiber, multi-point/quasi-distributed sensor that has multiple sensing points along the optical fiber and distributed sensor with continuous sensing elements along the embedded optical fiber. For the foundation SHM-system we chose the distributed sensor to be able to measure the variety of the strain along the reinforcement.

Experiments on how to incorporate the optical fiber sensors in the foundation have been conducted. The objective has been to ensure that valid results of the measured strain in the reinforcement and concrete are available when casting optical fibers into the concrete mass. In the laboratory of Aarhus University several small-scale concrete beams were cast with optical fibers along the reinforcement and after curing the beams were exposed to various loads. The test results were then compared with analytical calculations of the reinforcement and concrete stress level.

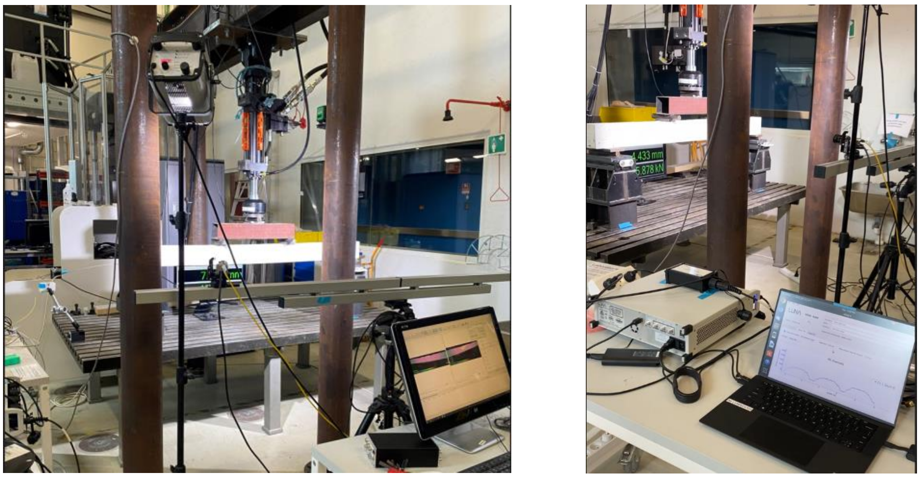

Figure 1-10: Photos of optical fiber experiments

Data acquisition

Obtaining accurate measures of the systems dynamic response is essential to the structural health monitoring system. The data acquisition process includes collecting impulses from the sensor, data transmission, analog to digital conversion, data storage and data cleansing, normalization, compression, and fusion. Depended on the fiber optical solution there are different data acquisition systems available on the marked. Figure 1-11 illustrates the principals of a structural health monitoring system including data acquisition hardware and visualization of the foundation behavior.

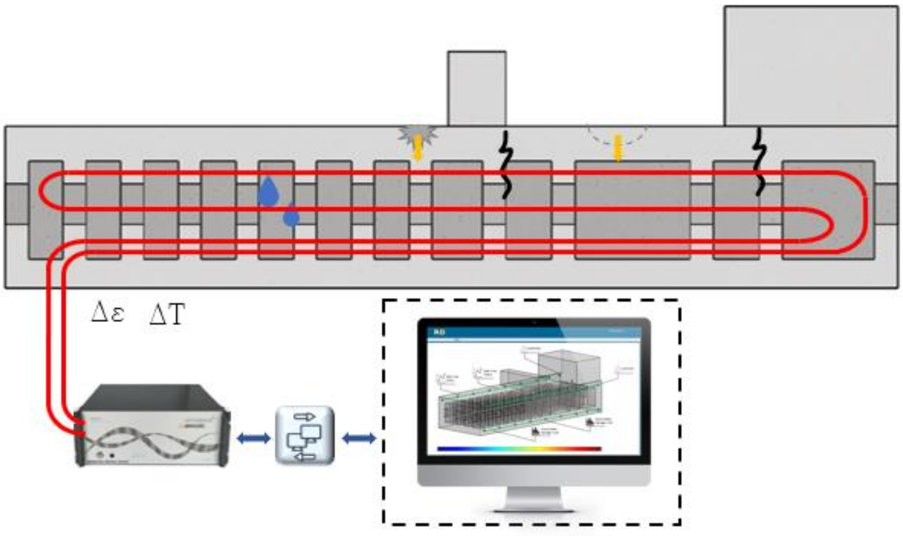

Figure 1-11: Structural health monitoring system principals.

For this EUDP project the brand/product of a structural monitoring system and data acquisition system has not been selected. A design description for the developed structural health monitoring system has been conducted including principals of the system, requirements specifications and things to consider for the integration of a monitoring system in the future test bench concept. The target is to include the monitoring system into future commercial test bench projects and hereby gain the knowledge about the foundation behavior, stress distribution, crack width, vibration levels etc. This insight can help increase the understanding of dynamic effects in a complex structure such as the large test bench foundation and create optimization potential for the foundation design.

5.5.2 Damage Counter

We have developed a digital damage counter software that is able to calculate the remaining lifetime in the foundation according to a desired or completed test scenario. The digital damage counter is based on analytical calculations and the results of the FE-model, and thus not physical measurements of the foundation behavior.

The process for the digital damage counter is as follows (see Figure 1-12):

- Input from a given test scenario is entered into the software
- The damage counter software converts the test scenario loads into loads applied in the foundation's mechanical interfaces
- Based on analytical calculations and the FE model, stresses are calculated in preidentified “hot spot” areas of the foundation, including stress level in reinforcement, concrete, and the anchor system.
- The dynamic effects from the test scenario are accumulated to total damage to the foundation's components and the software is thus able to calculate the remaining lifetime of the foundation.

Parallel to the digital damage counter, the idea is that based on the structural health monitoring system integrated into the foundation, you create input to the damage counter that is based on physical measurements.

The process for the physical damage counter is as follows (see Figure 1-12):

- A given test scenario is conducted on the test bench
- This test scenario entails physical loads applied in the foundation's mechanical interfaces

- The effect of the loads applied on the foundation are picked up by the structural health monitoring system and strains in the reinforcement, concrete and the anchor system are collected in the data acquisition system and converted into stress variations.
- These stress variations provide input to the damage counter which calculates the remaining lifetime of the foundation, based on physical measurements of the loads the foundation is exposed to.

With the two parallel damage counter systems, it will be possible to calibrate the FE-model and thus have a more reliable and accurate damage counter system. The digital damage counter can create assessments of residual foundation lifetime for future test scenarios and thereby help the customer assess the foundation "damage costs" of a future test scenario. Also, the damage counter will continuously collect the impact of damage on the foundation during operation, which may prove to extend the lifetime of the foundation and the test bench.

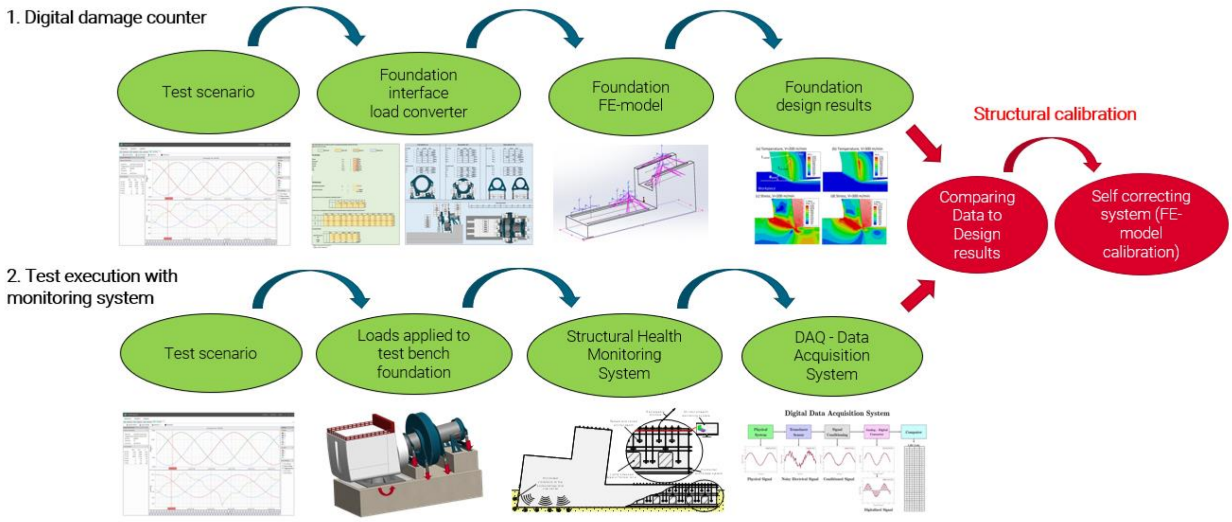

Figure 1-12: Illustrations of a digital damage counter

5.6 Work package 5: Update of Design Methods

Findings from the experiments and inputs to FE-analysis are gathered and the design manual, guideline, FE- and 3D-model etc. are updated as well as the monitoring system guideline and damage counter design description.

5.7 Work package 6: Dissemination

Articles and reports have been conducted during the project execution. This final EUDP report will create an overview on the challenges of test bench foundations. Also, two articles were released in journals about the challenges which were investigated through the EUDP project. Furthermore, R&D Test systems' experience in the wind turbine industry, Aarhus University's knowledge within concrete and the cooperation between partners in the EUDP project. The first article is published in EnergyWatch and the second is published in Metal Supply.

1. Danske ingeniører lægger betonfundamentet til moderne vindtests (energiwatch.dk)
   Link to article at Energy Watch: https://energiwatch.dk/Energinyt/Renewables/article13487671.ece

2. Forskningsprojekt skal optimere fremtidens testsystemer til vindmølleindustrien (energy-supply.dk)

Link to article at Energy Supply: https://www.energy-supply.dk/article/view/840275/forskningsprojekt_skal_optimere_fremtidens_testsystemer_til_vindmolleindustrien

Figure 1-13: John Simonsen, senior specialist at R&D Test Systems (to the left), og Frede Christensen, lector at Aarhus University (to the right) in the laboratories at Aarhus University.

3. The Nacelle Test Bench Foundation EUDP project video
   Link to video: https://www.youtube.com/watch?v=RnIgwkD6QQ4
4. R&D klar med en ny og optimeret konceptuel ramme med flere forbedringer (rd-as.com)
   Link to post: https://www.rd-as.com/da/insights/rd-forbedrer-designet-af-vores-eudp-finansierede-test-bench-foundation-projekt/
5. Danske ingeniører lægger betonfundamentet til moderne vindtests (rd-as.com)
   Link to post: https://www.rd-as.com/da/insights/danske-ingenioerer-laegger-betonfundamentet-til-moderne-vindtests/

6. Utilisation of project results

Today, R&D is one of the world's leading suppliers of turnkey solutions of test systems for the wind industry, which include foundation solutions. The obtained technological results will in the future be utilised of wind turbine producers for testing of different components and prototypes. The optimized foundation solution and the design optimizations developed in this EUDP project is already getting integrated in current projects and will be included in projects already in R&D's pipeline. R&D has several large test rigs in pipeline, where results from this EUDP project is of huge value. The findings from the EUDP project will be implemented in the upcoming test bench foundations. To mention one, R&D has during 2022 won the company's historically largest test bench project, which include a HALT nacelle test bench foundation for a 30 MW drive train setup illustrated in Figure 1-14. Furthermore, the EUDP project expects to increase R&D's project orders due to disclosure of the damage counter. Thus, the damage counter is part of the 30 MW test rig. Expectedly there will be competitors to a damage counter on the market. However, it is still a very immature technology on the market.

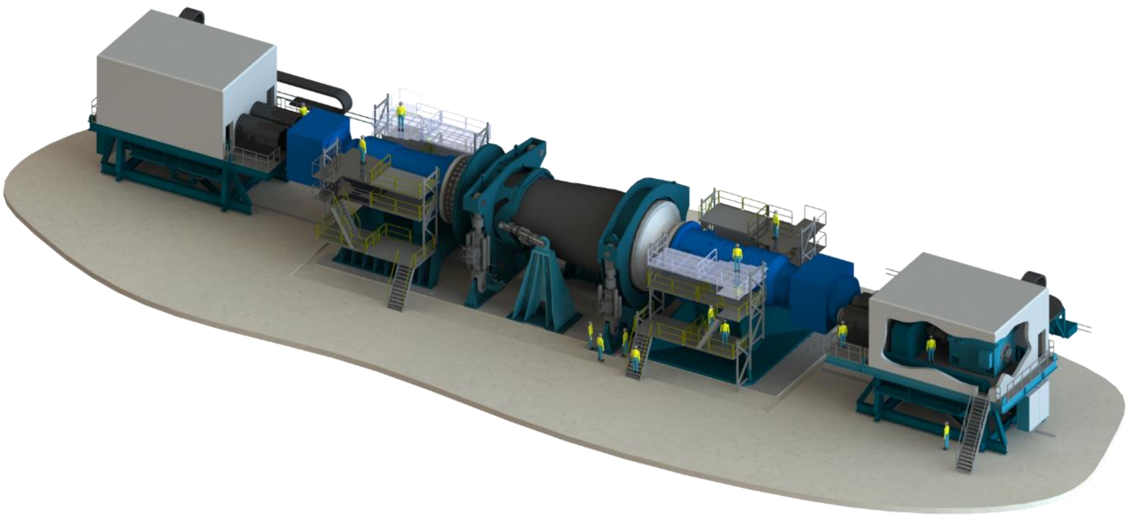

Figure 1-14: R&D Test Systems' historically largest test bench project won in 2022. A HALT nacelle test bench for 30 MW drive train setup.

Wind turbine producers and test bench operators, both nationally and internationally are asking for the ability to continuously foresee the remaining lifetime of the test bench including the vital and expensive test bench foundation. Initially, when the test benches are designed, the design life is approximately 20 years for a validation test bench. With integrated sensors, monitoring, and a damage counter tool, one can discover both deficiencies and hidden structural reserves of the test bench and estimate the damage of each use case to calculate the real lifetime of the test bench. Having more insights from the structure would lead to safer operations and, most importantly, go beyond the design life of the structure. Thus, the scope of WP3 and WP4 was to do numerous experiments and profound FE-simulations to develop a damage counter or a so-called Digital Twin and thus validate the new design concept for future 25-30 MW nacelle HALT test bench foundations. Commercially this adds a great value to the EUDP-project. For R&D to be able to include the Digital Twin/Damage Counter in our turn-key test bench solutions will make R&D even more competitive since our test benches would be used more efficiently. Moreover, it is likely that this extended knowledge of the stresses and concrete behavior will result in an extension of the lifetime of the HALT test bench foundations and, thereby less conservative design approach, resulting in reduced reinforcement steel, amount of concrete etc. and in that aspect a greener and more sustainable future solution.

7. Project conclusion and perspective

In the reporting period 2020-2023, the project has made significant progress towards the overall goal of developing and validating a new design concept for future test bench foundations.

Relevant test scenarios and requirement specification for the future nacelle test bench foundation solution have been established, based on upscaling current wind turbines in the marked. The project team have then done a deep dive into the foundation concept for a future nacelle test bench, and created the most ideal foundation design, considering execution/production challenges, cost and known design challenges. During the project execution different solutions and setups, including advantages and disadvantages of the individual solution has been identified to determine the most appropriate concept. The future foundation concept is concretized in a design manual. Also, the foundation concept has been validated by analytical calculations compared to FE-analyses and the concept has been illustrated in a 3D model.

In parallel to the EUDP-project, R&D Test Systems has developed, designed, and built new test benches where the knowledge created in this project has been of great help and foundation sub-systems developed in this project have been integrated in the commercial projects.

Going forward, R&D Test Systems will continue to provide test benches for the wind industry. The project has contributed to ensure that we also in the future have a valid foundation concept, where the expectation is that the foundation will be exposed to even higher loads applied, caused by wind turbine development, and increased power ratio per unit.

R&D Test Systems will continue to modify the structural monitoring system integration and further develop the foundation damage counter system. Based on the foundation damage counter, future clients of the nacelle test bench will have the opportunity to look at the residual lifetime of the foundation, based on actual measured strain in the foundation, and be able to assess how much damage a given future test scenario will have on the foundation structure.

8. Appendices

All deliverables within this EUDP project contain confidential information and is therefore not published with this report. Please reach out to R&D Test Systems if interested in more information or collaborations.