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Development, engineering, production, and life cycle management of improved FIBRE-based material solutions for the structure and functional components of large offshore wind energy and tidal power platforms

D6.6 (WP6): Measurements Report

Responsible Partner: TSI

Contributor(s): TSI, CIMNE, ENEROCEAN

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EXECUTIVE SUMMARY

This report presents a comprehensive analysis of the installation of Fibre Reinforced Polymer (FRP) in an existing steel-based W2Power prototype, together with the description and results of the monitoring systems employed. The monitoring systems include both a general system for the substructure and specific systems for the FRP tower. The Key Performance Indicators (KPIs) monitored include various aspects such as cabinet, power supply, data acquisition system, sensors, and signals.

The modal analysis of the platform was performed using a specific methodology, instrumentation, and test setup, leading to insightful results and conclusions regarding the structural dynamics of the platform.

Experiments with the W2 Power 1:6 prototype will be presented. These results provide a thorough understanding of the performance of the prototype, covering both the general monitoring system and the specific FRP tower monitoring system.

It also presents a framework for structural health monitoring based on digital twin models, focusing on their integration with real-world data and the use of sensor networks and monitoring systems. This approach improves the understanding of structural behaviour and facilitates predictive maintenance strategies.

NOMENCLATURE / ACRONYM LIST

Acronym	Meaning
FRP	Fibre Reinforced Polymers
FOS	Fibre Optic Sensors
GPS	Global Positioning System
SHM	Structural Health Monitoring
DT	Digital Twin
IMU	Inertial Measurement Unit
WP	Work Package
WiMAX	Worldwide Interoperability for Microwave Access
EMA	Experimental Modal Analysis
FRF	Frequency Response Function
MAC	Modal Assurance Criterion
MEMS	Micro Electro Mechanical Systems
DAQ	Data Acquisition

1. Introduction

This document summarises the methods, technologies, and results of the monitoring campaign for the floating wind turbine prototype W2Power. It provides a comprehensive overview of the strategies employed to integrate the different sensors into the prototype and the tools used to do all of this.

Throughout the report, the installation of FRP tower in the existing steel-based W2Power prototype is detailed, the monitoring systems implemented are described, and some results of the modal analysis as well as of the different tests carried out are shown. Besides, the development and implementation of the digital twin and structural health monitoring platform are described.

Each section provides an insight into the methodology, instrumentation, test setups, execution procedures, results, and their implications.

2. Installation of the FRP in the existing steel-based W2Power prototype

The FRP towers were designed with a strong focus on manufacturing and installation, since they need to be manufactured and installed on the W2Power prototype. This implied designing and manufacturing not only the FRP towers but also a functional and easy-to-install connection system of the new towers with the existing platform and nacelle. Extensive discussions were held until a final choice on the most appropriate connection design was made.

One important challenge is that the manufacturing and assembly processes of the different parts had to be done in different locations: the steel connectors were manufactured by Astican shipyard in the Canary Islands, the FRP tower was manufactured by Exail (previously IxBlue) shipyard in France and the final assembly and installation was done at Astican facilities, where the W2Power is located. This was successfully solved thanks to a manufacturing and assembly procedure thoroughly defined in advance and thanks to a close collaboration of all partners involved throughout the process, which can be summarized as follows:

Firstly, the four steel connectors, two for the top (tower-nacelle) joint and two for the bottom (tower-platform) joint, were manufactured by Astican under EnerOcean premises and coordination.

Figure 1 Bottom (left) and top (right) connectors.

The connectors were then sent to Exail facilities, where the FRP tower manufacturing works had already started, so they could be used as a template during the last part of the tower manufacturing process, both to drill the holes on it and to guarantee a good matching in the interface between the tower and the connectors. Finally, Exail assembled the top connector and preassembled the bottom one and sent the FRP tower to Astican shipyard.

Figure 2 FRP towers received at ASTICAN shipyard.

Once the FRP towers were received and before its installation, it was necessary to disassembly and remove the turbines and its cabling. These works were carried out by Astican with the support of Ingeteam and EnerOcean's supervision.

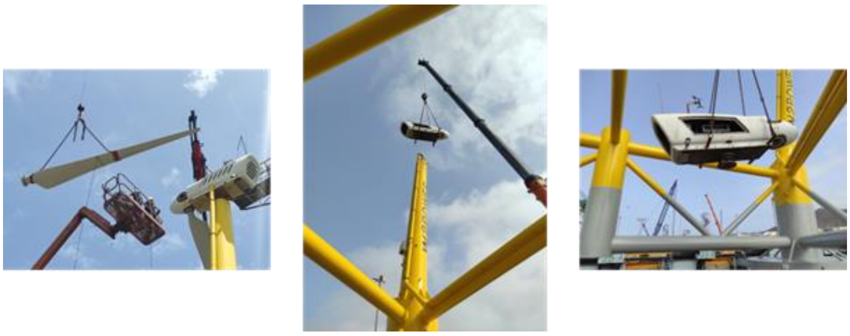

Figure 3 Disassembly and removal of the turbines and the cabling.

Once the turbines were stored in a safe place, the steel towers were cut and removed from the platform. After careful consideration, it was decided to cut the tower into two parts to ease the installation of the steel ring and the FRP tower on it.

Figure 4 Steel tower cutting.

The joining of the FRP tower with the steel tower base is a critical step: both in terms of technical complexity and in terms of novelty. For confidentiality reasons, pictures of the process will not be shown in this public report, but the procedure followed is explained below.

Firstly, some preparatory works were done on the steel tower base to ease the positioning of the steel ring on it. Once the steel ring is positioned and fixed to the steel tower base, the FRP towers were placed with the steel ones and the rings, ensuring that all the holes of the FRP towers fit well with the holes of the ring.

Then, abundant sealant was applied to the towers to make them watertight before filling the gap between the steel ring and the FRP tower with casting resin. This process was done by Exail (previously IxBlue) guaranteeing the times needed by the resin to fill completely the gap and to dry.

It is worth noting that, following Exail's experience in the assembly of the top connector of the tower, EnerOcean had Astican manufactured some steel plates like the ones used by Exail in the top joint. They allow having a flat surface -instead of the curved one due to the cylindrical shape of the tower- for the bolts and washers as well as an improved stress distribution. Furthermore, in the case of the bottom connection, these plates served an extra function: since they were manufactured in slightly different thicknesses, they could be used to absorb small differences in the gap observed along the tower section, avoiding potential risks when bolting afterwards.

Once the resin filling the gap was dry, Exail glued the steel plates to the FRP tower and, finally, they positioned the washers and bolts and tightened using a torque wrench. Deformations or even "cracks" can appear in the composite material if the tightening is not done properly, therefore Exail decided to do this process in a manual way and in two steps: first applying half of the specified torque and finally applying its full torque.

In this way, the tower, which was already assembled with the top connector, is now also fully assembled in its bottom part to the base of the steel tower thanks to the steel ring specifically designed for it.

The next step of the installation of the FRP towers consisted in its lifting, positioning, and fixation on the platform. This was a complex operation, due to several reasons but mostly because the new FRP towers had to maintain the symmetry and leaning angle that the original steel ones had. Once their correct position was achieved, the steel tower base was welded to the platform. This operation was successfully done by Astican under EnerOcean's leadership.

Figure 5 Lifting and assembly of the FRP towers.

Finally, the turbines were re-installed on the towers. The first step is the positioning and fixing of the nacelle on the new top connector of the tower and, subsequently, the blades are installed. This operation is a crucial mainly because any inaccuracy on the design or manufacturing of the top connector may result in not being able to fix the nacelle, and because any small inaccuracy on the positioning of the towers at its bottom may result in important misalignments between the turbines. Thanks to the collaboration between Ingeteam, Astican and EnerOcean this was accomplished without any inconvenience. This step ended with the installation of the turbine cabling, whose support system and route from the nacelle to the floater in cylindrical tubes had to be adapted for the new FRP tower.

Figure 6 Turbines and cabling reassembly.

Once the turbines were installed and its position and correct operation was verified, it can be concluded that the installation of the new FRP towers designed and manufactured in the project were successfully installed on the W2Power prototype.

However, because of the difference in weight between the new FRP towers and the original steel ones, one last operation needs to be performed: platform balance checking and ballast filling. The installation of the new FRP towers has led to an important weight reduction at the rear part of the platform, causing the platform to be unbalanced and unstable if no action is taken. The solution chosen is to add ballast in the central column located at the rear part between the two towers (column D), which is prepared for this purpose. However, since the volume available in it is limited and the ballast weight needed is significant, it was decided to employ a dense fluid with a density more than twice that of sea water. This novel dense fluid was designed, developed, and installed by Magellan & Barents S.L.

Figure 7 Dense fluid installation.

This is the last operation carried out in the dry dock of the shipyard. Now, the W2Power prototype is fully modified to hold the new FRP towers while keeping its original geometry and a weight distribution that guarantees its stability at sea.

Figure 8 W2Power prototype with FRP towers ready for load-out.

3. Description of monitoring systems

In parallel with the installation works of the FRP towers on the prototype, the monitoring and data acquisition system were also installed and exhaustively verified, since the availability and quality of the data collected during the testing campaign depend on it.

Two different monitoring system have been installed in the W2Power prototype: one aiming at monitoring the steel substructure, which has been designed by EnerOcean and CIMNE, and installed by EnerOcean, and another specific for one of the FRP towers, which has been designed and installed by TSI. Both systems are described in this section.

3.1. Substructure and general monitoring system

The existing monitoring system of the W2Power prototype has been checked and updated to meet the project requirements. This part of the more extensive W2Power prototype monitoring system was designed and installed with the objective of generating useful and high-quality data of the general dynamics of the platform and the structural behaviour of the FRP towers and substructure.

It is also worth noting that the information collected by this system is used to feed the digital twin developed on the WP3 of this project. For this reason, the installation of the new strain gauges has been carried out according to two criteria:

- Points identified as optimal for evaluating the amplitude of the main vibration modes of the structure. The specific methodology followed to determine the optimal points is presented later.
- Points selected for validating strain values in specific hot spots.

The main sensors that compose this monitoring system are:

- Video cameras on the top and bottom part of the towers
- Uniaxial and triaxial strain gauges connected to the iMeasures
- IMU (Inertial Measurement Unit) which have:
  - 3 axis accelerometers
  - 3 axis gyroscopes
  - 3 axis magnetometers
  - GPS module
  - Temperature sensor

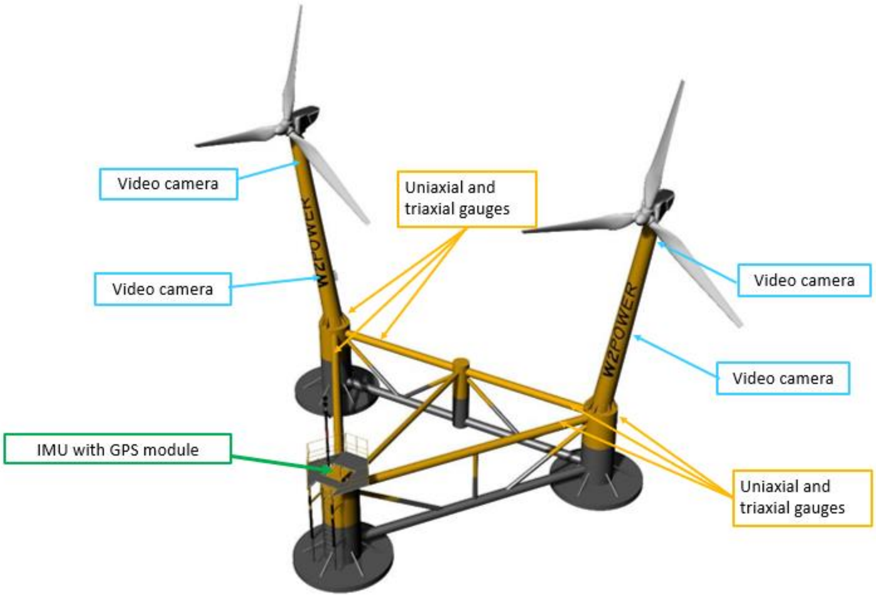

Figure 9 W2Power general monitoring systems.

The four video cameras that have been installed allow regular scheduled visual inspections to be carried out both with an operator and remotely and thus detect possible anomalies in the structure.

Figure 10 W2Power video cameras visual inspection.

The iMeasures are the devices designed and developed by EnerOcean to capture and process strain measured by strain gauges.

Strain gauges are sensors that measure the deformation of an object. They operate based on the property of certain materials to alter their electrical resistance when subjected to certain stresses that cause deformation. The variation in resistance also depends on the direction in which the stresses are applied. The gauge is attached to the object whose deformation is to be studied, and as the object deforms, so does the gauge, thereby altering its electrical resistance.

Uniaxial strain gauges are designed to measure deformation in a specific direction, making them useful for measuring magnitudes such as tension or compression in a material. In contrast, triaxial strain gauges measure deformation in three orthogonal directions: axial, radial and circumferential. They achieve this with multiple sensitive elements arranged in different orientations, unlike uniaxial gauges, which have only one (see Figure 11).

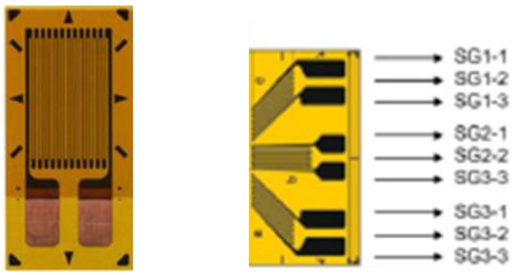

Figure 11 uniaxial strain gauge; Right: triaxial strain gauge.

On the other hand, an IMU standing for Inertial Measurement Unit, is an electronic device that measures and reports acceleration, orientation, angular rates, and other gravitational forces. It is composed of 3 accelerometers, 3 gyroscopes, and depending on the heading requirement, 3 magnetometers, one per axis for each of the three vehicle axes (roll, pitch, and yaw), a temperature sensor, and a GPS module with the GNSS technology. As a clarification:

- An accelerometer is a sensor used to measure acceleration forces, either static (such as gravity) or dynamic (such as vibration or motion). It detects changes in velocity or speed along one or more axes, typically in three dimensions: X, Y, and Z.
- A gyroscope is a device used to measure or maintain orientation and angular velocity. It works based on the principles of angular momentum and the conservation of angular momentum. Unlike accelerometers, which measure linear acceleration, gyroscope detect rotational motion.
- A magnetometer is a device used to measure the strength, direction, and variations in a magnetic field. It detects and quantifies the magnetic field intensity along one or more axes, typically in three dimensions: X, Y, and Z.

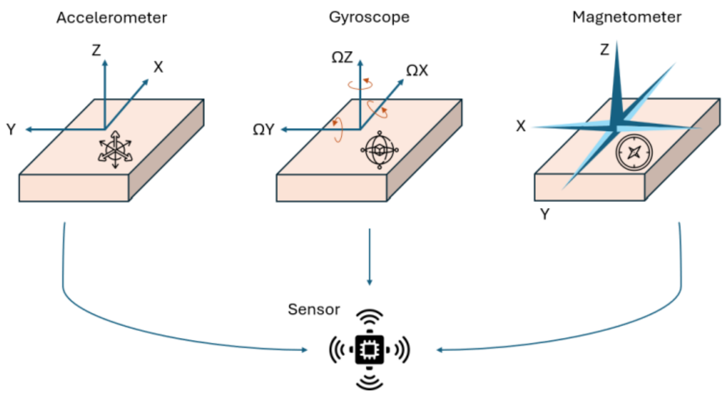

Figure 12 IMU (Inertial Measurement Unit).

- A GPS module using GNSS technology. GNSS stands for Global Navigation Satellite System and is the general term for satellite navigation systems that enable autonomous geospatial positioning with global coverage. The term includes, for example, GPS, GLONASS, Galileo, BeiDou and other regional systems. GNSS is a term used worldwide with different advantages being the most important the accuracy, redundancy and availability at all times. Although satellite systems do not fail often, GNSS receivers can receive signals from other systems when they fail. Even with limited line of sight, access to multiple satellites is an advantage. Common GNSS systems include GPS, GLONASS, Galileo, Beidou and other regional systems.

Figure 13 GPS module (source: Novatel).

- The last module is the temperature sensor. A temperature sensor is a device, typically, a thermocouple or resistance temperature detector, that provides temperature measurement in a readable form through an electrical signal.

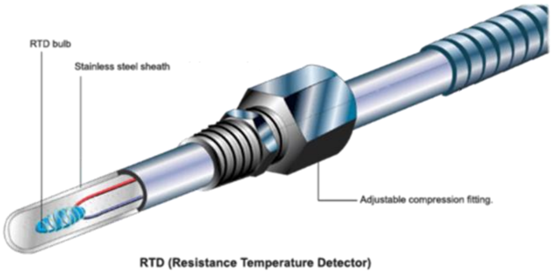

Figure 14 Temperature sensor (Source: Control and Instrumentation).

Several strain gauges were installed on the columns A and C of the platform (those columns holding the FRP towers) and its surroundings. More specifically, some have been placed on the composite part of the towers, some on the steel part and others on the bracers closest to the towers. Their exact locations were defined based on an optimization process carried out by CIMNE in WP4. All the gauges have been installed on the longitudinal direction of the element being monitored, i.e., the ones installed on the tower are aligned with its longitudinal direction, and the same happens with the ones installed on the columns and the bracers. There are a total of 48 strain gauges sending the data at 20 Hz. EnerOcean receives this data and pre-processes it to feed the digital twin. The figure below shows the final location of the strain gauges after their installation on the platform.

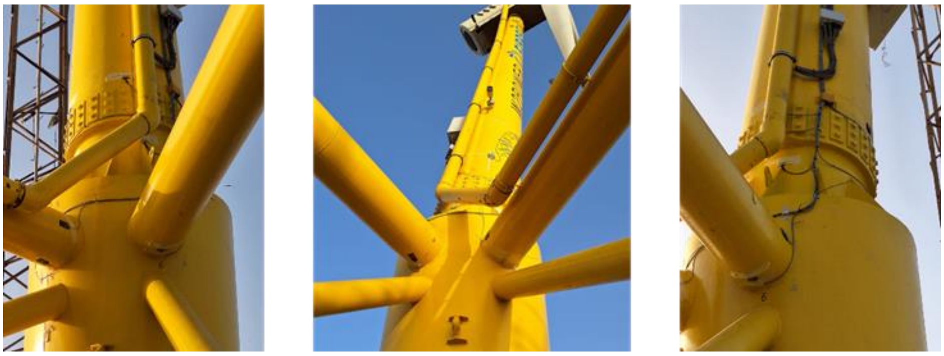

Figure 15 Strain gauges final installed

Two video cameras were installed in each tower, one on the nacelle and one on the supports manufactured for that purpose by Exail next to the electronic cabinets. During the installation, they were tested to ensure a correct recording as well as to define its aiming, so they capture the best area possible. The two cameras of the top allow doing visual inspections to the turbines in real time and, on the other hand, the low cameras cover all the floating structure.

Figure 16 Test of the video cameras at Astican's shipyard.

Regarding the Inertial Measurement Unit (IMU), it is installed inside the front column of the platform (column B) and gives very useful information related to accelerations, positioning, and gyros of the front column of the platform in real time and in a very accurate way. This device works sending data at 20 Hz and this data is pre-processed to generate outputs for the monitoring part and to feed the digital twin.

All the monitoring devices described above send the data to three industrial PCs installed in the platform, these PCs are connected to the router that send the data to a server at Plocan's facilities using the WiMAX or the 3G antennas. This is used to have a backup of all the data generated by the different monitoring systems. Besides, all the devices installed on the platform are prepared to reload in case the platform lose momentarily the power supply.

Another important step before the installation of all the monitoring systems mentioned above was to check and adapt the data acquisition systems of the platform. This was a crucial part because all the monitoring system depends on having a good communication between the platform systems and the onshore systems.

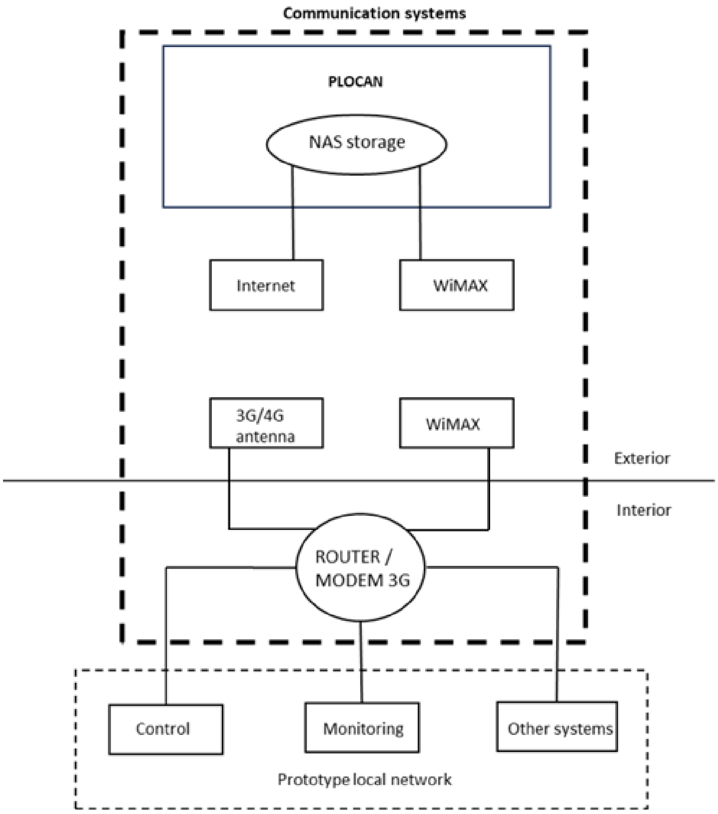

Figure 17 Communication systems.

As it can be seen in the previous figure, two ways of managing the communication were prepared. The main one uses two WiMAX antennas, one installed on the platform and the other at Plocan's facilities. They work using radio waves in the frequency range from 2.4 to 5.8 GHz and they must see each other with a clear view in order stablish the connection. The secondary one, which would be used in case the antennas lost the connection, consists of a router with a 3G antenna installed on the platform that would manage the connection in that case. During the installation, the WiMAX antennas were tested to ensure they could establish the connection without any inconvenience.

3.2. Specific FRP tower monitoring system

The selection of components, design, and technical justifications are extensively detailed in deliverable 4.8. In the subsequent pages, our focus shifts to the implementation methodology, encompassing the completion of the monitoring system and the installation process and the measurement for the firsts campaigns.

A primary aim of the FIBREGY initiative involved developing a Structural Health Monitoring (SHM) system to monitor the robustness of 1:6 scale FRP towers in the W2 Power Floating Offshore Wind Turbine.

The SHM system integrates a network of fibre optic sensors (FOS) installed within the fibres of the tower, alongside strain gauges, accelerometers, gyroscopes, and inclinometers affixed to its surface installed at 4 different levels of the FRP tower that is shown in the image below.

Figure 18 TSI installing the FRP monitoring system.

3.2.1. KPI´s to be monitored.

The development of a monitoring system to monitor the structural integrity of the FRP (Fiber Reinforced Polymer) towers is of vital importance for the success and longevity of floating offshore wind turbine (FOWT) platforms. To achieve this, a suite of key parameters is meticulously monitored during sea trials. These parameters serve as vital indicators of the towers' health, enabling early detection of potential issues and informed maintenance decisions, the principal list of KPI´s monitored is presented in the following table.

Damage Indicators	Description
Acceleration data	Vibration-based monitoring for rotative machinery condition inspection.
Displacements	Double integration of acceleration data for calculating platform displacements.
Motions	Real-time monitoring of global platform motions to understand sea energy effects.
Natural frequencies	Monitors structural natural frequencies to identify damages like scouring or brace failure.
Mode shapes	Visualizes tower deformation at resonant frequencies and detects defects.
Deformation	Tracks platform deformation and stress levels using strain gauges and sensors.
Inclination	Monitors lateral movements and stability using inclinometers.
Sea statistics	Records sea wave data for correlation with damage indicators.
Operational conditions	Monitors operation parameters like power and rotor speed via SCADA and PLC.
Fatigue loads	Impact of sea waves results in fatigue loads, influencing design assumptions.

Table 1 KPIs to be monitored of the FRP tower.

3.2.2. Monitoring system

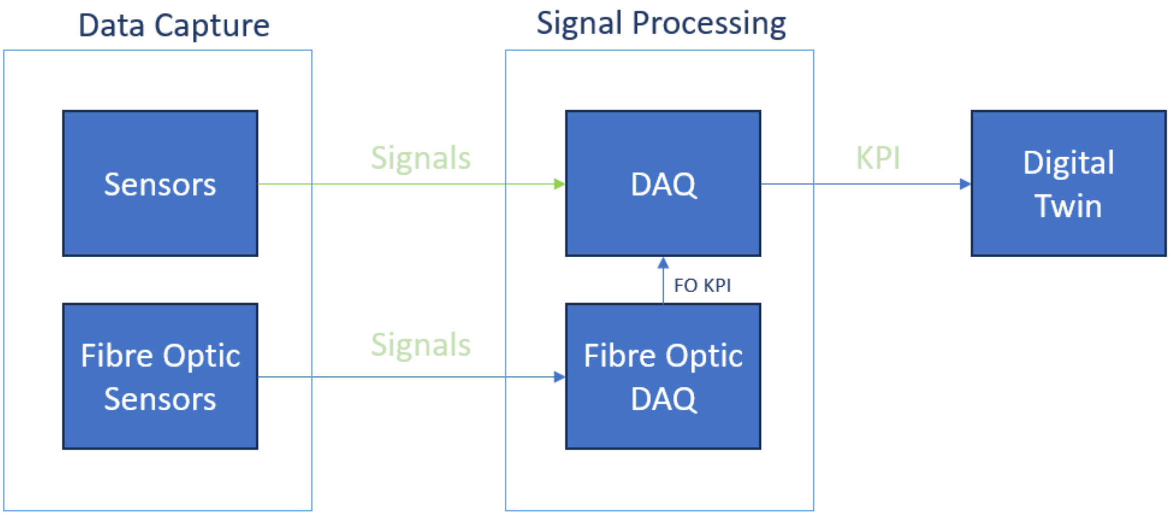

Figure 19 General architecture of the FRP monitoring system.

The backbone for generating critical data used by the digital twin developed in the project is the monitoring system described in the previous section. The primary function of this system is to capture phenomena using sensors and fibre optic technology, thereby generating raw data that is transmitted as signals to the data acquisition (DAQ) system.

In the case of FO sensors, the raw data is subjected to initial interpretation by a specialist device known as the FO interrogation unit. This device can process signals from fibre optic sensors. The interrogator then transmits the processed information to the general DAQ, which handles signals from all other sensors. The DAQ system then processes these signals to derive Key Parameter Indicators, which are critical for validating the model analysis performed by the Digital Twin.

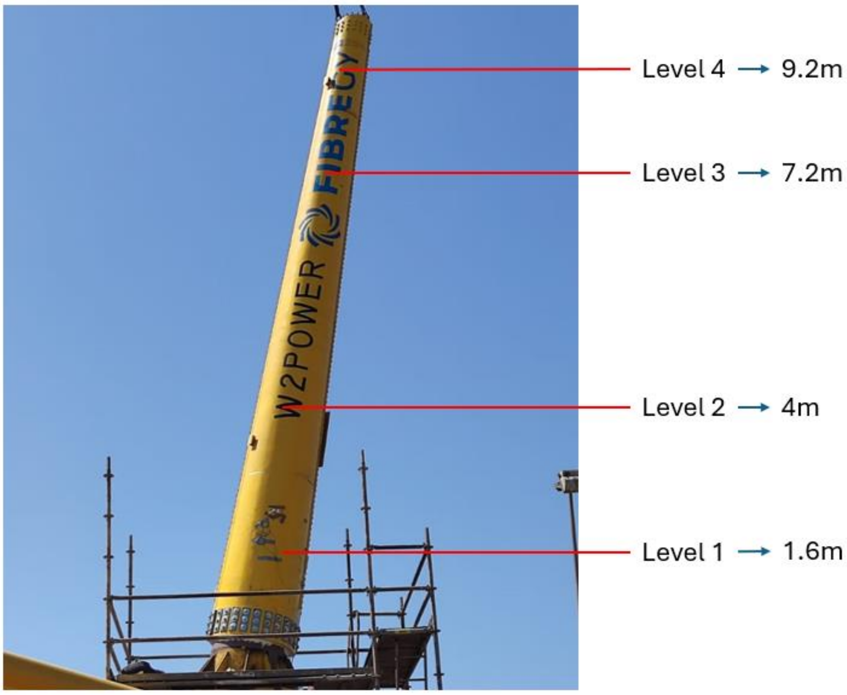

Figure 20 Levels of installation of the sensors.

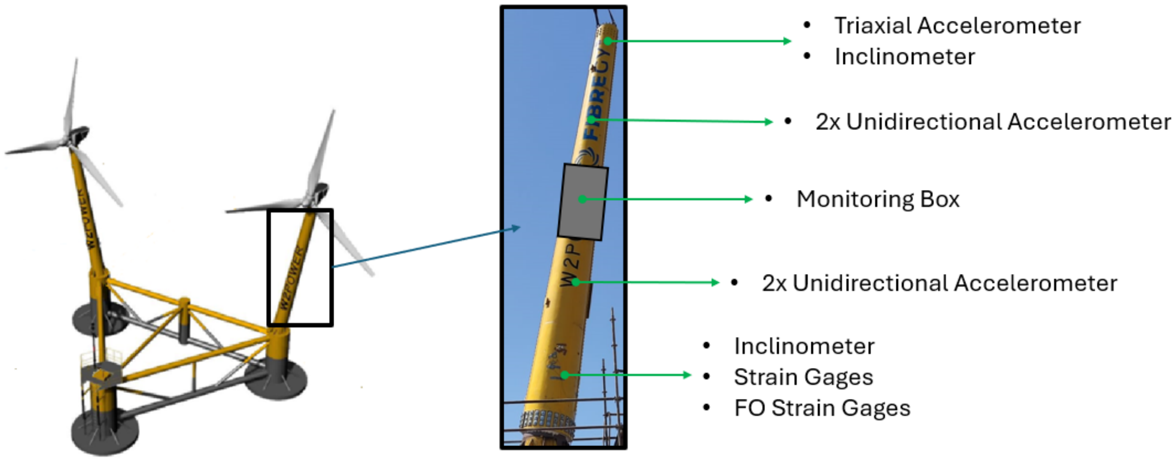

Figure 21 Disposition of sensors at the FRP tower.

The Figure 20 and Figure 21 show the four planes into which the FRP towering structure has been divided to make the installation of all the sensors selected for this project:

- Level 1
  - Inclinometer
  - 8 Strain gauges
  - 4 FO Strain gages
  - FO temperature sensor
- Level 2
  - 2 Unidirectional accelerometers (x; y)
- Level 3
  - 2 Unidirectional accelerometers (x; y)
- Level 4
  - Triaxial accelerometers (x, y, z)
  - Inclinometer

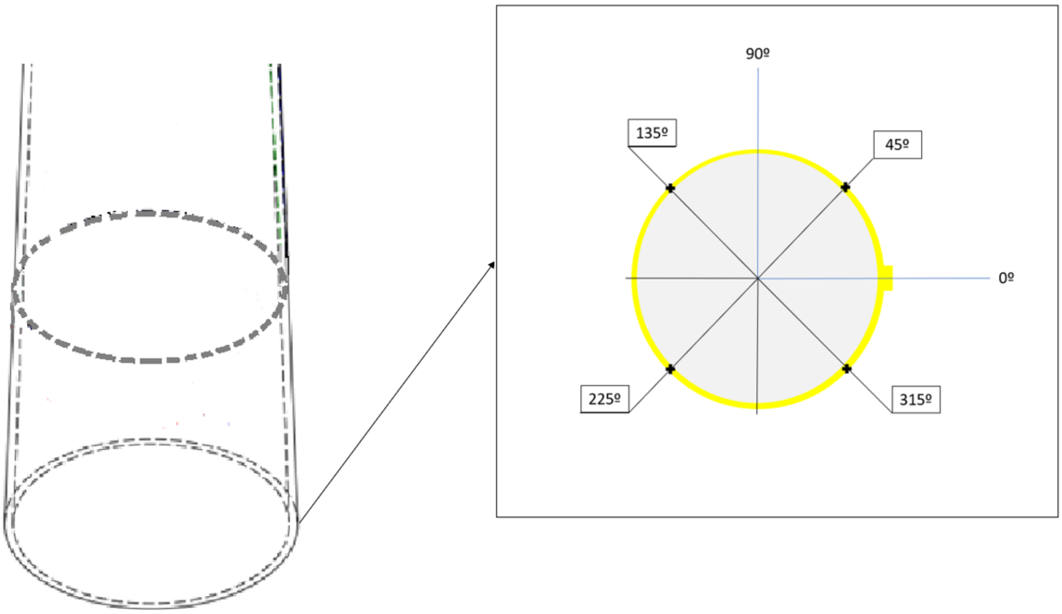

Figure 22 Installation angles.

Careful attention was paid to the angles of the FRP tower during the meticulous process of installing the different sensors. In particular, the angles were carefully considered when positioning the strain gauges. This included considering the wings created by the joint line of the connection between the FRP panels, which acted as a reference point at 0 degrees. The points chosen for installation were as follows:

- Angle 1: 45°
- Angle 1: 135°
- Angle 1: 225°
- Angle 1: 315°

3.2.2.1. Cabinet

Figure 23 Monitoring cabinet installed at the tower.

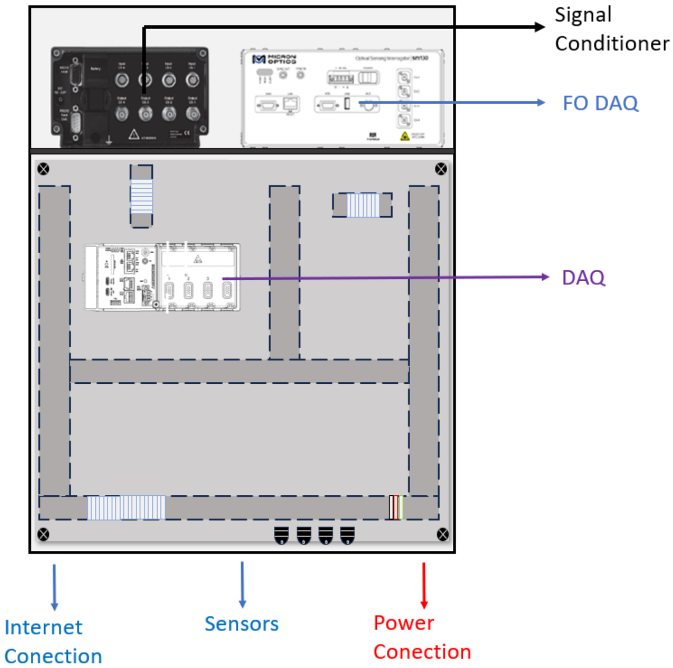

Figure 24 Main components of the FRP monitoring cabinet.

The Figure 24 presents the principal elements of the monitoring cabinet, that is composed of:

- Main devices
  - DAQ: This device processes the signals sent by the inclinometers, accelerometers and fibre optic sensors and strain gauges and generates the Key Parameter Indicators (KPI) that are sent to the Digital Twin.
  - Fiber Optic DAQ: This device serves for transmitting and receiving optical signals. Its primary function is to transmit a luminous signal and receive the optical signal in return sent back by the fibre optic strain gauges and temperature sensors, providing direct correlation to the phenomena.
  - Signal conditioner: The focus of the uniaxial accelerometers chosen for this project lies in detecting low-frequency phenomena. Therefore, ICP accelerometers were selected. To interpret the signals emitted by these accelerometers and convert them into a format understandable by the data acquisition system (DAQ), a signal conditioner was chosen (Nexus-2692). This signal conditioner effectively translates the signals from the accelerometers to millivolts per unit gravitational force (mV/g).
- Main connections into the cabinet
  - Internet connection: To reliably transmit Key Performance Indicators (KPIs) to the Digital Twin and ensure a stable Internet connection, the data is transmitted through EnerOcean's infrastructure using WiMAX technology. This ensures a consistent flow of data for real-time monitoring and analysis, critical for informed decision making.
  - Sensors: To send data to the DAQ, each sensor has a cable that runs from the sensor to the cabinet to transmit the information.
  - Power coaction: To be able to power the entire infrastructure of the cabinet and the sensors, a cable is used from the batteries of the EnerOcean infrastructure to the FRP monitoring cabinet. This cable transmits the power as a monophasic signal at 24VDC level.

3.2.2.2. Electrical Power Supply

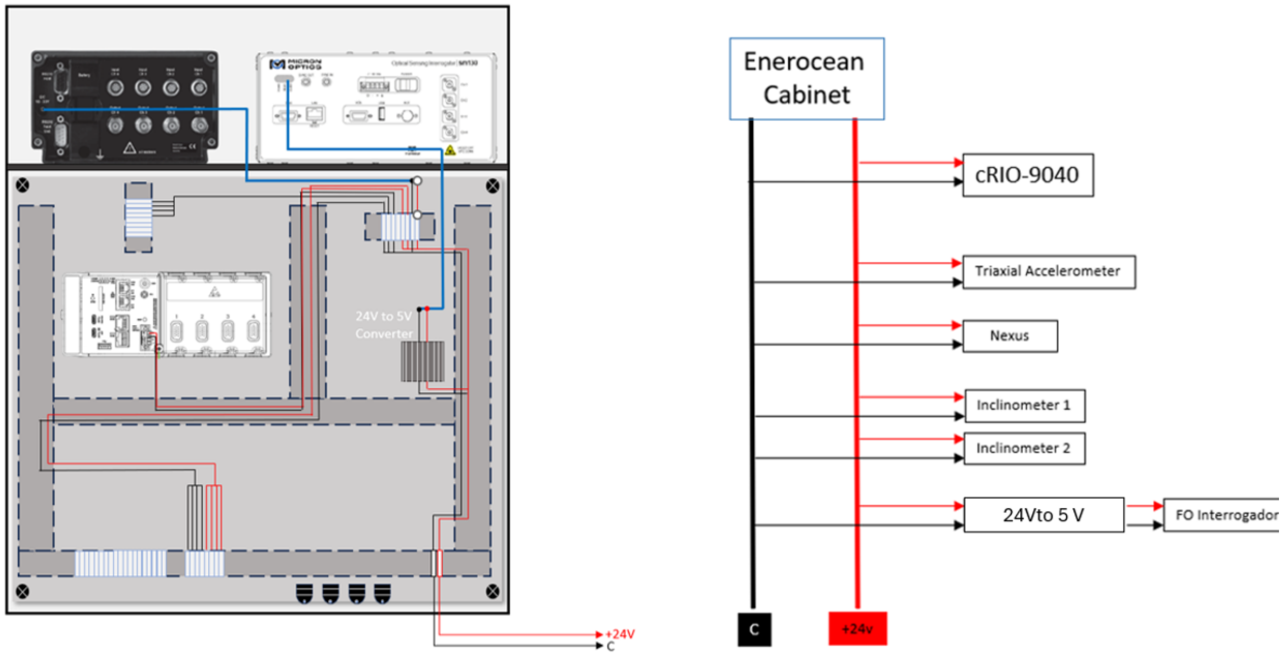

Figure 25 Electrical connections of the cabinet.

The Figure 25 shows the energy levels required for each device and sensor of the FRP monitoring cabinet and a schematic of the electrical connections:

- 24VDC
    - DAQ (cRIO9040)
    - Triaxial accelerometers
    - Signal conditioner (Nexus)
    - Inclinometers
- 5VDC
    - Fiber Optic Interrogator

3.2.2.3. Data Acquisition System

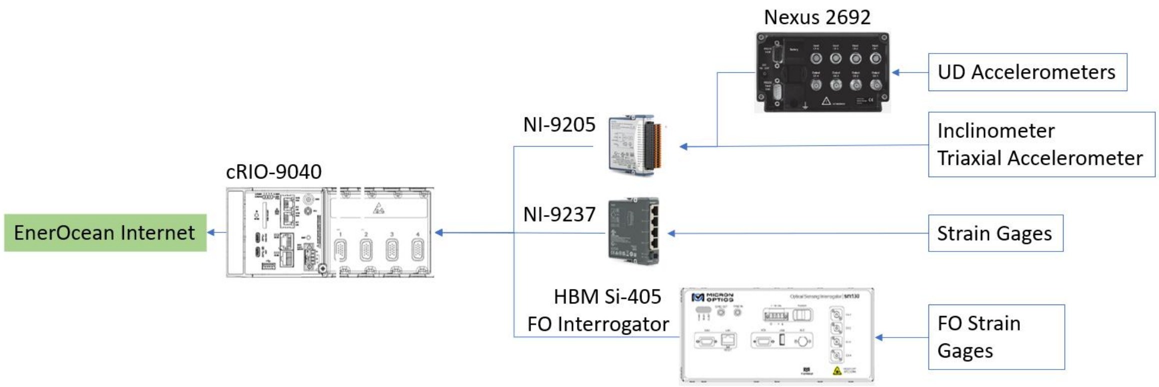

Figure 26 Connections of the sensors to the main devices of the monitoring cabinet.

The previous image shows the connections between the components of the monitoring system, in this project two different Data Acquisition Systems were installed and developed, a CompactRio-9040 and a Fiber Optic interrogator (SI405):

cRio-9040: Installed to process and postprocess most of the data generated by the sensors installed at FRP tower (accelerometers, inclinometers, and strain gauges) to generate the Key Performance Indicators of the SHM system. Installed in two of the four slots available on the NI-9040 were the NI-9205 module with 32 channels for analysing signals from accelerometers, gyroscopes, and inclinometers and the Ni-9237 module, which focuses on processing the signals of the strain gauges with its four channels. To make all the necessary processing software of this project it was used LabVIEW, developed by National Instruments.

SI405: This hardware was selected for the analysis of the strain and temperature signals acquired from the fibre optic sensors network; the strain-based fibre optic sensors installed at the surface of the tower.

3.2.2.4. Sensors

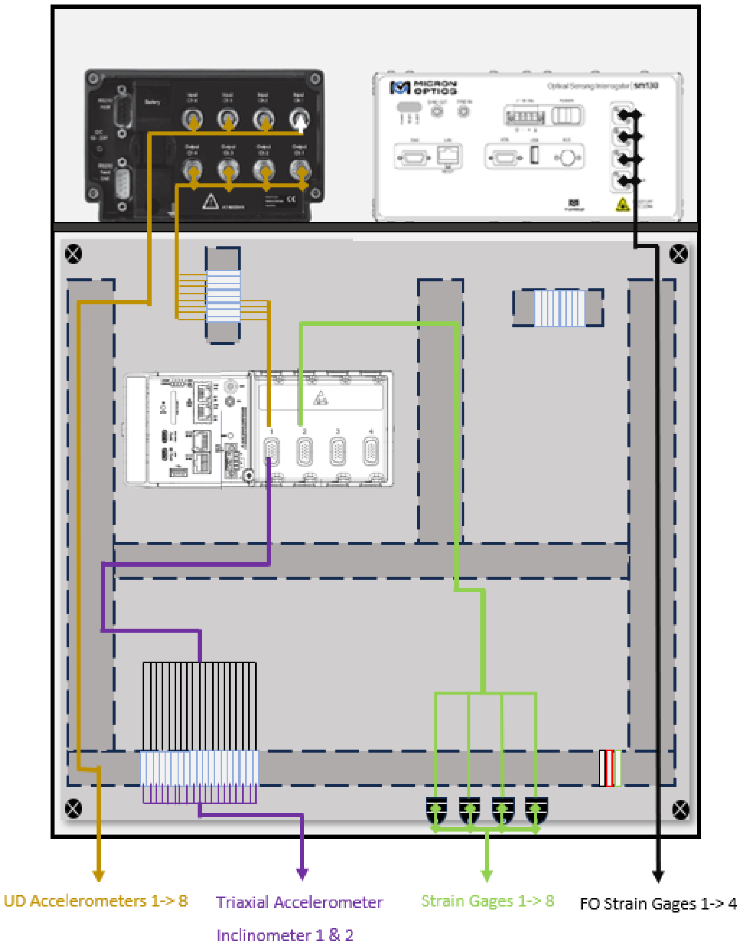

Figure 27 Schematic of the connection of sensor's cables to the monitoring cabinet.

From the monitoring cabinet exits four different cables relative to the connection of the sensors to the DAQ:

- Unidirectional accelerometers: 4 unidirectional cables that connects the accelerometers directly to the signal conditioner and this transmits the adapted signal to the DAQ.
- Inclinometers: 2 cables that connects to the DAQ.
- Triaxial accelerometer: 1 cable pass through the cabinet to connect to the DAQ.
- Strain gages: 8 cables pass through the cabinet to connect to the DAQ.
- FO strain gages and temperature sensors: 4 cables pass through the cabinet to connect to the sensors with the interrogator.

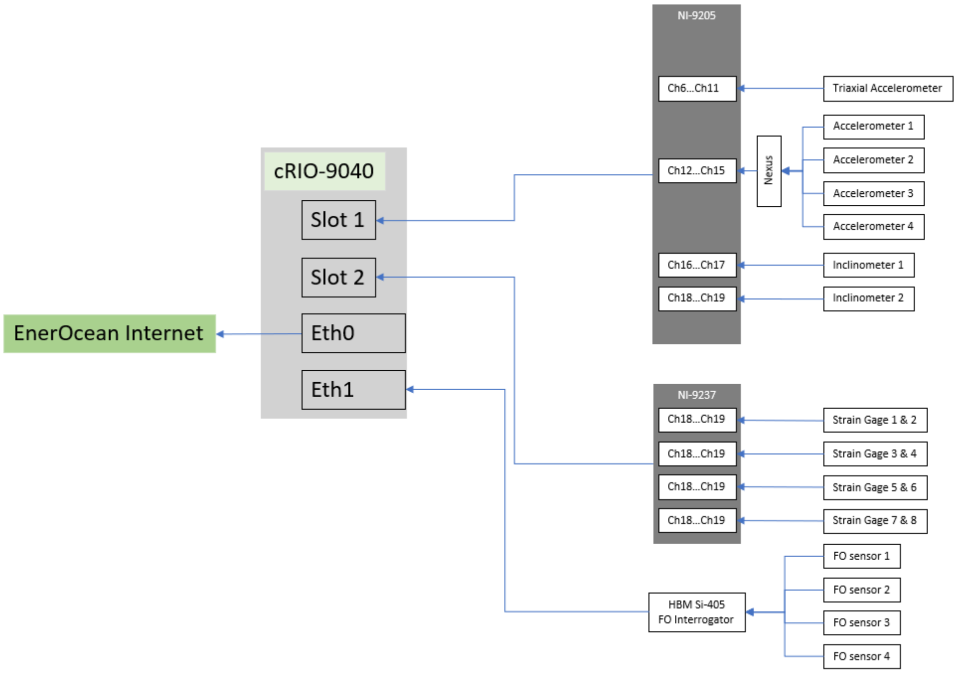

Figure 28 Connection of the sensors to the DAQ.

In the Figure 28 can be seen the order in which each single signal cable of the sensors is connected to their corresponding card of the compactRio-9040 DAQ

Accelerometers

Throughout the project's duration, accelerometers positioned at various levels of the tower were employed to record acceleration data. This data provided valuable insights into the natural frequencies, damping, and mode shapes of the structure.

- Accelerometers at three tower levels (4000 mm, 7200 mm, and 9200 mm) recorded acceleration data, enabling comprehensive analysis.
- Sensor orientation facilitated thorough monitoring of tower movements, capturing accelerations in X, Y, and Z axes at base and apex levels.
- Sensor models, including "Dytran 7576" and "B&K 4381," offered essential data for structural health assessment.

	Component	Heigh (cm)	Angular Position (°)	Measures
Level 2	2 Monoaxial B&K 4381	400	25	Accelerations X; Y
Level 3	2 Monoaxial B&K 4381	720	25	Accelerations X; Y
Level 4	1 Triaxial Dytran 7576	920	25	Accelerations X; Y; Z Rotations X; Y; Z

Table 2 Installation parameters of the accelerometers.

Figure 29 Unidirectional accelerometers installed at the FRP tower.

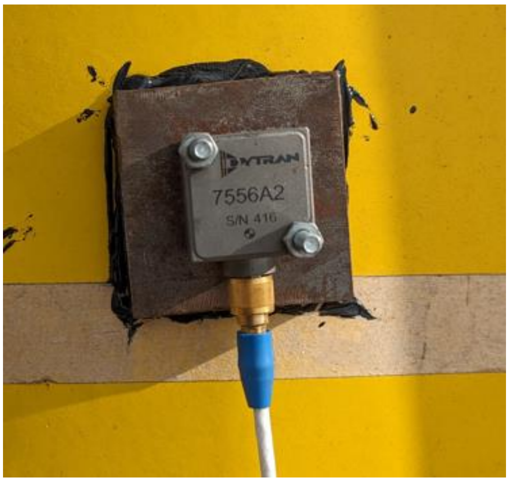

Figure 30 Triaxial accelerometer installed at the FRP tower.

In the previous images can be seen some of the accelerometers installed at the tower, to stick these sensors to the surface of the tower the sensors were connected to a stud glued to the surface with epoxy resin that corresponds with the black stain of the surface in the previous images.

Inclinometers

Stability monitoring of the W2Power platform was successfully achieved through the implementation of Level Developments' dual axis DAS-90-A inclinometers. These were positioned at Level 1 (1600mm) and Level 4 (9200mm) of the tower. These inclinometers provided information on the stability of the platform.

	Component	Heigh (cm)	Angular Position (°)	Measures
Level 1	Das90A	400	25	Inclinations X; Y
Level 4	Das90A	720	25	Inclinations X; Y

Table 3 Heigh of installation of the inclinometers

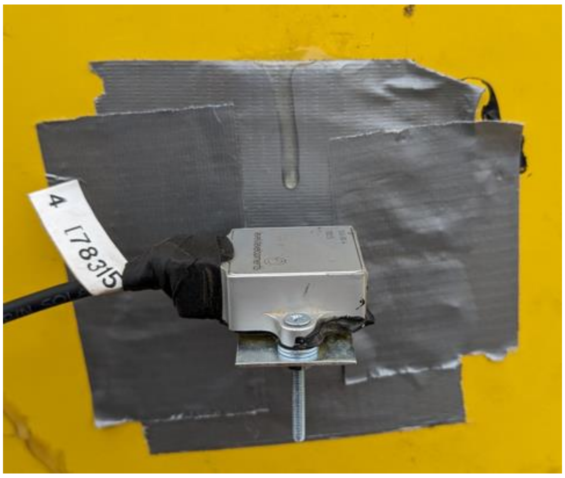

Figure 31 Instilled inclinometer at the FRP tower-

Strain Gauges

The deployment of strain gauges emerged as an indispensable tool for evaluating stress levels effectively in this completed project. This is particularly the case in high-stress areas. This approach was both reliable and cost-effective in monitoring strain. The deployment of strategically positioned strain gauges at Level 1, situated at a height of 160 cm, provided in situ data for stress analysis, enabling a comprehensive understanding of the structural performance of the tower.

The installation of eight strain gauges, positioned at 45°, 135°, 225°, and 315° angularly, formed a robust network for monitoring strain distribution. These gauges were configured in a half-bridge setup with measurement points strategically situated at 90° intervals across the tower's cross-section to facilitate comprehensive data collection.

Throughout the project, the strain sensor array captured the temporal variations in strain of the tower. The real-time monitoring capability permitted continuous assessment of structural integrity.

Figure 32 Stage of installation of the strain gauges.

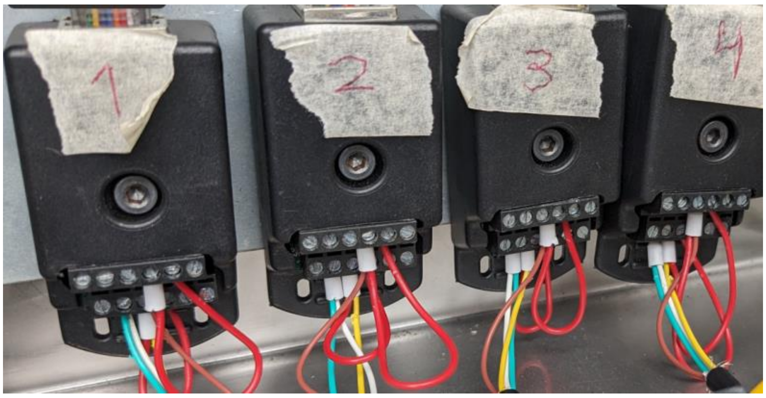

Figure 33 Connector of the strain gauges to the DAQ.

In the Figure 32 can be seen the installation made of the gauges during the project, one thing to consider is as can be seen in Figure 33 that the cables of the strain gauges were connected to a Rj-50 adaptor because that is the input format of the NI-9037 card that reads the signals.

<u>Fiber Optic Strain Gauges</u>

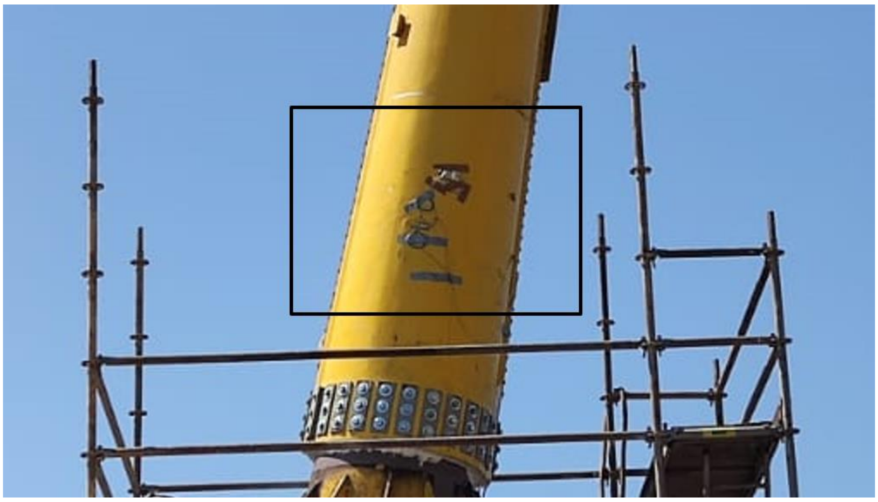

Figure 34 Original embedded fiber optic embedded sensors.

Figure 35 Installation of new fiber optic sensors at FRP tower surface.

One of the integral aspects of this project is the monitoring of the strain on the surface of the FRP tower. To ensure accurate measurements, four fibre optic strain sensors and one fibre optic temperature sensor have been installed. This arrangement compensates for strain variations caused by exposure to sunlight, which could otherwise distort the measurements.

As can be seen in Figure 34 and Figure 35 firstly the fiber optic sensors were embedded in the FRP tower panels, but, during the installation of the tower to the structure these measuring fiber optic channels broke so it was decided to install again the same sensors but now attached to the surface of the towers can be seen in Figure 35.

3.2.2.5. Signals

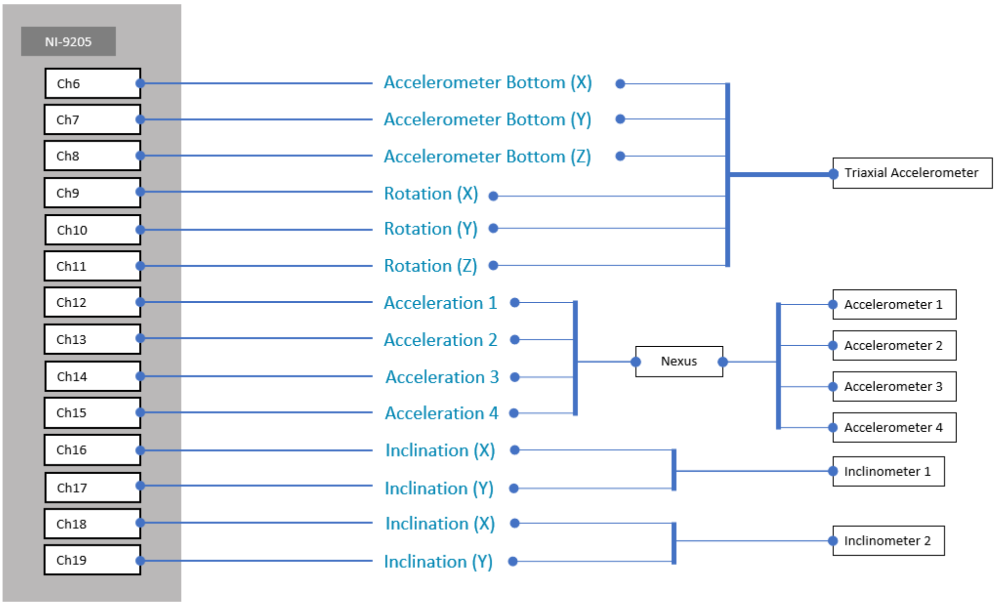

Figure 36 Signals processed by the Ni-9205 card.

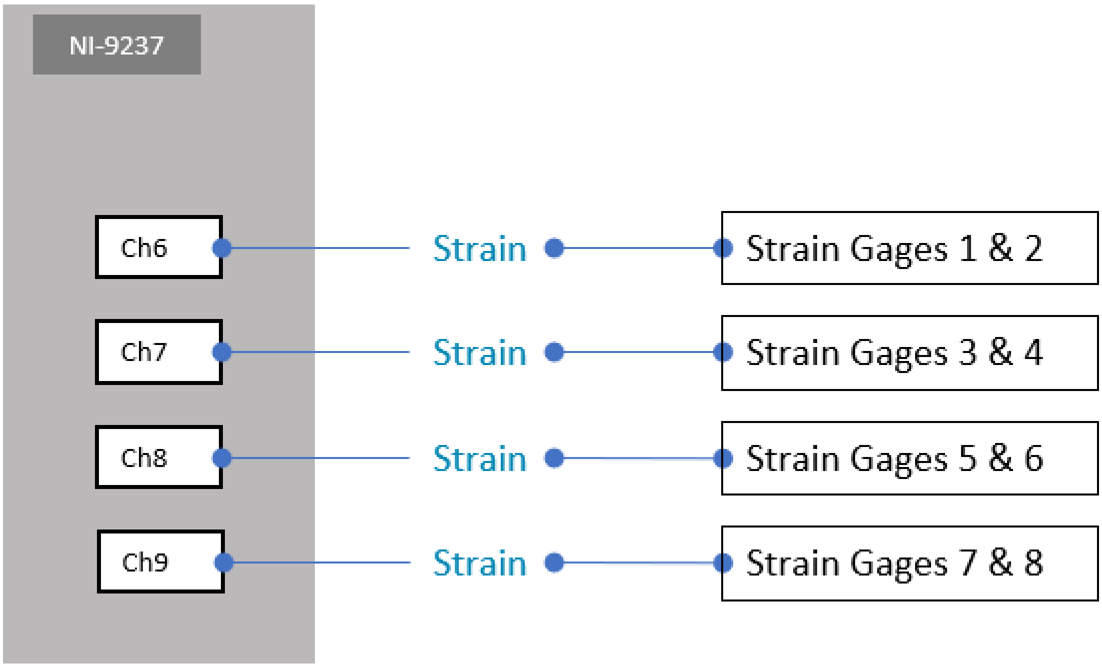

Figure 37 Signals processed by the Ni-9237 card.

The preceding images illustrate the channel distribution of all sensors wires responsible for transporting raw data, which will subsequently be processed by the DAQ. These images provide a clear indication of the card and channel allocated to each measurement.

Regarding the strain gauges, achieving microdeformation measurements for each channel necessitates a specific configuration. In this scenario, a half-bridge configuration is utilized, requiring two strain gauges per channel. One strain gauge functions as the primary measuring element, while the other serves for compensation purposes. This arrangement ensures accurate measurement and compensation for environmental factors, allowing for precise assessment of microdeformations.

4. Modal analysis of the platform

The objective of the experimental modal analysis (EMA) of the platform is to obtain the knowledge of the vibrational behaviour of this innovative power platform, more specifically of the towers and evaluate the structural effects produced by the exposure of the platform to the different environmental and metocean conditions. Considering that the two towers are geometrically identical, the EMA has been carried out on one of them.

The information obtained with the EMA has been used to validate the Finite Element Model of the FRP towers used in the digital twin.

4.1. Methodology

The EMA describes the dynamic behaviour of any mechanical structure by using the response of the structure (natural frequencies, mode shapes and damping) measured with accelerometers when applying a broadband excitation with a shaker or with a hammer (Bocko., 2013) (Ewins, 2000). The frequency response function (FRF) is a transfer function that describes the structural response to an applied force as a function of the frequency (Rantatalo, 2020).

Experimental modal analysis requires a definition of a mesh to get all the FRFs. The size of the structure, the mechanical properties of the material and the number of natural frequencies required to observe determine the resolution of the mesh. If one creates a fine measurement mesh with high resolution, the number of measurements will be too high, nevertheless reaching higher modes and less spatial aliasing.

The applied roving accelerometer methodology consists of exciting the structure in one position and measure the dynamic response in all points of the mesh by using, in this case, five accelerometers simultaneously and moving them to cover all positions of the mesh. Once all the FRFs have been obtained we need to apply a curve fitting to get the dynamic behaviour of the structure, obtaining the natural frequencies, mode shapes and damping.

The subject of the EM is one of the towers.

4.1.1. Instrumentation

The equipment used for these determinations is the following:

Impact Hammer Endevco 2305 (black tip, sensitivity = 0.197 mV/N)

Five triaxial accelerometers DJB/AT/14/TB.10 (sensitivity = 10 mV/g)

Acquisition unit LMS Scada's Mobile SCM205 (Siemens).

Both the impact hammer and the accelerometer were verified before and after the tests.

The LMS Scada's III acquisition and analysis system was driven using the specific module for modal analysis named Impact Testing, as part of the LMS TestLab 16A software. The processing of the measured data was carried out using the module Modal Analysis.

4.1.2. Test setup.

The test setup consisted of definition of the tower meshing, accelerometer fitting, determination of the hitting point, selection of the tip of the impact hammer (frequency range vs force amplitude), gain setup for the equipment and finally the protocol of testing.

The tower is almost cylindrical with a height of 9 m and diameter of 1600 mm at its basis and 700 mm at the top. To obtain the first 3-4 vibration modes and avoid spatial aliasing and considering that the displacement of the accelerometers along the whole surface of the tower is a very long-time consuming task, a uniform mesh with 20 points was defined, as shown in Figure 38 were also a general view of the tower can be observed.

The 20 mesh points were defined at five different levels, being the first level at 0.5 m from the basis and each level separated 2 m until the upper level, at 0.5 m below the top of the tower, where the wind turbine lies. Four measurement points were defined at each level, forming 90° angles with the adjacent points.

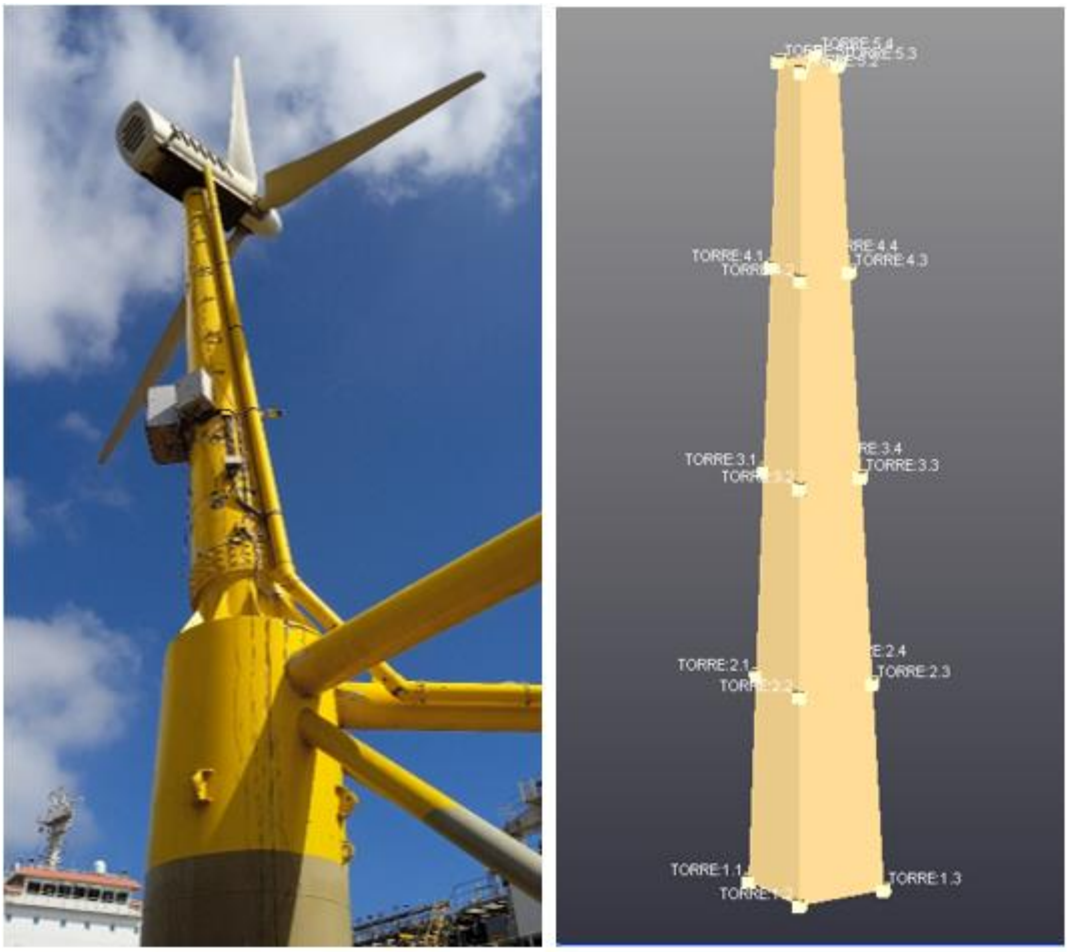

Figure 38 General view of the tower (left) & Creation of the meshing at the EMA software (right)

The Experimental Modal Analysis (EMA) tests used five triaxial accelerometers fit to the tower with bee wax The accelerometers were placed along one vertical, moving all of them to adjacent points, situated at 90°, to cover the 20 measurement points. The impact hammer hit 3 times at the selected point for each accelerometer configuration. Three axis measurements allowed full characterization of modal shapes for the first modes without having aliasing.

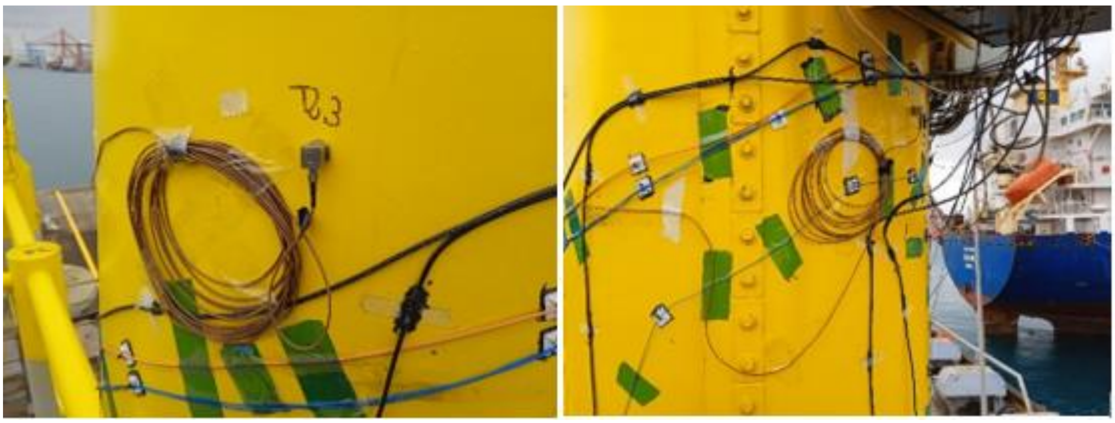

Figure 39 Accelerometer fixation with temporary bee wax.

4.1.3. Test execution.

When the measurement setup was defined (preliminary test preparation), the FRF measurements can be done. Each measurement consisted in hitting three times with the impact hammer at the selected point (point 3.1 and measuring in real-time the coherence between each hit to have maximum values (close to 1) in the whole bandwidth of interest, except in the anti-resonances where the coherence may be lower (Siemens, s.f.)

Figure 40 shows an example of coherence analysis with hammer excitation at point 3.1 and vibration response measurement at point 4.1. The upper plot represents the coherence values and the lower plot represent the FRF at that point. It can be observed how the coherence is 1 between 20 Hz and 200 Hz.

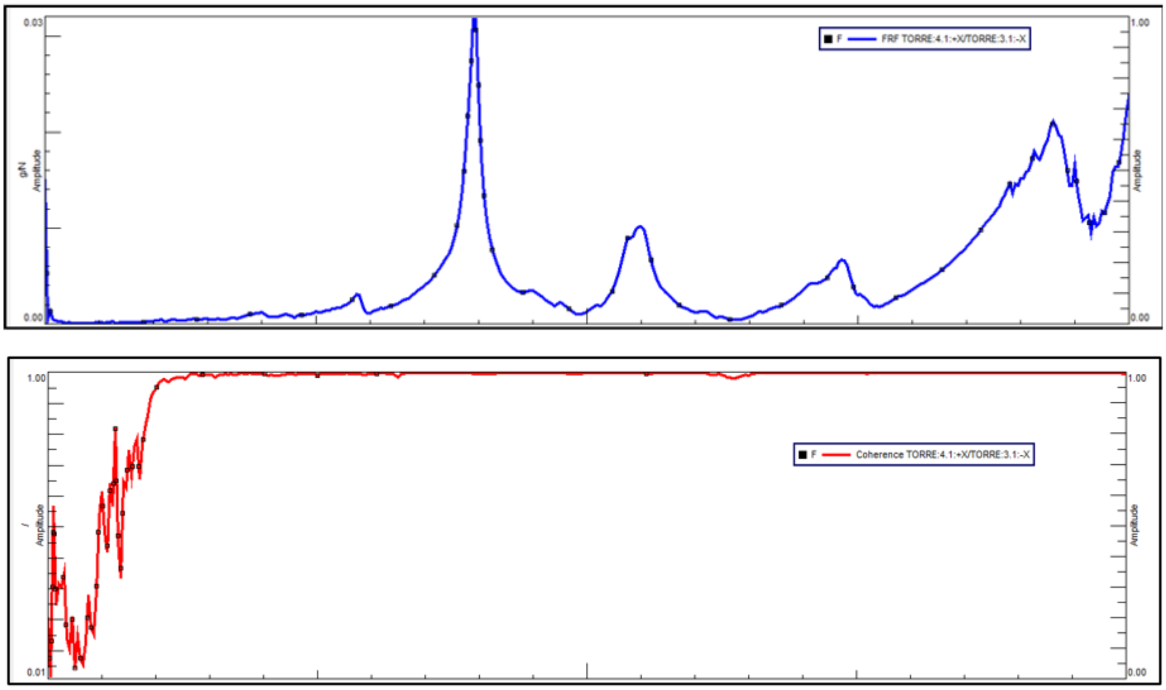

Figure 40 Coherence analysis.

At the end of the measurements, we have 20 FRFs corresponding to the transfer function between each pair excitation-response. We need to carry on a curve fitting process to find the natural frequencies and mode shapes, using LMS TestLab software.

4.2. Results of the modal analysis

The following table shows the normalized eigenfrequencies and modal damping for the first modes after the EMA of the tower.

Mode	Normalized frecuency	Damping
1- Radial mode	1,00	1,6
2	1,36	1,17
3- Torsional mode	1,59	301,2
4- Bending mode	1,83	3,86
5	1,89	2,16
6	2,21	39,5
7	2,46	3,01
8	2,53	1,23

Table 4 First modal frequencies and damping for the tower.

The appearance of the first four modes presented in the previous table is shown in the upcoming images. In these two views of each mode are presented, an isometric view of the deformed tower and a top view.

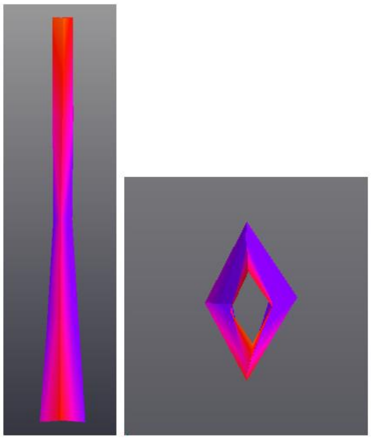

Figure 41 Mode 1– (Radial mode).

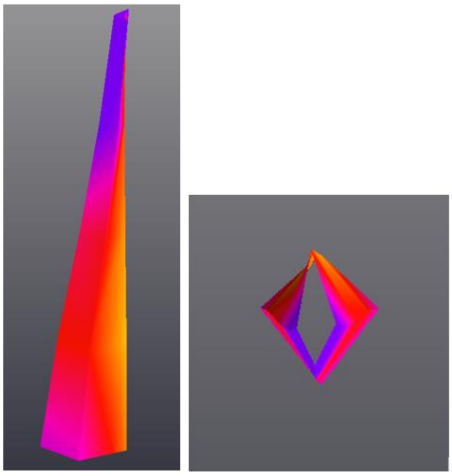

Figure 42 Mode 2.

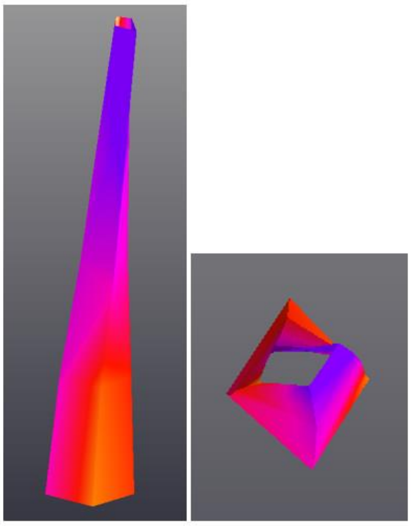

Figure 43 Mode 3– (torsional mode).

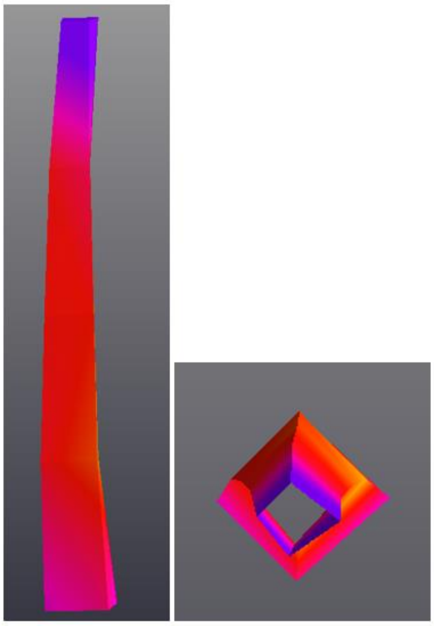

Figure 44 Mode 4– (bending mode).

The last step of the analysis is the validation of the model, applying the Modal Assurance Criterion (MAC) technique, which gives us the information about how alike the different modes are. The vertical bars represent how similar are the modes compared in each pair. The bars in the diagonal are always 100% because that is the comparison between each mode with itself, while the other positions show the similarity between other pairs of modes. High grade of similarity between separated modes may indicate spatial aliasing and the need for more measurement points (Siemens, s.f.). The MAC diagram of this experiment is presented in Figure 45.

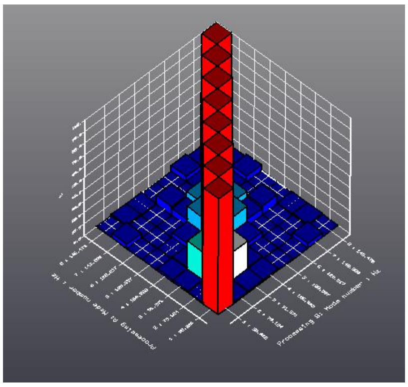

Figure 45: Modal Assurance Criterion of the EMA.

As seen in Figure 45, no aliasing is observed, except a 25% of similarity between modes 2 and 3.

4.3. Conclusions

As mentioned above, the information obtained with the EMA has been used to validate the Finite Element Model (FEM) of the FRP towers used in the digital twin. It has been verified that the modes identified experimentally can be found by the Finite Element Model. It has been confirmed that the FEM model exhibits vibration modes very close to the identified frequencies. However, due to the complexity of the structure's response (involving materials with significantly different stiffness), it has not been possible to directly compare the shapes of the corresponding local modes.

5. Experimental results of W2power 1:6 prototype

5.1. Substructure and general monitoring system results

Once all the monitoring systems were installed and properly configured, different tests were carried out to check the performance of the data acquisition system.

This procedure started with the testing of the of the data acquisition system at the dry dock, important to calibrate some of the sensors and to check their behaviour. During this process, all the data were analysed to detect noise patterns, drift in the output or any type of warning that implied a reconfiguration. Besides, a general check of all the mechanical and electronic systems was carried out at the dry dock.

Once the tests at the dry dock were considered satisfactory, the platform was loaded out. After that, a second check of the different sensors and electronic system was carried out afloat. These tests included the calibration of zero of the strain gauges in static condition, by using as reference the results of the digital twin.

5.1.1. Results at the dry dock

The first monitoring systems analysed were the strain gauges, they are identified with the gauge ID and the iMeasure ID to which they are connected.

At this point, there were generated two types of graphics, one to see the performance of the gauges through the time, and other to generate some useful statistics that help to determine the quality of the data. When representing these data, it is important to consider the symmetry of the structure, i.e., the strain gauges of the tower A have symmetry with the one in the tower C what is an interesting fact to consider during the comparison of the results. Under normal function, they are expected to follow a similar curve.

For these results, there have been generated the time response of the strain gauges in a small-time window to facilitate the visual analysis of the data.

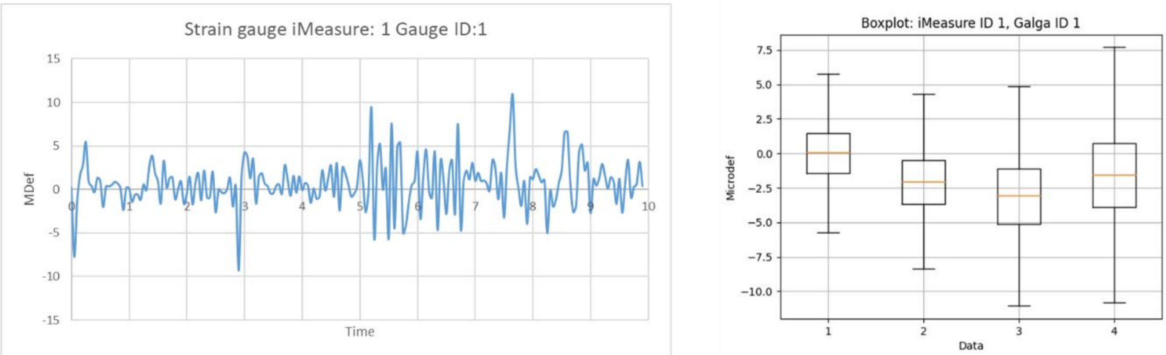

Figure 46: Strain gauge tower A, 1-1: left time series; right data analysis.

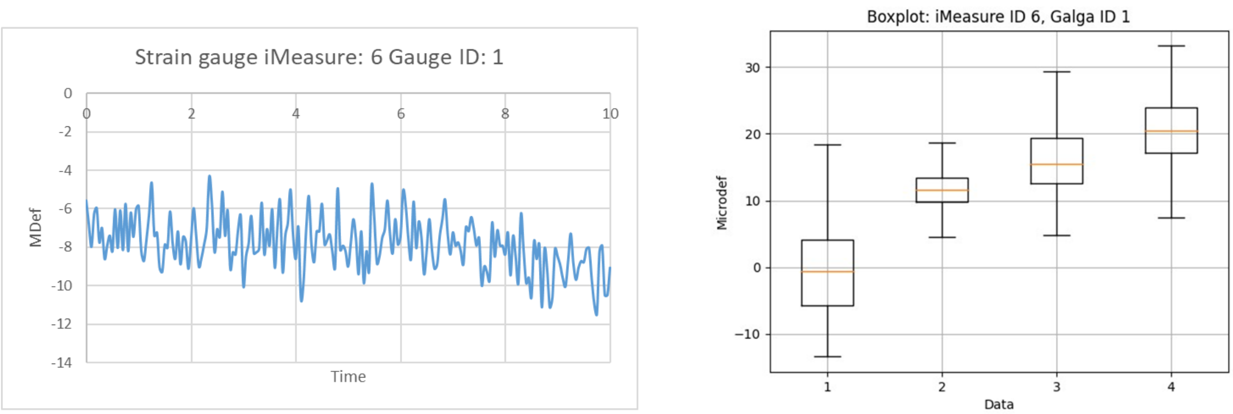

Figure 47 Strain gauge tower A, 6-1: left time series; right data analysis.

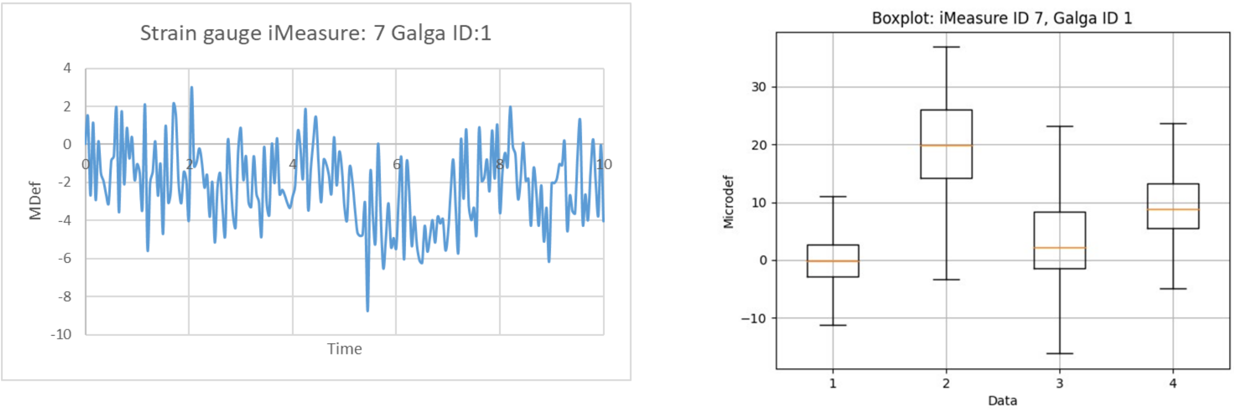

Figure 48: Strain gauge tower A, 7-1: left time series; right data analysis.

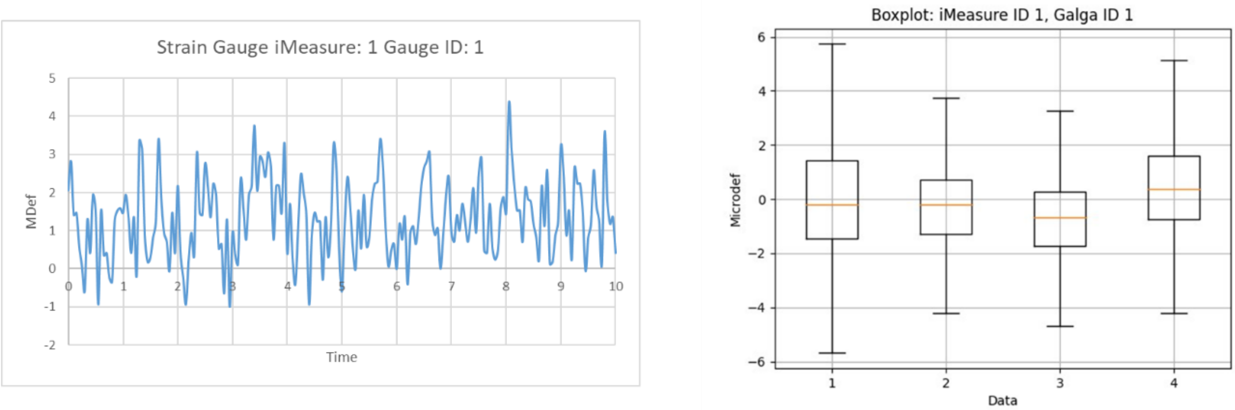

Figure 49 Strain gauge tower C, 1-1: left time series; right data analysis.

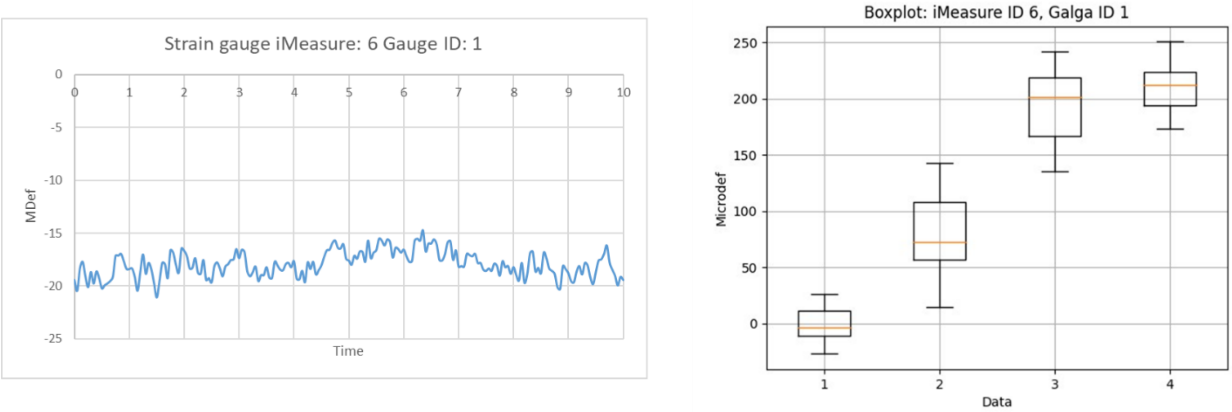

Figure 50: Strain gauge tower C, 6-1: left time series; right data analysis.

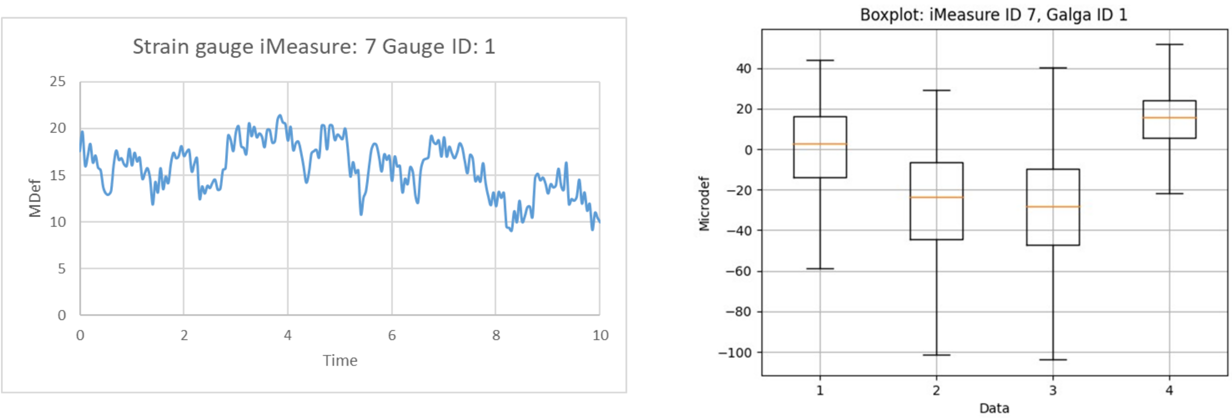

Figure 51: Strain gauge tower C, 7-1: left time series; right data analysis.

As it can be seen in all the previous graphics, the strain gauges installed on the structure do not experiment big dispersions what is a sign of the quality of the data generated by the sensors.

Regarding the time series (on the left), in all cases the output tends to maintain constant around the same values and with very little deviations. These is a normal behaviour considering that these are the output generated at the dry dock, so there were not expected big variations in the data. The strain gauge are highly sensitive sensors so its performance can be very influenced by temperature changes or electrical interference what produces some oscillations in the output.

The right graphics are the box and whiskers diagrams of all the recorded data in different time periods. This graph shows the distribution of the micro deformations for four different data sets and allow to see if there is any type of dispersion in the data recorded. Regarding its interpretation:

- Median: the orange lines inside the boxes. They seem to maintain constant along the time which means that there is consistency in the data set.
- Box: the outline of the boxes Indicates the value of the interquartile range (IQR), which is calculated with the difference between the third quartile (75%, upper edge) and the first quartile (25%, lower edge). This shows a moderate dispersion of data.
- Whiskers: These are the ends of the vertical lines, and they show the total variation of the data, excluding extreme values (outliers). The ranges are quite similar across all sets, indicating consistency in the variability of measurements.

In general, all the gauges were performing well taking into consideration the weather conditions in which they operated and their location.

5.1.2. Metocean conditions

For the results, it has been also measured the metocean conditions to make a comparison between the outputs of the IMU (Inertial Measurement Unit) and the general environmental conditions.

This is very useful because allows not only to validate de data but also to estimate the displacements and rotations that the platform suffered because of the wind and waves action.

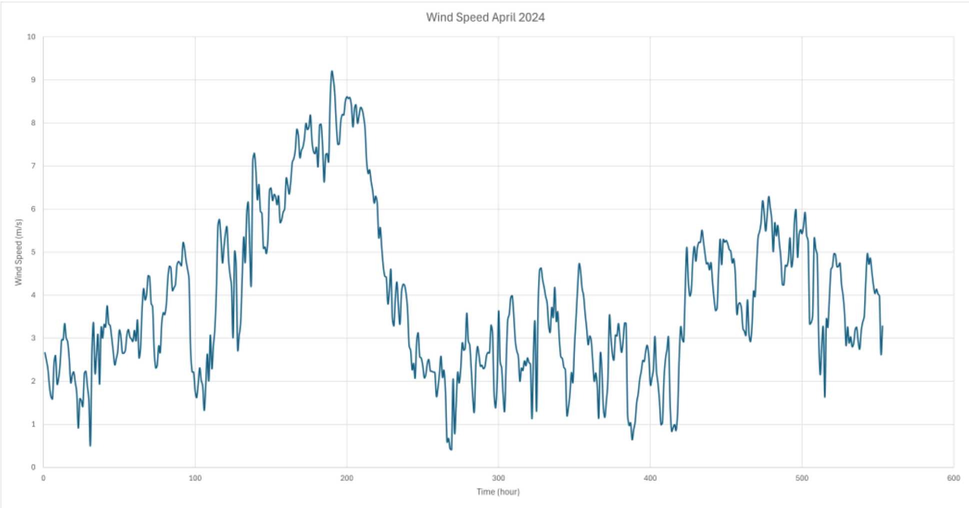

Figure 52 Wind speed metric.

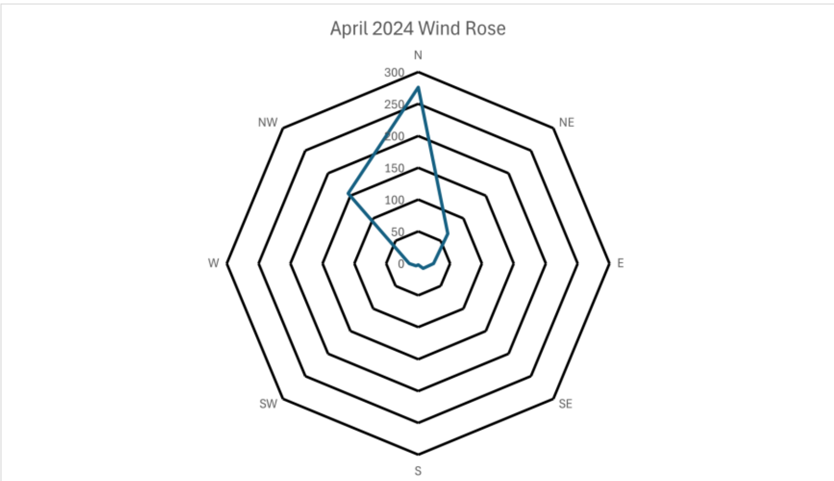

Figure 53 Wind rose metric.

As it can be seen in the Figure 53, the platform operated under a enviromental conditions with wind speed peaks of 9-10 m/s in North – Norht west direction.

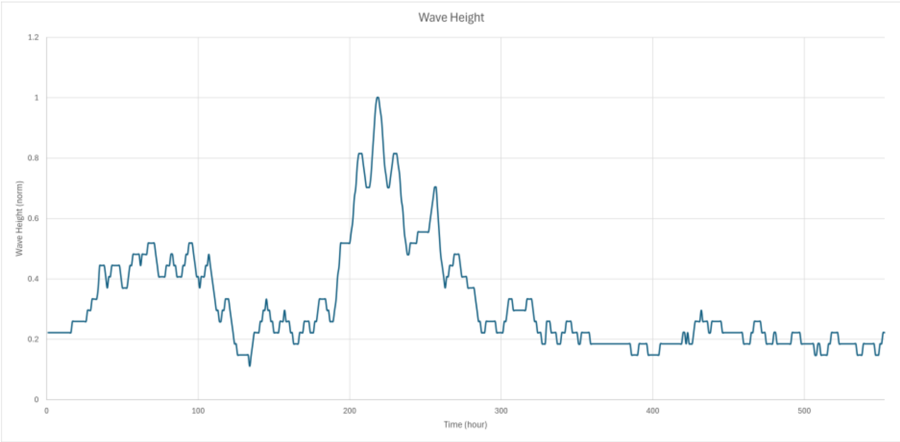

Figure 54 Wave Height

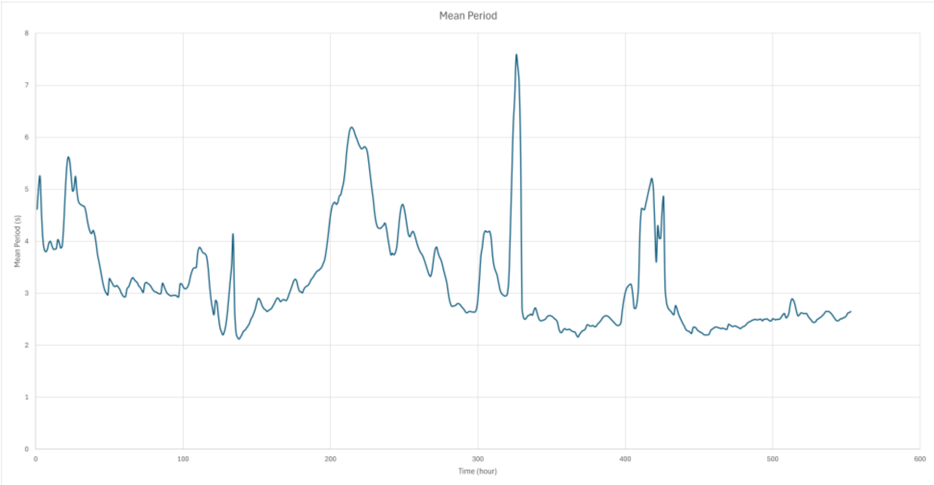

Figure 55 Mean Period.

The Figure 54 and Figure 55 shows the wave heigh and its mean period of a whole month. These graphic were compared with the ones generated with the data of the IMU as a validation and study of the effects of the wind on the the general behaviour of the platform. Due to confidetiality the Figure 54 were normalized with the maximum value of the serie.

5.1.2.1. Results afloat

As stated above, once the tests at the dry dock were considered satisfactory, the platform was loaded out. Then, a second check of the different sensors and electronic system was carried out. These tests included the calibration of zero of the strain gauges in static condition, by using as reference the results of the digital twin.

The examples of results presented in this section follow the same format used in the previous section, facilitating comparison with those generated at the dry dock. As mentioned earlier, due to the large amount of data generated by these sensors, only a small-time window is shown here, allowing for an overview of the gauges' performance.

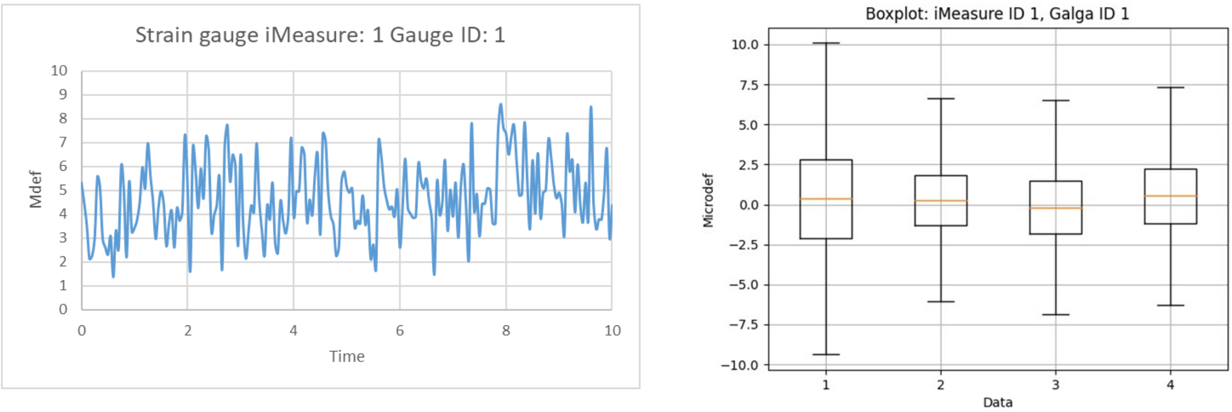

Figure 56 Strain gauge tower A, 1-1: left time series; right data analysis.

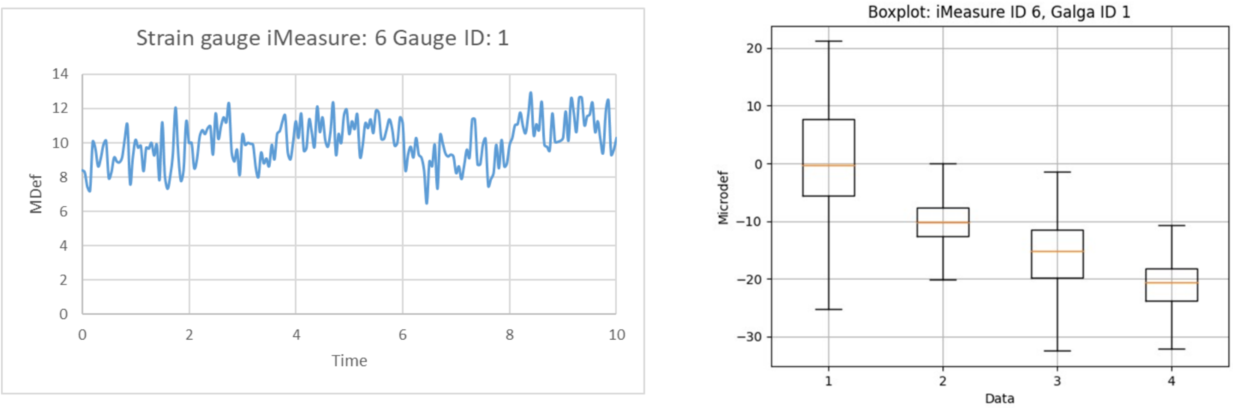

Figure 57 Strain gauge tower A, 6-1: left time series; right data analysis.

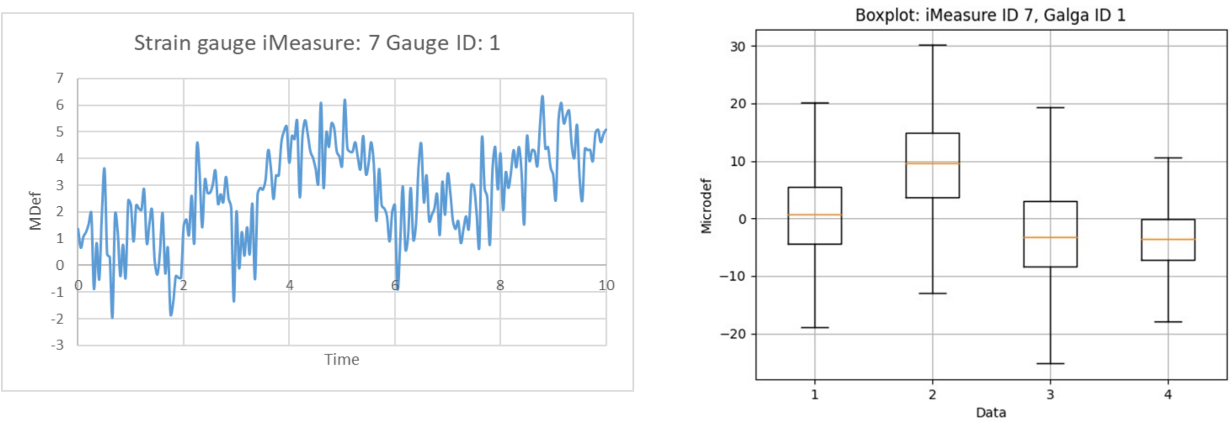

Figure 58 Strain gauge tower A, 7-1: left time series; right data analysis.

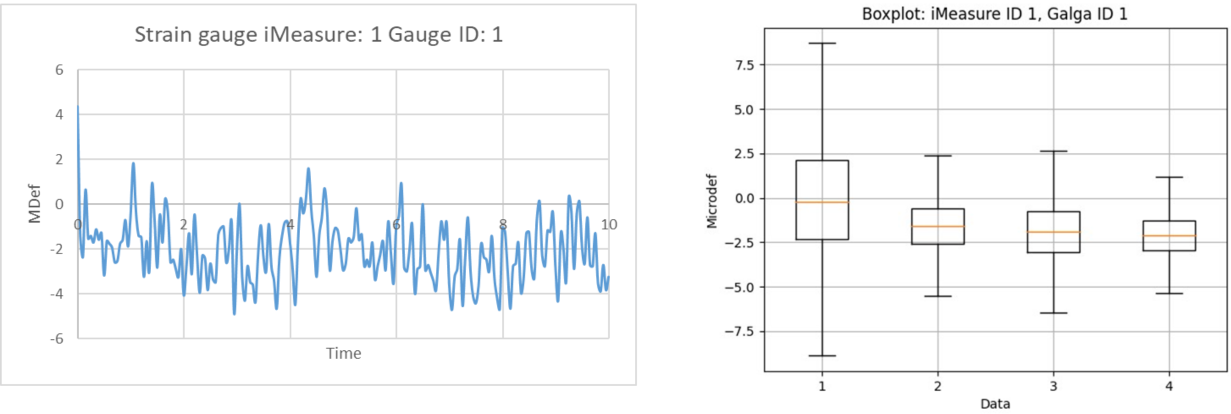

Figure 59: Strain gauge tower C, 1-1: left time series; right data analysis.

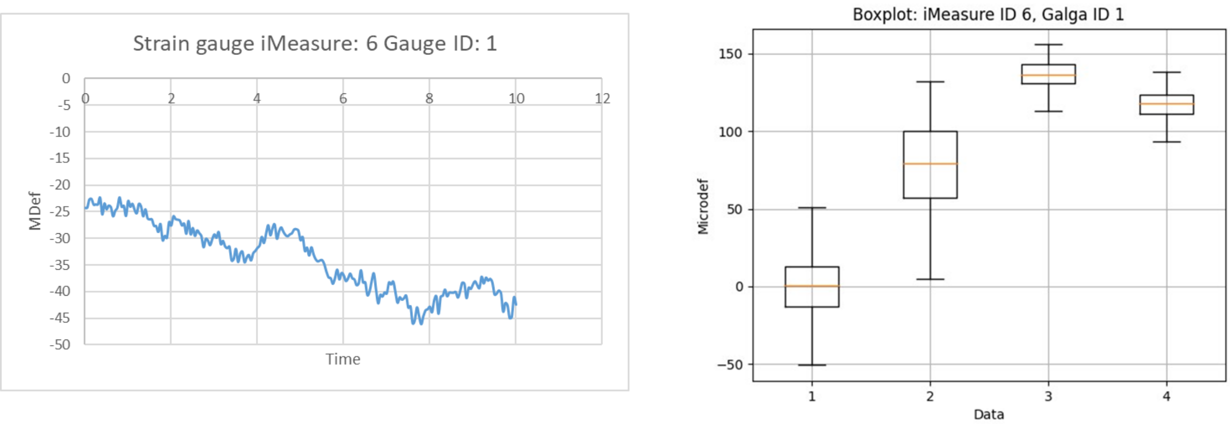

Figure 60 Strain gauge tower C, 6-1: left time series; right data analysis.

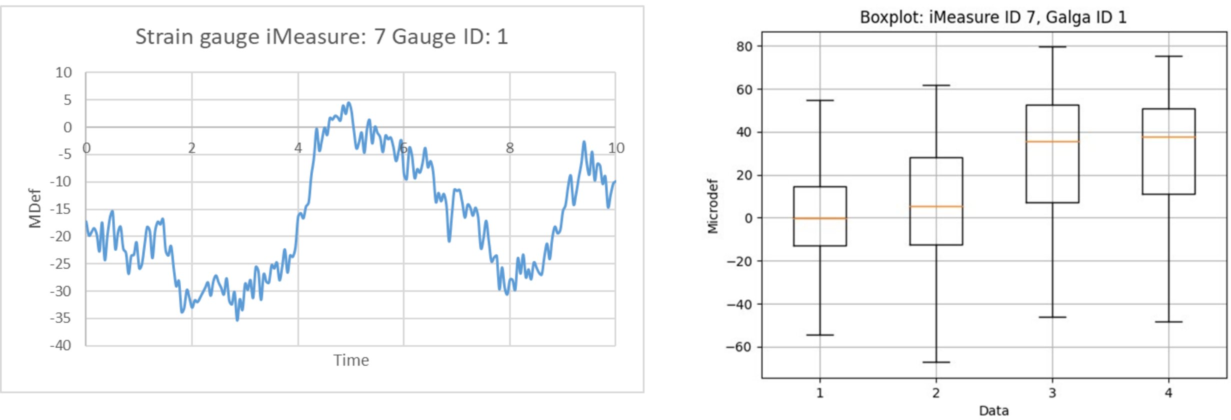

Figure 61: Strain gauge tower C, 7-1: left time series; right data analysis.

After analysing these results, was found that all the gauges were generating the data without any problems and that all the outputs were within range. In addition, all the data was processed and sent to feed the digital twin thanks to the communication system explained at 3.1.

These graphs are useful for understanding the mechanical behaviour of structures, facilitating the identification of potential structural issues and the validation of mechanical behaviour models.

On the other hand, there were also generated some graphics with the data collected from the IMU. These device gives allows to monitor the movements of the platform and its position in a very accurate way. Due to confidentiality all the graphics bellow were normalized with the maximum value of the whole time series.

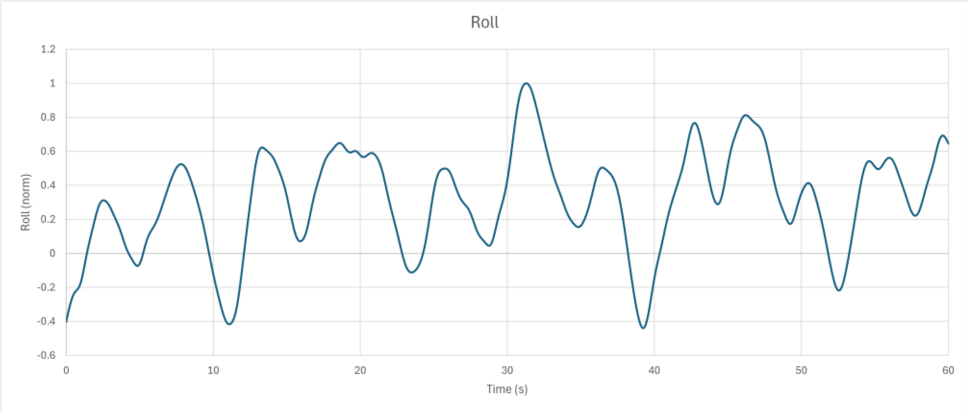

Figure 62 IMU roll output.

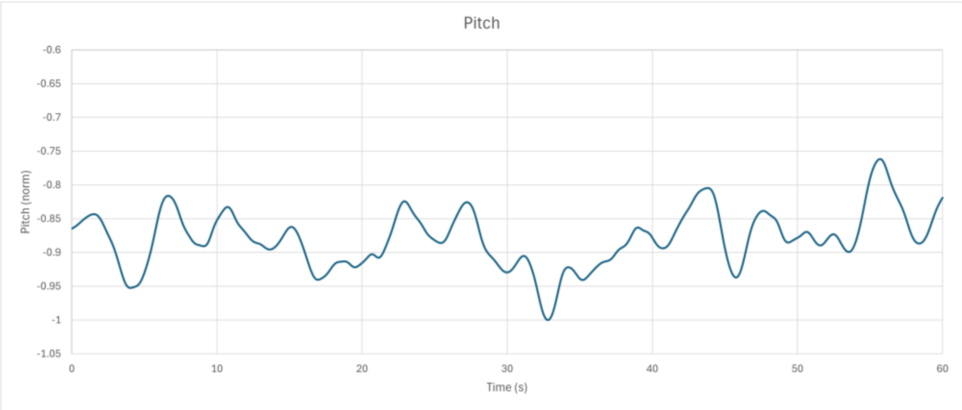

Figure 63 IMU pitch output.

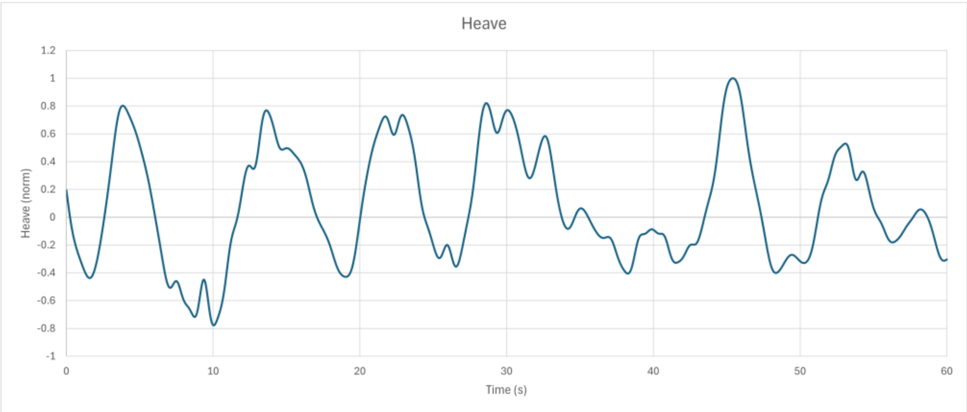

Figure 64 IMU heave output.

The Figure 62, Figure 63 and Figure 64 shows the roll, pitch and heave information generated by the IMU. These graphics can be compared with the ones of the Figure 54 and Figure 55 to see how the mean period of both signal is similar and is in range.

5.2. Specific FRP tower monitoring system results

Due to confidentiality reasons the y-axis or x-axis in some of the figures are hidden, the data was generated by measuring 10 minutes of every hour.

Similarly, to the previous case, once all the monitoring systems were installed and properly configured, different test were performed to check the performance of the data acquisition system.

The different tests started at the dry dock, aimed to calibrate some of the sensors and to check their performance. During this process, all the data were analysed to detect noise patterns, drift in the output or any type of behaviour that may imply a reconfiguration. Once the tests at the dry dock were considered satisfactory, the platform was loaded out. Then, a second check of the different sensors and electronic system was carried out.

5.2.1. Results at dry dock

- Inclinometer

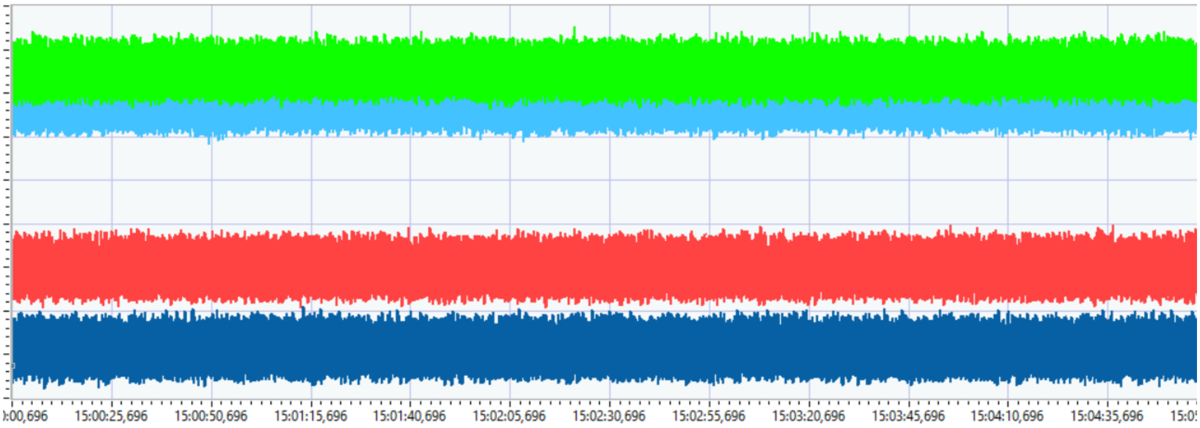

Figure 65 Inclinometer measurements at dry dock.

The previous graph shows the results of the measurement of the two inclinometers installed at the FRP tower. The measurements of the inclinometer installed at the bottom of the tower are highlighted in red (x-axis) and blue (y-axis). The green (x-axis) and cyan (y-axis) corresponds to the measurements of the inclinometer located at the top of the tower.

- Triaxial accelerometer

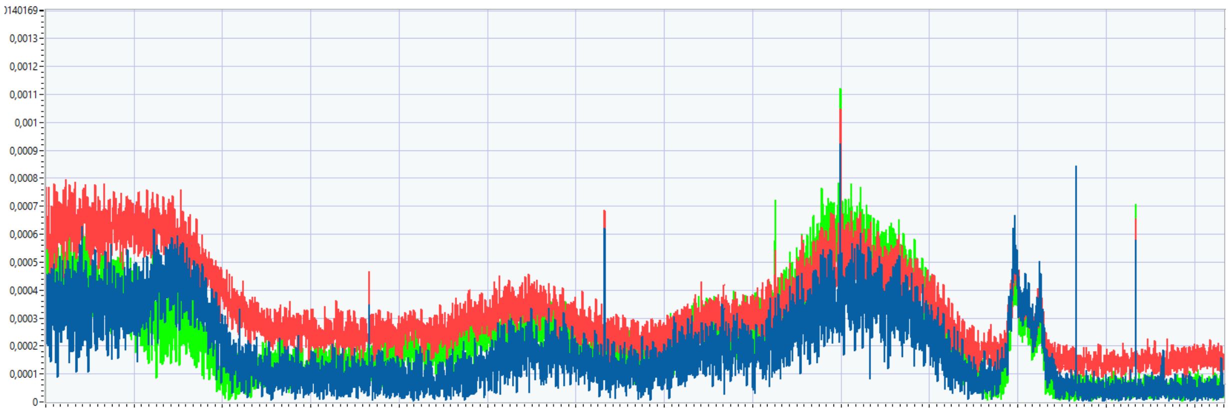

Figure 66 Triaxial accelerometer X Y Z measurement of phase magnitude at dry dock conditions.

The Figure 66 showcase the phase-magnitude calculation made at dry dock conditions of the triaxial accelerometer installed at the top of the FRP tower, the x-axis is represented by green, the results for the y-axis in green, and the results for the z-axis in blue.

- Unidirectional accelerometers

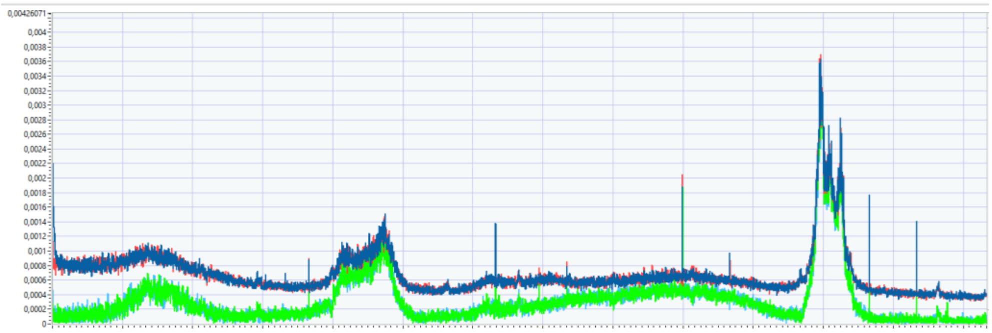

Figure 67 Uniaxial accelerometers measurement of phase magnitude at dry dock conditions.

The previous figure showcases the same magnitude-phase calculations showcased previously for triaxial accelerometer, but in this case depicts the results of the calculations for the four accelerometers installed at the second and third levels of the FRP tower:

- Level 2
  - Uni-directional accelerometer measuring x-axis in cyan.
  - Uni-directional accelerometer measuring y-axis in blue.
- Level 3
  - Uni-directional accelerometer measuring x-axis in green.
  - Uni-directional accelerometer measuring y-axis in red.

- Strain Gages

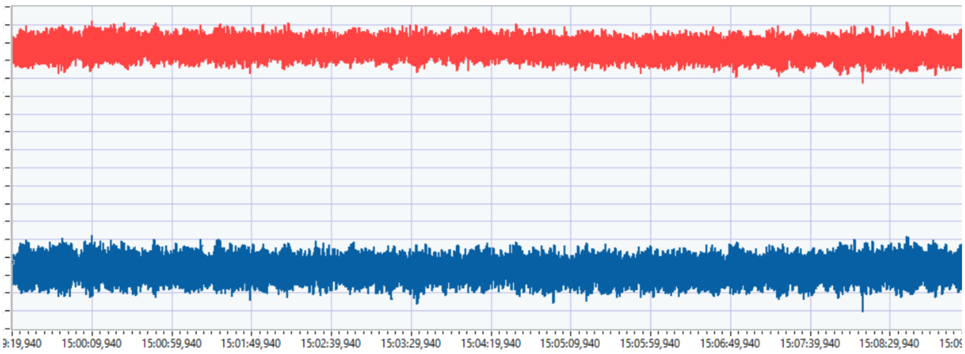

Figure 68 Strain gauges deformation measurements acquired by strain gages at dry dock.

In the previous image it is depicted the results at dry dock of the measurements of the strain gages located at 0° in red and the strain gage located at 45° in blue.

- Fiber optic strain gages

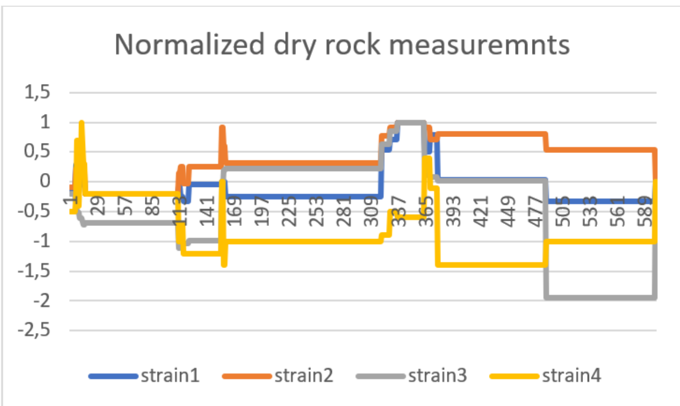

Figure 69 Normalized fiber optic strain measurements.

The previous image show cases the results of the fiber optic strain gages installed at the surface of the FRP tower.

5.2.2. Results afloat

- Inclinometer

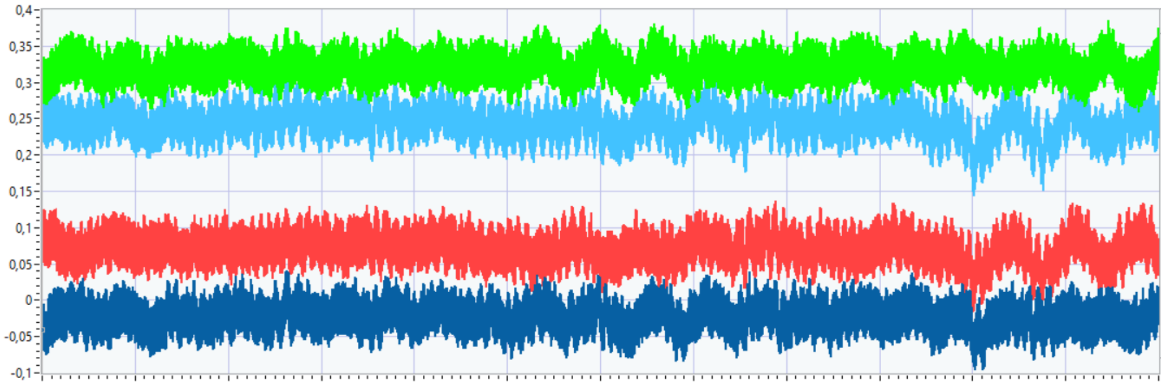

Figure 70 Inclinometer measurements.

The previous graph of both inclinometers measurements, the inclinometer installed at the bottom of the tower is highlighted in red (x-axis) and blue (y-axis). The green (x-axis) and cyan (y-axis) corresponds to the measurements of the inclinometer located at the top of the tower.

- Triaxial accelerometer

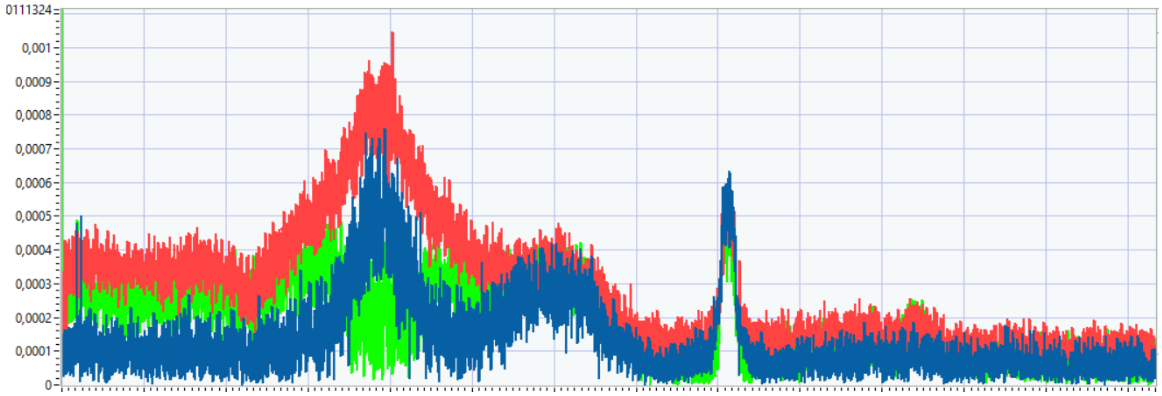

Figure 71 Triaxial accelerometer X Y Z measurement of phase magnitude conditions.

The Figure 71 showcase the phase-magnitude calculation made at afloat conditions of the triaxial accelerometer installed at the top of the FRP tower, the x-axis is represented by green, the results for the y-axis in green, and the results for the z-axis in blue.

- Unidirectional accelerometers

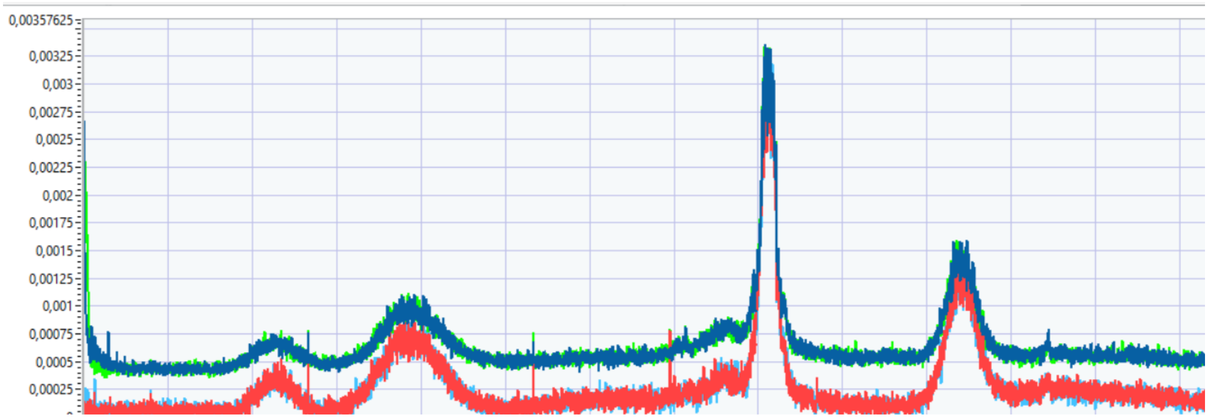

Figure 72 Uniaxial accelerometers measurement of phase magnitude.

The figure above displays the magnitude-phase calculations, illustrating the outcomes for the four accelerometers positioned at the second and third levels of the FRP tower at afloat state:

- Level 2
  - Cyan: Uni-directional accelerometer measuring the x-axis.
  - Blue: Uni-directional accelerometer measuring the y-axis.
- Level 3
  - Green: Uni-directional accelerometer measuring the x-axis.
  - Red: Uni-directional accelerometer measuring the y-axis.

- Strain gages.

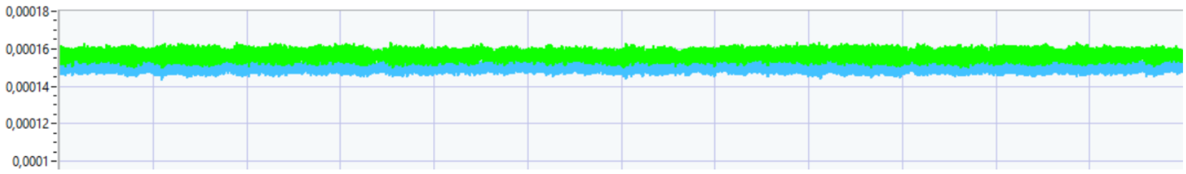

Figure 73 Strain gauges deformation measurements acquired by strain gauges.

In the previous image it is depicted the results at afloat of the measurements of the strain gages located at 0° in green and the strain gage located at 45° in cyan.

- Fiber optic strain gauges

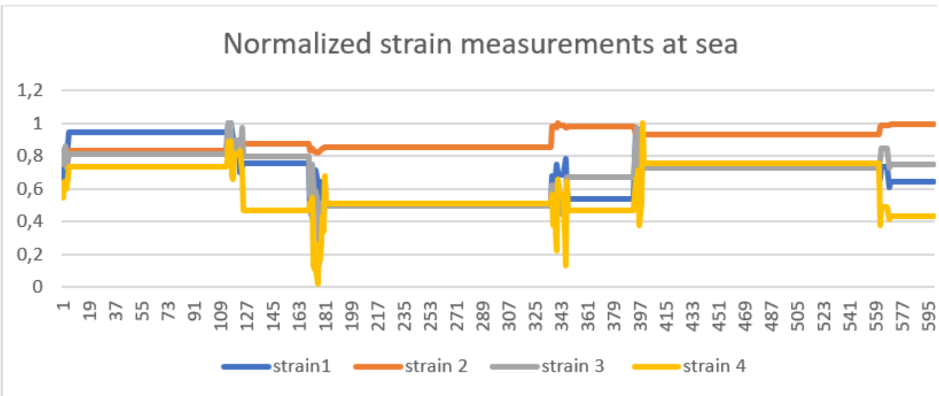

Figure 74 Fiber optic strain measurement.

The previous image show cases the results of the fiber optic strain gages installed at the surface of the FRP tower.

6. Digital twin model

The offshore renewable energy industry faces numerous challenges, including the need for reliable monitoring and maintenance of large-scale structures exposed to harsh marine environments. In response to these challenges, CIMNE has developed a novel Digital Twin (DT) methodology as part of the FIBREGY project, aimed at enhancing the structural health monitoring (SHM) and maintenance strategies of offshore wind platforms like the W2Power.

This DT model represents a convergence of state-of-the-art computational mechanics and advanced data analytics, embodying a hybrid approach that leverages both deterministic (physics-based) and probabilistic (data-driven) methodologies. By simulating real-world physical processes and integrating live data from the platform, the model provides a dynamic, adaptive framework that not only predicts potential failures but also suggests preventive measures to mitigate risks effectively.

The primary goal of this Digital Twin is to serve as a decision-support tool, enabling real-time insights and foresight into the performance and health of offshore structures. It aims to reduce operational costs, enhance safety, and extend the service life of renewable energy platforms. The subsequent sections detail the data analysis process used to ensure the model's accuracy and the results from its deployment during the sea trials of the W2Power prototype, illustrating the practical benefits and capabilities of this innovative technology.

6.1. Digital twin-based Structural Health Monitoring Framework

The Digital Twin (DT) model developed by CIMNE for the W2Power platform is a sophisticated simulation tool based on a physics-based model. At the core of the DT is a detailed finite element model (FEM) of the platform's structure, which adheres to stringent international standards including BV, DNV, LR, IEC, and ISO. This model uses the innovative Enriched Modal Matrix Reduction (EMMR) technique, which substantially reduces the number of degrees of freedom (DOF) in the simulation, decreasing computational loads while maintaining high accuracy. This feature is crucial for enabling simulations to be run nearly in real time, a necessity for responsive structural health monitoring (SHM).

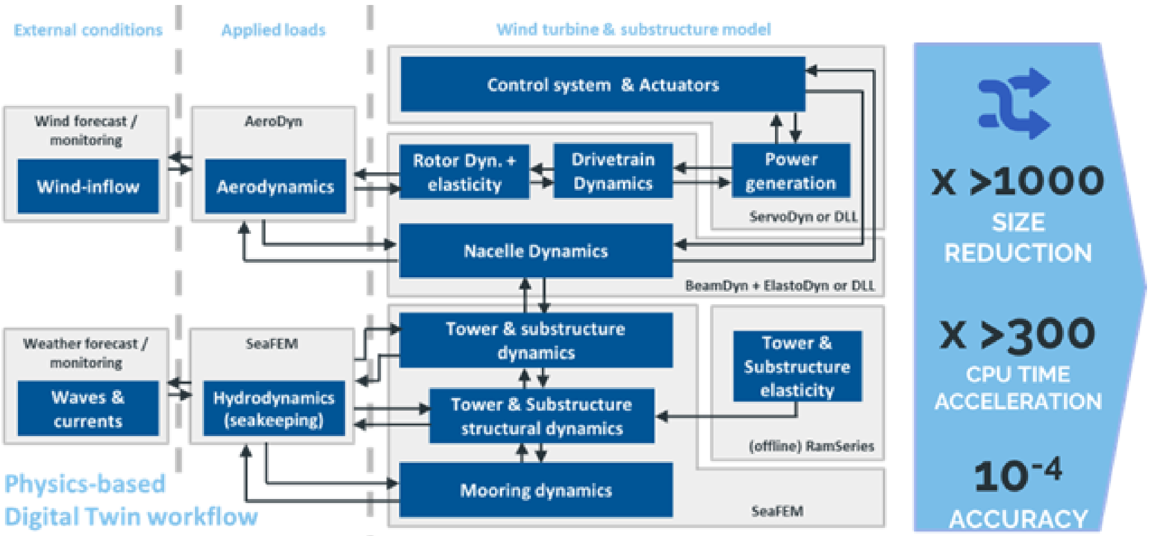

Figure 75 Physics-based aero-servo-hydro-elastic model.

The DT as well as the different monitoring systems described above has been integrated in a Structural Health Monitoring Framework. This framework was developed in the context of FIBRE4YARDS project. The Structural Health Monitoring (SHM) framework is a comprehensive system designed to monitor, analyse, and manage the health and performance of structures. Leveraging cutting-edge technology, this framework integrates various data sources, digital twins, and decision support systems, ensuring reliable and proactive management of structural integrity. Let's delve deeper into each component and understand how they interconnect to form a cohesive SHM system.

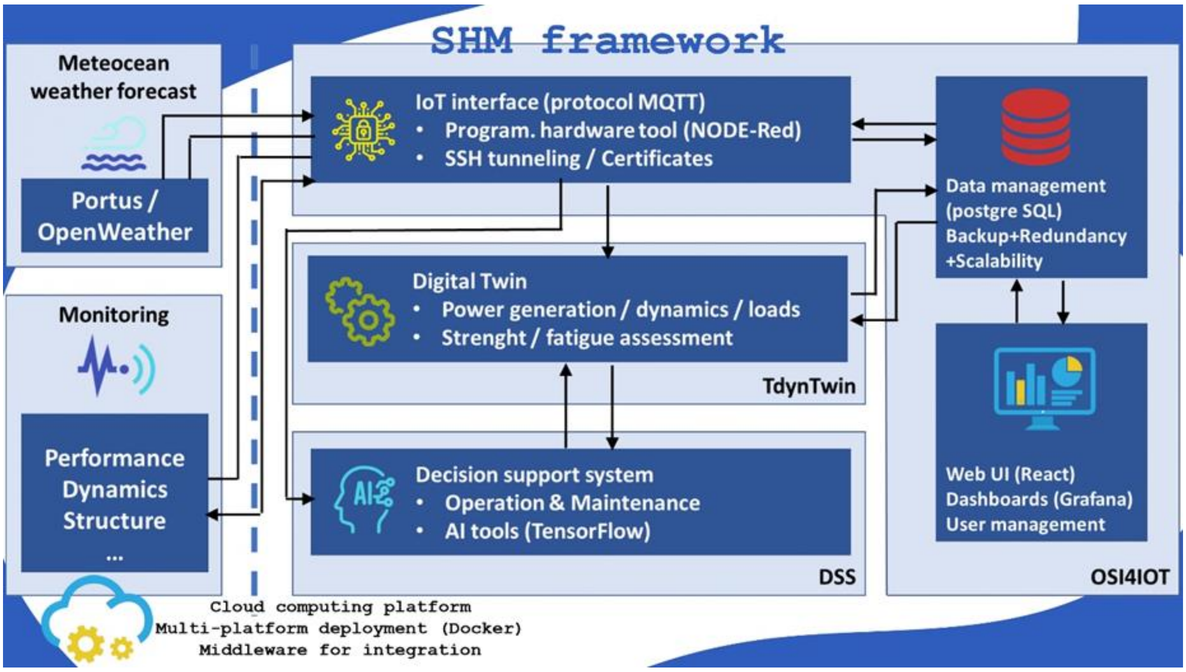

Figure 76 Structural health monitoring framework.

As can be seen in the figure above, the SHM framework integrates the following main features:

1. **Meteocean Weather Forecast:** The framework begins with meteorological inputs from systems like Portus/OpenWeather. These provide real-time weather data, which is essential for assessing environmental influences on structural health, such as waves, wind speeds, temperatures, and humidity.
2. **Monitoring:** This component includes performance dynamics and other structural monitoring systems, collecting real-time data on the structure's behaviour and condition. This data feeds into the rest of the system to inform decision-making and simulations.
3. **IoT Interface:** An IoT interface connects the data sources to the rest of the system, utilizing the MQTT protocol, program hardware tools (NODE-Red), and secure communication through SSH tunnelling and certificates. This ensures safe and reliable data transfer, linking the various monitoring components to the system.
4. **Digital Twin:** A digital twin serves as a virtual representation of the structure, allowing for simulations of power generation, load dynamics, strength, and fatigue assessments. This twin provides insights into the current state and potential future behaviour of the structure, aiding in proactive management.
5. **Data Management:** The data management component stores information in a PostgreSQL database, ensuring data backup, redundancy, and scalability. This storage solution supports the growing needs of the SHM system, allowing it to handle large datasets securely.
6. **Decision Support System:** The DSS, powered by AI tools such as TensorFlow, assists with operational and maintenance decisions. By analysing data from the digital twin and other sources, it guides responses to structural health challenges, ensuring timely and effective action.
7. **Web UI:** A web user interface, built using React, offers dashboards (via Grafana) for visualization and user management, making the system accessible and manageable for stakeholders.
8. **Integration:** The entire system is deployed on a cloud computing platform, with multi-platform support via Docker. Middleware ensures integration across all components, facilitating smooth data flow and functionality.

In summary, the SHM framework integrates diverse data sources, IoT interfaces, digital twins, and decision support systems to monitor and manage structural health efficiently. With robust data management, visualization, and integration mechanisms, it forms a comprehensive and scalable system that addresses both immediate and future structural challenges. Overall, the systems provide a robust framework for monitoring and predicting the structural health of offshore platforms.

6.2. Integration with Real-World Data

As stated above, the Digital Twin (DT) model developed for the W2Power platform offers a comprehensive solution for structural health monitoring (SHM) by seamlessly integrating real-world data from various sensors into its simulation framework. This integration ensures the DT provides accurate real-time insights into the platform's structural integrity and offers actionable recommendations.

The Digital Twin captures live data from a variety of sensors installed on the W2Power platform, reflecting its real-world state. This is visually represented by a composite image showing the W2Power wind turbine alongside its Digital Twin counterpart, illustrating the seamless connection between physical operations and digital simulations.

Figure 77 Real and digital twin image of w2power with a marker of a gauge sensor.

The previous figure shows the raw data collected from one of the platform's sensors, such as accelerometers or strain gauges, before processing. This data serves as input for the DT model, accurately representing the platform's response to environmental conditions and operational loads.

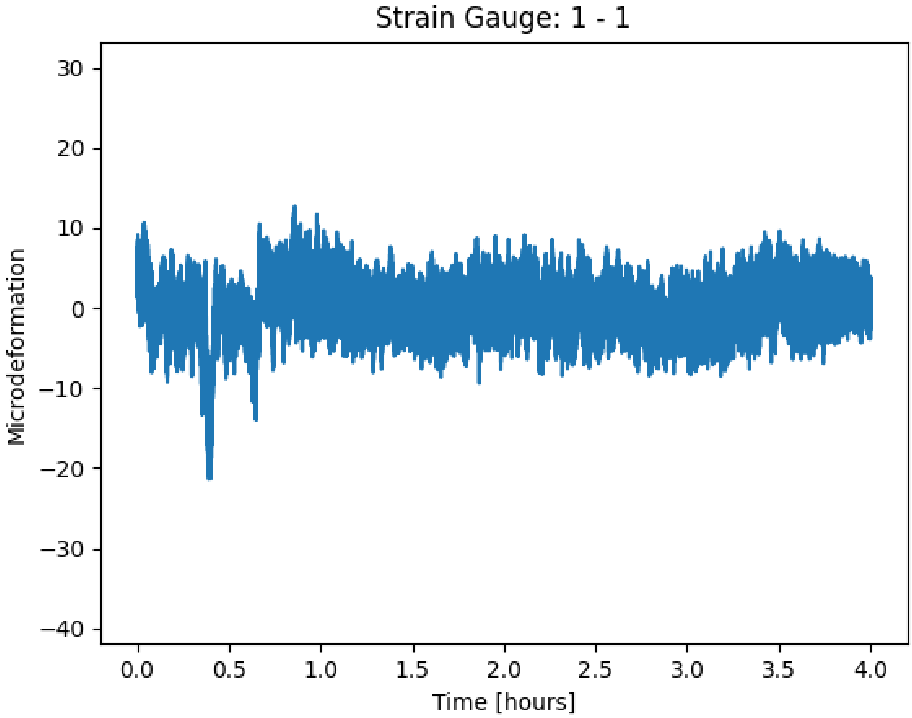

Figure 78 Raw data from sensor before being processed.

After processing, the sensor data is visualized in a chart on the DT platform, reflecting the platform's structural state. This processed data informs SHM strategies, aiding in maintenance scheduling, structural assessments, and operational optimization.

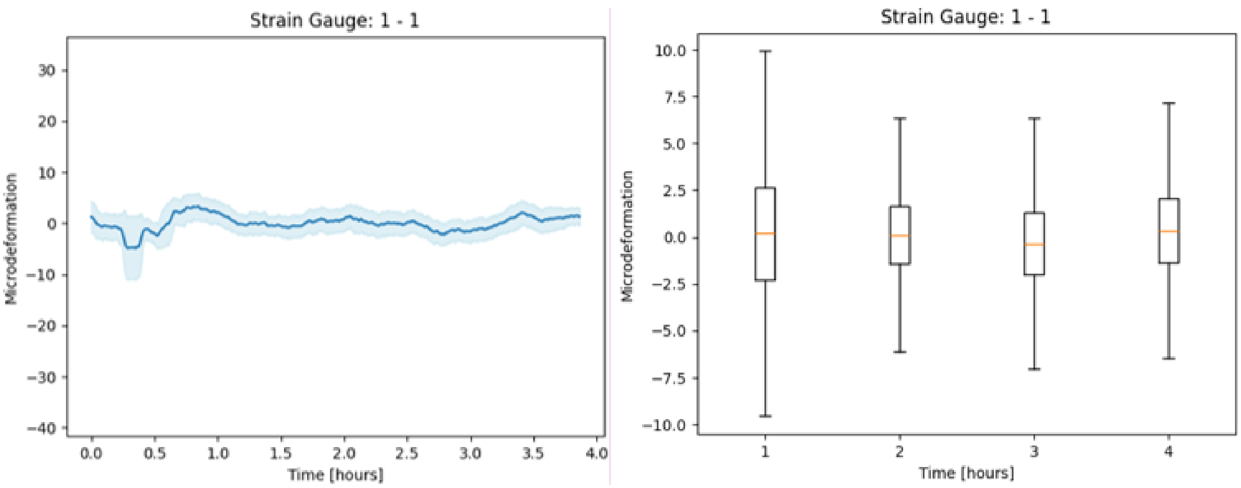

Figure 79 Raw data from sensor after being processed.

Figure 80 Processed data from sensor in the digital twin platform.

6.3. Sensor Network and Monitoring Systems

The W2Power platform's sensor network plays a critical role in providing accurate data for the DT.

The computational model underlying the DT model played a crucial role in optimizing the layout of the sensor network. By simulating different configurations and utilizing a genetic algorithm with data from the EMMR, the model helped identify the most effective arrangement for sensors to capture critical data on deformation modes. In fact, the sensor arrangement for the substructure is based on available information from the hydro-elastic analysis platform, aiming to provide the best approximation to the modal coordinates of the most energetic modes. The arrangement definition relies on the optimization algorithm proposed by Yao (al., 1993).

The criteria for the installation of strain gauges have been as follows:

- A minimum of 22 sensors (strain gauges) is estimated for substructure monitoring, along with different accelerometers.
- Half of the sensors will focus on monitoring deformations near hot-spot reading points.
- Half, n, of the sensors will be selected as the set that best allows monitoring the n-1 most energetic modes (in this case, n will be taken as equal to 10).
- At least one accelerometer is installed alongside one of the points from the previous set to better identify the frequencies of structural deformation modes.

It is worth noting that, additional accelerometers have been installed along the FRP tower, to characterize and validate the main vibration modes of the tower, as explained in the previous sections. Besides, different redundant strain sensors, accelerometers and inclinometers have been installed to verify its validity for monitoring the structural response of the FRP towers. Details of this installation are given in the previous sections.

The procedure for identifying the optimum position of the sensors has been as follows:

- The n (10) modes with the highest average elastic energy for a characteristic wind-wave condition has been identified.
- The position of the sensors is chosen from the list of nodes in the mesh used in the FEM analysis. A preselection of nodes located in an area over the draft, and at a maximum height of 4 m above the base of the towers, will be made. Additionally, the installation area will be limited to an area around columns A, B, and C (areas 1, 3, and 6 of Figure 81). The aim of this limitation is to eliminate areas that are more difficult to install or less protected. Specific details of the definition of these areas are provided below.

- From that list, the n nodes that allow for the most accurate regeneration of the selected n modes will be chosen. For this purpose, the algorithm proposed by L. Yao et al. has been used.

As a result of the optimization process, the arrangement of sensors is obtained, as shown in the figure below.

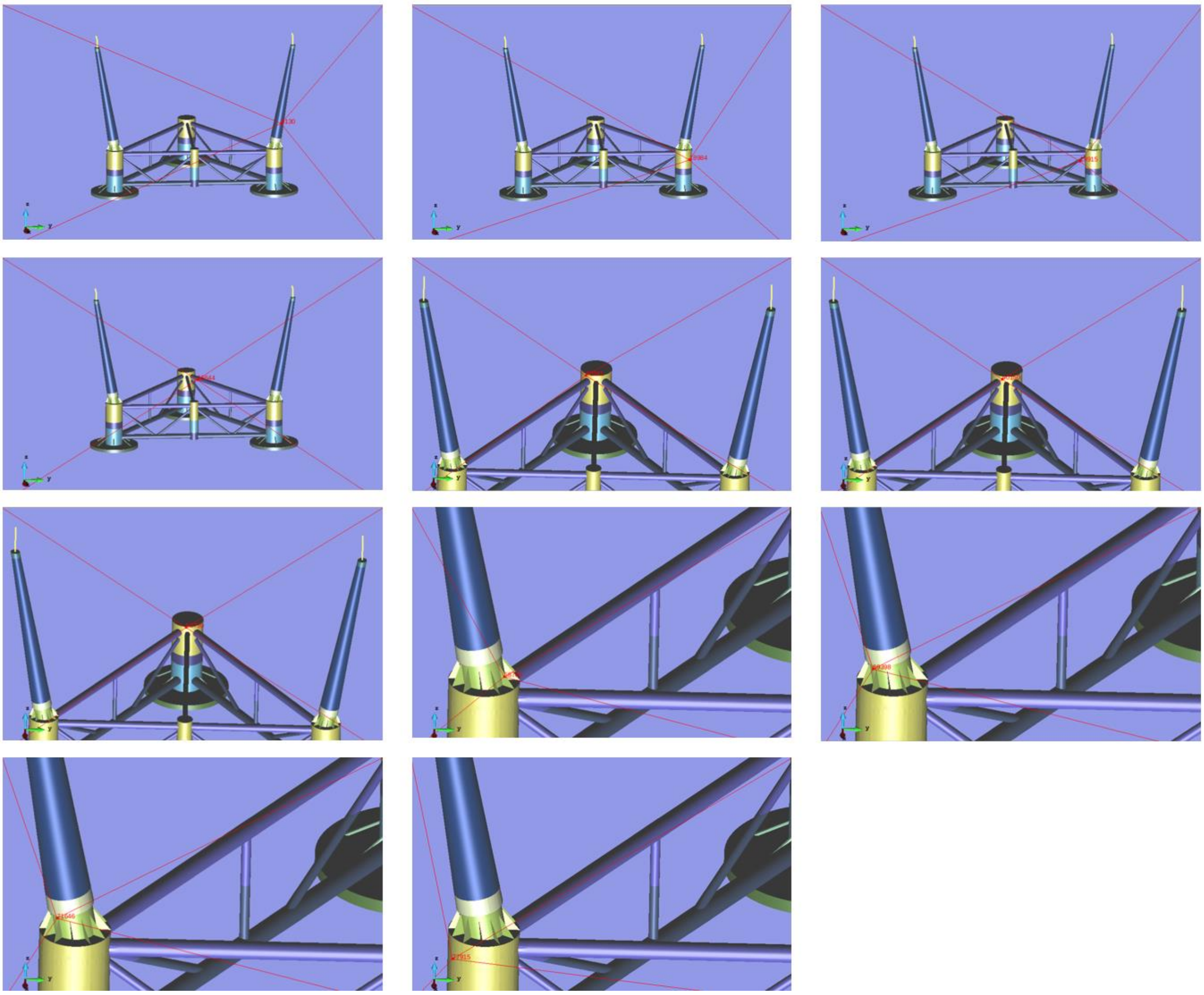

Figure 81 Position of the sensors for capturing the most energetic modes.

The position of these nodes has been identified as optimal for representing the behaviour of the 10 most energetic nodes, which account for approximately 83% of the total elastic energy in the case of the reference operation. The figure below shows those modes.

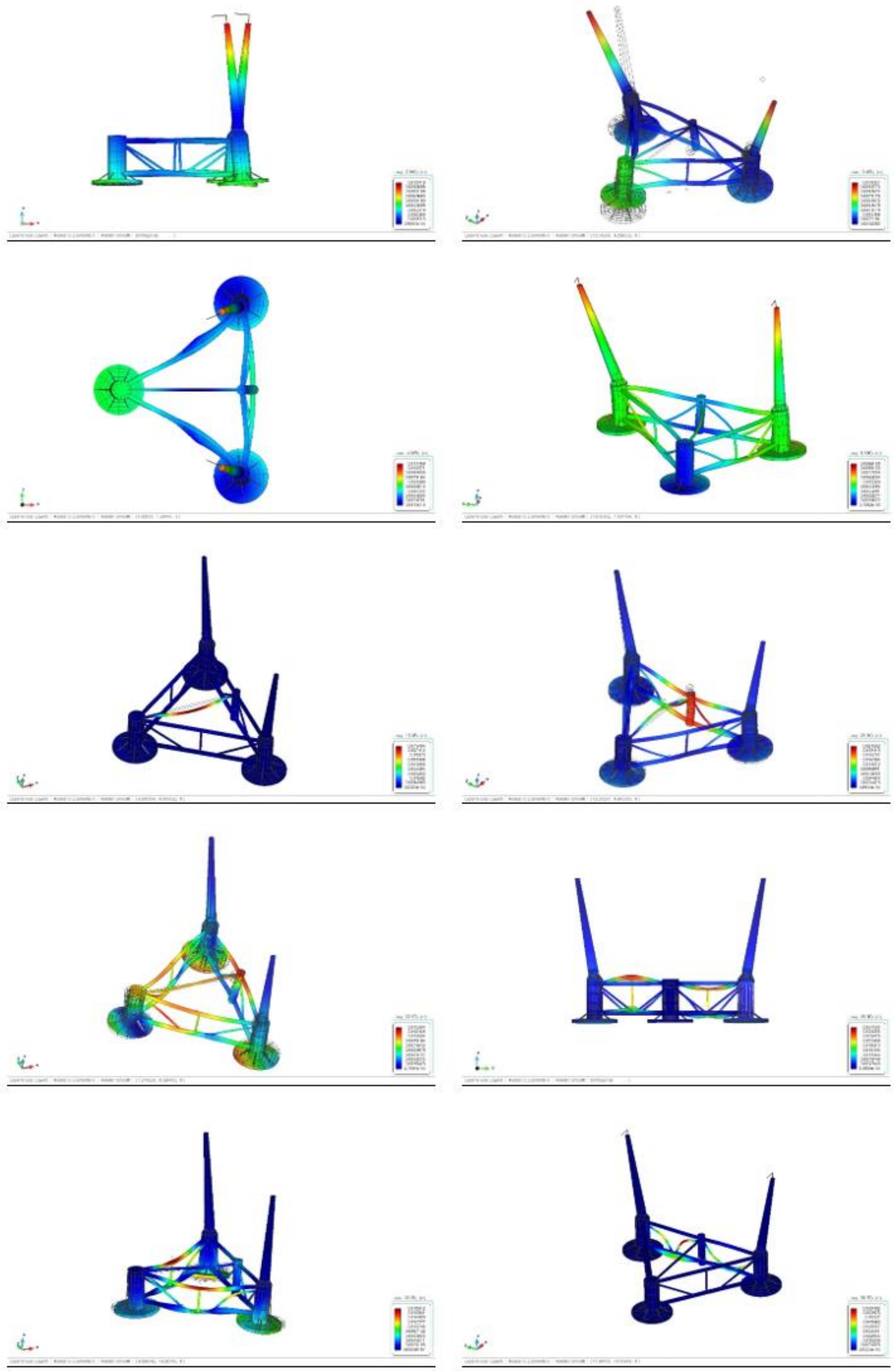

Figure 82 The 10 most energetic modes of the reference case (deformation is amplified for visual purposes).

It is worth noting that this optimization of the sensor arrangement, guided by advanced computational techniques, ensures comprehensive monitoring coverage, enhancing the reliability of the Structural Health Monitoring (SHM) system.

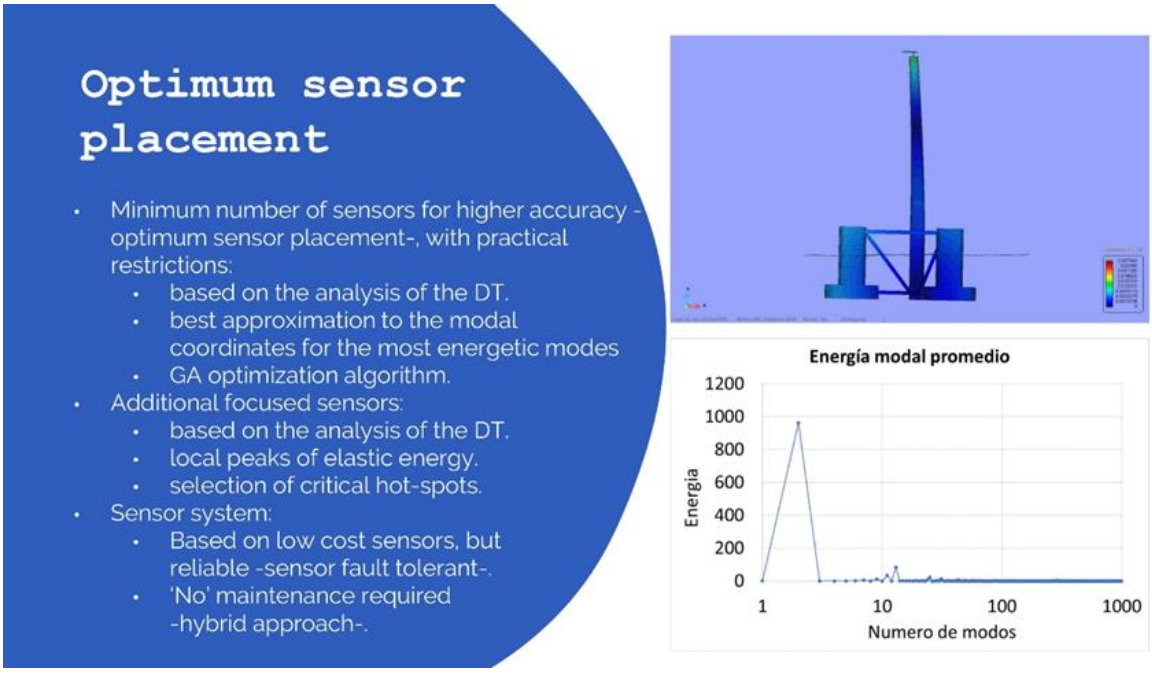

Figure 83 General methodology for optimum sensor placement.

As described in the previous sections, the monitoring systems is completed with a set of gauges for validation of hot spot and FRP tower strain, as well as additional (redundant) sensors for calibration and verification, including accelerometers and inclinometers.

As a summary, the sensor network of the SHM is split into two sub-system. The first of them is focussed on the substructure of the platform as presented in the figure below. It offers comprehensive environmental data, such as wave height and wind speed, which is incorporated into the DT's data-driven analytics.

Figure 84 EnerOcean sensors on DT platform.

The second sub-set is focused on the FRP tower and provides crucial information, including acceleration signals acquired by MEMS sensors, accelerometers, strain gauges, and fiber optic sensors. This data supports various analyses, including frequency tracking, statistical evaluation, and structural response comparisons.

• TSI sensors

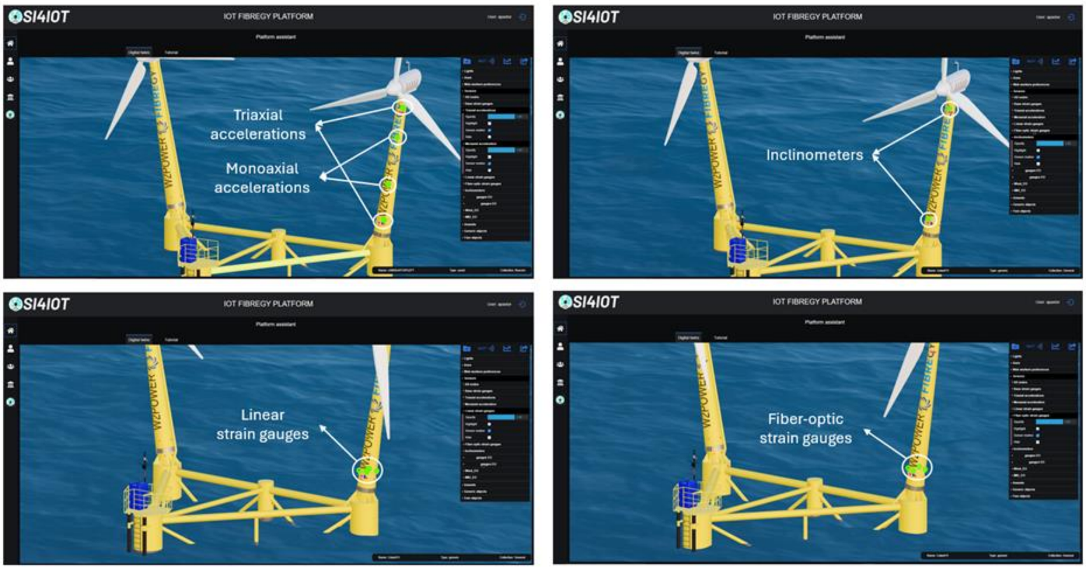

Figure 85 TSI sensors on DT platform.

The deployment of the Digital Twin yielded significant insights into the structural dynamics and operational integrity of the W2Power platform. The use of EMMR in the DT model allows for complex structural simulations to be performed in near real-time. This feature is pivotal for ongoing structural assessments and timely decision-making, enabling immediate responses to potential structural issues. The importance of this capability is supported by the data reported in Section 6.2 on real-time monitoring outputs, which is crucial for implementing preventive maintenance procedures and preventing catastrophic failures.

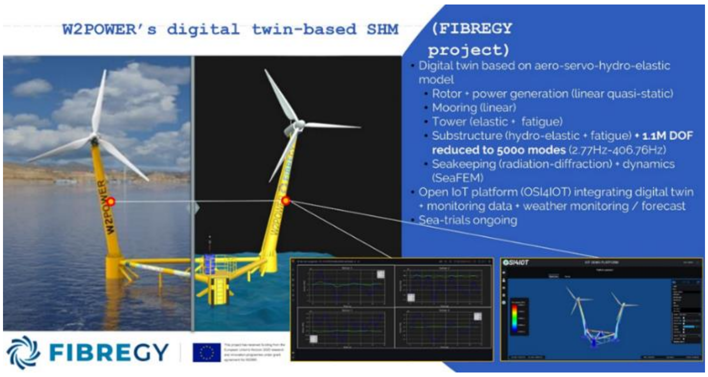

Figure 86 Implementation of the W2Power's SHM solution on DT platform.

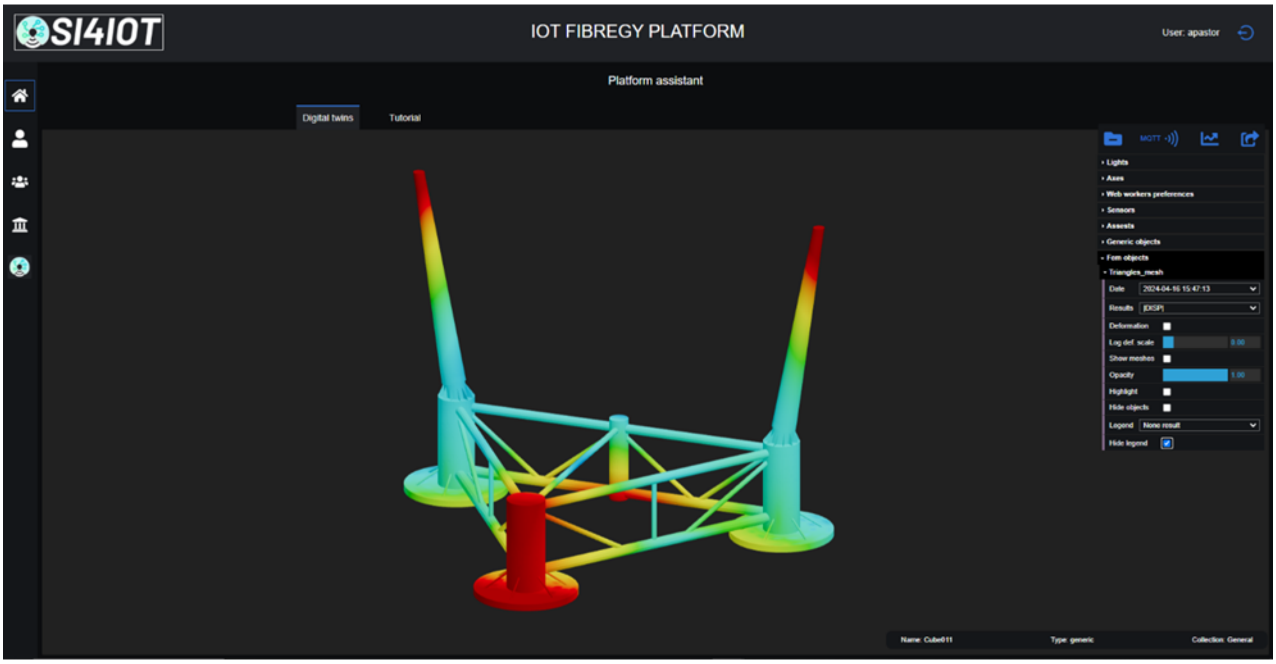

Figure 87 W2Power's structural results on DT platform.

Figure 88 W2Power's dashboard results on DT platform.

7. Conclusions

The use of fibre towers instead of steel is a major step forward in the search for alternatives to steel construction. Not only because of the weight reduction, but also because of the opportunities it offers in terms of design. In this last stage of the FIBREGY project, it was successfully completed the installation of the first FRP towers on a floating offshore wind platform (EnerOcean's W2Power 1:6 prototype) in the world. The integration of fibre towers into the steel platform has been a major advance that has allowed the development of guidelines and procedures that will facilitate the viability of these technologies in the future.

Monitoring has been a fundamental point in the study of the behaviour of the structure, making it possible to analyse the behaviour of both the steel and fibre parts and their viability. Two extensive monitoring systems have been installed especially focused on the data acquisition of the FRP towers behaviour and its effects on the whole structure. This provides highly valuable information for data analysis and digital twin, which enables a continuous optimization of the design and maintenance.

The digital twin model represents an advanced integration of data-driven analytics and physics-based simulations. By leveraging data from sensors installed on the W2Power platform, the model effectively mirrors the platform's real-world state. This integration allows for real-time insights into the structural health and operational integrity of the platform, significantly enhancing monitoring and predictive maintenance capabilities.

The digital twin's integration with a comprehensive sensor network optimizes the monitoring system's coverage and accuracy. This network includes sensors for capturing crucial data such as acceleration, strain, and environmental conditions, which is then processed and visualized on the digital twin platform. This comprehensive monitoring system, including data from EnerOcean and TSI sensors, provides valuable insights into the platform's structural dynamics.

This hybrid approach of the digital twin combines deterministic simulations through finite element modelling (FEM) with probabilistic data analytics, resulting in an accurate representation of the platform's state. This model utilizes the Enriched Modal Matrix Reduction (EMMR) technique, which reduces the degrees of freedom in simulations, enabling near real-time assessments. This feature ensures responsive structural health monitoring, facilitating immediate decision-making in response to potential issues.

Overall, the digital twin model offers a robust framework for structural health monitoring and predictive maintenance, reducing operational costs, enhancing safety, and extending the service life of the W2Power platform.

Finally, it worth to be mentioned as a future research work, the integration of real-time data into the DT model via machine learning techniques. This approach allows not only to refine the model's predictive capabilities but also allows for continual improvement through adaptive learning. This enhancement improves the accuracy of maintenance forecasts and helps in scheduling maintenance activities more effectively. Additionally, the adaptive learning capability of the DT enables it to adjust to changes in the platform's physical condition over time, such as material fatigue or damage from marine conditions. More data is still required to fully harness the potential for extending the operational lifespan of the platform.

8. References

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