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INFINITE

Aerospace composites digitally sensorized from manufacturing to end-of-life

D2.5
Validation of the Portable Reader

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List of Abbreviations

Abbreviation	Description
CFRP	Carbon fibre reinforced pollymer
GFRP	Glass fibre reinforced polymer
GMI	Giant Magnetiimpedance
NCF	Non-Crim Fabric
PR	Portable Reader
PRvX	Version No. X of Portable Reader
SHM	Structural health monitoring
TRL	Technology Readiness Level
TRM	Calibration method: Thru-Reflect-Match
VNA	Vector Network Analyser

2. INTRODUCTION

2.1 REPORT OBJECTIVES

This deliverable outlines the validation progress of the portable reader system (PRv1 and PRv3) within the INFINITE project, emphasizing its technical advancements and readiness for further industrial scaling. The objectives are structured to reflect both achieved milestones and pathways for improvement:

1. **Validate Core Functionality**: Demonstrate the system's ability to operate in controlled environments, correlating signals with mechanical loads, spatial orientations, and thermal variations ($R^2 \approx 1$ in ideal conditions).
2. **Identify Optimization Opportunities**: Highlight areas for refinement—including signal amplification, dynamic condition adaptability, and electromagnetic interference mitigation—to enhance robustness in complex environments.
3. **Chart Industrial Scalability**: Provide actionable insights to transition the system from laboratory validation (TRL4) to industrial piloting, focusing on cyclic loading tests, multifactorial stress simulations, and integration with conductive composites.

This report underscores the portable reader's potential as a foundational tool for structural health monitoring, while transparently addressing steps required to bridge controlled-environment success with industrial demands.

2.2 CONTEXT OF THE PORTABLE READING SYSTEM DEVELOPMENT

The Portable Reader (PR), developed in the INFINITE project, emerges as an innovative solution to address key challenges in sectors such as aerospace, where non-invasive, real-time monitoring of composite materials is critical. Its creation responds to the need to replace bulky laboratory systems and destructive inspection methods with a portable tool that can wirelessly read data from embedded sensors - magnetic microwires with exceptional properties (e.g., GMI effect) - in composites, without requiring disassembly or operational interruptions. These microwires, embedded directly into the materials, act as passive sensors capable of providing strain, temperature, and orientation information, thus facilitating predictive maintenance, manufacturing process optimization and the transition to a circular economy by identifying reusable components.

The tests performed with the PR have had three central objectives:

1. to validate its technical feasibility by demonstrating that it can correlate microwire signals with mechanical and thermal parameters under controlled conditions
2. to overcome limitations of previous versions, such as thermal instability and erratic measurements of PRv2, achieving a compact design (size of a PCB) and efficient interference management
3. to identify areas of improvement for industrial scaling, evaluating its sensitivity to factors such as spatial orientation, applied loads or electromagnetic interference, as well as its adaptability to complex environments (vibrations, highly conductive materials such as carbon fibre).

These tests lay the foundations for transforming composite materials into self-reporting "smart structures", capable of being integrated into sustainable industrial flows and guaranteeing operational safety in critical applications.

3. DESCRIPTION OF THE SYSTEMS

The first system implemented in the framework of the project, called LAB SYSTEM, was based on a Virtual Network Analyser (VNA) with coupled antennas that allow characterisation of the electromagnetic properties of materials by means of free-space measurements. The equipment was configured as an initial reference platform, based on commercial off-the-shelf components, prioritising conceptual validation over compact integration.

The assembly of this system coupled to a dynamic testing machine made it possible to verify the effect of stress on parts incorporating continuous microwires in their structure. In this way, the possible use of continuous microwires in glass-fibre reinforced parts was validated.

Faced with the constraint imposed by the conductivity of carbon, RISE developed a new approach that evolved into stand-alone portable systems, resulting in two key versions: Portable Reader v1 (PRv1) and Portable Reader v3 (PRv3). An intermediate version (PRv2) obviously existed, but it had critical limitations - such as measurement instability and overheating problems - that prevented its reliable use in testing. For this reason, tests performed with it have been excluded from this report.

In any case, the leap from PRv1 to PRv2 was also very significant as a radical miniaturisation was achieved. The size of the equipment was reduced to a standard printed circuit board, integrating antennas and coils into a compact element. However, the technical leap between PRv2 and PRv3 was decisive: the third version not only resolved the shortcomings of its predecessor, but also incorporated significant advances, such as signal stabilisation and efficient thermal management. This transition reflects the progressive maturation of the design from functional prototypes to robust operating systems, and lays the foundation for evaluating its performance under realistic conditions.

3.1 LABORATORY SYSTEM FEATURES

The equipment used to measure the magnetic permeability of the microwire specimens consists of a Keysight Streamline P5004B series vector network analyzer (VNA) and Flann Microwave model DP240-AB dual polarized antennas, configured to emit and capture electromagnetic radiation with high precision.

The P5004B VNA is a two-port device that operates up to 53 GHz and offers a dynamic range of up to 150 dB depending on frequency and configuration. Its operation is based on the generation of radio frequency signals that are transmitted through the antennas to the probe, and then analyzes the reflected and transmitted signals using S-parameters. These parameters allow to calculate electromagnetic properties such as magnetic permeability and permittivity using inversion algorithms such as Nicolson-Ross-Weir.

The Flann DP240-AB antennas, designed for a range of 2 GHz to 18 GHz, are key to the system due to their dual polarization capability, which allows signals to be emitted and received in both horizontal and vertical orientations simultaneously, which is essential for studying anisotropic materials. These antennas feature inter-port isolation of 25 dB typical. The low cross-polarization (-20 dB maximum) and close amplitude (±1.3 dB) and phase (±17°) tracking between ports ensure high measurement fidelity. The antennas' female SMA connectors facilitate integration with standard cables, while their electroformed construction ensures durability and accuracy.

Prior to any measurements, the system is calibrated using TRM (Thru-Reflect-Match) calibration, which is a widely used method for characterizing and correcting systematic errors in measurements of vector network analyzers (VNAs). TRM (Thru-Reflect-Match) calibration eliminates such errors using three known standards: a Thru, a Reflect (e.g., short/open) and a Match (precision load) connection. The VNA measures these standards, compares the results with their ideal characteristics and calculates the error terms that form a correction model.

Once calibrated, the VNA generates signals in the operating range of the antennas (2-18 GHz), which are radiated back to the microwire probe. The signals reflected and transmitted through the material are captured by the antennas and processed by the VNA, and then the S-parameters are calculated, allowing fast data transfer to a PC for display and analysis. Since the measured S-parameters are influenced by multipath propagation, unwanted reflections, and other interferences, especially in a non-anechoic environment, additional signal processing with time domain gating was performed. For these experiments, the time gating was placed between -290 ps and 310 ps.

3.2 PRV1 FEATURES

The PRv1 system is a semi-portable device designed to characterize the electromagnetic properties of carbon composite specimens with integrated magnetic microwires. It was developed by RISE to avoid the effect of carbon conductivity, analysing the effect of microwires on external magnetic fields applied.

Its operation is based on the interaction between a low frequency magnetic field, generated by a Helmholtz coil, and a radio frequency signal transmitted through the specimen. Simply put, the function generator feeds the Helmholtz coil with a very low frequency DC or AC current, which creates a nearly uniform axial magnetic field in the central region. Simultaneously, a Wi-Fi MIMO antenna transmits a 2.4 GHz signal towards the specimen. Under the influence of the magnetic field, the specimen modulates and partially re-emits that electromagnetic signal. The SENCITY Spot-S antenna then receives the signal altered by the specimen, and analysis of this response provides information on the effective magnetic permeability and hysteresis losses of the material.

Figure 1 (left) shows the PRv1, with all the components mentioned above, plus the necessary hardware (power supply, amplifier, analogue-to-digital converter, transceiver...) to modulate and manage the signals. This equipment is connected to the computer which incorporates the customised software to display the processed signal.

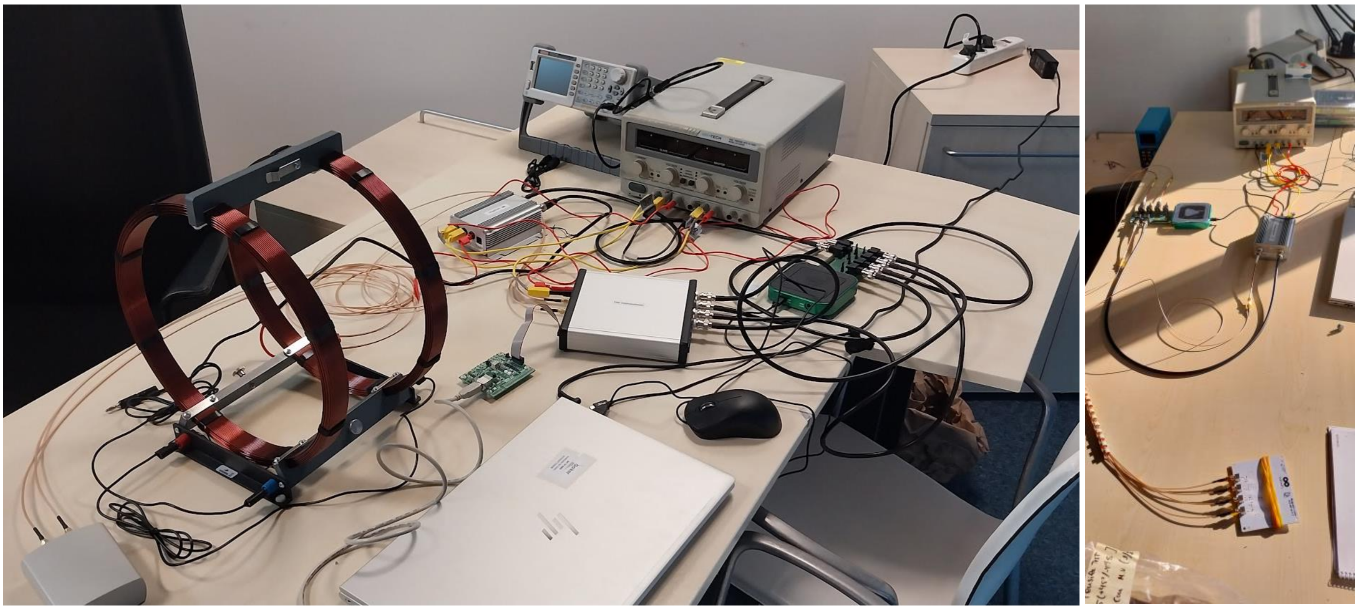


Figure 1: Assembly of PRv1 (left) and PRv2 (right)

3.3 PRV3 FEATURES

Portable Reader v2 achieved a substantial exercise in component integration by integrating the coil, antenna and some of the electronics on a simple PCB that facilitates portability (Figure 1-right). However, due to overheating of the PCB and unstable measurements, the second version was rejected and replaced by the new version (PVv3) which improved these aspects.

Finaly PRv3 was developed. Based on the idea of low frequency portable readers, it includes all the advantages incorporated in previous versions avoiding the initial limitations. A complete description of the components and software is detailed in *D2.3 – Construction of the Portable Reader System*

4. VALIDATION PLAN

4.1 VALIDATION OBJECTIVES

The Portable Reader System aims to demonstrate basic functionality, reliability, and readiness for practical use by: (1) assessing its ability to detect both non-integrated and integrated microwires in composites under controlled environmental conditions (e.g., moderate temperatures, static positions); (2) comparing its accuracy against lab-based; (3) validating core operational scenarios, including microwire detection in simple orientations, basic strain monitoring under static loads, and performance in near-realistic conditions; (4) confirming basic portability and robustness for use in accessible industrial settings (e.g., workshops, hangars); and (5) establishing foundational readiness for pilot-scale deployment in later project phases, with a focus on safety and adaptability to simple recycling processes. These objectives prioritize practicality over perfection, ensuring incremental progress toward industrial relevance while addressing key technical and sustainability requirements.

4.2 TYPES OF SAMPLES EVALUATED

Different types of specimens test or coupons were used for the study: 1) glass fibre composite (GFRP) specimens without microwires, 2) GFRP specimens with microwires and 3) carbon fibre composite (CFRP) specimens with microwires. Glass reinforced coupons were elaborated to avoid the effect of carbon conductivity onto measurements

General purpose GFRP specimens (without microthreads) were fabricated using a polymeric matrix based on SICOMIN SR Infugreen 810 epoxy system, catalysed with SICOMIN SD 8822 at a mix ratio of 100: 31, combined with a biaxial glass biaxial (0-90°) non-crimp fabric (NCF) reinforcement of 800 g/m² areal density, initially maintaining an equal ratio of 50% by weight between resin and reinforcement, subsequently adjusted to 60% reinforcement after considering resin losses during the vacuum process. Their fabrication involved manual impregnation of two layers of NCF with the resin, followed by vacuum press forming (Global SP) at 60 °C for curing, and final machining to obtain 600 mm × 600 mm × 2 mm thick square sheets with uniform edges.

The GFRP specimens with microwires replicated the same process and materials, but incorporated ferromagnetic microwires aligned unidirectionally between the two reinforcement layers, with a constant 5 mm spacing between them. Microwires were placed using a machined matrix with channels to position and fix them to an external cardboard frame with adhesive tape. This set (carboard frame with microwires) is integrated in the composite structure between the reinforce layers. Lately the frame is removed by means of mechanizing after curing and final processing.

The sensorized CFRP specimens were elaborated by IDEKO using the NCF with integrated microwires in fiber direction developed by TEIJIN. They followed an analogous design but with key differences: they were fabricated with carbon fiber as reinforcement and the microwires were integrated in grooves with 10 mm spacing between them, doubling the distance with respect to the sensorized GFRP ones. The technical and methodological details corresponding to the fabrication of the carbon fiber composite (CFRP) specimens with microwires, were provided directly by IDEKO, in compliance with its disclosure protocols and quality standards.

4.3 CHARACTERISTICS OF MICROWIRES

Magnetic microwires are ultra-thin structures manufactured using the Taylor-Ulitovsky method, which consists of the rapid solidification of a metal core encapsulated in a glass cover, with diameters ranging from 5 to 100 micrometers. Their composition includes cobalt-based alloys, such as $Co_{664.6}Fe_5B_{16}Si_{11}Cr_{3.4}$ and $Co_{72}Fe_4B_{13}Si_{11}$, as well as iron alloys such as $Fe_{777.5}B_{15}Si_{7.5}$. Cobalt-rich alloys stand out for their low coercivity (between 8 and 20 A/m) and exceptional magneto impedance effect (GMI), reaching maximum values of 600% at GHz frequencies, making them ideal for detecting magnetic changes associated with structural damage in composites. In contrast, iron microwires exhibit significantly lower GMI (less than 30%), limiting their practical utility. Optimization of these microwires focuses on increasing the diameter of the metal core (up to ≈40 µm) and reducing the thickness of the glass coating, thus improving magnetic sensitivity and GMI efficiency. These advances overcome technical challenges, such as interference caused by conductive carbon fibers, and position cobalt microwires, especially the $Co_{72}Fe_4B_{13}Si_{111}$ composition, as the most promising option for applications in embedded sensors in critical high-precision components.

4.4 PARAMETERS AND EXPERIMENTAL CONDITIONS

Three critical parameters were prioritized to evaluate the performance and feasibility of the **Portable Reader System**: **microwire orientation**, **response under mechanical load**, and **thermal behavior**. These parameters were selected due to their direct impact on the system's functionality in real-world applications, from manufacturing to in-service monitoring of aerospace components. Below is a detailed explanation of their relevance:

1. Microwire Orientation

- **Parameters evaluated**:
  - System sensitivity to changes in the spatial orientation of microwires (horizontal, vertical, angular).
  - Accuracy in detecting magnetic signals under different configurations.
- **Reason for study**:
  In aerospace composite materials, fibres and microwires are oriented in multiple directions to optimize mechanical properties. Validating that the Portable Reader can operate independently of orientation ensures its adaptability to complex designs and its ability to integrate into *Non-Crimp Fabrics (NCF)* without geometric limitations.

2. Response Under Mechanical Load (Force, Stress/Strain)

- **Parameters evaluated**:
    - Correlation between detected magnetic signals and applied forces (tension, compression, bending).
    - System stability under cyclic (simulating fatigue) and static loads.
    - Comparison with strain measurements from conventional methods.
- **Reason for study**:
  During a component's lifecycle, mechanical loads can generate deformations, cracks, or delamination. Validating the system's response under stress ensures it can detect anomalies in real time, providing reliable data for *Structural Health Monitoring (SHM)*. This is critical for preventing critical failures and optimizing maintenance interventions.

3. Thermal Behaviour

- **Parameters evaluated**:
    - Stability of readings under certain temperature ranges.
    - Effect of thermal gradients on measurement accuracy.
- **Reason for study**:
  Aerospace components are exposed to significant thermal fluctuations, both during manufacturing processes and in service (e.g., altitude variations). Validating the system's performance under these conditions ensures it is not affected by false readings or loss of sensitivity, guaranteeing operability in realistic scenarios.

5. TESTS PERFORMED

5.1 LAB SYSTEM

As explained before a lab system based on commercial components was set up at the beginning of the project, when portable reader was under development. This equipment allowed us to demonstrate the effect of different stimulus onto electromagnetic properties of the coupons with integrated microwires into their structure.

5.1.1 TENSILE TESTS WITH LAB SYSTEM

The previous described experimental set up was placed in a universal testing machine (SERVOSIS MUF10) allowing to perform dynamic tensile tests. Special tensile grips were manufactured to cover the full width of the flat specimens ensuring that the force was applied evenly over the entire surface of the specimen. This configuration, showed in Figure 2, allowed dynamic tensile tests to be performed on the coupons while measuring the S-parameters.

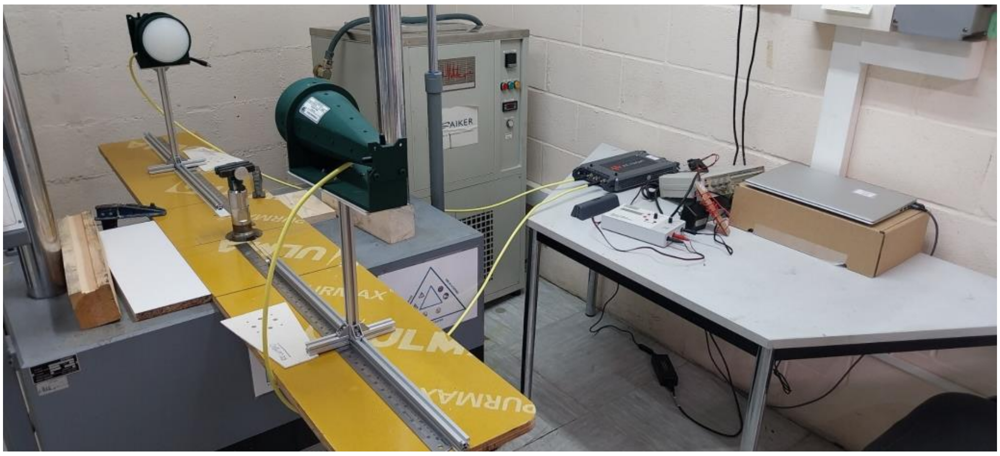


Figure 2: Tensile test set-up on flat planar glass specimen with microwires

Deformation tests were carried out by applying dynamic tensile test to the specimens and measuring simultaneously electromagnetic properties with the VNA and the antennas in each of the measurements. In general, as soon as force was applied, simultaneously data corresponding to the S-parameters in both reflection and transmission were recorded. Several trials were performed onto glass fiber reinforced composites to evaluate the effect of force applied onto electromagnetic properties.

Stress-strain tests were carried out, augmenting the applied force by increments of 1 kN and simultaneously measuring S parameters. As tensile stress is applied in a vertical way, both microwires and polarization direction of the antennas were oriented in that way. As aforementioned, the measurements of the S parameters were carried out at different stresses by gradually increasing the force supported by the specimen. It is noteworthy that the tests have been repeated on multiple occasions to replicate the results and check their robustness. Here below, the demonstrated results have been obtained from the first test series, presenting the most significant findings that were further validated in subsequent trials.

In the initial analysis of the data, the curves obtained in their graphical representation did not indicate a significant difference between the forces, as the variation in the parameters was small. However, there is a clear force dependence in the scattering parameters if the data points are studied in close-up. To better visualize the relative differences between the curves data normalization was carried out. This normalization consisted of dividing each of the values of the different amplitude and phase data by its corresponding data values of the lowest force (1 kN). It was in this case where the force and S11 correlation is clearly seen. Although a small difference between obtained values was found, we observed a clear trend that confirmed the dependence of the change of electromagnetic properties with the applied force.

We obtained same results when analyzing the reflection using the other antenna (S22). In this case, phase values decrease with a subsequent increase in force, opposite to reflection in the other antenna (S11). All normalized values are presented in Figure 3, using different colour/pattern to discern the obtained curves. The figure displays amplitude data (on the left) and phase values (on the right) of reflection scattering parameters S11 and S22.

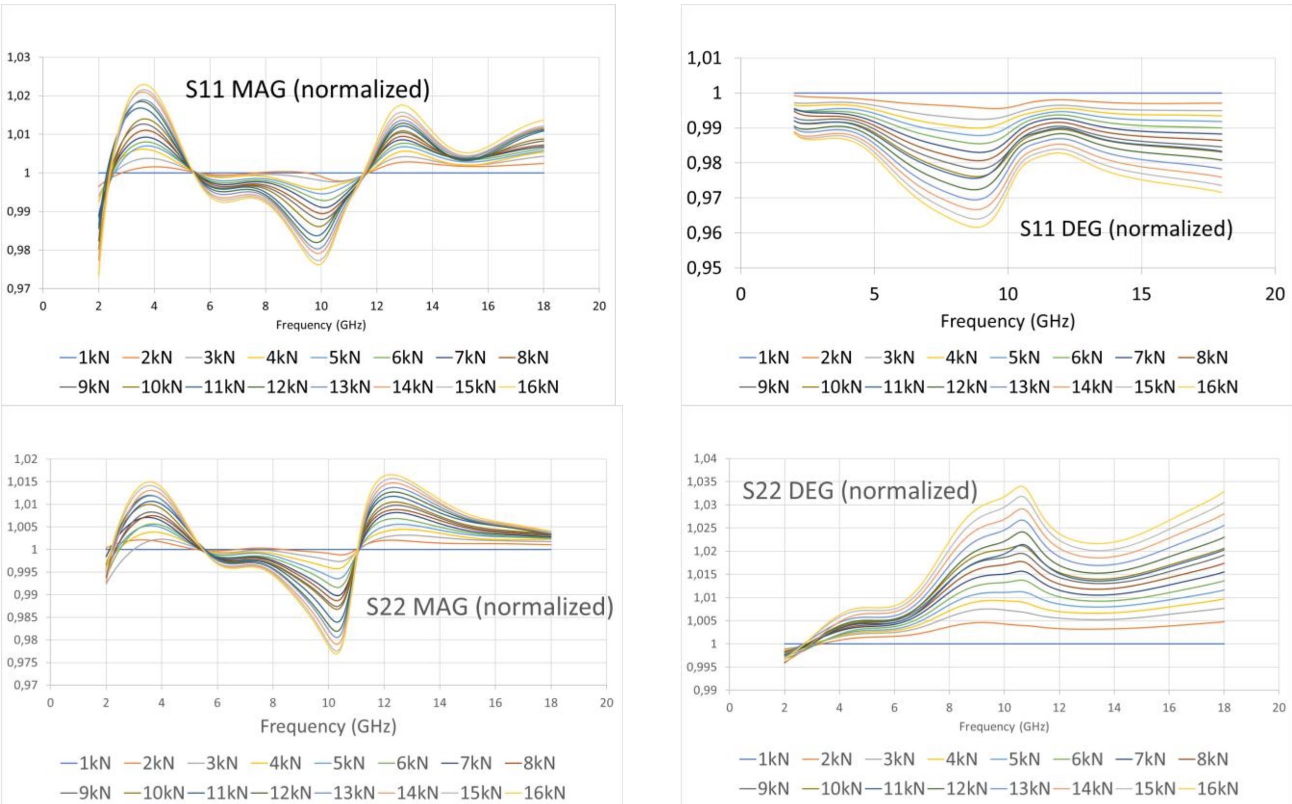
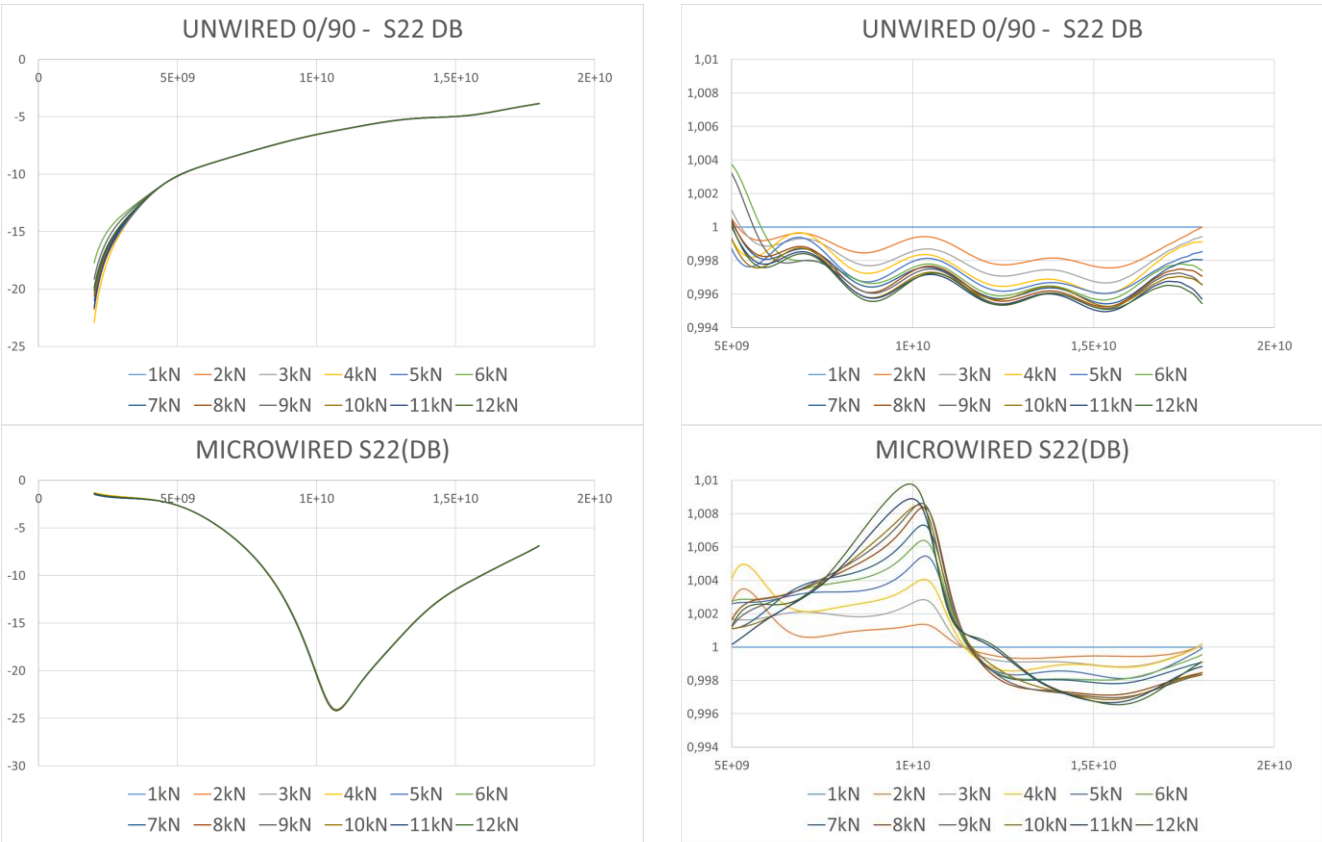


Figure 3: Signal obtained in the tensile test for different loading forces. On the y-axis, the magnitude and phase of reflection parameters (S11 & S22). On the x, the frequency

5.1.2 MEASUREMENT ON COMPOSITE WITH AND WITHOUT INTEGRATED MICROWIRES

Several test specimens were manufactured without microwires to confirm that the signal was due to the microwires and not to other composite materials such as the reinforcement or the polymer matrix itself. As can be seen in Figure 4, the microwires play a key role in the signal produced by the probe due to the appearance of a resonance peak along with the insertion of the microwires. Also normalized values show a clear dependence of the signal with the load applied that is not present on the unwired parts.



Fig

Figure 4: Signal obtained for measurements on specimens with and without microwires. The two graphs on the left are the absolute signal and the two on the right are the normalized signal.

5.1.3 ORIENTATION TESTS ON LAB SYSTEM

Using a disk-shaped specimen with a graduated element (Figure 5), the scattering parameters were determined with different orientations of the microwires with respect to the polarity of the antennas. Results were obtained for orientations between 0º and 90º, varying the orientation every 5 sexagesimal degrees.

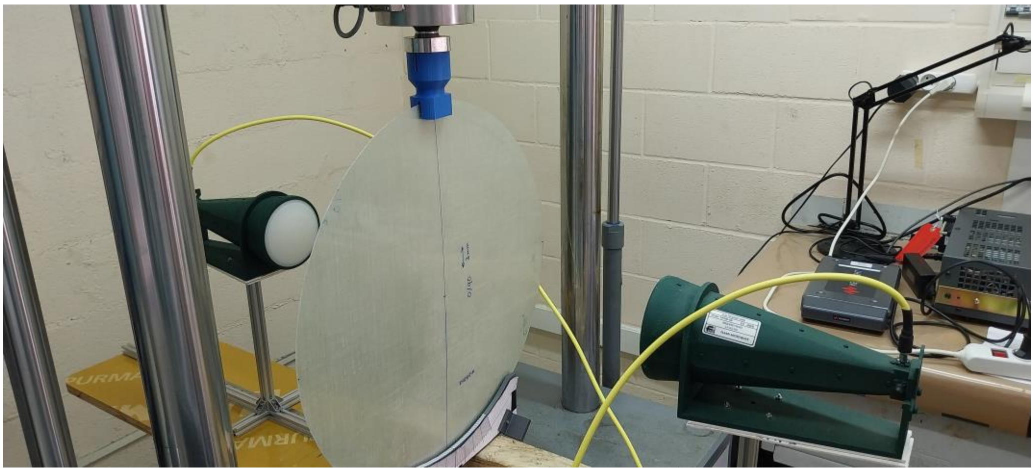


Figure 5: Set-up the laboratory measuring equipment on a circular probe to measure the effect of angular variation on the signal processed in the VNA.

The results of the measurements are shown in the Figure 6. The variation of the parameter used as reference, the S22, is evident. As the rotation angle of the disk varies, different resonance frequencies with varying amplitude as a function of the rotation angle appear.

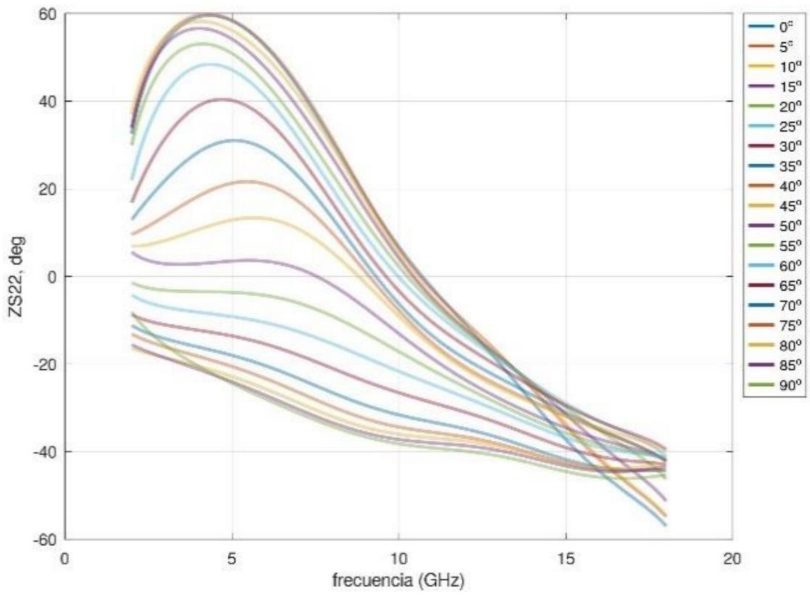


Figure 6: Effect of angular variation on the signal in the case of the circular glass specimen.

5.2 PORTABLE READER VER. 1

Preliminary tests were performed onto PRv1 to analyse carbon reinforced coupons and validate the concept conceived by RISE to avoid the shielding generated by the electrical conductivity of carbon fibre

5.2.1 ORIENTATION TESTS - PRV1

To measure the magnetic response of the sample under angular variation, a wooden board was used to ensure stability and accurate positional measurements (Figure 7). Angles were marked on the surface at 5° intervals, and the magnetic response of the sample was recorded at each step.

Figure 7: Placement and configuration of the carbon probe in the PRv1 for measurement of the effect of angular variation on the signal.

The observed behaviour (Figure 8) demonstrated an angular dependence of the sample's magnetic response. The signal amplitude decreased as the angle of the sample relative to the abscissa increased, consistent with the magnetic nature of the studied microwires and their inherent magnetic anisotropy.

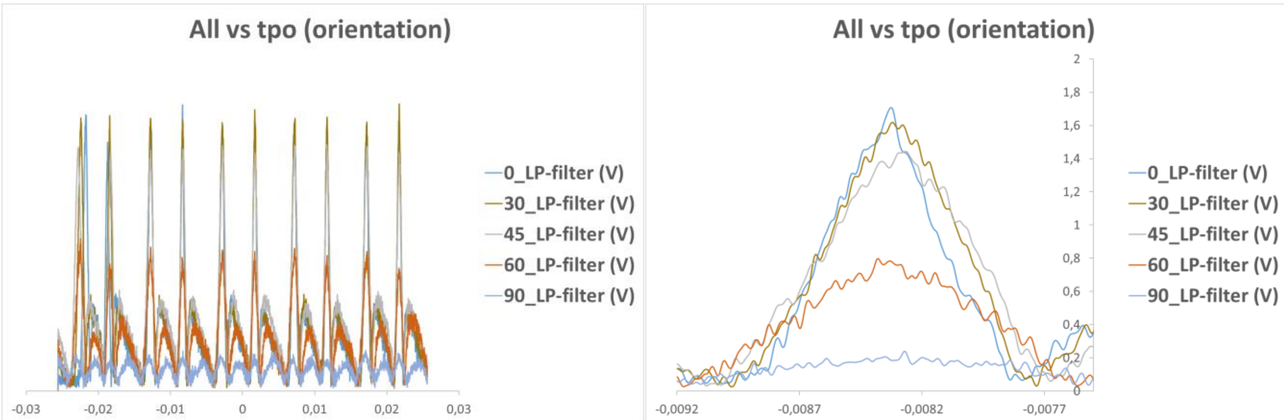


Figure 8: Results of the effect of specimen angle variation on PRv1. In the image above the periodic signal. In the image below, one of the peaks.

5.2.2 TEMPERATURE TESTS PRV1

For this preliminary test, the temperature at the center of the sample was increased using a heat gun and monitored with an IR thermometer (Figure 9). Simultaneously, the signal response was recorded using the reader system.

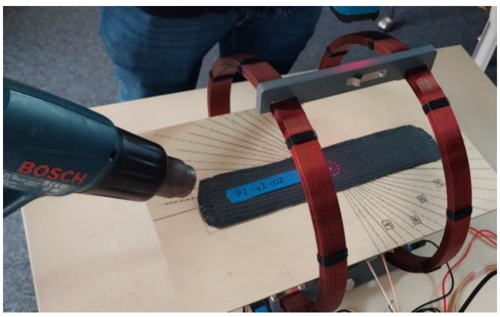


Figure 9: Configuration of the equipment for measuring the effects of temperature on the signal in the carbon probe in the PRv1.

This method was chosen for two main reasons:

- Experimental limitations required this approach to evaluate the influence of temperature. Subjecting the entire system to a uniform temperature (e.g., 80°C) posed a risk of damaging sensitive components, such as the antenna.
- The objective was not to obtain exact signal values corresponding to specific temperatures but rather to observe the qualitative behaviour—specifically, how the curves change with temperature compared to a sample at constant temperature. As such, a highly rigorous methodology was not necessary.

The results showing signal variation at different temperatures (°C) are presented in the Figure 10.

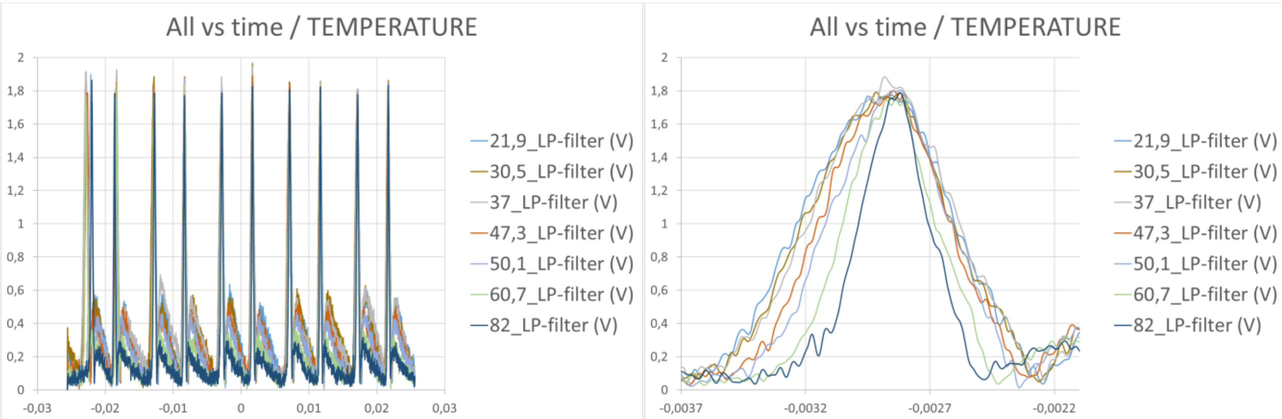


Figure 10: Results of the effect of temperature variation on PRv1. In the image above the periodic signal. In the image below, one of the peaks.

The results indicate a clear variation of the signal with temperature: as the temperature increases, the peaks become narrower. This behaviour aligns with the known temperature dependence of the Giant Magnetoimpedance (GMI), which is observed to increase with rising measurement temperature.

5.3 PORTABLE READER VER. 3

As explained above, all tests performed with version 2 of the handheld reader are not considered in the drafting of the deliverable due to their low reliability. Therefore, the results obtained with PRv3, once the equipment and software had been optimised by RISE, are presented below.

5.3.1 TEMPERATURE TESTS PRV3

The response of the specimen was analyzed for different temperatures. For this purpose, the carbon specimen with microwire inserts was placed in a heater, as shown in the Figure 11:

Figure 11: Set-up of the equipment for measuring the effect of temperature on the signal obtained from a carbon specimen with microwires using the PRv3. The specimen is placed in an aging chamber and a thermocouple is placed on the specimen.

The heater was set to different temperatures and, before taking the measurements the specimen was allowed to reach the oven temperature. To check this, the temperature measurements of the heater and the thermocouple positioned on the specimen were compared.

The result of measured voltage is shown in the Figure 12. The data processing of the final signals was obtained by averaging the data obtained at the different times of the test.

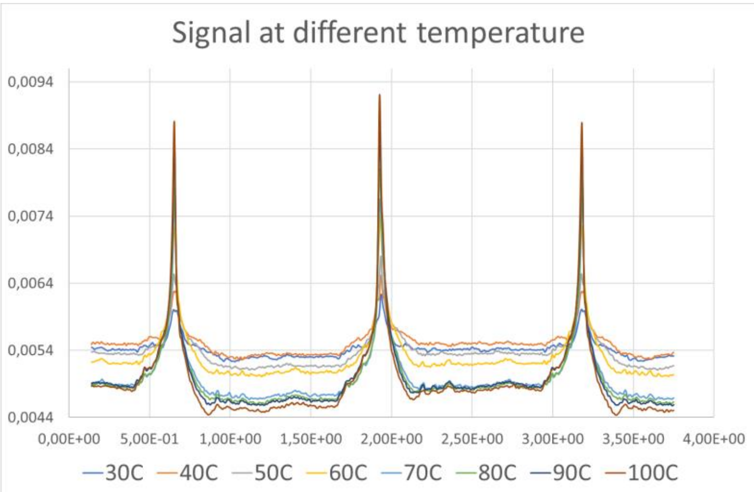


Figure 12: Results of the signals obtained for different temperatures.

As can be seen, the signal is temperature dependent. As the temperature increases, a clear phenomenon is observed: the width of the peak decreases and the height increases.

Thus, obtaining the area under the curve in one of the peaks and plotting it against the temperature, it was observed that the degree of correlation was high, indicating that there is indeed a correlation between the emitted signal and the temperature at which the specimen is located, as shown in the Figure 13.

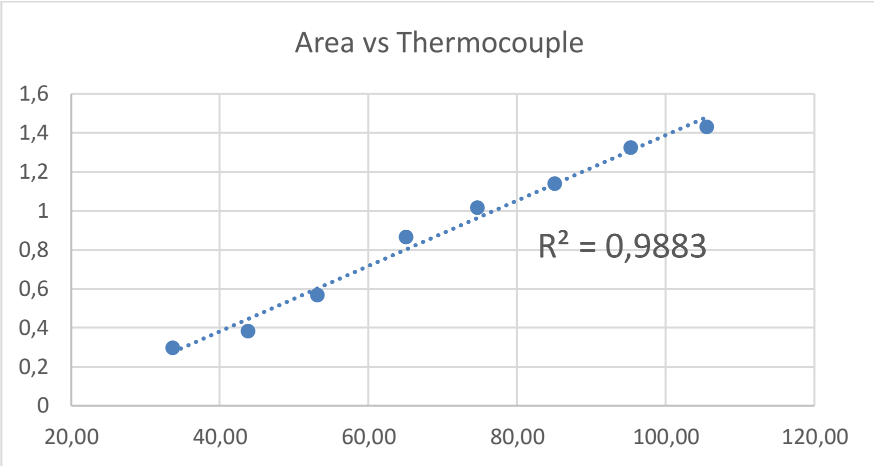


Figure 13: Relationship of area to temperature given by the thermocouple.

As can be seen in the images, the coefficient of determination is close to 1, which means that PRv3 has a remarkable predictive capacity or, in other words, it determines the signal with a more than acceptable level of accuracy.

5.3.2 TENSILE TESTS PRV3

At last, tensile tests were performed on a tensile testing machine, as shown in the Figure 14. Although the image shows two antennas (green), these were not part of the equipment.

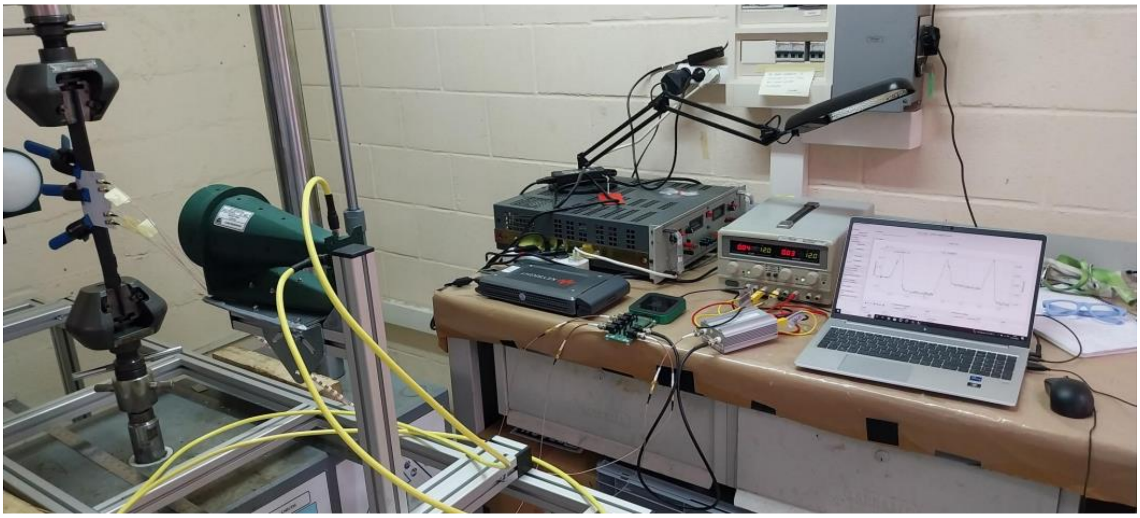


Figure 14: Set-up of the equipment for measuring the effect of tensile force on the signal obtained from the carbon specimen using PRv3

The signal was measured for different values of traction force, resulting in the graph below. The data processing of the final signals was obtained by averaging the data obtained at different times of the test. For each of the states a set of measurements (curves) was obtained, and the resulting measurement is the average of each of these measurements. A dependence of the signal on the applied force is observed (Figure 15): the higher the tensile force, the lower the signal.

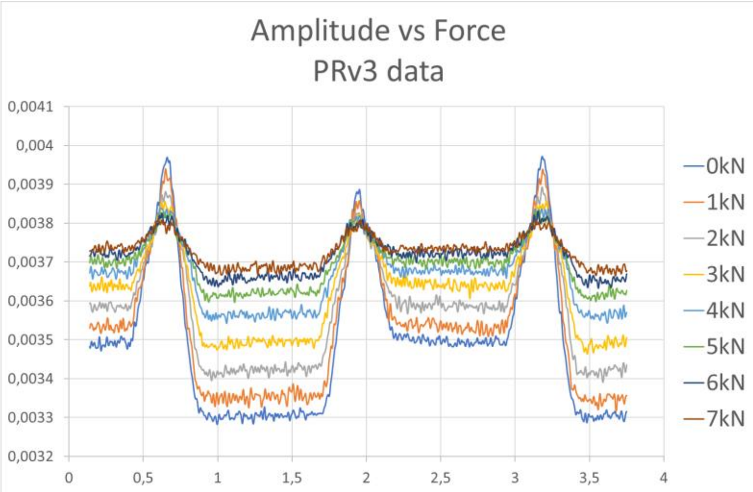


Figure 15: Effects of different stresses applied on the carbon specimen on the signal obtained.

A key variable in the analysis is the area under the curve, defined as the area enclosed between the recorded signal and a baseline plotted from the beginning to the end of the curve. This parameter allows to evaluate

1. Whether the relationship between signal width and height remains proportional (constant area) or whether it varies under different loading conditions.
2. The degree of correlation between the area under the curve and the magnitude of the applied tensile force. This reveals whether there is a quantifiable relationship between the signal emitted by the specimen and the mechanical stress to which it is subjected.

When plotting the calculated area versus tensile force, a significant correlation was observed, indicating that the signal responds systematically to changes in the applied

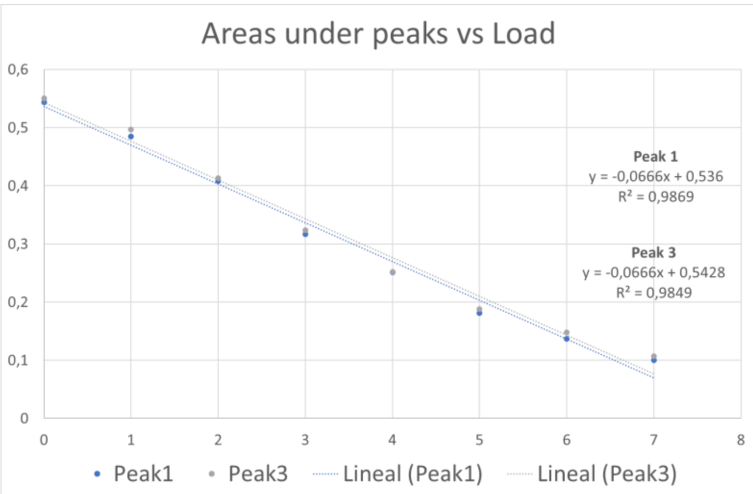


Figure 16: Relationship of the area under the curve to the applied force for different peaks.

As shown in the graphs, the coefficient of determination (R^2) reaches values close to 1, which demonstrates that the PRv3 model exhibits a robust predictive capability. In practical terms, this means that the system is able to estimate the signal with a statistically high accuracy, validating its reliability to quantify the material response to variations in the applied tensile force.

Results have been replicated with other test specimens and using other stress ranges (Figure 17 and Figure 18)

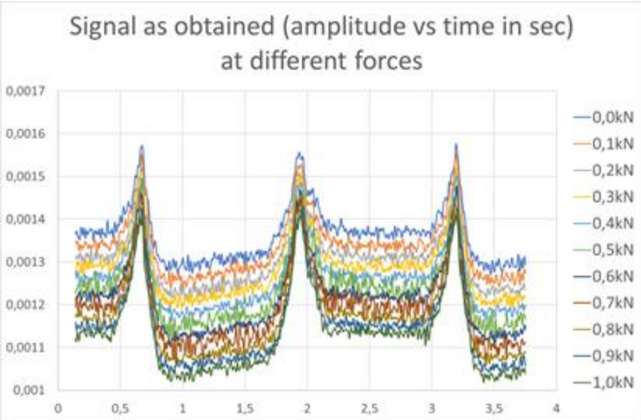


Figure 17: Effects of different stresses applied on the carbon specimen on the signal obtained in another test for a different force range

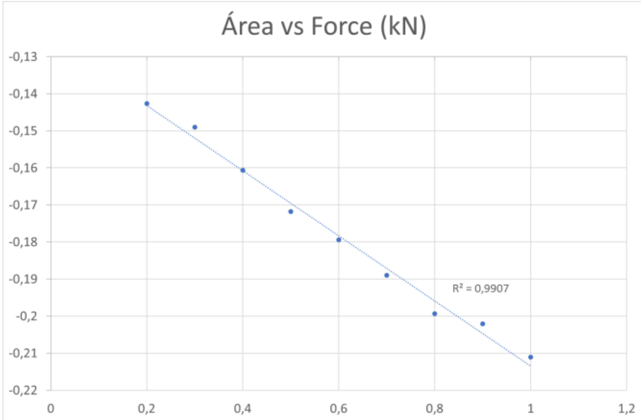


Figure 18: Relationship of the area under the curve to the applied force for different peaks in another test in relation to the previous figure.

Also, dynamic tests were performed in the same way. When the same loads were applied repeatedly in the same test, the results were found to be replicable, as shown in the graph below (Figure 19)

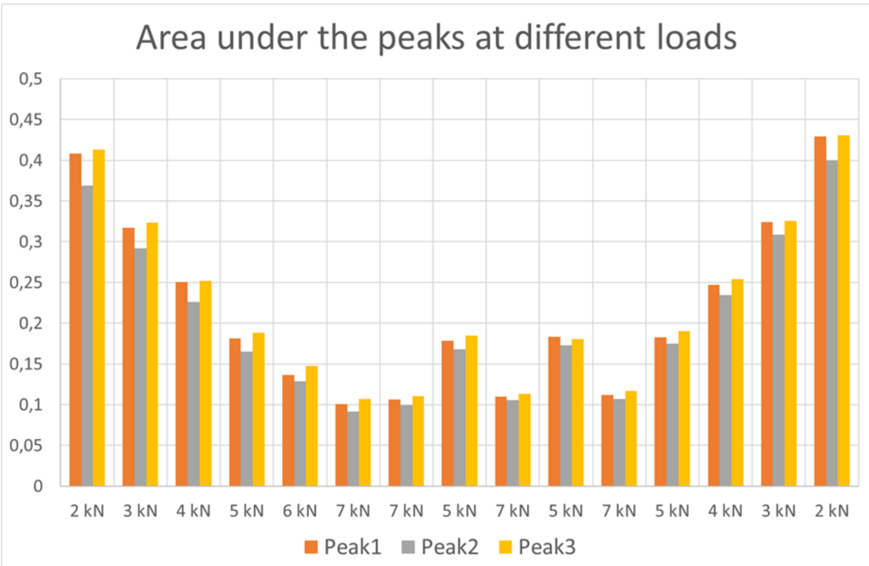


Figure 19: Comparison of the area under the curve for different values of tensile strength in the case of different signal peaks.

The x-axis shows the time and the y-axis the amplitude of the signal. In the test, loads were applied repeatedly at different times. The signal amplitudes obtained were practically the same. This tells us two things:

- There is replicability in the tests
- The material does not change its magnetic properties permanently after exposure to a load in the range studied.

Both in the study of the signal change with the applied voltage and in this last replicability test, the existence of magnetoelastic properties in the tested specimens is evident.

6. CONCLUSIONS

Continuous microwires have been integrated into reinforced composite flat parts and the adhesion between the polymeric matrix and the glass coated microwires is high enough to ensure an optimum matrix-fibre stress transfer when the composite is subjected to different stimulus.

Many measurements were conducted that show that the electromagnetic properties of glass-coated magnetic microwires can be read with an VNA in a free space environment without using a modulation ac magnetic field or static bias magnetic field in a non-anechoic environment. A clear dependence of measured scattering S parameters with stress applied has been identified over the entire bandwidth analysed (2 GHz – 18 GHz), with the best results obtained in the phase of reflection data (S11 and S22).

The validation of the portable reading system (PRv1 and PRv3) developed in the project has shown promising results, confirming its capacity to operate in controlled conditions and marking a remarkable technical advance. PRv3 stands out for its higher signal stability and improved thermal management compared to PRv2, positioning itself as a solid base for its evolution. However, analysis has revealed critical challenges that require additional optimizations to ensure its effectiveness in complex operating environments. So far, the system has successfully passed lab-scale tests (TRL4 level).

During the evaluations, a correlation between the recorded signals and parameters such as mechanical loading, spatial orientation and thermal variations was observed, supported by high coefficients of determination ($R^2 \approx 1$). These data, however, must be contextualized: the tests were performed under ideal conditions, with punctual practical limitations such as the shielding effect on carbon, which made it necessary to use substitutes (glass fiber). This finding highlights the need to further study electromagnetic interactions in highly conductive materials, as well as to adapt the system to heterogeneous industrial environments, where factors such as dynamic vibrations, humidity or extreme thermal cycles could affect its performance.

To consolidate the system, it is recommended to extend testing to more realistic scenarios that replicate adverse operating conditions: cyclic loading, multifactorial stress (mechanical-thermal-environmental) and prolonged exposure to electromagnetic interference. While static tests have shown repeatability, it is crucial to verify this consistency under dynamic vibrations and in advanced composites with varying conductive properties.

In summary,

- The laboratory system (VNA + antennas) allowed to validate the incorporation of the microwires in the composite structure and to verify that the signal variation can be detected with external elements.
- The PRv1 enabled to verify the concept of a reader based on the measurement of a magnetic field and its dependence on temperature and position/orientation.
- PRv3 has proved the clear dependence of the signal with changes in temperature and with the load applied in tensile tests.

The experimentation carried out led to the conclusion that it is possible to validate the concept proposed in the Portable Reader and that the system has passed the validation tests at laboratory scale.