Treball de Fi de Grau

Grau en Enginyeria en Tecnologies Industrials

Design and experimentation of a solar power system powering measurement chains in concrete structures strengthened with fiber-reinforced polymer rebars

REPORT

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Resum

Aquest treball de fi de grau té com a objectiu explorar la viabilitat d'utilitzar plaques solars per alimentar cadenes de mesura en estructures de formigó enfortides amb barres de polímer reforçat amb fibra (FRP).

Els principals objectius són: dur a terme una investigació profunda per entendre el funcionament de cada element que conforma el sistema, valorar diverses alternatives, identificar aspectes a tenir en compte respecte a la configuració del model, dissenyar un sistema d'energia solar a mida i realitzar-hi proves experimentals.

L'experiment implica una prova de flexió de 3 punts, on la barra de FRP s’ha sotmès a diferents condicions de càrrega. La mesura de la tensió ha sigut l'objectiu principal, tenint en compte la seva sensibilitat a la temperatura, factors ambientals i variacions de càrrega. La prova revela diferències entre la suspensió de càrrega directa i les suspensions seqüencials, destacant l'impacte de la magnitud de la càrrega, la distribució i la resposta estructural en els valors de deformació.

Els resultats han demostrat l'eficàcia dels panells solars per proporcionar energia sostenible per a les cadenes de mesura. L'anàlisi d'alternatives mostra el potencial de l'energia solar en aquests tipus de muntatges i com a conseqüència la possible contribució al desenvolupament sostenible dels sistemes de mesura en el sector de la construcció.

Resumen

Este trabajo de fin de grado tiene como objetivo explorar la viabilidad de utilizar placas solares para alimentar cadenas de medida en estructuras de hormigón fortalecidas con barras de polímero reforzado con fibra (FRP).

Los principales objetivos son: llevar a cabo una investigación profunda para entender el funcionamiento de cada elemento que conforma el sistema, valorar diversas alternativas, identificar aspectos a tener en cuenta respecto a la configuración del modelo, diseñar un sistema de energía solar a medida y realizar pruebas experimentales.

El experimento implica una prueba de flexión de 3 puntos, donde la barra de FRP se ha sometido a distintas condiciones de carga. La medida de la tensión ha sido el principal objetivo, teniendo en cuenta su sensibilidad a la temperatura, factores ambientales y variaciones de carga. La prueba revela diferencias entre una suspensión de carga directa y suspensiones secuenciales, destacando el impacto de la magnitud de la carga, distribución y respuesta estructural en los valores de deformación.

Los resultados han demostrado la eficacia de los paneles solares para proporcionar energía sostenible a las cadenas de medida. El análisis de alternativas muestra el potencial de la energía solar en este tipo de montajes y como consecuencia de la posible contribución al desarrollo sostenible de los sistemas de medida en el sector de la construcción.

Abstract

This final project aims to explore the viability of using solar panels for powering measurement chains in concrete structures reinforced with fiber-reinforced polymer bars (FRP).

The main objectives of the thesis are to carry out in-depth research to understand the operation of each element that makes up the system, assess various alternatives, identify aspects to take into account regarding the configuration of the model, design a custom solar energy system and carry out experimental tests.

The experiment involves a 3-point bending test, where the FRP rebar has been subjected to different load conditions. The strain measurement has been the primary focus, considering its sensitivity to temperature, environmental factors, and load variations. The test reveals differences between a direct load suspension and sequential suspensions, highlighting the impact of load magnitude, distribution, and structural response on strain values.

The results have demonstrated the effectiveness of solar panels in providing sustainable energy for measurement chains. The analysis of alternatives shows the potential of solar energy in this type of set ups and therefore the possible contribution to the sustainable development of measurement systems in the construction sector.

Contents

Abbreviations and Symbols

Rebar: Reinforcement bar

FRP: Fiber-reinforced polymer

PV: Photovoltaic

R: Resistor (Ω)

ε: Strain (μm/m)

RF: Radio frequency

DC: Direct current

AC: Alternating current

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1. Introduction

1.1. Motivation

Once reached the final part of the studies in Industrial Technologies Engineering, a final project must be developed based on the knowledge of some of the different disciplines worked on during the degree. This work is an opportunity to be able to apply all the skills acquired in the last years, and somehow face an engineering project within the academic field.

My motivation to pursue this thesis originates from my deep interest in addressing the urgent issue of climate change. This curiosity was further stimulated during my participation in a project focused on solar panels as part of the "Project II" course last year. The experience allowed me to witness firsthand the potential of solar energy in reducing the environmental impacts of traditional power sources.

1.2. Scope

The scope of this thesis is to focus on the development and testing of a solar-powered system specifically designed for powering measurement chains in concrete structures reinforced with FRP rebars.

The scope includes the research, design, and implementation, as well as the evaluation of the experiment results regarding the performance of the FRP rebar.

The scope does not extend to other aspects such as the detailed design of the concrete structures or the experimentation with those.

1.3. Prerequisites

- **Technical Prerequisites:** Adequate knowledge and understanding of concrete structures, FRP rebars, solar power systems, strain sensors, and related measurement techniques. Proficiency in relevant software tools and programming languages for data analysis and system control, achieved with the help of Ph.D. student Paweł Zielonka, from Politechnika Wrocłaska university.

- **Economic Prerequisites:** Sufficient financial resources to acquire the necessary equipment, materials, and components for the solar power system and measurement chains. All the equipment needed has been provided by Politechnika Wrocłaska university, where I've been doing my Erasmus this semester.

Regarding the administrative and legal prerequisites, these haven't been essential to carry out the project, however, they would be necessary if one wished to dig deeper into the experiment. Due to the compliance with applicable regulations related to the implementation of solar power systems, data acquisition, and experimentation in concrete structures.

1.4. Objectives

The objectives of this final thesis could be summarized in:

- Conduct a **comprehensive literature** review to **analyze** the properties and characteristics of FRP rebars, solar power systems, and measurement chain technologies with the aim of understanding how each of these elements will workthe system.

- Identify relevant design considerations and best practices in utilizing renewable energy for powering measurement chains in concrete structures.

- **Design and develop** a solar power system tailored specifically for powering the measurement chains in concrete structures strengthened with FRP rebars. **Selecting appropriate components**, including solar panels, controllers, batteries, and voltage converters, ensuring compatibility and optimal performance.

- Conduct **experimental tests** and measurements to **evaluate** the performance and effectiveness of the solar power system in powering the measurement chains.

2. Theoretical background

2.1. Concrete structures

First, it is necessary to understand how the most basic system in this project works, in other words, the canvas on which to operate: concrete structures.

Concrete is a composite material made from a mixture of cement, water, and aggregate (such as sand or gravel). When these components are combined, they form a hardened substance that can withstand a great deal of weight and pressure.

Concrete structures are typically designed using steel reinforcement bars, also known as rebar, which are embedded in the concrete. The rebar provides additional strength and stability to the structure, particularly in areas where the concrete may be subject to stress or tension.

The process of building a concrete structure typically involves pouring the wet concrete into molds or formwork, allowing it to dry and harden over time. Once the concrete has fully cured, the formwork can be removed, revealing a solid and stable structure that can support heavy loads.

Concrete structures are used in a variety of applications, from buildings and bridges to roads and dams. They offer several advantages, including strength, durability, and fire resistance, making them a popular choice for construction projects around the world.

2.2. Concrete structures strengtheners

Concrete structures are often strengthened with different materials and techniques, depending on the specific needs and requirements of the structure, the type and severity of the damage, and the available budget and resources. Some of the most common materials and techniques used to strengthen concrete structures include:

- **Steel reinforcement:** Steel bars or mesh can be embedded in the concrete to provide additional strength and stability. This technique is commonly used in reinforced concrete structures such as bridges, buildings, and parking garages.

- **Epoxy injection:** Epoxy resin can be injected into cracks in concrete to fill and strengthen them. This technique is commonly used to repair and strengthen concrete beams, columns, and other structural elements.

- **Shotcrete:** Shotcrete is a method of applying concrete to a surface using a high-pressure spray. It is often used to reinforce existing structures or to create a new layer of concrete on top of an existing surface.

- **Post-tensioning:** Post-tensioning is a technique that involves applying tension to steel cables that are embedded in the concrete. This can help to reinforce the structure and prevent cracking and other types of damage.

- **Fiber-reinforced polymer (FRP):** FRP is a lightweight and high-strength material that is often used to reinforce concrete structures. It is applied as a thin sheet to the surface of the concrete and can provide additional strength and stiffness.

This last technique is precisely the type of reinforcement that will be used in this project to reinforce the concrete structures that will be worked with.

2.3. Analysis of FRP rebars

2.3.1. Introduction to FRP rebars

As already mentioned, FRP (Fiber Reinforced Polymer) rebars are a type of reinforcement bar used in concrete structures, similar to traditional steel rebars. However, instead of steel, they are made of a composite material consisting of fibers such as glass, carbon, or basalt, embedded in a polymer resin matrix.

FRP rebars have several advantages over traditional steel rebars, including being lightweight, non-corrosive, and having a high tensile strength-to-weight ratio. They are also non-magnetic and non-conductive, making them ideal for use in structures such as bridges, marine structures, and buildings where the presence of steel may interfere with sensitive electronic equipment.

2.3.2. FRP composition

FRP is a highly sought-after construction material because of its resistance to corrosion and lightweight yet robust nature [1]. It is considered a composite material because it is a twisted structural reinforcing rod made from a combination of different materials, such as plastic resin and glass fibers. The blending of these materials produces FRP or fiber-reinforced plastic, which is impervious to the chloride-rich environment and has an advantage over corrosion-prone iron and steel.

The plastic resin used in FRP serves as a binding agent that adheres the glass fibers together in the structural layer, while also allowing for the incorporation of additional materials to enhance the final product's properties, such as fire resistance, temperature resistance, and improved durability against corrosives.

One significant difference between FRP rebar and steel rebar is their durability. Unlike steel, fiberglass rods can last up to 80 years due to their resistance to corrosion, acids, and rust formation, they remain durable and maintain their structural integrity over time.

FRP also boasts lower thermal conductivity than metal, making it an excellent heat insulator. A fiberglass mesh is frequently used in civil engineering and construction, especially in scientific and medical buildings where complex medical equipment and devices are present because FRP does not stand in the way of their performance.

Furthermore, the installation of FRP reinforcement is a straightforward process where rods are tied with joints, eliminating the need for welding. FRP rebar is an excellent option for those who wish to save money on construction or reinforcement works as it is significantly cheaper than steel and easier to transport to the construction site.

Overall, FRP's remarkable characteristics make it a highly versatile and valuable material in various construction applications.

2.3.3. What are FRP rebars usually used for?

FRP is a material that is becoming increasingly popular in structural and architectural applications where extreme temperature changes or corrosion are significant concerns [1]. Its long durability and robustness against corrosion make it a viable option in marine construction, IT, chemical processing industries, and healthcare facilities.

The range of applications for FRP materials is vast. For example, FRP can be used to fortify engineered structures that are exposed to dynamic and impact loads like wind, waves, high traffic, earthquakes, and blasts.

FRP can also be used to produce subsea pipes for deep water where buoyancy is essential. Stairways, walkways, and structures made from concrete, masonry, timber, and steel can all be reinforced with FRP mesh and rods.

Seismic retrofitting is one of the most notable uses of FRP, involving the alteration and enhancement of existing structures to increase their resistance to seismic activity. FRP rods are also used for reinforcing underwater pipelines, waterside platforms, and marine or coastal concrete projects like constructing wharves, fending groins, and water purifying facilities. Additionally, FRP is used for internal reinforcement projects for concrete structures and as a common reinforcement material in constructing manufacturing facilities and factories.

2.3.4. Comparison between FRP and steel rebars

It is worth it to highlight the differences between FRP and steel rebars ***Table 2.1*** due to the doubts that still exist regarding their properties and performances.

Properties	FRP rebar	Steel rebar
Weight	¼ of steel weight	10mm, 0.617kg/m (or 0.188 kg/ft)
Strength	206.5 MPa	248.2 MPa
Electrical conductivity	Non-conductive	Conductive
Thermal conductivity	Low	High
Corrosion resistance	High (unaffected by water)	Low (without expensive galvanization treatment bars of steel are subject to oxidation)
Heavy load resistance	No permanent deformation	Can be permanently deformed
Costs	Lower manufacturing costs, maintenance costs, and transportation expenses (related to lightweight)	Lower material costs but higher overall costs of production, transportation, installation, and technical maintenance

Table 2.1 *Comparison between FRP and steel rebars [2]*

While steel rebar is widely used and known for its strength, it has its drawbacks, such as being prone to moisture, corrosion and restricted in certain industries [2]. Additionally, its low initial cost is offset by high transportation and on-site installation costs. Moreover, corroded steel rebar requires costly maintenance over time and boosts the tensile load on concrete structures, something counterproductive to the objective sought to be achieved.

On the other hand, FRP rebar is resistant to corrosion and chemical reactions, making it ideal for marine and open-air applications. The tensile strength of FRP rebar is 20% higher than that of steel, and its material bonding force is considerably stronger, allowing for better operational endurance. FRP rebar is also customizable, making it possible to tailor the resins used in production to specific requirements.

Another advantage of FRP rebar is it's lightweight, weighing only one-fourth of steel rebar of the same size, reducing shipping and installation costs.

It also has better impact resistance, distributing the impact load and preventing surface damage, due to its difficulty to deform permanently. In similar situations, especially in reduced temperatures, steel products might be deformed.

However, FRP rebar differs from steel in its electrical and thermal conductivity, with steel being a good conductor and FRP having low thermal conductivity and zero electrical conductivity.

FRP rebar is often the preferred choice over steel rebar in many applications due to its superior resistance to thermal, corrosion, and chemical factors. Additionally, FRP's significantly lighter weight leads to reduced transportation costs. However, in industrial applications where electrical conductivity is necessary, steel rebars are still irreplaceable. Aside from these specialized cases, FRP rebar is an excellent cost-effective alternative to steel rebar.

2.3.5. Environmental impact on the properties of FRP Rebar

The use of FRP products has become widespread and has led to an increase in applied studies of various composite materials [3], their mechanical properties and characteristics, and their behavior under different environmental conditions.

FRP rebars have become a cost-effective alternative to traditional materials. They are particularly useful in harsh environments where reinforced concrete tends to lose mechanical strength over time when exposed to humidity, water, chemical substances, and thermal shock.

Nakada and Miyano's recent research [4] has revealed that FRP rebars are impacted to a lesser extent than steel bars in terms of durability and moisture absorption in humid environments. However, certain environmental factors, such as high temperature and humidity, can have a significant impact on the performance of FRP rebars in different climate zones, according to the research conducted by Marom.

In terms of corrosion and chemical resistance, composite materials demonstrate better properties compared to iron and aluminum. However, in extreme conditions of high temperature and moisture, only FRP bars with dense matrices are suitable for civil engineering and marine applications. The sustainability of FRP composites is another reason for their increased use in construction projects. Reports from different research teams indicate that FRP rebar performance in harsh environments is superior to that of reinforced concrete.

2.4. Measurement chains

In general, measurement chains refer to a system or a sequence of measurement components that are connected to measure a physical quantity. The measurement chain may include sensors or transducers, signal conditioning components, data acquisition systems, and data processing or analysis tools.

- **Sensor:** The sensor is the component that detects the physical quantity being measured. Sensors come in many different types, such as thermocouples, pressure transducers, or flow meters.

- **Signal conditioning circuit:** The signal conditioning circuit processes the signal from the sensor and prepares it for the next stage of the measurement chain. This may include amplification, filtering, or linearization of the signal.

- **Data acquisition system:** The data acquisition system samples the conditioned signal at regular intervals and converts it into a digital format that can be stored and analyzed by a computer.

- **Software:** The software provides a user interface for configuring the measurement system, acquiring data, and analyzing the results.

Each component in the measurement chain contributes to accurately and reliably measuring physical parameters such as temperature, pressure, displacement, or strain, among others. These measurements can then be used to monitor and control processes, improve product quality, ensure safety, or gather data for research purposes.

In this case, the magnitude to be measured is the strain in concrete structures strengthened with FRP rebars, therefore, strain sensors will be one of the main focus points in the system.

3. Analysis of alternatives

3.1. Strain sensors

A strain sensor is a device that measures the amount of deformation or strain that occurs in a material when it is subjected to an external force or load. These sensors typically consist of a sensing element, such as a metal foil or semiconductor, that changes its electrical resistance, capacitance, or inductance in response to the applied strain.

Strain sensors are used in a wide range of applications, such as in structural health monitoring of bridges, buildings, and other infrastructure, as well as in automotive and aerospace industries to monitor the performance of components under stress. They are also used in medical devices to monitor the deformation of tissues and organs, and in sports equipment to measure the strain on materials and optimize their design.

Strain sensors can detect changes in length, thickness, or circumference of a material when it is subjected to stress or strain, and this information can be converted into an electrical signal that is used for measurement and analysis. Overall, measurement chains and strain sensors are essential tools for understanding the behavior of materials and structures under different loading conditions.

The data collected by strain sensors can be used to analyze and optimize the performance of a system or structure. For example, in concrete structures strengthened with FRP rebars, strain sensors can be used to monitor the deformation and stress of the structure under load. This information can be used to optimize the design of the structure and to ensure its long-term durability and safety.

3.1.1. Types of strain sensors

There are several popular strain sensors used in various fields and applications. Here are some examples of the most used strain sensors and their respective areas of application:

- **Strain Gauges:** Strain gauges are widely used in structural engineering, civil engineering, aerospace, automotive, and manufacturing industries for applications such as stress analysis, load monitoring, deformation measurements, and material testing.

- **Piezoresistive Sensors:** These sensors utilize the changes in electrical resistance of certain materials under mechanical strain. They are commonly used in automotive applications, robotics, medical devices, and consumer electronics for measuring force, pressure, and acceleration.

- **Capacitive Sensors:** Capacitive strain sensors measure strain based on changes in capacitance between two conductive surfaces. They find applications in precision engineering, microelectronics, and nanotechnology for measuring tiny strains and deformations.

- **Fiber Optic Sensors:** Fiber optic sensors use optical fibers to measure strain based on changes in light propagation. They are extensively used in civil engineering, geotechnical monitoring, structural health monitoring, and aerospace applications due to their immunity to electromagnetic interference and ability to cover long distances.

- **Extensometers:** Extensometers are mechanical devices that directly measure strain by measuring changes in length. They are commonly used in materials testing, geotechnical engineering, and structural analysis.

- **Load Cells:** While load cells primarily measure force, they can also be used indirectly to measure strain by converting force into strain readings. Load cells are widely used in weighing scales and industrial automation.

3.1.2. Determination of the sensor: Strain gauges

Strain gauges and extensometers are the devices that might work better to carry out this project, due to their popularity in materials testing. However, as the aim of this project is to measure the bending of an FRP rebar through the power given by the solar power panels, a device that requires electricity to work is needed. So, this makes the strain gauges the best alternative to work with.

In ***Figure 3.1*** a strain gauge illustration is shown:

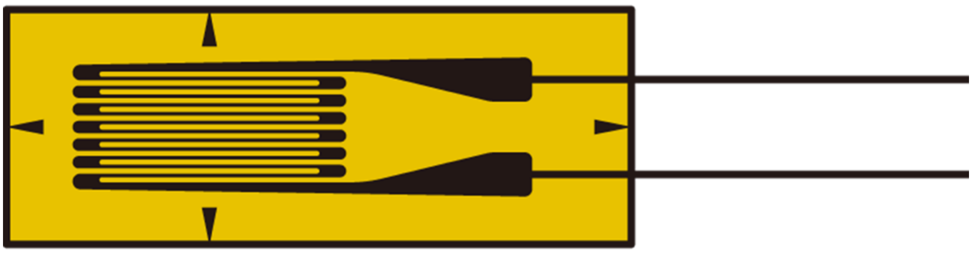

Figure 3.1 *Strain gauge illustration [5]*

As previously stated, strain gauges are commonly used to measure strain or deformation in materials. In civil engineering and geotechnical monitoring, strain gauges are frequently employed to identify potential failures in structures such as bridges and buildings. Continuous monitoring of these structures is crucial as any substantial deformation could pose risks of injury or even loss of life. Strain gauges are preferred in such applications due to their exceptional precision, effective performance even when placed at considerable distances from the test object, and the ease of their setup and maintenance over extended durations.

To go deeper into the subject is essential to understand what strain actually is. It consists of a dimensionless measurement, the quotient between the change in length and the initial length of the sample.

$$\varepsilon = \frac{\Delta l}{l} \qquad \text{(Eq. 4.1)}$$

These sensors are composed of a thin wire or foil made of a conductive material [6], (from about 1/1000 inch in diameter) such as constantan or foil-like semiconductors. This wire is usually arranged in a grid or pattern to optimize strain sensitivity. It is mounted onto the surface of the material being measured, usually using an adhesive; these glued strain sensors are commonly called Bonded Strain Gauges (see ***Figure 3.2***).

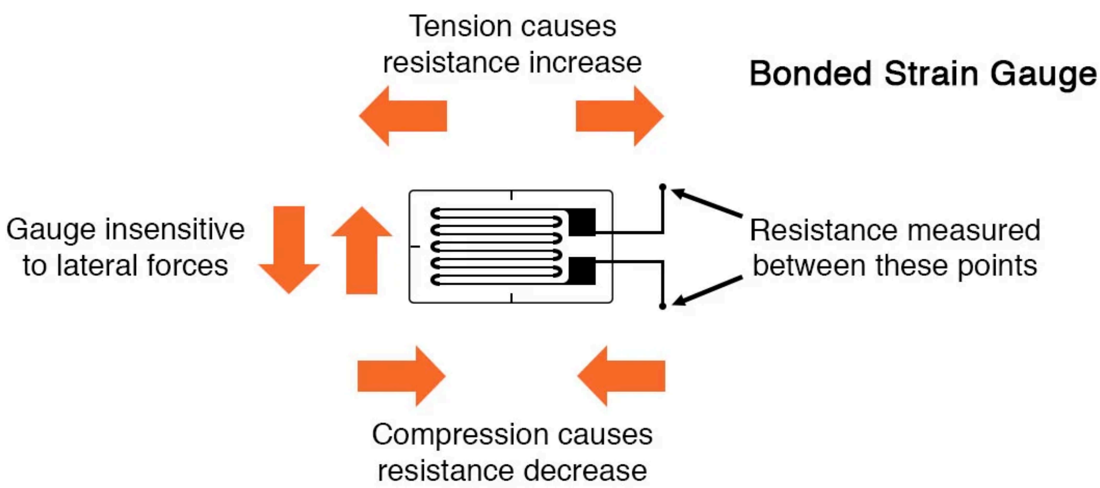

Figure 3.2 *Scheme of the operation of a strain gauge [6]*

Although strain depends on the changes of length, with these devices the important magnitude which brings the result is resistance. The strain gauge has a specific electrical resistance. When there is no strain, the electrical resistance remains constant. But when the material experiences strain, it deforms, and the strain gauge also experiences deformation. This deformation causes a change in the length and cross-sectional area of the foil.

Therefore, instead of working with precious equations, strain gauges use the Gauge Factor, which is the sensitivity of the gauge. By measuring the change in electrical resistance across the thin conductive foil, it converts the change in resistance to the change in length.

$$\varepsilon = \frac{\Delta R}{R} \quad \text{(Eq. 4.2)}$$

Typical resistance values of strain gauges range from 30 Ω to 3 kΩ when they are not subjected to stress. The resistance of the strain gauge only changes slightly, typically less than a percent, within the full force range it is designed for. This limitation exists due to the elastic limits of both the gauge material and the test specimen. If the forces applied were strong enough to induce larger resistance changes, it would cause permanent deformation to the test specimen and/or the gauge conductors, rendering the gauge ineffective as a measurement device.

Therefore, in order to utilize the strain gauge effectively, it is necessary to accurately measure extremely small changes in resistance. A bridge measurement circuit is necessary to meet the exacting precision required for such measurements.

3.1.3. Strain gauge circuits

3.1.3.1. Wheatstone Bridge

The Wheatstone Bridge is a circuit configuration used to measure an unknown electrical resistance by balancing it with known resistors [7]. It was invented by Samuel Hunter Christie in 1833 and later popularized by Sir Charles Wheatstone.

The Wheatstone Bridge consists of four resistors connected in a diamond shape, with the unknown resistor placed in one of the arms. The bridge is typically powered by a voltage source, and a galvanometer is connected between two junction points of the bridge. The galvanometer measures the voltage difference between these points, indicating whether the bridge is balanced or not.

The basic principle behind the Wheatstone Bridge is the balance condition, where there is no current flowing through the galvanometer. When the bridge is balanced, the ratio of the known resistors is equal to the ratio of the unknown resistor to be measured. This balance can be achieved by adjusting the values of the known resistors until no current flows through the galvanometer.

The formula for the balance condition of a Wheatstone Bridge is:

$$\frac{R_a}{R_x} = \frac{R_1}{R_2} \quad \text{(Eq. 4.3)}$$

Where R_1 and R_2 are the known resistors, and R_x is the unknown resistor. R_a is another known resistor that can be adjusted to achieve balance.

The Wheatstone Bridge represented in ***Figure 3.3*** is widely used for measuring unknown resistances accurately. It is commonly employed in various applications, including strain gauge measurements, temperature sensing, and resistance measurements in electronic circuits. The bridge configuration helps compensate for temperature changes and eliminates the effects of lead resistances and power supply variations, making it a reliable method for precise resistance measurements.

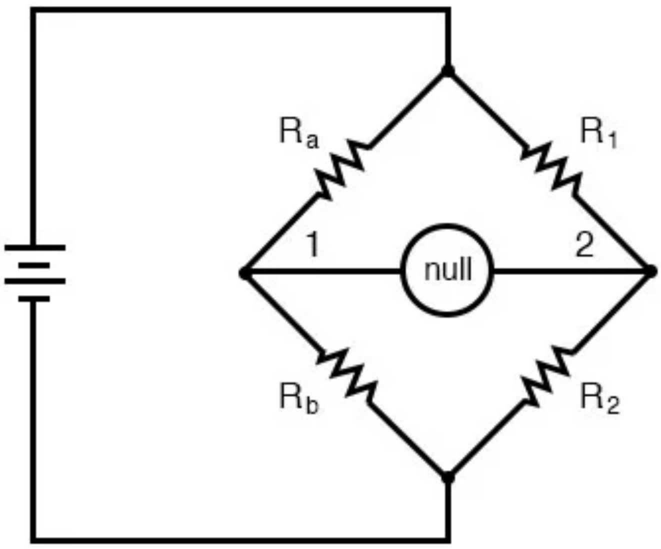

Figure 3.3 *Wheatstone Bridge scheme [7]*

3.1.3.2. Quarter-bridge train gauge circuit

In contrast to the previously described Wheatstone bridge, which relied on a null-balance detector and human intervention to maintain balance, a strain gauge bridge circuit detects and quantifies strain, based on the level of variance it produces. The strain gauge changes its resistance in response to mechanical strain or deformation.

This circuit incorporates a precision voltmeter positioned at the center of the bridge to precisely measure the extent of this imbalance. The magnitude of the output voltage indicates the amount of strain experienced by the object.

To achieve accurate measurements, the Wheatstone Bridge is typically connected to a signal conditioning circuit that amplifies and filters the output voltage, improving the overall sensitivity and accuracy of the strain measurement.

The configuration represented in ***Figure 3.4***, where a component of the bridge alters its resistance in accordance with the measured quantity, is commonly referred to as a quarter-bridge circuit.

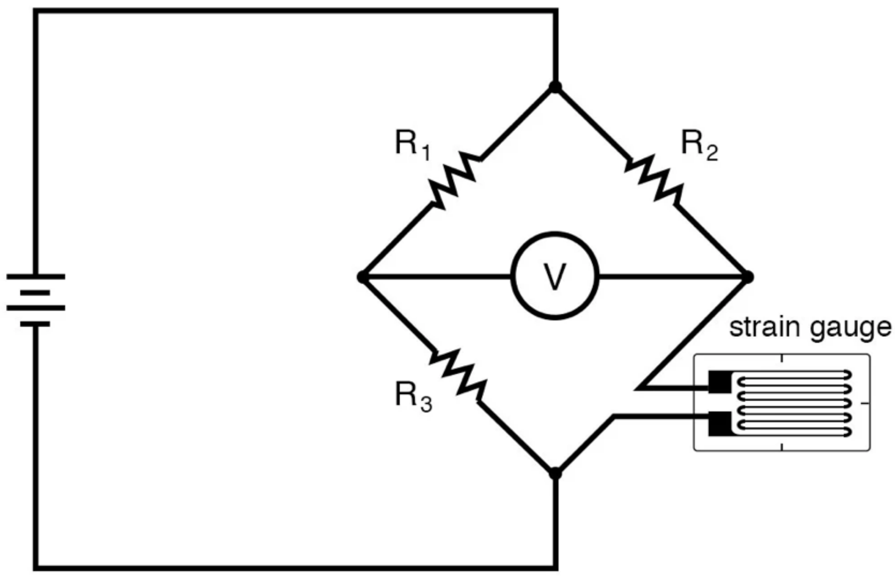

Figure 3.4 Quarter-bridge strain gauge circuit scheme [7]

3.1.3.3. Resistance changes in temperature

One drawback of strain gauges is their sensitivity to changes in temperature, which is a common characteristic of all conductors. As a result, the quarter-bridge circuit scheme shown below (***Figure 3.5***), functions as both a strain indicator and a thermometer.

This dual role may not be desirable if the sole intention is to measure strain accurately. Nevertheless, this issue can be overcome by using an additional strain gauge instead of. By doing so, both components of the rheostat arm (a variable resistor that is used to control the flow of electric current in a circuit) will experience resistance changes in the same proportion when the temperature fluctuates, effectively mitigating the impact of temperature variations.

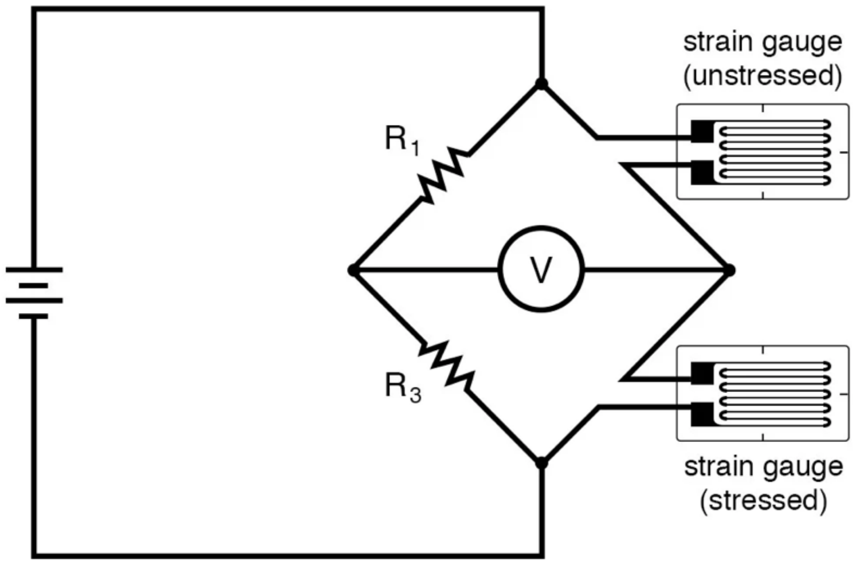

Figure 3.5 *Quarter-bridge strain gauge circuit temperature compensator scheme [7]*

Resistors R_1 and R_3 have equal resistance values, and the strain gauges are identical. In the absence of any applied force, the bridge should be perfectly balanced, resulting in a voltmeter reading of 0 V. Both gauges are affixed to the same test sample, but only one is positioned and oriented to experience physical strain (referred to as the "active gauge"). The other gauge is isolated from mechanical stress and serves solely as a temperature compensation device (referred to as the "dummy gauge").

If there are changes in temperature, both gauge resistances will vary by the same percentage, leaving the balance of the bridge unaffected. Only a differential resistance, which represents the difference in resistance between the two strain gauges, caused by physical force on the test sample, can disturb the bridge's balance.

3.1.3.4. Half-bridge strain gauge circuit

Although the bridge circuit now incorporates two strain gauges, only one of them is sensitive to mechanical strain. As a result, this configuration is still classified as a quarter-bridge.

However, if the upper strain gauge is repositioned in a way that it experiences an opposing force compared to the lower gauge (meaning that compression on the upper gauge corresponds to stretching on the lower gauge, and vice versa), both gauges will respond to strain. This arrangement is referred to as a half-bridge (***Figure 3.6***). By having both strain gauges either increase or decrease resistance in proportion to changes in temperature, the impact of temperature variations is nullified, minimizing measurement errors caused by temperature fluctuations.

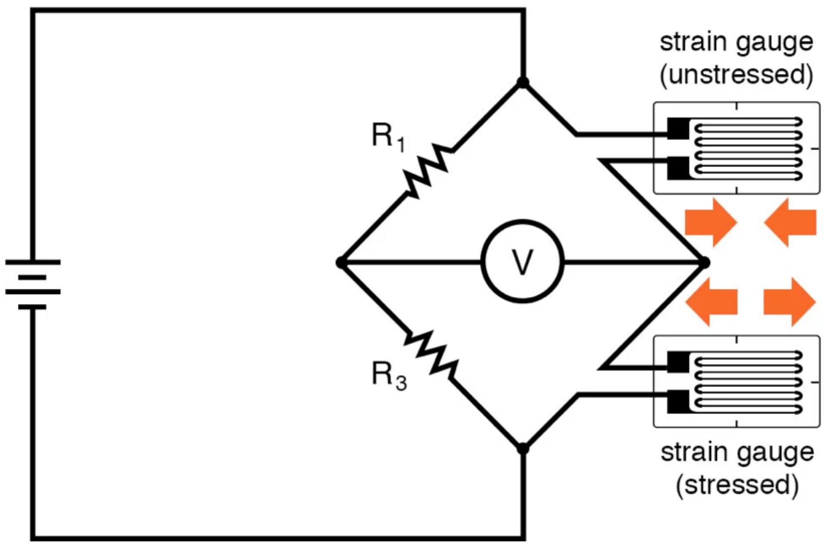

Figure 3.6 *Half-bridge strain circuit [7]*

3.2. Power Systems

Using strain sensors, it is possible to measure the deformation and stresses within the concrete structure and monitor its behavior over time. However, the measurement chains require power to function. There are several powering systems for sensors, depending on the type of sensor and its application. Here are some examples:

3.2.1. Piezoelectric powered sensors

These sensors are powered by mechanical energy, such as vibrations or pressure changes, which cause a piezoelectric material to generate an electrical charge. However, piezoelectric sensors may not be suitable for powering measurement chains in concrete structures reinforced with FRP bars because the piezoelectric effect can be affected by the stiffness and damping of the surrounding material, potentially leading to inaccurate measurements.

In ***Table 3.1***, a pros and cons list of powering sensors through piezoelectric methods is represented:

Pros	Cons
Self-powering: Piezoelectric-powered sensors can generate their power from the ambient mechanical vibrations in the concrete structure. This means that they do not require external power sources or batteries, which can be an advantage in hard-to-reach locations.	**Limited power output:** Piezoelectric-powered sensors can generate a limited amount of power, which can limit the number of sensors that can be used in a measurement chain.
Longevity: Piezoelectric-powered sensors have a long service life, as they do not require frequent battery replacements or maintenance.	**Dependence on mechanical vibrations:** The performance of piezoelectric-powered sensors is dependent on the availability and intensity of mechanical vibrations in the concrete structure. In the absence of sufficient vibrations, the sensors may not generate enough power to operate effectively.
High sensitivity: Piezoelectric-powered sensors can detect even the smallest mechanical vibrations, making them useful for monitoring the performance of concrete structures reinforced with FRP rebars.	**Temperature sensitivity:** Piezoelectric-powered sensors can be sensitive to changes in temperature, which can affect their performance.
Cost-effective: Piezoelectric-powered sensors can be more cost-effective in the long run since they do not require expensive external power sources or regular maintenance.	**Environmental factors:** The use of piezoelectric-powered sensors may be affected by environmental factors such as humidity, which can affect their sensitivity and reliability.

Table 3.1 *Piezoelectric powered sensors pros and cons*

3.2.2. Radio frequency (RF) powered sensors

RF-powered sensors use radio waves to transmit power to the sensor. These sensors have an antenna that captures the RF energy and converts it into electrical energy to power the sensor. Nevertheless, concrete is a highly absorptive material, which means that it can significantly attenuate RF signals. This may result in low power transfer efficiency and difficulty in obtaining reliable measurements.

In ***Table 3.2*** advantages and disadvantages of RF-powered sensors are presented:

Pros	Cons
Wireless: RF-powered sensors can be designed to operate wirelessly, which means that they can be easier to install and maintain compared to wired sensors.	**External power source:** RF-powered sensors require an external power source, which can be a disadvantage in hard-to-reach locations or areas without access to power.
Long-range communication: RF-powered sensors can communicate data over relatively long distances, which makes them useful for monitoring large concrete structures.	**Limited battery life:** RF-powered sensors that use batteries can have limited battery life, which can require frequent maintenance or replacement.
High reliability: RF-powered sensors can operate reliably in harsh environments and can withstand exposure to moisture, dust, and other environmental factors.	**Interference:** RF-powered sensors can be subject to interference from other sources of electromagnetic radiation, which can affect their performance.
High power output: RF-powered sensors can generate high levels of power, which can support multiple sensors in a measurement chain.	**High cost:** RF-powered sensors can be more expensive than other types of sensors due to their wireless capabilities and advanced technology.

Table 3.2 *Radio frequency powered sensors pros and cons*

3.2.3. Wired sensors

Some sensors, such as those used in industrial automation or building control systems, are powered by wired connections to a power source, such as an electrical outlet or a power-over-ethernet (PoE) connection. The downside of this option is that it necessitates physical wiring for power supply and data transmission. In the case of concrete structures reinforced with FRP bars, it may be difficult or impractical to install cables without damaging the reinforcing bars or affecting the structural integrity of the concrete. Additionally, wired sensors may not be suitable for monitoring concrete structures in remote or hard-to-reach locations.

Wired sensors positive and negative aspects are illustrated in ***Table 3.3***:

Pros	Cons
Reliable power source: Wired sensors can be powered by a reliable and constant power source, such as batteries or mains power, which means that they are not dependent on mechanical vibrations or external RF signals.	**Cost and complexity:** Wired sensors can be more expensive and complex to install and maintain compared to wireless or self-powered sensors, especially in hard-to-reach locations or large structures.
High accuracy: Wired sensors can provide high accuracy and precision in their measurements, which can be important for critical applications such as structural health monitoring.	**Limited flexibility:** Wired sensors are limited by the length of the cables that connect them, which can limit their range and placement options.
Easy installation: Wired sensors can be relatively easy to install and maintain, especially in locations with easy access to power and communication infrastructure.	**Risk of damage:** Wired sensors are more susceptible to damage from physical stress, environmental factors, or accidental damage to the cables.
Low interference: Wired sensors are less susceptible to interference from external sources compared to wireless sensors, which can make them more reliable in some environments.	**Maintenance requirements:** Wired sensors require regular maintenance to ensure that the cables and connections are intact and functional.

***Table 3.3** Wired sensors pros and cons*

3.2.4. Battery-powered sensors

Battery-powered sensors typically consist of three main components: the sensor itself, the electronic circuitry, and the battery. The sensor measures a physical parameter such as temperature, pressure, or vibration and generates a signal that is sent to the electronic circuitry. The electronic circuitry processes the signal and may transmit it wirelessly to a data acquisition system or store it locally for later retrieval. The battery provides power to the electronic circuitry, allowing the sensor to operate continuously.

For powering measurement chains in concrete structures, the most used system is a battery-powered system. This is because it is often not practical or feasible to provide a continuous source of power to the measurement chain in a concrete structure, particularly if the structure is already in use or if it is difficult to access.

In ***Table 3.4*** a list of advantages and disadvantages is showcased:

Pros	Cons
Self-contained: Battery-powered sensors are self-contained and do not require external power sources, which can make them easier to install and maintain in hard-to-reach locations.	**Battery life:** Battery-powered sensors have a limited battery life and may require frequent maintenance or replacement, which can be a disadvantage in hard-to-reach locations or structures that are difficult to access.
High flexibility: Battery-powered sensors can be placed in a variety of locations, as they are not limited by the length of cables or the availability of external power sources.	**Environmental factors:** Battery-powered sensors can be sensitive to environmental factors, such as temperature and humidity, which can affect their performance.
Low interference: Battery-powered sensors are not susceptible to interference from external sources, which can make them more reliable in some environments.	**Limited power output:** Battery-powered sensors have limited power output, which can limit the number of sensors that can be used in a measurement chain.
Moderate cost: Battery-powered sensors can be relatively cost-effective, especially compared to wireless or RF-powered sensors.	**Sustainability:** Battery-powered sensors require batteries that need to be disposed of properly, which can be an environmental concern.

Table 3.4 *Battery-powered sensors pros and cons*

3.2.5. Solar-powered sensors

Sensors that are used in outdoor environments or remote locations can be powered by solar energy. These sensors have solar panels that convert sunlight into electrical energy to power the sensor.

In ***Table 3.5*** pros and cons regarding solar-powered sensors are depicted:

Pros	Cons
Self-sustaining: Solar-powered sensors are self-sustaining and do not require external power sources, which can make them easier to install and maintain in hard-to-reach locations.	**Environmental factors:** Solar-powered sensors can be sensitive to environmental factors, such as shading and cloud cover, which can affect their performance.
Renewable energy: Solar-powered sensors use renewable energy from the sun, which can be a more sustainable option compared to batteries or other types of power sources.	**Upfront cost:** Solar-powered sensors can have a higher upfront cost compared to battery-powered or wired sensors.
High flexibility: Solar-powered sensors can be placed in a variety of locations, as they are not limited by the length of cables or the availability of external power sources.	**Limited power output:** Solar-powered sensors have limited power output, which can limit the number of sensors that can be used in a measurement chain.
Low interference: Solar-powered sensors are not susceptible to interference from external sources, which can make them more reliable in some environments.	**Maintenance requirements:** Solar-powered sensors require regular maintenance to ensure that the solar panels are clean and functional, especially in dusty or dirty environments.

***Table 3.5** Solar-powered sensors pros and cons*

3.2.6. Determination of the power system: Solar power with battery

Although nowadays the most common technique to power measurement chains is using battery-powered systems, solar power systems can be useful too. They can provide a sustainable and reliable source of power for the measurement chains and reduce the need for battery replacement or recharging. This is precisely the aim of this project, using solar panels to boost the strain sensors. Nevertheless, getting rid of the batteries won't be so easily accomplished. In order to work with solar power, using batteries will be required to store the energy that is generated. Therefore, the combination of a PV panel and a battery will build the system.

One of the advantages of solar-powered measuring systems is that they can be installed in remote or off-grid locations, where it may be difficult or expensive to run electrical cables. They also provide a clean and renewable source of power, which can help reduce carbon emissions and lower operating costs over the lifetime of the system.

However, the effectiveness of solar-powered measuring systems can be affected by factors such as weather conditions, shading, and the angle and orientation of the solar panels. It is essential to bear in mind that in order to use solar power, a solar panel or array must be installed in a location that receives sufficient sunlight throughout the day.

That's the reason why a battery will complement the system. The battery must be properly sized to ensure that it provides enough energy to power the measurement chain during periods of low sunlight.

3.2.7. Performance of solar-powered system combined with battery

Solar power is an increasingly popular option for powering measuring systems, including those used in railways. In railway applications, solar-powered measuring systems can be used to monitor track conditions, such as temperature, humidity, and vibration, as well as to monitor the performance of trains and other equipment.

Solar-powered measuring systems typically consist of solar panels, batteries, charge controllers, and power converters.

- **Solar panels**

The solar panels are used to capture sunlight and convert it into electrical energy, which is then stored in batteries for use when the sun is not shining or when the demand for power exceeds the capacity of the solar panels.

The solar panel converts sunlight into usable electricity through a process called the photovoltaic effect. The main component of a solar panel is a collection of solar cells made of semiconductor materials, usually silicon.

When sunlight shines on the solar panel, photons (particles of light) strike the surface of the solar cells. This interaction causes electrons in the semiconductor material to become energized and break free from their atoms, creating a flow of electrons.

Solar cells are structured in layers with an integrated electric field. This field helps direct the flow of energized electrons in a specific direction, creating a current. Metal contacts on the top and bottom of the solar cells capture this current and transfer it out of the panel as usable electrical energy.

- **Controllers**

Charge controllers are used to regulate the charging of the batteries to ensure that they are not overcharged or undercharged, which can reduce their lifespan.

- **Power converters**

Power converters are used to convert the DC voltage produced by the solar panels and batteries into the AC voltage required to power the measuring system.

However solar power systems can also incorporate DC/DC converters. They work by converting the DC voltage produced by the solar panels and batteries into the appropriate voltage level required for the measuring system. By employing DC/DC converters, the solar power system can seamlessly adapt and supply the appropriate voltage to power the measuring system or other AC-powered devices. This ensures compatibility and optimal functionality of the entire system.

- **Battery**

Although the final source of energy is solar power, this one will need a battery to store the energy generated. Therefore, it can be assumed that even if the source of energy is actually solar power, the battery will also serve as a source of energy, since the surplus energy will be stored there.

Batteries can be designed to operate for long periods of time without needing to be recharged or replaced and can be easily installed and maintained. They also provide isolation from external electrical sources, which can be important for accurate measurements.

One advantage of solar-powered measuring systems is that they can be installed in remote or off-grid locations, where it may be difficult or expensive to run electrical cables. They also provide a clean and renewable source of power, which can help reduce carbon emissions and lower operating costs over the lifetime of the system.

However, the effectiveness of solar-powered measuring systems can be affected by factors such as weather conditions, shading, and the angle and orientation of the solar panels. Proper design and installation are important to ensure that the system is optimized for the specific application and location.

4. Methodology and equipment

4.1. Project design

An illustration of the project design and methodology is represented in ***Figure 4.1***:

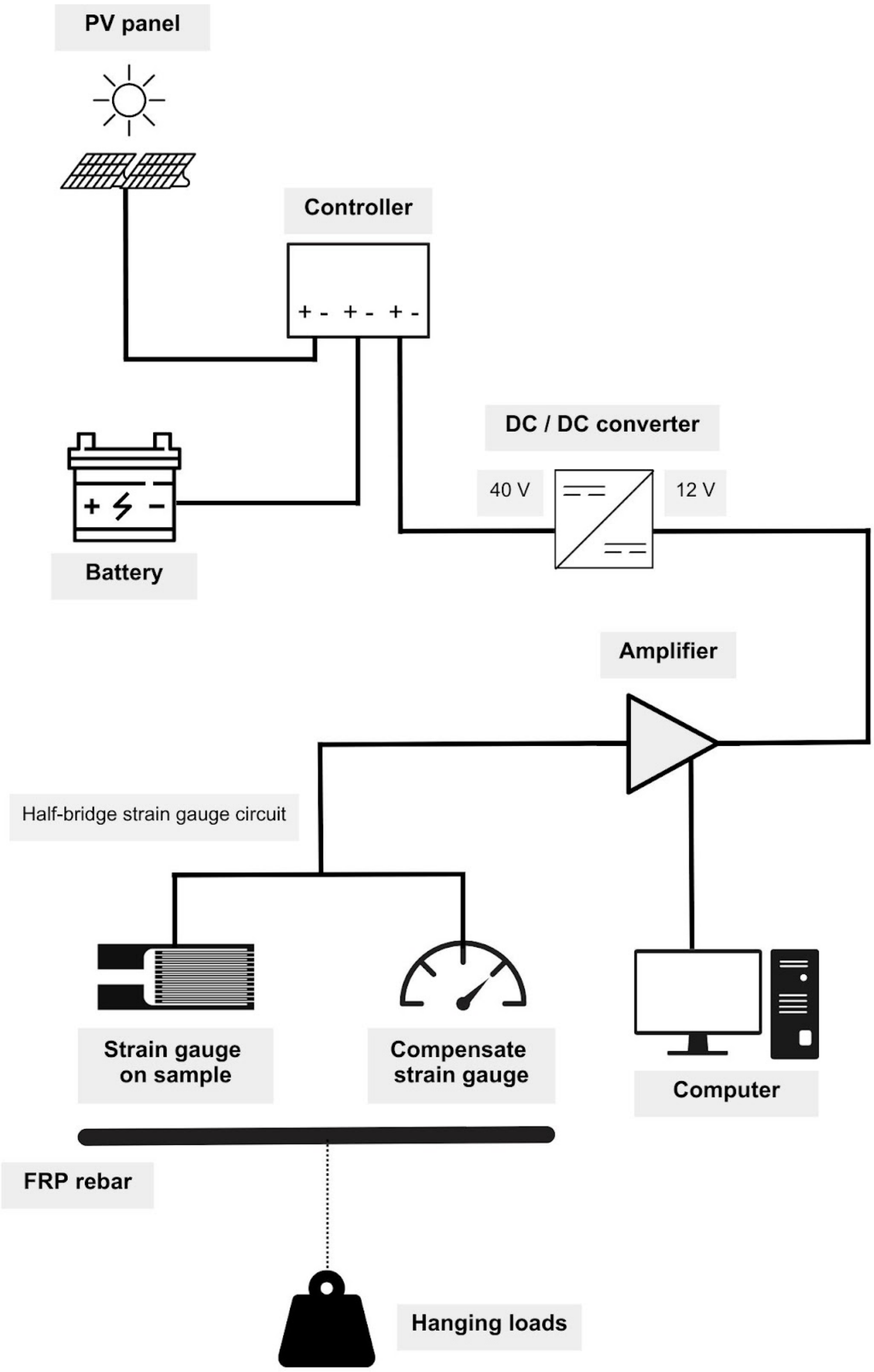

Figure 4.1 *Project design scheme*

4.2. Description of the elements in the system

4.2.1. Solar panel

The PV panel used is a monocrystalline panel (***Figure 4.2*** and ***Figure 4.3***). Monocrystalline panels consist of silicon with a well-organized structure, resulting in enhanced efficiency. This allows them to generate the same amount of energy in a smaller area. Consequently, monocrystalline modules are slightly more efficient compared to polycrystalline panels. For instance, polycrystalline panels typically have an efficiency rating of 16%, while monocrystalline panels range around 18%. Due to these characteristics, monocrystalline panels are also slightly pricier than polycrystalline panels.

Figure 4.2 *Solar panel used during the experiment*

Figure 4.3 *Solar panel used during the experiment*

4.2.2. Controller

When using PV panels, a controller is needed for several reasons. In the first place a controller helps regulate the charging process of batteries connected to the PV panels. It ensures that the batteries receive the correct voltage and current during charging, preventing overcharging, which can damage the batteries, and undercharging, which can lead to reduced battery performance.

Secondly, a controller helps manage the power output of the PV panels. It optimizes the energy transfer from the panels to the load or battery system, matching the voltage and current requirements of the connected devices.

Overall, a controller plays a crucial role in optimizing the efficiency, safety, and performance of a PV panel system by managing the charging process, regulating power output, and providing necessary protection mechanisms.

The controller model appears in ***Figure 4.4***, and a photo of the actual controller used during the tests is shown in ***Figure 4.5*** and ***Figure 4.6***.

Figure 4.4 *Model of the controller used during the experiment [8]*

Figure 4.5 *Controller used during the experiment*

Figure 4.6 *Controller used during the experiment*

4.2.3. Battery

A battery is essential to store the energy captured by the solar panels. As this test has been performed in Poland, the changing and cloudy weather is a big disadvantage. To be able to carry out the measurements during the evening or during a cloudy day, the battery (***Figure 4.7***) is a crucial element.

Figure 4.7 *Model of the battery used during the experiment [9]*

4.2.4. Rebar

The reinforcement bar used in the experiment consisted of a 1-meter-long fiber reinforcement polymer bar with 300-mm-long steel tubes on each side. The diameter of the FRP rebar was 8 mm, while the diameter of the reinforced parts were 16 mm.

The use of steel tubes for mounting the test machine is vitally important. The material may experience failure or deformation under the applied force. This can happen if the grips or clamps used to hold the composite material in place are not able to securely hold or distribute the applied load. Without proper support from the steel tubes, the composite material may buckle, fracture, or slip within the grips, leading to an unreliable test result.

Therefore, it is important to ensure that the composite material is securely and properly mounted to prevent any potential failure or displacement during testing.

In ***Figure 4.8***, a scheme with the dimensions of the FRP rebar is indicated, while in ***Figure 4.9***, a photo of the actual set up of the FRP rebar is shown.

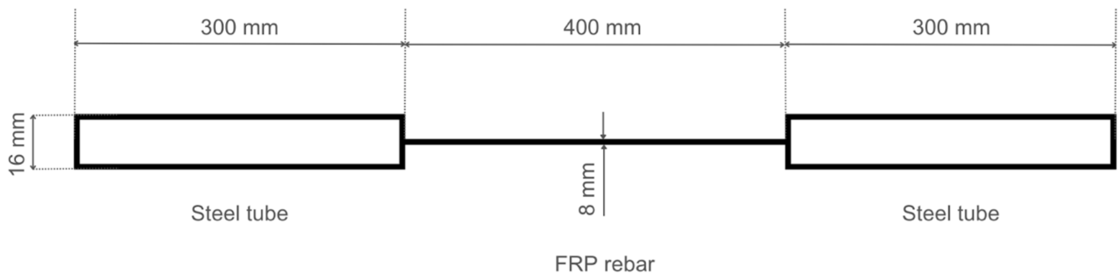

Figure 4.8 *Dimensions of the FRP rebar used during the experiment*

Figure 4.9 *FRP rebar and structure used during the experiment*

4.2.5. Hanging loads

The loads used in this experiment are the most common ones used in this kind of bending tests. **Figure 4.10** includes an image capturing the loads in suspension during the test, including 0,1 kg, 0,2 kg and 0,5 kg.

Figure 4.10 *Loads used during the experiment*

4.2.6. Strain gauges

A strain gauge circuit configuration known as a half-bridge was the one employed. As previously mentioned, this arrangement involves the use of strain gauges to measure mechanical strain, where one strain gauge is subjected to compression and the other to stretch.

By employing both gauges, the circuit becomes more responsive to applied force, allowing for improved strain measurement accuracy. Additionally, this configuration effectively canceled out temperature-induced measurement errors by ensuring that both strain gauges experienced proportional changes in resistance.

One strain gauge was attached to the FRP rebar (**Figure 4.11** and **Figure *4.12***), precisely in the middle, where the load was suspended. While the other one was glued next to it, acting as a compensator strain gauge to minimize the influence of the temperature and the sun.

Figure 4.11 *Strain gauge and structure used during the experiment*

Figure 4.12 Strain gauge and structure used during the experiment

In the previous pictures, it's hard to appreciate the strain gauge, in the following one (***Figure 4.13***) an accurate zoom of a general strain gauge (not the actual one used during the tests) is represented).

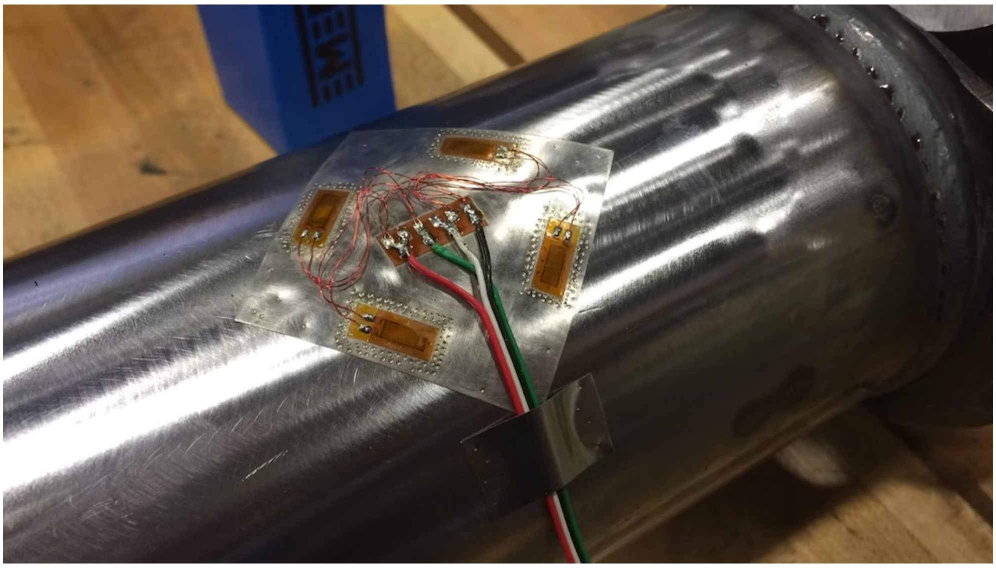

Figure 4.13 *Zoom of a general strain gauge [10]*

4.2.7. Voltage converter (DC / DC)

Usually, solar panels generate electricity at a high voltage, such as 40 V, which in this case, is not compatible with the device used. The use of the DC/DC voltage converter from 40 V to 12 V is necessary to adapt the power received from the solar panel to a different voltage level that is suitable for the measuring system. Both **Figure 4.14** and **Figure 4.15** illustrate the actual voltage converter employed during the tests.

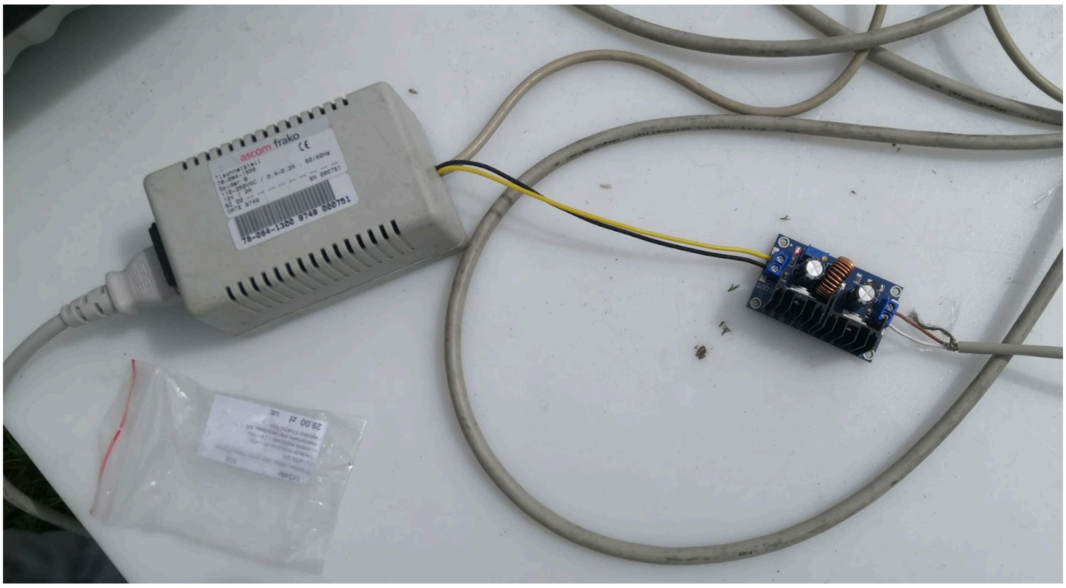

Figure 4.14 *DC/DC converter used during the experiment*

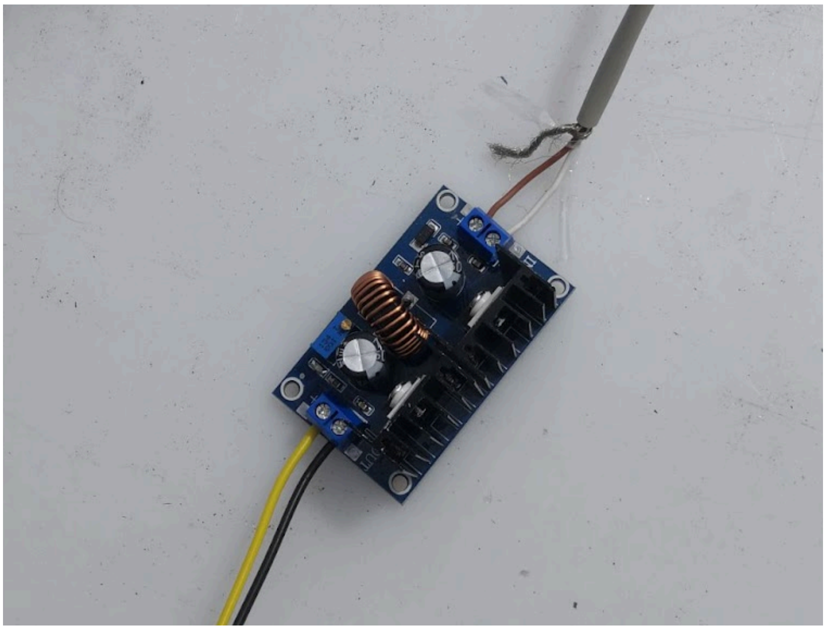

Figure 4.15 *Zoom of the DC/DC converter used during the experiment*

4.2.8. Amplifier

An amplifier is an electronic device that increases the amplitude or strength of a signal. Under these circumstances, a strain gauge amplifier is needed, due to the really small differences of voltage.

As previously stated, when the strain gauge is subjected to deformation, its resistance changes. However, the change in resistance due to strain is typically very small and may not be easily measurable or useful on its own. This is where an amplifier comes into play.

The amplifier is designed to take the small variation in resistance as its input signal and amplify it to a level that can be easily measured or utilized. It does this by applying a gain to the input signal, which effectively multiplies the amplitude of the signal.

In **Figure 4.16** and **Figure 4.17** photos of the amplifier while conducting the tests are shown, whereas an accurate picture of the model can be appreciated in **Figure 4.18**.

Figure 4.16 *Amplifier used during the experiment*

Figure 4.17 *Amplifier used during the experiment*

Figure 4.18 *Model of the amplifier used during the experiment [11]*

4.2.9. Software

The software used in this project, and with which the results of the bending experiment were obtained is Catman HBM (**Figure 4.19**). It was basically chosen based on its availability in the systems of the Politechnika Wrocławska University. However, this wasn't the only advantage, this program is specifically designed for data acquisition, visualization, and analysis in the field of measurement and testing.

Figure 4.19 *Catman HBM software illustration [12]*

It helps to connect and acquire data from various measurement devices, such as sensors, transducers, and data acquisition systems. The software enables real-time visualization of acquired data, allowing you to monitor measurements as they happen. This feature is particularly useful in dynamic testing scenarios where immediate feedback is required.

The software offers a user-friendly interface for visualizing measurement data in different formats, including graphs, charts, and tables. It also supports customizable reporting, allowing you to generate professional reports with the relevant measurement data and analysis results.

4.3. Important factors to consider

4.3.1. Length - stiffness

Overall, in a bending experiment, there is a relationship between the length of a material and its stiffness. The stiffness of a material refers to its resistance to bending or deformation when subjected to an external force.

In general, for a fixed material and cross-sectional shape, the stiffness of a bar increases with an increase in its length. This means that longer rods tend to be stiffer than shorter ones of the same material and cross-sectional dimensions.

This relationship can be explained by considering the behavior of the material under bending. Longer beams have a larger moment of inertia, which is a measure of their resistance to bending. As a result, longer beams can tolerate higher bending moments and exhibit less deflection or deformation compared to shorter beams.

It's important to note that this relationship assumes other factors such as material properties, cross-sectional shape, and boundary conditions remain constant, as studied in this degree.

4.3.2. Ambient temperature impact

This bending test has been carried out with a really small wire. It’s important to note that when this one is heated, it extends. In other words, higher the ambient temperature higher the strain. However, it also extends during the effort in the process of the experiment.

Therefore, it’s crucial to consider the impact of the temperature around the wire and distinguish it from the stretch due to the strain (which is precisely the one that needs to be measured). Hence, through the temperature compensator in the half-bridge strain gauge circuit, the temperature noise has been reduced to the maximum possible.

4.3.3. Thermal coefficients

This experiment is conducted with an FRP rebar. As has been previously stated, FRP means Fiber Reinforced Polymer, which means a polymer matrix and fiber reinforcement compose the material.

The compensator strain gauge, positioned on one side, is in contact with an epoxy resin containing carbon fiber. Meanwhile, the strain gauge on the sample, which is located at the center of the rebar, is composed of epoxy resin with glass and basalt fiber in the core.

The key is that each of them, carbon fiber and glass, and basalt fiber, have a different thermal expansion coefficient. So, when the sun heats the sample, different tension in both strain gauges is produced.

Therefore, the difference of the thermal coefficients can result in unstable measurements.

5. Results and discussion

5.1. Experiment description

Once the system design is clear, the next step is evaluating if this one works. The experiment that has been carried out, is a 3-point bending test, due to the 3 supports that take place in the scenario, 2 to stabilize each side and 1 in the center with the load in suspension. See **Figure 5.1**.

The setup involved placing the FRP rebar horizontally on two supports, with a certain distance between them. The rebar was positioned in such a way that it formed a span between the supports.

The 3-point bending test is commonly used to evaluate the flexural performance of materials, including FRP composites. It provides valuable insights into the structural integrity and suitability of the rebar for concrete reinforcement applications.

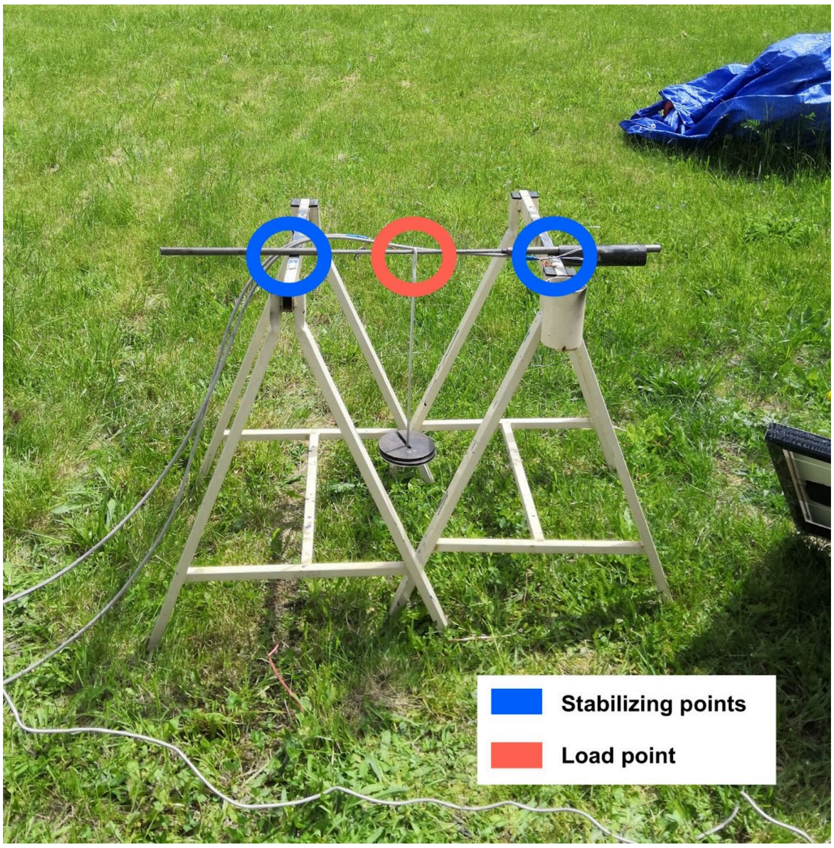

Figure 5.1 *3-point bending test scheme*

In the beginning the stabilization points were at 800 mm from each other (**Figure 5.2**), however this length was reduced to 600 mm (**Figure 5.3**), leaving 200 mm on each side. By reducing this length there's more stiffness, and more load can be applied. Therefore, by increasing the weight gradually, a more precise observation can be carried out.

Figure 5.2 *Structure with the stabilizing points at 800 mm*

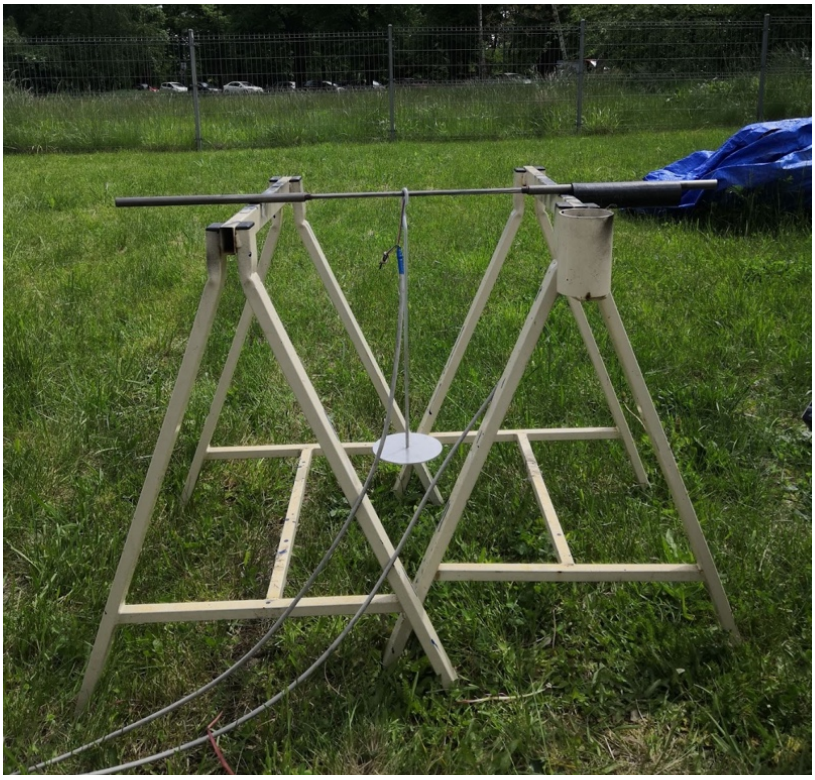

Figure 5.3 *Structure with the stabilizing points at 600 mm*

Before applying any load, the main focus was on measuring the strain in micrometers per meter. It should be noted that errors in the results may arise due to temperature, sunlight, wind, and other environmental factors. Therefore, it was important to keep the strain value as low as possible when no load was present, as this provided a more accurate representation of the actual conditions.

5.2. First test: Single load

In the first conducted 3-point bending test on a FRP rebar, a load of 1 kg was directly suspended. The experimental data was plotted on a graph with time (s) represented on the abscissa axis and strain (μm/m) on the ordinate axis (**Figure 5.4**).

The experiment started at second 0, and approximately at second 10, the 1 kg weight was suspended, resulting in an immediate increase in strain. However, between second 7.5 and 10, a slight deadlock in the strain can be observed. This can be attributed to a minor human error caused by hand tremors while placing the weight on the hanging support.

Once the weight of 1 kg was properly deposited, the strain rapidly rose to 200 μm/m within nanoseconds. This strain level remained relatively stable throughout the duration of the test until its completion.

The recorded data provides insights into the behavior and response of the FRP rebar under the applied load, demonstrating the immediate impact of the weight and subsequent stability in strain.

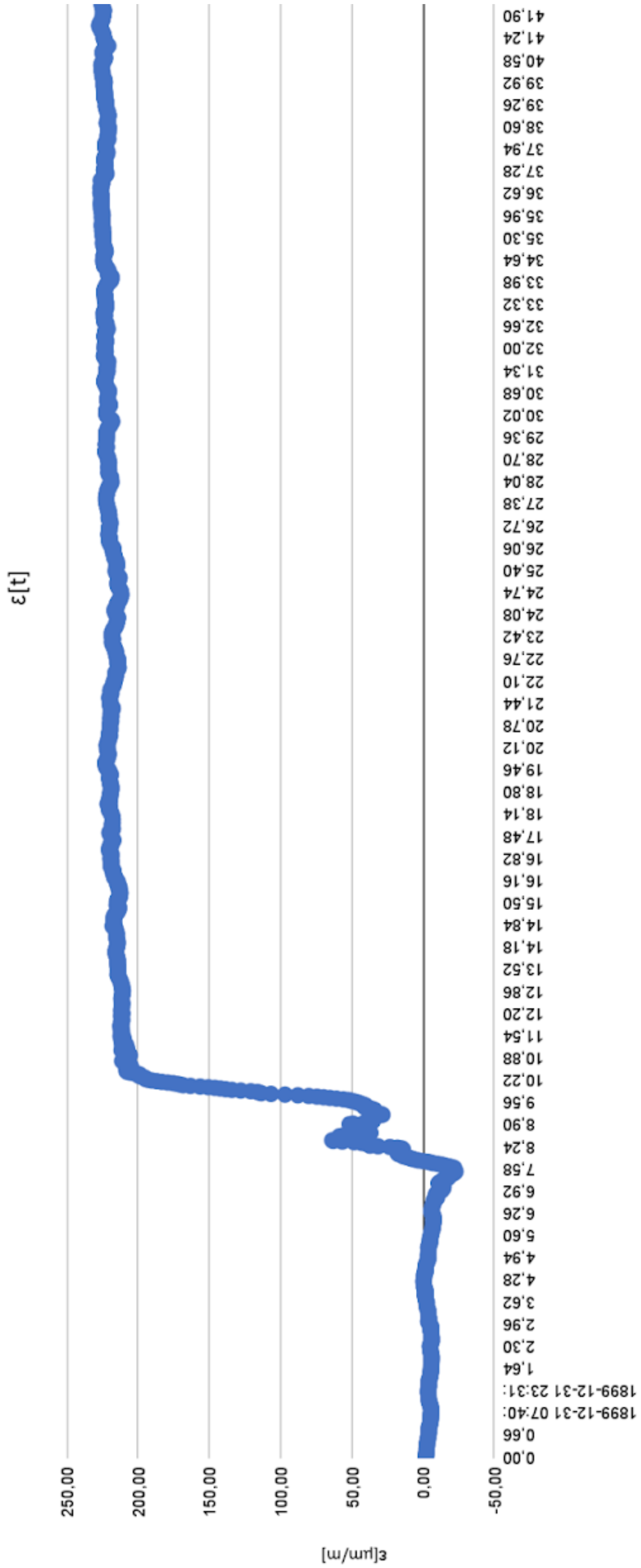

***Figure 5.4** Strain - Time graph of the single load test*

5.3. Second test: Sequential loads

In the second 3-point bending test, a sequence of weight suspensions was conducted. Initially, a 0.5 kg load was suspended, followed by a 0.2 kg load, another 0.2 kg load, and finally, a third suspension of 0.2 kg. The experimental data was represented on a graph with time (s) on the abscissa axis and strain (μm/m) on the ordinate axis (**Figure 5.5**).

Like the previous experiment, the test began at second 0, and at approximately second 62, a 0.5 kg load was applied. In contrast to the previous experiment, minimal oscillations were observed during the initial suspension, indicating improved stability. The strain reached a value of 100 μm/m, which aligns with the expected outcome since the weight deposited was half compared to the first test, where the strain reached 200 μm/m.

At second 183, a 0.2 kg load was suspended, resulting in an unstable region due to hand tremors. It took until the second 189 for the strain to rise to 150 μm/m, representing an additional increase of 50 units.

This suspension of 0.2 kg was repeated at second 312, and at second 318, a strain of 200 μm/m was observed, reflecting a similar increase of 50 units as in the previous suspension. While there were minimal oscillations, it took approximately 6 seconds for the strain to stabilize.

The last suspension occurred at second 431, and it wasn't until second 439 that the strain rose to 241 μm/m. However, in this case, the increase in strain was 40 μm/m, deviating slightly from the previous increments. At second 509, the strain briefly reached 249 μm/m but quickly stabilized around 241 μm/m again.

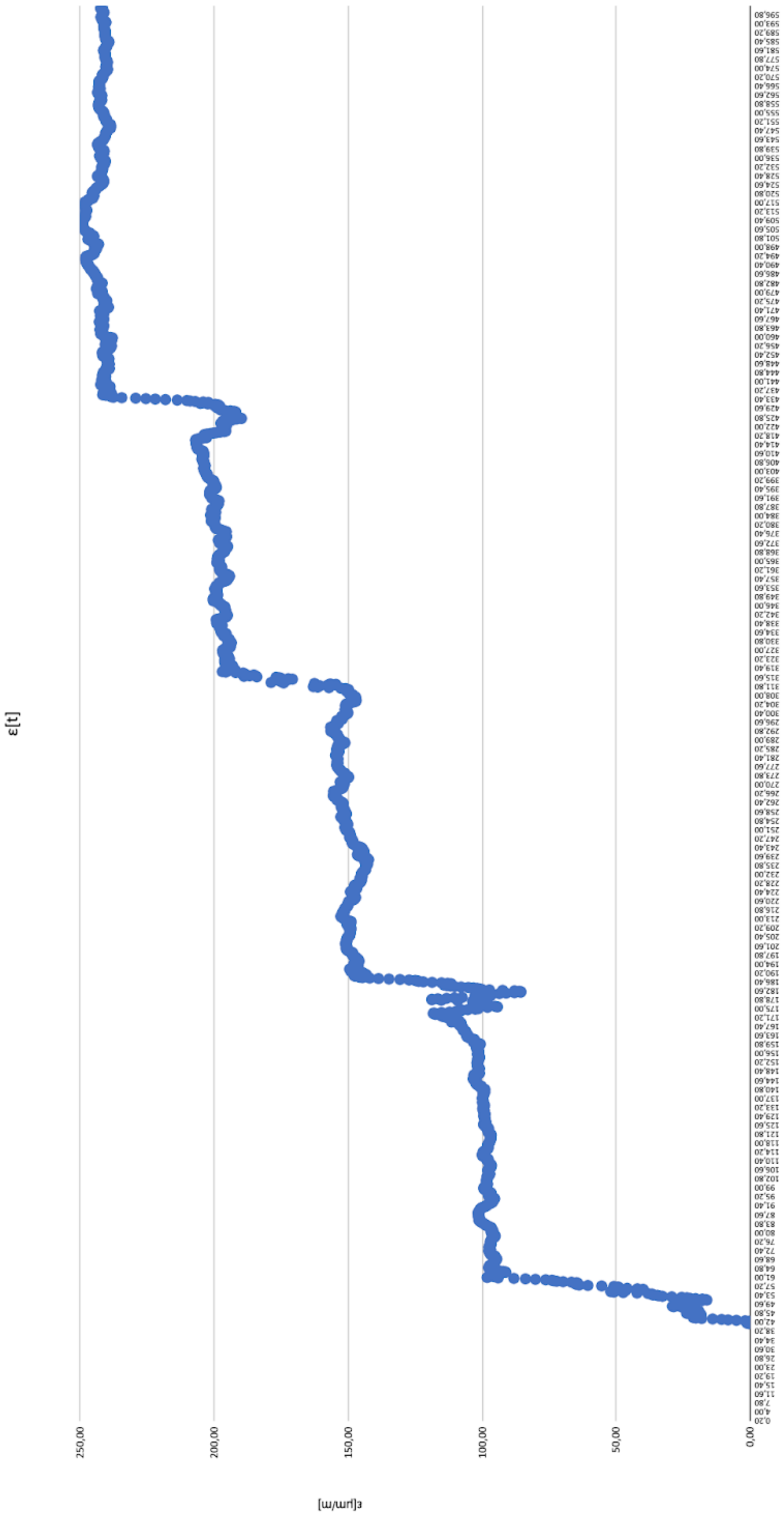

***Figure 5.5** Strain - Time graph of the sequential loads test*

5.4. Differences in strain response

The main differences between the two tests, where a 1 kg load was directly suspended in the first test and a sequence of suspensions was performed in the second test, can be attributed to several factors.

- **Load Magnitude:** In the first test, a single 1 kg load was applied, resulting in a higher initial strain compared to the second test. The sequence of suspensions in the second test involved lighter loads (0.5 kg and 0.2 kg), which contributed to lower strain values.

- **Load Distribution:** The distribution of loads in the second test differed from the first test. Instead of a single heavy load, the second test involved multiple lighter loads. In the first test, the sudden application of the 1 kg load could have caused a rapid increase in strain. However, in the second test, the sequential suspensions allowed the structure to adapt gradually, leading to a slower strain buildup. This distributed load arrangement may have led to a more gradual strain increase, resulting in lower peak strain values. Reason why in the last suspension of the second test the increase in strain is lower (40 µm/m instead of 50 µm/m).

- **Multiple load suspensions effect:** Regarding the stabilization time to reach the final strain, the longer stabilization period in the second test (between 6 and 8 seconds) compared to the first test (1 second) can be attributed to the cumulative effect of multiple load suspensions. Each suspension introduced additional strain, requiring more time for the structure to adjust and stabilize. The sequential nature of the suspensions in the second test prolonged the stabilization process.

5.5. Performance discussion

The conducted tests involving the 3-point bending of FRP rebars and the measurement of strain provide valuable insights and contribute to the understanding of the material's behavior under different loading conditions. The obtained data from the tests can be analyzed and discussed to draw meaningful conclusions.

In the single load test, it was observed that the strain rapidly reached a value of 200 µm/m. This result is consistent with the applied load and provides evidence of the material's response to the specific loading condition. The subsequent stability of the strain indicates that the **FRP rebar can effectively handle the applied load** without significant deformation.

In the second test, where a sequence of suspensions with varying loads was applied, it was noticed that the maximum strain achieved was lower compared to the first test. As previously stated, this difference can be attributed to the cumulative effect of multiple loading events. Additionally, the longer time taken for the strain to stabilize in the second test can be indicative of the material's response to repetitive loading, allowing for stress relaxation and redistribution over time.

Overall, the tests and their data provide meaningful information regarding the behavior of FRP rebars under different loading conditions. They demonstrate the material's capability to withstand applied loads and provide valuable insights into its strain response. The differences observed between the two tests can be attributed to factors such as load magnitude, loading sequence, and material behavior.

6. Planning

This section aims to show the chronology of the realization of the project from its beginning to its end. A Gantt Diagram illustration is shown in ***Figure 6.1***, and then below is the overall summary in ***Table 6.1***.

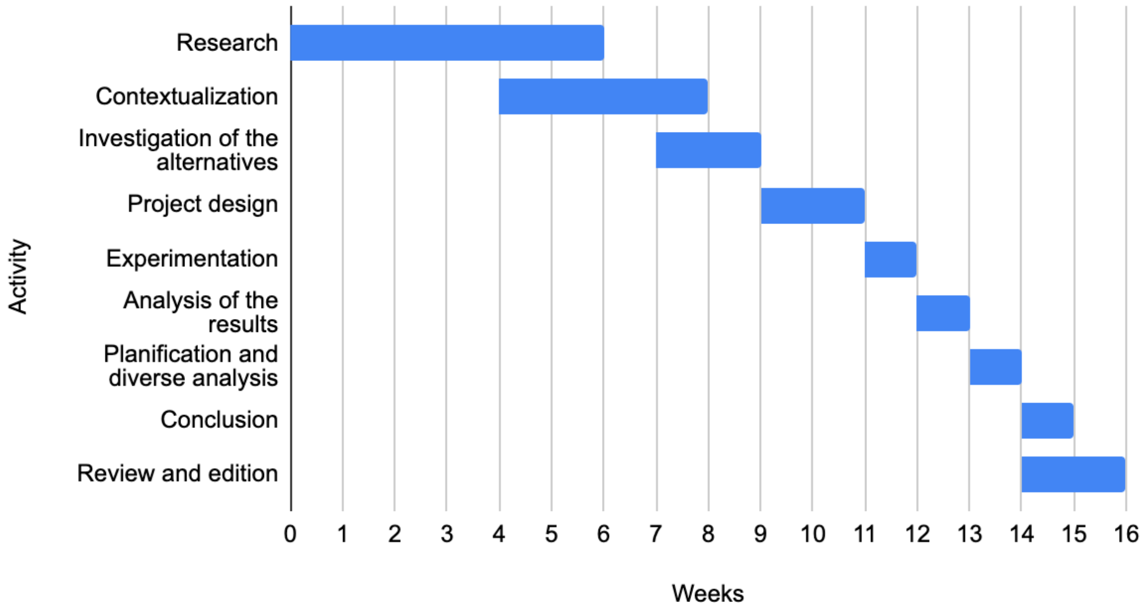

Figure 6.1 *Gantt chart of the project*

Activity	Start on week	Duration (weeks)	Initial date	Final date
Research	0	6	06/03/2023	10/04/2023
Contextualization	4	4	03/04/2023	01/05/2023
Investigation of the alternatives	7	2	24/04/2023	08/05/2023
Project design	9	2	08/05/2023	22/05/2023
Experimentation	11	1	22/05/2023	29/05/2023
Analysis of the results	12	1	29/05/2023	05/06/2023
Planification and diverse analysis	13	1	05/06/2023	12/06/2023
Conclusion	14	1	12/06/2023	19/06/2023
Review and edition	14	2	12/06/2023	23/06/2023

Table 6.1 *Project planning by dates*

This final thesis has been carried out during the spring semester of the 2022-2023 course. The decision of the project idea was taken at the beginning of March and the whole process lasted until the end of June, setting the duration of the project to 16 weeks.

This project has been carried out while the author was doing her Erasmus in Poland. The academic course in Poland starts later than in Barcelona, that's why the choice of the title took a little more time than usual.

In the moment in which the subject of the project had been delimited, a deep search on each of the elements that make up the system began. In this case, it was the first time working with solar panels and measurement chains, the little knowledge and experience in these areas meant that a large part of the project had to be devoted to research and analysis of the diverse alternatives, which lasted for about 9 weeks.

From here, once the entire mechanism had been understood, the draft and work methodology were created. The next step was to put into practice everything previously designed. The experimentation was carried out during a week of several tests.

Henceforth, the final stretch began with the analysis of the results. During the following week, the temporal planning and the different economic, social and environmental analysis were carried out. After putting all the breakdown into perspective, the final conclusion was made. Finally, the last two weeks were used to review and improve the project and correct mistakes.

7. Economic assessment

To perform the economic study of this project, both human and technological resources must be considered. In order to break down the budget well, differentiating adequately between the human team, the elements used, the software, and the energy consumption is crutial.

In ***Table 7.1*** the activities regarding human labor are presented, with the cost per hour that would suppose having an industrial engineer hired.

Activity	Dedicated hours [h]	Cost per hour [€/h]	Total cost [€]
Research	90	14	1.260
Project design	40	14	560
Experimentation and analysis	40	14	560
Edition	45	14	630
		Total cost	**3.010**

Table 7.1 *Human resources budget*

According to "Estudio de Remuneración 2023: tendencias y salarios" [13], the average industrial engineer gross salary in Spain with less than 3 years of experience is between 25.000 - 30.000 € per year. To simplify the calculations, it has been assumed 14 € per hour.

On the other hand, evaluating the cost of each software and tools equipment used is essential for the budget too (***Table 7.2*** and ***Table 7.3***).

Software tools	Price [€]	Amortization [years]	Use time [months]	Total cost [€]
Microsoft Office Pack	69	1	4	23
Catman Easy HBM	1953,94	1	1	162,83
Canva	0	0	4	0
Computer used during the tests (Asus)	850	5	4	56,67
Computer used during the drafting (MacBook Pro)	1.620	5	4	108
			Total cost	**350,5**

Table 7.2 *Software tools budget*

Tool equipment	Quantity [units]	Price [€]
Pack including solar panel, controller, battery and wires needed	1	500
DC / DC converter	1	14
Amplifier	1	300
Strain gauges	2	8
FRP rebar	1	0,50
Hanging support and loads pack	1	130
	Total cost	**952,5**

Table 7.3 *Tool equipment budget*

It should be noted that both the Microsoft Office Pack and Catman Easy HBM softwares were provided at no cost by ETSEIB, UPC and Politechnika Wrocławska University respectively, as well as the tools and equipment.

It's essential to bear in mind the energy consumption of all the elements that have been part of the system (**Table 7.4**). The average price of electricity in Poland in December 2022 was 0,1604 € per kWh [14], so:

Element	Unit price [€]	Energy [kW]	Use time [h]	Cost [€]
MacBook Pro	0,16	0,04	240	1,54
Asus	0,16	0,1	2	0,03
Measurement chain	0,16	0,046	2	0,01
			Total cost	**1,58**

Table 7.4 *Energy consumption budget*

Finally, the total budget is calculated in ***Table 7.5***:

Human resources cost	3.010 €
Software tools cost	350,5 €
Tool equipment cost	952,5 €
Energy consumption cost	1,58 €
Total cost	**4.314,58 €**

Table 7.5 *Total budget*

The total budget for the project is 4.314,58 €. It is important to highlight that IVA has already been considered in the price of each equipment tool and software. Regarding the salary of the workers, it is a gross salary, therefore all relevant taxes as IRPF and social security are acknowledged.

8. Environmental assessment

Certainly, this project contributes to reducing the energy expense by working with renewable energies through PV panels. However, a study of the energy consumed while carrying out the project has been made. It's important to highlight that all the tasks performed during the whole process of the project, both editing, and experimentation have been considered.

In terms of energy consumption during the design and editing phase of the project, the laptop used was a MacBook Pro from the year 2014, with a power consumption fluctuating around 40 W. The energy expenditure of this phase considering the project has lasted 16 weeks, where work has been conducted 5 days a week, for 3 hours each day:

$$40\ W \cdot 16\ weeks \cdot 5\ days \cdot 3\ h = 9.600\ Wh$$

$$9.600\ Wh \cdot \frac{1\ kW}{1000\ W} = 9{,}6\ kWh$$

Regarding the experimentation phase, the whole system must be considered. Knowing that the input current is approximately 0,2 A when the voltage input is 230 V:

$$0{,}2\ A \cdot 230\ V = 46\ W$$

Bearing in mind that both tests took for around 2 hours:

$$46\ W \cdot 2h = 92\ Wh$$

$$92\ Wh \cdot \frac{1\ kW}{1000\ W} = 0{,}092\ kWh$$

Moreover, the laptop used for the experimentation was an Asus, with a power consumption of around 100 W, due to its powerful processor given that it is an academic tool from Politechnika Wrocławska University.

$$100\ \mathrm{W} \cdot 2\ \mathrm{h} = 200\ \mathrm{Wh}$$

$$200\ Wh \cdot \frac{1\ kW}{1000\ W} = 0{,}2\ kWh$$

$$\boldsymbol{Total\ consumption} = 9{,}6 + 0{,}092 + 0{,}2 = \mathbf{9{,}892\ kWh}$$

Based on this data, an assumption of the CO_2 emissions has been made. It is known that 1kWh of electric energy approximately equals to 0,45 kg of CO_2. Therefore, the total emission of kg of CO_2 sent to the atmosphere is:

$$\boldsymbol{CO_2\ emissions} = 0{,}45\ \frac{kg\ CO_2}{kWh} \cdot 9{,}892\ kWh = \mathbf{4{,}451\ \boldsymbol{kg\ CO_2}}$$

Element	Energy [W]	Use time [h]	Energy consumption [kWh]
MacBook Pro	40	240	9,6
Asus	100	2	0,2
Measurement chain	46	2	0,092
		Total consumption	**9,892 kWh**
		Total CO_2 emissions	**4,451 $kg\ CO_2$**

Table 8.1 *Total CO2 emissions summary*

When considering the project's overall energy consumption (see **Table 8.1**), it can be concluded that it has an insignificant energy footprint due to its low energy requirements. In addition to consuming minimal energy, this project holds great significance as it operates with renewable energies. By utilizing renewable energy sources, such as solar power, the project aligns with sustainable practices and contributes to reducing environmental impacts and promoting a greener future.

9. Social and gender equality assessment

Although this project is not directly involved in any social or genre area, it's worth analyzing the social context in which it has been developed.

By conducting an analysis of the performance of solar power systems in concrete structures strengthened with FRP rebars, this thesis contributes to the knowledge and advancements in renewable energy and sustainable construction practices. This research has broader implications for addressing climate change, energy efficiency, and the development of environmentally friendly technologies.

Regarding gender equality, the project conducted encourages equity by being inclusive to all, without discriminating against any group due to their personal circumstances.

As a woman in a field where women are underrepresented, this thesis serves as an example of female involvement and achievement in a traditionally male-dominated area. According to "Dades estadístiques i de gestió, UPC" [15] during the period of 2021-2022 in ETSEIB, 458 women enrolled to "Enginyeria en Tecnologies Industrials" degree, while the total amount of students was of 1.871. This supposes that only around 24,5% of the students were female. This figure may sound very low, although compared to previous years it has been increasing little by little.

However, today's society should not conform and should promote and make visible women working in jobs traditionally headed by men. By completing this thesis in a field related to engineering, stereotypes are challenged and a contribution to breaking gender barriers is made.

It's worth acknowledging the collaboration and support received from the tutor and the PhD student, who are both men. This demonstrates that collaboration across genders promotes diversity of thought and experiences, leading to more robust research outcomes and contributing to each other's success.

10. Conclusions

In conclusion, this thesis focused on designing a solar power system for powering measurement chains in concrete structures strengthened with FRP rebars and doing the respective experimentation.

The tests conducted in this research demonstrated the **effectiveness of the solar power system** in providing sustainable energy for measurement chains. The results revealed significant differences between the direct 1 kg load suspension and the sequential suspensions, highlighting the **influence of load magnitude**, **load distribution**, and **structural response** on strain values.

Moreover, the longer stabilization time observed in the sequential suspensions indicated the cumulative effect of multiple load applications. This finding points out the importance of **allowing sufficient time for the structure to adapt** and stabilize under varying load conditions.

The analysis of alternatives, including strain sensors and power systems, provided comprehensive **information on different alternatives** for measuring and powering the measurement chains. The utilization of solar power showcased its potential in reducing energy consumption and contributing to sustainability goals.

The methodology and equipment utilized in the project were carefully designed and described. Factors such as **length** and **stiffness relation**, **ambient temperature impact**, and **thermal coefficients** were considered.

Overall, the findings and knowledge generated through this study can inform future research, optimize the design and performance of FRP-reinforced structures, and contribute to the sustainable development of the construction industry.

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