TAMPERE UNIVERSITY OF TECHNOLOGY

Degree Programme in Materials Science

CARLA MAIA

WIRELESS STRAIN SENSING AS NDT METHOD FOR PLASTIC COMPOSITES

Master of Science Thesis

Examiners: Professor Pentti Järvelä
And Docent Mikael Skrifvars
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ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
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The rapid increase in the use of plastics composites mainly in primary structures has brought with it the challenge of ensuring the damage inspection in a fast and precise way. Traditional NDT methods are not adequate for the complexity and anisotropy of composite materials. New and improved NDT methods are a necessity.

A strain sensing technique to be applied on the non-destructive evaluation of fiber reinforced plastic composites have been designed and developed. The system is based on a combination involving WSN technology and the conventional resistance strain gauges sensors, which detect surface strains on the components. The experimental results demonstrated that this technique is capable of collecting strain information of the composites under service and conditions where the components are subjected to bending strains and under harsh environments, such as during contact with seawater. The setup is an inexpensive technology that is easy and practical to install even in the most difficult production sites since it is a wireless based system. The long duration tests showed that this battery powered based system has the ability to collect strain data for a long period of time allowing saving energy. The strain sensing system developed here has several practical applications in strain and stress measurements in the structural monitoring and quality assurance of virtually every sector of industry in which plastic composites are related.

Due to the positive results obtained in this study, further research on this field should be encouraged. Additional research on the reliability of this wireless strain sensing system in different environments (e.g. temperature, humidity) and loading conditions are crucial for the deployment of this technology into different applications and composite industries.

PREFACE

This thesis is based upon studies conducted from April 2010 to December 2011 as a part of Wind project which was financed by TEKES. This research work resulted from the collaboration of the both expertise in composite materials and testing (Plastic and Elastomers laboratory at Tampere University of Technology) and in Wireless network technology (Kokkola University Consortium Chydenius) and involved the co-operation with industrial partners.

I am grateful to my supervisors Pentti Järvelä and Mikael Skrifvars for the chance to work in this project, for their guidance and for the simplicity, rare to find among alike. A special thanks to Timo Hongell and Jukka Ihalainen for the precious help in the experiments, the advices and exchange of opinions and thoughts during this work. I am thankful to Kim Sjödahl from Exel Composites for providing so promptly the testing profiles. My acknowledgment to Ilari Jönkkäri, Matti Hautala and Maija Hoikkanen for the assistance.

My eternal gratitude to my family, especially to my father. For being the non-conformist side on me, the silent mind reader.

To all the free minds around the world, who wish for no boundaries.

Tampere, 13th January 2012

Dedicated to the troubadour of full moon.
Not only for whispering the secrets, but for singing them sometimes.

TABLE OF CONTENTS

ABBREVIATIONS AND NOTATIONS

ΔE	*Voltage*
ΔL	*Change in length*
ΔR	*Change in resistance*
CFRP	*Carbon fiber reinforced composite*
E	*Modulus of elasticity*
$\tilde{E}$	*Error of the actual strain along the gauge axis*
$\varepsilon_p, \varepsilon_q$	*Maximum and minimum principal strains*
ε_x	*Strain in the direction of measurement x*
$\varepsilon_x, \varepsilon_Y$	*Strains in the reference axes X,Y*
$\varepsilon_x` - \varepsilon_x$	*Misalignment error*
FRPs	*Fiber-reinforced plastics*
GFRP	*Glass fiber reinforced composite*
K	*Gauge factor*
K_t	*Transverse sensitivity coefficient*
K_{t1}, K_{t2}, K_{t3}	*Transverse sensitivity correction factors for gauges 1,2 and 3*
L	*Initial length*
NDT	*Non-destructive testing*
R	*Non- deformed resistance*
r	*Ratio between the minimum and maximum principal strains*
R1, R2, R3, and R4	*Resistances 1, 2, 3 and 4*
SFRP	*Synthetic fibers reinforced composite*
S-T-C	*Self-temperature compensated*
UD	*Uni-directional*
V_{ex}	*Excitation voltage*
WSN	*Wireless sensor network*
α	*Angle between the direction of measurement x and the direction of the maximum principal strain*
α	*Thermal expansion coefficient*
β	*Angular misalignment*
$\varepsilon'_1, \varepsilon'_2$	*Indicated strains*
$\varepsilon_1, \varepsilon_2$	*True strains 1 and 2*

ε_a, ε_t	*Strains parallel and perpendicular to the primary axis of the gauge*
ε_m	*Strain in the strain gauge*
θ_p	*Angle between the maximum principal strain and the specimen reference axis X*
v_0	*Poisson's ratio on which the manufacturer's gauge factor was measured*
ρ	*Density*
σ	*Strength*

1. GENERAL INTRODUCTION

In the recent years the use of composite materials has expanded into a wide variety of market places. Products that have been produced from composite materials are almost unlimited; some typical examples include aircraft structures, space vehicles, rocket motor cases, turbine blades, automobile components, pressure vessels, and several sporting goods. The huge market coverage of the composites is mainly attributed the primary feature that represents this class of materials, which is their very high strength to- weight ratios, making those an excellent competitor with most of materials and an increasingly important research structural material.

Within the broad area of composites the fiber-reinforced composites are by far the most commonly applied. Fiber-reinforced composites developed from specialised prototype materials in the 1950s to high performance materials with new and improved structural applications being regularly announced. From the beginning of their development, there was the requirement to find suitable methods which could predict the conditions of the structures composed by these materials. [1][2][3]

However, the increase use of fiber-reinforced composites has created the need for the development of new and more reliable non-destructive testing (NDT) methods to study the integrity and serviceability of the composite structures at the various production stages and also in service. The detection of flaws in composites is particularly difficult because of the inhomogeneous anisotropic and layered nature of this class of materials. Additionally, the failure mechanism is more complicated in composites than many other conventional materials such as metals. [4] Therefore, dealing with the stress and strain analysis of composites involves special care and additional considerations due to the complex nature of these materials.

Several NDT methods have been applied for detection and characterization of defects and material evaluation of composites. The strain gauges are actually one of the simplest and lowest cost available techniques for the stress analysis of the composites and simultaneously within the NDT methods. The application of strain gauges permits the analysis of the surface strains acting in the composite materials and if properly used by taking into consideration the special features of composites, it represents a very reliable strain sensing analysis method allowing accurate results that are essential in the predictions of the condition and life time of the components. [5] The use of resistance strain gauges is very common however its study and applications when combined with a wireless system are still quite premature. A wireless strain gauge system can offer

several advantages over the traditional wired gauge system for the strain analysis, including cheaper equipment and an easier and more practical implementation.

1.1. Research objectives

The general goal of this thesis is to find and study a new measuring NDT (non-destructive testing) method to be applied in the quality assurance and health monitoring of plastic composites. In addition, it aims the development of easy to use and practical equipment that can installed in production sites of the composite industry and that increases both user safety and enables saving costs. The specific objectives of this work can be described as following:

- Development and design of new NDT strain sensing system, that is both practical and inexpensive and capable to provide information about the strain and stress on the material
- Study of the reliability of the strain sensing system in harsh environments.

1.2. Scope and methodology

A wireless strain sensing system was implemented and designed in order to obtain strain information on the fiber-reinforced plastic composites. The material used for the tests was carbon fiber/epoxy composite profiles fabricated by a pultrusion process. This wireless strain system resulted from a combination of WSN technology with the commonly used foil resistance strain gauge sensors. The system was specifically designed to attend the requirements of an adequate, practical and cost effective strain sensing technique. The tests were performed by simulating a harsh marine environment, which involved the immersion of the material and the strain gauges in seawater and with a constant bending strain for a long period of time. Strain information was collected along the time by using a conventional wired strain gauge system simultaneously with the wireless strain setup, in order to compare the behaviour between the two systems.

2. THEORETICAL BACKGROUND

2.1. NDT methods on composite material

Currently, composite materials are manufactured and developed constantly and new and improved applications of these materials are a continuous demand. Hence, the use of composite materials in critical structural applications is more important than ever and so it is to assure its structural integrity. The complexity of these materials during manufacturing and in service maintenance represents a challenge in developing ideal and optimized non-destructive methods. The traditional NDT methods, which were mainly based on the behaviour of metals, were inappropriate and often misleading when applied to anisotropic and inhomogeneous composite materials. The first non-destructive evaluation techniques developed to inspect composite structures consisted of using tap tests and a few ultrasonic-based inspection methods. [6] Fig. 2-1 shows the traditional approach of evaluating defecting in boats.

Figure 2-1. *Traditional inspection of the composite structures. [6]*

Most composite boat owners may still recall a surveyor assessing hull condition by tapping it with coins and according to this method, a bright ringing tone means a good laminate condition, while any dull, muffled sound could be the indicative of troubles. [7]

In advanced technological applications such as aerospace and due to the industrial focus on economics and safety, it is critical to use and develop robust and

practical composites NDT methods. Recent composite NDT comprises a broader range of modified traditional and new tools including ultrasonic, x- ray, acoustic emission, thermal, optical, electrical, variety of hybrid methods and etc. Room for improvement and further development of the currently existent NDT methods still exists, and it is encourage by the fast changing field of the composite materials.

2.1.1. Defects on composite materials

Composite structures are often complex and formed by layers of dissimilar materials. Commonly, composite mechanical damages are in the form of delaminations or debonds, broken fibers due to impact, fatigue damage that affects the zone of composite material via micro cracking or can be caused by thermal damage from prolonged exposure to heat above resin cure temperatures. [8] Fig. 2-2 shows in detail a debonding in a fiber reinforced plastic. List of all possible defects and damages which are possible to occur in a composite structure are listed in Table 2-1.

Table 2-1. *Defects in composites.*

Delaminations	*Missing adhesive*
Disbonds	*Misoriented fibers/ply*
Porosity	*Wavy fibers*
Contamination	*Mislocated ply/details*
Improper cure	*Impact damage*
Resin rich/poor	*Thermal damage*
Damaged fiber	*Thickness variance*
Voids (dimensional problems)	*Cracks*
Interface integrity	*Loss of properties(modulus)*
Structure problems (geometry)	

These defects can result from the raw product such as fibers, matrix and prepregs, as well as due to poor bonding between the fibers and matrices and between individual lamina. Alternatively, they can be related to a variety of service conditions and failure modes under many different circumstances. Such damages can occur during manufacturing, installation, operational conditions and/ or unavoidable in design because of the requirement to introduce discontinuities such as cut-outs, ply drops or structural connections. The detection and evaluation of damage in composites is compounded by the fact that damage is not visible to the naked eye and can occur in many different forms. [8] [9]

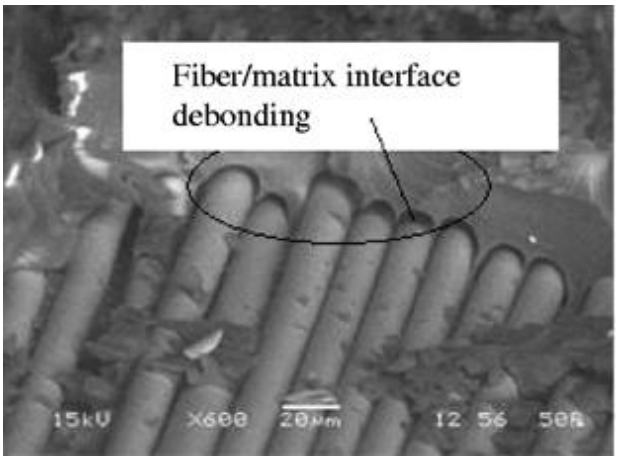


Figure 2-2. *SEM image of fiber/matrix debonding. [10]*

2.1.2. NDT practices for composites

Non-destructive technique is defined as the development and application of the technical methods for the detection, location, measurement and evaluation of discontinuities, defects and other imperfections in a material. It includes the assessment of integrity, measurement of geometrical characters, properties and composition of materials and components without impairing their intended use or application. [8] [9] There are various NDT methods in practice for composite materials, which are listed in Table 2-2.

Table 2-2. *NDT practices for composites.*

Most common NDT practices	***Advanced** techniques*
Ultrasonic	X-Ray tomography
Acoustic Emission	Laser ultrasonic
Tap Test	Holography
Resonance	Laser-optical
X-ray	Vibro-thermography
Visual	Acusto-ultrasonic
Optical	D-sight
Thermal	Neutron radiography
Sensor based techniques	Microwaves
Resistance-based Sensors (e.g. strain gauges)	Time resolved thermal methods
In-situ Sensors	
Remote Sensors	
Embedded Sensors	
In-Process Monitoring	

NDT can be used as a methodology for initial inspection of the structures to confirm the structural integrity or to monitor the material progress such as under service loads or changes over time. Moreover, NDT techniques help to analyse the reasons for failure of the structure, for global inspection and proof tests in quality control. Orientation breaks and waviness of fiber material, state of cure, porosity and cracking of matrix and debonding, delamination and moisture in the interface can be easily observed without impairing the intended use or application of the structure. Similarly, in the matrix the state of cure, porosity and cracking. [8] [11] [12] The importance of the NDT in composite materials [9] [11] can be summarized as:

- Increment in the confidence level in the use of composite materials in safety critical components
- Reduction in test program costs/timescales by optimizing testing/analysis
- Reduction in industry costs can be expected by providing improved testing and design procedures
- Facilitation of material development and increased flexibility in design
- Lower maintenance costs through better understanding of damage/defect influence on residual life of structures and improved and more effective inspection techniques.

2.1.3. Strain sensing

Strain is an important factor on the structural integrity and in the material´s condition monitoring. High magnitude, repetitive strains may lead to fatigue or yielding in the material. [13]

Strain sensing is thus, an important NDT technique in the structural control of a structure. Strain sensing is commonly used to monitor the reaction of a structure or structural element when subjected to load. This method is also applied to monitor the behaviour or rate of deterioration of structures in service, like crack growth.

Several types of strain sensors are available, including optical fibers, piezoelectric (resistance strain gauges) sensors, electrostrictive sensors, magnetostrictive sensors and piezoresistive sensors. The sensors are normally attached to or embedded in the structure. The electrical resistance strain gauges are one of the simplest and inexpensive strain sensors. [14]

2.2. Basics of fiber-reinforced plastic composites

The first fiber-reinforced plastics (FRP) materials were made by the petrochemical industry after the World War II which used glass fibers embedded in polymeric resins. The outstanding combination of features such as high-strength, high-stiffness structural fibers with low-cost, lightweight, environmentally resistant polymers made these

composites materials with better mechanical properties and durability than the each one of the constituents separately. [15] Nowadays, FRP materials have a widely acceptance in the market and new and improved structural applications of these high performance materials are constantly being announced to meet the demands of new markets and customer requirements.

2.2.1. Fiber-reinforced plastics structure

As the term FRPs clearly indicates, these materials are composites made of reinforcing fibers with a plastic matrix. FRPs are typically organized in a laminate structure, such that each lamina (or flat layer) contains an arrangement of unidirectional fibers or woven fiber fabrics embedded within a thin layer of light polymer matrix material. Fig. 2-3 shows a laminated composite structure. The fibers are responsible to attribute the strength and stiffness whereas the matrix, which is most commonly made of polyester, epoxy or nylon, binds and protects the fibers from damage, and transfers the stresses between the fibers. [16] [17]

Plastics technology uses different fiber types to reinforce the composite. The all category of fibers include glass fibers, carbon fibers, synthetic fibers and natural fibers. This work focus uniquely on the study of UD carbon fiber reinforced plastics (CFRP).
In addition, fillers or modifiers might be added in order to smooth manufacturing process, provide specific and special properties, and/or reduce product cost. [16] [17]

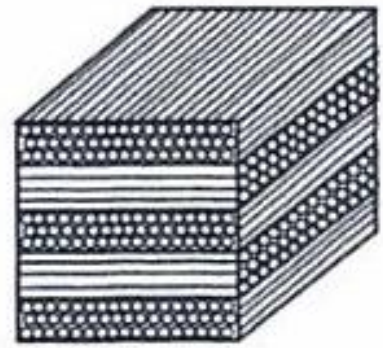


Figure 2-3. *Laminated composite structure. [18]*

2.2.2. Importance of the fibers in FRPs

It is well known that materials in fiber form are stronger and stiffer than used in bulk form. Furthermore, it is more likely the existence of flaws in bulk material than in fibers, which affects the strength of material. Fibers also have better molecular and crystallographic alignment and its shape consist of very small crystals. In addition, fibers have the advantage of low density comparatively to other materials. [16] The

fibers represent the largest volume fraction in the composite and for that reason the most important element in the fiber reinforced composites (FRC), playing the most important role of the tensile, compression, flexural or shear strength and stiffness of the FRP composites. [17] Properties of some important fibers are represented in the Table 2-3.

Table 2-3. *Characteristic values of the diffrent fiber types. [19]*

Material	E, GPa	σ_b, GPa	ρ, kg/m^3	E/ρ, MJ/kg	σ_b/ρ, MJ/kg	cost, $/kg
E-glass	72.4	2.4	2,540	28.5	0.95	1.1
S-glass	85.5	4.5	2,490	34.3	1.8	22-33
aramid	124	3.6	1,440	86	2.5	22-33
boron	400	3.5	2,450	163	1.43	330-440
HS graphite	253	4.5	1,800	140	2.5	66-110
HM graphite	520	2.4	1,850	281	1.3	220-660

The fibers can be in several forms, commonly they are present in the form of long and continuous fibers, but they can also be discontinuous fibers, particles, whiskers and even weaved sheets. Typically, fibers are added with ductile matrix materials, such as metals and polymers, to make them stiffer, while fibers are combined to brittle matrix materials such as ceramics to increase toughness. Some factors are important to take into account, such as the length-to diameter ratio of the fiber, the strength of the bond between the fiber and the matrix, and the amount of fiber, since these have an effect the mechanical properties of the materials. In order to effectively transfer the applied load from the matrix to the fiber, it is crucial that a high length-to-diameter aspect ratio is achieved. [20]

2.2.3. Carbon fiber reinforced composites properties

Carbon fiber composites mainly those with polymeric matrices, have become the dominant advanced composite material for aerospace, automobile field and boating, sporting goods, and many other applications due to their high strength, high modulus, low density, although it can relatively expensive material. [21] Carbon fiber reinforced polymer is thus, a very strong and light material. Epoxy is the most commonly used polymeric matrix, but other polymers, such as polyester, vinyl ester or nylon, are in some cases used.

Carbon is a very light element, with a density of about 2.3 g/cc and with stiffness significantly higher than glass. Carbon fibers can also have up to 3 times the stiffness of steel and up to 15 times the strength of the construction steel. The structure of can be crystalline, amorphous or partly crystalline. In its crystalline form, carbon has the structure of graphite as seen in Fig. 2-4. A graphitic structure is made of densely

packed hexagonal layers, stacked in a lamellar style resulting in mechanical and thermal properties which are highly anisotropic and giving to the component designers the possibility to control the strength and stiffness of the components by varying the orientation of the fibers. [17] [21]

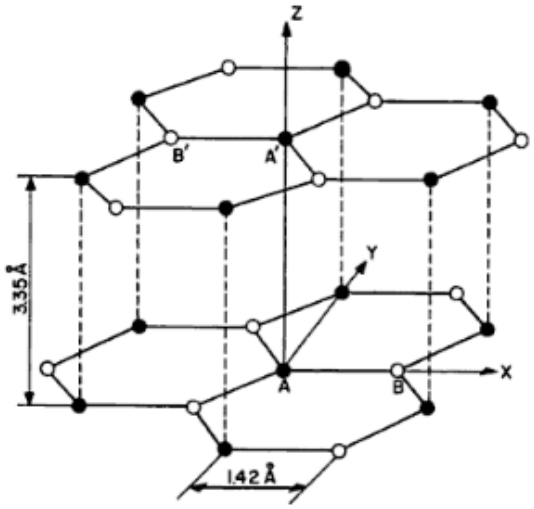


Figure 2-4. *The crystal structure of graphite. [21]*

Besides the broad range of exceptional properties, carbon fiber-reinforced polymers (CFRPs) have a long service lifetime when protected from the sun. However, despite its high initial strength-to-weight ratio, the main structural limitation of CFRP is its lack of a fatigue endurance limit. As result, failure cannot be avoided when the component is subjected to a high enough number of stress cycles.

Additionally, composites show very complex failure modes and for that reason the fatigue failure properties of CFRP are difficult to predict. Therefore, when used in applications which require critical cyclic-loading conditions, considerable strength safety margins need to be employed to provide suitable component reliability over a sufficiently long service life. [22] In addition, non-destructive evaluation techniques are also of valuable help in the prediction of the structural condition and stresses acting on the component.

2.2.3.1 Carbon fibers

Carbon fibers have been made initially from natural cellulosic fibers such as cotton or linen for thousands of years. However, it was Thomas Edison who, in 1878 took cotton fibers and later, bamboo, and converted them into carbon in his quest for incandescent lamp filaments. [23] [24]

Carbon fibers represent the strongest of all reinforcements used in polymer composites reinforcement offering the highest specific modulus and highest specific strength of all reinforcing fibers.

Initially, synthetic rayons in the textile form were carbonized to obtain carbon fibers for high temperature applications. In 1960 the PAN process was invented. This method was more economical due to higher carbon production, which is 50% against 30% for rayon, and it consists in a simpler fabrication process. Additionally, PAN based fibers also showed superior physical properties compared to rayon based fibers. Nowadays, PAN based fibers are known as the most important precursor for the fabrication of high strength carbon fibers. Later carbon fibers were also manufactured from pitches, which are an inexpensive type of precursor. Pitches extracted from petroleum, asphalt, coaltar, and PVC are the most typically used ones. The properties of pitch carbon fibers are lower than those produced from PAN, because the pitches are normally isotropic before pyrolysis, and the isotropy is kept in the fibers. Therefore a special stretching treatment is needed for these fibers in which the orientation of the larger planes is done under tension parallel with a high temperature treatment (of 2000 and 3000˚C). This treatment allows obtaining carbon fibers with very good properties, but it is very expensive. This treatment can be eliminated by using mesophase pitches. They have a high level of molecular orientation permitting to get a truly graphitic crystalline structure during the carbonization/graphitization phase, unlike PAN [3]. For this reason, the ultra-high modulus carbon fibers are nowadays mainly manufactured from mesophase pitches. [23][27] Table 2-4 shows the tensile properties for carbon fibers fabricated from different precursor types. Typical values of tensile properties of different carbon fibers are shown in the Table 2-4.

Table 2-4 *Axial tensile properties of carbon fibers produced from different precursors. [23]*

Precursor	Tensile strength (GPa)	Tensile modulus (GPa)	Elongation at break (%)
PAN	2.5–7.0	250–400	0.6–2.5
Mesophase pitch	1.5–3.5	200–800	0.3–0.9
Rayon	≈1.0	≈50	≈2.5

Carbon fibers show excellent resistance at high temperatures compared to other materials, these fibers do not suffer from stress corrosion or stress rupture failures at room temperatures, as it happens for glass and organic polymer fibers. Other remarkable properties of carbon fibers are their good electrical conductivity, thermal conductivity, and low linear coefficient of thermal expansion. [23] [25] The main disadvantages of this fiber type it is that they are brittle and are relatively more expensive than the other fibers.

The two main sectors of carbon fiber applications are high technology sector, which includes aerospace and nuclear engineering, and the general engineering and transportation sector (for example in racing vehicles, ships, space crafts and sports goods) and also for engineering components such as bearings, gears, cams, fan blades, etc., and automobile bodies. [26] [27]

2.2.3.2 Epoxy resin

The resin is a crucial component of the composites. There are two classes of resins which are classified as thermoplastics and thermosets.

The thermoplastics soften when heated and harden when cooled and these processes can be totally reversible and may be repeated. These materials are normally produced by the simultaneous application of heat and pressure. They are linear polymers without any cross-linking in structure where long molecular chains are bonded to each other by secondary bonds and/or inter-wined. On the other hand, thermosets require heat and pressure for their moulding into a defined shape. They are formed into a permanent shape and cured by chemical reactions such as extensive cross-linking. They cannot be re-melted or reformed into another shape but decompose upon being heated to too high a temperature. The term thermoset implies that heat is required to permanently set the plastic. Most thermosets composed of long chains that are strongly cross-linked (and/or covalently bonded) to one another to form 3-D network structures to form a rigid solid. Thermosets are generally stronger, but more brittle than thermoplastics. These characteristics make the thermoset resin based composites more desirable for structural applications. [19] [28] The epoxies resins belong to the thermosets class. The material properties and cure (hardening) rates can be specifically formulated to meet the requirements of the application in question. Epoxy resins are widely used because of their versatility, high mechanical properties, and high corrosion resistance. They shrink less than other materials i.e., from 1.2% to 4% by volume which helps them for their excellent bond characteristics when used as adhesives. In addition, epoxies are also less affected by water and heat than other polymer matrices used in composites. Epoxy resins are also favoured for their simple curing process that can be achieved at any temperature between 50^{o}C to 150^{o}C. Their main drawback is their cost, which is higher than for other resins. [19]

Epoxies are in general found in aeronautical, marine, automotive and electrical device applications. Although epoxies can be expensive, it may be worth the cost when high performance is required. Some other disadvantages are its toxicity and the fact that the epoxy hardeners can cause allergic reactions.

2.2.3.3 Pultrusion process

There are several methods to manufacture fiber-reinforced composites. Composite structures are manufactured using a wide variety of manufacturing routes. The ideal processing route for a particular structure will depend on the chosen fiber and matrix type, processing volume, quality required, and the form of the component. All these issues should be addressed right from the beginning of the development cycle for a component or structure. The method used to produce the carbon fiber/epoxy composite material used in this study was the pultrusion process.

Pultrusion is a cost effective method for high volume production of constant cross section parts. Typical examples of parts fabricated by this method include various rods and bar section, ladder side rails, tool handles, and electrical cable tray components and now bridge beams and decks. Due to uniformity of cross-section, resin dispersion, fiber distribution and alignment, excellent structural components made of composite materials can be fabricated by pultrusion. Thus, this consists in the manufacturing method of choice for structural shapes of FRP composites. The main advantages of the use of this method are the consistency of the product and for being an economic method of producing FRP composites. Pultrusion is a continuous moulding process that combines fiber reinforcements and thermosetting resin. This fabrication technique is highly automated and it consists of ‘‘pulling’’ a thermosetting resin impregnated on reinforcing fibres through a heated curing die (where curing takes place) at speeds of up to 3 m/min, which depends on the size and complexity of the profile shape. Different laminate lay-ups are possible with reinforcements of mats, fabrics and multi-axials. The finished profiles are cut to length by a saw at the end of the line. [2] [29] [30] Fig. 2-5 shows a schematic representation of the pultrusion technique.

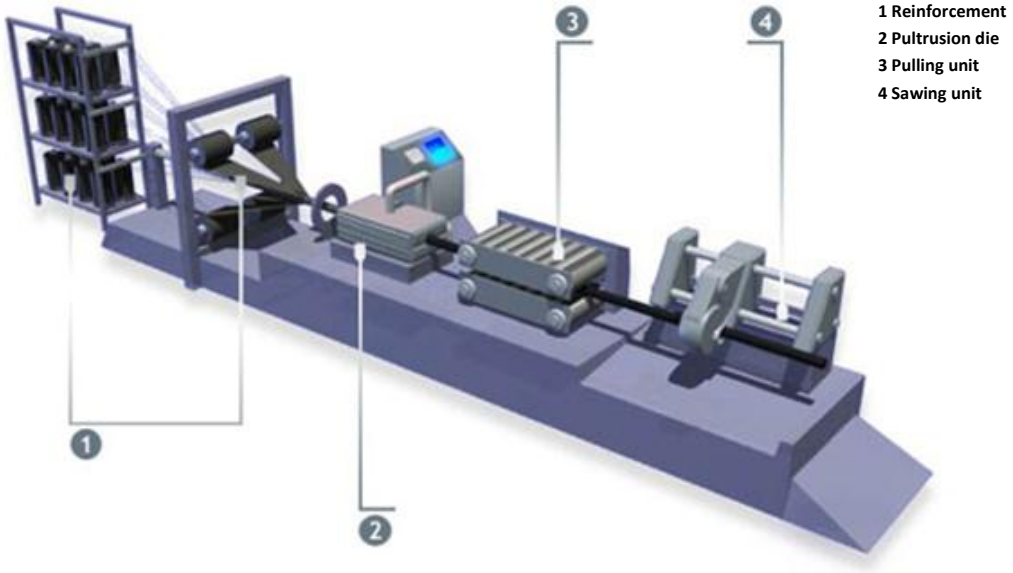


Figure 2-5. *Pultrusion process for producing FRP composites.* [29]

In this process both open-section and single or multi-celled closed section profiles can be produced. The fibre reinforcements can be fibre bundles (called roving for glass fibre and tows for carbon fibre), continuous strand mat (also called continuous filament mat), and nonwoven surfacing veils. In pultrusion, fibre volume fractions of 35–50% are typically utilized. Nowadays, bidirectional and multidirectional woven, braided, and stitched fiber fabrics have been used to produce pultruded profiles with improved mechanical properties. Normally, thermosetting reinforced resins are used in pultrusion, being the polyester and vinyl ester groups the most common resins. In addition, phenolic, epoxy, and also thermoplastic resins have been used for the pultrusion process. [2]

2.2.4. Anisotropic material response

Fiber reinforced composite materials show an anisotropic behaviour. This means that some properties vary depending upon to the direction or geometric axis they are measured along.

A requirement for a composite to be isotropic in a specific property, such as Young's modulus, is that all reinforcing elements must be randomly oriented. However, a randow orientation of fibers is not easily achieved for discontinuous fibers, because the majority of processing methods for fiber reinforced composites tend to result in a certain orientation to the fibers. Continuous fibers in the format of sheets are commonly used deliberately in order to obtain a composite with anisotropic response in a particular direction that is known to be the principally loaded axis or plane. [20]

An orthotropic material is one class of material which falls within the anisotropic material´s behaviour, in which the uni-directional fibers composites are well characterized. It is described by the difference in materials properties or strengths in different orthogonal directions.

For fiber composites reinforced with directional continuous fibers, the individual layers are placed one on the top of the other according to the desired reinforced effect, thus constructing a laminate as seen previously in Fig. 2-3. The fiber reinforcement in the individual layers is often aligned in one direction (unidirectional reinforced single layer or UD-single layer). The composites with the described characteristics typically show orthotropic properties. The schematic representation of a layer of an orthotropic composite material is given in Fig. 2-6.

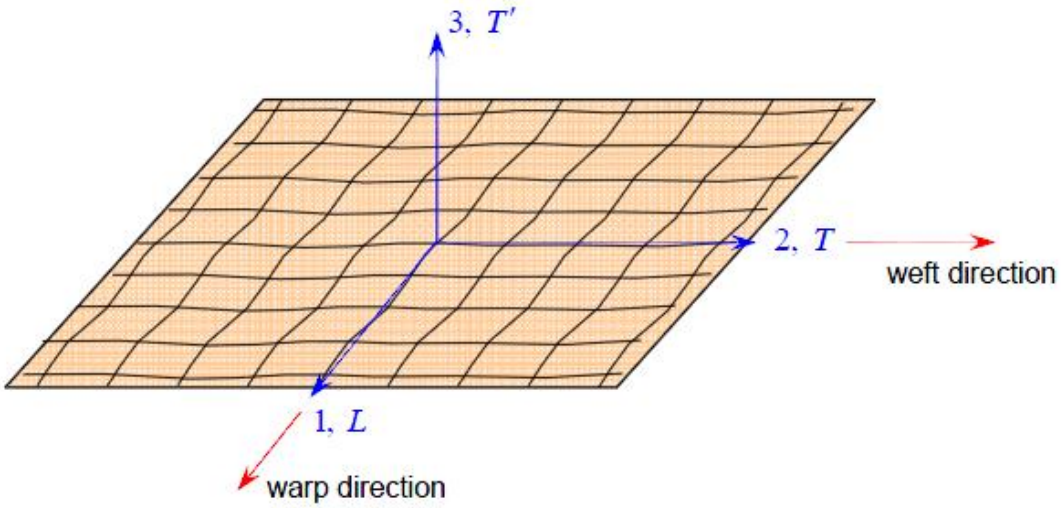


Figure 2-6. *A layer of an orthotropic composite material. [31]*

As previously referred, the laminates consist of layers of unidirectional composite composites reinforced with woven fabrics. Normally, the woven fabrics are made of unidirectional filaments interlaced at 90˚, one in the wrap direction and the other in the weft direction. These layers have tree mutually orthogonal symmetry planes, and from the elastic point of view they behave like an orthotropic material. The material directions (1, 2) will be respectively taken in the wrap and the weft direction. These directions are denoted L and T. The directional 3 orthogonal to the plane of the layer is also denoted T´. [31] This just referred orthotropic response shown by many fiber reinforced composites and mainly by uni-directional fiber composites is very relevant as it affects the performance of the strain gauges sensors which are normally calibrated for the use on isotropic materials, as it is described in a detailed manner in the section 2.4 under the topic Strain gauges applied to composites.

2.3. Strain gauge sensors

Strain gauges are solid-state sensors which are bonded to the surface of a component representing the most common sensing element to measure surface strain of components. Solid-state sensors for mechanical signals are based on the piezo-resistive effect, which is the change of the resistance of an object when it is subjected to a mechanical strain. This effect was first reported by Lord Kelvin in 1856, where he verified that the electrical resistance of copper and iron wires increased when subjected to tensile stresses. This observation ultimately led to the development of the modern strain gauge independently at California Institute of Technology and Massachusetts Institute of Technology in 1939. [32]

2.3.1. Structure of strain gauges

There are many types of strain gauges but the most commonly used are electrical resistance gauges. A typical foil resistance strain gauge as shown in the Fig. 2-7 is comprised of a length of folded wire adhered to some type of suitable backing material, often plastic. The thin plastic backing helps in the protection and support the delicate metal foil. [33]

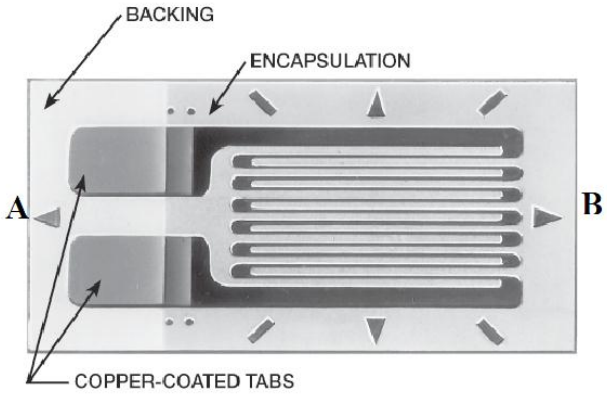


Figure 2-7. *Illustration of a typical, resistance foil strain gauge. [34]*

The backing is then cemented to the surface of the test material with the folds in the wire running parallel to the direction in which strain is to be measured in. For example, in Fig. 2-7 strain will be measured in the AB direction. Electrical connections are made by soldering lead wires to the strain gauge "solder tabs" which are copper-coated. [33] Foil strain gauges are available in hundreds of shapes and sizes. The strain gauge shown in the figure is a “uniaxial strain gauge”. Other common strain gauge configurations [33] can be seen in the Fig. 2-8 and these are:

- Rectangular, three-element strain gauge rosettes which consist of three individual strain gauge elements oriented precisely 45° apart, allowing the resolution of principal strains and principal directions regardless of the orientation of the rosette or the applied stress/strain.
- Delta, three-element strain gauge rosettes which consist of three individual strain gauge elements oriented precisely 60° apart, allowing the resolution of principal strains and principal directions regardless of the orientation of the rosette or the applied stress/strain.
- Biaxial strain gauges which consist of two individual strain gauge elements oriented precisely 90° apart, allowing strain measurements in two orthogonal directions.

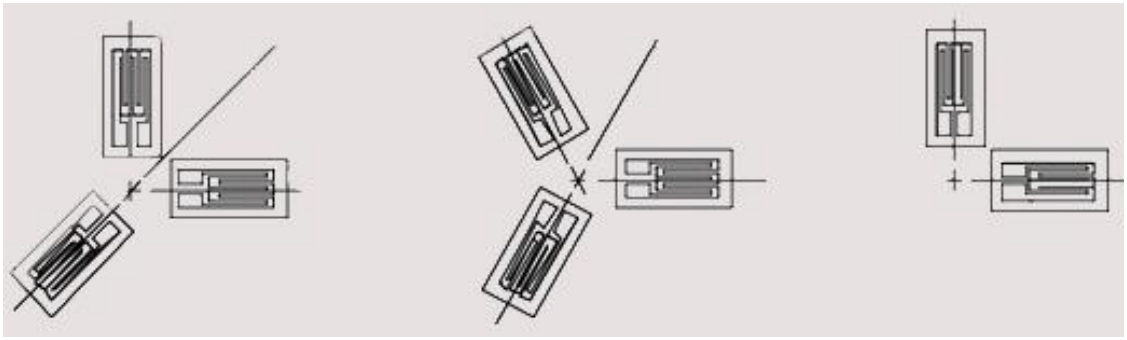


Figure 2-8. *Different configurations of strain gauges a) Rectangular rosette, b) Delta rosette c) Biaxial strain gauges.*

More strain gauge configurations and different gauge patterns are explained in the section of strain gauge selection for composites. Furthermore, strain gauges are available in several standard resistances, which are described later in this chapter.

2.3.2. Principle of strain gauge

When a force is applied to a component, the length of the component changes. Strain is the ratio of this change in dimension to the original length, and strain gauges are used to measure it.

The underlying concept of the strain gauge is very simple. In essence, an electrically-conductive wire or foil (i.e. the strain gauge) is bonded to the structure of interest and the resistance of this wire is measured before and after the structure is loaded. Since the strain gauge is firmly bonded to the structure, any strain induced in the structure by the loading is also induced in the strain gauge. Since the strain gauge contains conducting material this distortion causes a change in the strain gauge resistance thus serving as an indirect measure of the strain induced in the structure. By measuring this change in resistance we can measure the strain. The change in resistance is measured through a Wheatstone bridge arrangement. [33] [35]

Using the Fig. 2-7 to exemplify the strain gauge principle, when the test material is then loaded, the surface to which the gauge is attached will either elongate or shorten in the AB direction. If the material elongates, then the wire in the gauge will increase in length and decrease in diameter, increasing the electrical resistance in the wire. Conversely, if the material shortens, the wire in the gauge will decrease in length and increase in diameter, decreasing the electrical resistance in the wire.

2.3.3. Gauge factor

Strain gauge manufacturers perform standard calibration measurements for each lot of strain gauges they produce. When a user purchases a strain gauge, the manufacturer provides the results of these measurements in the form of several calibration constants.

One of these constants is the "gauge factor." The gauge factor allows the user to convert the change in gauge resistance to the corresponding strain level. [33] [35]
The gauge factor, K, of a strain gauge, relates the change in resistance (ΔR) to the change in length (ΔL). The gauge factor is constant for a given strain gauge, and Rg is the non- deformed resistance of the strain gauge (or initial resistance), ε_m is the strain in the strain gauge, so the Eq. 2.3.1 relates the terms giving K as [35]:

$$K = (\Delta R/R_g)/ (\Delta L/L) = (\Delta R/R_g)/\varepsilon_m \quad \text{Eq. (2.3.1)}$$

Depending on the foil material, hundreds of different types of strain gauges are commercially available, each having been developed in response to a demand for a gauge to meet or withstand specific conditions, typically being in the range of 2.0 to 2.1. The copper-nickel alloy provides a gauge factor around 2.0. [35]

2.3.4. Strain gauge resistance

The resistance of a strain gauge is defined as the electrical resistance measured between the two metal ribbons or contact areas intended for the connection of measurement cables. Strain gauge manufacturers produce strain gauges with three standard resistances: 120 Ω, 350 Ω, and 1000 Ω. The 120 Ω resistance is the most commonly used, although 350 Ω and 1000 Ω strain gauges are also widely available and applied. [36] The user selects the desired resistance when ordering the strain gauge according to the intended application.

As discussed previously, strains are sensed by bonding a strain gauge to a structure of interest and subsequently measuring the strain gauge resistance before and after the structure is loaded. Consider the magnitude of the resistance change which must typically be measured. Assume a measurement resolution of 10 x 10-6 m/m = 10 μm/m is required (a typical measurement). The change in resistance which corresponds to a strain of 10 μm/m can be calculated using the Eq. 2.3.2 [37]:

$$\Delta R = (K)\ (Rg)\ (\varepsilon m) = (2.00)\ (120\Omega)\ (10x10{-}6m\ /m) = 0.0024\Omega \quad \text{Eq. (2.3.2)}$$

Thus, a resistance change from 120 Ω to 120.0024 Ω must measure, which is a very small change. In fact, it is very difficult to measure such small changes in resistance using "normal" ohmmeters.

2.3.5. Wheatstone bridge

Due to the fact that the strain is an invisible infinitesimal phenomenon, the resistance change caused by strain is extremely small. Thus, it is very difficult to precisely

measure such small resistance change using a conventional ohmmeter, for that reason a strain amplifier using an electric circuit called a Wheatstone bridge is used to measure the change in resistance. Typically there are four arrangements. The strain gauge can be connected into a Wheatstone bridge circuit with a combination of four active gauges (full bridge), two gauges (half bridge), or a single gauge (quarter bridge). In the cases of the half and quarter circuits, the bridge is completed with precision resistors. [32]

As show in Fig. 2-9, the Wheatstone bridge circuit consists of four "arms." Each arm contains a resistance (i.e. resistances, R1, R2, R3, and R4). An excitation voltage V_{Ex} (typically 2 to 10 volts) is applied across the bridge. V_0 is the output voltage of the bridge. If all the resistances are equal (i.e. R1= R2=R3=R4) then V_0 is zero and the bridge is said to be balanced. [38]

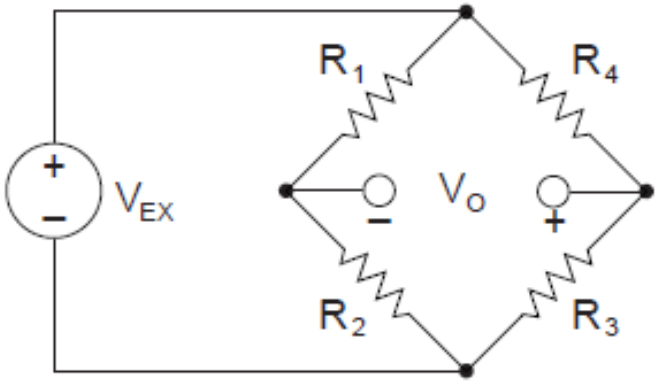


Figure 2-9. *Wheatstone bridge arrangement. [38]*

When stress is applied to the bonded strain gauge, resistance changes will happen and as results Wheatstone bridge is unbalanced. A signal output results from this, which is related to the stress value. Due to the fact that the signal is very small, the signal conditioning electronics provides amplification to increase the signal level to 5 to 10 volts. Accurate external data collection systems like recorders or PC Data Acquisition and Analysis Systems are needed for the process.

The gauge sensor, can occupy one, two, or four arms of the bridge, depending on the application. For four active gauges it is a full bridge, for two gauges is a half bridge and for a single gauge is a quarter bridge. In a quarter arm Wheatstone bridge circuit, a single strain gauge with variable resistance R1 is used (i.e., R1 = Rg) and the other three resistances are fixed value resistors. As stress is applied to the bonded strain gauge, a resistive change (ΔR) takes place and unbalances the Wheatstone bridge. The resulting voltage is then V_0 which is given by [33] [39]:

$$V0 = \frac{V_{Ex}}{4}\left(\frac{\Delta R}{R_g}\right) \qquad \text{Eq. (2.3.3)}$$

By combination of the Eqs. 2.3.2 and 2.3.3 results in:

$$\varepsilon_m = \frac{4}{K}\left(\frac{V0}{V_{Ex}}\right) \qquad \text{Eq. (2.3.4)}$$

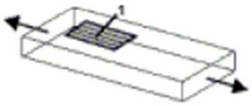
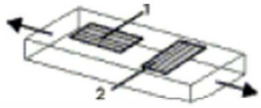
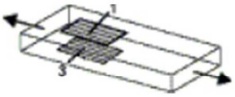
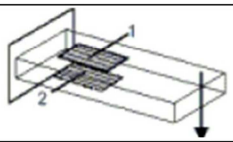
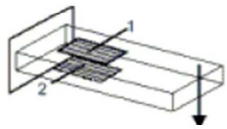
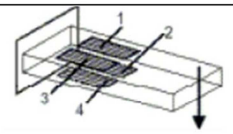
The Eq. 2.3.4 consists of an important result. It shows that the strain in the strain gauge, ε_m, is related to the quantities, K, V_0, and V_{Ex}. Generally though, the Eq. 2.3.4 is not applied directly, instead, strain gauge amplifiers which have been calibrated according to that equation are used to provide a direct readout of strain. [33]

2.3.6. Positioning strain gauges

Bending, axial, and shear strain are the most common types of strain measured. There are many ways the strain gauge can be positioned in the testing materials. The actual arrangement of the strain gauges will determine the type of strain that can be measured and the output voltage change. Table 2-5 shows the possible positions of the strain gauges according to the strain type and the general advantages and drawbacks for each arrangement are explained in the column of details.

For example, in the case of an axial loading, if a positive (tensile) strain is applied to gauges 1 and 3, and a negative (compressive) strain to gauges 2 and 4, the total strain would be 4 times the strain on one gauge. As seen in the table for axial strain case. If total strain is four times the strain on one gauge, this means that the output will be four times larger. Therefore, greater sensitivity and resolution are possible when more than one strain gauge is used. [41]

Table 2-5 *Arrangement of strain gauges for different strain types. [40]*

Strain	Gauge Setup	Bridge Type	Sensitivity MV/V at 1000 uE	Details
AXIAL		¼	0.5	**Good:** Simplest to implement, but must use a dummy gauge for temperature compensation. Also responds to bending strain.
		½	0.65	**Better:** Temperature compensated but it is sensitive to bending strain.
		½	1.0	**Better:** Rejects bending strain, but not temperature. Must use a dummy gauge for temperature compensation.
		Full	1.3	**Best:** More sensitive and compensated for both temperature and bending strain.
BENDING		¼	0.5	**Good:** Simplest to implement, but must use a dummy gauge for temperature compensation. Responds equally to axial strain.
		½	1.0	**Better:** Rejects axial strain and is temperature compensated.
		Full	2.0	**Best:** Rejects axial strain and is temperature compensated. Most sensitive to bending strain.
TORSION AND SHEAR		1/2	1.0	**Good:** Gauges must be attached at 45 degrees from centerline. Axial and bending forces produce equal strain and are rejected.
		Full	2.0	**Best:** More sensitive full-bridge version of previous setup. Rejects both axial and bending strains.

2.4. Strain gauges applied to composites

The methods of experimental stress analysis which were initially developed for isotropic materials are logically more difficult to apply on composites due to their high anisotropy and heterogeneity. Therefore, these methods must be adapted to the composites, requiring special procedures and different data analysis. In addition, for anisotropic materials the principal strain direction does not necessarily coincide with the principal stress direction. [42] [43]

Strain gauges are still the most used experimental method to measure mechanical strain on isotropic as well as composite material applications. The orthotropic behaviour of composites, however, influences the performance of strain gauges that are calibrated for use on isotropic materials. Therefore, for composite applications there are several special considerations and procedures that should be followed in order to insure accurate and repeatable measurements [44]. This section considers the use of strain gauges for composites by providing special considerations that should be taken into account and some typical errors that may occur if precautions are not implemented.

2.4.1. Transverse sensitivity

The expression "transverse sensitivity" means that a strain gauge will show a response to a strain field acting perpendicular to the major axis of the gauge. Several factors such as the grid geometry, gauge alloy, gauge backing and encapsulation materials, and manufacturing variables may be in the origin of this effect. The transverse sensitivity is not a desired effect, since it results in a strain measurement which corresponds to a combination of the gauge response to both axial and transverse strains. Composite materials are especially susceptible to transverse sensitivity errors, due to their highly orthotropic behaviour. [45] Therefore, in order to obtain precise strain measurements, transverse sensitivity corrections must be done.

2.4.1.1 Errors due to transverse sensitivity

The errors in strain measurements due to transverse sensitivity are normally small since the transverse sensitivity itself is small. In contrast, for biaxial strain fields which are characterized by extreme ratios between principal strains, the percentage of error in the smaller strain can be very high if the transverse sensitivity is not corrected. [46] Eq. 2.4.1describes the percentage error, if no correction is done due to transverse sensitivity [43]:

$$\tilde{E} = \frac{K_t[(\varepsilon_t/\varepsilon_a)+\varepsilon_m)}{1-\nu_0 K_t} \text{ x } 100 \qquad \text{Eq. (2.4.1)}$$

Where,

$\tilde{E}$ = the error as a percentage of the actual strain along the gauge axis.

ν_0 = the Poisson's ratio of the material on which the manufacturer's gauge factor, K, was measured (usually 0.285).

ε_a, ε_t = respectively, the actual strains parallel and perpendicular to the primary sensing axis of the gauge.

The transverse sensitivity coefficient K_t is one of the calibration parameters supplied by strain gauge manufacturers with each strain gauge. The value of K_t is normally within a range of about -0.05 to 0.05. (or -5% to 5%). [45]

For the particular case of uniaxial stress in a material with a Poisson's ratio υ_0 of 0.285 (same as υ_0 of steel which is the material used in the calibration), the error is zero because the gauge factor given by the manufacturer was measured in such a uniaxial stress field and already includes the effect of the Poisson strain.

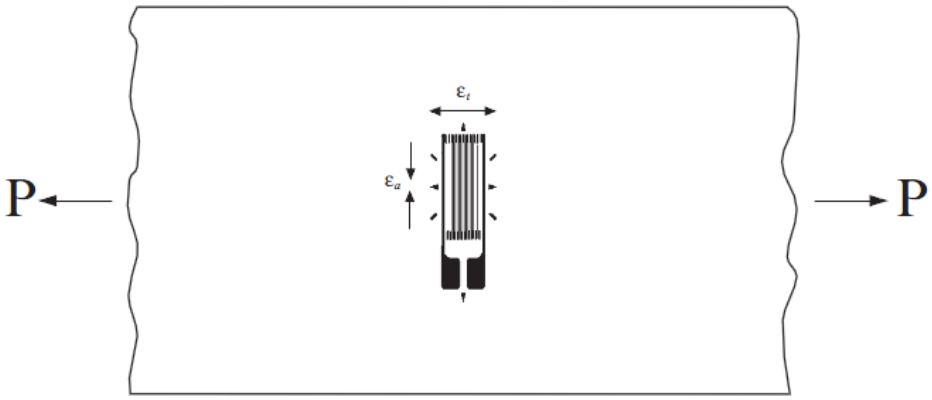


Figure 2-10. *Representation of the axial strain ε_a, and transverse strain ε_t for a strain gauge oriented perpendicularly to the stress application. [46]*

Therefore, when a strain gauge is used under any other condition than those applied in the gauge factor calibration, there exist always some percentage of error due to transverse sensitivity. In other words, any gauge shows transverse sensitivity and may require corrections, if [46]:

- Used on a material with a different Poisson's ratio; or
- used on steel, but subjected to other than a uniaxial stress condition; or
- even used on steel with a uniaxial stress condition, but aligned with other than the maximum principal stress

2.4.1.2 Transverse sensitivity corrections

The effects of transverse sensitivity should always be considered in measurement applications where the strain field and/or test material do not match that which was used during gauge factor calibration. Either it should be demonstrated that the effect of transverse sensitivity is negligible and can be ignored, or, if not negligible, the appropriated correction should be made.

In Fig. 2-11 it is illustrated a specimen of unidirectional composite material in which correction for transverse sensitivity was applied. In this case, two gauges are used; one of the gauges is used to correct the transverse errors in the other gauge. [43]

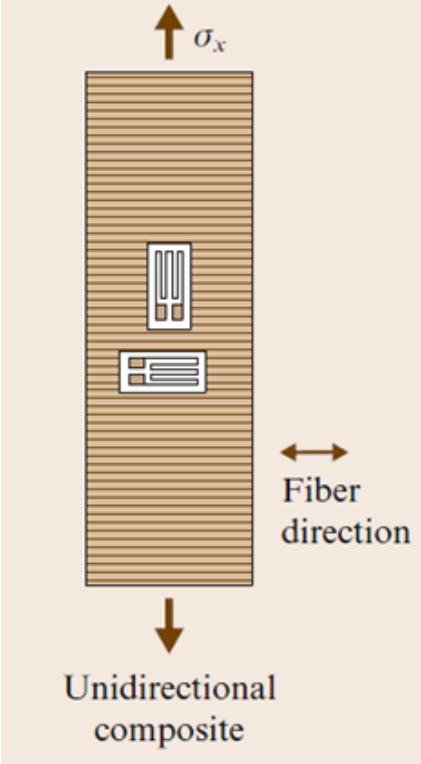


Figure 2-11. *Transverse sensitivity correction in a unidirectional composite material. [43]*

For the case when orthogonal gauges are used biaxial strain gauge rosette corrections are generally applied. The correction equations are given in (2.4.2 and 2.4.3), which gives the true strains ε_1 and ε_2, obtained from the indicated strains $\varepsilon'_1$and ε'_2, and the transverse sensitivity correction factors K_{t1} and K_{t2} for the gauges 1 and 2 [43]:

$$\varepsilon_1 = \frac{\varepsilon'_1(1-\nu_0 K_{t1}) - K_{t1}\varepsilon'_2(1-\nu_0 K_{t2})}{1-K_{t1}K_{t2}} \qquad \text{Eq. (2.4.2)}$$

$$\varepsilon_2 = \frac{\varepsilon'_2(1-\nu_0 K_{t2}) - K_{t2}\varepsilon'_1(1-\nu_0 K_{t1})}{1-K_{t1}K_{t2}} \qquad \text{Eq. (2.4.3)}$$

In addition, the equations for a rectangular rosette (as shown in Fig. 2-8) are given in following as Eqs. 2.4.4, 2.4.5 and 2.4.6. Normally, K_{t1} and K_{t3} are equal to each other [43]:

$$\varepsilon_1 = \frac{\varepsilon'_1(1-\nu_0 K_{t1}) - K_{t1}\varepsilon'_3(1-\nu_0 K_{t3})}{1-K_{t1}K_{t3}} \qquad \text{Eq. (2.4.4)}$$

$$\varepsilon_2 = \frac{\varepsilon'_2(1-\nu_0 K_{t2})}{1-K_{t2}} - \{K_{t2}[\varepsilon'_1(1-\nu_0 K_{t1})\,(1-K_{t3}) + \varepsilon'_3(1-\nu_0 K_{t3})\,(1-K_{t1})]\} \times [(1-K_{t1}K_{t3})(1-K_{t2})]^{-1} \quad \text{Eq. (2.4.5)}$$

$$\varepsilon_3 = \frac{\varepsilon'_3(1-\nu_0 K_{t3}) - K_{t3}\varepsilon'_1\,(1-\nu_0 K_{t1})}{1-K_{t1}K_{t3}} \quad \text{Eq. (2.4.6)}$$

2.4.2. Influence of the misalignment of the strain gauge

Whenever a strain gauge is attached on a mechanical component or on a test specimen, gauge alignment is an important consideration. When the gauge is not aligned precisely in relation to the loading direction or geometry of the component, the strain information that is recorded comes with errors and /or misinterpretation of the data. In the case of isotropic materials, this effect is not very significant. However, in the case of unidirectional composites, misalignment can introduce significant errors due to its high orthotropic behaviour. [5]

The misalignment error from strain gauges applied on composites is influenced by the same parameters as with isotropic materials, i.e. the gauge misalignment angle, the ratio between the principal strains, and the angle between the maximum principal strain and the aligned strain gauge direction. [47]

2.4.2.1 Theory for the misalignment error evaluation

When a strain gauge has an angular misalignment β in relation to the direction x (Fig. 2-12), the, the measured strain in the direction x (ε_x) is affected by an error ε_x` - ε_x in respect to the principal strains difference ε_p - ε_q, given by [48]:

$$\frac{\varepsilon'_x - \varepsilon_x}{\varepsilon_p - \varepsilon_q} = \frac{1}{2}[\cos 2(\alpha+\beta) - \cos 2\alpha] \quad \text{Eq. (2.4.7)}$$

Where α is the angle between the direction of measurement x, and the direction of the maximum principal strain, ε_p, and seen in Fig. 2-12.

This error can also be given as the following Eq. 2.4.8:

$$\frac{\varepsilon'_x - \varepsilon_x}{\varepsilon_x} = \frac{[\cos 2(\alpha+\beta) - \cos 2\alpha]}{\frac{1+r}{1-r} + \cos 2\alpha} \qquad \text{Eq. (2.4.8)}$$

Where $r = \varepsilon_q / \varepsilon_p$ is the ratio between the minimum and maximum principal strains.

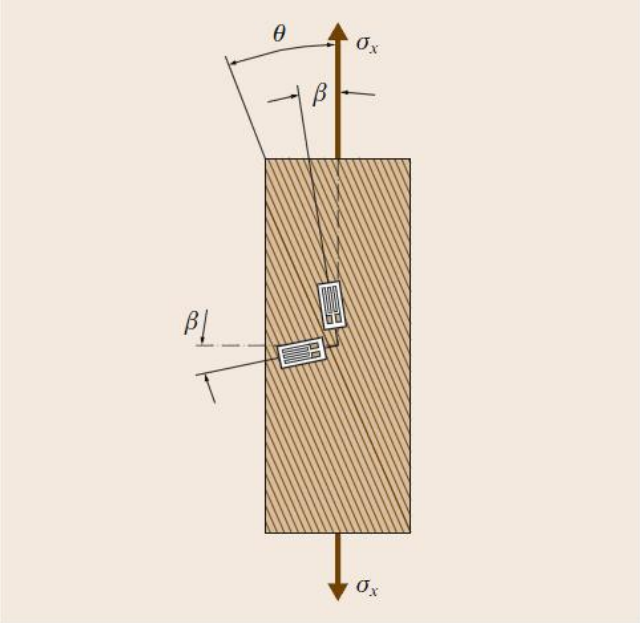


Figure 2-12. *Gauge misalignment nomenclature. [43]*

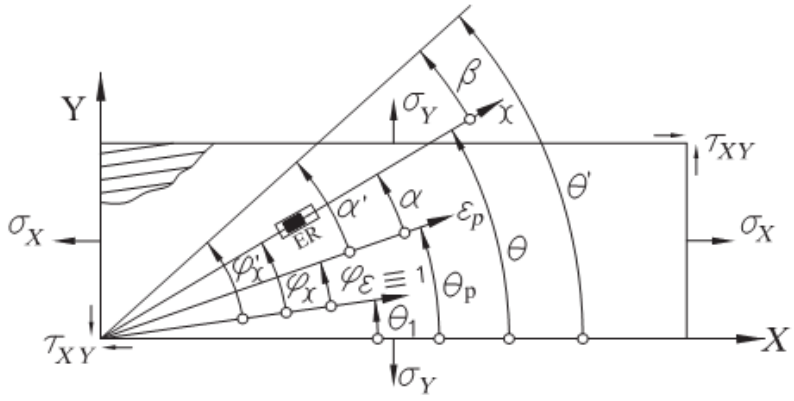


Figure 2-53. *Angles and axes notation for an orthotopic composite lamina. [48]*

The misalignment errors are highly dependent on the angle α. When the direction of measurement is coincident with the principal strain direction (α=0˚ or 90 ˚), the error is quite small. The error is particularly large when the direction of

measurement has an angle of 45˚with the principal strain directions. That is the reason why the misalignment error is small for isotropic materials, since the strain gauges are normally aligned with the direction of the principal strains. [42] Fig. 2-14 demonstrates the difference of the misalignment in both cases, isotropic and orthotropic materials.

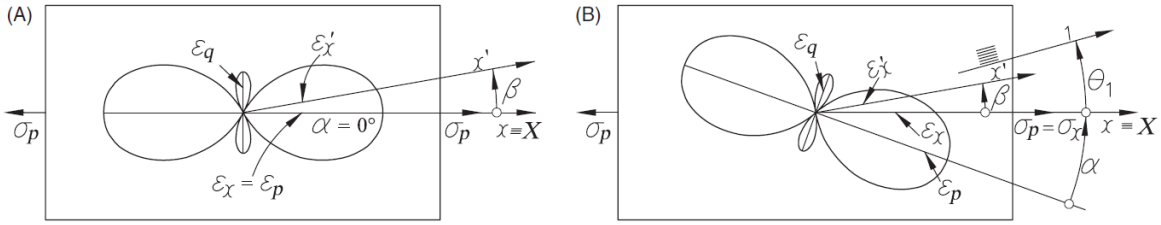


Figure 2-14. *Effect of the strain gauge misalignment (β is the angular misalignment) on the measurement of strain: (A) isotropic materials, (B) orthotropic material. [42]*

2.4.3. Temperature compensation

When a strain gauge is attached to component or to a test sample which is subjected to both mechanical loads and temperature variations, the gauge measurements are a combination of strains induced by both effects. A process called as temperature compensation has the objective to separate the effects of the mechanical loads making it independent of the temperature effect on it.

The strain gauge output which results from temperature variation can occur for two reasons: the electrical resistance of the gauge changes with temperature, and the coefficient of expansion of the gauge may be different from that of the underlying material. [49] There are generally three major methods of temperature compensation.

2.4.4. Temperature compensation methods for composites

2.4.4.1 Self-compensated strain gauges

A self-temperature compensated (S-T-C) strain gauge shows zero thermal output when installed on a specific material under test. This method can be very efficient for other materials than for composites. In the case of composite materials, this is not a practical form for temperature compensation. The reason is the dependence of the coefficient of linear thermal expansion according to the direction. Thus, for each test there is the need of different S-T-C strain gauge for each direction of measurement, otherwise the all

thermal compensation is lost. Therefore this is not a very applicable method in the case of composite materials. [42]

2.4.4.2 Dummy gauges

The dummy gauge method is currently the most widely used compensation method for the thermal output in tests on composite materials .The dummy compensation method requires a second gauge to be installed in a half-bridge configuration with the active gauge, as illustrated in the Fig. 2-15. [5]

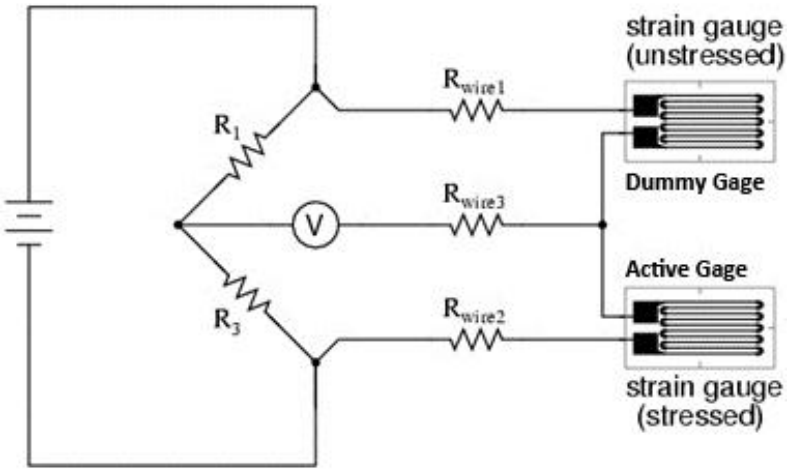


Figure 2-15. *Temperature compensation with a dummy gauge in half bridge. Unstressed gauge material of same composition and same temperature. [50]*

There are three requirements that are important to be fulfilled in order to accurately perform the dummy compensation. First, the dummy gauge must be from the same gauge lot as the gauge that measures the combined thermal and mechanical components. Second, the dummy gauge must be installed on an unconstrained specimen of the same material, of approximately the same volume and aligned in the same orientation with respect to the fibers as the loaded specimen. Finally, the two specimens (one loaded and the other unconstrained) must be in the same thermal environment and close from each other. When these requirements are not fulfilled large errors can occur. The two gauges are then connected in a half-bridge configuration and the thermal output from each gauge cancel. [43]

2.4.4.3 Self- heating effects

In accordance with the Joule's law, the application of voltage to a strain gauge creates a power loss which results in the generation of heat. The generated heat is dissipated in the form of conduction by the substrate material and the surrounding environment. The creation of heat is mainly related to the excitation voltage of the strain gauge circuit and also to the resistance of the strain gauge. The capability of the substrate material to neutralize the generated heat is related to its power density, which is a measure of its ability to act as a heat sink. When self-heating is not neutralized accordingly, the gradual heating of the substrate material occurs, which can originate creep of the substrate material, and also signal hysteresis and drift. Self- heating is not beneficial some steps are important to be taken to avoid it and eliminate future errors. [51]

The careful strain gauge selection is one crucial aspect in the elimination of the self-heating effect. This means that a proper combination of gauge resistance, excitation voltage, and gauge size is enough to avoid the problem. Typically, high gauge resistance levels create less self-heating, large grid areas permit more efficient dissipation, and low excitation levels decrease self-heating. However, when reducing the excitation level, there is the drawback that the circuit sensitivity is also reduced. In addition, higher-resistance and larger gauges are more expensive. Thus, an adequate combination taking into account all these aspects should be achieved in order to obtain the best results. [51]

The shelf-heating effect is especially problematic in the case of composite materials. The reason is that the majority of composite materials are fabricated with polymer matrices and polymers having low power densities are poor heat sinks. Therefore, it is very important to select gauges with a higher resistance and larger grid area, and/or use lower excitation levels as compared to strain gauges used for traditional materials. A range of acceptable power densities for composites is 0.31–1.2kW/m2. A rule-of-thumb recommendation was developed for strain gauge applications on composites [52] in which:

- Size: 3mm (0.125 in.) or larger;
- Resistance: 350Ω or higher;
- Excitation voltage: 3V or less.

For the cases where there is need to measure locations with high concentration of strain, smaller gauges can be used, by reducing the excitation levels.

2.5. Strain gauges selection principles for composite materials

The initial step when preparing for any strain gauge installation is the selection of the appropriate gauge for the specific application. It might at first appear that the gauge choice is a simple task, of no great consequence to the stress analysis, but it is quite the opposite. Careful and rational selection of the gauge features and parameters is a very important step. It permits the optimization of the gauge performance for specified environmental and operating conditions, obtaining accurate and reliable strain measurements, contributing to the ease of installation, and minimizing the total cost of the gauge installation. [53]

The following parameters [54] should be taken into account when selecting a strain gauge:

- Gauge length
- Gauge pattern
- Gauge series
- Resistance
- Self-temperature compensation
- Other options

Therefore, after considering all these parameters during the process of selecting a strain gauge according to the specific application and testing conditions, virtually the ideal strain gauge should be small in size and mass, low in cost, easily attached, and highly sensitive to strain but insensitive to ambient or process temperature variations. The following sections explain in a more detailed manner the factors influencing in the choice of the gauge mainly in the case of composite materials.

- **Gauge length:**

The gauge length of a strain gauge is the active or strain-sensitive length of the grid, as show in the Fig.2-16. The end loops and solder tabs are considered insensitive to strain because of their relatively large cross-sectional area and low electrical resistance.

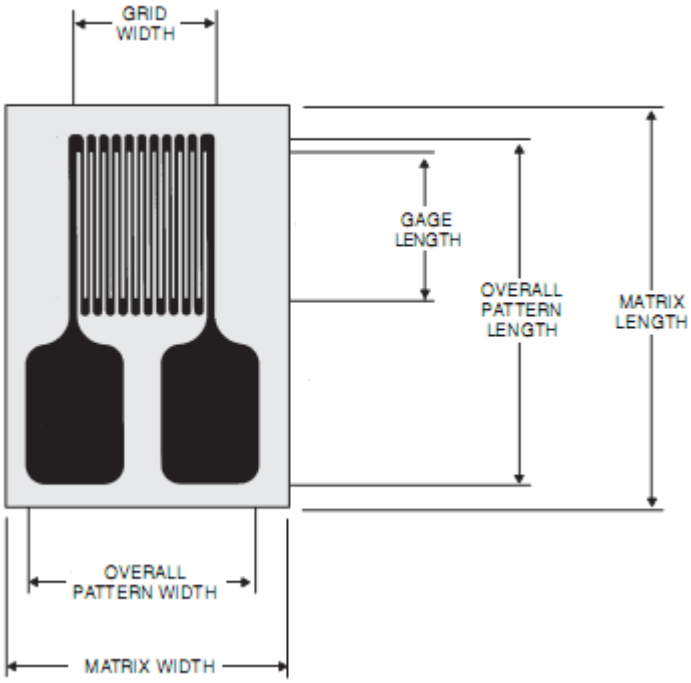


Figure 2-16. *Schematic representation of the gauge length in a foil resistance strain gauge. [55]*

The gauge length is the most important factor among all in determining the gauge performance under a given set of conditions. This fact is mainly true in the case of composite materials due to their typical high homogeneity compared with other materials. Normally, smaller gauges originate more experimental scatter than larger gauges and therefore should be avoided, unless in the case of measuring area with high strain gradients. In the cases of composites, gauges of 1/8 in (3 mm) length or greater usually offer better performance in terms of stability and strain range. In addition, with reinforced plastics, it is compulsory that the gauge length be large with respect to the dimensions of the underlying inhomogeneities in order to obtain any meaningful strain measurements. [54] [56]

- **Gauge pattern:**

Gauge pattern commonly refers to the number of the grid (uniaxial/multi-axial) and the layout of the grid (planar/stacked).The choice of the gauge pattern is mainly dependent on what it is expected to obtain from the experiments, for instance, whether one two or three axes are of interest, or whether normal or shear strains are needed. Most manufacturers of strain gauges offer an extensive range different patterns which suit a wide variety of applications in research and industrial projects, some configurations are presented in Fig. 2-17.

Concerning to the number of grid, two options exist, the uniaxial and the multi-axial. An uniaxial strain gauge has a single grid for measuring strain in the grid direction and is generally selected, if only one direction of strain needs to be investigated or in the case that the cost is an issue. Two or three single uniaxial gauges are usually less expensive than a bi-axial or tri-element strain gauge, and obtaining approximately the same results. For the case of a bi-axial strain rosette (0°-90° Tee rosette), there are two perpendicular grids and this type is used to determine principal strains when the directions of principal axes are known. A tri-element strain rosette (0°-45°-90° rectangular rosette or 0°-60°-120° delta rosette), has three independent grids in three directions and is normally used if the principal stresses need to be investigated but the principal axes are unknown. [37] [56] Finally, the strain gauges with shear patterns in which there is two chevron grids used in half-bridge circuits for direct indication of shear strains.

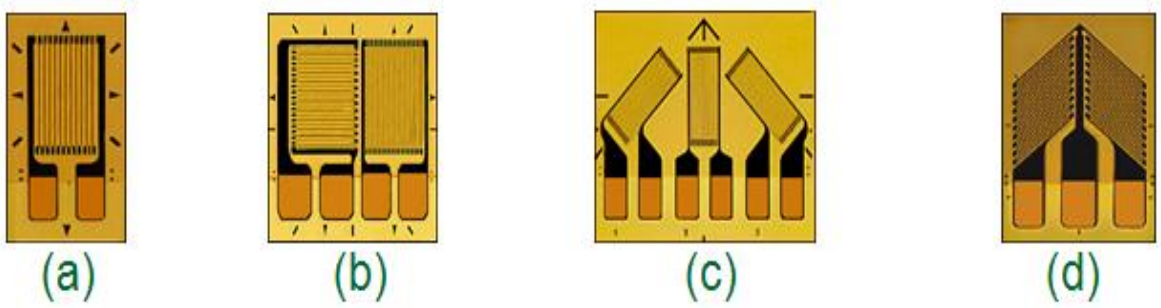


Figure 2-17. *Some of the strain gauge patterns available. (a) Uniaxial Gauge (b) Biaxial Rosettes (c) Three-Element Rosettes (d) Shear Patterns. [57]*

About the layouts, there are two different options for the multi-axial strain rosettes types (tee, rectangular, and delta); these are the planar and stacked configurations, as seen in Fig. 2-18. The planar rosette is etched from the strain sensitive foil as an entity, with all gauge elements lying in a single plane. The stacked rosette is manufactured by assembling and laminating two or three properly oriented single-element gauges. [43] However, in general the planar rosette is preferable over the stacked rosette configurations, because it has better heat dissipation characteristics and creates less reinforcement effects. Furthermore, stacked configurations offer the drawback of being more expensive and should be used only in the case the space for mounting is limited. [54] [56]

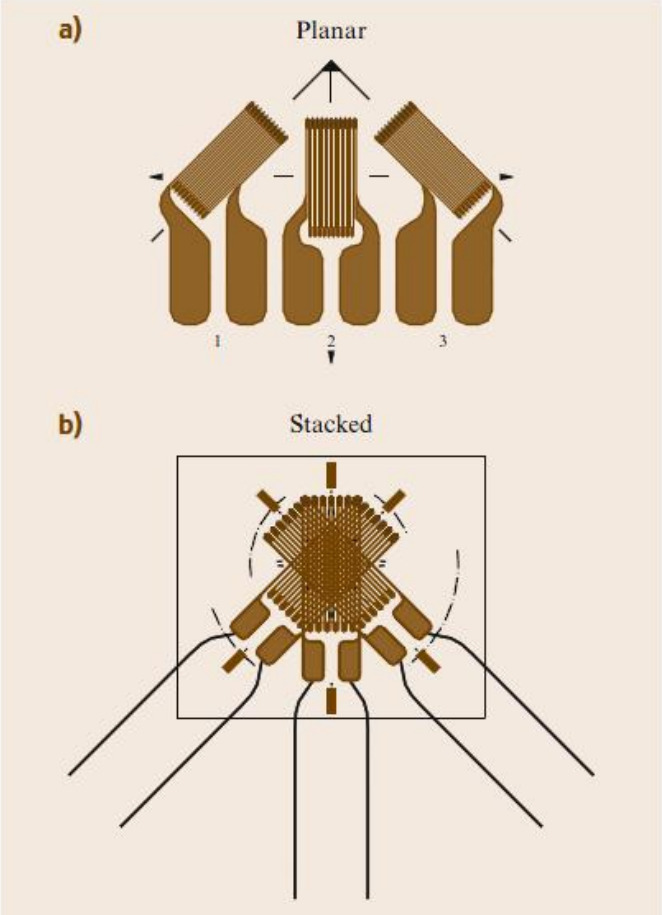


Figure 2-18. *Rectangluar rosettes (of the same gauge length) in (a) planar and (b) stacked construction. [43]*

- **Gauge series:**

The gauge series is related to the materials (foil and backing) that composed the strain gauge. There are several available choices according to the temperature range, fatigue characteristics, and stability. The most commonly used sensing grid alloys used for composites are constantan and Karma. Both materials show good sensitivity, stability, and fatigue resistance properties. Karma offer better stability at temperatures over 65 ◦C (150 ◦F), but is more difficult to solder to than constantan. In the case of backing materials, polyimide is very adequate for composites and permits for maximum elongation, while fiber glass reinforced phenolic offer better temperature stability. [43] [54]

- **Resistance:**

The resistance of a strain gauge is defined as the electrical resistance measured between the two metal ribbons or contact areas intended for the connection of measurement

cables. The range comprises strain gauges with a nominal resistance of 120, 350, 600, and 700 Ohms. [37]

The gauge resistance can be an important factor because of the low thermal conductivities of the composite materials. High-resistance gauges (350 ohms or greater) are commonly preferred to decrease the heat dissipation in the case of composites materials. [56]

- **Self-temperature compensation:**

As explained before in the previous sections, the S-T-C is generally not an option for composite materials, therefore, there is no need to consider the S-T-C number when selecting strain gauges for composites as any available S-T-C value can be appropriate.

- **Other options:**

As a result of the low thermal conductivities which characterize the class of composites, it is preferable to select gauges with preinstalled lead wires. Another option is to attach the lead wires before the gauge bonding. The prewiring is considered a good practice in the case of materials with low thermal conductivities because it eliminates the risk of damaging the test material during the soldering operations. [56]

2.6. Wireless strain sensing

As it is known repetitive strains of high magnitude may conduct to the fatigue or deformation of the material. Therefore, strain is an important measurement for structural integrity and monitoring of the component´s condition and functional life as it can estimate the structure's loads, moments, and stresses. Strain data can only be obtained by placing sensors near the points of interest. [13]

The combination of strain gauges sensors with careful design of the system for the specific application and component can be used to create very accurate transducers of torque, load, pressure, and acceleration. Hence, the integration of strain sensors into structures, machinery and in the environment, coupled with the efficient delivery of sensed information, provide tremendous benefits to society. Some potential advantages include: fewer catastrophic failures, conservation of natural resources, improved manufacturing productivity, improved emergency response and improved homeland security. However, limitations to the widespread use of sensors in structures and machines still exist. One of the main limitations is related with the numerous bundles of

long lead wires that are associated with the conventional strain sensing systems. Lead wires are commonly subjected to breakage and connector failures. Additionally, lead wires represent a significant time consuming installation and long term maintenance costs, limiting the number of sensors that may be deployed, and therefore reducing the overall quality of the obtained strain data. [13] [58] [59] Wireless sensing networks (WSN) are the best solution in this case. As it eliminate these costs and making the installation faster and easier. An ideal wireless sensor is networked, consumes very little power, is smart and software programmable, capable of fast data acquisition, reliable and accurate in long term measurements, it has a low cost and fast installation, and requires no real maintenance. [60]

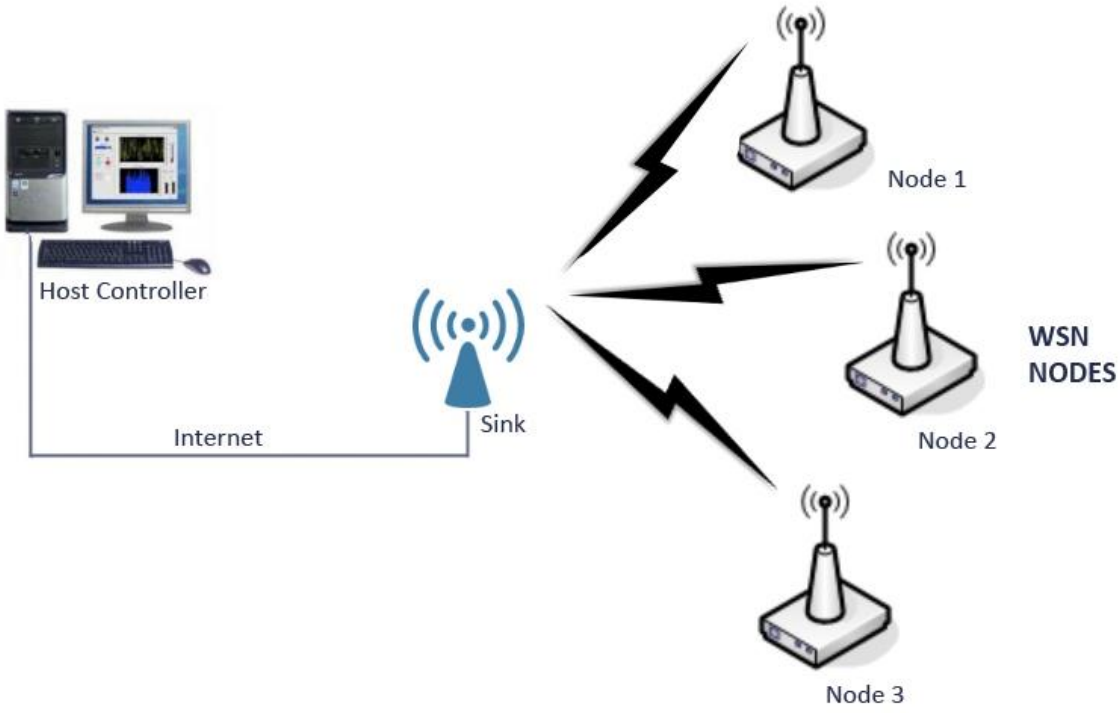


Fig 2-19. *A wireless network architecture.*

Although, strain gauges are a widely used strain sensing technique, their use with a wireless network system is still in its preliminary phase, in spite of the numerous range of structural health monitoring applications that the wireless strain measurement may be used. Some of the widespread applications of WSNs are mainly found in civil and industrial applications such as smart home or environment monitoring [61] [62] [63]. As an example, one remarkable use of the wireless strain sensors is in automotive application for the quality control of the gaps in body panels and doors [64].

A WSN consists of a set of wireless sensor nodes where each node measures a physical value using selected sensors. [65] The sensor modules communicate with one

another and with a central processing unit, in order to send the sensor data value to a database through specific sink nodes. A typically WSN is shown in Figure 2-19.

Normally, the strain nodes that constitute a WSN system operate with a fast dynamic response and are capable of self-configure themselves, which allows quick and easy system setting even in the most difficult locations. The selection of the ideal sensors and wireless communications link for the wireless system requires knowledge of the application and a pond ration of the benefits and problems they may involve. Battery life, update rates, and size are the main design considerations for a WSN system. [13]

3. EXPERIMENTAL

Pultruded carbon fiber-reinforced plastic composite samples are the material used for the tests. On its surface foil resistance strain gauges are attached. The material is positioned in bending fixtures and subjected to a constant bending load (a bending displacement correspondent to a 30% of bending strength of the material) and immersed in seawater tanks for an elongated period of time of approximately one month at room temperature. During that time, strain measurements are taken for the composite samples by using the attached strain gauge sensors.

The strain data is continuously collected simultaneously by two independent strain gauges setups. One is a traditional wired strain gauge arrangement and the other is a Wireless strain gauge system. The Wireless strain gauge system consists basically in a configuration that results from a wireless sensor network (WSN) integrated with the conventional strain gauges sensors. From the strain data obtained, the reliability of the wireless stain gauge system and its use as a Non-destructive technique and health monitoring analysis of composites is investigated by evaluating and comparing it with the results of the traditional wired gauge setup.

3.1. Materials

The composite materials used in this study are HS carbon fiber/epoxy profiles with a volume fraction of fibers of 65%, fabricated by a pultrusion process. The material was provided by *Exel Composites*. The received profiles with rectangular cross-sectional geometry were of 1000 mm in length, 2 mm in thickness and 10.15 mm in width. Furthermore, a data sheet including some properties of the composite was also included containing the results of the tests conducted by *Exel Composites* to obtain the mechanical properties of the materials. The tests were conducted using HS carbon fiber/epoxy plates of 2mmx20mm in dimension. The summary based on those results is shown in the table 3-1.

The resistance strain gauges used in this research study are *320 Ohms General Purpose strain gauges* with linear pattern made by Vishay Micro-Measurements. These gauges kind are suitable for composite materials and are also sensitive to extremely small amounts of force. A representation of the strain gauge type used in this study is shown in the Fig. 3-1. According to the Strain Gauge Designation System utilized by

Table 3-1 *Mechanical properties of HS carbon fiber/epoxy pultruded profiles.*

Meter weight [g/m]	62,7
Tensile Stiffness [GPa]	127,0
Tensile Strength [MPa]	1995,8
Bending Stiffness [GPa] (32mm)	104,4
Bending Strength [MPa] (32mm)	1481
ILSS [MPa]	78,5

Vishay Micro-Measurements [66], this gauge type is described as C2A-06-125LW-350. More information on the strain gauge designation system used by Vishay Micro-measurements is found in Appendix A. This designation is related to the general features of the selected strain gauge type. In this study, the gauge foil alloy is made of constantan in self-temperature compensated form and the backing materials consists of a thin, laminated polyimide film. Additional details on the specific gauge type used in this study are given in Appendix B.

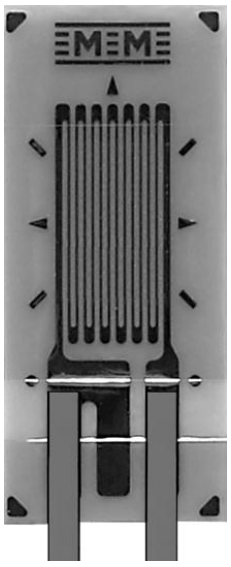


Figure 3-1. *General Propose C2A-06-125LW- 350 strain gauge manufactured by Vishay Micro-Measurements. [55]*

This single element gauge type comes already with pre-attached ready-to-use cables, meaning that the step required for soldering the lead wires to the solder tabs of the gauge are no longer needed and making the process to attach the strain gauge easier and saving time. An unfortunate characteristic of strain gauges is that of resistance

change with changes in temperature, as it was previously explained. Hence, the strain gauges used in this project are self-temperature-compensated (STC) gauges, enabling strain measurements without receiving any thermal effect.

3.2. Surface preparation and strain gauges installation

3.2.1. Surface preparation

The 1000 mm long HS carbon fiber/epoxy profiles were cut into smaller samples of approximately 250mm in length each.

Surface preparation of the testing sample is the most important step in the bonding of strain gauges. A careful surface preparation provides an adequate adhesion of the gauges to the sample surface and the guarantee that the gauges are not going to unglue from the surface during the tests. The surface of the samples was thus appropriately prepared following the steps indicated in the literature for the surface preparation of composites samples in the strain gauge bonding and in the Vishay Micro-Measurements manual for Surface Preparation for Strain Gauge Bonding [67].

First, the sample surface was very well cleaned with a degreasing agent in order to remove any grease and oil present on the surface. Following an abrading process, in which the area where strain gauges are to be positioned is slightly abraded by using silicon-carbide paper to sand away uneven surface and obtain a smooth gauging area for the bonding step (320 grit was first used, followed by 400 grit). Layout lines were made on the surfaces by a burnishing operation, indicating the accurate locations and orientation of the strain gauges on the test surface. The surface was further cleaning with distilled water and a cleaning solution to remove any residues remaining from the abrading step and from the burnishing. In the final step the surface was neutralized with a neutralizing solution to bring the surface condition back to an optimum alkalinity of 7.0 to 7.5pH, which is suitable for the Vishay Micro-Measurements strain gauge adhesive systems. The samples were allowed to dry.

3.2.2. Strain gauges installation

The M-Bond AE-10 Vishay Micro-Measurements [68] strain gauge system was the adhesive system used to bond the strain gauges to the samples. Information and using procedure for the M-Bond AE-10 adhesive system is found in the Appendix C. This system involves a mixture of epoxy resin and a curing agent which is used to glue the

gauge on the sample surface. Two strain gauges were positioned parallel in the same side for each sample as seen in Fig 3-2. This gauge positioning is known to be the very sensitive to measure strains in the case of bending loads. No soldering of lead wires was performed as this strain gauge type is with pre-attached lead wires. After the gauge gluing, pressure clamps were applied to keep the gauges on their position and preceded to the curing at room temperature for approximately 48 hours.

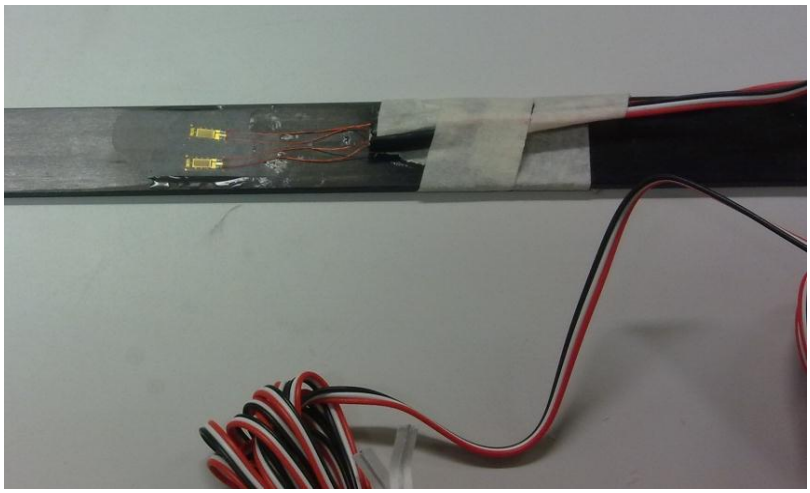


Figure 3-2. *Detail of a HS carbon fiber/epoxy sample used in the tests. Two strain gauges are attached in parallel on one side of the sample.*

3.2.3. Water-proofing coating

For conditions requiring contact with water or other fluids, it is absolutely required the use of protective coatings on the strain gauge. The coating protects the gauges against moisture and other contaminants which may affect the gauge stability. This is especially important for long term measurements.

When preparing the gauges for this study, a silicon polymer coating was properly applied on the strain gauges, which besides giving waterproofing features also provides protection against the highly corrosive environment due to the seawater. The silicon type used to coat the gauges is a free acetic acid silicone type; therefore, it does not contain any vinegar content on its composition, which could be corrosive to the metallic wires of the gauges.

3.3. Equipment

3.3.1. Wired strain gauges tests

The Model D4 Data Acquisition Conditioner manufactured by Micro-Measurements as seen in Fig. 3-3, is the measuring device used for the strain data in the conventional wired strain gauge tests. [69] The Model D4 Data Acquisition Conditioner is a portable, USB-powered precision instrument for use with resistive strain gauges and it has four channels of data acquisition. Each channel allows one gauge to be connected by using wires and strain data is collected; a total of four strain gauges can be connected simultaneously using this device. Additionally, each channel of input accepts either full, half, or quarter-bridge configuration. This device is compatible to use with the 350-ohm strain gauges type selected for the tests in this study.

Figure 3-3. *Micro-Measurements model D4 data acquisition conditioner. (a) Details on the front panel, (b) Details on the back panel. [69]*

The software used for the strain sensing measurements by this wired system came included with the D4 device, from the supplier.

3.3.2. Wireless strain system tests

The wireless strain gauges tests in this study are done by using the CiNetStrain system which is a WSN configuration.

The main components of the wireless CiNetStrain system are the CiNet nodes, which were developed and designed at Kokkola University Consortium Chydenius. This wireless system is shown in detail in the Fig. 3-4. The nodes are made of relatively cheap materials, battery powered and they are programmed to take strain measurements at each second. Additionally, they use the cross-layer architecture. The cross-layer architecture allows implementing a wireless sensor network's basic tasks, it has power saving functionalities and reduces computational and memory requirements. [65] [70]

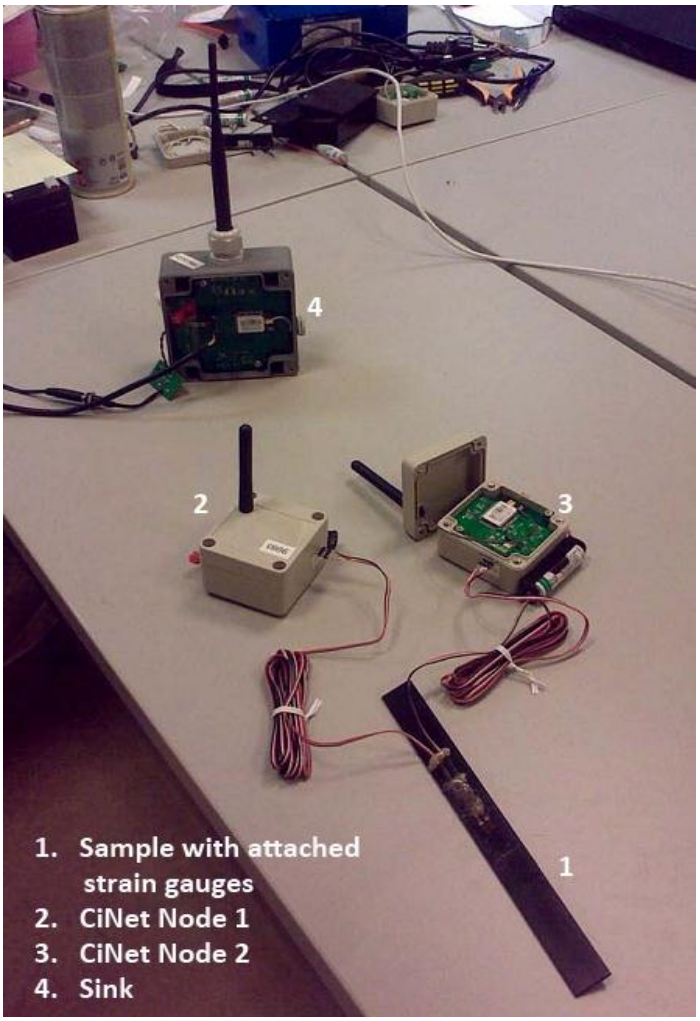


Figure 3-4. *The Wireless CiNetStrain system.*

For the tests, the strain gauges attached to the sample are connected to the nodes through the lead wires where each node collects strain data which is wirelessly transferred to a sink and transmitted to a data base. This system also permits a real time deployment. The strain values are displayed in a real time graphic in the software which was especially developed for this study at Kokkola University Consortium Chydenius. This is advantageous as it allows real time study of the strain values applied on the components at any moment in real time.

3.4. Testing methods

3.4.1. Three point bending flexural tests

Three point bending tests were performed in a Universal testing machine Messphysik, Beta 20-10/4x11 at a constant cross-speed of 10 mm/min at room temperature. The tests were conducted in accordance with the ASTM D 790-03 [71] and consisted of placing each composite sample on the bending fixture, loading it until the rupture, and recording the flexural stress-strain response of the material. The test configurations are shown in the Table 3-2.

Table 3-2 *Three Point Bending Test Configurations.*

LOAD CELL	**2 kN (450 lbf)**
SPECIMEN GEOMETRY	Rectangular
SPECIMEN DIMENSIONS	Length 250 mm, thickness 2 mm, width 10.75 mm
CROSSHEAD SPEED	10 mm/min
TESTING SPAN	150 mm

For the initial preparation and before the running of each test, the sample was rested on the two supports of the bottom fixture, perpendicular to the loading nose. After that, the upper anvil was manually adjusted to just barely touch the composite sample. After this initial preparation, the test was run and automatically stopped at rupture. A sample before the bending test starts can be seen in the Fig. 3-5.

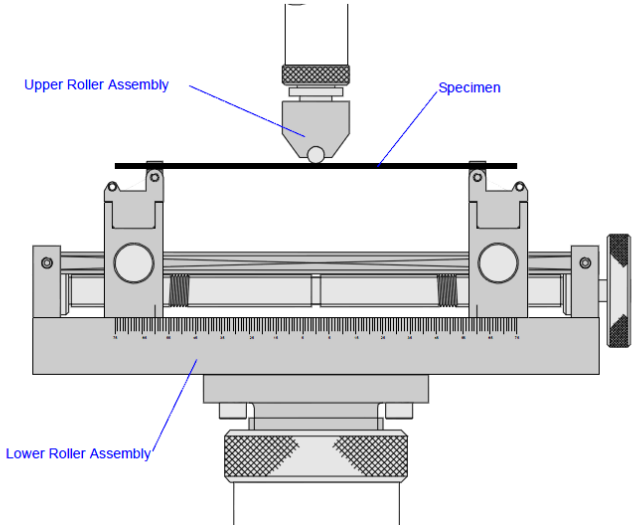


Figure 3-5. *Sample rested between supports before the start of the three point bending test. [72]*

3.4.2. Seawater tests

The equipment used for the seawater tests consists of screw-adjustable Three Point bending fixtures, in which a complete rotation (360˚) of the screw corresponds to an approximate bending displacement in the sample of 1mm. The distance between supports is of 150 mm.

Initially, the composite samples with the attached strain gauges were positioned in bending fixtures in which a constant bending strain was applied. After that, the bending fixtures are immersed in 30cm long glass tanks containing 1.2 litres of seawater. A three point bending fixture and a glass tank used for this study are represented in the Fig. 3-6.

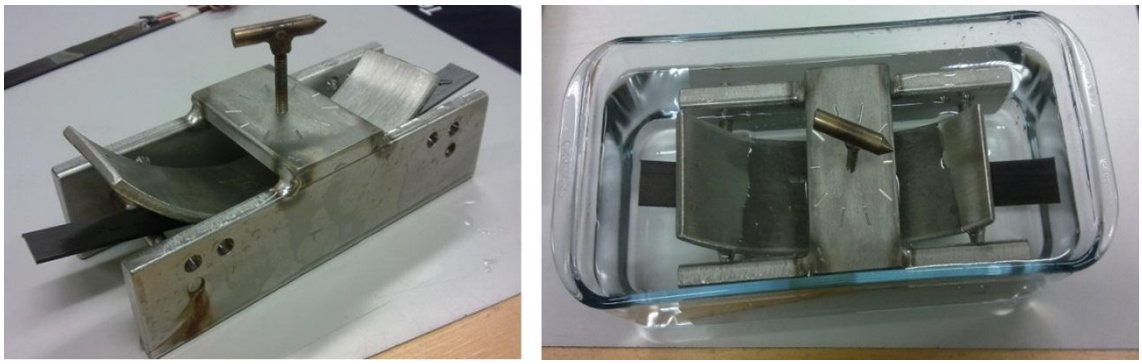


Figure 3-6. *(a) A screw-adjustable three point bending fixture with a composite sample placed on it. (b) The bending fixture immersed in a 30 cm tank containing seawater.*

The fixtures with the placed HS carbon fiber/epoxy samples were kept in the seawater water tanks for nearly one month at room temperature. During that time, strain measurements were taken in a daily basis by using both the wired and the wireless strain gauge systems, as described previously. Measurements of the seawater pH values and seawater temperatures and room temperatures were also registered during the tests. Moreover, as the seawater evaporated along the testing time, the tanks were refilled in order to keep a constant quantity of seawater on the tanks during all the experimental period.

3.4.3. Strain sensing setup and measurements

The setup used to obtain the strain measurements resulting from the seawater tests consist of an experimental arrangement which is composed simultaneously by the conventional wired Strain gauge and the wireless strain system (as described before), and as illustrated in the Fig. 3-7.

In the strain sensing setup, there are three seawater tanks, each tank containing one bending fixture with a HS carbon fiber/epoxy, which by its turn has two parallel strain gauges. The two leftmost tanks seen in the experimental setup of the figure are connected to the wired strain system, composed by the D4 Data Acquisition Conditioner.

Figure 3-7. *The strain sensing setup.*

There are in total four channels in D4 equipment, in which each channel is collecting strain data from one single strain gauge. The other tank (on the right side of the Fig. 3-7) is part of the wireless strain gauge system. For this wireless system, the two strain gauges are connected to the two nodes. The nodes wirelessly convey the strain information to the sink node that transfers this data the laptop pc by USB. The strain measurements are daily taken with duration of about one hour long for each test. The strain data collected by the two systems are recorded and stored into different data files which are later evaluated and studied separately.

3.4.3.1 Calibration of the wireless nodes

All devices that are to be used for measurement require a calibration so that the output can be converted to conventional units of measurement. Furthermore, as the wired strain system measurements, which are taken by the D4 device produce strain results in microstrain, the CiNetStrain nodes composing the wireless system needed to be calibrated to obtain also microstrain values. This process is performed so that the information resulting from both systems can be compared. The calibration of the CiNetStrain nodes of the wireless system was done to calibrate the system in micro strain, which corresponds to the voltage output of the bridge.

Bending strain was used to do the wireless system calibration. The strain was measured by a reference system (using the D4 device) and the wireless system using different strain values. The resulting values were compared and the linear calibration was done.

4. RESULTS AND DISCUSSION

4.1. Flexural tests

Three Point Bending Flexural Tests were carried out in order to study the flexural behaviour and determine the flexural properties of the HS carbon fiber/epoxy composite material used in the seawater experiments. According to the obtained bending load-displacement data, the flexural properties of the material were determined. The Table 4-1 represents the results from the flexural tests using a minimum of five samples.

The Flexural strength values were calculated in accordance of ASTM D 790-03 [71]. For the case when the support span-to-thickness ratios are greater than 16 to 1 the following Eq. 4.1.1 is applied:

$$\sigma f = \left(\frac{3PL}{2bd^2}\right)\ [1 + 6\left(\frac{D}{L}\right)^2 - 4\left(\frac{d}{L}\right)\left(\frac{D}{L}\right) \qquad \text{Eq.(4.1.1)}$$

Where:

σf is the flexural stress, in megapascals (MPa);
P is the load, in newtons (N);
L is the span, in millimeters (mm);
d is the thickness of the specimen, in millimeters (mm);
b is the width of the specimen, in millimeters (mm);
D is the maximum deflection in the centerline of the specimen at the middle of the support span, in millimeters (mm).

Additionally, the maximum bending force and the correspondent displacement as well as 30% of the maximum bending force and the associated displacement at 30% of maximum load were also determined for the tested samples as seen from the Table 4-1.

Table 4-1 *Flexural properties of the HS carbon fiber/epoxy composite.*

Sample	***Flexural Strength (MPa)***	***Maximum Flexure Load (N) [P]***	***Displacement at Maximum Flexure Load (mm) [D]***	***30% Maximum Flexure Load (N)***	***Displacement at 30% Maximum Flexure Load (mm)***
1	1405.05	210	33	63	8
2	1450.99	211	35	63.3	9
3	1464.75	213	35	63.9	9
4	1431.07	211	34	63.3	9
5	1471.62	214	35	64.2	10
Mean	**1444.70**	**211.8**	**34.4**	**63.54**	**9**
Standard deviation	**27.04**	**1.64**	**0.89**	**0.49**	**0.71**

Comparing the determined flexural strength values and the maximum flexural load for the HS carbon fiber/epoxy composite samples with the ones reported by the supplier (in Table 3-1), of approximately 1481 MPa for the flexural strength and 32mm for the maximum displacement, it is observed a very good accordance between the experimental determined results and the standardized values provided by the supplier.

The average maximum flexural load for the HS carbon fiber/epoxy composite material is 593 N, meaning that the material fractures for bending loads above this value, with a correspondent displacement of 34.33 mm. The average displacement at 30% Maximum Flexure Load of 9 mm is the result which will in an approximate way applied on the bending fixtures for the later seawater tests.

4.2. Seawater tests

The seawater experiments were carried out in order to collect strain measurements along the time. The strain information obtained results from the constant bending displacement (9 mm) applied on the composite material by the screw-adjustable bending fixtures and immersed in seawater. Both the wired and the wireless system are started simultaneously for each test.

Before the starting of the tests, all the strain gauge sensors were adjusted to zero, so that no bending load is applied. After that, the same strain value was applied in all the samples until it reach strain a value of around 2100με (this procedure was done in the first day of the measurements, only). This micro strain value was calculated as an

approximate correspondence to the 9 mm displacement value at 30% maximum flexural load, previously determined from the initial flexural tests.

4.2.1. Warm up of the nodes

During the initial strain measurements taken with the Wireless strain gauge system it was verified that the nodes required some time, in order to warm up and collect more accurate and stable strain values. The warm up time basically defines how long the device must power up the sensor before a stable sensor reading is taken.

Tests were conducted during nearly one hour period, to determine the approximate time the nodes take to complete the warm up process. Fig. 4-1 represents graphically the warming up of the nodes registered during the tests.

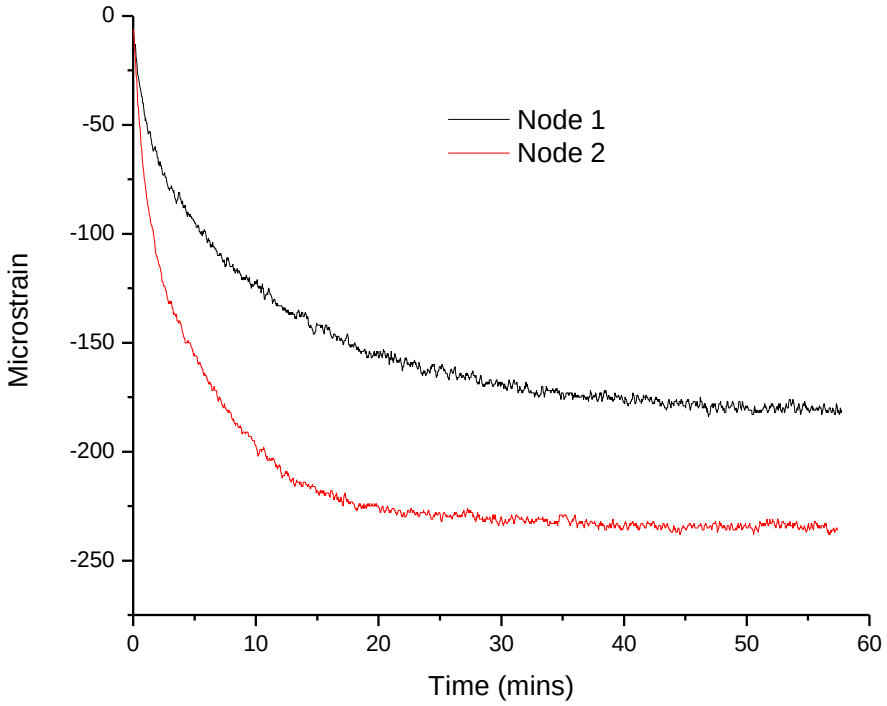


Figure 4-1. *Warm up phase of the wireless nodes.*

It is seen that during the warming up, the strain values decrease exponentially with the time until it reaches steady state in which stable strain values are registered. In average the nodes require from 30 to 40 minutes to finalize the warm up process. Therefore, for the strain sensing measurements and for each time the tests are performed, about 45 minutes are given to the warming up phase of the wireless nodes and before starting to collect stable strain data.

4.2.2. Temperatures and pH values

At the beginning of each test, the room temperature and the temperature of the seawater in each individual glass tank were taken. The temperatures values for certain specific days of the experiments are seen in the Table 4-2.

Table 4-2 *Temperature measurements.*

Days	*1*	*4*	*8*	*14*	*19*	*22*	*25*	*28*	*Mean*
Room (°C)	*23*	*22.9*	*22.2*	*20.5*	*20.7*	*20.8*	*20.7*	*20.8*	*21.45*
Tank 1 (°C)	*20*	*21.1*	*20.9*	*19.2*	*19.0*	*19.2*	*19.0*	*19.2*	*19.87*
Tank 2 (°C)	*20.9*	*21.0*	*20.9*	*19.1*	*18.9*	*19.1*	*18.9*	*19.1*	*19.73*
Tank 3 (°C)	*20.8*	*21.2*	*21.2*	*19.2*	*19.1*	*19.2*	*19.1*	*19.2*	*19.7*

The seawater used in this study was collected from the sea in Kokkola. The pH of the seawater was measured with a value of around 6.5, which indicates that is it slightly acidic. This rather unusual pH value for the seawater (which is normally approx. 8.0), results from the mixture of fresh water (from river) with the sea, which typically occurs for that location.

4.3. Calibration of the wireless gauge system

Based on the calibration procedure of the wireless system, as previously described. The linear conversion equation was determined as:

$$y = -0.3512x + 4.2988 \qquad \text{Eq. (4.2.2)}$$

Where,
x is the input in ADC values and y is the output as micro strain value.

Using the existing function (equation 4-2), one can simply convert the ADC values to strain measurements with a linear calibration factor. Therefore, the wireless nodes composing the wireless gauge system are linearly calibrated to obtain micro strain values. These two values are configured in the software used for the wireless system prior the strain sensing tests, as: FACTOR= −0.3512 OFFSET= 4.2988.

4.4. Results of wired gauge system: channels reliability

Channel 1 and 2 of the wired gauge system were both connected to gauges immersed in the same seawater tank (tank 1 in Fig. 3-7). This means that these channels were reading and collecting strain data belonging to the same composite sample subjected to equal conditions during the experimental and thus, it is meaningful to compare the output of both channels. Fig. 4-2 demonstrate the results obtained for both channel 1 and channel two, during the 28 days of the strain sensing.

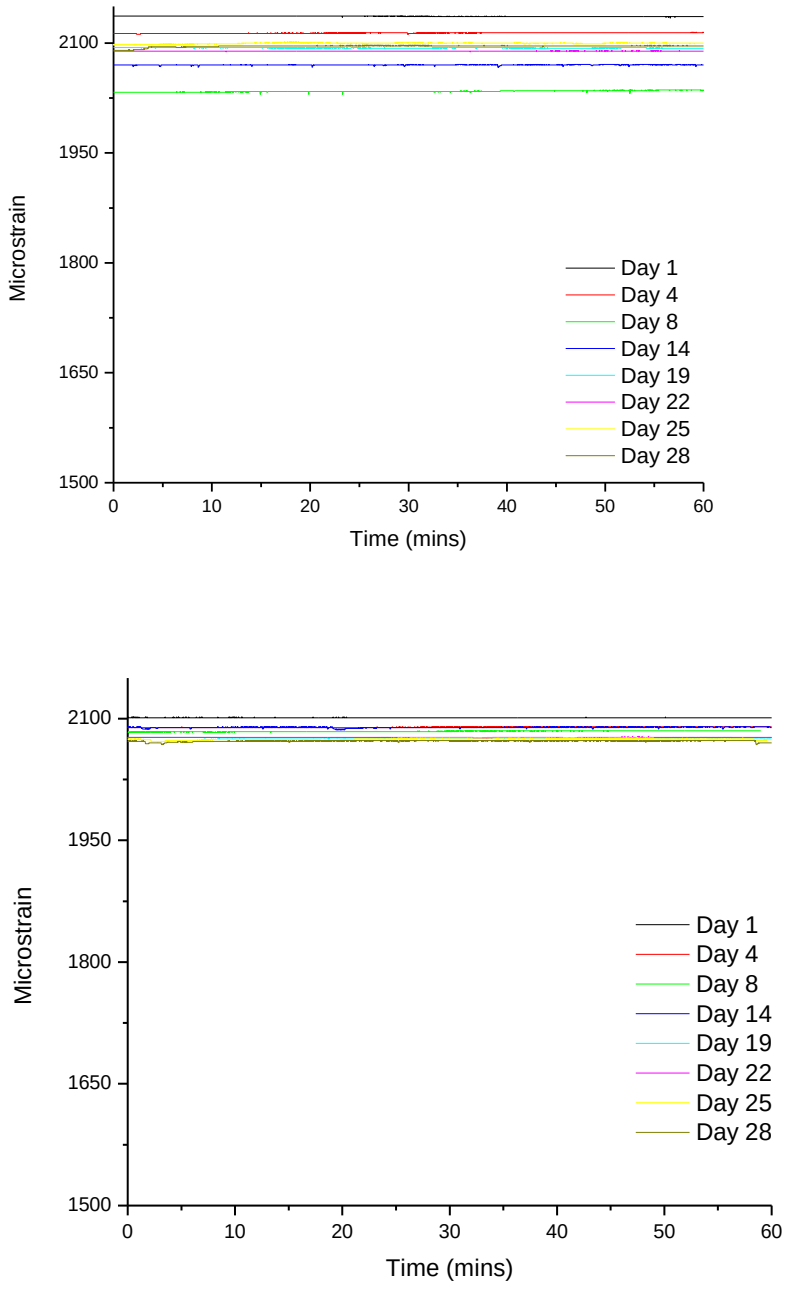


Figure 4-2. *Microstrain measurements for Channels 1 and 2 during the 28 days of experiments.*

From the graphics analysis is possible to observe very approximate and stable results for the channels 1 and 2. The values obtained are quite close and do not show any significant range of deviation from the initial applied microstrain value of 2100. Meaning that the reliability of these both channels is good and they are working properly.

For channels 3 and 4 which also were connected to gauges attached to the same composite sample and positioned in the same tank (tank 2 in the Fig. 3-7). The results for channels 3 and 4 are show in the graphics of Fig. 4-3.

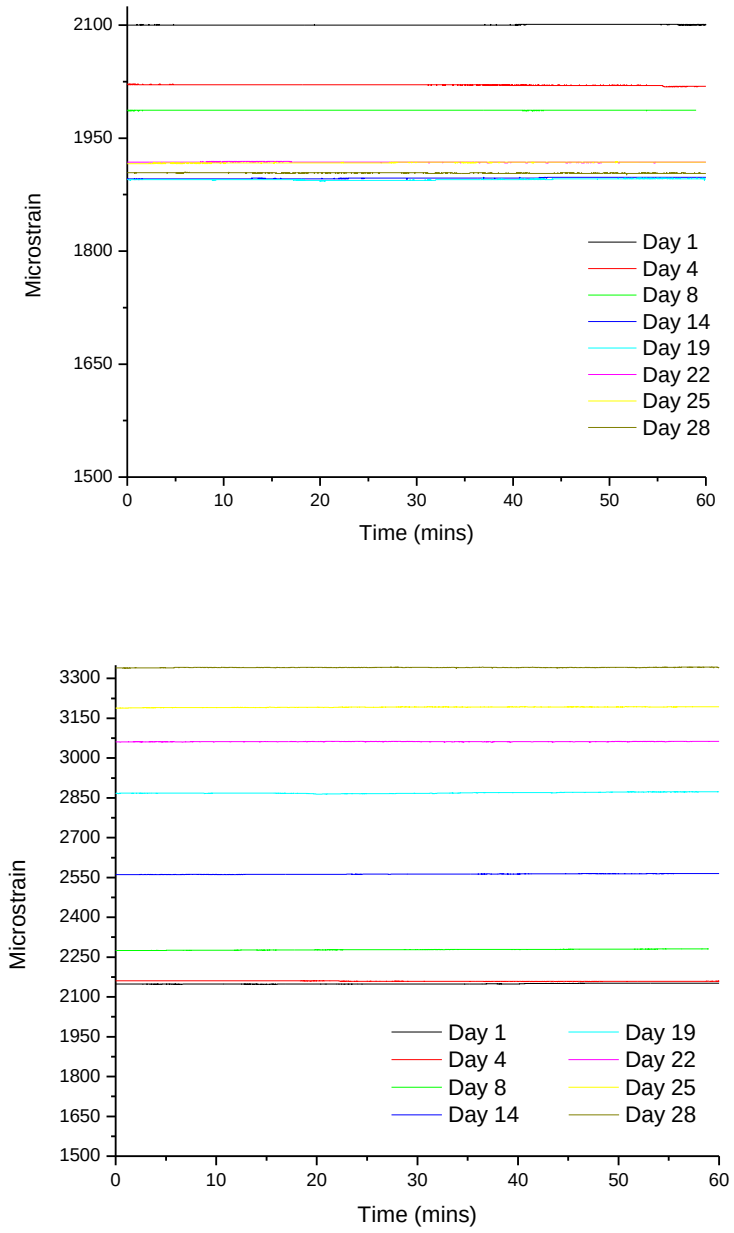


Figure 4-3. *Microstrain measurements for Channels 2 and 3 during the 28 days of experiments.*

Unlike channels 1 and 2 which show a very close compatibility in the results, the same is not verified for the case of channels 3 and 4. These two channels show complete distinct behaviours, which is demonstrated by their contradictory results. In addition, there a very big gap and a considerable detachment from the initial strain value (2100µe) along the time, observed for both channels and this effect is even more pronounced in the case of channel 4.

The graph of the Fig. 4-4 illustrates the box charts of the four different channels on the wired strain system. The graphic shows the distribution of microstrain data at a glance. Information on the median, standard deviation and the microstrain data range it is represented.

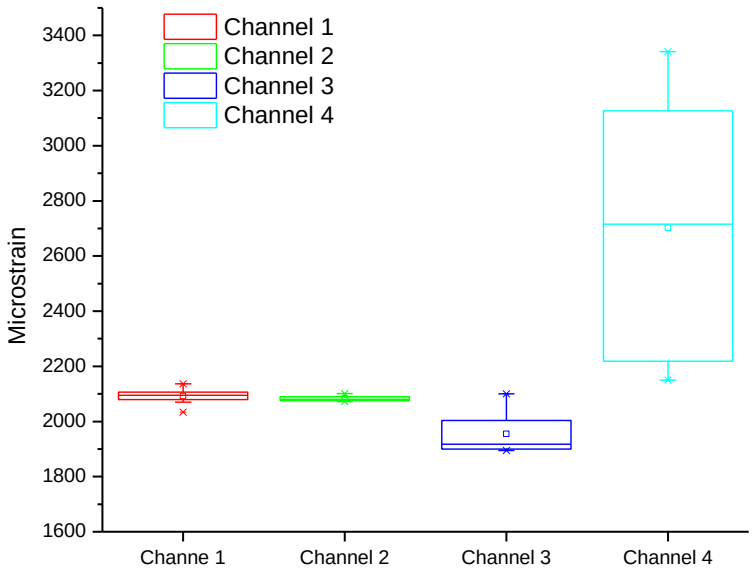


Figure 4-4. *Box charts of the channels.*

The information given by the box plots confirms the previously referred observations on the channels performance. Channels 1 and 2 are quite precise and are able to provide stable results along the time. On the other hand channels 3 and 4 demonstrate a noticeable deviation from the median value, especially for the channel 4.

However, any conclusions on the reliability of the channels 3 and 4 it is still premature to be taken at this point. There are several factors involved in the test (such as the adhesive and coating performance or the stability of the bending fixtures) that can influence the accuracy of the results. Although, there is the possibility that the channels possess some defect due to the manufacturing of the device, this chance is quite remote and unlikely.

4.5. Results of wireless gauge system: nodes reliability

During the strain sensing tests, the wireless nodes (1 and 2) were connected to the strain gauges of the same sample on the tank 3. The following Fig. 4-5 represents the results obtained for the node 1 and node 2, respectively. Moreover, the fig 4-5 shows the box plots, containing information on the distribution of microstrain data for both nodes.

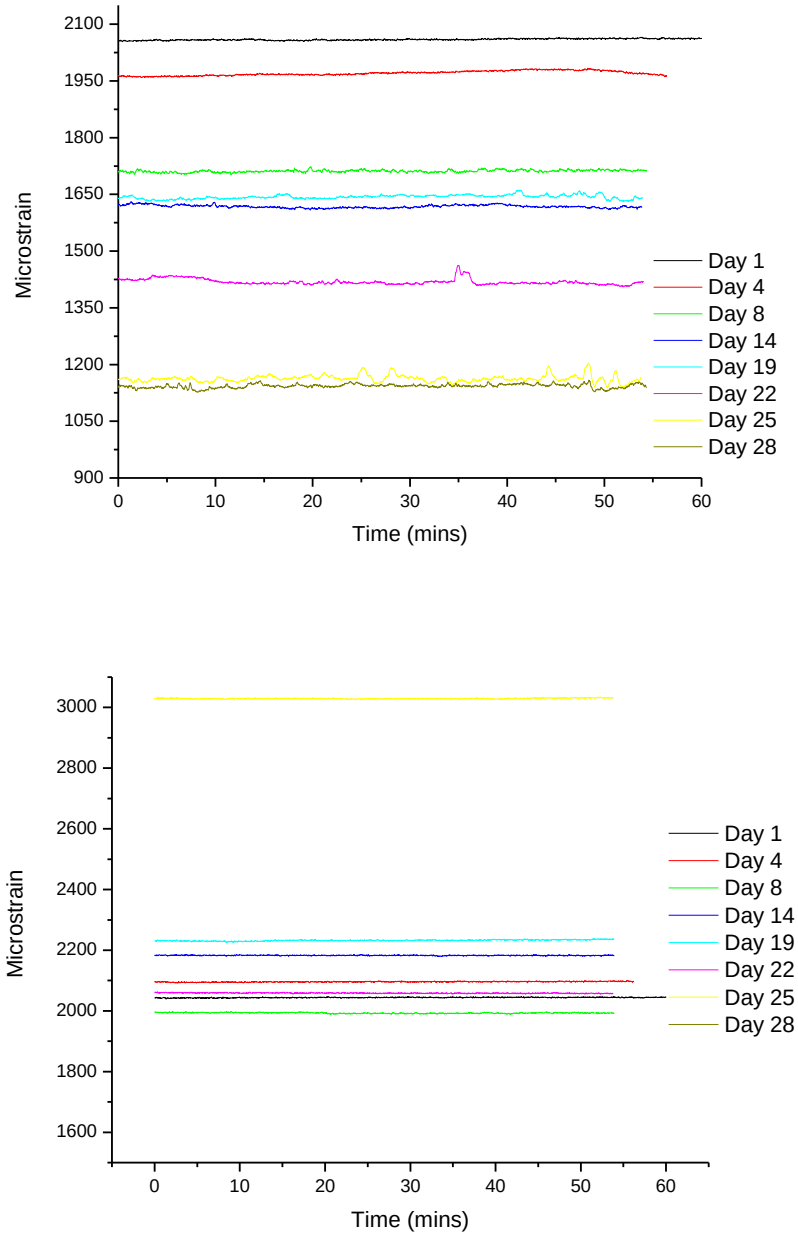


Figure 4-5. *Microstrain measurements for Nodes 1 and 2 during the 28 days of experiments.*

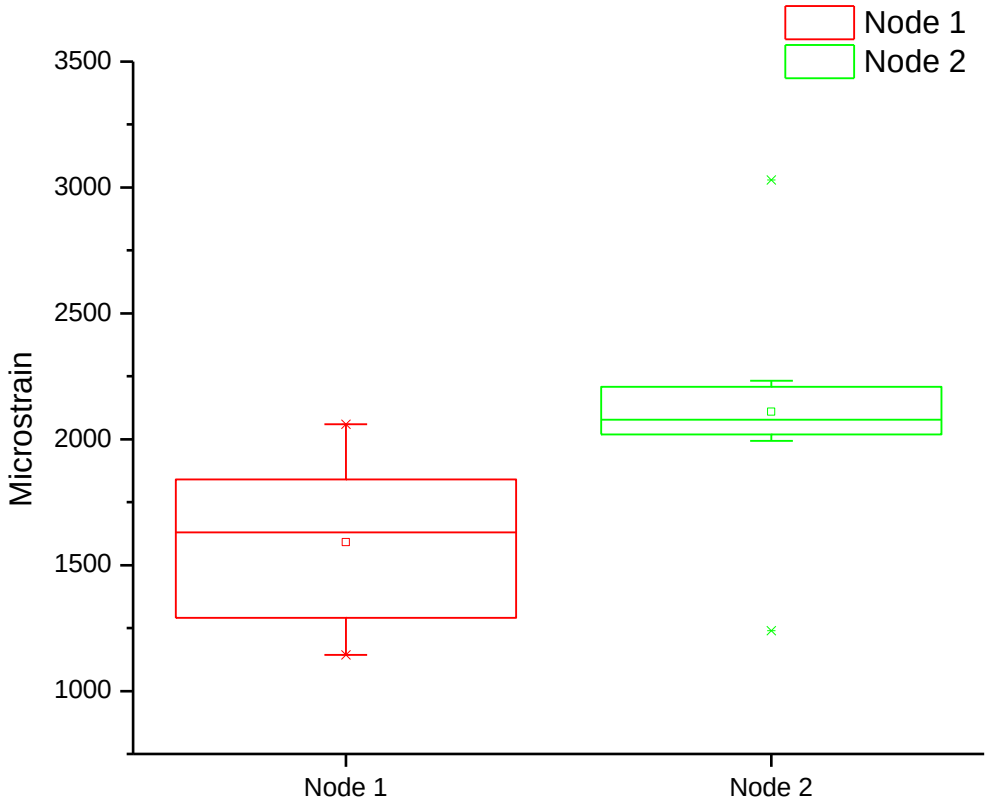


Figure 4-6. *Box charts of the nodes.*

After revision on the results of the nodes in the wireless system and by comparing the strain output of the both nodes, it is necessary to refer that there is no consistency on the results, as each nodes followed completely distinct patterns on the strain measurements. There is a very significant deviation of the microstrain values for the initial 2100 microstrain, along the 28 days of experiments. This effect is reflected by the broad range observe in the box chart, especially for the node 1.

It can be concluded that the wireless strain gauge system is collecting properly strain data and also variations of strain on the materials along the time. However, as previously pointed for the channels cases, conclusive affirmations on the reliability and precision of the nodes and the wireless system cannot be withdrawn without further experimental tests and additional analysis on other factors that might be influencing the results.

4.6. Factors affecting the results

4.6.1. Water absorption and thickness swelling

The most probable reason to explain the unstable strain results along the time, lies on the water absorption and thickness swelling effects commonly experienced by fiber-reinforced plastics composites when in contact with liquids or moisture for a long period of time. Not only the polymeric matrix, but also the reinforcing fibers are able to absorb moisture. This hydrophilic nature of the fibers that are sensitive towards water absorption can cause instability in the properties of the material along the time. There are three distinct mechanisms [73] that conduct the moisture penetration into composites materials, which are described as following:

- diffusion of water molecules into the micro gaps between polymer chains, which is the main mechanism,
- capillary transport into the gaps and flaws at the interfaces between fibers and polymer, due to incomplete wet ability and impregnation, and
- transport by micro cracks in the matrix, formed during the compounding process

Due to the thickness swelling of the composite material, the surface attached strain gauges on the samples might have partially debonded from the surface and contribute for the instability of the results.

4.6.2. The silicone coating and adhesive influence

The thickness of the silicone coatings might also have affected the experiments. If the layer silicone polymer protecting the strain gauges from the sweater is not thick enough, the water can penetrate until the gauges. Due to the highly corrosive properties of the seawater, a minimal contact with the strain gauges is enough to damage them. Additionally, the existence of air bubbles on the coating can easier the penetration and diffusion of the seawater.

The epoxy adhesive used to glue the strain gauges to the material surface is another factor that can cause lack of stability in the experiments. It is known that epoxy hardens and has a brittle behaviour when it dries. Therefore, due to the constantly applied bending load along the time, the epoxy can easily break (due to its lack of flexibility) and contribute to both the debonding of the gauges and to the entrance of seawater through the coating.

5. CONCLUSIONS AND FUTURE WORK

NDT methods are crucial for composite materials as it increment the confidence level in the use of these materials in safety critical components and allow the reduction of the costs associated with their ma maintenance costs through better understanding the defects influence on residual life of structures.

This main objective of this research study consisted on the development of a new and practical strain sensing system to be used in the non-destructive analysis of the fiber-reinforced plastic composites quality assurance and health monitoring. A wireless strain gauge system which is a combination of WSN technology with the commonly used foil resistance strain gauge sensors was specifically designed to attend the requirements of an adequate, practical and cost effective strain sensing technique.

Strain sensing tests, simulating a marine harsh environment (using seawaterwater) were performed in which carbon fiber/epoxy composites with attached strain gauges were immersed for a period of 28 days, being subjected to a constant bending strain. The experiments consisted of simultaneous measurements using a conventional wired gauge system and the new wireless strain gauge system. Based on the results of the tests performed by the systems, it has been demonstrated that the wireless gauge setup is capable of detecting and providing strain information for composite materials as well as evaluating the strain variations occurring along the time. Therefore, it can be said that the principal goal of developing a new strain sensing system for the non-destructive testing for the study of fiber-reinforced composites was fulfilled, as the wireless gauge system has ability to collected strains values and it can be used a beneficial method on the prediction of the residual life-time, detection of defects and/or damages and on the structural condition of composites materials.

However, the strain values were unstable along the experimental time. The exact factors causing the lack of constancy in the results are not well identified. Some options are the water absorption and swelling of the composite that might have unglued the gauges form the surface, or the entrance and contact of seawater with the gauges due to the not enough thickness of the silicone coating (or existence of air bubbles on it) or even because of the brittle properties of the epoxy adhesive. The contact of strain gauges with the corrosive seawater can easily damage the gauges. Therefore, the reliability and the accuracy of the wireless gauge system cannot be concluded so far.

Certainly, further tests and research need to be carried out focusing on understanding the behaviour and precision of this new strain sensing system. An

alternative methodology to continue this study can be done by incorporating both wireless and wired system connected to strain gauges in the same sample material, rather than separating each system to study distinct samples, as it has been done so far. This new approach could be valuable in order to make an easier comparison on the results of the both systems and allow some conclusions on the reliability of the wireless gauge system.

The influence of water absorption and thickness swelling experienced by fiber-reinforced plastics composites when in contact with liquids or in humid environments for a long period of time need to be addressed. Tests to observe the influence of the development of swelling stresses must be conducted. Additional tests simulating different service conditions are also crucial to be performed. The study on the effects of different working environments (such as dry conditions, and tests involving temperature and humidity variations and different loads) and how these parameters influence on the results of the wireless gauge system is important as it can broaden the applicability of the system into several different industries and applications.

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APPENDIX A: STRAIN GAUGE DESIGNATION SYSTEM

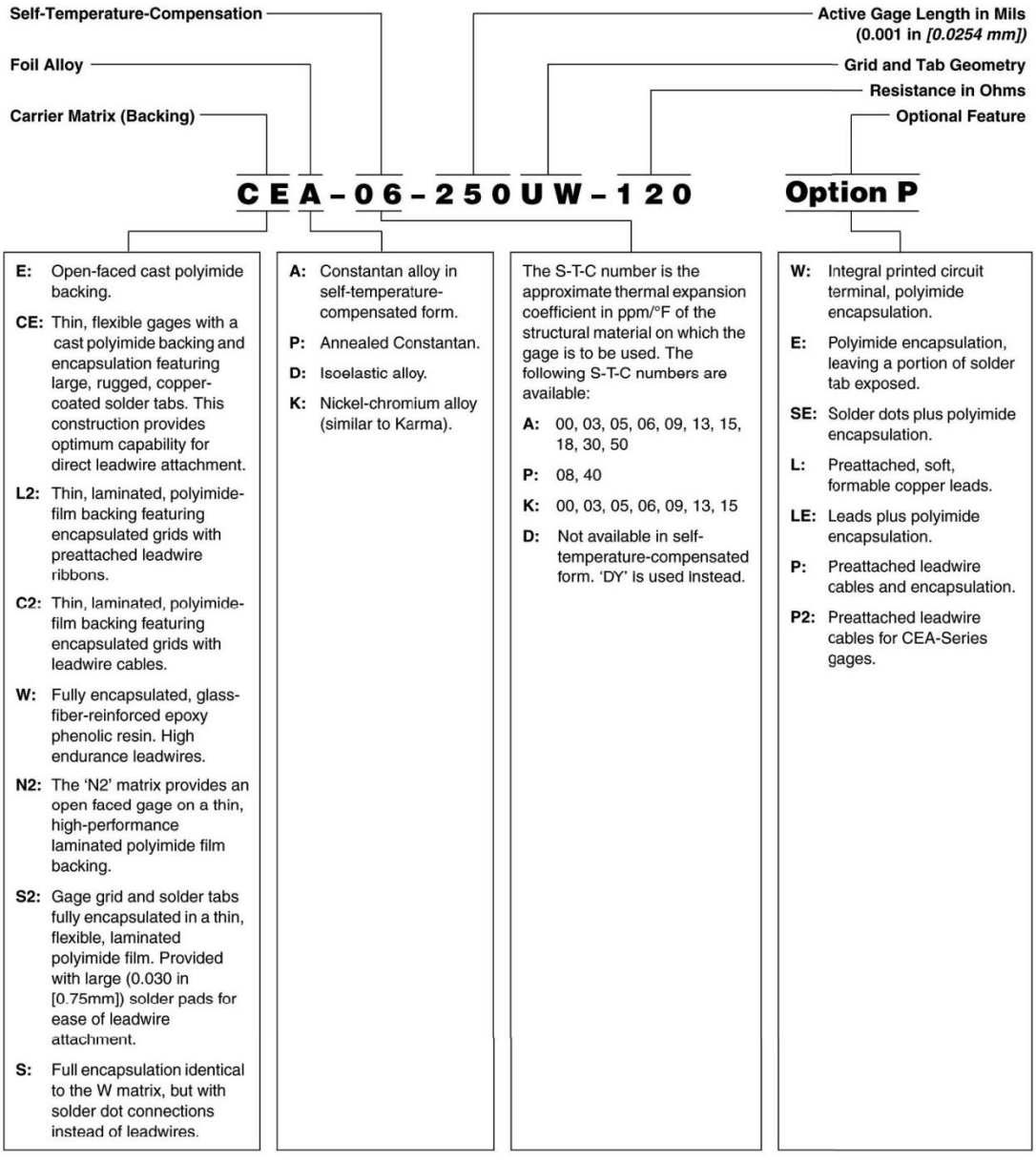
Designation System

Vishay Micro-Measurements

VISHAY PRECISION GROUP

Stress Analysis Gages

The Strain Gage Designation System described below applies to Vishay Micro-Measurements General-Use Strain Gages.



APPENDIX B: STRAIN GAUGE C2A-06-125LW-350

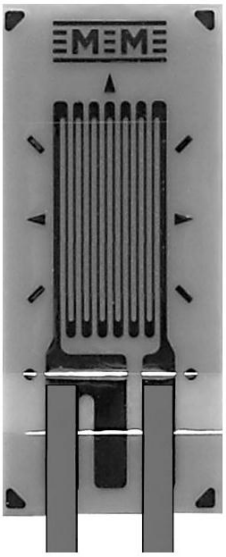
VISHAY PRECISION GROUP

125LW

Micro-Measurements

General Purpose Strain Gages - Linear Pattern

GAGE PATTERN DATA



actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS)	OPTIONS AVAILABLE
L2A-XX-125LW-120 L2A-XX-125LW-350 C2A-XX-125LW-120 C2A-XX-125LW-350	120 ± 0.6% 350 ± 0.6% 120 ± 0.6% 350 ± 0.6%	

DESCRIPTION

Widely used general-purpose gage.

Pb-free RoHS COMPLIANT

GAGE DIMENSIONS

Legend: ES = Each Section, S = Section (S1 = Sec 1), CP = Complete Pattern, M = Matrix

inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.125	0.238	0.070	0.080	0.315	0.170
3.18	6.05	1.78	2.03	8.00	4.32

GAGE SERIES DATA See Gage Series data sheet for complete specifications.

Series	Description	Strain Range	Temperature Range
L2A	Encapsulated constantan gages with preattached ribbon leads.	±3%	−100° to +250°F [−75° to +120°C]
C2A	Encapsulated constantan gages with preattached ready-to-use cables.	±3%	−60° to +180°F [−50° to +80°C]

Example of an L2A Construction

Example of a C2A Construction

Note 1: Insert desired S-T-C number in spaces marked XX.

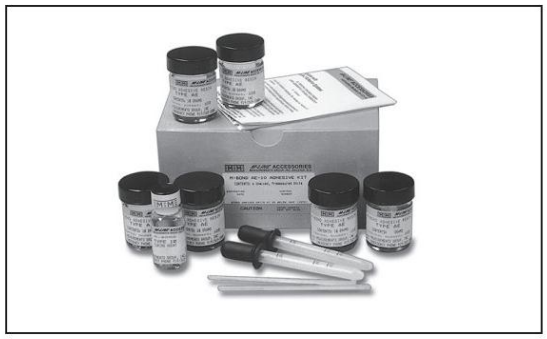
APPENDIX C: ADHESIVE SYSTEM

VISHAY

M-Bond AE-10

Vishay Micro-Measurements

Strain Gage Adhesive



OTHER ACCESSORIES USED IN AN M-BOND AE-10 INSTALLATION:

- CSM Degreaser or GC-6 Isopropyl Alcohol
- Silicon-Carbide Paper
- M-Prep Conditioner A
- M-Prep Neutralizer 5A
- GSP-1 Gauze Sponges
- CSP-1 Cotton Applicators
- PCT-2A Cellophane Tape
- HSC Spring Clamp
- GT-14 Pressure Pads and Backup Plates

DESCRIPTION

Two-component, 100%-solids epoxy system for general-purpose stress analysis. Transparent, medium viscosity. Cure time as low as six hours at +75°F [+24°C] may be used. Elevated-temperature postcure is recommended for maximum stability, and/or tests above room temperature. Highly resistant to moisture and most chemicals, particularly when postcured. For maximum elongation, bonding surface must be roughened. Cryogenic applications require very thin gluelines.

CHARACTERISTICS

Operating Temperature Range:
Long Term: –320° to +200°F [–195° to +95°C].

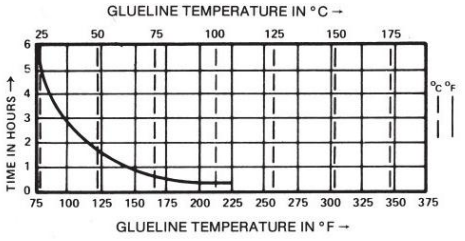
Elongation Capabilities:
1% at –320°F [–195°C];
6% to 10% at +75°F [+24°C];
15% at +200°F [+95°C].

Shelf Life:
12 months at +75°F [+24°C]; 18 months at +20°F [–7°C]. If crystals form in resin jar, heat to +120°F [+50°C] for 30 minutes. Cool before mixing.

Pot Life:
15 to 20 minutes at +75°F [+24°C]. Can be extended by cooling jar or by spreading adhesive on clean aluminum plate.

Clamping Pressure:
5 to 20 psi [35 to 140 kN/m^2].

Cure Requirements:
Preferred Room-Temperature Cure: 24-48 hours at +75°F [+24°C].
Recommended Postcure: 2 hours at 25°F [15°C] above maximum operating temperature.



PACKAGING

Kit:
6 mixing jars [10 g ea] Resin
1 bottle [15 ml] Curing Agent 10
6 calibrated pipettes
6 stirring rods

Bulk:
200 g Resin
40 g Curing Agent 10
3 calibrated pipettes

References: Instruction Bulletin B-137, "Strain Gage Applications with M-Bond AE-10, AE-15, and GA-2 Adhesive Systems", included in each kit.