Health Monitoring of a Large Composite Structure

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ABSTRACT

The present paper describes the development of smart composite plates and a practical application of optical fibre strain sensor technology in the marine industry environment.

The recent advances in fibre optical sensing technique and its intrinsic characteristics allow the health monitoring of structures in real time, giving data about its mechanical behaviour under normal function conditions.

The set-up consists in one optical fibre, with three Bragg grating sensors, embedded between layers of a thin composite laminate, in manner to shape a gage 45 degrees gage rosette. Those smart composite plates are calibrated in laboratory before practical application in the boat structure.

A sensor network can be created with several composite plates bonded in each side of the hull, positioned at locations with high loads due to sea environment.

The health monitoring show the results in simple and quick real-time concerned to performance evaluation, optimization of manufacture process and failure analysis of the boat structure.

1. INTRODUCTION

The information available about conventional materials are very extensive, this allows the optimization of projects in the marine industry. However the composite materials have been studied in the last few years but it still remain some gaps of dynamic performance about big dimension composite structures like large dimension boats.

The need to understand the behavior of this kind of composite structure lead to the integration of a network sensors that give real-time data about the state of the structure in service.

Optical fiber sensors, specially the Bragg sensors, have been implemented in composite structures due to a large of advantages like: small dimensions, possibility to measure temperature and loads in controlled areas, be embedded between layers of composite laminates without no damage for the host material. These sensors are immune to the influence of electromagnetic fields and electric isolation.

A fiber Bragg grating (FBG) is a periodic modulation of the refractive index of the core of a single mode optical fiber, observed by exposure of UV light exposure in a spectral region around 1544-1548 nm. This fabrication process is based on a photosensitive mechanism, which is observed in Ge-doped optical fibers. When a broadband light is traveling through the fiber, the grating promotes the back reflection of the wavelength band. Therefore when is applied a mechanical axial load to the Bragg sensor, the FBG central wavelength will vary with the change of these parameters experienced by the fiber and the corresponding wavelength shifts.

The figure 1, shows the dependency of the wavelength and strain, it is possible to observe the linearity of the Bragg sensors and the wavelength spectrum.

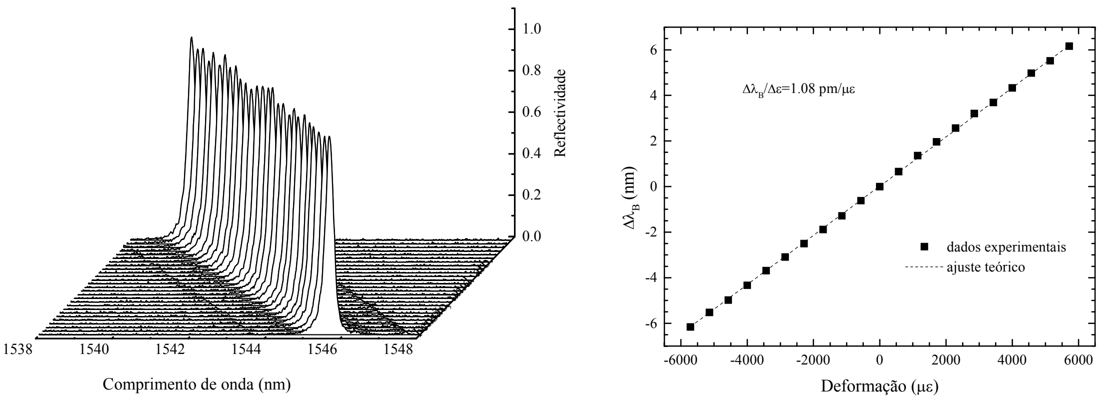


Fig. 1. Wavelength spectrum and theoretical behavior of sensor Bragg strain versus wavelength.

The purpose of this work is to develop smart composite plates to health monitoring a boat structure in real time, giving data about its mechanical behaviour under normal function conditions. This information can be used to evaluate the structure performance, optimize the manufacture process and identified cracking and failures in the composite structure, so that damage can be avoided.

Nowadays this new technology based on optic systems turn to be very helpful to reduce manufacture costs and improve the performance on marine construction.

2. SMART PLATES PRODUCTION

The sensing technique used to monitor the boat structure is composed by several composite plates in which is embedded one single optical fiber with three Bragg grating sensors with the shape of a rosette. The smart plate measure the local stress distribution in three principal directions, 0º, 45º and 90º. Figure 2, shows the set-up of the optical fiber embedded in the laminate.

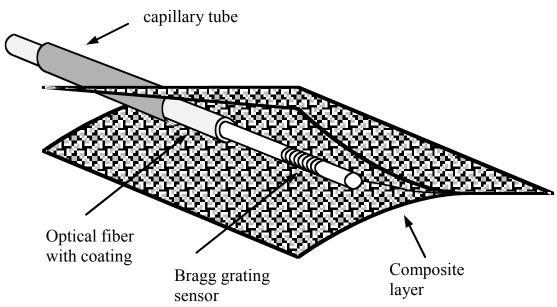


Fig. 2. Set-up of the optical fiber embedded in the laminate.

The smart plates are constitute by the following elements:

- Two layers of carbon/epoxy twill prepreg;
- One optical fiber with three Bragg sensors;
- Dimension: 200*300 mm.

It is possible to observe, in figure 3, the geometry of the optical fiber rosette, this geometry turn to be the most efficient, easily and quickly to manufacture. The end of the laminate is a fragile point between the laminate and the optical fiber, so is necessary to protect this with a metal capillary tube.

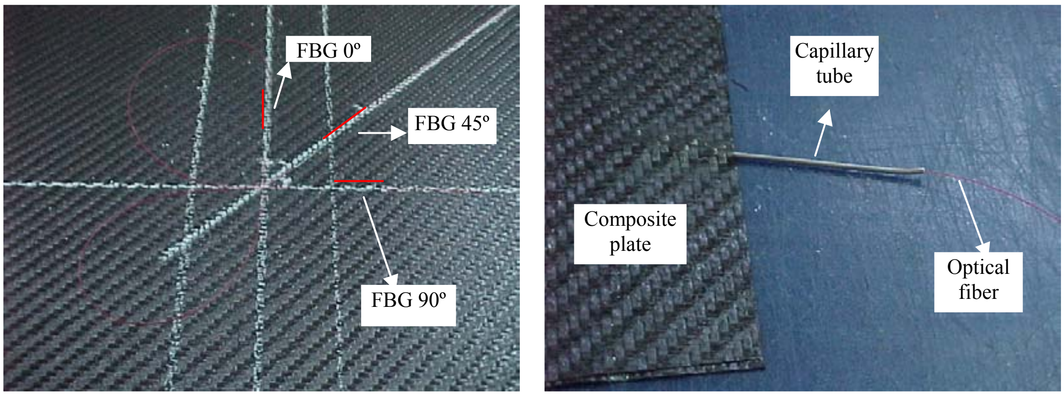


Fig. 3. Rosette configuration in the laminate and visual aspect of the capillary tube in the end of smart plate.

The study of the rosette configuration show that the security curve of the optical fiber is approximately 20 mm, otherwise it can appear some problems in the answer of the optical system, due to the lost of signal. The plate is sealed in vacuum bag and cured in an autoclave at the temperature of 140 ºC during 1 hour and 2 bar of pressure, shown in figure 4.

Fig. 4. Vacuum bag and cure cycle in the autoclave.

3. SENSOR BRAGG THEORETICAL CALCULATIONS

The transduction mechanism in these types of sensor is based on relating the changes in the wavelength of light to the measured of interest, i.e. strain, is presented a resumed way to calculate strain.
The strain coefficient at constant temperature is giving by:

$$\frac{1}{\lambda_B} \times \frac{\delta\lambda_B}{\delta\varepsilon} = 0.78\times10^{-6}\ \mu\varepsilon^{-1}$$

$$\boldsymbol{\delta\varepsilon} = \frac{\delta\lambda_B}{\lambda_B \times 0.78 \times 10^{-6}}$$

δε – Strain (micron)
λ_B – Bragg Grating Sensor Wavelenght,1550 nm
$\delta\lambda_B$ – Difference between **λ_B** and the sensor reflection signal (nm)

4. LABORATORY TESTES OF THE SMART PLATES

After production, the smart plates were connected to the optical system to verify the wavelength spectrum and tested in laboratory for callibration.

An electric rosette gage were bonded in the plate to compare the results with the optic rosette. The tensile tests were performed in a Universal INSTRON, model 4208. The plate was fixed with clamps to the load cell, and it was applied loads by steps.

Figure 5, presents the smart plate prepared to be tested with clamp zones, electrical rosette bonded in the center exterior surface of the laminate.

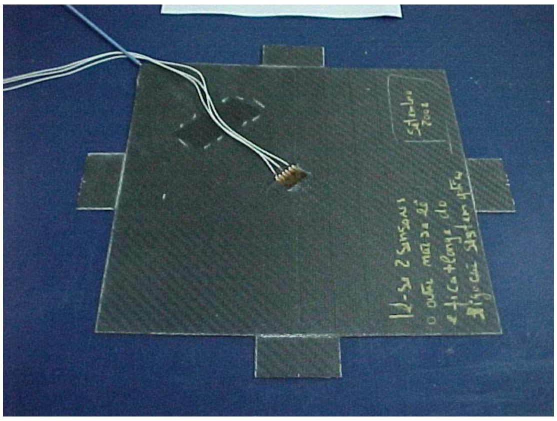


Fig. 5. Smart plate prepared to be tested in the laboratory.

To assure that the optical rosette measure properly it was prepared four types of smart plates, with the same dimensions 250*300 mm, to be tested:

Plate 1

- Two layers of carbon/epoxy prepreg, Twill 2/2;
- One optical fiber with three Bragg sensors (rosette);
- One electric rosette.

Plate 2

- Two layers of carbon/epoxy prepreg, Twill 2/2;
- One optical sensor, direction 0º;
- One electric unidirectional gage, direction 0º.

Plate 3

- Two layers of carbon/epoxy prepreg, Twill 2/2;
- One optical sensor, direction 90º;
- One electric unidirectional gage, direction 90º.

Plate 4

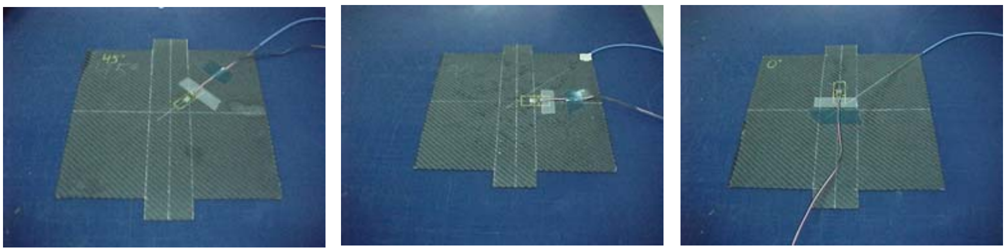
- Two layers of carbon/epoxy prepreg, Twill 2/2;
- One optical sensor, direction 45º;
- One electric unidirectional gage, direction 45º.

The results obtained by the electrical rosette are used as a reference to be compared with the optical strain results.

Otherwise it is important to understand if the use of the optical rosette have some influence in the measure of strain. The plates with one sensor (plate 2,3,4), was tested at the same conditions and the results compared with the optical rosette.

The grating of the optical Bragg sensor is coated with a polymeric coating to decrease the risk of fracture.

The figure 6, shows the plates with unidirectional sensors in the 45º, 90º and 0º direction.

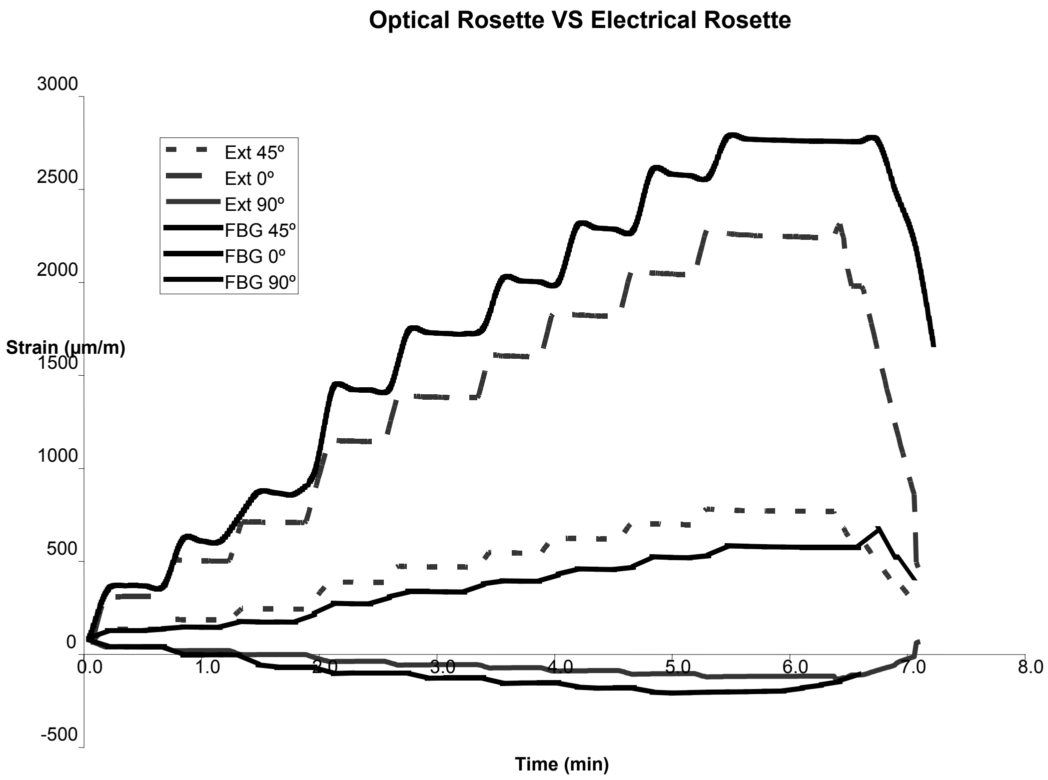


Sensors at 45º Sensors at 90º Sensors at 0º

Fig. 6. Smart carbon plates with unidirectional optical and electric sensors, at 45º, 90º and 0º directions.

5. DISCUSSON OF THE LABORATORY RESULTS

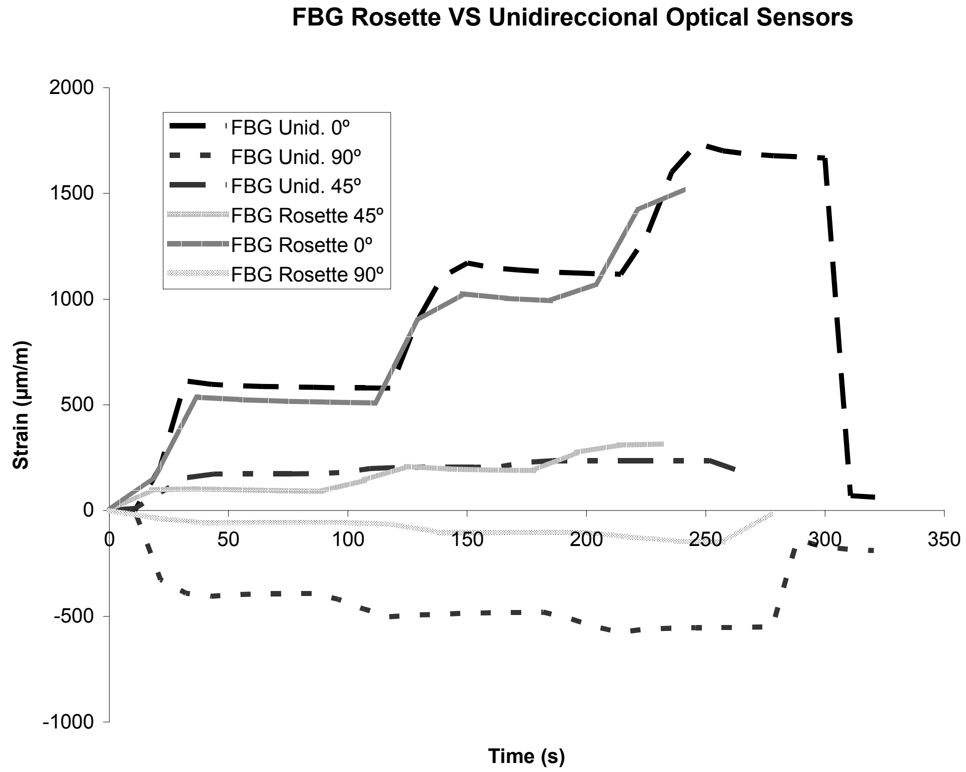
The graphic 1, presents the results obtained with the optical rosette and the electric rosette gage, the plate was loaded in random steps.



Graphic 1. Performance of optical sensing rosette and electric rosette.

The two sensing systems present comparable results, both had the same response to the applied load. In the 0º direction the strain measured in the optical sensor was bigger than the electric gage. In the other two directions (90º and 45º), this behavior change and the electric system present higher values of strain.

The graphic 2, presents the optical sensing rosette results and the unidireccional optical sensor. In this experiment the applied loads in the tensile tests were different from the experiment above.
All the plates had the same test conditions in order to have comparison of results.



Graphic 2. Performance of optical sensing rosette and unidireccional optical sensors.

The reflective signal obtained by the optical rosette and the unidireccional optical sensors show the same behavior for the 0º and 45º direction. However in the 90º direction, where the fiber is submitted to compressive loads, present different results. This could happen because the original conditions of stress in the unidireccional sensor in the direction 90º wasn't properly adjusted in the set up of the test equipment..

6. LABORATORY TESTS CONCLUSIONS

The optical Bragg sensor rosette was produced and tested in the laboratory presenting a good performance and prove that can be used instead of conventional electrical gages. Therefore, after this laboratory experiences the behavior of the smart plates are well known and now can be bonded in the boat. The smart plates can be applied for health monitoring in real time of composite structures giving data about the strain distribution that happens in normal service conditions.

7. EXPERIMENTAL SET-UP IN THE BOAT STRUCTURE

The fishing boat used for health monitoring has 24 m length and 12 m high. The thickness is variable being the highest 100 mm at the bottom and 45 mm on top. The materials constructions are essentially glass fibre/polyester resin. It is important to put the smart plates in strategic points to give results of the behavior of all structure under normal service conditions. The smart plates, 200X300 mm^2, with the optical rosette were similar to the plates used in laboratory experiments. The painting was removed from the surface of the hull with a grinder and cleaned with a solvent. The bonding adhesive used was Spabond 720 from SP Systems, epoxy based with faster cure. The bonding was assisted with vacuum. The good adhesion between the surfaces allows efficient transfer of the loads from the hull to the smart plate.

The system proposed and developed for monitoring the boat structure in service, is presented in Figure 7. The optical system were constituted by two smart plates located at port aft and forward, and two smart plates starboard forward and aft.

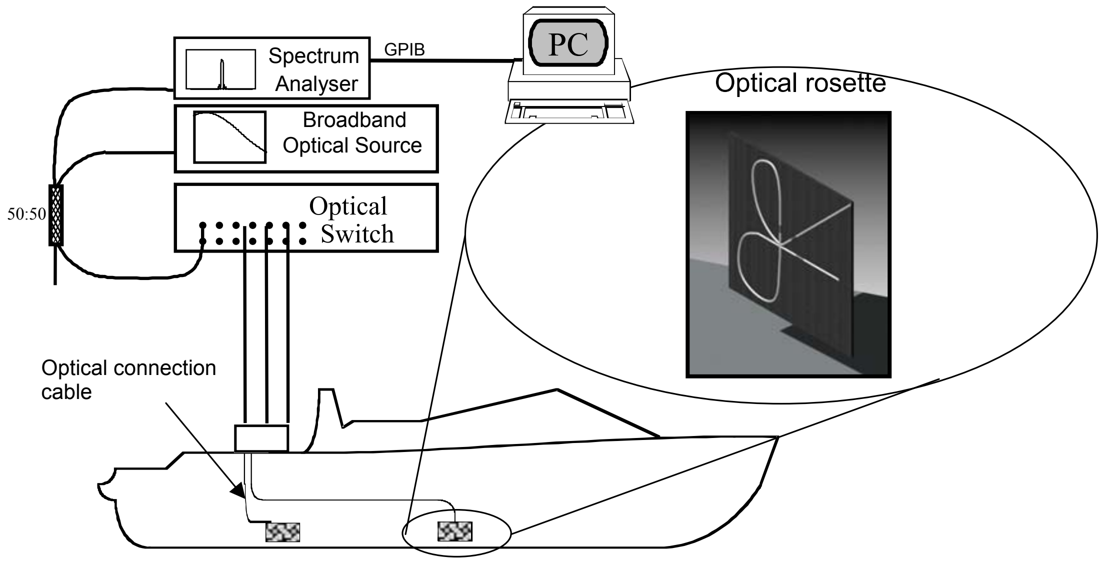


Fig. 7. Set-up of the sensing network and location of the smart plates in the boat.

8. RESULTS OF THE HEALTH MONITORING ON THE BOAT

The optical system was located in the cabins. The optical cables connected to the smart plates were directed through the ventilation ducts. The strain was measured since the boat left the port till it returns three hours later.

Figure 8, presents the graphic of results showing the performance in the port forward of the hull. It is possible to observe the strain in FBG sensors and the strain in the principal directions calculated through the results of FBG sensors. At the beginning FBG (0º) sensor shows compressive loads and after 30 minutes turned to tensile loads. FBG (45º) and FBG (90º) sensors present only compressive loads.

In Figure 9, the graphic of results show the performance in the port aft of the hull. It is possible to view the strain in FBG sensors and the strain in the principal directions. The strain in this part of the hull is bigger than in the port forward.

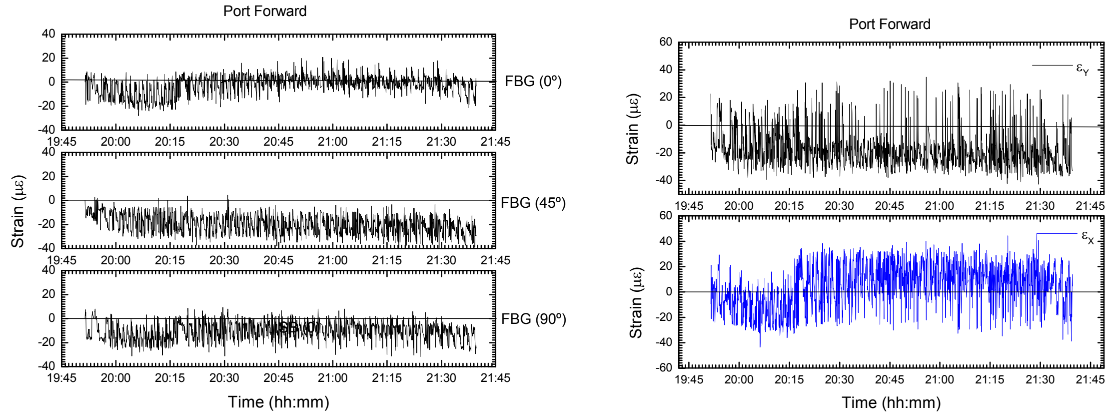


Fig. 8. Smart plate located at Port Forward. Results of the optical rosette and calculation of the strain in the main directions.

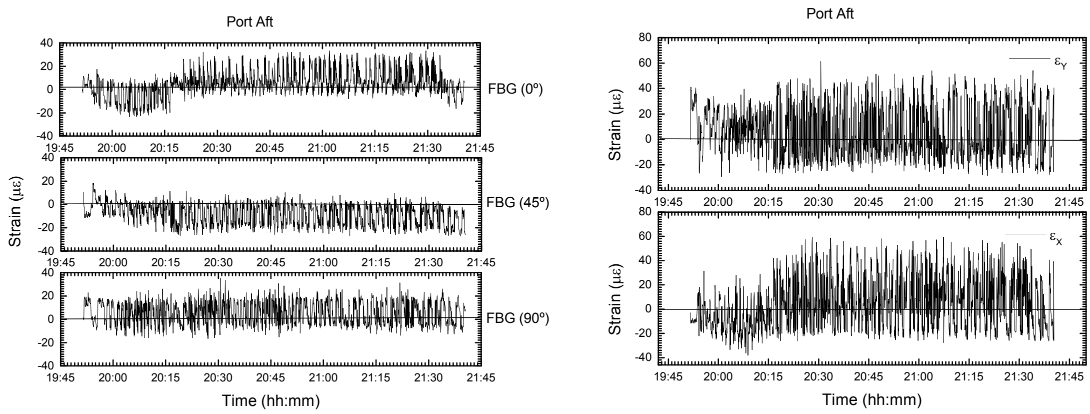


Fig. 9. Smart plate located at Port Aft. Results of optical rosette and calculations of the strain in the main directions.

9. DISCUSSION OF RESULTS

The analysis of graphic results demonstrate that strain in the principal directions are bigger at port aft (-20 e -40µm) than port forward (-20 e -20µm). Hence the strain in the principal directions are also bigger at port aft (-20 e -40µm) than starboard aft
(-20 e -20µm). Even the strains are low, due to the high thickness of the hull, it is possible to observe that the loads are different at the port and starboard. This is explained by the sea slamming on the hull. The research work demonstrate that the health monitoring in real time with the smart plates was possible and the data obtained is useful to optimize the hull structure.

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