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# FIBER-OPTIC SENSING IN THE AMERICA'S CUP – The 2010 Deed of Gift Match

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## SUMMARY

At Team Alinghi, the Swiss 2010 Deed of Gift Match Defender, an advanced fiber-optic sensing system was designed and integrated in the high-tech composite structures for monitoring strains and loads with a live feed to on-board crew and "pit-lane" engineers on chase boats. The objective of realizing lightweight structures and the unknowns about both quasi-static and dynamic load cases explain the need of real-time monitoring to ensure the safety of the yacht and the sailors. Team Alinghi adopted the fiber Bragg grating optical sensors as a main tool to monitor the yacht "health". This paper presents the fiber optic system while describing overall objectives and challenges.

## 1. INTRODUCTION

A Deed of Gift Match in the America's Cup is synonymous of a "non-friendly" competition between Defender and Challenger for which an agreement on the Rules has not been found and therefore the only governing document is the 1851 Deed of Gift (the paper *creating* the America's Cup) under which no particular restriction is applied on the racing yacht size except on the length. It is therefore clear that all competing teams try to design and build the fastest yacht within the given length and that such yacht is typically, nowadays, a multihull (Figure 1 – courtesy Alinghi/Carlo Borlenghi).


Figure 1 [AL5 catamaran]

In order to give shape to the naval architect's ideas, structural and composite engineers are faced with the non-common task of predicting loads and deflections of a racing machine never seen before, sailing in a weather pattern not always known. The strength, stiffness and weight of the complex composite elements that make up the yacht structure are key factors to come up with a winning design. Hence, in order to calibrate the sophisticated simulation tools with real-life data and to understand how the effects of the environment and sailing loads affect the performance and the safety of the boat and her sailors, it was necessary to perform on-line, real-time structural health monitoring on key points of the 115' catamaran structure.

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The Alinghi design team chose a combination of electronic sensors and optical fiber Bragg grating sensors for building such measurement tool. In this paper, we present an overview of the design, installation and operation of the fiber-optic system used by Team Alinghi to monitor the behavior of its composite sailing catamaran during testing as well as in racing conditions.

## 2. THE FIBER-OPTIC YACHT MONITORING SYSTEM

For the 33th America's Cup deed of Gift Match in 2010, Team Alinghi designed a catamaran with an overall length of 40 meters, a beam of about 20 meters and a weight of about 10 tons. A wing mast 65 meters tall was supporting the sails powering the yacht. The two hulls, the two cross-beams, a bowsprit, two diagonal aft tubes made up the huge platform (Figure 2), with solid carbon rod cables stabilizing and stiffening the cross-structures. Rudders and curved dagger boards completed the package.

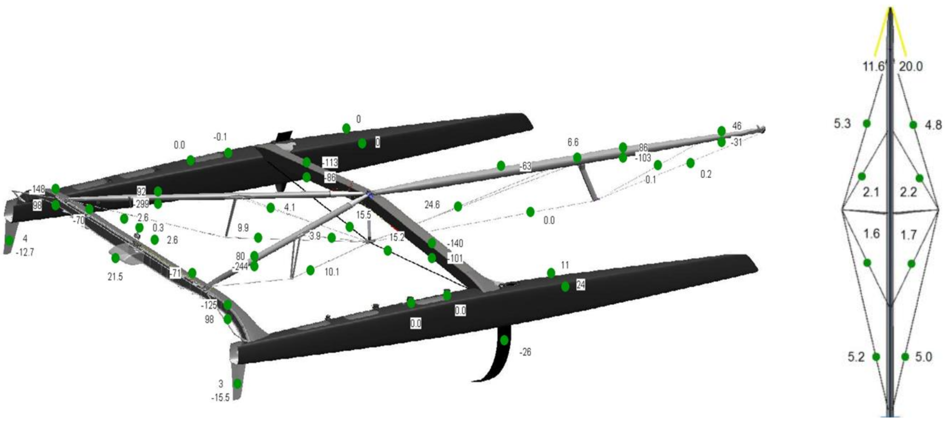

Figure 2 [AL5 platform & rig monitoring system lay-out]

Even though finite-element analysis (FEA) was used to model the stresses in key components, the real-life and ultimate load cases were hard to define as they resulted from unique combinations of winds acting on the sails and hydrodynamic forces on the appendages and hulls. In addition, the dynamic behavior was even harder to predict, and having real-time measurements of the effect of the loads on the structure was of great value and a major safety tool. Hence, a fiber-optic monitoring system was used to monitor the overall mechanical behavior of the Alinghi 5 (AL5) catamaran during the sailing sessions and to prevent overloading conditions (Figure 2 – pictures not in scale). Measuring on-line strains on the boat allowed for the detection of unexpected damage and for alerting about excessive loads, as well as for the validation of the yacht's VPP models and expected performance. Information gathered from the monitoring system was also used for mapping follow-up inspections based on conventional NDT methods.

The fiber-optic monitoring system measured strains and loads around the yacht at an acquisition rate of 10Hz. Fiber Bragg grating strain sensors were used since a compact, low-weight, reliable and rugged sensing system was required. Such optical fiber strain gauges, due their small size and flexibility, are ideally suited for material embedding or surface mounting onto the composite parts of the yacht. In addition, shape of the spars and appendages could be computed real-time by using the discrete strain measurements.

## 3. STRAIN & LOADS MEASUREMENTS

Over the last few years, optical fiber sensors have seen increased acceptance and widespread use for structural sensing and health monitoring applications in composites, civil engineering, aerospace, marine, oil & gas, and smart structures. In particular, fiber Bragg grating (FBG) strain sensors have been used extensively in a variety of structural health monitoring applications, due to their flexibility, light-weight and EM immunity [Krohn et al. (2015), Sigg et al. (2015)].

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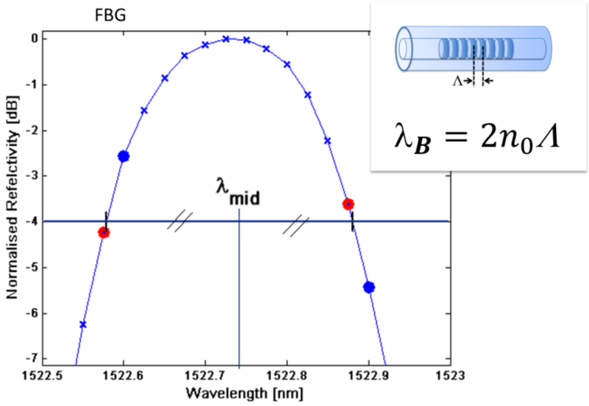


Figure 3 [FBG sensor reflection spectrum and Bragg peak wavelength tracking]

Standard Fiber Bragg grating sensors are written in telecom single-mode optical fibers over a length of 5 to 10 millimeters and selectively reflect light around their Bragg resonance wavelength $\lambda_B$, which is proportional to the core effective refractive index $n_0$ and the grating period $\Lambda$ (Figure 3).

Fiber Bragg gratings resonance wavelength shift $\Delta\lambda_B/\lambda_B$ depends on both total strain $\varepsilon_{total}$ and temperature changes $\Delta T$ according to the following equation [Yoon et al. (2006), Farahi et al. (1990)]:

$$\frac{\Delta\lambda_B}{\lambda_{B0}} = K_\varepsilon \varepsilon_{total} + K_T \Delta T$$

where $K_\varepsilon$ is the strain coefficient, $K_T$ is the temperature coefficient and $\Delta T$ is the temperature change. Total strain $\varepsilon_{total}$ is defined as the linear superposition of the bending strain $\varepsilon_{be}$, axial strain $\varepsilon_{ax}$, pure torsion strain $\gamma_{to}$, direct shear strain $\gamma_{ds}$ and thermo-mechanical strain $\boldsymbol{\varepsilon_{tm}}$:

$$\varepsilon_{total} = A(\varepsilon_{ax} + \varepsilon_{be} + \varepsilon_{tm}) + B(\gamma_{ds} + \gamma_{to})$$

where *A* and *B* depend on the orientation of the fiber-optic gage $\vartheta$ with respect to the structure under test principal axis of strain:

$$A = cos^2(\vartheta) - \ sin^2(\vartheta)$$

$$B = 1/2\ sin^2\,(2\vartheta)$$

Figure 4 schematically reports the main elements of the fiber Bragg grating monitoring system. The fiber optic strain sensors were installed on a structure and interconnected to an interrogation unit via optical cables and optical connectors. The measurements were made in reflection using an acquisition unit based on a swept laser light source, which tracks and detects the fiber Bragg gratings resonance wavelength shift $\Delta\lambda_B$. Since every sensor reflects light at a specific wavelength band, several sensors can be wavelength multiplexed on the same fiber strand, which greatly reduces weight and cabling complexity with respect to the traditional foil resistive strain gages. The strain information is coded into the fiber Bragg grating wavelength shift and thus not affected by losses or optical power dynamic changes occurring along the optical cables.

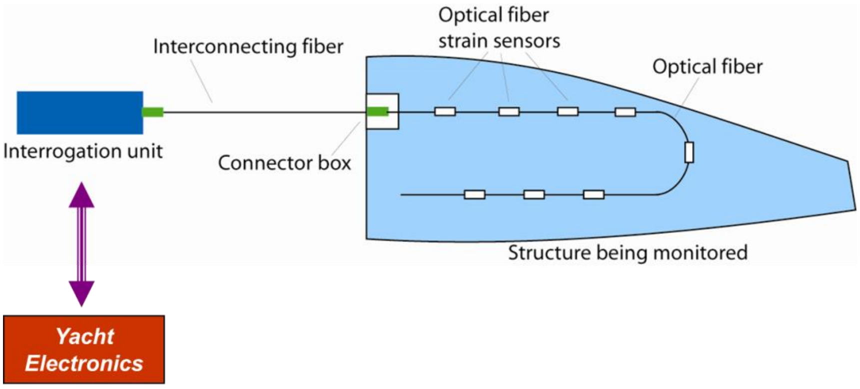


Figure 4 [Monitoring system general lay-out]

The final lay-out of the fiber-optic monitoring system for the Alinghi 5 catamaran is shown in Figure 2. Overall, nearly 160 FBG strain sensors embedded or surface-bonded onto the CFRP laminate were used to set-up the system to measure strains and loads experienced by all the main structures of the Alinghi 5 platform and rigging (hulls & beams, spars, appendages and cables).

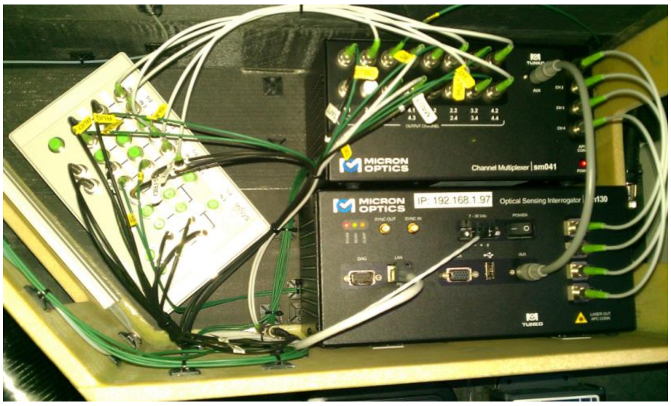


Figure 5 [Micron Optics FBG interrogation unit sm130-700 and switch cassette sm041-416]

The interrogation unit and cables distribution panel (Figure 5) was installed in the starboard hull and inter-connnected via the boat LAN to the yacht electronics where strains, loads and deflections (i.e. real-time shape changes) are processed. Data was real-time made available to both crew and engineers via the on-board telemetry system and simultaneously logged and time stamped in a SQL database for post-processing analysis.

The FBG sensor arrays were custom-designed for each part of the boat. After their production, the arrays were installed on the parts according to the specific monitoring objectives discussed with the design team, e.g. for longitudinal strain or in-plane shear strain measurement. Since the FBG sensors are sensitive to both temperature and strain [Yoon et al. (2006), Farahi et al. (1990)], strain-isolated FBGs were used to measure temperature changes and correct for apparent thermal strain components. The structural parts to be monitored were built of carbon fiber reinforced polymer (CFRP) ranging from very light sandwich panel (e.g. hulls, beams and mast shells) to massive monolithic structures for the high loaded structures (e.g. rudders, dagger boards and spars).

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Solid CFRP fiber cables were used for the under-platform and mast rigging. Several sensors installation processes were specifically developed according to the type of element to monitor taking into account each structure geometry and manufacturing process. Figure 6 reports the check-list that was used for defining a reliable installation process.

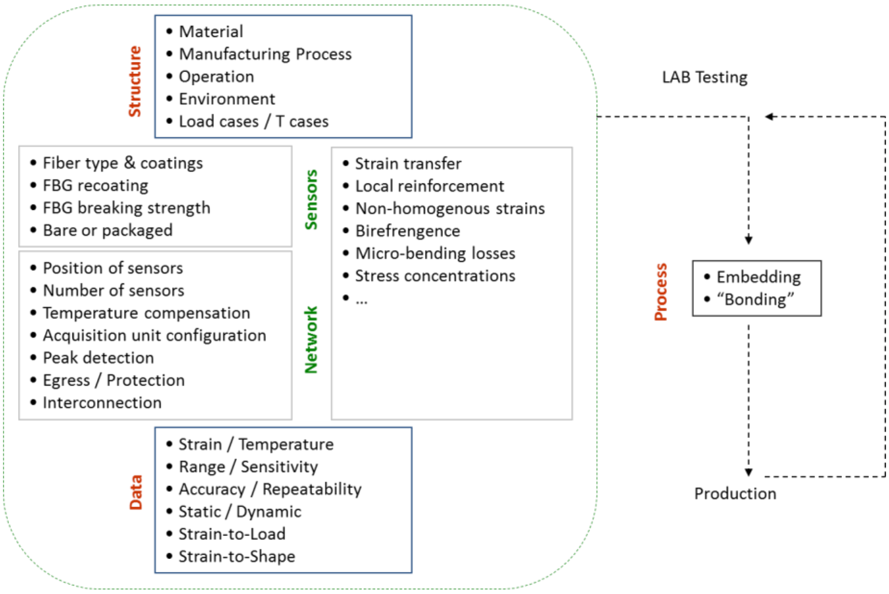


Figure 6 [FBG sensors installation process development guidelines]

### 2.1 *Pre-preg* embedding

Fiber optic sensors are so small that can be easily put in-between plies of uncured *pre-preg* (a layer of carbon fibers pre-impregnated with resin). The sensors finally result completely embedded and protected inside the composite parts. The shape and mechanical properties of the structure are not modified by the integration of the small diameter fiber-optic sensing strands. The egress point of the optical fiber from the composite also needs to be designed and engineered in order to survive to the cure cycles and the entire manufacturing process.

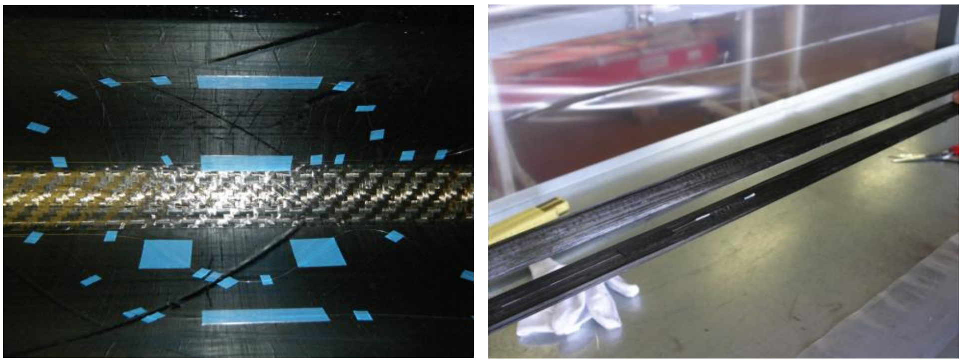

Figure 7 [Embedding FBG sensing arrays in AL5 spars (left) and rigging (right)]

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Here we report two examples of optical fiber sensors embedding in:

- the bowsprit built with *pre-preg* material, female molds and one shot autoclave curing (Figure 7 left): several fibers with several FBG sensors oriented along the longitudinal axis of the spar or at ± 45 degrees are laid down prior to the vacuum bagging and curing phases
- a carbon rod made of *pre-preg* (Figure 7 right): an optical fiber array with two FBG sensors is laid down and aligned with the unidirectional carbon fibers; the first FBG is directly in contact with the *pre-preg* material for measuring strain while the second one is inserted in a plastic tube for measuring temperature changes only; the tensile load on the cable is obtained from the measured axial strains by using the theoretical EA of the CFRP cable or by a load calibration on a test bench

**2.2 Surface bonding & post-embedding**

Fiber sensors can be also installed on the surface of the cured laminate, as we would normally do with a traditional foil strain gauge. On top of the bare fibers and sensors, a few plies of thin woven fabric can be laminated with a wet lay-up process to mechanically protect the fiber optic cables and sensors against the elements (Figure 8 left). Similarly, for some structures like the appendages, small U-grooves were made on the structure surface and the fiber sensing arrays were bonded at the bottom of the U-groove. The tiny groove was finally filled with epoxy without affecting the final shape of the composite part (Figure 8 right).

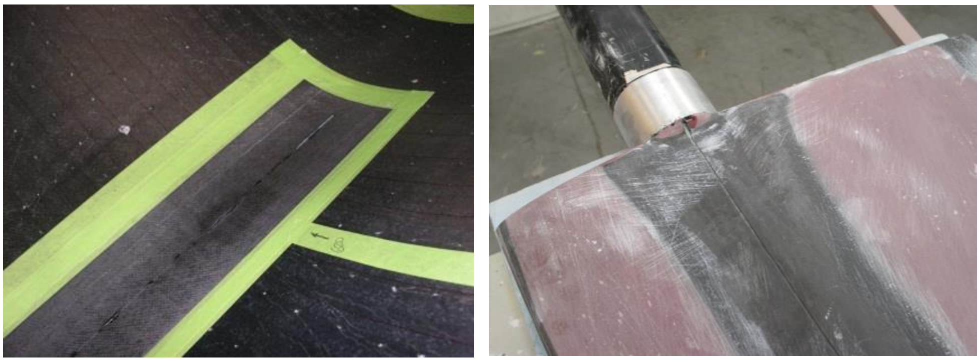

Figure 8 [Sensors installation onto solid CFRP structures: beams surface (left) and in U-groove for appendages (right)]

A major advantage of the fiber-optic sensing technology is that the sensors readings can be used throughout the entire lifetime of the structure: to monitor the manufacturing process (e.g. curing process in autoclave and residual stresses), to perform bench load testing (Figure 9 left: the Alinghi 5 boards testing set-up is shown; boards were structurally tested to full sailing loads and at the same time strains to bending moments calibration was performed) and finally to measure sailing and racing loads (Figure 9 right: mast tube fore-aft and lateral bending strains at a specific cross section are displayed as a function of time and sailing True Wind Angle readings).

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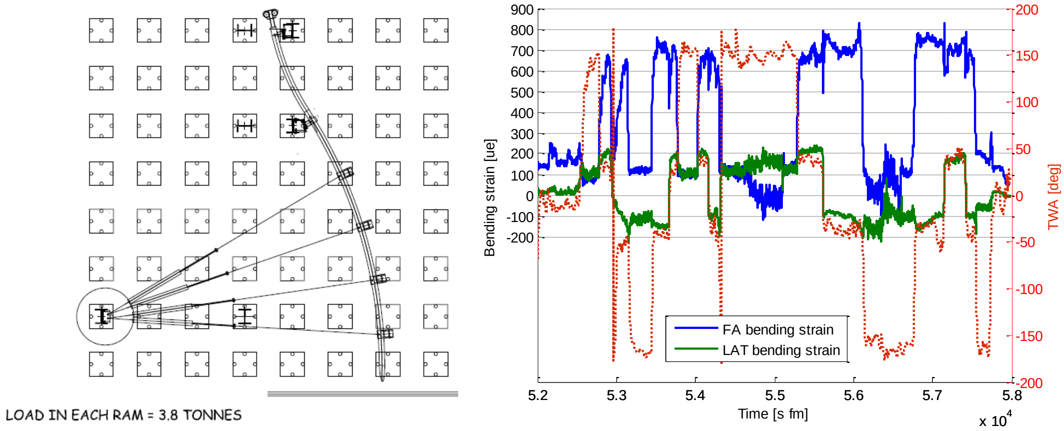


Figure 9 [AL5 boards load testing set-up (left) and mast tube bending strains during sailing (right)]

## 4. SHAPE MEASUREMENTS

By designing the network of strain sensors in order to be able to decompose the measured total strains into bending and pure torsion components, both deflections and angles of twist were computed for spars and appendages.

### 4.1 Measuring Deflections

The shape monitoring of the mast tube is taken as an example to describe our strain-to-shape methodology. FBG strain sensors positioned at several cross-sections and measuring longitudinal total strain at the sides and at the front of the spar (red and blue dots in Figure 10) are used to decompose measured total strains into fore-aft bending strain $\varepsilon_{be}^{FA}$ and lateral bending strain $\varepsilon_{be}^{LAT}$.

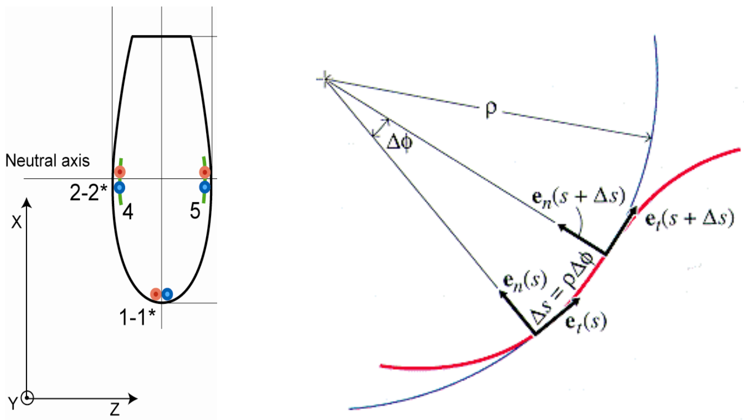


Figure 10 [Strain sensors lay-out at one cross section of the Alinghi 5 mast tube (left); shape reconstruction process (right)]

Local curvature $k$ (defined as the reciprocal of the radius of curvature) is computed by using the fore-aft or lateral bending strain $\varepsilon_{be}$ value and the distance of the sensor from the neutral axis $d_{NA}$ at every instrumented cross section:

$$k = \frac{\varepsilon_{be}}{d_{NA}}$$

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Once the local curvature at the instrumented cross sections is obtained, interpolation is performed along the entire length of the structure to obtain the curvature $k = k(y)$ as a function of the longitudinal axis $y$. Finally the deflections as a function of the longitudinal axis of the structure are numerically reconstructed step-by-step as depicted in Figure 10 (right) by solving the Frenet-Serret equations. As in the case of the measured strains and calculated loads, the deflections were exploited during both bench-testing and sailing phases. As an example of such shape measurement, Figure 11 reports the reconstructed shape of an instrumented main-sail batten during sailing.

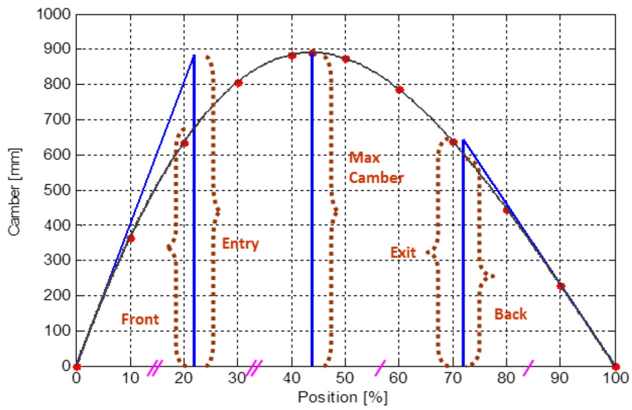
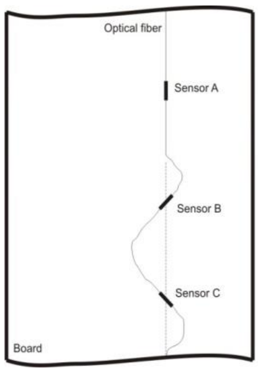



Figure 11 [Main-sail batten deflection measurements]

## 2.2 Measuring Angle of Twist

By combining the total strain readings of sensors at ±45 degrees with respect to the rotation axis (as for the lay-out reported in Figure 12), the pure torsion shear strain $\gamma_{to}$ can be obtained at the different instrumented cross section of a structure (e.g. mast tube or board). And the angle of twist per unit length $\theta$ is then calculated from the shear strain and distance $r$ of the sensor with respect to rotation axis:

$$\theta = \frac{\gamma_{to}}{r}$$



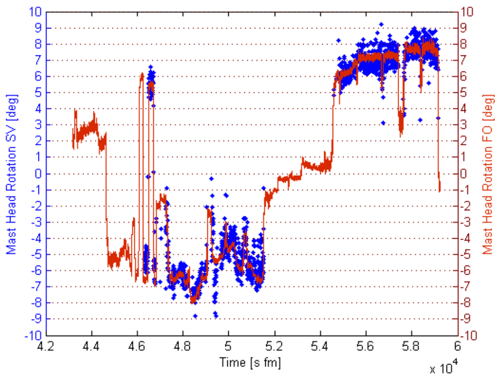




Figure 12 [Sensors layout for board angle of twist measurements (left); mast head twist as a function of time (right)]

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After interpolating the angle of twist per unit length along the structure $\theta = \theta(y)$ (e.g. the mast or the boards), the angle of twist $\varphi = \varphi(y)$ was reconstructed by means of a numerical integration:

$$\varphi(y) = \int_0^y d\varphi(y) = \int_0^y \frac{\gamma_{to}}{r} dy$$

Figure 12 (left) reports the mast head angle of twist measurements during sailing for the mast tube as a function of time with the yacht sailing upwind and downwind for both the fiber-optic system (red) and a video camera based system (blue dots).

## 5. FIBER-OPTIC SENSING SYSTEM DESIGN AND OPERATION

In order to guarantee a successful design, implementation and operation of the fiber-optic measurement system, the following topics have been addressed:

- FBG sensors design & fabrication
- Sensors interrogation & peak detection algorithms
- Bonding & embedding processes
- Sensing network design
- Installation, cabling and inter-connections
- Real-time shape reconstruction algorithms
- Data publishing & analysis application software

The definition of the sensing arrays is made at the design state of the single structures, taking into account the measurement objectives for each specific part, and the structural designers modeling, also in order to optimize the number of sensors on each channel of the optical interrogation unit. After installation, the fiber-optic monitoring system was set-up and used throughout the entire life-cycle of the boat construction and operation:

- The first measurements are taken during the load testing of the single components, and they are crucial to proof test the mechanical behavior of the single parts or assemblies.
- The fiber-optic measurements are used then during first sea trials, when the boat is proof tested before sailing at full pace. During and after sailing, the measurements are compared with the predicted values given by the structural and yacht designers.
- Knowledge of the loads and dynamic shapes throughout every single sailing session and during racing is finally critical to ensure that limit values are never exceeded and to help with the boat performance development.

In summary, the fiber optic system has been used throughout the whole Team Alinghi campaign of the 33rd America's Cup. The raw strain data were used to set the alarms for monitoring the sailing sessions and for dock data analysis. The measured and processed values took an important role in the analysis of the yacht behavior, with the mechanical and calibration tests ran before the sailing sessions allowing to back-calculate structural loads and bending moments.

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The fiber-optic sensing technology applied to sail racing turned to be a perfect fit (many sensors can be put on a single fiber allowing for simplified cabling, can be surface mount or embedded directly into the structures material and the optical fibers hosting them are small and lightweight), robust (sensors are immune to electromagnetic interference, are resistant to the salt water environment and do not need electrical power supply) and reliable (good signal to noise ratio together with strain information encoded into the FBG Bragg wavelength).

As a matter of fact, a measurement tool was developed that is ideal for:

- Design & manufacturing validation
- Dynamic loads real-time monitoring
- Performance development

## 6. CONCLUSIONS

This work has presented the particular challenges of designing and sailing an extreme sailing boat, matching the opposed requirement of being light but stiff, safe but faster than your competitor's. The fiber-optic sensing technology proved to be an effective & reliable way to incorporate a large count of strain sensors without adding excessive weight and at the same time detect quasi-static and dynamic loads, as well as helping boat handling.

Team Alinghi recognized the benefits, advantages and reliability offered by a complete monitoring system based on the optical fiber FBG sensing technology. The system has been used successfully throughout the completed race cup campaign, as well for performance analysis and new yacht configurations development. The quality of the data and its accuracy, have been acknowledged by the entire design team, and this technology is used today by all participants to the 35th America's Cup.

## REFERENCES

1. Farahi, F., Webb, D.J., Jones, J.D.C. and Jackson, D.A, "Simultaneous Measurement of Temperature and Strain: Cross sensitivity Considerations", in *Journal of Lightwave Technology*, 8(2):138–142, 1990.
2. Krohn, D.A., MacDougall, T.W., and Mendez, A., *"Fiber Optic Sensors: Fundamentals and Applications, Fourth Edition"*, SPIE Press, 2015.
3. Sigg, A., Costantini, D., Mendez, A., "*Structural Health Monitoring of an America's Cup Sailing Catamaran using Embedded FBG Sensors*", in Proceedings of the European Workshop on SHM, 2015.
4. Yoon, H-J., Costantini, D.M., Limberger, H.G., Salathé, R.P, Kim, C-G., and Michaud V., "In situ Strain and Temperature Monitoring of Adaptive Composite Materials", in *Journal of Intelligent Material Systems and Structures* 17: 1059, 2006.