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Investigations of Marine Safety Improvements by Structural Health Monitoring Systems

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ABSTRACT: The paper presents a first approach of the structural health monitoring (SHM) system, dedicated to marine structures. The considered system is based on the fibre optic (FO) technique with Fibre Bragg Grating (FBG) sensors. The aim of this research is recognition of possible practical applications of the FO techniques in selected elements of marine structures. SHM and damage detection techniques have a great importance (economical, human safety and environment protection) in the wide range of marine structures, especially for ships and offshore platforms. The investigations reported in this paper have shown major potential of FBG sensors. They are suitable for strain–stress field and load monitoring of the wide range real structures used in different conditions. The FO sensors technology appears as very attractive in many practical applications of future SHM systems.

1 INTRODUCTION

In this paper authors presents examples of FBG (*Fibre Bragg Grating*) sensors applications in the SHM (*Structural Health Monitoring*) technology for marine structures. The idea of the SHM is to build a system that contains many sensors and is able to evaluate the structure condition. One of the most promising sensors are those based on FO technology, especially FBG sensors. The first structure on which the FBG sensors were mounted assigned to measure strain and temperature was Beddington Trail Bridge – Calgary (Canada) described by Measures et al. 1993. In the following sections, the authors describe applications of this enabling technology to SHM of marine structures like Horyzont II ship and offshore structure model.

Because of their advantages like, high corrosion resistance, immune to electromagnetic interference and multiplexing capabilities, FBG sensors can work properly in the harsh marine environment for many years (up to 20) (Lee 2003) and are very interesting for SHM systems. Application of SHM techniques allows one to increase both human and environmental safety in marine industry with simultaneous reduction of maintenance costs.

1.1 *FBG sensors*

A Bragg grating is a permanent periodic modulation of the refractive index in the core of a single mode optical fibre by exposing the core of the optical fibre to an interference pattern of intense UV-laser light (Bass et al. 2001). The length of the FBG sensor is in the range 1-25 mm and depends on the application. This periodic perturbation in the core index of refraction allows coherent scattering to occur for narrow wavelength band of the incident light travelling within the fibre core. A strong narrowband back reflection of light is generated, centred around the maximum reflecting wavelength value λ_B, when the resonance condition is satisfied:

$$\lambda_B=2n_{eff}\,\Lambda \quad (1)$$

where n_{eff} is the effective refractive index and Λ is the periodicity of the perturbation (Udd 2006). The schema of FBG sensor is shown in Figure 1. The λ_B is dependent upon the geometrical and physical properties of both the grating and optical fibre. The key point of these FBG sensors is their wavelength-encoded nature, which is an absolute parameter providing reproducible measurements (Udd 2002).

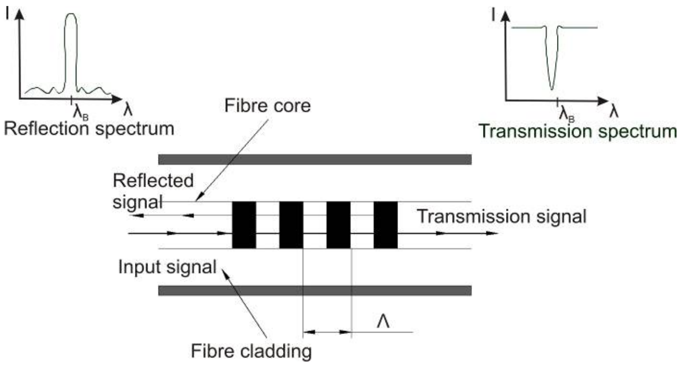

Figure 1. The schema of a FBG sensor

The FBG sensors are sensitive to both strain and temperature. Because of the cross sensitivity on those two parameters in the case of strain measurement additional sensors dedicated to temperature sensing are needed. The changes in those two parameters are linearly proportional to changes in measured wavelength (Udd 2006).

Most of the conventional sensors used in SHM applications are based on transmission of electric signals. These sensors are usually not small. They are local sensors and cannot be easily multiplexed and embedded in a structure. There is also a problem with protection against the corrosion processes in marine environments. Conventional strain gauges mounted on an offshore platform CB271 were completely unusable after one year in Bohai Sea, while the FBG sensors mounted close to them work properly (Ren et al. 2006). In some cases, the signals from electric strain gauges could not be discriminated from noise because of electrical or magnetic interference. On the contrary to strain gauges the FBG sensors have small size and weight, multiplexing capabilities and are immune to electromagnetic field and have high corrosion resistance. They can also be mounted onto the structure (Ren et al. 2006) or even embedded (Wang et al. 2001) into material of an element during its manufacturing. Those advantages make them to be a very interesting tool in SHM systems mounted on marine structures especially for those made from composite materials.

2 MARINE STRUCTURES

Marine structures like marine vessels and offshore structures surrounded by a harsh marine environment are exposed to long-term cyclic loadings comes from continuously acting sea waves and short-term extreme loads such as severe storms, seaquakes or collisions. The marine environment (sea water) results in fast corrosion, erosion and scour processes. Those phenomena increase the size of existing damage and also initiate its growth. Any damage of marine structure can results in ecologic catastrophe because of the oil which is extracted by offshore platforms or fuel in marine vessels. Another important point for using SHM systems is increasing the safety level for people working on marine structures.

Nowadays the newly designed structures are designed using FEM (*Finite Element Method*). The next step are the sea trials for a prototype. The designers are interested with strain and temperature distribution over the structure. At the designer level those information can be then utilized for optimization of the structure like it was in the case of Fast Patrol Boat HnoMS Skjold (Wang et al. 2001).

The SHM systems can be also used on marine structures during they exploitation. Nowadays developed SHM systems for marine vessels are especially designed for ships hulls monitoring. Such systems based on FBG sensors exist for example on Fast Patrol Boat HnoMS Skjold (Wang et al. 2001), minecountermeasure vessel HnoMS Otra (Torkildsen 2005).

2.1 *Marine vessels*

SHM systems based on FBG sensors can by performed for both prototypes (Wang et al. 2001) and serial production vessels (Torkildsen et al. 2005). Those systems are especially used for ship hull monitoring. The FFI (*Forsvarets forskningsinstitutt, Norwegian Defence Research Establishment*) has been involved in the development of a SHM system based on FBG sensors since 1995 (Torkildsen et al. 2005). In 1999 the first system CHESS (*Composite Hull Embedded Sensor System*) was installed on a prototype HnoMS Skjold of the Skjold class Fast Patrol Boat in the purpose of SHM of composite hull and collecting information about its real loading achieving under normal work (Wang et al. 2001).

Nowadays there is the extended SHM system for hull monitoring developed by FFI that contains different kind of sensors for measuring air pressure, profile of meeting wave, weight distribution and GPS for determination the speed and position of the ship (Figure 2) (Torkildsen et al. 2005).

The idea use FBG sensors is to monitor static and dynamic strains at critical positions of the hull. The sensors should be located for measurements of global moments and forces acting on the hull (Torkildsen et al. 2005).

The purpose of using SHM system for ship hull monitoring is verification of model results, condition-based maintenance to reduce cost and non-operative periods, damage detection and evaluation of residual hull strength. An extended SHM system will also include monitoring and recording of the ship motion, operating parameters and sea waves parameters (Torkildsen et al. 2005). The results are presented to the crew on the bridge, in the machine control room, and operational rooms (Torkildsen et al. 2005). Alarms are activated when the hull loads approach the ship design limits (Torkildsen et al. 2005).

The advantages of systems based on FBG sensors are especially visible for implementation of new materials and construction designs. Because of the advantages of composite materials like, a high strength-to-weight ratio, good impact properties and low infrared, magnetic and radar cross-sectional signatures, design versatility (Mouitz et al. 2001) nowadays there is a wide range of naval structures being developed using FRP (*fibre reinforced polymer*) (Rao 1999). This development is driven by the need to enhance the operational performance (e.g. increased range, stealth, stability, payload) but at the same time reduce the ownership cost (e.g. reduced maintenance, fuel consumption costs) marine vessels (Mouitz et al. 2001).

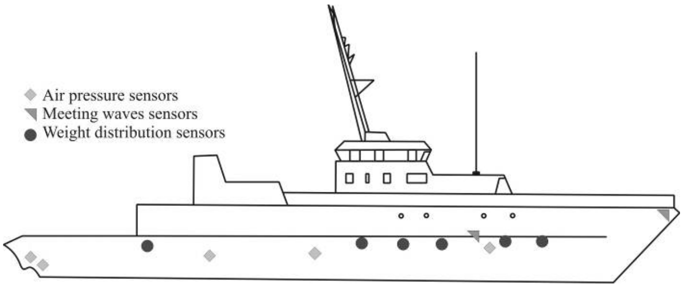

Figure 2. Overview of environmental and operational sensors on HnmMS Otra (based on Torkildsen et al. 2005)

Composite materials have been used for the construction of naval patrol boats since the early 1960s. The first all-GFRP patrol boats were built for the US Navy and were used during the Vietnam War. Nowadays the largest all-composite naval patrol boat is Norwegian HnoMS Skjold of the Skjold class Fast Patrol Boat (Mouitz et al. 2001). The boat was built in 1999 (Wang et al. 2001). HnoMS Skiold is a twin-hull SES (*Surface Effect Ship*) made of fibre reinforced polymer composites sandwich panels (Wang et al. 2001, Mouitz et al. 2001). The boat is 47 m long, 13.5 m wide and its weight is about 270 tons. A SES is a principle based on a catamaran hull where lift fans blow air into an air cushion trapped between the hulls. HnoMS Skjold was designed for high speed – for example 45 knots at sea state 3 (Wang et al. 2001).

On a prototype HnoMS Skjold a system CHESS was installed in the purpose of SHM of composite hull of the boat and collecting information about its real loading achieving under normal work. The project was a join between the US Naval Research Laboratory, Washington, DC and the Norwegian Defence Research establishment. The most important application of the system was verification of assumed balances the weight optimization and structural strength requirements of the composite hull (Wang et al. 2001).

The first step during SHM system design was created a FEM model allowing for define strain/stress field in the hull loaded by sea waves during different sea states. Calculated strain/stress fields were used for determine a localisation of FBG sensors embedded into composite hull (Wang et al. 2001). The chosen locations (Figure 3) allowed for analysis the most significant wave loads like: vertical bending (hogging/sagging), horizontal bending, torsion (twisting moments), vertical shear force and longitudinal compression force (Wang et al. 2001).

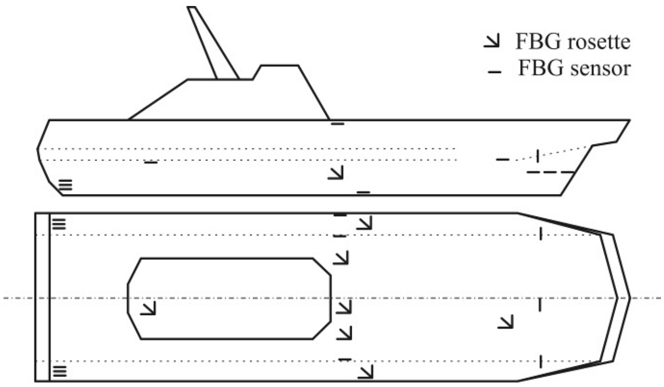

Figure 3. Schema of the location of FBG sensors on HNoMS Skjold (based on Wang et al. 2001))

The systematic sea-keeping tests using the CHESS system on HnoMS Skjold were performed in May to June. Registered dates were collected during sailing thought the sea and routine operations with the vessel. There were mounted few conventional strain gauge in the purpose of verification of strain measured by an array of 56 FBG sensors. The agreement between those two methods was good, but data from strain gauge were disturbed by electromagnetic field influence. Basing on the data from the SHM system important changes in HnoMS Skjold boat design were performed (Wang et al. 2001).

2.2 *Offshore platforms*

Offshore structures surrounded by a harsh marine environment are exposed to long-term levels higher of cyclic loadings comes from continuously acting sea waves, accumulating of floating ice shocks, and short-term extreme loads such as severe storms, seaquakes and accidental collisions. Additionally they are exposed to corrosion, erosion and scour. Those phenomena increase size of existing damages (Ren et al. 2001, Sun et al. 2007).

Because of existence of thermal errors, large zero drifts, non repeatable readings, difficult signal conditioning and high susceptibility to moisture and corrosion influence of sea (cauterization of sea), electrical sensors are restricted in the offshore platform application. Those disadvantages do not occur for FBG sensors (Ren et al. 2001, Sun et al. 2007).

Bohai Ocean Oil Field is one of main ocean oil fields in China. There is very heavy ice force in winter which become the main environmental force of offshore platforms. In 1969 and 1977 two platforms collapsed by heavy ice force action. Since 1980's, the ice conditions, ice pressure on and response of platforms in Bohai ocean have being monitored under support of China Ocean Oil Company (Ou et al. 2004).

One of the SHM systems was installed on CB32A steel jacket platform in Bohai under the project supported by the National Hi-tech Research and Development Program of China. The Platform with jacket height 24.7m will be built in 2003 and located in water depth 18.2m. The system includes 259 FBG sensors, 178 polivinylidene fluoride sensors, 56 fatigue life meters, 16 acceleration sensors and a set of environmental condition monitoring system (Ou et al. 2004).

Sun at al. 2007 built a model of an offshore platform CB32A in the scale 1:14. The model consisted of steel pipes is 2.69 m tall, 1.55 m long and 1.5 m wide. There are (Figure 4) 7 FBG strain sensors, two accelerometers and one temperature compensation FBG sensor installed on the structure. A recording, storage and interrogation system was put in the office occurred about 100 m from the model. This was in the purpose of investigating the ability of making measurements using a long distance system (Sun et al. 2007).

One of the investigated dynamic loading was Tianjin wave which is a kind of seismic wave measured for the first time in the base of Tianjin hospital in Tangshan in China and named from the place of the first appearance. Tendency of responses from two types of sensors (the FBG strain sensors and electrical strain gauge) were the same and maximal values of measured parameter were close to each other. The level of a disturbances was about 10 με and only 1 με for strain gauge and FBG sensors, respectively. In the compare with strain gauges, FBG sensors showed its particular feature which is insensitivity on influence of electromagnetic field and high ability of dynamic strain measurements in systems with low vibration frequencies (Sun et al. 2007).

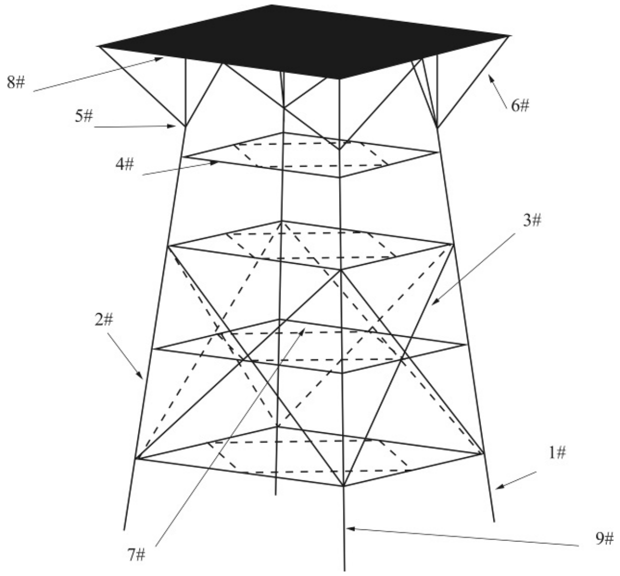

Figure 4. Location of FBG sensors on offshore platform model: 1# – 7# – strain sensors, 8#, 9# – accelerometers, 10# – temperature compensation sensor (based on Sun et al. 2007)

FBG strain and temperature sensors were implemented into SHM system on steel CB271 offshore platform located in the Bohai Sea, of East China. A FBG sensors rosette was located on the bottom side of a middle support. Temperature compensation FBG sensor was located close to it. The FBG sensors were covered by epoxy layer in the purpose of protect under destructive influence of environment. This system correctly monitor on line responses of the structure (its strain) under loading of sea waves and waves generated by several hundred-tone ships sailing close to the platform (Ren et al. 2006).

The state of the FBG sensors array was checked one year later. They were working as good as in the moment they had been mounted. No significantly decrease of the sensitivity was observed. However electrical strain gauges located close to them were damaged because of corrosion influence of the sea water. This allowed the FBG sensors to show its advantages allowed them to being a part of SHM system permanently installed on offshore structure (Ren et al. 2006).

One of the most dangerous accidents being able to damage the offshore structure and installation mounted on it is a collision with a vessel. Because of this a registration of changes of strain during such accidents is very important. Such accident was happened and was observed in sensors measurements on 20 July 2004. There was no dangerous of damage occurrence because the value of the registered strain induced by the ship impact was in the linear-elasticity range of the material. Equally important like a ship collision is loading from ocean waves. The level of the strain introduce from strong ocean wave impaction of the ocean can be closed to those measured during the ship collision (Ren et al. 2006).

3 DAMAGE DETECTION EXPERIMENT BASED ON MEASURED STRAINS

Certain number of the offshore production platforms exceeded their working life assumed by design engineers. Growing possibility of the catastrophic failure should be prevailing for production stop and removal of such objects. On the other hand prolonging the production beyond working life makes extra financial profits. In such situation the optimal solution is to install a SHM system on such structures which early warns about a structural problem.

Before starting field investigations there is a need for checking SHM systems on some laboratory-size models. In the first step a space frame leg model of typical offshore jack-up rig was constructed and tested, see Figure 5. The model consists of 3 main chords which are connected by horizontal and diagonal brace elements.

The braces of the structure were covered by 16 FBG strain sensors located at bay level 2 and 7 counting from the bottom. Additionally 6 bare FBG sensors were glued on each chord. Also 2 FBG acceleration sensors were mounted in the upper part of the structure.

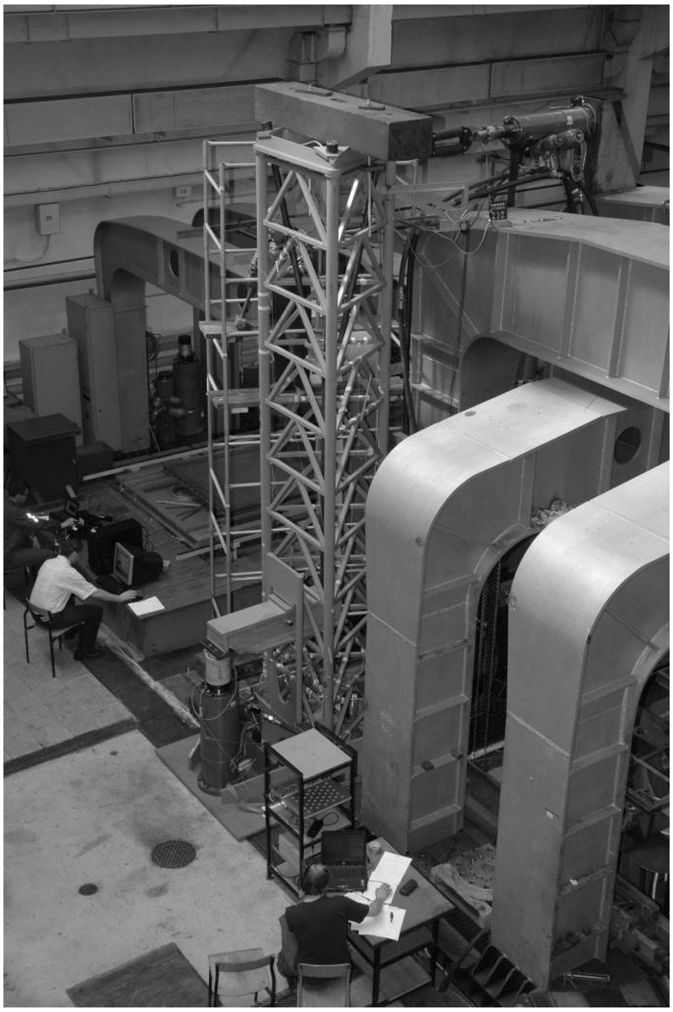

Figure 5. The leg model of jack-up rig with 1500 kg top mass.

The behaviour of the leg model was analyzed under different conditions. Damage was located at the bottom part of the model and it was modelled as chord's yielding, partial and also entire chord cutting (with open and closed gap) and cutting of the bottom K-brace of the leg model. Concurrently different loading scenarios was taken into account: hammer impacts to impart free vibrations of the model and 10kN horizontal shaker to induce forced vibrations. Vibration experiments were done for unloaded leg model, leg model with added 1500 kg top mass and the leg model loaded by vertical load up to 500 kN from hydraulic actuator situated on the floor.

The main aim of the investigations was the identification of damage influence on readings from sensors glued to different members of the leg model.

In this paper the authors consider here only the static loads and show the results of 2 selected sensors for one damage scenario i.e. chord's yielding at bay level 1, see Figure 6.

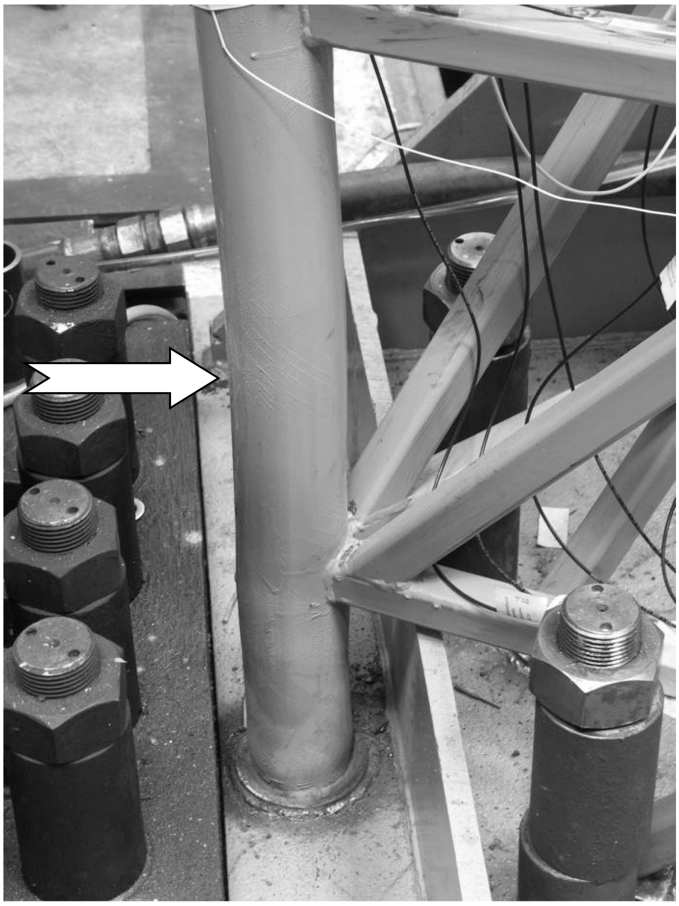

Figure 6. Bottom part of chord A after yielding.

The most promising is the fact, that local yielding can be detected by sensors situated relatively far from the damage.

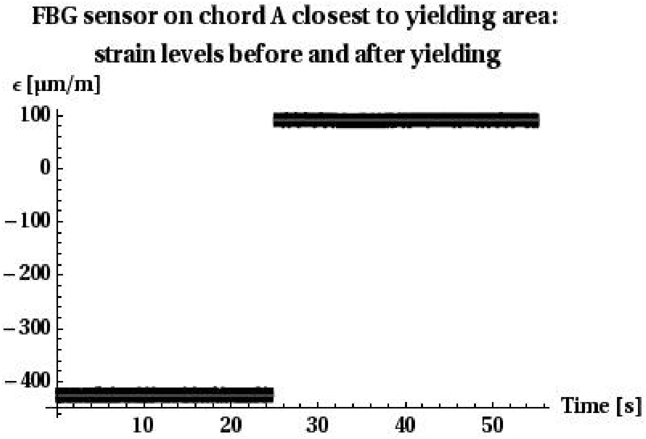

Figure 7. Strain level increase after local yielding.

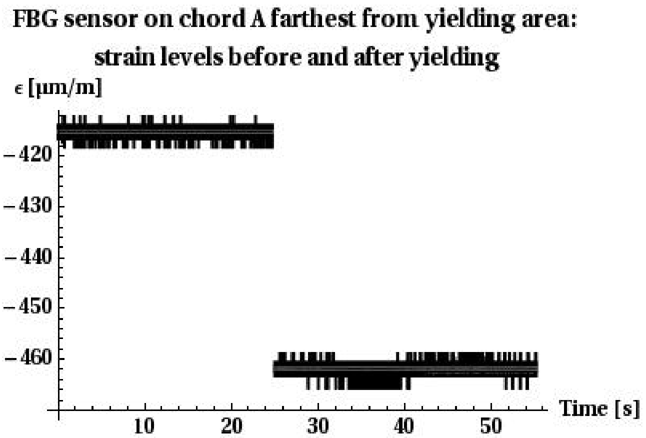

Figure 8. Strain level decrease after local yielding.

4 SCHEME OF SHM SYSTEM ON REAL MARINE STRUCTURE

The authors present a first approach of the SHM system, dedicated to marine structures. The considered system is based on the fibre optic technique, especially on FBG sensors. The aim of this research is recognition of possible practical applications of the fibre optic techniques in selected elements of marine structures. The authors have been performing initial investigations on Horyzont II ship. The FBG based system will be compared with classical measurement techniques, e.g. piezoelectric accelerometers. The environmental loading conditions will be also monitored.

Designed SHM system is located on a mast of Horyzont II ship (see Figure 9). FBG sensors are placed in the bottom area of the mast (see Figure 10) where predicted strain-stress level is the highest. The authors finally planned to use 5 FBG sensors for strain measurements and one FBG sensor for temperature compensation. Three of FBG strain sensors are arranged for a strain rosette. So, strain-stress absolute values with main axis directions can be determined with the rosette. One FBG sensor is located one meter higher than the rosette, just for longitudinal stress distribution determination. Another FBG is placed on the same highest as previous one, but for stress level determination in lateral direction. Three seismic, piezoelectric accelerometers (ACC) are placed on the navigation deck, close to the mast foundation. Seismic ACC can record low frequency movements of the ship in the all directions. Accelerometers give us information about environmental loading, mainly about sea waves excitations. Other environmental loading, like wind force, temperature, atmospheric precipitation, will be registered with other collaborated meteorology system.

The authors worked out methodology of the first step of the measurements. Determination of the dynamic characteristics of the mast is the main target of those investigations. First of all, zero signals will be recorded before and after ship's voyage (in the harbour). Tests on the open sea will be performed in two variants: dynamic (100 Hz scan frequency) and quasi-static (1 Hz scan frequency). The measurements are planned during heavy weaver in Gdansk Gulf area as well as in the open Baltic Sea.

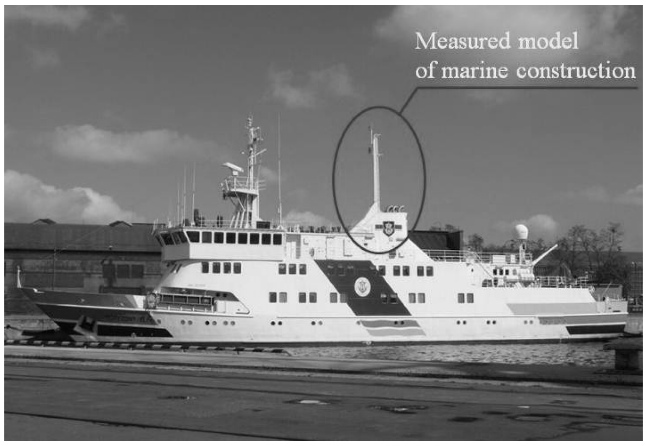

Figure 9. Location of the SHM system based on FBG sensors

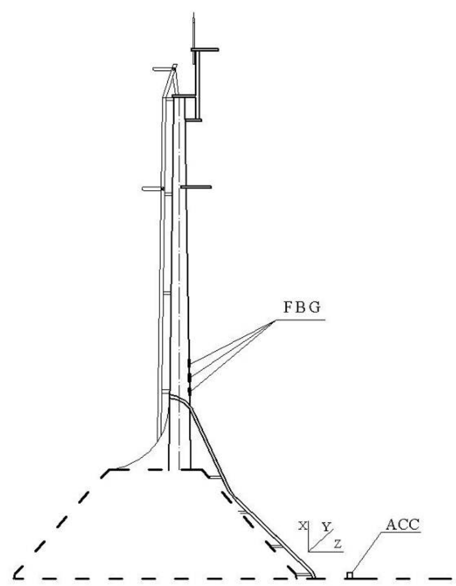

Figure 10. Sensors displacement on the mast

5 CONCLUSION

Marine structures are working in corrosion environment (sea water). Application of SHM techniques allows one to increase both human and environmental safety in marine industry with simultaneous reduction of costs. One of the problems which must to be solved during designing of such system is to find sensors appropriate sensors which could work properly through whole life time of the structure. FBG sensors advantages in compare with conventional strain gauges like immunity to electromagnetic field interference, high corrosion resistance and multiplexing capabilities make them promising tool for SHM technologies implementation to marine structures, like marine vessels and offshore platforms. In the presented examples FBG strain sensors are used as a part of complex SHM systems implementation on a fast patrol boat HnoMs Skjold (Wang et al. 2001), minecountermeasure vessel HnoMs Otra (Torkildsen et al. 2005) of Norwegian Navy. Another marine structures are offshore platforms. Ren et al. 2006 showed that only FO sensors mounted on offshore platform CB271 on Bohai Sea survived a year of installation of the platform. Strain gauges in contrast were completely destroyed by corrosion processes and were unusable for measurements (Ren et al. 2006).

Searching for new constructing solutions and new materials application in combine with high safety and ecologic requirements will result in implementation of SHM systems based on FBG sensors to many marine structures not only the new designed ones.

FO sensors will be a critical technology in many aspects of future SHM systems. FBG sensors are suitable for strain-stress field and load monitoring of wide range of real-world structures under different conditions. The results obtained with the FBG sensors show good agreement with the electric strain gage. Additionally, the FO sensor network has several advantages: it does not suffer from zero drift, it is self-calibrating, it has low mass, it is immune to electromagnetic interference and it has high multiplexing capability. FBG sensors are more reliable in determination of frequency spectrum of the signal then classical electrical strain gauge. FBG sensors are better suited for long-term monitoring systems.

The investigations reported in this paper have shown big potential of FBG sensors for SHM systems dedicated for such difficult structure as marine ships and offshore platform. Structural damage can be detected on the base of: strain-stress field dynamic characteristics (analytical-empirical self learning system), loads level and counter identification for structure uncertainty determination (on the base fatigue), nonlinearities on the base of known load level, changes of mode shapes and frequencies and changes of structural damping characteristics.

The FO sensors technology appears as very attractive in many practical applications of future SHM systems.

ACKNOWLEDGEMENTS

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