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Smart Fibre Optic Methods for Structural Health Monitoring of High Pressure Vessels for Hydrogen Storage

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1 Introduction

High pressure composite tanks of IV generation (700 bar) for Hydrogen storage must fulfil sharp norm within safety. Simultaneously tank must be cheap and light. Conceptions „on board monitoring” making use of light fibres sensors appear especially promising. These sensors are inbuilt in the structure of composite without changing composite mechanical properties. Moreover, sensors are spark less and resistant against electromagnetic disturbance. They have large range of measurements and can easily collaborate with electric system of cars. The method is included in NDT.

Optimal solution requires hybrid approach what means the both numerical model of composite tank and measurement system are required. The numerical model allows an optimal arrangement of sensors reducing their number and current comparison of measured strains with values derived from model. The paper presents applications of two optical fibre based systems which create a structural health monitoring systems for high pressure vessels “on-line” monitoring. The original FEM model required application of so-called homogenisation procedures and it enabled determination of strains within variety of length scales as well as damage accumulation. Some results were obtained under StorHy project (6FP, Integrated Project).

2 Optical Fiber Sensors Built in the Composite Structure

Application of monitoring systems (periodical or continuous) to check up the effort state of composite vessels is becoming necessity because of safety requirements that must be met by gaseous fuel tanks (methane, hydrogen) in cars. Standard methods of visual inspection will not detect defects which may have critical influence on the technical status of the monitored construction, whereas typical measurement systems (e.g. resistance strain gauges) all too often get damaged in adverse environmental conditions [1,2,3]. Ever growing popularity in the field of monitoring technical condition of industrial objects is being gained (on-board monitoring system) by modern measuring methods based on optical fiber technology. It stems, among other things, from many advantages that optical fiber sensors have over standard methods. The obvious one being their application at high levels of electromagnetic interference and in other adverse conditions (high dust concentration, high temperature, high pressure, significant deformations). Moreover these sensors are characterized by high measuring sensitivity in wide ranges of measurements (deformation, temperature). Simultaneously due to their small geometric dimensions and relatively small mass, it is possible to position the measuring head inside the structure of the object (e.g. building them in into the composite material) or installation on its surface. Thanks to their high potential for multiplexation it is possible to create, the nervous system of the object

being monitored. Additionally such applications like fuel tanks (with high degree of safety) regard to the so-called spark-proof safety [4].

In order strain state monitoring two types of optical fiber sensors were installed: point sensors in the form of FBGs as well as interferometric sensors with long measuring arms (SOFO®) [5]. A fiber Bragg Grating is a structure made in the core of a single-mode optical fiber (figure 1a), characterized by periodical changes in the value of the refractive index [6]. Presence of such a modulated structure inside the core of the optical fiber causes part of the optical radiation transmitted through the optical fiber to be reflected from the grating structure, and the remainder is propagated without any loss. The wavelength reflected from the Bragg grating, the so-called Bragg wave (λ_B) is described with the relation $\lambda_B = 2 \cdot n_{\text{eff}} \cdot \Lambda$ (n_{eff} – effective refractive index of the optical fiber core, Λ – Bragg grating constant) [6].

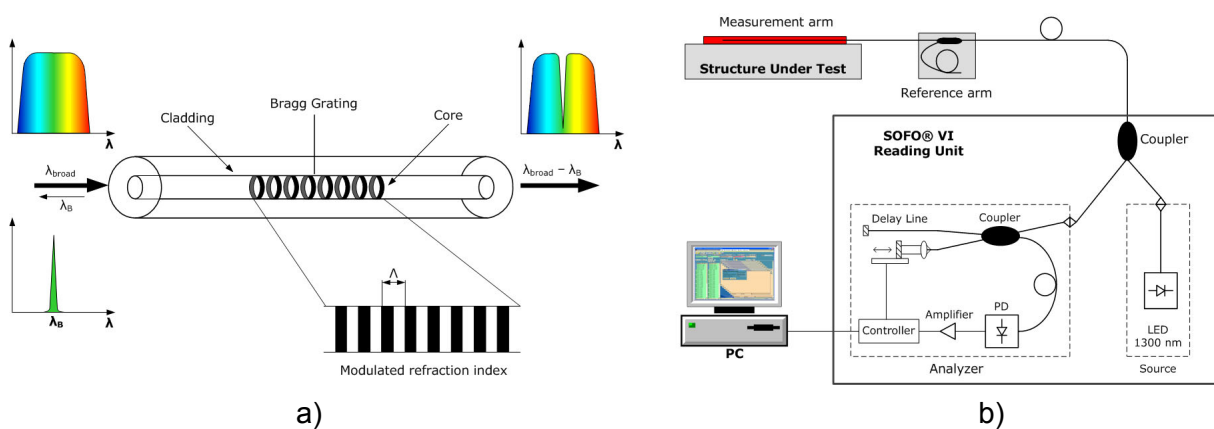


Figure 1: Scheme of fiber Bragg gratings principle of operation (a) and scheme of Smartec SOFO interferometric measuring system (b) [on the basis of: 6,7,8].

Sensors bonded to the external surface of the monitored construction, or located in the material structure are subjected to deformations causing change in Bragg wavelength, which becomes the touchstone for measured deformations. It should be emphasized, however, that change λ_B in real measuring systems is the result of the simultaneous influence of temperature and deformations [6], which can be measured in ranges reaching: $-270^\circ\text{C} \div 800^\circ\text{C}$ and $-3\% \div 3\%$ respectively.

Interferometric optical fiber sensors (SOFO®) are characterized by modulation of light signal phase propagated in the measuring system. Measuring heads in the form of single-mode optical fiber may attain from a few centimeters to a dozen or so meters and are either integrated with the surface of the monitored object (e.g. in the shape of special tape – the so-called SMARTape) or located inside the monitored structure (and as in the case of test vessels are buried in the composite). These sensors are designed to measure displacements (deformations). The idea of measurement consists in analyzing the difference in phases of optical signals propagating in two arms of the Michelson interferometer – measuring and reference arms (figure 1b). The measuring arm is in direct contact with the examined construction. The reference arm is separated mechanically from the monitored object, but is nevertheless close enough for the temperature of both arms to be the same. This allows eliminating the influence of temperature fluctuation on measurement results. The change in

the phase of the light wave which occurs is the result of the change in the length of the optical fiber constituting the measuring head. As a result of interference of both beams it is possible – through analysis of interference fringes – to quantitatively determine the deformation of the sensors, and thus the deformation of the monitored construction. Applied interferometric sensors belong to a group of sensors with long measuring arms (long-gage sensors), so the measured deformations are the average value for the whole length of the sensor.

3 Defects Detection and Localization

In order to estimate the vessel's technical condition (to detect any kind of critical defects to avoid dangerous situation) the analytical analysis of measured data from sensors is required. It was proposed to analyze local strain distribution inside the composite material and compare it with the numerical model of the strain field for selected value of internal pressure. Any deviations could indicate potential defects. However, the perfect model of composite pressure vessel is always different from the real object. So in order to create real working on-board monitoring system it was decided to calculate an artificial factor, called ABS factor, and compare it with the specified threshold level. The ABS is calculated as an absolute value of the difference between pressure-curve slopes (fig. 2) for a new vessel (without load history) and current measuring state. At the same time it is also possible to compare signals from selected sensors. For a vessel without defects the dependencies between various sensors for the following load cycles should be the same (or very similar). If any defect occurs, then the interdependence between selected sensors will be disturbed.

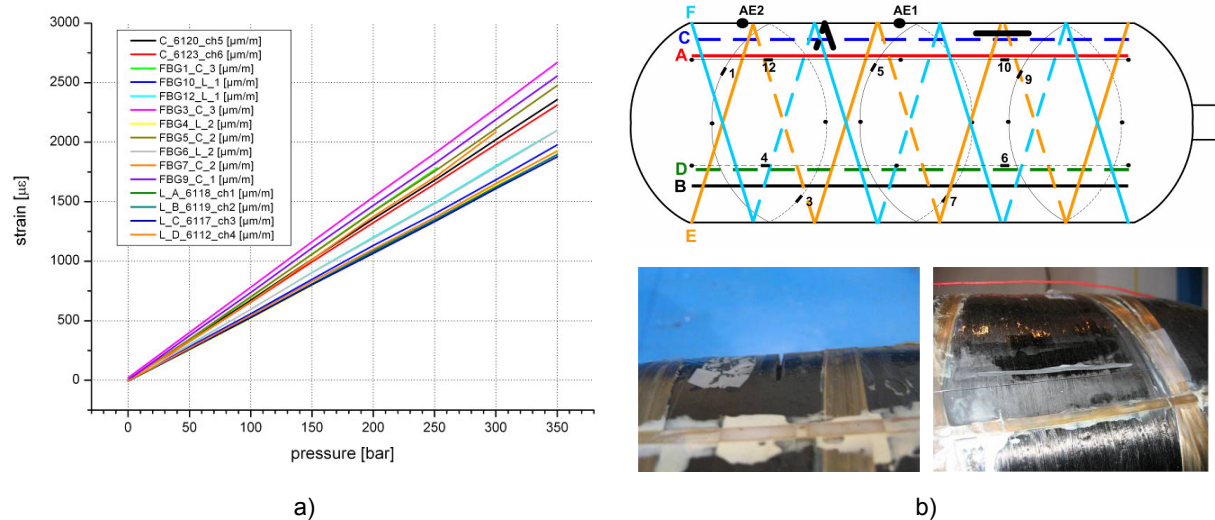


Figure 2: Exemplary pressure – strain curve (a) for a brand new high pressure composite vessel (without external flaws) [4] and sensors displacement on the vessel surface as well as view of programmed defects - flaws (b) [9].

Exemplary results analysis of differences in deformation coefficients for a static load test for the vessel with and without defects in the shape of longitudinal and circumferential flaws in the range of 0 to 350 bar were set out in figure 3. The results obtained confirm the assumption that local defecting of the composite material causes local change in the slope

coefficient of the curve pressure-deformation, which was expressed by ABS coefficient (absolute value of the slope coefficients difference) [9].

The analysis of the obtained results (Fig. 3) indicates there are perturbations in the strain field of the measured vessel. It is possible to notice that after the first defect was made (Step 2 - flaw in longitudinal direction: 8 cm long, 2 mm deep) almost all the sensors showed different strain values in comparison with the reference measurement (Step 1). The most sensitive for longitudinal defect was the sensor located in the circumferential direction (FBG7). After the next defect was made (Step 3 - flaw in cross direction: 10 cm long, 2 mm deep) changes in strain field distribution were observed. These deformations were clearly registered by longitudinal sensors, especially by fiber Bragg gratings (i.e. FBG4). It arises from fact that SOFO sensors are longer than FBG and average the strain value from whole length of the vessel. FBG sensors are shorter and made the measurements on the comparatively smaller area. In the final step both defects were enlarged (the depth of each was 4.5 mm) and all sensors registered changes in measurands. It is possible to notice that such small defects were earlier indicated by FBG sensors rather than by the SOFO ones. It follows from the length of the sensors in comparison with the defect's length.

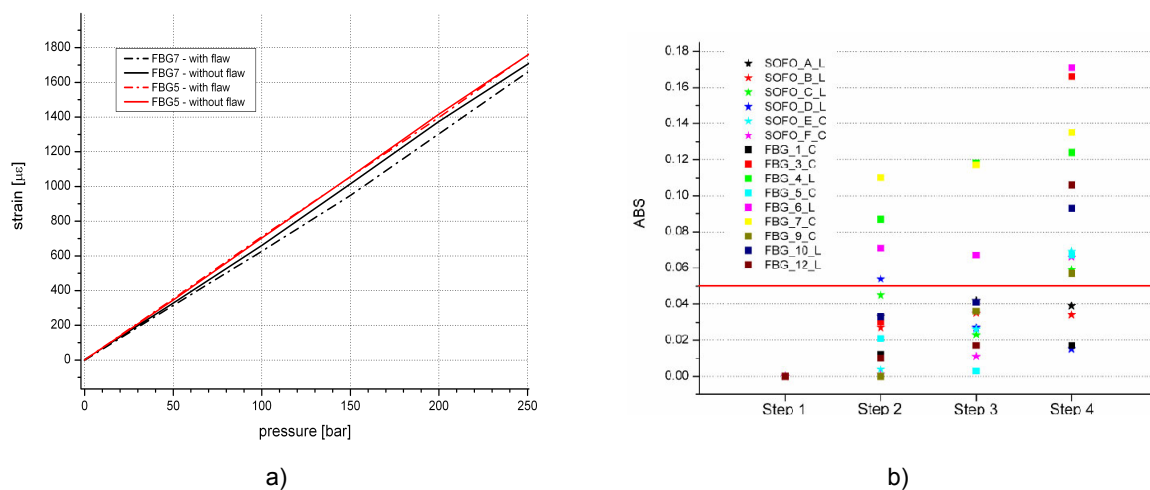


Figure 3: Exemplary pressure – strain curve for vessel without and with defect in cross direction (after Step 2) measured by selected FBG sensors (a) and analysis of obtained results (b); detection of defects in high pressure vessel without flaw (Step 1) and with various flaws (Step 2 ÷ Step 4) [9].

In order to check an algorithm of defect detection in real conditions test vessel was put to the cycling test. A prototype high pressure vessel type III (fully wrapped metallic liner) with nominal working pressure 700 bar was cycled in a pressure range from 20 to 875 bar and about 700 cycles were accomplished.

Figure 4a (upper graph) shows the local strains in the circumferential direction registered in the destruction moment of the vessel and corresponding to that event signals from Acoustic Emission sensors (lower graph). It is worth noting that the damage to the vessel (the broken line in fig. 4a) was preceded by a considerable increase in local deformations (of the order of $1500 \div 3000 \mu\epsilon$) observed in various points of the structure. This was caused by the steel

liner under the strengthening composite layer getting leaky. It is also possible to observe a fine correlation between the increase in RMS signal (from AE), which testifies to the high level of the damage to the composite material, as well as increase in local strains registered by FBGs [9].

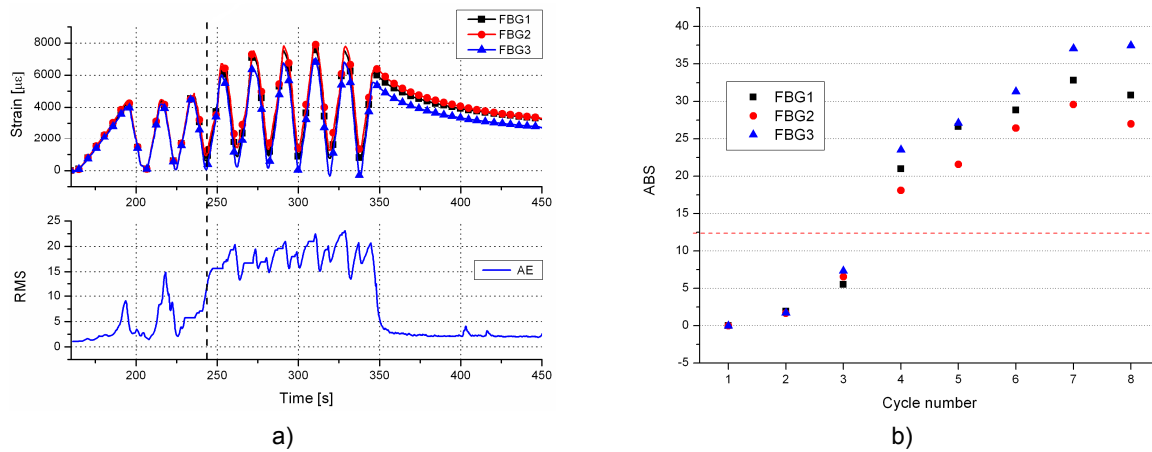


Figure 4: Local strains (a) registered by FBGs in circumferential direction (upper graph) as well as signal from AE (lower graph) in the destruction moment and analysis of obtained results – detection of defect in a high pressure vessel (b) [5].

In Figure 4b there is an analysis of strain values measured in the last 8 cycles presented. As was described earlier, for each of the pressure-strain characteristics measured by FBG sensor, the curve slope was calculated and compared with reference one. The analysis of ABS for each of the sensors indicates there are perturbations in the strain field of the tested vessel. It is worth noticing that after cycle no. 3 (damage beginning) an ABS coefficient increased meaningfully. It indicates dangerous situation in a high pressure vessel [5].

4 Summary

Fiber optic sensor technology offers the possibility of implementing “nervous systems” for infrastructure elements that allow health and damage assessment. In the present work Fiber Bragg Gratings used in measurements give information on local strain values of the composite layer of the vessel caused by internal pressure. This relationship is of linear character. SOFO sensors are longer than FBG ones and average the strain value from the whole surface of the vessel.

For the purpose of monitoring the condition of the entire vessel one should carry out a comparative analysis of the deformations measured at different points. Pressure (static) tests conducted for the vessel with local defects point to the distortion of the symmetry of the strain field resulting from composite discontinuity of the carrying layer. The cyclic tests of steel liner based on the high pressure vessel showed that during cycling there is a significant increase in strain before damage. The experiments with defected vessels and proposed sensors configuration showed that monitoring system based on Fiber Bragg Gratings is more sensitive to defects that occur than SOFO ® one. It is possible to detect the defects (flaws) in the earlier stage.

In spite of essential differences between selected measurement techniques: FBG (short gage sensor - local measurements) and interferometric SOFO® (long gage sensor – average value), both of presented OFS methods can be useful for monitoring and comparing obtained results with numerical model of high pressure composite vessels for hydrogen storage.

In the present work optimization of the number and arrangement of the sensors was not considered. This problem is very complicated and currently is investigated in a few research centers. It should be assumed that in the future applications of high pressure composite tanks for gaseous fuels storage signals from optical fiber based sensors (like: strain, temperature, damage accumulation) will be compared with results from numerical modeling. It means that for each type of vessel a mathematical model of strain field distribution and damage accumulation for each tank and each geometry of the composite structure will be created.

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