Health monitoring of a full composite CNG tanks using long-gage fiber optic sensors

Branko Glisic*[a], Daniele Inaudi[a]

[a]SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland, ,

ABSTRACT

The Compressed Natural Gas (CNG) used as a carburant in automotive industry offers low cost and notably less pollution. Full composite tank used to store the CNG onboard features low weight and extended lifespan. However, the safety issues and maintenance fees remain a challenge for its use in ordinary cars. The structural health monitoring of tanks with accent to damage detection can significantly increase the safety and decrease the maintenance fees. Structural health monitoring and damage detection of composite tanks impose important challenges to the monitoring strategy and monitoring system to be used. The issues of non-intrusive installation of sensors, their topologies and network, and particularly analysis and interpretation of resulting data are very complex. The long-gage interferometric sensors of SOFO type, for direct embedding in the full composite tank during production are developed. The sensor consists of single mode optical fiber embedded into the very thin composite tape. Such packaging offers to optical fiber excellent protection during handling and embedding and makes sensor non-intrusive to the tank material. Appropriate topologies of the sensors are combined in single sensor network used to monitor strain state and damage. The results of monitoring are analyzed at several levels, and the damage is detected using algorithms combining the global deformation and changes in both the tank stiffness and sensors cross-correlation. The monitoring strategy, sensors used in full composite tank monitoring, installation issues and the results of the structural health monitoring performed in laboratory are presented in details in this paper.

Keywords: Full composite tanks, health monitoring, long-gage fiber optic sensors, compressed natural gas, damage detection

1. INTRODUCTION

Natural gas is more and more used as a carburant in automotive industry since it offers low cost and less pollution. This is why it is notably employed in public bus transportation. The gas is stored in tanks that can be made out of still or composite material combined with steel or aluminum liner or finally fully made out of composite material.

Full composite tank consists of polymer liner reinforced with composite structure – reinforcing carbon fibers embedded in polymer matrix. Depending of curing process of the matrix, the tanks can be thermoset or thermoplastic. The advantages of full composite tanks are light weight, extremely high resistance, linearly-elastic behavior and consequently, they are not subject to fatigue. All these advantages makes the composite tanks more suitable for potential use in automotive industry, not only in public transportation buses, but also used in ordinary cars.

Several issues are related to the use of compressed natural gas (CNG) in ordinary vehicles. According to European Norms, for the safety reasons, it is necessary to make annual control of tanks which is uncomfortable (the user has to leave the vehicle in the garage for several days) and expensive (approximately 2000 € per inspection).

In order to simplify periodical control, check structural integrity and increase safety it was decided to develop and apply structural health monitoring system to full composite CNG tanks. The system is to be permanently installed on tanks with possibility to be simply interrogated on-board, more in details during the filling at filling stations and systematically every three years. The monitoring system is supposed to detect the structural condition changes that decreases the performances and lead to damage that can imperil the lives and goods. If such a change is detected the warning will be activated and user recommended to make systematic inspection of the tank.

Development of structural health monitoring system involved development of monitoring strategy, sensors and installation procedures. All these features as well as the most important laboratory tests that proved the system performance and applicability are presented in this paper.

* glisic@smartec.ch; phone +41 91 610 18 00; fax +41 91 610 18 00; www.smartec.ch

2 FULL COMPOSITE TANK

Full composite tank consists of cylindrical part that finishes at both extremities with the domes. Metallic openings for the valves are inserted at tops on both domes. The tank contains polymer liner and carbon filament with thermoset matrix. Thin protection and labeling layer containing glass filament is installed on cylindrical part of the tank. Finally, special protection shapes are installed on domes which are considered as the most fragile parts of the tank.
There are principally two directions for carbon filament layers, longitudinal and circumferential (hoop). The glass filament is only installed in hoop directions. The structural behavior of tank is linearly-elastic with maximal expected strain in circumferential direction at burst pressure of 1.6% approximately. The strain in longitudinal direction is nearly two times lower, consequently the tank always burst (by design) in the cylindrical part.
Schematic representation of the tank is presented in Figure 1. The expected pressure-strain diagrams for both directions are presented in Figure 2. The service regime of tanks under different conditions is summarized in Table 1.

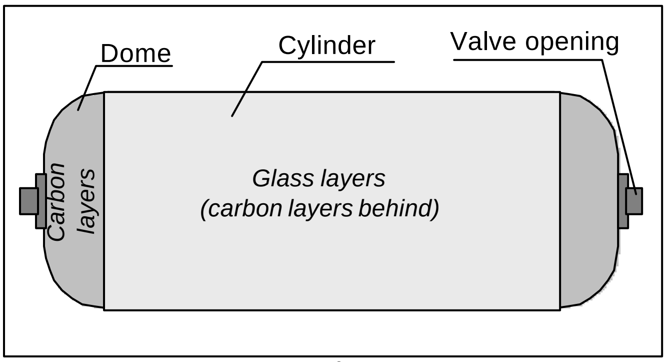

Fig. 1: Schematic representation of tank and its components

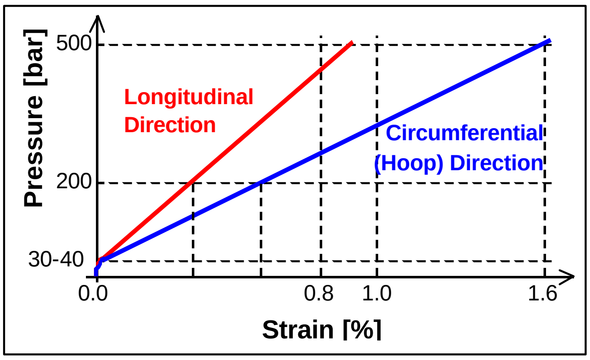

Fig. 2: Expected strain-pressure diagram of tank

Table 1: Service regime of tanks

	Pressure	@ Temperature
Working Pressure (WP)	108 Bar	-40 °C
	200 Bar	+15 °C
	288 Bar	+65 °C
Maximal Filling Pressure (MFP)	260 Bar	Any
Testing Pressure (TP)	300 Bar	
Minimal Burst Pressure (BP)	470 Bar	Ambient
Average Burst Pressure	540 Bar	Ambient

3 SELECTED MONITORING SYSTEMS

The damage can appear on tanks at any position, and this is why it is necessary to cover the surface of tank as much as possible with sensors. The use of short-gage sensors for this purpose requires a large number of sensors and as a consequence expensive and complicated sensor network and complex data post-processing. Using the long-gage sensors it is possible to cover large surface of tank using few sensors, decreasing the costs of sensing system and simplifying the data handling.
The SOFO systems, static[1] and dynamic[2] in combination with Fibre Breaks system are selected since they provide for long-gage sensors necessary to cover all the surface of the tank with limited number of sensors and allow monitoring on structural level. Moreover, the sensors features high resolution and long-term stability. The same sensors are to be used for both, SOFO and Fibre Breaks readings.
Fibre Breaks (FB) reading unit is to be installed on-board and is to control if the sensors are intact. If cracks occur on the tank surface, they will break the sensors and this can be seen on the FB reading unit.
SOFO reading units (static and dynamic) are to be installed on the filling stations and are to be used simultaneously with filling. Primary parameters (average strains measured with different sensors) are combined in order to make possible evaluation of the tank performance on a structural level.

This paper is concentrated to detection of damage through monitoring of changes in tank's structural behavior. The several tests are performed mainly using the static SOFO system. This is why this system is presented here in more details.

Static SOFO system (French acronym for Surveillance d'Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers) is based on low-coherence interferometry in optical fiber sensors [2]. The system is composed of sensors, a reading unit and data acquisition and analysis software. The standard sensor consists of two optical fibers called the measurement fiber and the reference fiber and contained in the same protection tube. The measurement fiber is coupled with host structure and follows the deformations of the structure. In order to measure shortening as well as the elongation, the measurement fiber is prestressed to 0.5%. The reference fiber is loose and therefore independent from the structure's deformations; its purpose is to compensate thermal influences to the sensor. The optical signal (light) is sent from the reading unit through a coupler to the sensor, where it reflects off mirrors placed at the end of each fiber and returns back to the reading unit where it is demodulated by a matching pair of fibers. The returned light contains information concerning the deformations of the structure, which is decoded in the reading unit and visualized using a portable PC. The functioning principle of the SOFO system is presented in Figure 3.

Typical sensor length (gage-length) ranges from 200 mm to 10 m, wile the resolution reaches 2 µm (0.002 mm) independently form the gage length and with an accuracy of 0.2%. The dynamic range of the sensors is 0.5% in compression and +1.0% in elongation.

The SOFO system was developed in early 1990's and since 1995 it was commercialized and applied to the monitoring of a wide range of civil structures, such as geotechnical structures, bridges, dams, residential and industrial buildings, just to name a few (3, 4, 5, 6). The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 8 years, making it ideal for both short- and long-term monitoring. Being designed for direct embedding in concrete, the sensors allow easy installation; require no calibration and feature high survival rate (better than 95% for concrete embedding). The long gage-length makes them more reliable and accurate than traditional strain sensors, averaging the strain over long bases and not being influenced by local defects in material (e.g. cracks and air pockets). More information on the SOFO system and its applications can be found in the references [3].

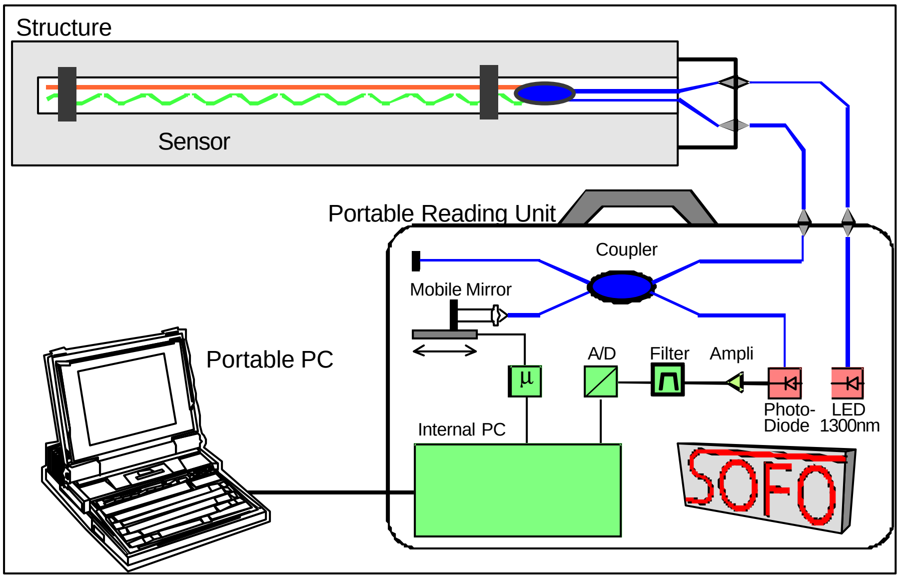

Fig.3: Components and functional principle of the SOFO system

4 DEVELOPMENT OF SENSOR AND INSTALLATION PROCEDURES

4.1 SMARTape

While the reading unit and software can be directly used for composite tank monitoring, sensors must be modified and adapted to the host material. Composite materials, in general, are often manufactured in form of filaments, tapes or sheets, while sensors are to be embedded within the structure, depending on the structural layers that have to be monitored. Improper embedding of the sensors may be a source of delaminating that causes a significant decrease of

mechanical properties. Sensor can also be installed on the surface of the structure, and in this case the optical fiber has to be protected against environmental influences.
On the other hand, if the sensor is designed to monitor strain or deformation, it is necessary to guarantee a good bonding between the optical fiber and the composite. Finally, for an industrial deployment of fiber optic sensors in this domain, it is necessary to package the sensors in a way that makes them as easy to handle as other components used for composite production.
The solution in found in pre-packaging the measurement optical fiber in a thin composite tape[4], that can than be embedded or surface mounted on the composite structure. The tape gives to the optical fiber necessary protection against an accidental damaging during handling and installation. The fiber-reinforced composite tape with integrated optical fiber is called SMARTape. The typical cross-section of SMARTape with typical dimensions, is presented in Figure 4, and its appearance in Figure 5.
The SMARTape sensing performance was laboratory tested[4]. In addition mechanical, microscopic and fatigue tests were performed. The results confirmed the same sensing performance as in case of standard SOFO sensor and excellent mechanical (robust, resistant, elastic, with no fatigue), thermal (temperature range from –40°C to +300°C) and chemical performance (resistant to aggressive environments).

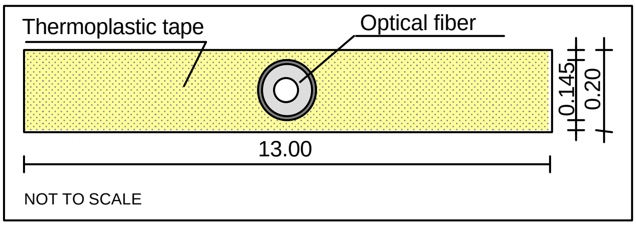

Fig. 4: Typical cross-section of SMARTape

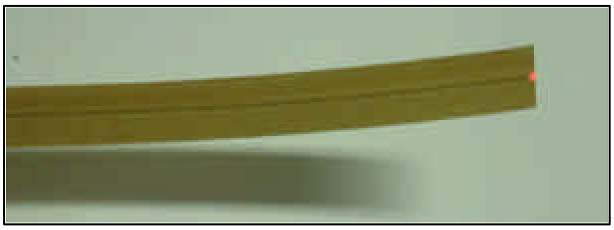

Fig. 5: View to SMATape with inserted light

4.2 Installation procedures

In order to optimize the installation procedure, it was decided to embed the SMARTape between the last carbon and the first glass layer. In this way, the structural behavior of the tanks is not affected, the installation is performed fast and easy all through the fabrication process and the glass layer offers necessary protection to the sensors. The installation of the sensors is successfully performed on two tanks that are later tested (see Sec. 6 and 7). The sensors embedded in the tanks are shown in Figure 6.
The reference fiber of the sensor, necessary for temperature self-compensation (see Sec. 3) can not be embedded since it has to be strain free. Therefore, this fiber along with the coupler is to be installed in small connection box. The boxes with reference fibers and couplers are also presented in Figure 6.

Fig. 6: View to full composite tanks with embedded SMARTapes and connection boxes

5 MONITORING STRATEGY

From the structural point of view it is interesting to monitor two principal directions of strain, i.e. longitudinal and circumferential direction. Longitudinal direction was monitored using the sensors parallel to longitudinal axis of the tank, while for circumferential direction helicoidally shaped sensors were used. Since the expected strain in the tank was as high as 1.6%, the length of helicoidal sensor was limited due to dynamic range of the SOFO reading unit, and therefore three full heliocoids are included. In case of damage, an increase of flexibility of the tanks was expected. In addition a global deformation of the tank is expected – bending, ovalization, etc.
Another particularly important aspect to be monitored is the symmetry of the tank behavior. The strain field in tank is expected to be symmetrical with respect to the plane perpendicular to the axis of the tank and crossing the middle of the cylindrical part, and rotationally symmetrical with respect to axis itself. In case of damage, the strain field is expected to loose the symmetry.
To detect the damage, the behavior of the tank is assessed at three levels:

1. In case of damage the tanks is expected to become more flexible; therefore, the slope of the strain-pressure diagram is expected to increase
2. In case of damage the tanks is expected to deform (bend, ovalize, etc.); as a consequence, axially symmetrical pairs of sensors will measure different values of strain
3. In case of damage the strain field in the tank is expected to loose the symmetry; hence, the coefficients of linear correlation between the sensors will change.

Finally, for the purposes of completeness, symmetry and redundancy, two helicoidal sensor with opposite angles and four longitudinal sensors shifted for approximately 90° were installed on each tank. The schema of sensors topology is presented in Figure 7. The view to tanks with installed sensors is presented in Fig. 6.

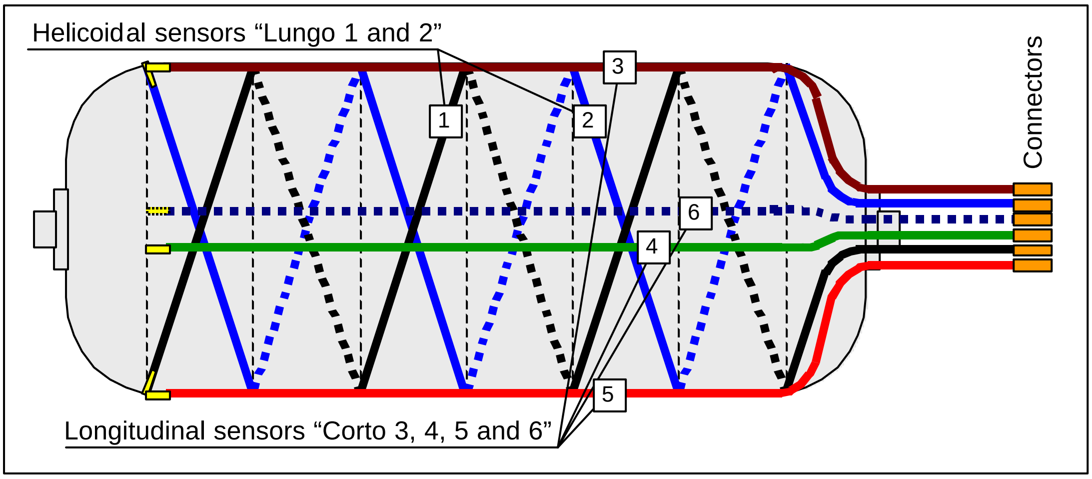

Fig. 7: Topology of sensors (SMARTapes) embedded in tank

6 TESTS DESCRIPTION

6.1 Introduction

Two groups of tests were performed, the first on non-damaged tanks and the second on damaged tanks. The presentation of all the tests exceed the topic of the paper and that is why they are all mentioned by only the most important are presented and discussed in details. The results of two tested tanks, named "A" and "B" are presented in this paper.

6.2 Test on non-damaged tanks

The following test were performed on non-damaged tanks:

1. Pressurization (static, step-by-step increase and decrease of pressure with simultaneous measurements)
2. Cycling (dynamic pressurization and depressurization with simultaneous measurements)
3. Temperature test (variation of temperature conditions of pressurized and non-pressurized tanks)

The aim of test was (1) to examine and learn the behavior of non-damaged tanks under different load conditions, (2) to test sensor performances under different load conditions and (3) to evaluate the sensors topology. The tests were performed in different places using the hydraulic pressurization. An example of hydraulic pressurization chamber used in test is presented in Figure 8.
The most significant test for the tank structural condition assessment was static "step-by-step" test. This test consists of increase of pressure from an established minimum value to an established maximum value with constant increments. When the maximum is reached, the pressure is decreased form the maximum to the minimum value, again with constant increments that are not necessary equal to the increments of pressure increase. For example, minimum value is 0 bars, maximum value is 250 bars, and increments (steps) for increasing phase can be 25 bars (10 steps) while for decreasing phase it can be 50 bars (5 steps). Thus, the parameters of this type of tests are the maximum and minimum values of pressure and increasing and decreasing steps. The increase and decrease of pressure is slow and measurements are performed when the pressure is stabilized. The pattern of this test is schematically represented in Fig. 9.

Fig. 8: Example of set-up used in test

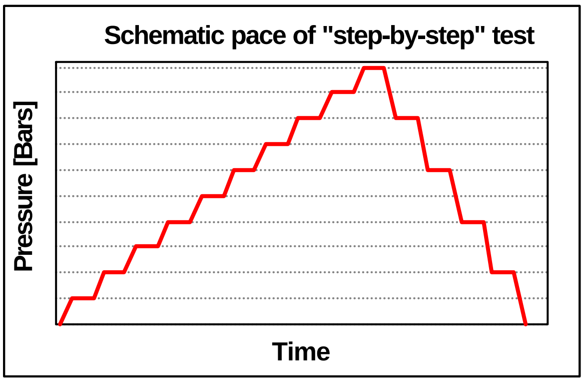

Fig. 9: Schematic representation of step-by-step test pattern

6.3 Tests on damaged tanks

Two types of artificial damage were applied to tanks:

1. Longitudinal and circumferential cuts
2. Controlled and uncontrolled shocks with hammer to low pressurized and non-pressurized tank that create internal delaminating

In both cases the damage was increased following prescribed schedule and after each increase a step-by-step test was performed. The specifications of the tests are given in Tables 2 and 3.

Table 2: Specifications of "cut" test

	No damage step-by-step	No damage cycling	Damage: circumferential cut, width 10 mm, length x depth given below		
			lxd=150x4 mm step-by-step	lxd= 190x4 mm step-by-step	lxd= 190x7 mm step-by-step
Tank "A", Pressurized to	300 Bars	350 Bars	300 Bars	250 Bars	200 Bars

Table 3: Specifications of "shock" test

	No damage step-by-step	No damage cycling	Damage: shocks, C-controlled, U-uncontrolled		
			5xC at 2 Bars step-by-step	5xC at 0 Bars step-by-step	5xC at 2 Bars + 5xC at 0 Bars step-by-step
Tank "B", Pressurized to	300 Bars	350 Bars	250 Bars	200 Bars	175 Bars (burst at 185 Bars)

The aim of tests was (1) to examine structural behavior of the tanks under different damage conditions and (2) to test the performance of the monitoring system and its ability to detect the damage. The damaging of the tanks is presented in Figures 10 (tank "A") and 11 (tank "B").

Fig. 10: Damaging of tank "A" (cuts) and view to damaged tank

Fig. 11: Damaging of tank "B" (shocks) and view to damaged tank after burst

7 TESTS RESULTS

7.1 Step-by-step tests of non-damaged tanks

As previously mentioned, the step-by-step test was essential to understand the structural behavior of the tanks. Since the analysis presented in this subsection is based on results obtained from global monitoring using long-gage sensors, the material of tank is observed at macro level. This means that all parameters are presented in terms of average values. An example of typical pressure-strain diagram obtained from the tests is presented in Figure 12. General observations taken from these tests are the following:

1. High linearity between the pressure and the average strain measured by SOFO sensors is noticed; the coefficient of linear correlation R^2 was better than 0.99 in all tests with few exceptions
2. Quantitatively comparable behavior of symmetrical sensors was registered, which means that the thanks were not subject to significant torsion and ovalization during the tests
3. Quantitatively comparable behavior was registered between the same type of sensors (longitudinal and hoop) instilled on different tanks (A and B) during the tests, which means that the thanks have approximately the same mechanical properties

The circumferential (hoop) and longitudinal reinforcing carbon fiber layers are approximately perpendicular to each other, and therefore the (average) Poisson's ratio is low. Absence of torsion and ovalization lead to conclusion that the shear strain in circumferential and longitudinal direction can also be neglected. Thus, the strain in circumferential direction of cylindrical part can be considered as constant over the cross-section. Due to different radial stiffness of the cylindrical part of the tank and the dome, the bending moments are generated at the interface of these two parts. These bending moments are localized at the interface plan and rapidly decrease along the cylinder. As a consequence the strain in longitudinal direction is not constant neither over the length nor over the cross section, and sensors measures its average value. The pressure-strain relation for each SOFO sensor can be expressed as (see Figure 12):

$$\varepsilon_S = f \times P + D \qquad (1)$$

Where: ε_S –average strain in sensor; f – coefficient of flexibility, P – pressure; D – shift.

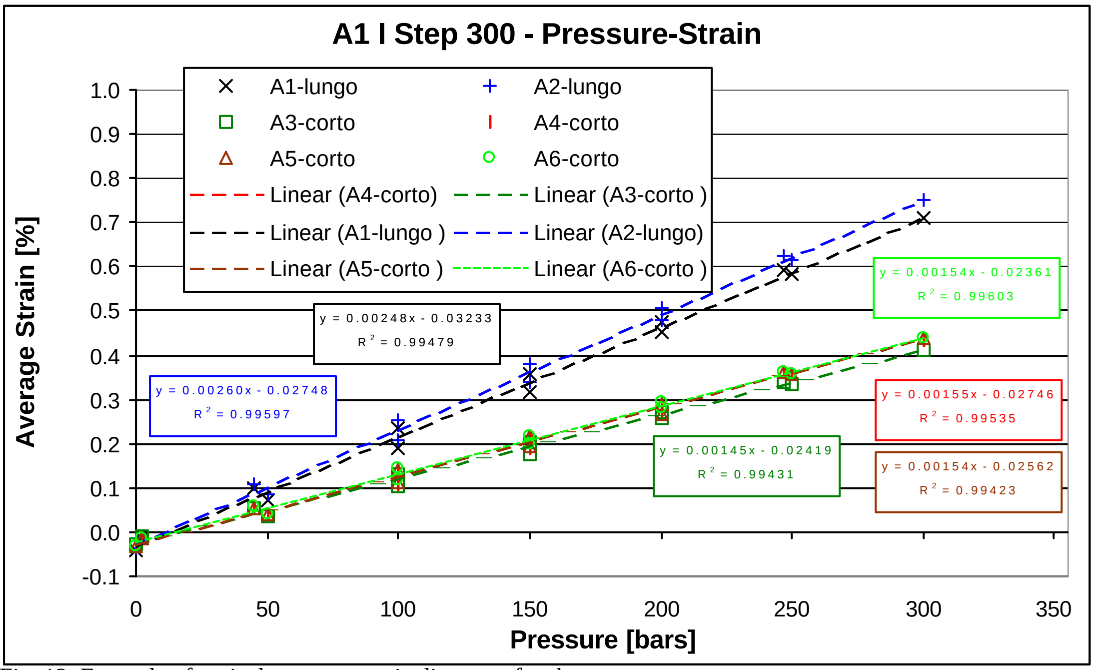

Fig. 12: Example of typical pressure-strain diagram of tanks

The value of coefficient of flexibility is very stable and repeatable after cycling of temperature tests and over long periods (measured after 6 months), while the value of the shift can vary, depending on magnitude of previous load, number of cycles, age and temperature. Since the flexibility is stable and repeatable parameter of tank, this parameters is particularly observed during the artificial damage tests.

The other important parameter, also very stable and repeatable, is coefficient of linear correlation between the sensors. It is determined for each sensor with respect to selected reference sensor. An example of diagram of sensors correlation is presented in Figure 13. Sensor Corto 6 is used as a reference.

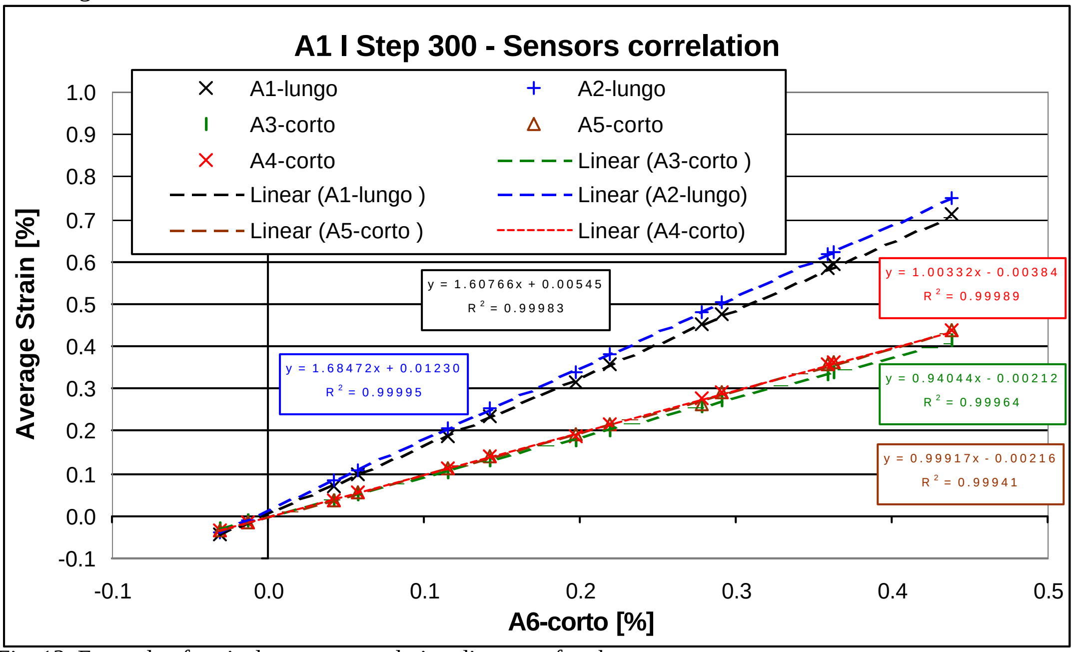

Fig. 13: Example of typical sensors correlation diagram of tanks

7.2 Damage detection

The artificial damage tests involved progressive damaging of tanks. The damaging was successfully detected and algorithms for its detection developed. The damage was assessed via monitoring system pursuing the following steps:

1. Coefficient of flexibility is determined for each sensor before the damaging
2. Coefficients of sensors correlation are determined before damaging; one sensor is kept as reference and correlation with each other sensor is determined
3. Coefficients of flexibilities and of sensors correlations are determined after each damaging step
4. Absolute and relative evolution of flexibilities and the relative evolution of sensors correlations are observed simultaneously; relative evolution represents the change in coefficients with respect to non-damaged state of the tank

The following indicators of damage were observed:

1. Increase of flexibility indicates damage
2. Increase of relative evolution of flexibility indicates damage
3. Increase or decrease of relative sensors correlations indicates damage
4. Separation of lines of sensors correlations indicates damage

All these indicators are presented in case of tank “A” in Figures 14 to 16 (see also Tables 2 and 3). Similar results are obtained in case of tank “B”.

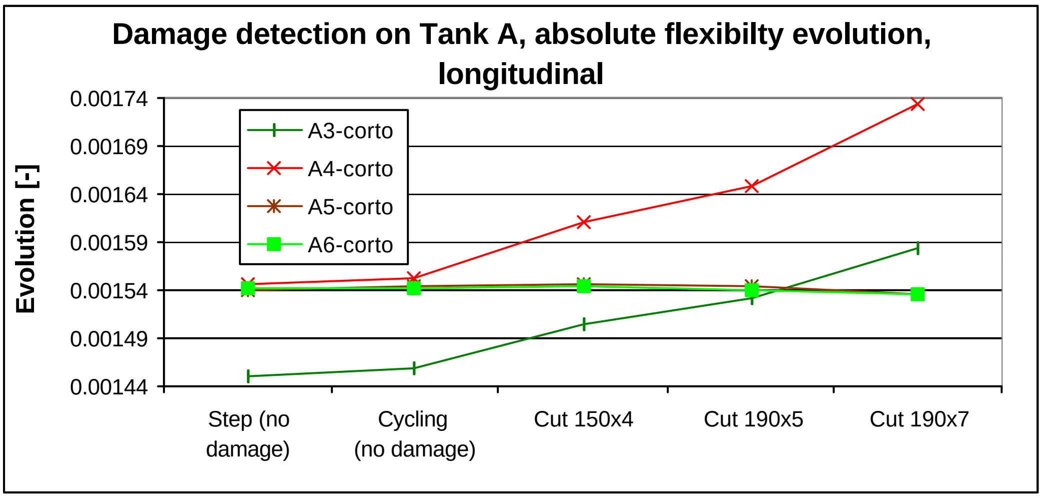

Fig. 14: Increase of absolute flexibility coefficients indicates the damage between sensors A3 and A4 (see Fig. 10)

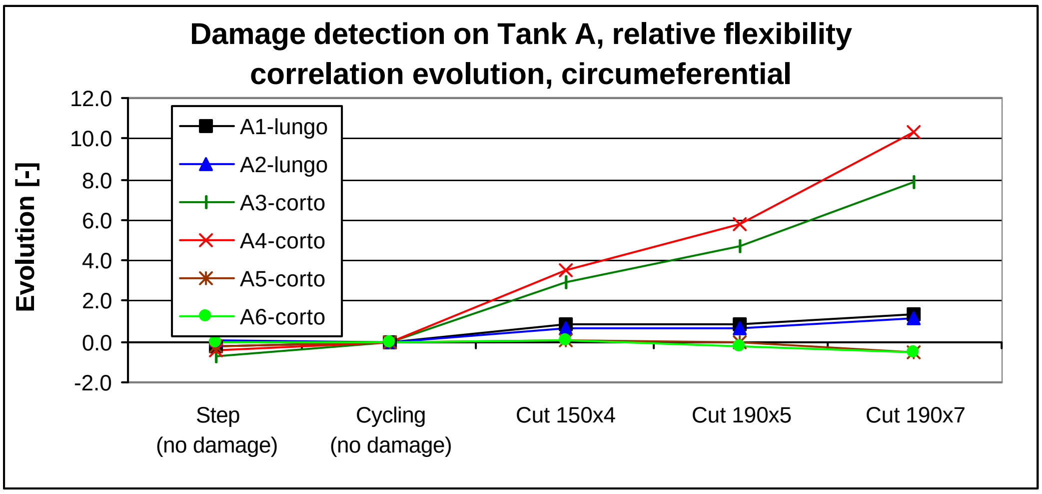

Fig. 15: Increase of absolute flexibility coefficients indicates the damage; hoop sensors are also slightly affected

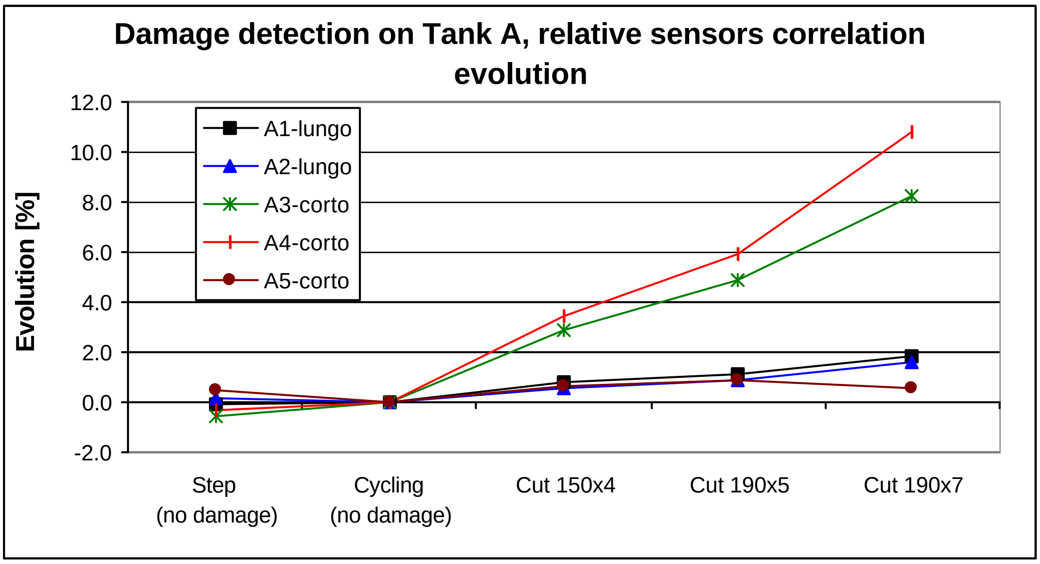

Fig. 16: Change (increase) of flexibility coefficients indicates the damage; separation of lines indicates damage too

8 CONCLUSIONS

Method for composite CNG tanks health monitoring was developed and presented. Development included development of monitoring strategy, sensors and installation procedures. Monitoring strategy consisted of selection of sensors topology and damage assessment algorithms. The method was laboratory tested and results have proven its performance at all levels. The damage indicators were identified and correlated with the damage during the tests. In the next phase of project, the system will be tested on-board, on tanks installed in prototype vehicle.

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