Structural Health Monitoring of Composite Structures using embedded PZT Sensors in Space Application

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ABSTRACT

The use of composite structures in the space domain has increased significantly over the past years owing to its high strength to weight ratio. Because of the criticality and huge amount of money associated with these missions, there is an urgent requirement to monitor the structural integrity and its degradation by novel SHM techniques.

In this paper we use ultrasonic guided wave technology and study the different possibilities of embedding piezoelectric sensors (PZT) into the carbon composites made by filament winding. We demonstrate the sensing capabilities of our developed sensor system to damages which can arise due to any accidental low-energy impact. A series of lab test was conducted on composite coupons to inspect the ability of PZT sensors to detect individual damages with high probability based on their distance from the impact location. The results show that PZT sensors are very promising in detecting all the damages caused by impacts with varying energies and can be a possible answer to needs of the structural health monitoring and non-destructive evaluation of advanced space structures.

1. INTRODUCTION

Composite materials are currently believed to be the cutting edge technology for the future space vehicles. There exist many different composite materials and many different ways of their manufacturing (Harris et al., 2002). The main advantage of composites is much lower weight and higher strength than classical metallic structures. Although they are utilized very often, there is still significant lack of understanding of their mechanical properties and related risks (Chiachio et al., 2012). Behavior of the composite materials is very complex and its proper investigation requires many experiments and theoretical modeling (Chiachio et al., 2013).

Composite structures manufactured for space industry must meet strict criteria because their failure could cause fatal damage of the vehicle. Among some of the most critical composite space structures belong pressure vessels, which store propellant. A Composite Overwrap Pressure Vessel (COPV) is a vessel with metallic liner overwrapped by nonmetallic fibers. Maximal operating pressure in standard COPV can reach up to 300-400 Bars and therefore the whole structure must be absolutely flawless otherwise it would cause immediate burst. Details about COPV design can be found in (Ni & Chang, 2012).

Currently, the COPVs for space industry are very carefully tested by various nondestructive techniques (NDT) directly after manufacturing. Apart from visual inspection, the COPVs are usually tested by acoustic emission, eddy currents, thermography, ultrasound, shearography etc. (Ni & Chang, 2012). These methods often require special test beds and highly skilled operators.

However, the flawless state of the COPV after manufacturing does not imply the same flawless state before its final inflation for launching to space. During transportation of COPV from the manufacturer to assembly place and also following installation to the spacecraft (satellite, rocket…) there is a risk of an accidental damage on the tank. Typically, it can be accidental tool impact during installation or collision of the tank with any other object. Although these accidents have quite low energies, their consequences can be fatal. From the security perspective, the COPV should be tested before launching. However, it is not possible by conventional NDT methods because the whole tank's surface is usually not accessible. Currently, this issue is mitigated by designing COPVs with security margins (winding redundant carbon layers …), which makes tanks more heavy and expensive.

Another way of avoiding this issue is installation of suitable sensor system directly into COPV structure. Data from these integrated/embedded sensors can be processed and used for testing presence of defect or damage without any direct access to the tank. This approach is known as Structure Health Monitoring (SHM). There are currently several technologies which are able to monitor COPV directly without human interaction and among some of the most promising ones are Fiber Bragg Gratings (FBG) and Ultrasonic Guided Wave (UGW) method. FBG technology uses sensors embedded in optical fibers and monitor differences in the local stresses. FBG sensors were successfully integrated between metal liner and composite overwrap or directly into the overwrap of COPV for instance by (Grant, 2005) or (Pereira et al., 2013). The UGW uses piezoelectric sensors and propagate ultrasonic waves through the structure. For general review of UGW see e.g. (Raghavan & Cesnik, 2007). This approach has been used for monitoring many different types of structures and damages (e.g. fatigue (Peng et al.,2012) or metallic liners of the COPVs (Ottaviano, 2013)).

The aim of this paper is to describe a series of experiments for detecting damages caused by low energy impacts by piezoelectric sensors (UGW) integrated in carbon fiber composite structures. These tests are designed to provide basic assessment of such detection system and its further possible use for structural health monitoring, condition based maintenance and fault adaptive control of COPVs (forced reduction of internal pressure etc.).

2. COPV DESIGN AND TEST SPECIMENS

Generally, COPVs consist of a metallic liner and a composite overwrap. Space applications usually use titanium liner because of its relative high strength, considerable corrosion and oxidation resistance and good fatigue characteristics. The liner's main purpose is to prevent propellant leakage. The composite overwrap is wound from high performance carbon fibers and coupled by epoxy resin. Usually, there are several layers of winding in two main directions: hoop and helical (Tam & Griffin, 2002). The top layer is sometimes covered by one more additional layer from glass fibers. The glass layer serves for protecting carbon layers and making the visual inspection of the tank surface easier. The proposed experiments were designed for investigating possibilities of embedded sensors between different layers of COPVs.

2.1. Test coupons

The test coupons for laboratory experiments were designed to represent only the carbon overwrap without the metal liner. The piezoelectric sensors have been embedded between various layers and their detection capabilities were verified. All the test coupons were cut out from a composite tube with diameter 226mm (see Figure **1**).

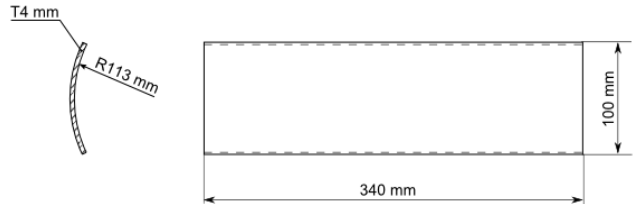

Figure 1. General drawing of the test coupon.

Several different composite layouts with different sensors placement were tested. The main differences between the specimens are in different thickness of the carbon layers, presence of glass layer and sensors' placement in between the different layers. Figure **2** shows one of the tested layouts. The bottom part of the depicted coupon consists of carbon helical winding. The top part is a glass layer and carbon layers with hoop winding. There are piezoelectric sensors (mounted on two flexible printed circuits) placed between the top and bottom part of the coupon.

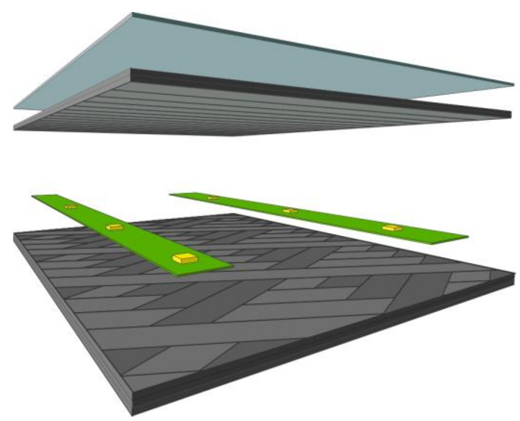

Figure 2. Example of a test coupon.

The manufacturing process of the coupons starts with winding composite carbon fibres T700 with helical layout (4 layers with fibres at 65˚) with no metal liner inside and then overwrapping it by radial winding (fibres in 90˚ with respect to the axis of the tube) in two further layers. The fibre/matrix material for each layer is carbon/epoxy it is additionally covered by glass/epoxy layer to provide protection to the real COPV. The prepared composite tube is cured at 40˚C and then it is cut to several pieces which are used as the test coupons.

2.2. Sensor system

The piezoelectric sensors are mounted on a thin flexible printed circuit (Kapton) to make the embedding process easier (replacing cables). The sensors are made of piezoceramic material (NCE51) and their dimensions are 5×5×0.5 mm. Each coupon contained 5-6 sensors distributed on two flexible strips. The strips are placed between selected layers (see next section) during the manufacturing process and covered by resin. Embedding sensors into carbon layers can significantly decrease strength of the overall composite structure but these experiments were intended mainly for verification of the sensors capabilities. The optimal layout for sensors would be subject of a consequent research and investigation.

3. EXPERIMENTS SETUP

Experiments were designed to investigate capabilities of piezoelectric sensors to detect low energy impacts. The manufactured test coupons went through a series of steel ball impacts with defined energies. Embedded sensors were used to collect signal before the impact and after the impact. The two signals were then compared to each other.

COPVs must withstand very high internal pressure that causes also high stresses in the carbon overwrap. This phenomenon was simulated in the test coupons by introduction of artificial tensile load. Each state of the structure (before and after impacts) was measured under several different tensile load levels.

Sensors are excited by 3 cycles of sinusoidal wave weighted by Gaussian window. Frequency of the wave is 200 kHz. The obtained signals are the values of voltage on the sensors recorded with respect to time. Sampling frequency is 12MS/s.

3.1. Processing of results

The detection is considered to be successful if signals measured under one physical state are similar to each other but different from signals measured under varied physical states.

For the sake of visualization, damage indices are computed for all measured signals by comparing them with the baseline signals. The damage index represents the observed variability (with respect to the baseline) and it is computed as overall energy extracted from Short Time Fourier Transform (window length 0.21ms). The visualization of the damage is consequently based on the computed damage indices and processed by adjusted version of WEMAT algorithm (Hedl et al., 2012). This algorithm triangulates observed damage indices on the whole plane. The extent and severity of the damage is not estimated directly from the data. The only analyzed information is its localization based on intensity of observed variability of the measured signals. Produced visualizations show estimated distribution of damage (source of the observed variability in the signals) in relative scale. Therefore it is possible to estimate position of the damage.

3.2. Experiments description

Three distinct test coupons were manufactured that mainly differ in sensor placement with each other (see description below). Each coupon was artificially damaged by impacts with different energies. Therefore, there is no direct comparison of the results between each specimen. The major outcome of the experiments is to examine how the ultrasonic waves interact with impact damages and what impact energies are provably detectable.

3.2.1. Test coupon 1

The first test coupon does not contain sensors embedded directly in the carbon layers. Sensors are placed below the final glass layer (see Figure **3**). The hatched layers represent carbon layers. The top white layer represents glass layer and the two gray rectangles represent piezoelectric sensors. This layout does not affect strength of the composite structure but perhaps the ultrasonic waves cannot reach the underneath deep layers to detect damages.

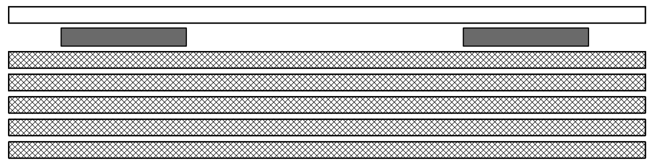

Figure 3. Schematic composition of the test coupons.

The coupon 1 was tested by two impacts with energy 14J. This energy is approximately related to an accidental impact of a tool with weight 1 kg dropped from a height of 1.4 meter. Each impact was aimed at different location to avoid interactions between the induced damages.

3.2.2. Test coupon 2

The sensors in the test coupon 2 were covered by one layer of carbon fibers and one layer of glass fibers (see Figure **4**). This layout slightly changes mechanical properties of the composite structure.

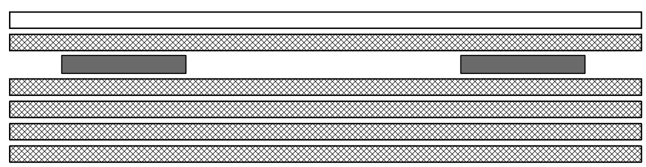

Figure 4. Schema of the test coupon 2 with sensors placed under one carbon layer.

The test coupon 2 was tested by two impacts with the same energy 6J. This energy is approximately related to accidental impact of a tool with weight 0.6 kg dropped from 1 meter height. The impacts were aimed at the same location as before to test the influence of progressively increasing damage.

3.2.3. Test coupon 3

The test coupon 3 has sensors embedded approximately in the middle of the coupon material thickness. The sensors are covered by two layers of carbon fibers and one addition layer of glass fibers (see Figure **5**).

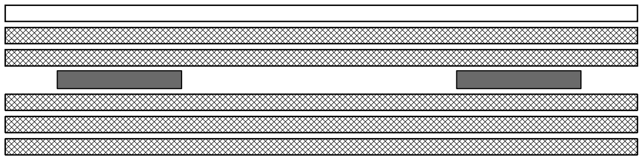

Figure 5. Schema of the test coupon 3 with sensors under two carbon layers.

There were tested three impacts to the same location and each impact has twice time higher energy than the previous one. Particularly, the tested energies were 6 J, 12 J and 24 J. This test was designed to investigate influence of rapidly expanding damage.

4. RESULTS

Each of the impact damages was measured by the embedded sensors and visualized by WEMAT approach. The resultant images show intensities of observed signal variability over the test coupons. The red color signifies higher damage than the blue on the scale of expected damage. One test coupon contains 8 sensors and therefore there are 28 different sensor pairs. The WEMAT images are constructed from damage indices calculated for these 28 pairs and interpolated on the whole surface of the test specimen. The white dot represents exact location where the impact took place. It is used for verification of the obtained results.

4.1. Test coupon 1

The sensor system embedded in the coupon 1 was tested by two independent impacts with energy 14 J. The impacts significantly damaged the top glass layer in a way that visual inspection can easily detect it. The sensor system provably detected and localized both impacts and the results can be seen in Figure 6 and Figure 7. Figure 7 represents the observed damage by the second impact only, which means that it does not represent cumulative damage caused by both impacts together.

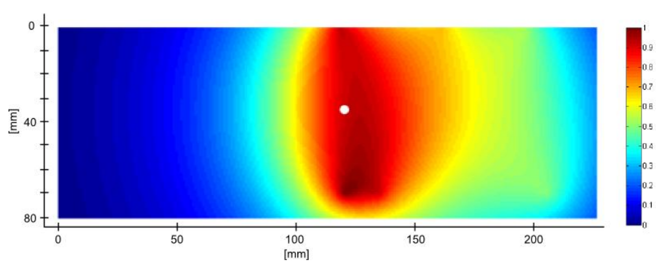

Figure 6. Test coupon 1 – first impact (14 J).

The observed variability in the signals could be caused only by the damage of the glass layer and therefore it is unclear whether this impact also broke the carbon fibers in the underneath layers. In this application, it is not crucial to monitor defects of the glass layer because it serves only for protecting and inspecting purposes. On the other hand, damages in the carbon layers are critical from the perspective of the overall strength of material and therefore they must be monitored very carefully. Nevertheless, due to significant extent of the damage, it is expected that the carbon layers suffered by damage too.

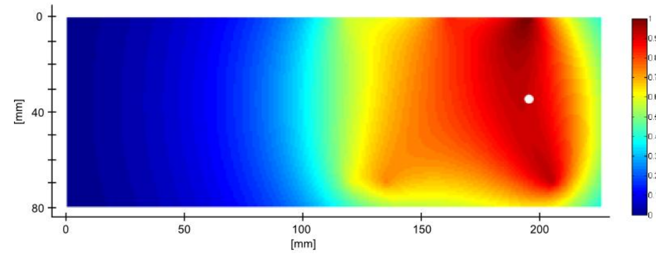

Figure 7. Test coupon 1 – second impact (14J).

4.2. Test coupon 2

The test coupon 2 contains sensors under the last carbon layer. The energy of impacts was decreased (in comparison to the test coupon 1) to 6 J and the impact was repeated with the same energy at the same location. The result of the first impact can be seen in Figure 8. The result indicates that the biggest damage is located 3 cm from the actual impact location. There are two possible explanations for this fact. The first one is that the impact really caused bigger damage in more distant locations (e.g. debonding of layers), and the second explanation is related with resolution of sensor system itself. It is not possible to perfectly localize all the possible damages by only eight sensors and therefore the obtained results must have some limit resolution. In whichever case, the results can be considered as successful and the detection is provable (if obtained precision is good enough for intended application).

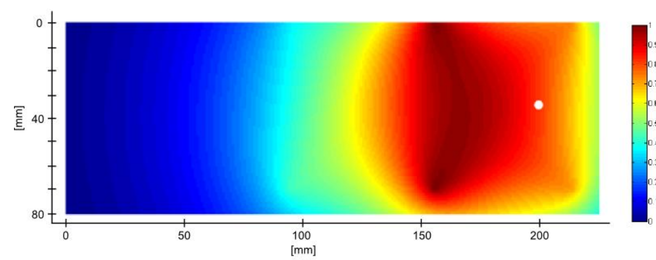

Figure 8. Test coupon 2 – first impact (6J).

On the other hand, the second impact (same place and same energy) was not detectable at all. The damage did not increase its extent and therefore the measured sensor responses are exactly as same as after the first impact.

4.3. Test coupon 3

The third test coupon has the sensors embedded under two carbon layers, which mean that they are located approximately in the middle of the coupon's thickness. The results from the first impact (6J) are comparable with the results from the first impact on the test coupon 2 but with more precise localization.

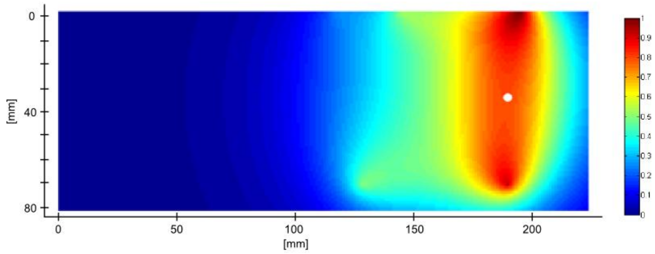

Figure 9. Test coupon 3 – second impact (12J).

Figure 9 shows results from the second impact 12J (same location as the first impact). The damage is very precisely localized and detection is provable. The results show that the second impact significantly damaged the test coupon (unlike to the test coupon 2) and the embedded sensors were able to detect it even from more substantial depth. The third impact (24J) has the same characteristics but with wider detected extent of the damage. All three impacts were successfully detected and moreover the magnitude of the observed variability in the signals was increasing with increasing energy of impacts.

5. CONCLUSION

This paper summarizes results from conducted experiments on test coupons, which were designed as a simplified representation of the composite overwrapped pressure vessel. These experiments investigate possibility of detecting low energy impacts by embedded piezoelectric sensor system.

In general, pressure vessels operate under very high internal pressures and therefore even very small damage can lead to critical consequences. It was shown that these small damages can be detected and localized by comparing measured ultrasonic signals with their baselines.

The investigated test coupons contain sensors in three different layouts and the main difference between them is in depth of their placement. All the three layouts were able to detect all the tested impacts (from 6J to 24J) but the sensitivity is generally better when the sensors are closer to the surface.

These experiments proved that health monitoring of carbon composites is feasible and they opened a way for developing complete monitoring system. The main advantage of using such system would be obtaining quick and reliable information about current state of the composite structure. This information can be further utilized for condition based maintenance or fault adaptive control. Composites and COPVs are extensively used in space industry, which requires the highest level of intelligent and autonomous systems. Currently, there is no known issue, which would prevent using this technology in space. Therefore, there are several possibilities how to use the collected information for better and safer operations of spacecrafts.

Conducted experiments have demonstrated possibilities of detecting and localizing low energy impact damages. Further research should focus on determining the type and extent of these damages and estimating their severity.

ACKNOWLEDGEMENT

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