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Application of complementary optical methods for strain investigation in composite high pressure vessel

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ABSTRACT

The work presents the methodology of displacement and strain measurements (in type IV composite high pressure hydrogen and methane storage vessels in areas of the gaseous fuel cell vehicle. The research was conducted in vessels with so called programmed defects in the form of notches and delamination. The complementary optical methods, namely: optical fibre sensing based on Bragg gratings (FBG) and digital image correlation (DIC) method were used for performing local and full-field displacement/strain measurements respectively. It has been shown that DIC can be successfully applied as the method for defect identification in full field of view and that it can support an optimal localization of FBG sensors and their calibration. As FBG sensors are devoted to be integrated with the vessel structure, the proposed methodology constitutes a solution to the difficult problem of building an efficient Structural Health Monitoring (SHM) system for composite high pressure vessels for gaseous fuels. At the same time the measurement data from both systems supports calibration of numerical models of the vessels.

1. Introduction

Composite high pressure vessels are more and more frequently used in automotive industry, aviation, emergency services and power industry. This results from their advantages such as high strength/stiffness-to-weight ratio [1], and excellent resistance to fatigue and corrosion [2,3]. The main area of composite vessels applications is gaseous fuel storage: hydrogen (CH2 vessel), methane (CNG vessel) or their blends. Hydrogen is used mainly in fuel cells (FC). The latest CH2 vessels allow to compress hydrogen at 70 MPa. High pressure enables to provide, despite of low hydrogen density, an appropriate amount of the fuel at reasonable volume, making it possible for a vehicle to cover a range of 600–700 km on one refuelling.

According to the current regulations [4,5], in the case of CH2 vessels, 70 MPa Nominal Working Pressure (NWP), made of the carbon-epoxy composite (CFRC), the Burst Pressure (BP) cannot be lower than 157.5 MPa. In the case of structures reinforced with glass fibre (GFRC) the required BP reaches 255.5 MPa. It means that the material of the vessels with compressed hydrogen or methane works in high-effort conditions which requires monitoring of the health of these structures. Although the binding legal regulations [4,6] require the vessels to undergo periodical checks only, however several currently conducted works [7,8,9,10] aim at applying continuous monitoring. This may allow to decrease high safety coefficients of vessels with a SHM system, including a decrease of their weight and hopefully their costs.

The analysis of recent literature [7,8,11,12,13,14,15,16] and Internet sources [9,10],shows that the best solution is using optical fibre sensors for this purpose. The reason is their resistance to electromagnetic interference, intrinsic safety, easy integration with composite material structure and high sensitivity in a long term measurement. These sensors are permanently fixed on the vessels surface or embedded in the structure of composite material and allow to continuously control technical condition throughout the whole exploitation period. Moreover, apart from embedding in the composite structure, they allow to assess and control the whole manufacturing process (e.g. initial strain, initial fibre tension, hardening temperature, internal pressure) [1,14].The basic measurement technique used in the analysed works is the fibre-optic technique using sensors with luminous wavelength modulation, the so called Bragg Grating, FBG) [1,8,11,12,13,16,17,18]. Other FO sensors, such as interferometric ones, SOFO®, Fabry-Perot (F-P) type [15,19,20], or distributed sensors [21] are less often applied for this purpose.

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The works on applications of optical fibre methods for strain measurements in vessels [8,11,12,13,16] so far have mostly referred to low pressure vessels with thin walls. However, it is of key significance that in the case of CH2 composite vessels with nominal operating pressure 70 MPa, the thickness of the carrying wall of the vessel can be even from 20 up to 50 mm. Hence, in the case of such complex structures the measurement of construction strains in many places, including also on the wall thickness becomes necessary. An introduction of other than optical fibre sensors (with a small cross-section diameter) between the subsequent composite layers results in initial defection of the composite material (a kind of notch). In the case of strain gauge sensors, which are sometimes used, local structure discontinuity occurs (e.g. local delamination) which can be precursors of a fault development during vessel exploitation (cyclical refuelling and using up the fuel in vessels).

On the other hand, there are numerous works in which optical measurement methods are used to analyse strains in composite materials to provide information about a structure behaviour in a full field of view [22]. The most commonly used methods encompass highly-sensitive techniques using coherent light (digital speckle pattern interferometry DSPI and digital speckle pattern shearing interferometry DSPSI [23], grating (moire) interferometry GI [24]) and incoherent light, with lower sensitivity, among which currently the most popular is the digital image correlation method [25]. The major advantage of these techniques is the possibility of simultaneous detecting in full-field of view heterogeneities in a composite material which occur due to different phenomena: defects or cracks within material, mechanical set-ups causing parasitic effects, strain gradients due to distributed mechanical properties. The major disadvantage (due to architecture of interferometric and vision based systems) is connected with difficulties in implementing these techniques for long term monitoring during exploitation of composite structures under investigation.

The above consideration has clearly indicated the necessity to develop a new non-destructive methodology of measurement and monitoring of strain distribution in composite, high-pressure vessels type IV (polymer liner, operating pressure up to 70 MPa) assigned for storage of compressed hydrogen and methane. This methodology should take into account the following requirements:

- ensuring necessary measurement data for the identification of vessel numerical models, additionally these data should “cover” the vessel surface as densely as possible,
- definition of the areas with the biggest effort (critical ones) in the whole vessel and thereby indication of sensor locations,
- continuous diagnostics of a vessel in a vehicle during long lasting exploitation (on-board monitoring system), including refuelling and periodical diagnostics,
- independence of strain measurement of the influence of ambient temperature,
- strain measurement in vessels of various geometry and dimensions (various applications of vessels: automotive, stationary, transportation),
- ensuring measurement of relatively large deformations (in comparison with the ones occurring in metal vessels) and high sensitivity in a wide measurement range,
- guaranteed resistance to electromagnetic interference, spark-proofness and easy integration of sensors with composite material structure,
- defect identification in a vessel resulting from random events and progressing degradation of composite strength parameters due to e.g. fatigue,
- ensured validation of SHM used for a vessel.

Unfortunately, there is no a single measurement method which would satisfy all the above requirements. This is why we have proposed to develop a “hybrid” measurement and data analysis procedure which applies two different optical methods, namely:

- digital image correlation method (DIC) for full-field, global strain determination at the whole surface of a vessel in laboratory conditions;
- optical fibre sensors, FBG type for point-wise, local strain measurement and monitoring during exploitation of a vessel.

The combined use of these methods should allow to benefit from the advantages of each of them, simultaneously discarding their particular limitations.

The application of DIC method, which is mainly a laboratory one, allows to indicate the most critical areas of a vessel, particularly important for its security and exploitation. At these identified locations the FBG sensors, used for “on-board” monitoring of a vessel, will be installed.

The paper is organized as follows: in Section 2 the fundamentals of both methods are described. Next (Section3) the methodology of investigations performed by the combined methods is described. In Section 4 the results of experimental works together with their discussion are presented. Finally, the conclusions and further works are outlined.

2. Displacement and strain measurement in composite structure investigations

2.1. 3D digital image correlation method

Digital Image Correlation is the well-established method for displacements, strains and shape measurements [25]. 2D DIC (with one digital camera) and 3D DIC (with two digital cameras) variations of the method are widely used and accepted in the field of experimental mechanics [26,27]. The general operation diagram for 2D DIC and 3D DIC methods is shown in Fig. 1

The straightforward measurement procedure requires to acquire a set of images of an object under investigation which is subjected to any kind of load. One of the images is selected as a reference image (in most cases an image acquired before the load is applied) and the remaining images are subjected to the correlation analysis. The reference image is divided into small sub-images or subsets. The subsets are subsequently matched against similar subsets in images acquired in different load states. Repeating the procedure for all subsets from the reference image

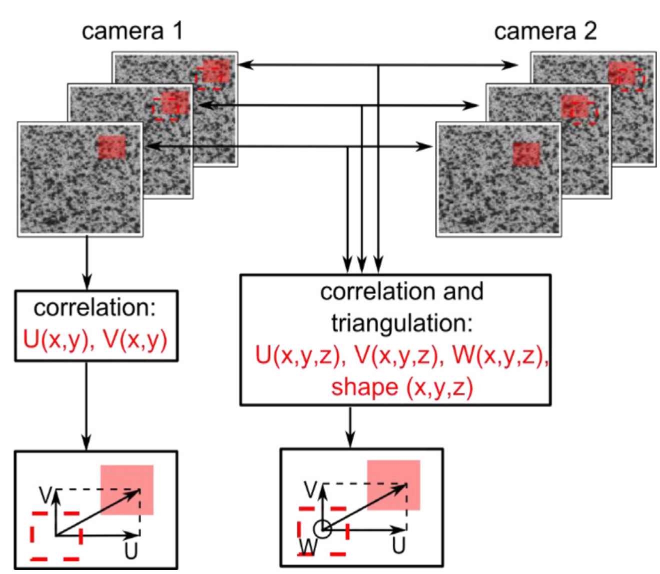

Fig. 1. General DIC method operation diagram: 2D DIC system uses one camera to determine in plane displacements U(x,y) and V(x,y), while 3D DIC system uses two cameras to determine in-plane U(x,y), V(x,y) and out-of-plane displacements W(x,y) and the shape (x,y,z) of a tested object.