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Application of an experimental modal analysis on composite pressure vessels for monitoring prestress conditions

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ABSTRACT

Due to high specific stiffness, fibre reinforced plastics are the dominant material group for the design of mobile pressure vessels. At the Federal Institute of Materials Research and Testing (BAM) aging process of composite pressure vessels is studied to be able to give more accurate lifetime predictions in future. Investigations are based on type III breathing air cylinders consisting of an aluminium tank which is fully wrapped with carbon fibre reinforced plastics. Goal is to detect changes of residual stresses over life time which directly affect fatigue strength. Within this paper an approach is presented to monitor residual stresses via an experimental modal analysis (EMA). First, the influence of changed stress conditions on modal parameters is analysed via a numerical study. Secondly, a test bench for an EMA is set up. To be able to analyse cylinders of different prestress condition, several specimens are prestress modified via high-temperature and high-pressure treatment. During modification processes, specimens are monitored via optical fibres to control prestress modifications. Through experimental measurements of the modified specimens via EMA changes in prestressing can be detected. Finally, validity and accuracy of the EMA is evaluated critically by comparing all numerically and experimentally obtained data.

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1 INTRODUCTION

Through technological progress in material science and the associated application of new materials and material combinations, light weight constructions are becoming of increasingly interest for the major part of all industrial sectors. Within the pressure vessels industry, the design of lightweight constructions is already state-of-the-art. Especially the usage of fibre reinforced plastics (FRP) is getting more and more popular as it provides weight advantage and high stiffness properties by the same time. However, with the application of these comparably new material group, degradation behaviour is not studied satisfactorily yet. Additionally, complex interactions between multiple materials of a hybrid construction do complicate assumptions according to the degradation process. Hence, accurate lifetime predictions are not possible. As federal institution for the public technical safety, the Federal Institute of Materials Research and Testing (BAM) investigates questions of material and fatigue behaviour of the mentioned structures. The presented paper stands in context to the current research project “COD-AGE” in which aging behaviour of composite pressure vessels is studied. For test specimen, type III breathing air cylinders are used which consist of an inner aluminium tank, defined as liner, which is fully wrapped with a carbon fibre reinforced epoxy composite. This type of pressure vessel features residual stresses which influence life time duration significantly.

Aim of this work is to develop a non-destructive analysis method based on an experimental modal analysis (EMA) to capture and monitor residual stresses according to aging process.

2 RESIDUAL STRESSES IN TYPE III PRESSURE VESSELS

When focusing on the question of lifetime prediction, first, the main cause of failure needs to be defined. Analysing the hybrid materials of a type III pressure vessel, service live is limited by fatigue strength of the metallic liner part. Failure is typically caused by an axial crack in the aluminium liner[1-2]. In order to increase load cycle strength of the aluminium, compressive residual stresses are induced into the liner during manufacturing process via autofrettage[3-4]. During this process, a high-pressure load is applied to the vessel which causes a permanent plastically deformation of the liner. Because of its higher strength properties, the composite reinforcement only deforms elastically. Consequently, under zero-load condition elastic restoring forces of the reinforcement cause compressive stresses inside the liner. Relying on the boiler equation, the permanent induced prestress features a 2:1 ratio between circumferential and axial direction[5].

Due to aging effects in liner and composite, residual stresses will decrease with increasing service live[6-8]. Especially degradation effects of the polymer may cause a relaxation of the reinforcement and consequently reduce inner prestress conditions. To measure prestressing in complex structures, mostly only damaging test methods can be used, e.g. via strain gauges[9]. Using this method, first, a strain gauge is attached on the surface of the affected structure. After having cut out the area including the strain gauge, the released part will either stretch or contract. Hence, magnitude and direction of the initial residual stress can be determined. Applying this technique, a decrease of 25% to 50% of the initial prestress condition has been determined by measuring 15-year-old pressure vessels which had already reached its end of service life. In order to determine the reduction of residual stresses according to its aging progress, the use of a non-destructive measurement technique is aspired. For measuring technique an EMA is chosen where the influence of prestressing on modal parameters is analysed.

3 FINITE ELEMENT SIMULATION

3.1 Set-up of the finite element model

In order to detect prestressing, the structural response of the cylinder is analysed, based on the modal parameters stiffness, mass and damping. As prestressing affects structural stiffness it can be detected via a modal analysis. To reproduce the complex dynamic behaviour of a composite pressure vessel, a detailed finite element (FE) model is set up via the commercial code ANSYS.

The designed FE model consists of 70.000 20-noded Solid186 elements exhibiting a quadratic displacement behaviour[11], illustrated by the left part of Figure 1. Liner and composite reinforcement are designed as separate parts and merged into one final assembly. The composite part consists of 14 different layers of carbon fibre reinforced plastics (CFRP). All layers feature orthotropic material behaviour according to individual fibre orientation and layer thickness derived from the examined specimen. The liner part consists of isotropic aluminium material considering variable wall thickness in axial direction. Both, liner and composite part, are bonded via multiple point constraints in order to neglect influences of changing contact stiffness under different load and prestress condition. Influences of other contact formulations has been discussed previously[10]. Furthermore, the model is constrained with a flexible support.

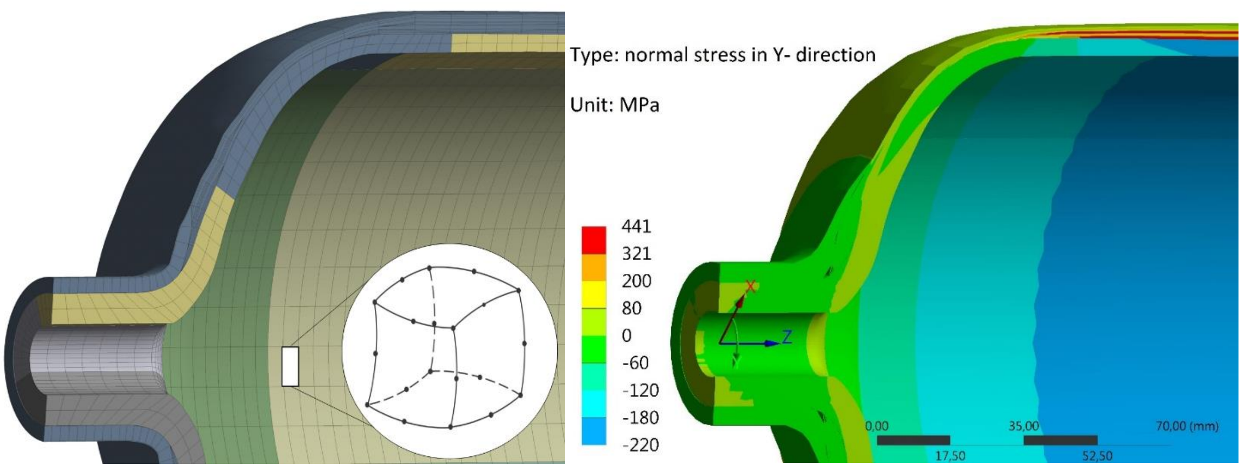

Fig. 1 - Composition of the used 20-noded SOLID186 element type[11] and the merged FE model; Initial stress distribution inside the hybrid structure of a type III pressure vessel

In a first step, a structural analysis is run to simulate the initial stress condition inside the whole hybrid structure. Residual stresses have been implemented through the application of thermal loads into the liner part, only. The resulting stress distribution is illustrated by the right picture in Figure 1. It shows compressive stresses in the liner part, indicated by blue colours, and tensile stresses in the FRP (red-yellow colours).

In the following, a modal analysis and a harmonic structural response analysis are performed to determine influences of different prestress conditions on the dynamic behaviour. Principle of these studies is the fundamental equation of motion (Eqn. (1)) which characterises stiffness (K), mass (M) and damping (C) of the structure and considers all outer forces (F).

$$[M] \cdot \{\ddot{u}\} + [C] \cdot \{\dot{u}\} + [K] \cdot \{u\} = F \qquad (1)$$

Via modal analysis, eigenfrequencies are obtained through the solution of the eigenvalue problem based on the equation of motion of a free and undamped multiple-mass oscillator, expressed by Equation (2). Doing this, Equation (1) needs to be uncoupled and damping is neglected.

$$[M] \cdot \{\ddot{u}\} + [K] \cdot \{u\} = 0 \tag{2}$$

Considering prestressing, stress stiffening effects of the structure are first calculated within the static analysis and stored inside a stress stiffness matrix [S]. In the following, the stress stiffness matrix is included into the global stiffness matrix as shown by Equation (3)[12]. Consequently, when solving the eigenvalue problem and extracting modal parameters, influences of prestressing are considered.

$$[M] \cdot \{\ddot{u}\} + [K + S] \cdot \{u\} = 0 \tag{3}$$

Based on the calculated eigenvalues, a frequency response function (FRF) is obtained via a harmonic analysis considering material-damping and a harmonic excitation. The resulting FRF gives an overview of the structural response of the model over a specific frequency range.

3.2 Results

Representing a brand new and an old pressure vessel, states of the two different prestress conditions are calculated. The implemented residual stresses inside the cylindrical part of the liner are set to -200 MPa/ -110 MPa and -150 MPa/ -85 MPa (new and aged condition, stress in circumferential/ axial direction). Subsequently, solutions are calculated and compared with another.

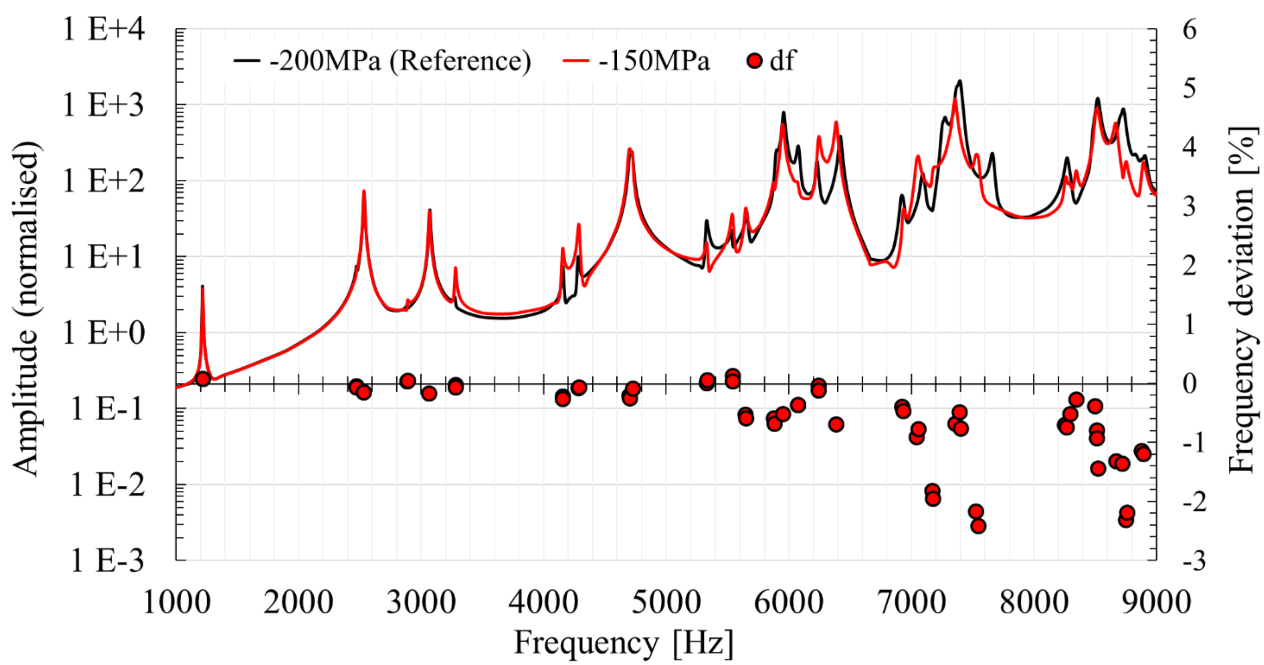

Fig. 2 – Calculated FRFs and related resonance shifts up to a frequency of 9000 Hz according to a reduced prestress condition of 50 MPa.

The FRFs are determined via prestressed harmonic analysis within a frequency range up to 9000 Hz. Results are illustrated in Figure 2. The upper graphs illustrate the resonance spectrums of a new (black line) and stress-reduced vessel (dotted red line), showing amplitude over frequency. It is shown that a prestress modification results in a shift of resonances. The dedicated relative values of frequency deviation are shown over frequency and are illustrated by the red points below the graphs.

For most resonances a lowered prestressing results in lowered frequencies. Prestress sensitivity of affected resonances clearly increases with increasing frequency. Hence, highest influence can be detected for resonance frequencies > 7000 Hz. In contrast, there are multiple remaining resonances which are less influenced by prestress modifications, even within the higher frequency range.

4 EXPERIMENTAL MODAL ANALYSIS

4.1 Set-up of the test bench

Based on the findings which have been obtained via FE simulation, a test bench for an EMA is set up as shown in Figure 3. The aim is to prove the influence of prestress modification on the structural response as already shown by numerical simulation. Analogue to the flexible FE boundary condition the pressure vessel is bedded in soft foam as illustrated. The cylinder is excited via modal hammer which hits the pressure vessel at the top and the middle side of the cylindrical part as well as at the rear end of the cylinder. Analysing the excitation signal a frequency range up to 9000 Hz is covered. Resonances of higher frequencies cannot be excited strong enough to receive a measurable response signal. Hence, the presented EMA is limited to a maximum frequency of about 9000 Hz. To observe system response three acceleration sensors are applied on the outer surface as illustrated. All signals are processed via a 4-channel measuring card which is connected to a PC with corresponding software.

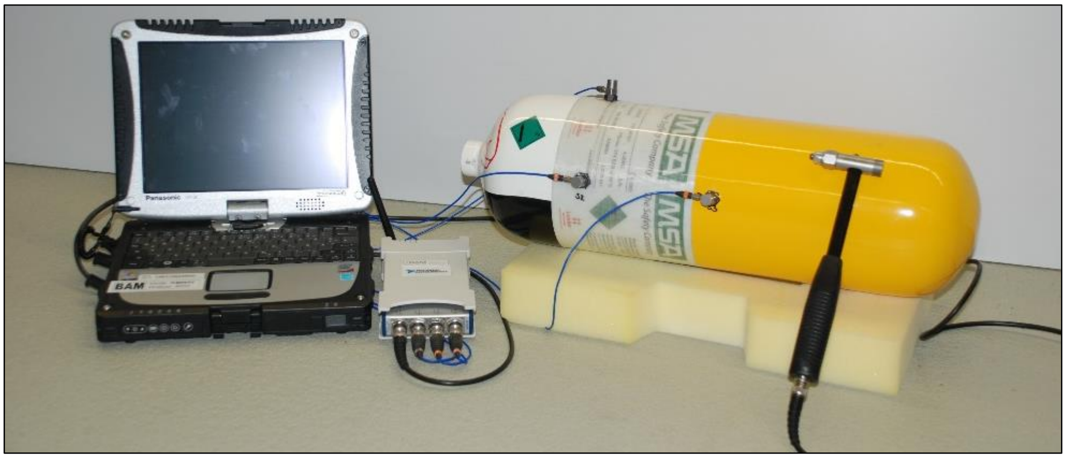

Fig. 3 – Experimental set-up of the test bench for an experimental modal analysis.

Each measuring cycle consists of 50 to 60 single measurements where the cylinders are excited via modal hammer at the three given points. Measurement inaccuracies as well as noise are reduced significantly by sorting and averaging captured data.

After having recorded all signals within the time domain, input and output signal are transferred into the frequency domain ($E_{j(\omega)}$, $A_{i(\omega)}$) via Fast-Fourier-Transformation (FFT).
In the following, the transfer function $H_{ij(\omega)}$ is calculated according to Equation (4).

$$H_{\mathrm{ij}(\omega)} = \frac{A_{\mathrm{i}(\omega)}}{\mathrm{E}_{\mathrm{j}(\omega)}} \tag{4}$$

The measuring campaign consists of three breathing air cylinders of the same design type which are analysed via EMA. To be able to measure different states of prestress condition all specimens are prestress modified during the measuring campaign.

To reduce the initial prestress condition a relaxation of the composite material is aspired. This is realised via creep test where a high-pressure load is applied to the cylinders for 100 hours under high temperature. Creep tests are common procedures to accelerate aging of composite materials[13]. However, temperature must not exceed glass transition temperature T_g of the epoxy resin to ensure constant physical properties of the composite material. The glass transition temperature of the used epoxy was estimated to be about 95 °C[14]. Hence, maximum temperature of the creep test was set to 85°C. Furthermore, pressure and temperature loads must not cause a yielding of the metal liner. Consequently, maximum pressure was limited to 500 bars. Table 1 gives a summary of the chosen test parameters.

Table 1: Applied process parameters of the creep test

PRESSURE LOAD [bar]	TEMPERATURE [°C]	LOADING TIME [h]	EST. STRESS REDUCTION (φ-direction)
500	85	100	20 MPa

The distributed strain of specimen A is monitored using a surface applied optical fibre in order to receive information about the structural behaviour during the creep test as well as to capture permanent deformation. The optical fibre is attached on the outer composite surface of the cylinder covering the whole axial length as well as approximately 300° of the circumference of the middle part of the cylinder. Resulting changes in prestressing can be estimated from the determined strain data as well as from geometrical and stiffness properties of the hybrid structure.

Figure 4 shows the circumferential permanent deformation measured after the creep test in the middle of the cylindrical part of specimen A. When analysing the strain information, local discontinuities over the whole circumference of the cylinder are visible. Shown discontinuities rely on the orthotropic material properties of the FRP and are manly related to the fibre orientation of the outer composite layer. Due to the multi-layered set-up of the composite reinforcement it is assumed that strain amplitudes are reduced inside the subjacent layers. Hence, only the mean value of the measured discontinuous deformation curve is used to estimate related changes of prestress in the liner. However, local discontinuities of the resulting prestress inside the liner may occur but are initially neglected in this study.

The very right column of Table 1 shows an estimated change of prestress of the liner in circumferential direction. Although only specimen A was equipped with optical fibres, similar changes in prestressing can be assumed for specimen B and specimen C due to similar test conditions.

Before having modified the specimens, reference measurements have been done to capture its initial structural behaviour via FRF. In the following, results of the post-modified measurements are compared to the initial spectrums in order to obtain changes of the structural response.

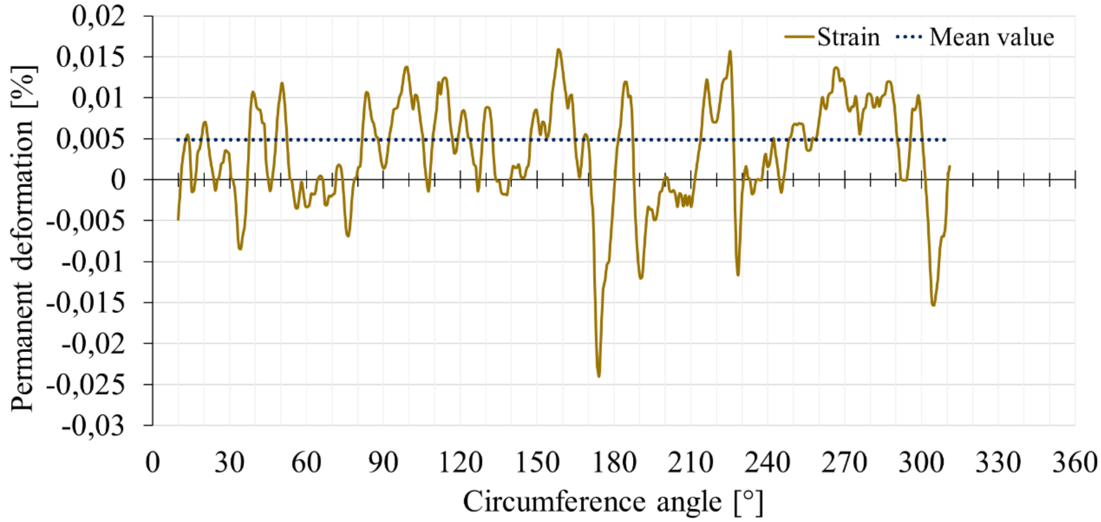

Fig. 4 – Remaining circumferential strain of a type III pressure vessel after creep test measured on the composite surface.

4.2 Results

Three breathing air cylinders have been measured via EMA in order to determine its individual FRF and to detect prestress modifications. All specimens are measured in new as well as in modified condition. Subsequently, results are compared to each other. Figure 5 shows a section of the experimentally determined FRFs of specimen B before (black line) and after (red dotted line) the creep test.

When comparing both graphs, a left-sided shift of the FRF can be observed in regions close to resonances. Especially resonances between 6000 Hz and 6500 Hz and above 7000 Hz are decreased in frequency according to the loss of prestress. All relevant resonances are labelled (A1 – C2). Remaining resonances are not or only slightly altered. Because of the restricted number of sensors, not all existing resonances could be captured.

When analysing the FRFs of the remaining specimens, a similar trend can be observed. Analogue to specimen B, a reduction of the resonances frequencies for specimen A and specimen C after the creep test is determined, too.

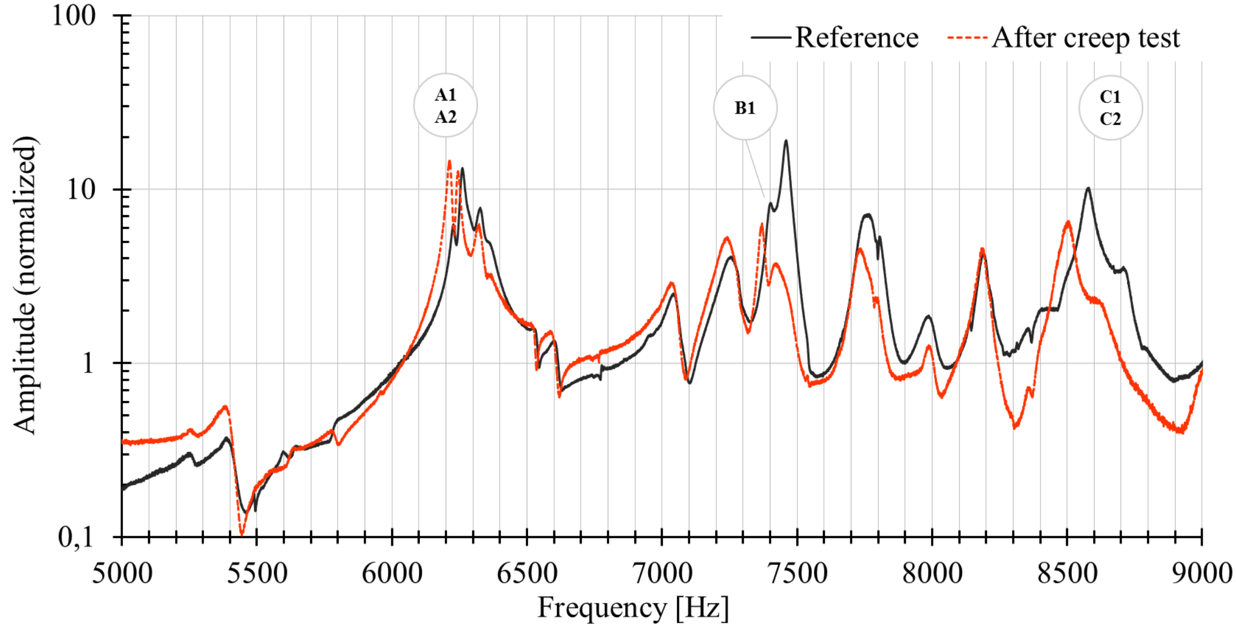

Fig. 5 – Frequency response functions of specimen B in new and aged condition in a frequency range from 5000 Hz – 9000 Hz

Table 2 shows frequency changes of selected stress-sensitive resonances of all specimens related to its prestress modification. As explained earlier, estimated stress deviations of specimen B and specimen C (stated in brackets) are not measured directly and are adopted from specimen A. It is shown that a prestress reduction results in lowered resonance frequencies. When comparing results, identical resonance modes seem to react with different sensitivity on the individual prestress modifications.

Specimen A shows the highest frequency change in average when comparing all specimens with another. Hence, it can be assumed that prestresses in specimen A have been reduced comparably most.

Table 2: Frequency shifts of selected resonances according to the applied prestress modification.

	EST. STRESS REDUCTION (φ-direction)	RESONANCE FREQUENCY SHIFT (EMA) [%] (Resonances according to *Fig. 6)* A1	A2	B1	C1	C2
SPEC. A	-20MPa	-0,4	-0,6	-0,6	-1,5	-1,7
SPEC. B	(-20MPa)	-0,2	-0,3	-0,4	-0,9	-1,1
SPEC. C	(-20MPa)	-0,1	-0,3	-0,4	-0,8	-0,2

5 CONCLUSIONS

Within the presented work an approach is shown to detect modified stress conditions in type III pressure vessels via an EMA. To study the dynamic behaviour, first, a precise FE model was set up. Based on numerical results, the influence of a stress modification on the modal parameters was analysed. A correlation between prestress resonance frequencies was found. Decreased prestress mainly results in decreased resonance frequencies, prestress sensitivity generally increases with increasing mode number and frequency. Furthermore, stress-sensitive modes were identified.

Based on numerical findings, a test bench for an EMA was set up. Within a case study, three type III breathing air cylinders of the same design type were modified in its initial prestress condition via creep test. All specimens had been measured in reference and modified condition via EMA in order to obtain its characteristical FRF. Additionally, strain behaviour was captured via optical fibres during modification process to be able to estimate values of changes in prestress. Based on the gained data, results of both conditions were evaluated and compared to another. Analogue to the numerical findings, the specimens showed a clear response to the applied prestress modification. Creep tests caused a permanent positive deformation of the specimens and a resulting reduction of prestress which resulted in lowered resonance frequencies, too.

Because of anisotropic material properties of the FRP, the used averaged stiffness properties and measurement uncertainties, the real value of changes in prestress of the modified pressure vessels could be estimated only. Effects and influences of local discontinuities were neglected. Hence, measurement accuracy of the applied EMA cannot be fully verified yet. In future, the modified specimens will be analysed via destructive methods in order to obtain more accurate information about the reached prestress modification. Furthermore, additional cylinders are planned to be modified and measured via EMA to prove shown results and increase significance of the developed method.

AUTHOR CONTRIBUTION STATEMENT

The presented manuscript was written by S. John. All findings are worked out by S. John including the performance of all presented studies and EMA measurements. Fibre optical measurements are performed and analysed by R. Eisermann. G. Mair supervised the work and manuscript writing. All authors reviewed the manuscript.

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