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Modal analysis of composite plates: Digital image correlation method application

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Abstract

Composite materials and structures are widely used and applied in many industries owing to their advantages, such as satisfactory stiffness-to-mass ratio and corrosion resistance. However, during their operating life, responsible parts subject to complex loads may change and their properties might deteriorate. To ensure structural integrity it is necessary to monitor and regularly check the performance of composite structures. This paper investigates the change of frequency characteristics of two rectangular composite (carbon-epoxy) plates after inflicting structural damage. Following the necessary preparation of the structure's upper surfaces by white-and-black stochastic pattern, the responses (free vibratory movement) of structures to momentary excitation were recorded by an optical, contactless 3D digital image correlation (DIC) system that contains a set of ultrafast cameras. In order to determine the natural frequencies of the plates, the recorded time-domain responses were post-processed, i.e. converted to the frequency domain by fast Fourier transform (FFT). The reduction in values of natural frequencies is observed on the damaged structures. The performed experiments demonstrate the applicability of the DIC method in the structural health monitoring of composite parts.

1. Introduction

Composite materials are a combination of two or more different materials that are joined together to achieve significantly better structural, thermal and other performance than that of the starting constituent components [1]. Composite structures are used in many fields of mechanical engineering (aerospace, naval, automotive [2], etc). They are often made of synthetic materials with a high strength-to-weight ratio and require strictly controlled production conditions to achieve the optimal and required characteristics.

Composites usually comprise two phases, matrix and reinforcement (filling). Reinforcement has the most influence on the mechanical characteristics of stiffness and strength, and in laminar composites, it is in the form of fibres [3]. The matrix transfers the loads to the fibres, protects the fibres from external influences and can be metal, ceramic or polymer. The properties of the newly formed material depend not only on the materials of the matrix and reinforcement but also on the connection and interaction between them, as well as the geometric arrangement and shape of the filling in the matrix [4]. For that reason, each composite structure is new and should be separately investigated. Furthermore, as the part ages, its properties may deteriorate and should be regularly inspected.

Knowledge of the dynamic characteristics of the structure, e.g. stiffness and damping coefficients, natural frequencies and modes, etc. provides an insight into the structure's current condition. Any change in the structure, due either to damage or reparation, leads to alteration of the mentioned parameters. By comparing the initial parameters of the undamaged structure to the presently measured values, it is possible to draw conclusions about the current state and reliability of the structure, conceive a maintenance plan, etc. Structural health monitoring implies the detection of even the slightest structural changes in time. Such a method includes several activities: determination of parameters of an undamaged structure, repeated or regular monitoring of those parameters during the exploitation (by measurement and/or numerical simulation) and establishing a relation between the structure's functionality and observed changes in frequency characteristics.

This paper investigates the possibility of applying a novel, contactless, non-invasive method [5-10] to observe the changes in the natural frequencies of composite plates that have been deliberately damaged. Here, damage is defined as a series of changes in material structure and/or physical characteristics that affect the performance and integrity of the whole system. In general, with multi-layer structures, it is more often in the form of delamination [11,12]. The investigated composite laminates differ in lay-up sequences which results in quite different starting mechanical properties but also a dynamic response to excitation. The employed contactless optical system does not affect the plate properties in any way and enables rather fast and efficient determination of natural frequencies of all types of structures (different composite structures, both undamaged and damaged).

2. Methodology

The following section provides detailed descriptions of the investigated plates and employed experimental setup.

2.1 Plates description

For experimental testing, two different rectangular laminates of the same dimensions (380 × 80 × 2.3 mm) were prepared. Both plates are of the carbon-epoxy composition and were manufactured by the simplest wet lay-up method. In both cases, eight layers of unidirectional carbon fibre cloth (areal weight of 300 g/m^2 and thickness of 0.3 mm) were wetted out by epoxy resin by hand and allowed to cure at room temperature according to the manufacturer's instructions. The approximate resin content was 38 %. Since the geometry of the plates is simple there was no need to use a particular mould.

The tested structures correspond to the aircraft wing or wind turbine blade spar and are intended to endure primarily bending loads and normal stresses. Epoxy resin is commonly employed in aerospace and wind energy applications for its good wetting, as well as satisfactory structural characteristics. It is chemically inert and is applicable in a wide range of operating temperatures, as well as in conditions of increased humidity (since it is not very sensitive to water). On the other hand, epoxy resins are sensitive to radiation, abrasives, chemicals, etc. Although different types are available, carbon fibres are generally recognised for their high tensile characteristics (strength and elasticity modulus). According to the catalogue, the employed carbon cloths (12.000 filament count) have a tensile strength in the main direction of 4400 MPa, tensile modulus of 240 GPa, expected elongation of 1.8 % and density of 1770 kg/m^3.

The lay-up sequences of the two plates are provided in Table 1. In both cases, the most common angles (measured with respect to the longitudinal axis of the plate) were used. Plate 1 is balanced, comprising a repeated array of four different orientations, whereas plate 2 is symmetric, with only two orientations employed: 0° (along which the tensile characteristics are the highest) and 90° (along which the tensile characteristics are the lowest). Different lay-ups affect the structural properties of the plates. Even though their dimensions are the same, their mechanical characteristics are quite different and they should be separately tested. In this case, plate 2 is more rigid owing to a greater number of plies oriented at 0°.

An illustration of a damaged plate is provided in Figure 1. The imposed damage is complex, comprising a horizontal notch measuring 35 × 2 mm at a distance of 270 mm from the free end of the panel, a notch measuring 20 × 2 mm that continues perpendicularly to the previous one and a horizontal notch measuring 15 × 2 mm. It was inflicted by a sharp cutting tool that ensured that no additional pre-cracks were generated. Since these plates correspond to load-bearing wing spars subject to bending, this damage should simulate the propagating crack that is initiated in the vicinity of the clamped end.

Table 1. Lay-up sequences of the plates

Plate	Lay-up sequence, °
1	90 | + 45 | − 45 | 0 | 90 | + 45 | − 45 | 0
2	0 | 90 | 0 | 90 | 90 | 0 | 90 | 0

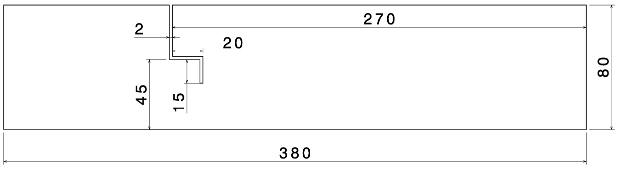

Figure 1. Appearance and dimensions of the damaged geometry

2.2 Experimental methods

Since dynamic loads are always present it is imperative to know in advance the natural frequencies of the structure and ensure they are sufficiently far from the excitation frequency. Furthermore, since frequency characteristics are not constant, but can change in time due to the modifications of the structure, they should be regularly checked. One possible approach to the determination of a structure's dynamic behaviour is experimental modal analysis. It starts with the excitation of the structure by a modal/impact hammer or a shaker, followed by the detection of the structure's response (movement). In the classical approach, the structure's movement can be measured by strain gauges, extensometers, accelerometers, etc. which are fixed to a finite number of points. Although available and economical, this method provides a limited amount of data and may affect the measured properties (since the attached sensors slightly change the total mass and geometry of the inspected part). On the other hand, the use of state-of-the-art optical equipment enables simultaneous measurement of the movement of a much greater number of points (representing larger patches or even complete structures).

A novel and attractive contactless digital image correlation (DIC) system based on the principles of digital photography and modern computer technology can be used for point displacement measurement [5,6]. A typical DIC system [9,10] consists of a sensor unit (A) (in our case two high-quality, ultrafast cameras FASTCAM SA6 75K-M3 with 32 GB memory, maximum recording frequency 75.000 fps, maximum resolution 1920 × 1440 pixels), a power control device for image recording (performed by the Photron software package here) and a system for data acquisition, processing and analysis (B) (in our case done by the ARAMIS software package) and a sample set-up (C), see Fig. 2. DIC systems use a series of sequentially recorded digital images to determine (calculate) displacement and the corresponding stress fields. The surface of the tested object is coloured by a stochastic pattern whose points are transformed into corresponding pixels in the images.

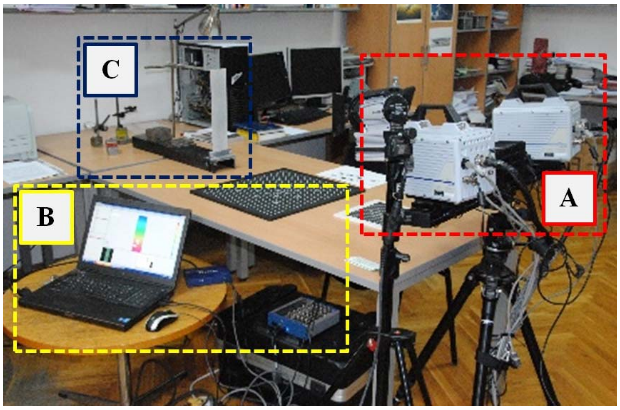

Figure 2. DIC system

2.3 Experimental set-up

In the beginning, it is necessary to adequately prepare the surface of the specimens for the recording. It is usually done by colouring the surface white and stochastically spraying black dots over it. However, in this case, an inverse method was employed since the surface of the carbon-epoxy plates is black. Randomly distributed white lines and dots were drawn over a portion of the plate that was recorded, Fig. 3. Different line thicknesses and densities were tried, but the presented pattern provided the best results.

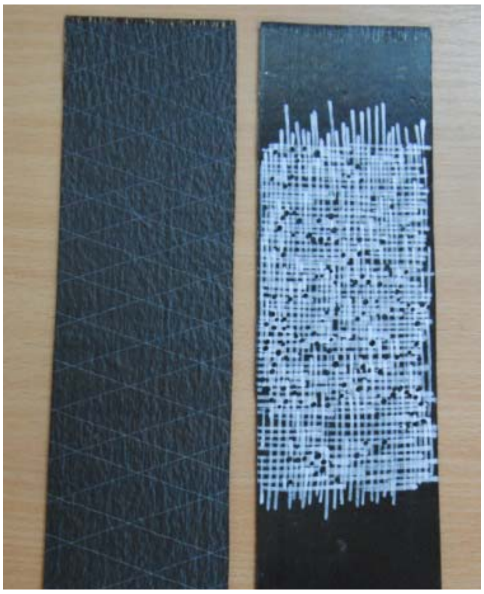

Figure 3. Plate prepared for the recording

In this investigation, every plate is clamped at one edge as presented in Figure 4. It is excited on the other end by a modal hammer and allowed to oscillate freely. The plate response/movement is recorded by the DIC system since modal analysis, in its simplest form, requires only the measurement of the response of the structure. The recording was started immediately after the mechanical impact to obtain high-frequency modes that are quickly damped due to the rigidity of the composite plates. Usually, the measurements lasted just for a few seconds. The applied frame rate was high (3000 fps) and the resolution of the images was lowered (1024 × 512 pixels) to capture just the painted part of the structure.

Figure 4. Investigation of the damaged plate

3. Post-processing of the results and discussion

3.1 Post-processing

Since gathered data are numerous, usually, only a representative portion of the surface was processed. This was achieved by defining a mask that defines the borders of the domain of interest (green zone in Figure 5). That domain is then split into rectangular facets of the dimension 16 × 12 pixels. The points belonging to each facet are correlated (by statistical methods) in the left- and right-camera images to form a 3D displacement field. To perform the correlation it is necessary to define a referent (neutral) point that is marked by the yellow cross in Figure 5.

The resulting displacement field can be either analysed in whole in each stage, or information on the movement of a single, arbitrary point (red square in Figure 5) can be gathered throughout the stages to form a time-dependent displacement curve illustrated in the lower left corner of Figure 6. Such a function can then be Fourier transformed to the frequency domain. The high accuracy of the DIC system enables a precise determination of the natural frequencies and oscillation modes of the tested plates.

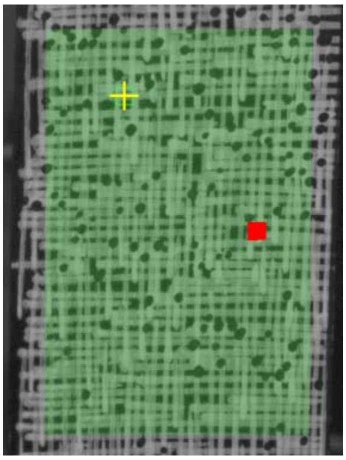

Figure 5. Masked portion of the surface

Each set of images (from the left and right camera) corresponds to an enumerated stage. The resulting displacement in the *z*-direction (along the plate width) in one moment in time measured in the global coordinate system of the control volume on a chosen portion of the plate surface is coloured in Figure 6. The blue colour corresponds to the smallest and red to the highest measured values.

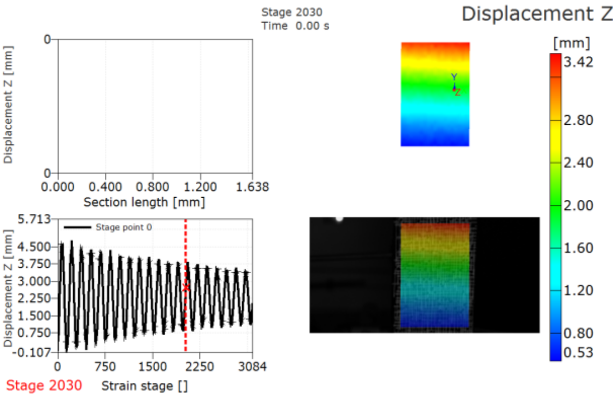

Figure 6. Analysis in ARAMIS software

3.2 Results and discussion

The main outcomes of the performed experimental modal analyses are the natural frequencies of both composite plates (undamaged and damaged)). Information on natural frequencies from the experimental testing is obtained indirectly from the measured structural responses (illustrated in Figures 7 and 9) that are then converted to frequency domain (illustrated in Figures 8 and 10). Tables 2 and 3 show all the processed results and accentuate the observed differences between the undamaged and damaged plates.

Plate 1 (balanced type) is an elastic structure with low damping. Only the first two natural frequencies were successfully documented. The first mode seems dominant, while the other, higher tones are attenuated quickly and are difficult to distinguish from signal noise. The same trend is apparent in the damaged structure. The inflicted change resulted in an approximate 15 % decrease in the values of the first two natural frequencies. Although this was to be expected since the total mass of the plate is slightly reduced, the observed (not negligible) difference clearly points to the change in plate dynamic characteristics and can be used as a useful parameter (quantifier) for monitoring the structure's current state.

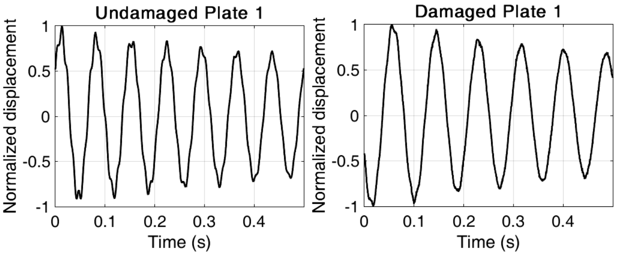

Figure 7. Response of plate 1 in the time domain, undamaged (left) and damaged (right)

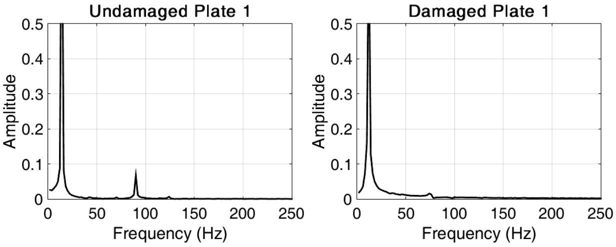

Figure 8. Response of plate 1 in the frequency domain, undamaged (left) and damaged (right)

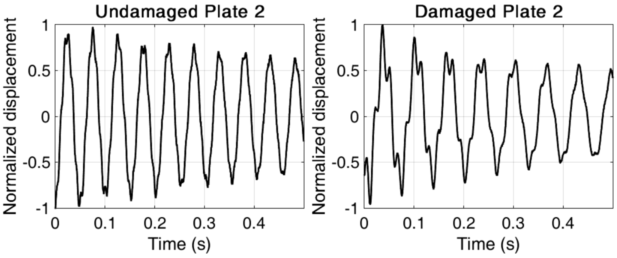

Figure 9. Response of plate 2 in the time domain, undamaged (left) and damaged (right)

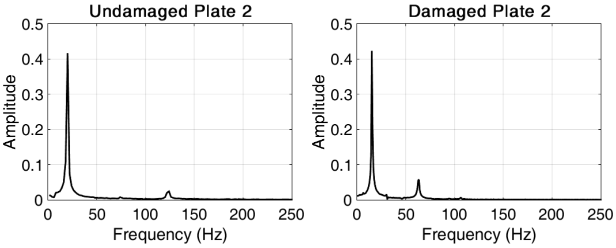

Figure 10. Response of plate 2 in the frequency domain, undamaged (left) and damaged (right)

Plate 2 (symmetric type) behaves similarly to a unidirectional structure that was investigated in previous studies [10]. It is significantly more rigid than plate 1. The first three modes were successfully captured and they all decrease after damaging the structure, although by different percentages. The first natural frequency diminishes the most (by approximately 23 %), while the other two natural frequencies decrease by 16 and 14 %, respectively.

Table 2. Measured frequencies of plate 1

Mode	Undamaged	Damaged	Relative difference, %
ν_1, Hz	14.0 ± 0.5	11.9 ± 0.5	− 15
ν_2, Hz	90.0 ± 0.5	75.5 ± 0.5	− 16

Table 3. Measured frequencies of plate 2

Mode	Undamaged	Damaged	Relative difference, %
ν_1, Hz	19.5 ± 0.5	15.1 ± 0.4	− 23
ν_2, Hz	75.0 ± 0.5	63.2 ± 0.4	− 16
ν_3, Hz	123.0 ± 0.5	106.3 ± 0.4	− 14

4. Conclusions

The paper describes the application of a DIC system in the determination of modal characteristics of different composite plates. The benefits of using this novel, non-invasive method in the experimental modal analysis are numerous: there are no adverse effects on the structure and the properties of interest are not modified by additional sensors; it is possible to simultaneously perform measurements on a great number of points (patches of the structure); measurement accuracy is satisfactory; experiments and post-processing of the results can be conducted in a short amount of time.

On the other hand, the requirements for the successful application of the DIC system include: adequate preparation of the specimen (applying the appropriate pattern on the surface), sufficient and steady levels of illumination, correct excitation of the structure, suitable data acquisition and post-processing.

Although natural modes depend on the structure in question, the performed study demonstrates that it is possible to capture several first natural frequencies, even on elastic composite structures. It is also shown that even slight changes in geometry may result in significant changes in natural frequencies, thus confirming they can be used as valid parameters for structural health monitoring of composite structures (laminates) often encountered in aerospace applications. In real operation, failure of composite parts is usually hard to visually detect (since it occurs within the laminate), so the proposed method may serve as a reliable alternative.

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References

[1] V.V. Vasiliev, E.V. Morozov, Mechanics and Analysis of Composite Materials, Elsevier Science, Oxford, 2001.

[2] A. Vencl A., Tribology of the Al-Si alloy based MMCs and their application in automotive industry, in L. Magagnin (Ed.), Engineered Metal Matrix Composites: Forming Methods, Material Properties and Industrial Applications, Nova Science Publishers, New York, 2012, pp. 127-166.

[3] M. Elices, J. Llorca (Eds.), Fiber Fracture, Elsevier Science, Oxford, 2002, DOI: 10.1016/B978-0-08-044104-7.X5000-X

[4] R.M. Jones, Mechanics of Composite Materials, Taylor & Francis, Philadelphia, 1999.

[5] F. Hild, S. Roux , Comparison of local and global approaches to digital image correlation, Experimental Mechanics, Vol. 52, No. 9, 2012, pp. 1503-1519, DOI: 10.1007/s11340-012-9603-7

[6] D. Wang, J.E. Mottershead, Measurement precision and spatial resolution with Kriging digital image correlation, Strojniški vestnik – Journal of Mechanical Engineering, Vol. 62, No. 7-8, 2016, pp. 419-429, DOI: 10.5545/sv-jme.2016.3736

[7] A. Fathi, J.-H. Keller, V. Altstaedt, Full-field shear analyses of sandwich core materials using digital image correlation (DIC), Composites Part B: Engineering, Vol. 70, 2015, pp. 156-166, DOI: 10.1016/j.compositesb.2014.10.045

[8] M.A. Caminero, M. Lopez-Pedrosa, C. Pinna, C. Soutis, Damage monitoring and analysis of composite laminates with an open hole and adhesively bonded repairs using digital image correlation, Composites Part B: Engineering, Vol. 53, 2013, pp. 76-91, DOI: 10.1016/j.compositesb.2013.04.050

[9] M. Baltić, J. Svorcan, B. Perić, M. Vorkapić, T. Ivanov, O. Peković, Comparative numerical and experimental investigation of static and dynamic characteristics of composite plates, Journal of Mechanical Science and Technology, Vol. 33, No. 6, 2019, pp. 2597-2603, DOI: 10.1007/s12206-019-0507-7

[10] M. Baltic, J. Svorcan, O. Pekovic, T. Ivanov, Comparative numerical and experimental modal analysis of aluminum and composite plates, in N. Mitrovic, M. Milosevic, G. Mladenovic (Eds.), Computational and Experimental Approaches in Materials Science and Engineering, Springer, Cham, 2020, pp. 61-75, DOI: 10.1007/978-3-030-30853-7_4

[11] G. Molero, S. Du, M. Mamak, M. Agerton, M.M. Hossain, H.-J. Sue, Experimental and numerical determination of adhesive strength in semi-rigid multi-layer polymeric systems, Polymer Testing, Vol. 75, 2019, pp. 85-92, DOI: 10.1016/j.polymertesting.2019.01.012

[12] S. Du, Z. Zhu, C. Liu, T. Zhang, M.M. Hossain, H.-J. Sue, Experimental observation and finite element method modeling on scratch-induced delamination of multilayer polymeric structures, Polymer Engineering & Science, Vol. 61, No. 6, 2021, pp. 1742-1754, DOI: 10.1002/pen.25697