IMPACT DAMAGE INFLUENCE ON VIBRATION CHARACTERISTICS OF WOVEN COMPOSITES

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Abstract. The present paper investigates the influence of impact damage on vibration characteristics of woven composites. For this purpose, small plate specimens with dimensions of 60 × 70 × 1.5 mm were cut from the large panel made of carbon fiber woven composite with five-layers. The damage was introduced into the tested specimens in the energy range of 2-6 J by INSTRON Dynatup 9250 HV Impact Tower and accurately characterized by application of pulse-echo ultrasonic scanning technique: Hillger ultrasonic system USPC 3010 HF. Finally, the dynamic characteristics: natural frequencies and corresponding loss factors are determined from the free vibration analysis of impacted specimens by using POLYTEC PSV-500 laser vibrometer operating on the Doppler principle. The results show that damage shifts the natural frequencies of plates and increases their damping properties. Therefore, changes in dynamic characteristics, especially in loss factors, can be used for structural health monitoring. It was found that damaged areas higher than 6% of the specimen's total area affect significantly loss factors of bending vibration modes and less loss factors of twisting modes. Additional effect, demonstrating an increase of lower natural frequencies with an increase of impact energy, can be explained by a residual curvature of small plate specimens.

Keywords: composite, impact damage, dynamic properties.

Introduction

The operational life of a structure or a component is often limited by the initiation and subsequent growth of cracks or damage. They may exist as basic defects in the constituent materials, or they may be induced in construction during service life. The presence of cracks or damage may result in a loss of performance or even in the total failure of the structure. Therefore, damage detection at the earliest possible stage becomes a very important issue to promote life extension and to prevent catastrophic failures of lightweight composite structures.

Currently utilized damage identification methods can be subdivided into the following categories: visual or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiography, eddy-current methods, thermal field methods [1], electric methods [2]. Accessing these techniques is time-consuming and costly. Some of them are also impractical in many cases such as in service aircraft testing and space structure. Almost all these techniques require that the vicinity of the damage is known in advance and that the portion of the structure being inspected is readily accessible. Subject to these limitations, these non-model (experimental) methods can provide only local information and no indication of the structural strength at a system level.

The model-based methods give the possibility to detect, locate and characterize damage in lightweight composite structures by examining changes in measured vibration response. The basic idea behind this technology is that modal parameters (frequencies, mode shapes, modal damping) are functions of the physical properties of the structure (stiffness, mass, damping). Therefore, changes in physical properties will cause detectable changes in the modal properties [3], and frequency [4] and time [5] transient responses. According to the dynamic response parameters analyzed, these methods can be subdivided into modal analysis [6; 7], frequency domain [8], time domain [9] and impedance domain [10]. The effectiveness of the whole group of model-based techniques, however, is dependent on the accuracy of the structural model and these methods may have difficulties when applied to complex structures. Model-dependent methods can provide global and local damage information and do not require direct human accessibility of the structure. They are cost-effective and are relatively easy to operate. However, there are still many challenges and obstacles before these methods can be implemented in practice.

Another class of damage identification methods [11] is based on the modification of structural model matrices such as mass, stiffness and damping to reproduce as closely as possible the measured static or dynamic response from the data. These methods solve the updated matrices by forming a constrained optimization problem based on the structural equations of motion, the nominal model and the measured data as in the inverse problems [12]. Comparisons of the updated matrices to the original correlated matrices provide an indication of damage and can be used to quantify the location and extent of damage. The differences in these algorithms can be related to the objective function to be minimized, constraints placed on the problem and numerical scheme used to implement the optimization.

All examined methods can be used for the development of real-time non-destructive “health-monitoring” technique receiving growing attention in recent years. Among them, the damage characterization technique in composites by monitoring changes in the dynamic characteristics or in the vibro-acoustic response of the structure [13] seem to be attractive and promising. For this reason, the sensitivity of vibration characteristics of woven composites from the impact damage is investigated in the present study. The damage in composite, introduced with different impact energy, is accurately characterized by application of ultra wave scanning technique. To avoid any influence of exciting and measuring devices on the vibrating object, the loudspeaker and POLYTEC laser vibrometer operating on the Doppler principle are used. The dynamic characteristics: natural frequencies and corresponding loss factors are determined experimentally from the free vibration analysis.

Materials and methods

To study influence of impact damage on dynamic properties of woven carbon fibre specimens, 6 specimens with dimensions of 60 × 70 mm were cut from one plate with total thickness of 1.5 mm made of 5 layers of carbon fibre twill prepreg (200 gr·m^{-2}). The plate was manufactured by hand lamination method and heat treatment in the oven (120 °C for 2 h) in a vacuum bag (0.8 bar).

INSTRON Dynatup 9250 HV Impact Tower equipped with the striker with a diameter of 30 mm was used to introduce impact damage of 2, 3, 4, 5 or 6 J to the prepared specimens (Fig. 1). One of the specimens was not damaged and is kept as reference. After the introduction of damage each specimen was scanned by Hillger ultrasonic system USPC 3010 HF using the pulse-echo method (Fig. 2) to obtain high-quality damage images and evaluate the degree of damage.

All specimens were measured by POLYTEC PSV-500-3D Scanning Vibrometer (Fig. 3) before and after the impact in frequency range of 0-6.4 kHz with step of 0.5 Hz to determine their natural frequencies and corresponding loss factors. The frequency range was chosen to obtain 8 natural frequencies. The smallest possible step for this frequence range was applied to determine the loss factors by the peak-picking method [4] with the possible higher accuracy. Taking into account small weight of the specimens, non-contact excitation by the loudspeaker was applied to eliminate the influence of the weight of the excitation device [14]. Free-free boundary conditions were physically realized by hanging the specimen on a thin thread that minimizes the influence of fixation on the dynamic properties of the specimen.

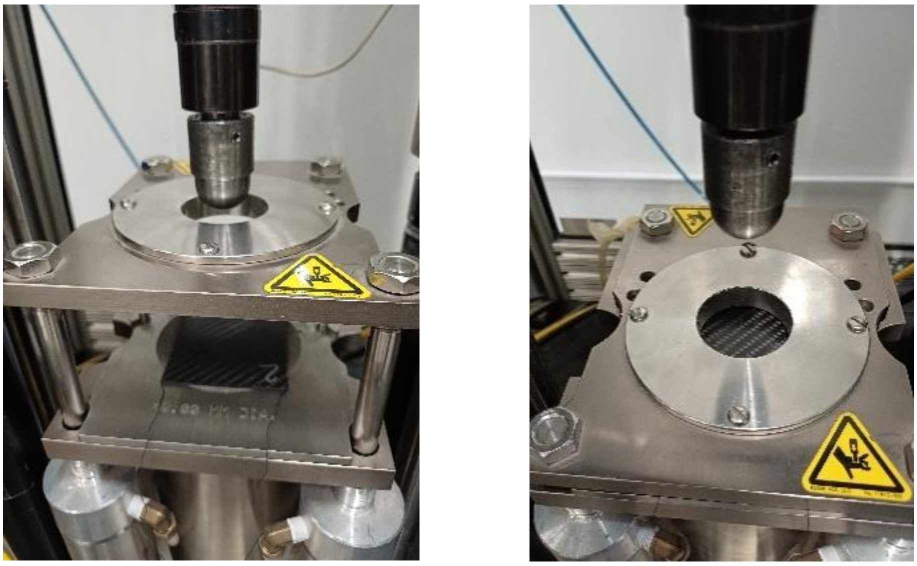


Fig. 1. **Introducing of damage to the specimens**

Fig. 2. **Ultrasonic scanning of specimen in water**

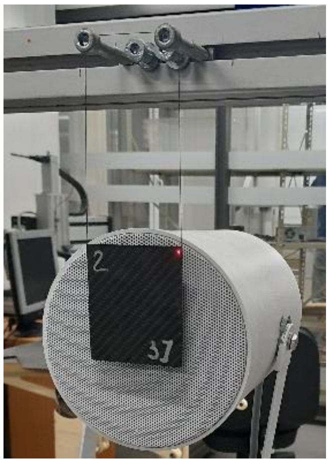


Fig. 3. **Specimen with free-free boundary conditions excited by loudspeaker**

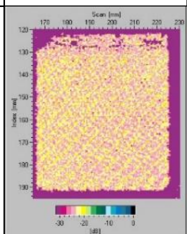
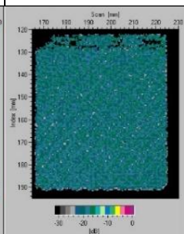
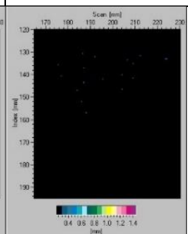
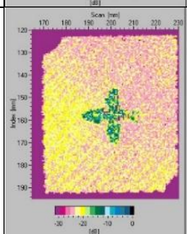
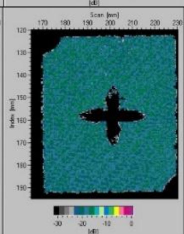
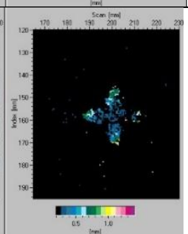
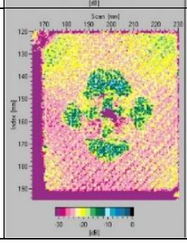
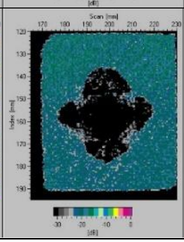
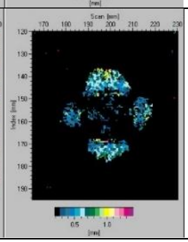
Results and discussion

Results of the ultrasound testing showed that with an increase in the impact energy from 2 to 4 J, an increase in the linear dimensions of cruciform damage is observed. Further increase in the impact energy leads to “rounding” of the damaged area. This could be explained by the boundary conditions - the specimens were clamped along all 4 sides during the impact; therefore, further growth of the cruciate damage is impossible. Results of the ultrasound testing for non-impacted specimen as well as for specimens impacted by energy of 4 and 6 J are presented in Table 1.

Dependency of the damaged zone area on the impact energy is presented in Figure 4; it is seen that the damage area is almost proportional to the impact energy in the range of 0-5 J. Impact energy of 6 J caused damage with the area more than 2 times larger in comparison with the 5 J impact.

Table 1

Results of ultrasound testing

Impact energy, J	Specimens after impact	Top surface echo	Bottom surface echo	Defect depth	Linear dimensions of the damage, mm	Damaged area, cm^2
0					-	-
3					30 x 27	2.7
6					42 x 42	10.9

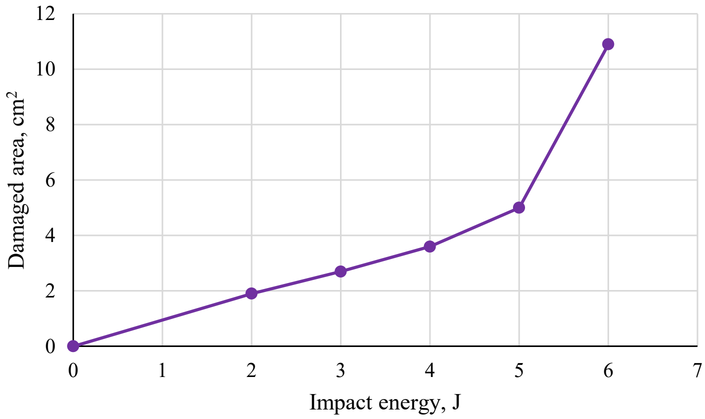


Fig. 4. **Dependency of damaged area on impact energy**

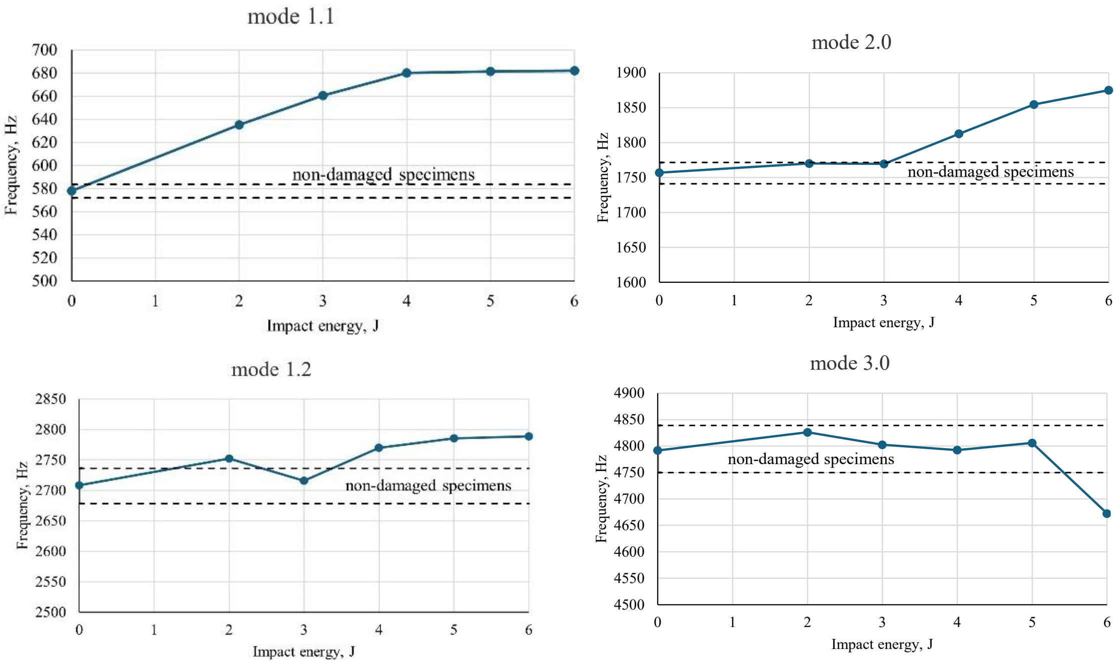


Fig. 5. **Dependencies of specimen natural frequencies on impact energy**

Fig. 6. **Curved shape of specimen after impact**

Eight resonances were found for each specimen by analysing their frequency responses obtained by the laser vibrometer. Since the vibration tests were executed for all specimens before impact, the boundaries of each natural frequency and corresponding loss factor of non-damaged specimens were determined. Changes in dynamic characteristics caused by the impact were analysed relative to this range. The results show the increase of natural frequencies on the applied impact energy (Fig. 5). This effect could be explained by the residual curvature introduced by the impact (Fig. 6), that increases the geometrical stiffness of the initially plane plate specimen. Increase of stiffness caused by this curvature is higher than the reduction in stiffness caused by material destruction in the impact zone. It is necessary to note that this effect is more visible for lowest vibration modes - both twisting (mode 1.1 in Fig. 6) and bending (mode 2.0 in Fig. 6). For higher vibration modes (twisting mode 1.2 and bending mode 3.0 in Fig. 5) the influence of the impact energy on natural frequencies is smaller. For mode 3.0 also the decrease of natural frequency is observed in case of the highest impact energy (6 J).

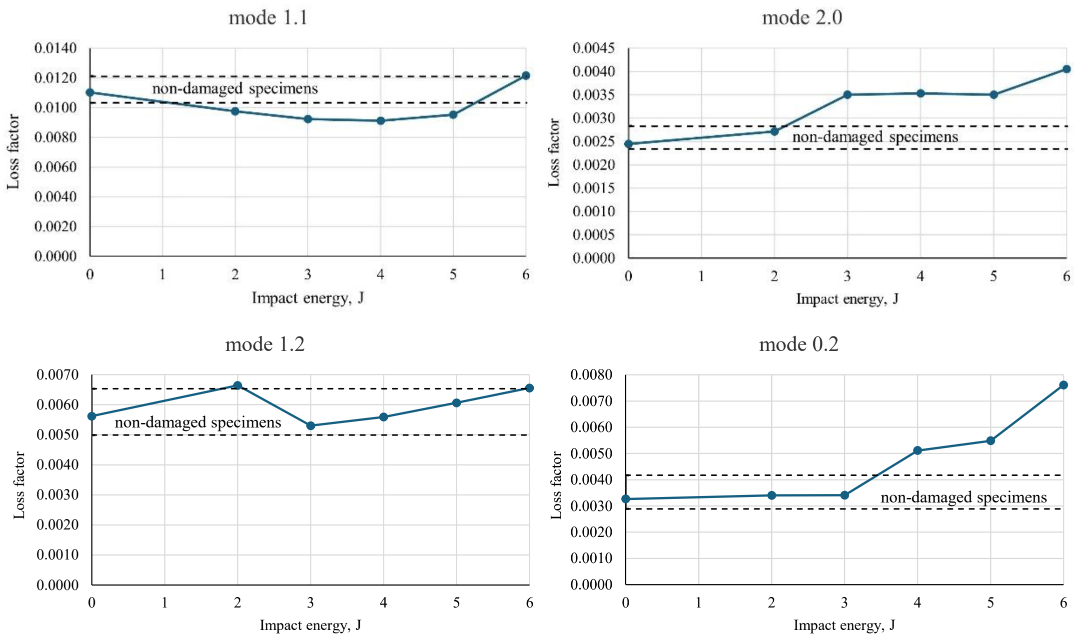


Fig. 7. **Dependencies of specimen loss factors on impact energy**

Influence of impact energy on the damping properties is different for different vibration modes (Fig. 7). It is almost imperceptible for vibration modes with a predominance of twisting (modes 1.1, 2.1, 1.2). For bending modes (2.0, 0.2, 3.0) this influence is most noticeable and can be expressed in an increase in the loss factor up to 2 times with an impact energy of 6 J as it is shown in Fig. 7 for mode 0.2.

Conclusions

It was found that impact damage influences the dynamic properties of specimens, therefore their change can be used for structural health monitoring. The positive shift in natural frequency with increasing impact energy was unexpected but explainable for small specimens. This effect should not be observed for localized damage in large structures when the area of damage is significantly smaller than the area of the structure. At the same time, the study demonstrated that with increasing of damage, the loss factor of the specimens increases due to increased internal friction in cracks and delamination. This effect is evident when the damaged area exceeds 6% of the total specimen area.

Acknowledgements

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Author contributions

Conceptualization, P.A.; methodology, P.A. and O.D.; software, P.A.; validation, A.K; formal analysis, A.K and O.D..; investigation, P.A., A.K, and O.D.; data curation, P.A., and A.K.; writing – original draft preparation, P.A.; writing – review and editing, P.A. and A.K.; visualization, P.A., O.D.; project administration, A.K.; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

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