CHARACTERISATION OF IMPACT-CAUSED CHANGES OF THE ANISOTROPIC MATERIAL DAMPING OF COMPOSITE LAMINATES

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Abstract

The presented investigations deal with the effect of impact-caused damage on the anisotropic material damping properties of fibre-reinforced composites. Plates made of glass fibre reinforced epoxy were damaged in controlled impact tests using different combinations of impactors and impact energies. Subsequently, the out-of-plane anisotropic damping and stiffness properties in the damaged zone were determined using dynamical mechanical analysis technique. The results revealed complex changes of both anisotropic material damping and stiffness due to impact-caused damages. Additionally, a nonlinearity of anisotropic material damping depending on the damage severity was observed at higher excitation frequencies. The findings indicate a potential applicability of anisotropic material damping as input data for future generation of structural health monitoring systems.

1 Introduction

Damage evolution in fibre-reinforced composite components is often initiated by a low to medium energy impact event. Therefore, early and reliable detection of initial damages during the entire operational lifetime is considered as a vital function that could be implemented into future generations of smart composites. Currently, the presence of impact damage is typically determined in various schedule-based, non-destructive tests, e.g., x-ray inspections or ultrasonic examinations which are cost and labour intensive.

During recent years, several vibration-based structural health monitoring (SHM) methods that overcome the aforementioned limitations were developed. A common feature of these methods is an indirect assessment of the damage condition, with the reliability depending on the information content in the analysed physical quantities. On the one hand, most of the known approaches base on the analysis of measurable parameters of propagating mechanical waves after an interaction with damage zone or of damage-caused change of structure’s modal properties. On the other hand, although numerous authors state that material damping is especially sensitive to different failure modes of composite materials, SHM approaches using this physical quantity as the main information carrier about the structural condition are barely reported.

In general, the properties of composite materials are anisotropic and they can be adapted in the design process according to the expected load conditions of the engineered component. The aimed anisotropy can however be locally changed by an impact event, which causes typically a combination of delaminations, fibre breakages, and matrix cracks. As a result, material properties including also aforementioned material damping change from the designed anisotropy to an unknown anisotropy state. Such change is complex and depends both on the initial material properties and on several factors describing the impact event, e.g., its energy as well as geometric and viscoelastic parameters of the impactor.

2 State of the art

Damping is defined as irreversible change of one type of energy into other type of energy, mostly heat. Such conversion was firstly observed by COULOMB in 18th century but until now, the complex sources of damping, especially in fibre-reinforced materials, are not fully understood. The fist approach to summarise and unify the contemporary knowledge about damping for typical engineering materials including composites was attempted by LANZAN [1]. He has stated that the parameters influencing the material damping as well as their interactions are of such complex nature that their every possible combination needs to be considered as a separate problem in order to generate sound foundations required for the elaboration of adequate theory of damping. This approach was subsequently followed, e.g., by NELSON and GIBSON [2-3] resulting in an identification of composite-specific sources of the energy dissipation as:

- high contribution of the viscous nature of the matrix,
- small to moderate contribution of the viscosity of fibres, and
- damping resulting from the properties of the interphase.

A damage occurrence unavoidably alters the contribution of the aforementioned sources to the overall damping. Additional energy dissipation arises from the dry friction between all possible combinations of bonded and unbonded microscopic components of the composite material and from other not fully understood phenomena occurring in the damaged regions.

A practically relevant problem of impact-caused damages and their effect on the properties of fibre-reinforced composites was addressed by ABRATE in a comprehensive review [4]. He reports numerous investigations regarding the properties of the matrix, the reinforcing fibres, and the fibre-matrix interfaces and their effect on the impact resistance. The influence of layup, thickness, size, boundary conditions on impact response was already investigated as well [5-6]. In many studies, the effect of the size and shape of the impactor, the material it was made of, and its angle of incidence on the impact response of the composite structures was examined [7-8]. An experimental determination of residual properties like compressive, tensile, flexural or fatigue strength as well as structural dynamic behaviour establishes another impact-related research field [9-10]. Regarding this field, development of simplified analytical models predicting impact-caused changes of the aforementioned properties was addressed. Investigations regarding the alteration of the material damping due to an impact event, however, are barely reported. An example of such investigations was conducted by KOSTKA et al. [11]. In his studies, a local change of material damping caused by an impact event was analysed. Extended analysis of composite material damping anisotropy in relation to damage condition were, according to the knowledge of the authors, never addressed. This issue is investigated in the current study with the aimed goal of application of this parameter in a future generation of structural health monitoring systems.

3 Experimental investigations

The main objective of the experimental investigations was a characterisation of changes in anisotropy of material damping caused by damage inflicted in various impact tests. For the experiments, 18 rectangular plate specimens were manufactured and subsequently damaged through controlled impact loads with different combinations of impactor tip shapes and impact energies. The damaged specimens were finally segmented into smaller test coupons and analysed using dynamical mechanical analyser in order to determine the residual viscoelastic material parameters.

3.1 Test specimens

For the here conducted studies, glass fibre reinforced epoxy resin plies were stacked into typical aircraft-laminate layup – [90/0]$_{5s}$. A plate with dimensions 1500 x 3000 x 2.7 mm was fabricated using autoclave technique. This technique typically allows manufacturing of basic-geometry structures with relatively low scatter of mechanical and physical properties. The parameters controlling the manufacturing process were set according to the recommendations of the preform-tape producer. The consolidated plates were segmented into 100 x 100 mm specimens using water jet cutting technique.

3.2 Damage inducing impact tests

The tests were conducted in order to introduce damage through impact loading. An impact and crash test stand developed at the Institute and Lightweight Engineering and Polymer Technology (Fig. 2a) was used for this tests. The configuration of the damage-inducing test regarding combinations of impactors and impact energies is presented in the table 1. The impactors with identical mass but different tip shape (Fig. 2b) were selected in order to investigate the impactor shape-specific damage conditions.

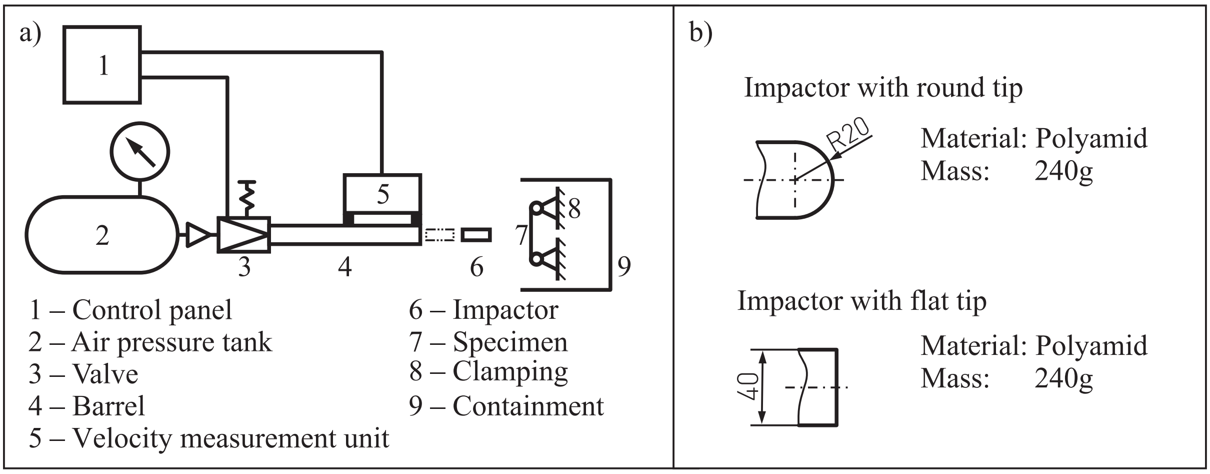


Figure 2. Schematic drawing of impact and crash test rig (a). Tip geometries of the applied impactors (b).

	Energy 95 J	**Energy 115 J**	**Energy 125 J**
Round impactor's tip	3	3	3
Flat impactor's tip	3	3	3

Table 1. Number of specimens for different combinations of impactor's tip shape and impact energy in the impact tests.

After the impact tests, the specimens were examined using air-coupled ultrasonic analyser. The results of this examination (Fig. 3a) combined with pictures taken under high-intensity light (Fig. 3b) were used in order to precise determine the position and extent of the damaged zone. From every specimen one coupon containing the damage zone in either 0°, 45° or 90°

angle in laminate coordinate system was cut. Similarly, test coupons in the three angles were also cut from undamaged regions. The coupons were used in order to characterise the anisotropic reference and residual viscoelastic properties. The dimensions of all coupons are depicted on the figure 4.

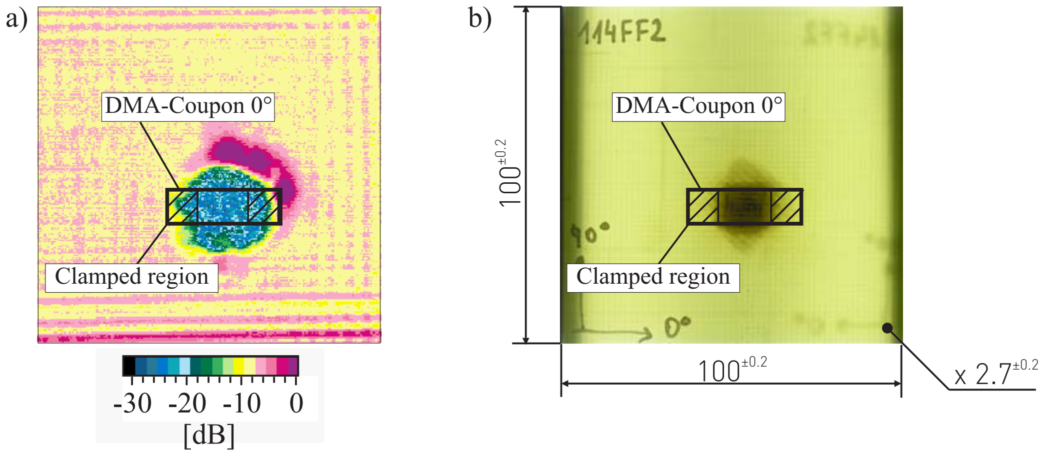


Figure 3. Sample results for an impact test with round tip impactor and 130 J impact energy: Ultrasonic examination (a) and high-intensity light test (b) with marked position of the coupon cut line.

4 Characterisation of the damage zone

The determination of the mechanical properties of the coupons was conducted using a dynamical mechanical analyser produced by TA-Instruments. In dynamical mechanical analysis (DMA), the mechanical properties are determined based on the phase lag between the oscillating excitation and the material response. In general, the characterisation can be conducted for different load, boundary, and environmental conditions, which enable study of influence of different combinations of these factors on material properties.

The investigated mechanical properties were the loss modulus describing the material damping, and storage modulus as a parameter characterising the stiffness. The displacement-amplitude controlled excitation with constant amplitude of 15 µm, frequency sweep between 1 and 35 Hz and boundary conditions resulting from the used single cantilever clamping (Fig. 4) were applied. The temperature and relative air humidity were set to 23°C and 40 %, respectively. The relative error in measurement of moduli of the used device is 1% but the geometrical accuracy of the coupons, presence of shear forces in the used single cantilever beam clamping significantly increase this error to approximately 10–15% [12].

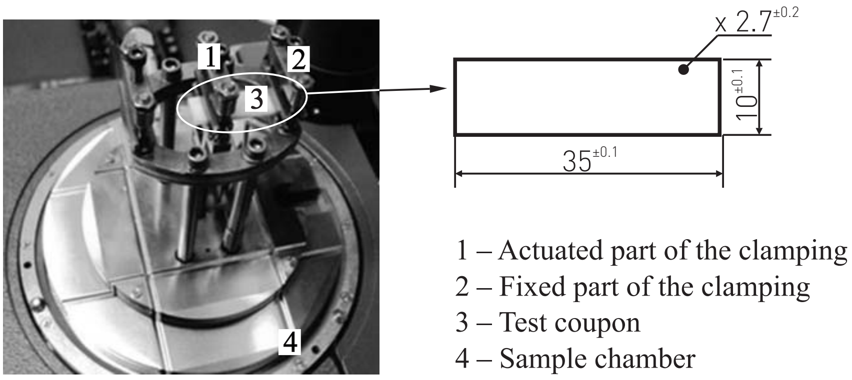


Figure 4. Overview of the dynamical mechanical analyser sample chamber with mounted test coupon.

In order to minimise the influence of clamping conditions, the start of DMA was preceded by unmounting and mounting again the analysed test coupon. Using such procedure the loss and storage moduli were determined five times and averaged for every coupon.

5 Results and Discussion

The results of the high-intensity light test as well as microscopic analysis of the damaged specimens revealed significant differences in the characteristics of introduced damage due to different impactor shapes (Fig. 5). Whereas for the impactor with flat tip the introduced damage was in general larger and of a diffuse nature, the impactor with round tip caused damage clearly marked by an indentation and characterised by high number of fibre and inter-fibre cracks as well as delaminations. This effect can be explained by the fact that the overall kinetic energy of the impact event was focused on the areas specific for the impactor tip shape. This result confirmed the studies conducted by Yang and Cantwell [7].

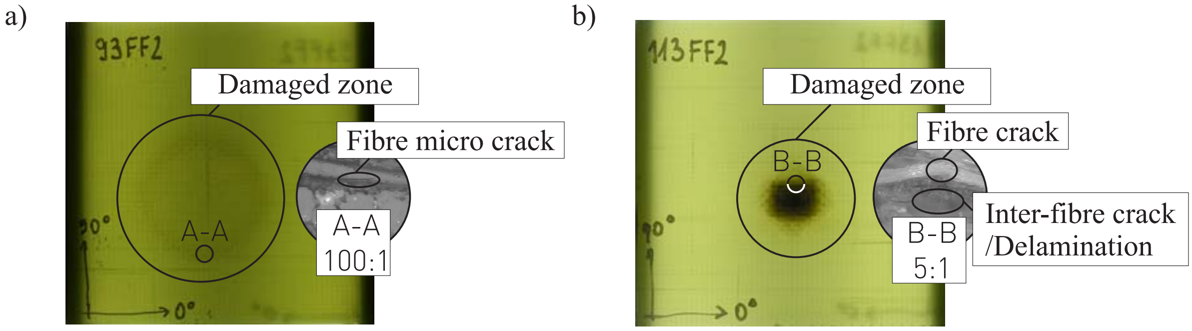


Figure 5. Different characteristics of the damaged zone for caused by impactor with flat (a) and round (b) tip and impact energy of 95 J.

The residual anisotropic mechanical properties in the damage zone were analysed based on the results obtained using DMA. For such analysis, anisotropy change factor (ACF) was introduced as:

$$ACF = \max\left[\frac{E_{CUR}(\theta)-E_{REF}(\theta)}{E_{REF}(\theta)}\right] \quad \text{for } \theta = 0\ldots\frac{\pi}{2} \tag{1}$$

where $E_{CUR}(\theta)$ is the loss or storage moduli of the investigated material determined in an angle θ in the laminate coordinate system, and $E_{REF}(\theta)$ is the reference moduli of the investigated material determined in an angle θ in the laminate coordinate system

A curve describing the residual anisotropic damping and stiffness properties was calculated based on the results obtained in the DMA for three angles, polar transformation, and results of a curve fitting procedure (Fig. 6 and 7). Additionally, the *ACFs* for all introduced damage conditions were calculated.

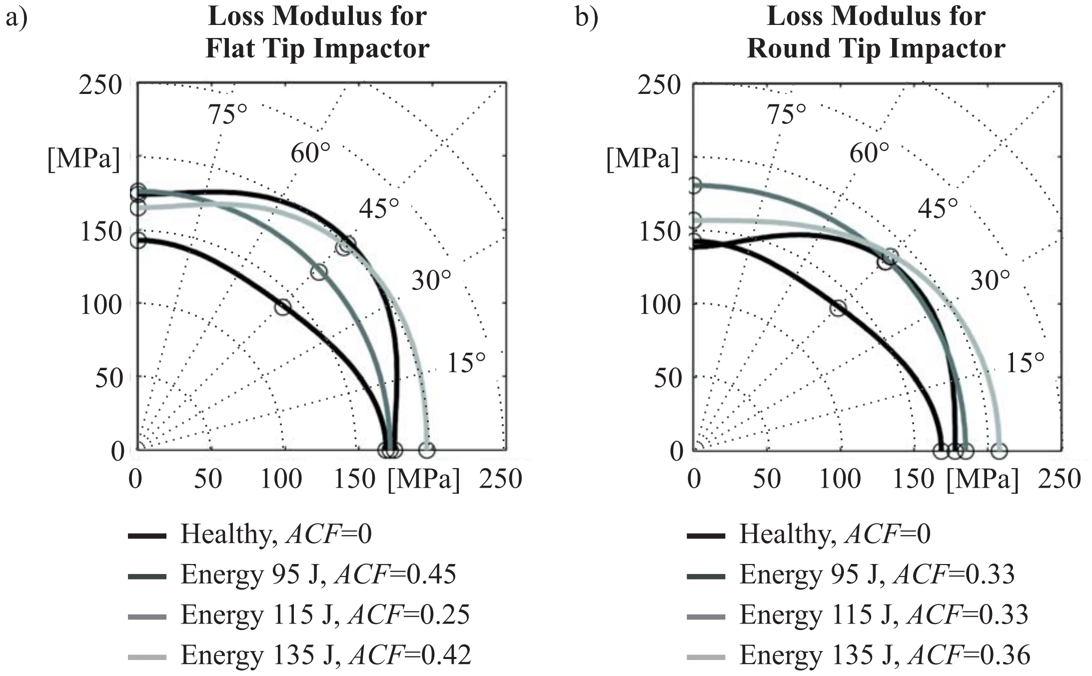


Figure 6. Change of loss modulus anisotropy due to impact event using flat (a) and round (b) tip impactor for the excitation frequency of 1 Hz.

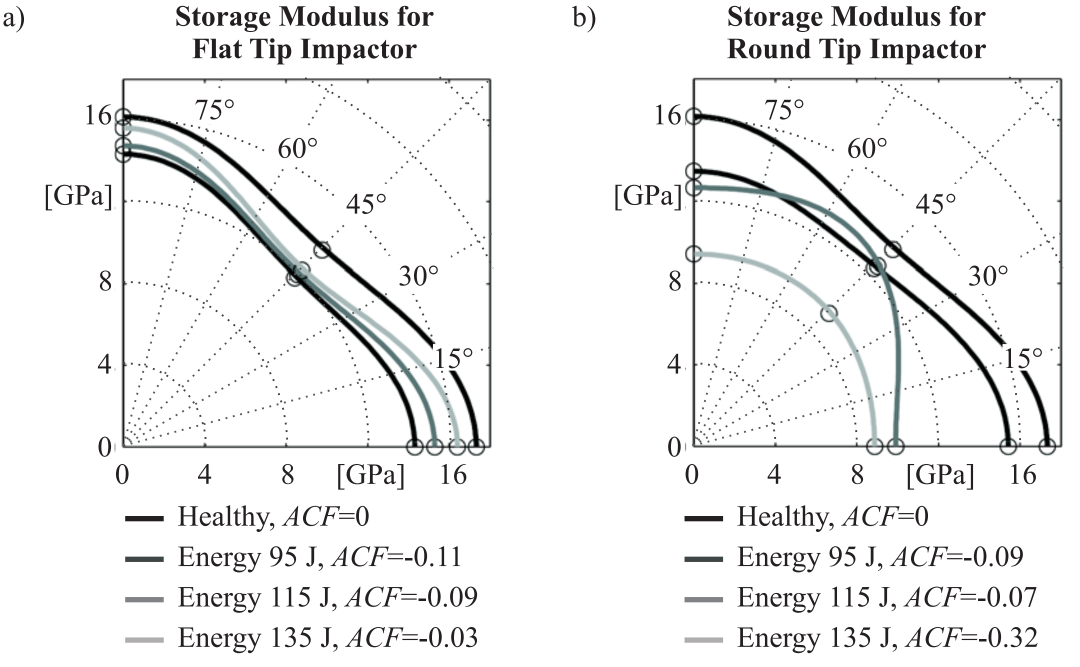
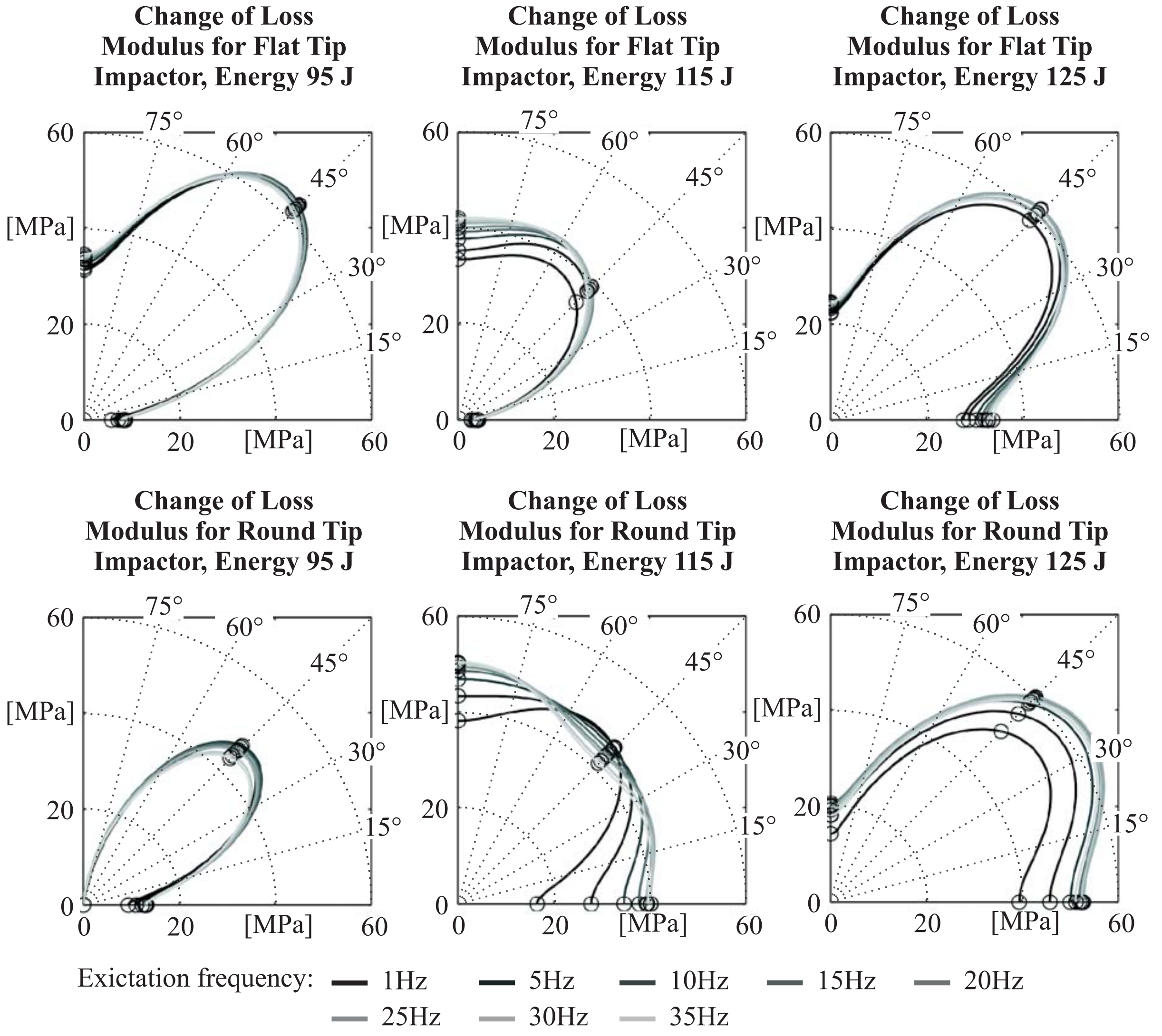


Figure 7. Change of storage modulus anisotropy due to impact event using flat (a) and round (b) tip impactor for the excitation frequency of 1 Hz.

The obtained results revealed significant changes of the anisotropy of material damping resulting from impact events. The biggest change of material damping was observed in 45° angle for both impactor types. The cause for such phenomena can be found in the fact that the reinforcing fibres are oriented only in 0° and 90° angles of the laminate. Therefore, the impact event can cause more severe damages in the 45° what results in a relative motion between the microscopic components of the composite material under forces in DMA tests. Such motion manifests itself in an increased energy dissipation and hence higher value of measured material damping.

In opposition to the apparent changes in the damping anisotropy, the alteration of stiffness was ambiguous. Whereas for the impact using the round tip impactor, the storage modulus significantly decreased, for the flat tip impactor barely any change was observable. This status results from the different severity of damages regarding the reinforcement fibres introduced in the impact test. Since the stiffness of the composite material is inherited mainly from the stiffnesses of the reinforcing fibres, fibre breaks cause its significant change.

In the next investigations, changes of anisotropic material damping for damaged coupons and their alteration due to excitation frequency were analysed (Fig. 8). As a reference, the determined anisotropic material damping of undamaged coupons was used.


Change of Loss Modulus for Flat Tip Impactor, Energy 95 J

Change of Loss Modulus for Flat Tip Impactor, Energy 115 J

Change of Loss Modulus for Flat Tip Impactor, Energy 125 J

Change of Loss Modulus for Round Tip Impactor, Energy 95 J

Change of Loss Modulus for Round Tip Impactor, Energy 115 J

Change of Loss Modulus for Round Tip Impactor, Energy 125 J

Figure 8. Change of loss modulus due to impact event as a function of frequency and impact event configuration in reference to (Reference: anisotropic damping of undamaged coupons).

Whereas for the relatively light damages higher excitation frequencies did not caused any significant changes in values of the anisotropic material damping, the same analysis conducted for severe damages resulted in considerable variations. Such condition can be explained by a nonlinear nature of the damaged material, e. g, due to kinematic nonlinearities of unbonded fibres.

6. Summary

In the presented investigations, the influence of the impact energy and impactor's tip shape on the anisotropic material damping and stiffness was analysed. The results revealed complex changes of both anisotropic material damping and stiffness due to impact-caused damages. Additionally, a nonlinearity of anisotropic material damping for higher excitation frequencies for severe damaged samples was observed. The incorporation of determination of complex changes of material damping anisotropy into structural health monitoring systems have potential to significantly increase the reliability of detection of light impact damages. The determination of damping properties of fibre-reinforced composites can be conducted using material-integrated actuating/sensing elements. Additionally, the consideration of impact-caused damping alteration can be a vital enhancement of the present composite simulation strategies typically assuming only stiffness degradation.

Acknowledgments

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