INVESTIGATION ON WAVE PROPAGATION IN COMPOSITES AS REQUIREMENT FOR IMPACT DETECTION

Mircea Calomfirescu*, Axel S. Herrmann*, Christian König, Jan Müller*****
***Faserinstitut Bremen e.V., **Bremer Institut für Konstruktionstechnik (BIK), ***Bremer Institut für angewandte Strahltechnik (BIAS)**

Keywords: *impact identification, wave propagation, SHM, composites, FEM*

Abstract

This paper investigates elastic waves excited by low velocity impacts and their propagation in composites in order to identify impact events. A monitoring strategy is presented to localize impacts and reconstruct their force-time histories. The proposed method is based on stress waves measurements with piezoelectric sensors coupled with a numerical optimization algorithm using explicit FEA results.

1 Introduction

The use of composite materials for structural applications has increased steadily during the last three decades due to their excellent specific quasi-static mechanical properties. In addition to their quasi-static behaviour composite structures have to perform well also under various types of impact loading. In the aircraft industry the residual compressive strength of an impact-damaged composite structure has become the design-limiting factor in many cases [1]. In contrast to metal or aluminum structures, low-velocity impacts on composites often create damages, which are not visible to the naked eye, consisting of internal delaminations, matrix cracks and fibre failure. In order to ensure structural integrity and maintain safety aerospace structures have to be inspected. At the present there are a variety of non-destructive, traditional inspection techniques (NDT) available such as radiography, ultrasonics, thermography and shearography [1]. The major disadvantages of these techniques are related to high cost, damage detection sensitivity, time consuming and require the structure to be out of service. Therefore, a system that automatically detects impact events would make inspections more efficient by localizing the inspection area only for significant impact loading cases.

Recently, many impact identification methods have been reported in the literature [2-6]. They are based on measurements of stress waves, which are excited by the impact itself. Most of them are based on model-based techniques. These techniques rely on a mathematical model which is able to describe the dynamic behaviour of structures including the stress wave propagation. For general complicated structures covering various types of joints, stiffeners, rivets, complicated shapes and varying thickness, this approach is not applicable since it is not possible to obtain a mathematical model.

In this paper, an approach is proposed for monitoring impact events based on explicit finite element analysis coupled with a numerical optimization algorithm. This approach may have the advantage that it is also applicable for complicated structures taking into account progressive failures and loss in stiffness.

2 Theory

2.1 Lamb waves propagation

When a plate-like structure is impacted Lamb waves are excited, which can be measured by piezoelectric sensors. Lamb waves [7] are dispersive plate waves which occur for tractionfree forces on both surfaces of the plate. The velocity of these waves depends on the product of frequency of excitation and thickness of the plate. A description of Lamb wave propagation characteristics for plates can be given in the form of dispersion curves. Such curves illustrate the plate-mode phase velocity vs. frequency (Fig. 1).

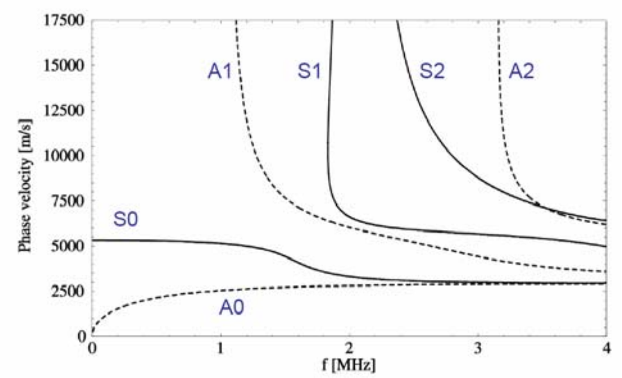

Fig. 1: Theoretical dispersion curves

Each curve in Fig. 1 represents a specific mode. The symmetric Lamb modes are called S_0, S_1, S_2, … and the antisymmetric ones A_0, A_1, A_2….starting with the mode with the lowest frequency (Fig. 2).

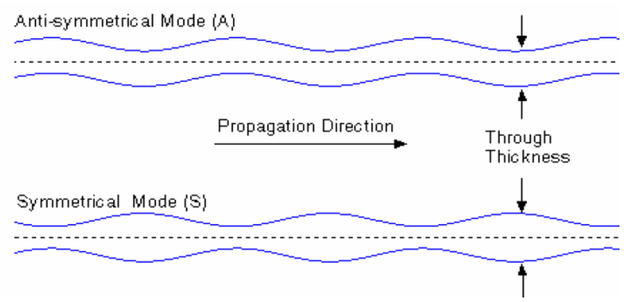

Fig. 2: Symmetric (S) and antisymmetric (A) modes

The phase velocity c_p is defined as $c_p=\omega/k$, ω being the angular frequency and k, the wave-number. In composite laminates, the dispersion curves are strongly influenced by the inherent anisotropy and heterogeneity of the laminate. However, the exact analytical treatment of waves in composites is much more complicated and consumes more computational cost than that of waves in an isotropic plate.

Since flexural wave is the dominant mode for low velocity impact of the composite plate [3] the dispersion behaviour of this wave mode will be investigated. The classical plate theory (CPT) is a widely used approximate theory for describing motion in thin plates where the wavelength (λ) is much larger than the plate thickness. The resulting CPT dispersion relation in the direction of propagation θ is given by:

$$c_p(\theta)=\sqrt[4]{\frac{\omega^4\cdot D_\theta}{\rho\cdot h}}\text{, where}$$

$$D_\theta=D_{11}\cdot\cos^4\theta+2\cdot(D_{12}+2\cdot D_{66})\cdot\cos^2\theta\cdot\sin^2\theta+D_{22}\cdot\sin^4\theta$$
$$+4\cdot D_{16}\cdot\cos^3\theta\cdot\sin\theta+4\cdot D_{26}\cdot\cos\theta\cdot\sin^3\theta$$

The CPT theory is only valid in the low frequency range or for wavelength much greater than the plate thickness, since it neglects transverse shear deformation and rotary inertia. Accordingly, a higher-order plate theory is examined to obtain solutions of waves in composites for higher frequencies. The dispersion behaviour predicted by this theory put forth by *Tang et al.* [8] is obtained when the determinant of the following matrix is set to zero.

$$\begin{vmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{vmatrix}\quad\text{where,}$$

$$M_{11}=D_{11}\cdot k^2\cdot\cos^2\theta+2\cdot D_{16}\cdot k^2\cdot\cos\theta\cdot\sin\theta+D_{66}\cdot k^2\cdot\sin^2\theta$$
$$+A_{55}-I\cdot\omega^2$$
$$M_{12}=D_{16}\cdot k^2+(D_{12}+D_{66})\cdot k^2\cdot\cos\theta\cdot\sin\theta$$
$$M_{13}=i\cdot A_{55}\cdot k\cdot\cos\theta$$
$$M_{21}=D_{16}\cdot k^2+(D_{12}+D_{66})\cdot k^2\cdot\cos\theta\cdot\sin\theta$$
$$M_{22}=D_{66}\cdot k^2\cdot\cos^2\theta+2\cdot D_{16}\cdot k^2\cdot\cos\theta\cdot\sin\theta+D_{22}\cdot k^2\cdot\sin^2\theta$$
$$+A_{44}-I\cdot\omega^2$$
$$M_{23}=i\cdot A_{44}\cdot k\cdot\sin\theta$$
$$M_{31}=-i\cdot A_{55}\cdot k\cdot\cos\theta$$
$$M_{32}=-i\cdot A_{44}\cdot k\cdot\sin\theta$$
$$M_{33}=A_{55}\cdot k^2\cdot\cos^2\theta+A_{44}\cdot k^2\cdot\sin^2\theta-\rho^*\cdot\omega^2$$
$$(\rho^*,I)=\int_{-\frac{h}{2}}^{\frac{h}{2}}\rho(1,z^2)\,dz\,;\;A_{ij}=\kappa_i\cdot\kappa_j\int_{-\frac{h}{2}}^{\frac{h}{2}}(Q_{ij})_k\,dz\quad for\quad i,j=4,5$$

In order to solve this problem, one has to find the root which approaches zero when the frequency is zero. Since k as a function of ω is known the phase velocity is determined by the equation already mentioned above.
For impact detection arrival times will be used at different points on the structure. Therefore wave velocities have to be known in each propagation direction. Fig. 3 shows the theoretical phase velocity of a flexural waves for a given frequency in a CFRP laminate.

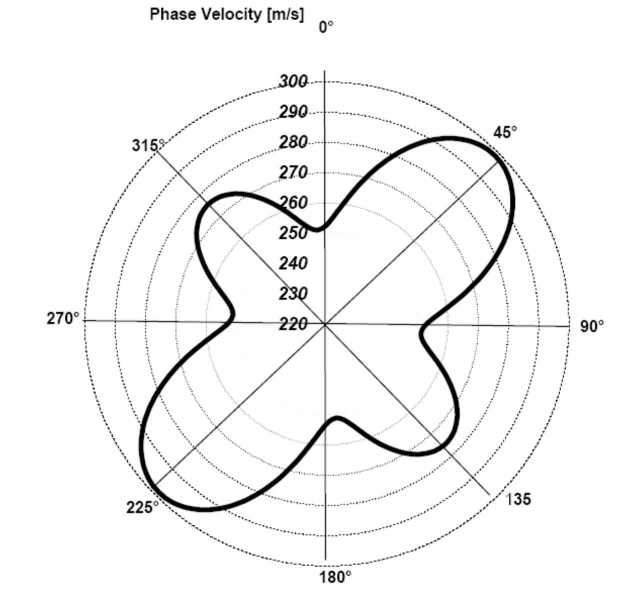

Fig. 3: Theoretical phase velocities of flexural waves in a $[45,-45]_{4s}$ CFRP plate for ω =10 kHz

2.2 Damping in Composites

When materials are set in vibration some of the elastic energy is converted into heat. However the various mechanisms by which this takes place are collectively termed energy dissipation or material damping. Composite materials dissipate energy during vibrations with much more intensity than do simple isotropic materials. Therefore the attenuation of wave propagation due to material damping in composites cannot be neglected. As well known from stiffness characteristics, damping shows also an anisotropic behaviour in composites. Therefore an Excel-based software was developed to predict anisotropic damping factors based on the theory of complex moduli.

The complex moduli can be expanded into real and imaginary parts [9]:

$$E^* = E' + i \cdot E''$$

The damping factor d can then be expressed as:

$$d = \frac{E''}{E'}$$

The well-known mixture rules and lamination theory can then be used to approximate damping for extensional and flexural vibrations for different lay-ups and different directions. Fig. 4 illustrates the flexural damping factor for a CFRP laminate. The calculation is based on measurements presented in [8] at unidirectional laminates.

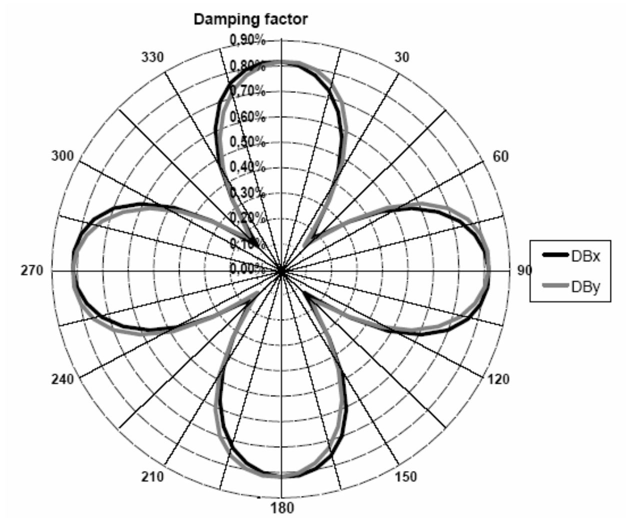

Fig. 4: Damping of flexural vibrations in $[45,-45]_{4s}$ CFRP plate for f =250 Hz

2.3 Signal Processing Methods

In order to localize impacts, arrival times of stress waves has to be defined. Since flexural waves are dispersive, arrival times depend on the frequency. Therefore different signal processing methods in the time-frequency domain have to be discussed. In this section two different methods of time-frequency analysis, the Short-Time Fourier Transform (STFT) and the Wavelet Transform (WT) are highlighted.
The STFT uses a constant time-window which is transformed by the Fast Fourier Transform (FFT) in the frequency domain. This time window is then shifted to a new position in time and the transform is repeated. Thus,

mathematically, the STFT can be expressed as a windowed FFT [10] and can be calculated by:

$$F(\omega,b) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t) \cdot g(t-b) \cdot e^{-i\omega t} dt \quad ,$$

where *f(t)* is the function windowed by *g(t)* for all *b*. Because the selected time window has a constant size it is not possible with the STFT to obtain high resolution in the time and in the frequency domain. In this context the WT may offer some advantages, regarding the time vs. frequency resolution. The WT uses a scale variable *a*, which is a positive number and a function ψ as the analysing function. The WT is defined as

$$F(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \cdot \psi\left(\frac{t-b}{a}\right) dt \ .$$

As mother wavelet the Gabor function can be used [11], because this provides good resolution in the time and in the frequency domain.

3 Experimental Set-Up and Measurements

The experimental set-up consists of a CFRP plate (500x500x4 mm³) with four surface-mounted PZT (PIC255) sensors from PI-Ceramic a digital oscilloscope and a notebook (Fig. 5 and Fig. 6). The PZT- sensors were embedded in a polymer substrate by the DuraAct® technology by Invent GmbH (Fig. 7). The sample is impacted by a hand-held, instrumented hammer with a mass of 160g. The PZT sensors are able to capture the plate waves without any amplifiers well and are sampled at 2 µs.

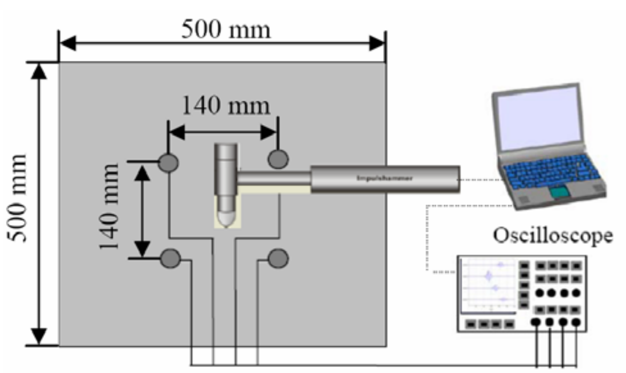

Fig. 5: CFRP Plate with surface mounted PZT-Sensors

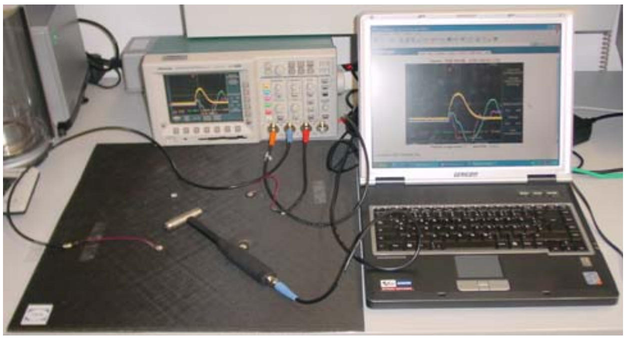

Fig. 6: Experimental Set-up

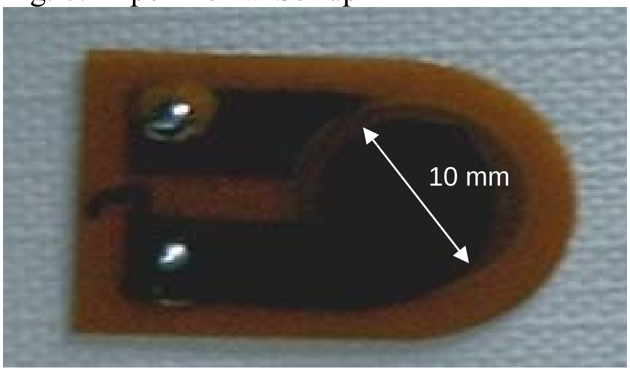

Fig. 7: embedded PZT- Sensor by the DuraAct® technology

For the impact hammer tips of different materials are available in order to vary the contact force characteristics. Copper, plastic and rubber tips are available. As shown in Fig. 8 (force triggered at 100 N) with the copper tip the shortest contact time can be reached in the range of 1ms. The plastic and rubber tips cause longer contact times up to 8ms.

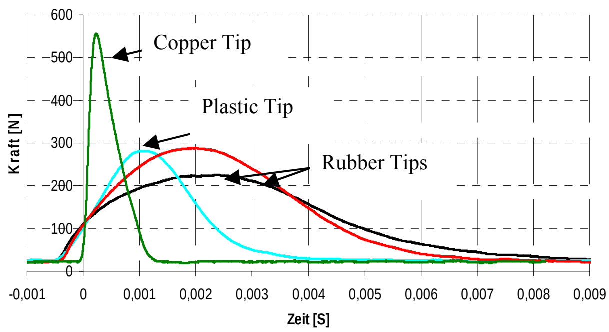

Fig. 8: Contact Forces for different hammer tips

Fig. 9 shows the strain histories measured at two sensor positions. The waves were excited by an impact with the contact force history illustrated as shown in Fig. 10.

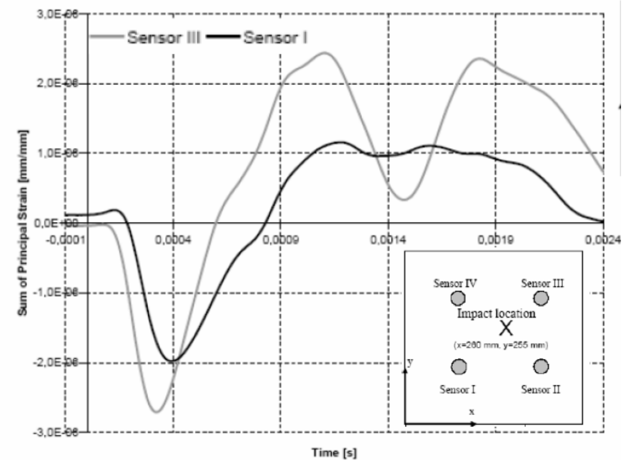

Fig. 9: Strain histories on sensors I and III

The distance from the impact position to sensor I resp. sensor III is 110mm resp. 88 mm. Thus the first peak is at 0,32 ms and at resp. 0,39 ms. The time difference of 0,07 ms corresponds to a wave propagation velocity in the 45° direction of about 315 m/s which is the theoretical phase velocity at a frequency of about 11 kHz.

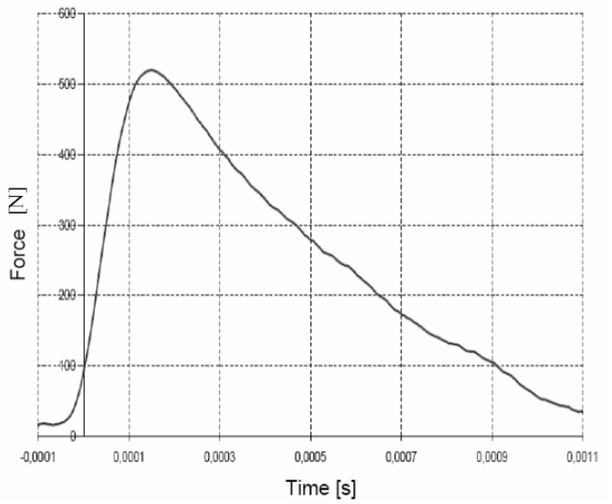

Fig. 10: Contact force history

3 Finite Element Analysis

The transient finite-element analysis was performed using the commercial software package LS-DYNA. The time step of the calculation was 0.1 µs, the number of 4-node shell elements about 100000. To ensure an accurate solution of the FE-analysis in wave problems it is not sufficient to use a fine mesh only in the impact zone, but the entire model must be discretized to a suitable mesh density. Fig. 11 displays the wave propagation at four different times after the impact.

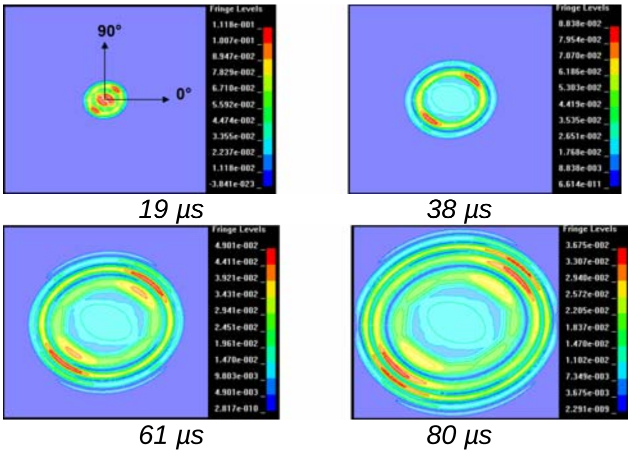

Fig. 11: Finite element simulation of wave propagation in an orthotropic CFRP plate

More details about the FEA can be taken from [12]. To verify the results of the transient finite element analysis two different experimental methods for the visualization of the wave propagation after the impact were applied:

- the method of photoelastic coating (BIK Bremen) [13]
- the method of holographic interferometry (BIAS Bremen) [14].

The comparison between the FEA-results and experimental tests of a quasi-isotropic plate obtained by the coating method are shown in Fig. 12.

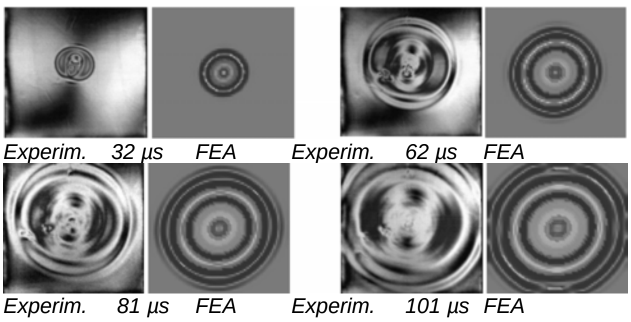

Fig.12: Wave propagation in a quasi-isotropic CFRP plate

A quantitative comparison between the FEA-results and measured differences of principal strain is displayed in Fig. 13.

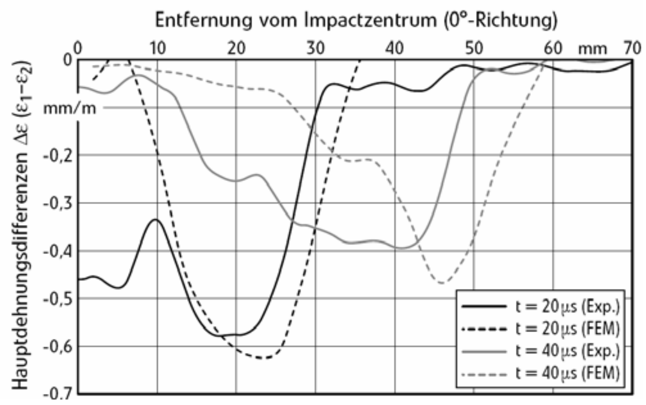

Fig. 13: Principal strains: Measured by the method of photoelastic coating and simulated by FEA

4 Impact identification strategy

Since the explicit Finite-Element is validated and verified the optimization tool LS-OPT is planned to be used in order to identify in two steps resp. two optimization loops (Fig. 14):

- the impact location (1. loop)
- the force-time of the impact (2. loop)

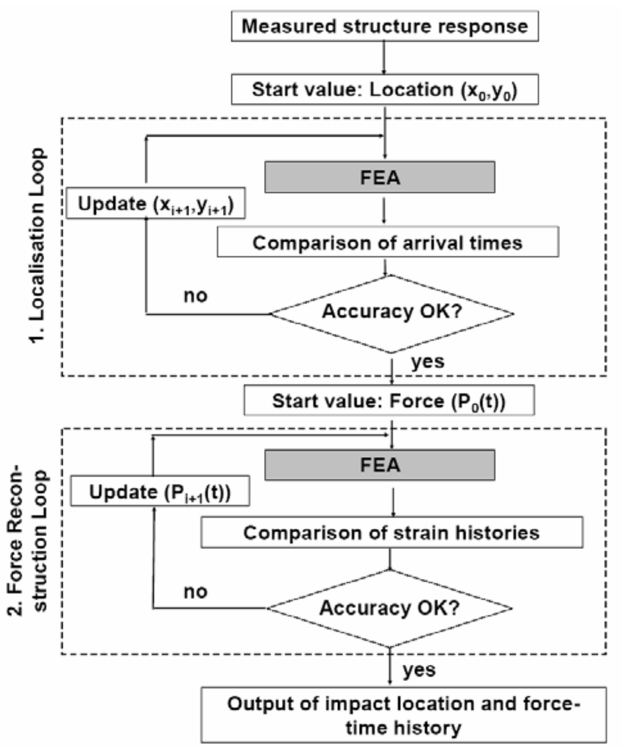

Fig. 14: Proposed impact identification process

By using FEA data it is expected that also impact on more complicated structures like stiffened panels can be detected. Moreover it remains to be investigated the implementation of anisotropic damping in the framework of user-defined material models. The commercially available material models of LS-DYNA can take into account only isotropic damping.

5 Summary and Outlook

In this paper the theory of wave propagation in composites for impact detection is shortly highlighted. An experimental set-up based on measurements with piezoceramic sensors is presented. In order to identify impact events different signal processing techniques in the time-frequency domain for non-stationary signals are studied. The Wavelet Transform appears to be a very attractive method.

Transient Finite-Element Analysis of wave propagation with LS-DYNA are presented and compared to experiments. Moreover, for a better understanding of the wave propagation experimental visualization methods like the method of photoelastic coating and the holographic interferometry were applied.

An impact identification strategy is presented which consists of an optimization of numerical data based on measurements provided by piezoceramic sensors. It is still to investigate experimentally the real attenuation of elastic waves due to energy dissipation and the wave propagation in damaged composites.

6 Acknowledgment

The financial support of this research by a grant from the DFG (Deutsche Forschungsgemeinschaft) is gratefully appreciated.

References

[1] Reid S.R and Zhou, G. *Impact behaviour of fibre-reinforced composite materials and structures*, CRC Press Cambridge, 2000.

[2] Okafor A. C, Chandrashenkhara and Jiang Y.P. Location of impact in composite plates using waveform-based acoustic emission and Gaussian cross-corelation techniques. *SPIE Proceedings* 2718, pp 291-302, 1996.

[3] Doyle, J.F. Experimentally determining the contact force during the transverse impact of an orthotropic plate. *Journal of Sound and Vibration,* 118, pp 441-448, 1987.

[4] Choi, K and Chang, F.-K. Identification of impact force and location using distributed sensors. *Journal of AIAA*, Vol. 34, No. 1, pp. 136-142, 1996.

[5] Gaul, L and Hurlebaus S. Identification of the impact location on a plate using wavelets, *Mechanical Systems and Signal Processing*, 12(6), pp. 783-795, 1997.

[6] Park, C. Y, Lee, I. G, Kim, I.-G and Lee Y.-S. Low velocity impact monitoring for composite sandwich panels using PVDF sensors, *Proceedings of 2nd European Workshop on Structure Health Monitoring*, pp. 423-430, 2004.

[7] Viktorov, I. A. *Rayleigh and Lamb Waves*, Plenum Press, New York, 1970.

[8] Tang, B , Henneke, E.G. and Stiffler, R.C. Low Frequency Flexural Wave Propagation in Laminated Composite Plates, *Proceedings on a Workshop on Acousto-Ultrasonics*: Theory and Application, Blacksburg Virginia, pp. 45-65, 1987.

[9] Hanselka, H. Ein Beitrag zur Charakterisierung des Dämpfungsverhaltens polymerer Faserverbund-werkstoffe, *PhD. Thesis*, TU-Clausthal, 1993.

[10] Strang, G and Nguyen, T. *Wavelets and Filter Banks*. Wellesley, Wellesley-Cambridge Press, 1996.

[11] Kishimoto, K., Inoue, H., Hamada, M. and Shibuya, T. Experimental wavelet analysis of dispersive waves by means of wavelet, *Journal of Applied Mechanics*, 62, pp. 212-217.

[12] Calomfirescu, M., Herrmann, A.S., König, C. and Müller, J. Numerische und experimentelle Untersuchung der Wellenausbreitung in Faserverbundstrukturen, *Materialprüfung*, 5, Mai 2006.

[13] Franz, T. Experimentelle Untersuchung von impact-belasteten versteiften bzw. gekerbten Platten aus Faserverbundwerkstoffen, *Ph.D. Thesis*, Universität Bremen, 1998.

[14] Schnars, U., Jüptner, W.: Direct recording of holograms by a CCD target and numerical reconstruction, *Applied Optics*, 33(2), pp. 179-181, 1994.