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DAMAGE DETECTION AND MONITORING OF COMPOSITE STRUCTURES WITH THE USE OF PIEZOELECTRIC SENSORS

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Abstract. *Damage detection in fiber-reinforced composite laminated panels using Lamb waves (wave propagation) is demonstrated with the use of a sensor array. Experiments are conducted to empirically characterize the wave propagation behavior in a manufactured laminate. Piezoelectric patches are used as sensors and actuators in the experiments. Composite laminates are manufactured with an embedded defect to simulate inter-ply delamination. Delaminations are one of the most severe defects associated with multilayered laminated composite structures. The experimental results are also compared with a numerical analysis for cylindrical panels with the use of 3D finite elements. A lot of numerical results allow us to understand better the influence of various parameters on the form of wave propagation in cylindrical multilayered shells. Based on numerical results it is possible to determine the effect of the delamination on the guided wave propagation in curved structures.*

1 INTRODUCTION

The increasing demand in lowering maintenance costs in engineering structures made of composite materials contributes to the growing development of structural health monitoring systems. Such systems would insure continuous knowledge of the structural state of the monitored structural components, possibly allowing directed maintenance and maintenance task optimization. Techniques used to realize the checking must obviously not damage these structures. Many methods have been developed during recent decades, and they have all been grouped under the term of Non-Destructive Testing (NDT) methods, such as: e.g.: mechanical (ultrasonic, acoustic emission), thermal (thermography), magnetic (Eddy current), X-ray (tomography) and visual (penetrant testing, CCD camera) optical fiber methods. The number of inspection methods grow and depends on application in particular type of construction [1-3]. The principles, application, advantages and limitations of those methods has been described by Hellier [4]. Kuhn et al. [5] have been shown and discussed some characteristics of the most common NDT methods used in industry.

Few methods are able to monitoring the structure in real time. One of this is the Acoustic Emission (AE) method, that has long been recognized as a viable technique for real-time monitoring of metallic and composite structures, giving useful information not only on the presence of defects, but also on their evolution and position [6–11]. Structural health monitoring (SHM) techniques based on guided waves propagation have been the subject of interest for researchers since 1980. A literature review of the most salient studies on ultrasonic guided waves was presented by Su, Ye and Lu [12]. A classification of dynamic-based SHM techniques as a relationship between interrogation frequency and damage size was presented by Gopalakrishnan et al. [13]. Guided waves are able to propagate for relatively long distance and have high sensitivity to both surface and embedded structural damage. Accordingly, guided waves have been widely used to develop various damage identification algorithms.

The efficient and effective use of composite materials in design applications is directly connected with the good knowledge of the static and fatigue strengths of the material. There is a variety of failure modes associated with static and/or fatigue damage, including: 1) matrix cracking, 2) interfacial debonding, 3) fiber breakage, and 4) delaminations.

There have been many works on wave propagation problems related to composite shells. The first work (Lord-Rayleigh [14]) of this field dealt with wave propagation in a semi-infinite solid. In 1917 Lamb published the first work [15] of dealing with guided wave propagation in thin elastic specimens. Mirsky [16] and Nowinski [17] solved for axially symmetric waves in orthotropic shells. Chou and Achenbach [18] provided a three-dimensional solution for orthotropic shell as well. Nayfeh [19] discussed scattering of horizontally polarized elastic waves from multilayered anisotropic cylinders embedded in isotropic solids. Yuan and Hsieh [20] proposed an analytical method for the investigation of free harmonic wave propagation in laminated shells. The numerical description of the waves traveling into waveguides and slen-der structures has also raised many interests – information about those problems is discussed in Ref. [21].

The first introduction of Lamb waves as a means of damage detection was made by Worlton [22] in 1961. He noticed that distinguish characteristics of the various modes of Lamb waves can be useful in nondestructive testing applications. Prosser et al. [23] used acoustic emission to identify cracking of thin composite specimens; also outlined the difficulties associated with acoustic emission. Wevers [24] outlined the advantages of acoustic emission techniques over other NDE methods for identifying damage in a loaded composite component. Lakshmanan and Pines [25] used and developed a wave propagation method to identify delaminations and transverse cracks in Gr/Ep composite rotorcraft. Ihn and Chang [26] used spectrograms to process guided wave signals obtained from an array of piezoelectric transducers to detect and monitor fatigue crack growth.

In this study, damage detection in fiber-reinforced composite laminated panels using Lamb waves is demonstrated with the use of a sensor array. Experiments are conducted to empirically characterize the wave propagation behavior in a manufactured laminate. Piezoelectric patches are used as sensors and actuators in the experiments. Experiments were conducted to detect the presence of damage in a composite laminate. These results are used to quantify the difference in the cases of perfect and defected structures. The experimental results are also compared with a numerical analysis for cylindrical panels with the use of 3D finite elements. A lot of numerical results allow us to understand better the influence of various parameters on the form of wave propagation in cylindrical multilayered shells. The problems of optimization and positioning sensors were also discussed due to possibility of detecting damage the laminate, in which the location of the defect is unknown. Then, the results are compared with the FE model.

2 DETECTION OF DAMAGE

Elastic waves are generated by an actuator (one of the grid piezoelectric transducers (PZT)) and recorded using the remaining PZT transducers (from the same grid – Figure 1). The shape of system of PZT transducers, shape and number of PZT influence on the quality (sensitivity) and accuracy of detection of defects in the test of composite structures. An additional issue is the control and detection of failure sensors, which is discussed among other in the works [27, 28].

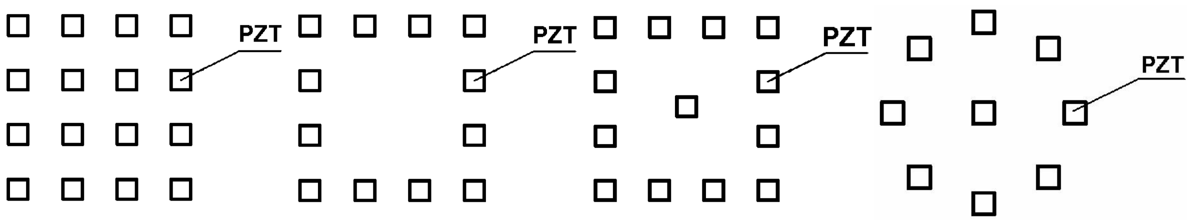


Figure 1: Examples of systems of PZT transducers.

A comparison of the wave signal for the structure without any damage and disturbance in the propagation of the wave induced by delamination. The location of this damage is defined as follows:

$$d = \frac{v_g \Delta T}{2} \tag{1}$$

where ν_g is the velocity of wave propagation, ΔT is the difference between the signal of the incident wave and the wave disturbed by the damage.

The correlation coefficient ρ_{ab} between the original and distorted signals was calculated for individual sensing paths in the time domain to get the perception to damage near the sensing paths. The damage index (D) is defined as:

$$D = 1 - \rho_{ab} \tag{2}$$

3 OPTIMIZATION PROBLEMS

Optimization problems deal with the analysis of structures with some response (denoted by R) requirements. In general structures with actuators can be optimized using three computationally different strategies. In the first, the most common optimization problem the objective function to be minimized is the response of the system, i.e.:

$$\underset{\mathbf{s}}{Min}\, R(\mathbf{s}) \tag{3}$$

The vector s denotes the set of design variables.

The response tuning is the second problem. It can be treated as the alternative or sometimes equivalent optimization problem to the above:

$$\underset{\mathbf{s}}{Min}\left[R_l(\mathbf{s}) - R_{l-1}(\mathbf{s})\right], l = 2,3,... \tag{4}$$

In addition, as the third problem volume or weight minimization of a structure has been considered here, in which:

$$\underset{\mathbf{s}}{Min}\, V(\mathbf{s}) \tag{5}$$

The problem of shape optimization of piezoelectric transducers has been discussed among others in the works [29–34].

Optimal location of sensors concerns the best location of sensors and their required number. To solve this problem, the optimization procedures have been applied. In addition, the information of composite structures and wave propagation in the material has been used.

Simple methods have been used to find the best configuration of transducers. This is done by adding or removing one or more sensors and evaluated the relationship between the transducers, signal quality and accuracy of fault location in order to find the best combination. Development of methods of combinatorial optimization based on biological and physical analogy allows the use of such genetic algorithms, neural networks, simulated annealing, etc.

Optimal location of sensors and actuators over a structure can be different for different criteria based upon: maximization of modal forces/moments applied by the PZT actuator, maximization of deflection of the host structure, minimal change in host structural dynamics, desired host structural dynamics, minimization of control effort/maximizing energy dissipated, minimization of host vibrations, maximization of degree of controllability/observability of modes of interest, etc.

4 EXPERIMENTAL ANALYSIS

4.1 Piezoelectric transducers

Piezoelectric materials are characterized as being able to produce a mechanical strain when an electrical field is applied to the piezoelectric actuator. The converse effect has also been observed, which has led to their use as sensors. Sensors respond to a physical stimulus and transmit a resulting impulse. When a device is actuated by power from one system and supplies power, than it is called as piezoelectric transducer.

Piezoelectric transducers are usually made in the shape of rectangular (Fig. 2) or round plane-parallel plates (see Ref. [35]), cut from a piezoelectric crystal so that the plate has been properly oriented with respect to the crystallographic axis, in particular in relation to the polar axis. Along this axis, the effect is highest for the longitudinal deformation, and therefore the plate, which has ultrasonic transducer longitudinal waves, is cut perpendicular to the polar axis.

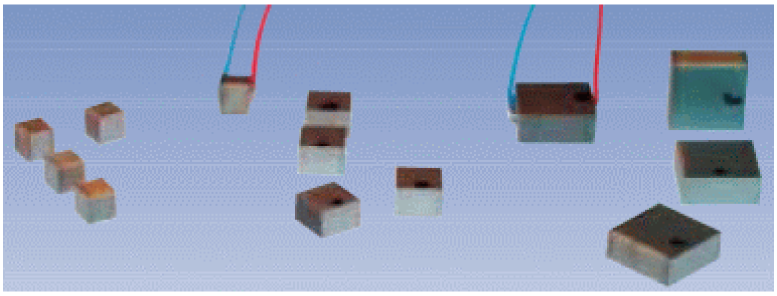


Figure 2: Piezoelectric transducers.

Piezoelectric transducers are made of ceramic materials often. These generally have better hardness and high-temperature strength. In the micro electromechanical systems it is also used the thick ceramic film and tree-dimensional ceramic structures. More information of piezoelectric transducers we can be find in the works [35, 36].

4.2 Damage detection

Damage detection in composite laminated panels using Lamb waves is demonstrated with use of a sensor array. Experiments were conducted to characterize empirically the wave propagation behavior in a manufactured laminate. Piezoelectric patches were used as sensors and actuators in the experiments. Sensor arrays and associated processing were used for wave number decomposition and filtering of the Lamb wave modes. Composite laminates were manufactured with an embedded defect to simulate inter-ply delamination– see Fig. 3. Experiments were conducted to detect the presence of delamination damage in a composite laminate.

A cylindrical panel made of glass woven roving having the mechanical and geometrical parameters was made of 8 layers and had the following geometrical parameters: L=298 [mm], R=92 [mm], t=1.8 [mm] , h_1=h_2=t/2 – Fig. 3. An excitation signal took the form of sine wave function was modulated with the Hanning window and was applied at the left piezoelectric actuator in Fig. 4 (piezoelectric transducer No. 1); its frequency is varies from 50-500 [kHz]. The piezoelectric sensors (on the right side in Fig. 4 - piezoelectric transducer Nos. 2-5) were placed close to the local square delamination having the size 10 [mm] and being in the middle of the laminate – see Fig. 3.

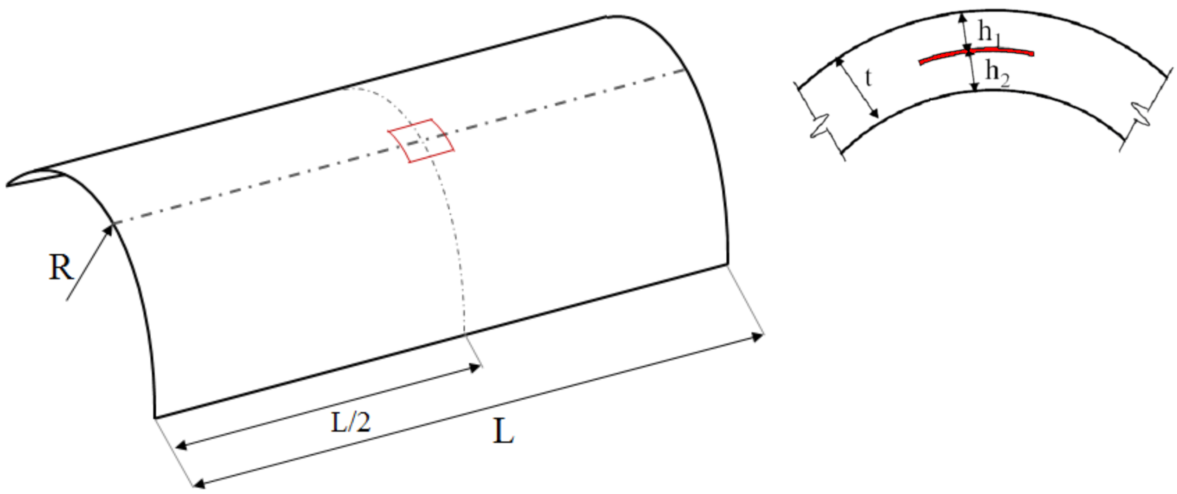


Figure 3: A cylindrical panel with a single delamination.

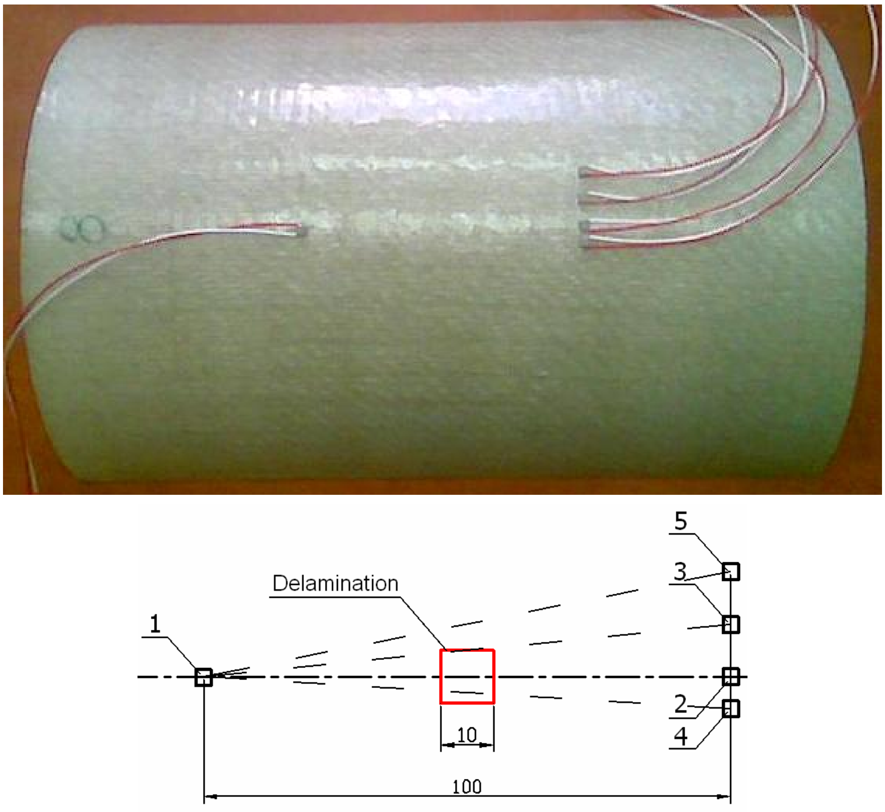


Figure 4: General configuration of the cylindrical panel with one actuator No. 1 and sensors Nos. 2-5 – they are located parallel to the delaminated area.

The wave propagation in the panel with local delamination was analyzed experimentally. The excitation signal and the response signal were generated and collected by the analyzer and then those signals were converted to digital ones with the use of MATLAB package.

Figure 5 demonstrates the response signals obtained experimentally for the perfect and imperfect (with the single delamination) cylindrical panel. As it may be seen there is a visible difference between response signals for perfect and imperfect shells for excitation signal frequency 100 [kHz]. Various excitation signal frequency was considered in Ref. [37].

However, the reasonable detection of the size and the location of delamination require the careful analysis and optimal design of the location and number of piezoelectric sensors and actuator. In addition, in the delaminated region the interference between generated and reflected waves is observed that affects the signal collected by the sensor (see Figs 7). In order to obtain better experimental results it is necessary to conduct further work dealing particularly with the optimal design of sensors number, locations and the frequency of the excitation signal.

The locations of piezoelectric sensor and actuator have significant effects on the displacement response. Different locations are presented in Figs 6 and 8. The response result (Figs 7 and 9) are plotted for one value of the signal excitation frequency equal to 100 [kHz]. The amplitude of response displacement is strongly affected by the distance between sensor and actuator – compare results plotted in Figs 5 and 9. The growth of the distance reduces the amplitudes. For the sensor and actuator located in the parallel direction to the delamination the amplitude for imperfect shell is lower than for perfect one, whereas for other locations the amplitude is higher – compare the results presented in Figs 5 and 7, 9.

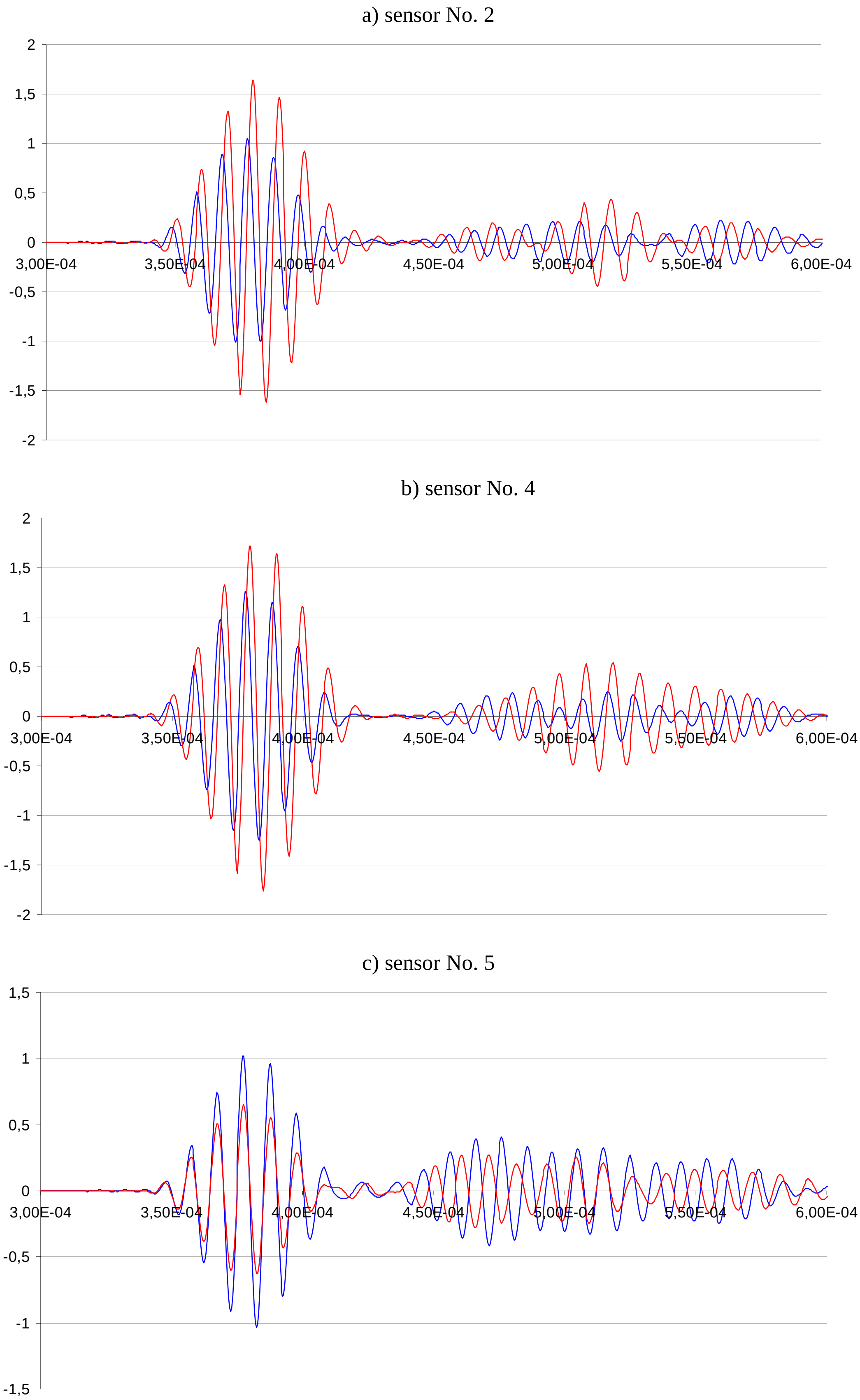


Figure 5: Experimental wave propagation results (blue line – without delamination, red line – with delamination); for frequency equal to 100 [kHz].

Figure 6: Configuration of the cylindrical panel with the sensor and actuator – they are located below delaminated area 5 [cm] from the panel edge.

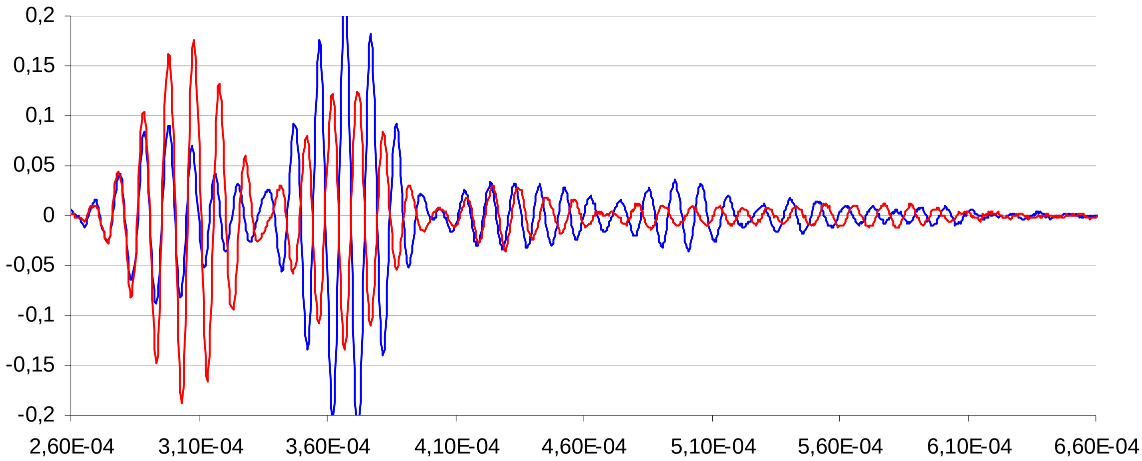


Figure 7: Experimental wave propagation results (blue line – without delamination, red line – with delamination); frequency is equal to 100 [kHz].

Figure 8: Configuration of the cylindrical panel with the sensor and actuator – the actuator is located above delaminated area 5 [cm] from the upper panel edge and the sensor 5 [cm] from lower panel edge.

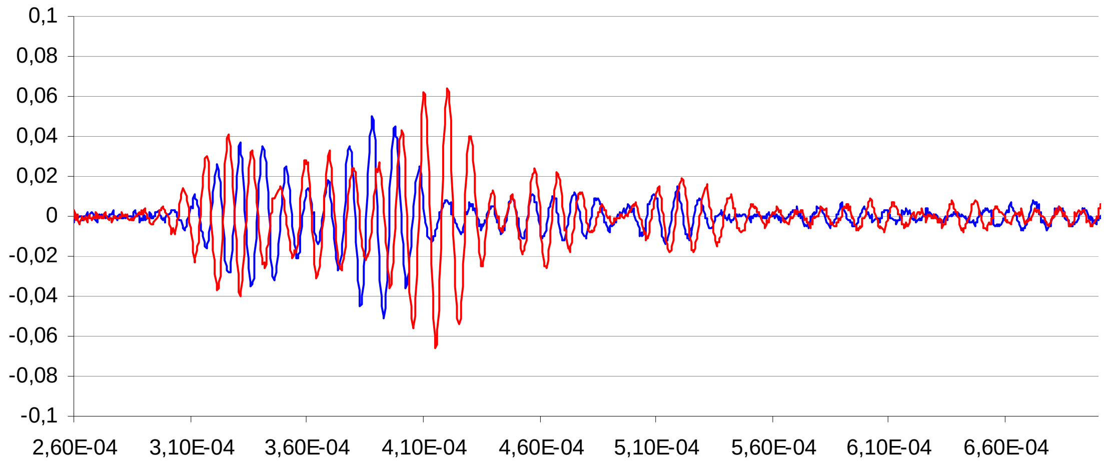


Figure 9: Experimental wave propagation results (blue line – without delamination, red line – with delamination); frequency is equal to 100 [kHz].

5 FINITE ELEMENT MODELING

5.1 Finite element modeling and simulation of guided wave propagation

Modeling methods and sensing technologies are the crucial areas of SHM. In fundamental axioms of SHM defined by Worden [38] the damage detection analysis is possible by comparison of two state system (intact and defected) because a sensors cannot measure flaws. The system of sensors applied to the structure gives a set of raw data which have to be processed to identification and localization of potential damage. It indicates to importance of modeling of damage and a damage detection algorithms. Common modeling techniques like the finite element method, spectral finite element method, finite difference techniques, boundary element methods and other were successful applied to SHM. The choice of accurate and efficient computational method depends on the size of damage that needs to be detected.

5.2 Finite Element Method modeling assessments

Among all numerical methods FEM is one of the most versatile, powerful and widespread due to its ability to model complex geometries. In this study the FE ANSYS package was applied to evaluate dynamic behavior of composite structure. FE modeling of composites is more complex than of isotropic materials, particularly due to the presence of complex stiffness and variety of failure modes. An appropriate finite element model of structural damage have to fulfill a several requirements which have been pointed out by Ye, Su [39]. The size of finite elements used to model a geometry of the structure depends on the speeds of the medium in which the signal is propagating and on the signal frequency. The mesh density should feature at least 8 nodes per wavelength to deliver good spatial precision. The time step for dynamic calculation should be less than the ratio of the minimum distance of any two adjoining nodes to the maximum wave velocity. The laminate should be divided into sub-laminates in thickness to characterize individual laminae especially when we consider interlaminar delamination in composite structure. In the present study the 3D solid95 finite element type with a 20-nodes was used in modeling a structure. A higher order version of a classical 8-nodes solid element with three degrees of freedom per node and fulfillment of presented requirements allow to obtain an accurate results of the numerical analysis.

Modeling of structural damage is crucial for the development of dynamic-based damage identification. The number of different modes of failure cause that this subject has attracted intensive research efforts over long period. Considered in this study delamination can be modeled by stiffness reduction method, kinematics based method or duplicate node method. the most adequate technique based on completely model the entire of the defect can be used either the 1D beam elements or 2D and 3D finite elements. Detailed information of the modeling of delamination we can be find in the works [36, 40, 41].

The most common techniques for the generation and receiving of guided waves is the use of piezoelectric elements. A PZT patches can deliver wide frequency responses with low power cost. A light and small structures are suitable for integration into a structures with good coupling capacity. Moreover, the sensor network can be configured by application a number of PZT elements to achieve a multi-point measurements for reliable analysis. In FEM model a concentrated force applied to the considered composite cylindrical panel varies with time function and simulate the load generated by real PZT element with 100kHz excitation frequency. The excitation signal was generated by one actuator and the data from the sensors placed after defected zone was compared with the results from an intact structure.

5.3 Results of numerical analysis

In this study a cylindrical panel with a single delamination in the middle (Fig. 3) is considered. A cylindrical panel was made of glass woven roving having the following properties: $E_{long}=E_{circumf}=13.14$ [GPa], $G_{12}=4.1$ [GPa], $\nu_{12}=0.25$, $\rho=1100$ [kg/m^3].

As it has been mentioned the any observations of waves is strongly dependent both on locations of the actuator/s and sensors (Fig. 1). Let consider the actuator and sensors configuration in the form presented in Fig. 4. Various localization of the sensors are taken into account to determine the influence zone of delamination on wave propagation path.

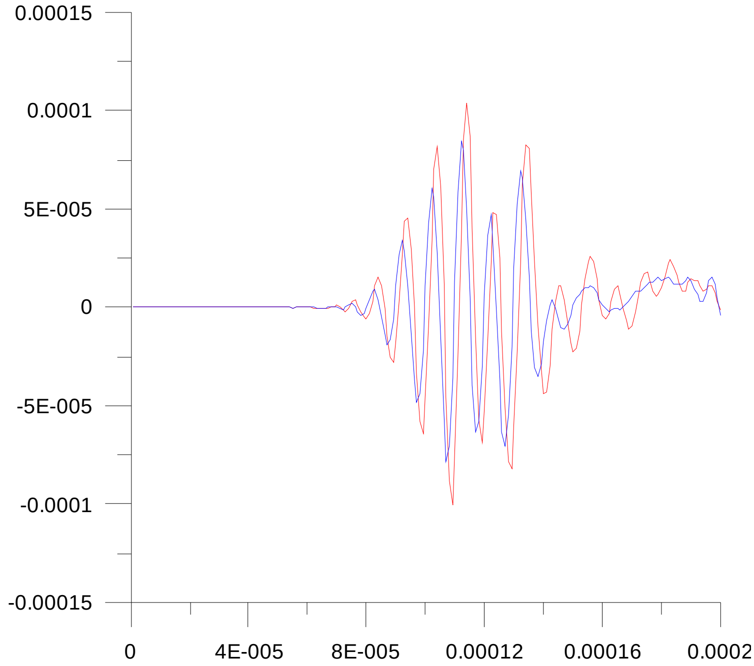
The wave propagation for construction is disturbed by the delamination. We can observe the defect influence zone after delamination which broaden with the distance between propagating waves and the delamination. The influence of delamination on wave propagation can be observed by comparison signal of the intact and defected structure.

Figure 10 illustrates the response signals obtained for the perfect and imperfect (with a single delamination) structures. Even if the signal passes through the whole delaminated area (sensor No. 2) the difference between displacement for the defected and perfect structures is small. The most significant difference between response signals is observed by sensors placed outside of the defect influence zone (sensor No. 5). The signal observed by sensor No. 5 is going near the corner of the delamination. The greater distance from defected area cause a lower disturbance of response signals.

The experimental results are also compared with a numerical analysis for cylindrical panels for the signal excitation frequency equal to 100 [kHz]. The difference between the perfect and imperfect (with the single delamination) cylindrical panel plotted in Figs 5 and 10 demonstrate very good agreement. The form of response signal is strongly affected by the location of sensor and actuator.

The size of the defect influences on wave propagation. To the effect of delamination size on the dynamic behavior of the structure (a cylindrical panel with a square delaminations of different sizes) is analyzed in the work [40].

a) sensor No. 2



a) sensor No. 5

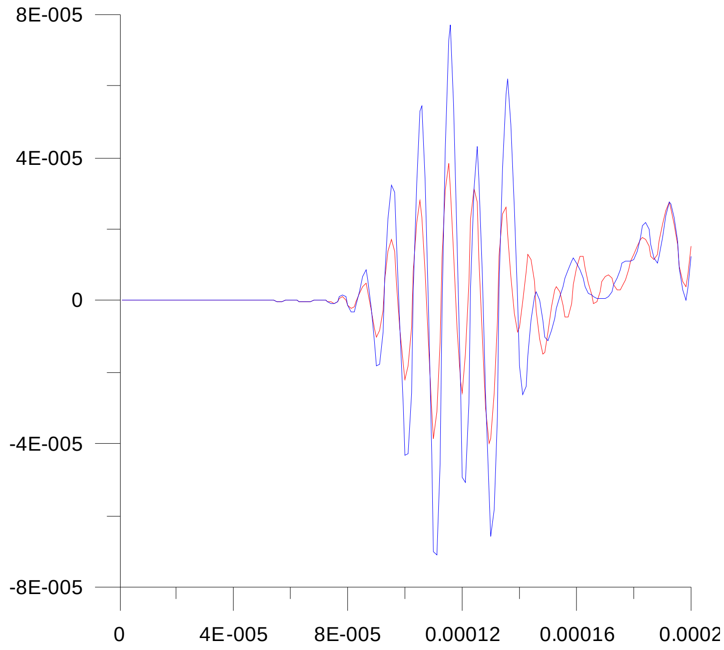


Figure 10: Numerical wave propagation results (blue line – without delamination, red line – with delamination); for frequency equal to 100 [kHz].

6 CONCLUSIONS

- Results of damage detection in composite laminated panels are demonstrated with use of piezoelectric patches.

- The amplitude of the response is strongly affected by the excitation signal frequency and location of sensor and actuator; therefore, the optimization of they location and number is required.
- Modeling of composite structures having smart piezoelectric sensors or actuators are very similar to conventional composite layered structures, however, there is one difference reflected in the constitutive laws in the form of the electromechanical coupling.
- Optimal location of sensors and actuators over a structure can be different for different criteria.
- The composition of experimental and numerical results demonstrates very good agreement.
- A lot of numerical results allow us to understand better the influence of various parameters on the form of wave propagation in cylindrical multilayered shells.
- Based on numerical results it is possible to determine the effect of the delamination on the guided wave propagation in curved structures.
- The shape of system of piezoelectric transducers, the shape and the number of PZT sensors have a great influence on the quality and accuracy of damage detection.

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