Methods Based on the Phenomenon of Elastic Wave Propagation (Guided Waves) – Interaction with Damage

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ABSTRACT

Structural Health Monitoring (SHM) is a multidisciplinary technology devoted to development and implementation of methods and systems that realize inspection and damage detection by integration with structures.

This chapter covers the major SHM disciplines which are based on topics such as piezoelectric transducers, elastic waves propagation phenomenon, phased array techniques, damage mechanics and 3D laser vibrometry applications.

Among various techniques available the chapter presents selected numerical simulations and experimental validations of considered structures. Also the chapter provides helpful information about dispersion, mode conversion, thermo–mechanical processes and wave scattering from stiffeners and boundaries. It can allow one to optimise excitation signal parameters and sensor placement, as well as enable analysis of signals reflected from damage. It also includes a variety of techniques being related to diagnostics (damage size estimation and damage type recognition) and prognostics.

1.0 INTRODUCTION

Discussing the problems of elastic waves propagation in Structural Health Monitoring (SHM) applications is necessary to provide basic definitions on the NDT (Non Destructive Technology) and ENDT (Extended Non Destructive Technology) methods.

NDT methods are of interest for many years and have found wide application in various branches of technique. Moreover, NDT methods are still widely used because of their accuracy and effectiveness. However, NDT methods also have their drawbacks. The most important are – a long time of inspection and the need to involve staff with high qualifications. Thus, the cost for applying NDT methods is relatively high. The most commonly used NDT methods include: conventional ultrasounds with frequency analysis, nonlinear ultrasounds, eddy current, strain gauges, laser excited ultrasounds, and many others.

Extended NDT methods are of interest for several last years. ENDT methods were caused by the need to detect defects which cannot be detected with classical NDT methods.

There is a long list of examples of such defects: composite element contaminated by moisture (water, skydrol, etc.), composite panel contaminated by chemicals (silicon, etc.), thermal degradation and defects in composite bonds. Also surface contaminants of composite elements that appear during the manufacturing process are included to those examples.

The most commonly used ENDT methods include: active thermography with optical excitation, active thermography with ultrasound excitation, electro–mechanical impedance technique, terahertz technology (THz), and many others.

Structural Health Monitoring (SHM) methods represent completely different strategy of inspection. Traditional structural strategy of inspection uses data from the initial design and manufacturing process to create a service manual. The strategy based on Structural Health Monitoring (SHM) technology creates feedback loops within the design, manufacturing and maintenance procedures. It provides additional knowledge about a specific design performance, material quality and structure condition respectively.

The most commonly used SHM methods include: vibration based methods, guided wave methods, fiber optics techniques, acoustic emission, comparative vacuum monitoring, electromagnetic layer, and many others.

2.0 THE GUIDED WAVE DAMAGE DETECTION PRINCIPLE

2.1 The Guided Wave Principle

This lecture is dedicated to guided wave methods which are based on the phenomenon of elastic wave propagation and their interaction with damage. Guided waves contain packets which are superpositions of various modes of propagating waves. They have an infinite number of modes associated with propagation and mathematical equations of guided waves must satisfy physical boundary conditions of a structure. The best known guided waves that occur in plates are named Lamb waves.

A health monitoring system based on guided wave propagation seems to be an effective method for a quick and continuous inspection of metallic and composite structures. Developing such methods and then applying them during manufacturing and operation of metallic or composite structures allows for evaluating degradation, and therefore remaining life, of such structures, Figure 1. Differences in the responses may be used for proper assessment of a failure location. Responses, measured at different points, can give information about the location of imperfections (failures).

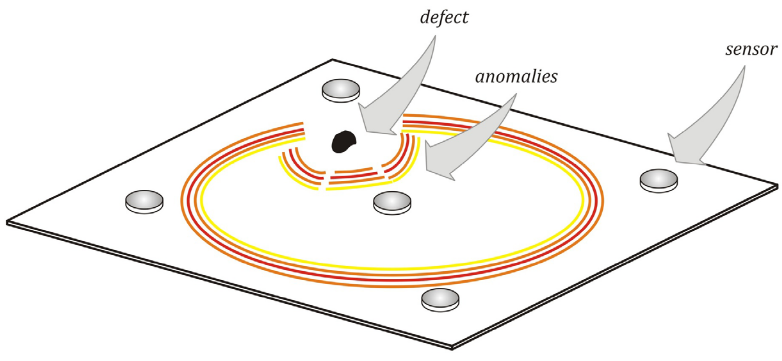


Figure 1: Guided wave propagation and interaction with a damage.

2.2 Simulation of Guided Waves

Discussing an efficient method to model numerically elastic waves propagation for damage detection there are several possibilities. One of them widely used last decade is Spectral Finite Element Method (SFEM), [1].

Discussing evaluation of degradation and therefore remaining life of structures we need define levels of health monitoring. Relevant literature describes widely defined five degrees of failure detection:

Level 1: Detect the existence of damage.

Level 2: Detect and locate damage.

Level 3: Detect, locate and quantify damage.

Level 4: Estimate remaining service life (prognosis).

Level 5: Self diagnostics.

Some sources define also **Level 6**: Self healing.

The levels of failures are very important in theoretical and experimental analysis. The Level 1 represents the simplest process of damage detection. Level of complexity increases from the Level 1 to Level 5. Grater levels need more for analytical models and experimental tasks.

Among various techniques available, guided waves are forced by a system of piezoelectric transducers. Guided waves induced by piezoelectric transducers are extensively used for damage detection purpose. Guided waves propagate through a structure and interact with failures. The features of reflected waves are recorded by sensors localized in selected places of an analyzed structure, Fig.1. Then the features recorded by sensors through signal analysis and statistical classification convert sensor data into damage information.

Taking all into consideration the problem of damage detection indicates the following problems:

1) Modelling of structures,
2) Selection of sensors (type, etc.),
3) Location of sensors,
4) Implementations of sensors,
5) Method of measurements,
6) Effective signal processing method, and
7) Visualization and interpretation of results.

Numerical models constitute the foundation for developing perfect tools for designing and verifying new concepts of signal processing and testing methodology. In this presentation a numerical model based on time–domain spectral finite element method has been developed to simulate elastic wave propagation in metallic and composite structures induced by the piezoelectric transducers. Generally 2D model has been investigated (Figure 2) however also 3D element formulation is given (Figure 3). The model solves the coupled electromechanical field equations simultaneously in 3D case.

Delaminated composite plate, [6]	*3D Spectral Element, [7]*

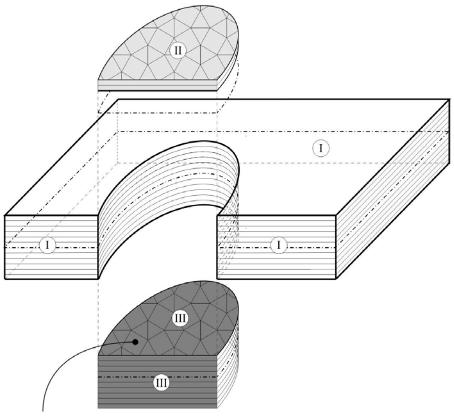


Figure 2: 36 node plate spectral finite element Mindlin's plate theory | homogenization 36 nodes |5 degrees of freedom per node.

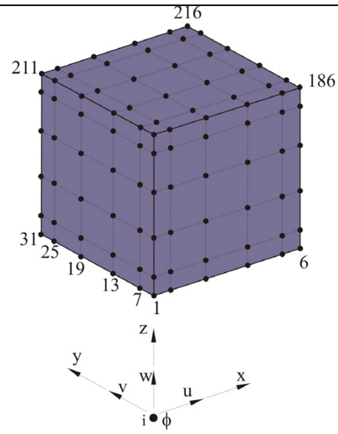


Figure 3: 216 nodes | 3 mechanical degrees of freedom per node – displacements u, v, w | one electrical degree of freedom.

2.3 Experimentation with Guided Waves

The presentation contains discussion on selection of sensors (i.e. type, size, physical properties, sensitivity, cost, etc.) and their location. The sensor location depends between others on the number of sensors, expected location of failures, signal processing procedures, environmental conditions, costs, etc. It can allow one to optimise excitation signal parameters and sensor placement.

Problem of implementation depends on many parameters. It depends on investigated structure (metallic or composite), environmental conditions, places (surfaces) of location, expected sensitivity, expected load, etc.

Method of measurement depends on equipment which is necessary to selected technique (i.e. PZT sensors or FBG sensors) (Figures 4 and 5), expected sensitivity (i.e. a size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation), cost, etc.

3.0 GUIDED WAVE DAMAGE DETECTION APPLICATIONS

3.1 On Modelling of Structural Stiffness Loss Due to Damage

An important element of the guided waves modeling, their propagation and interaction with damage is an appropriate modelling of failures damages. The state of the art for modelling and detection of degraded zones in metallic and composite structures is described in the work by Ostachowicz and Krawczuk, [2]. Generally there are three major methods for damage modelling:

1) Continuous models,
2) Discrete – continuous models, and
3) Discrete models.

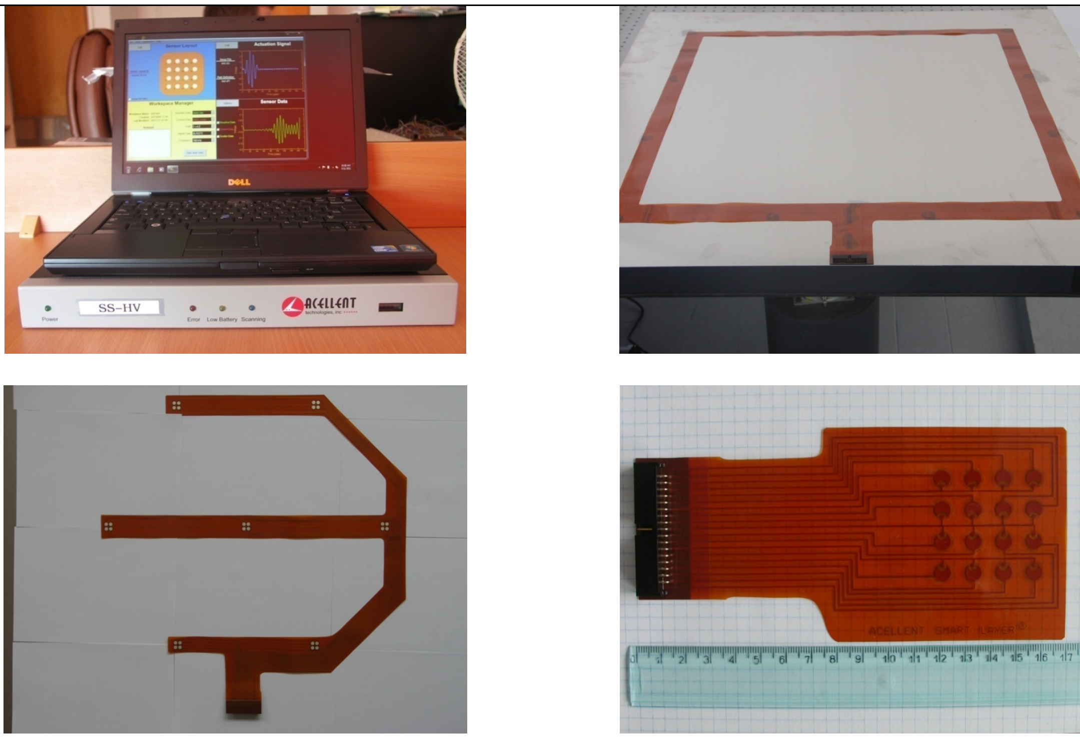


Figure 4: Custom made equipment and piezoelectric layers designed at IFFM.

Figure 5: Design of piezo – based SHM systems.

Obviously discrete methods are more attractive and those methods are primarily developed in last two decades. The most commonly used discrete methods include: Boundary Element Method, Transition Matrix Method, Graph Method, Analogue Method, Finite Element Method and Spectral Finite Element Method (SFEM). All details, particularly for SFEM are explained in [2].

3.2 Damage Detection in Composite Structures – Potentials and Limitations

Lamb waves propagate in the form of symmetric and antisymmetric mode. Moreover, the number of modes is unlimited and therefore in a structure must be respected many different modes. Symmetric and asymmetric modes propagate at different velocities. Assuming a constant plate thickness the velocities are dependent on frequencies.

Furthermore, in the case of composite materials, considering velocities we should take into account the direction of wave propagation. The Figures 6 and 7 explains the problem of velocities in a composite plate.

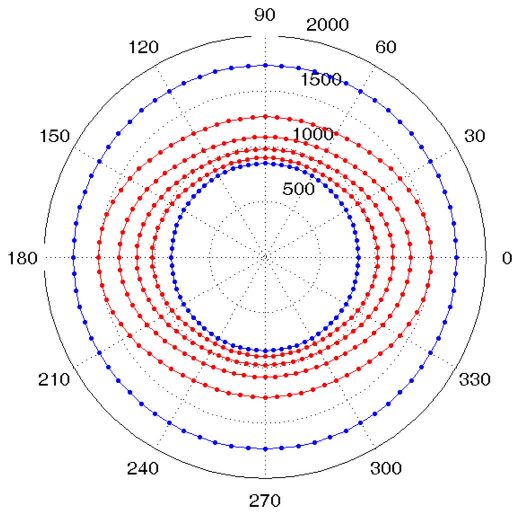


Figure 6: Composite plate (glass – epoxy). Group velocities (m/s) for different volume fraction (vol=0,20,40,60,80,100%).

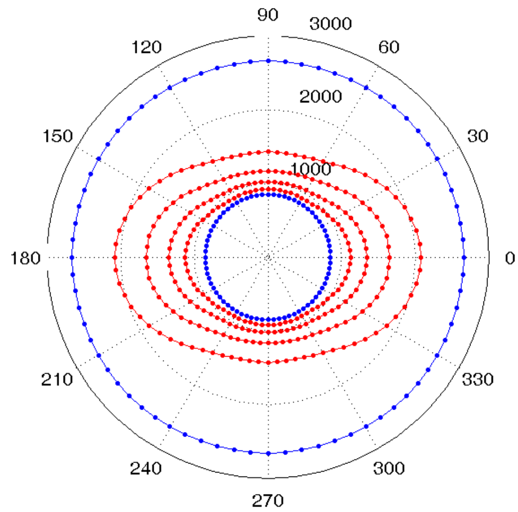


Figure 7: Composite plate (graphite – epoxy). Group velocities (m/s) for different volume fraction (vol=0,20,40,60,80,100%).

The next important problem which must be taken into consideration is wave mode conversion and reflection. The problem can be explained on the Figure 8. There is depicted a simple, multilayer composite beam with a crack. The diagram shows two waves – symmetrical (S_0) and antisymmetrical (A_0) which propagate with different velocities. When the waves rich the failure (means the crack) the modes are converted: S_0 to A_0 and A_0 to S_0. Obviously the reflected waves propagate with different velocities. Similar situation is depicted in the Figure 9 where the initial A_0 wave is reflected from delamination and converted to the S_0 mode (which propagates faster).

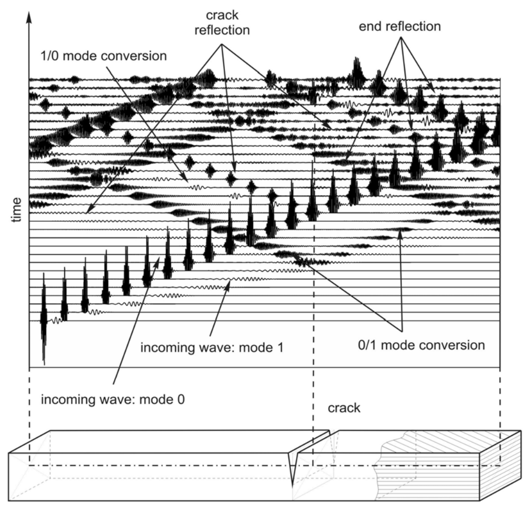


Figure 8: Symmetrical (S0) and antisymmetrical (A0) waves in a multilayer composite beam with a failure.

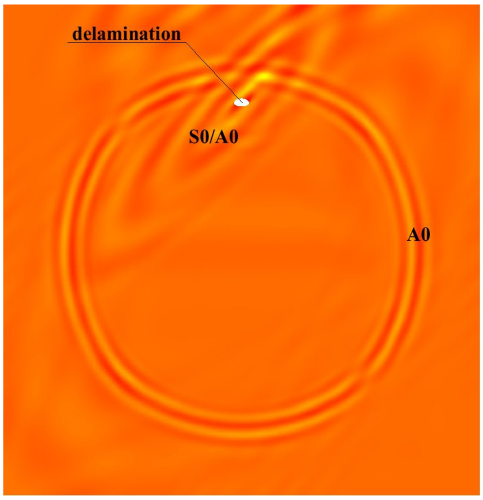


Figure 9: A0 wave is reflected from a delamination and converted to the S0 mode.

The next substantial problem concentrates around influences of environmental conditions on wave propagation. The relevant literature presents many crucial parameters as i.e. temperature, initial stresses, moisture, icing, chemical contamination, thermal degradation and many others. Wave velocity dependence on temperature is presented in [3] and a stiffness reduction of the structure due to temperature field, which influences on velocity changes presents [4].

The stiffness reduction of the structure due to temperature field is very important in the case of composite structures. Temperature strongly influences on the changes of Young modulus (even 90% in some temperatures). This fact results in changes of velocities, for instance a propagating wave slows down travelling through heated up region without reflection.

The next important problem which influences on wave propagation is wave attenuation in composites. Discussing attenuation reasons we should take into consideration i.e., geometrical wave attenuation (energy conservation), material damping, leakage (due to surroundings, i.e. steel rod in rock), and others. It should be noted that damping in composite laminates depends on stack sequence so that wave attenuation depends on angle of propagation (Figure 10).

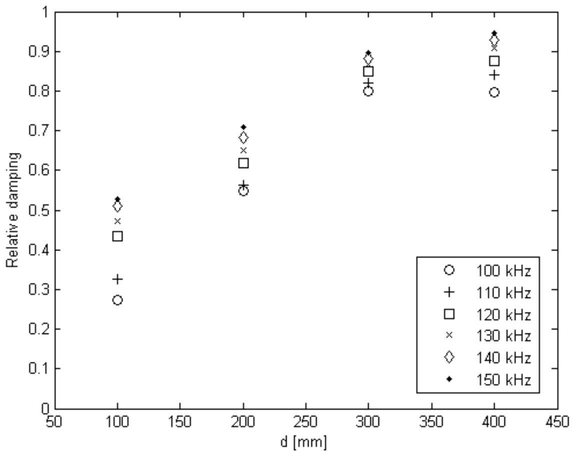


Figure 10: Relative wave damping vs. a distance from excitation.

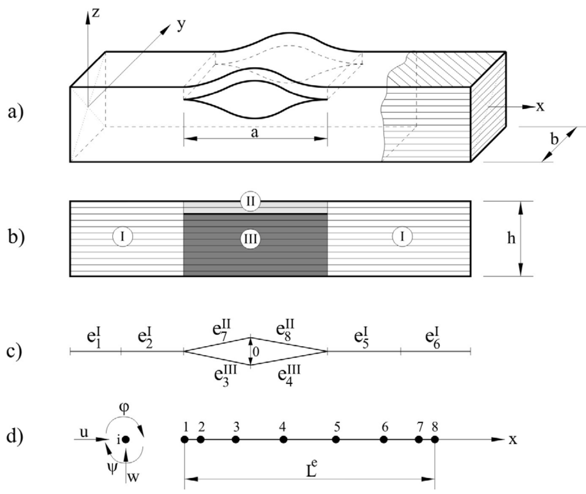


Figure 11: A multilayer composite beam with delamination – a contact effect modelling.

Contact effect in a delamination also influences on wave propagation. The problem can be explained on the multilayered composite beam (Figure 11). The equation of motion can be present in the following form:

$$\mathbf{M}\cdot\mathbf{a}_{t+\Delta t} + \mathbf{K}\cdot\Delta\mathbf{u} = \mathbf{P}_{t+\Delta t} - \mathbf{F}_t$$

where: **M** – matrix of inertia, **K** – stiffness matrix, $\mathbf{P}_{t+\Delta t}$ represents external forces and $\mathbf{F}_t$ represents internal forces (in delaminated zone).

In the considered case discrete frictionless contact is assumed. Also condition of no penetration between the nodes in contact in the transverse direction is predicted. When on the time step Δt the penetration for any pair of contacting nodes is detected the algorithm adjusts the current time step and calculates a new time step for which the penetrations vanish and only one pair of contacting nodes stays in contact. Figures 12 and 13 show some resulting signals for the non-contact and contact model respectively considering a higher frequency considering the transverse displacements in the middle of delamination at the upper and lower node of interface (delamination location h1/h=0.25, excitation 30 kHz in transverse direction).

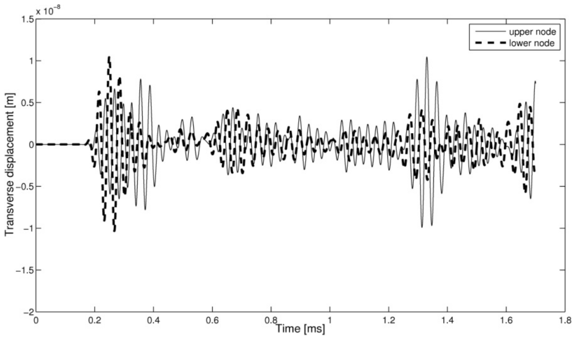


Figure 12: Non-contact model.

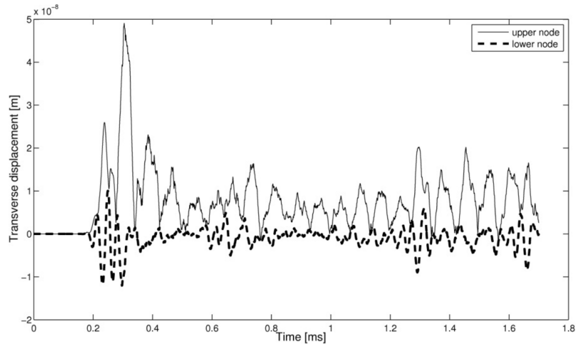
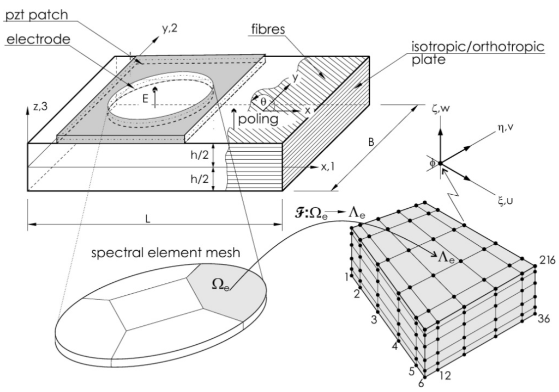


Figure 13: Contact model.

3.3 Temperature and Moisture Influence on Lamb Waves in Composite Laminates

The contamination leading to weak bonds may have various origins (moisture, release agent, hydraulic fluid, poor curing of adhesive, etc.). The following provides a few examples where these environmental effects have been considered in the simulations.



Spectral Finite Element Method (SEM)
(Figure 14)

- Gauss – Lobatto – Legendre nodes distribution.
- Homogenized composite properties – one layer of spectral elements per thickness.
- Diagonal mass matrix M – fast computation.

Figure 14: A multilayer composite plate modeled by spectral finite element method.

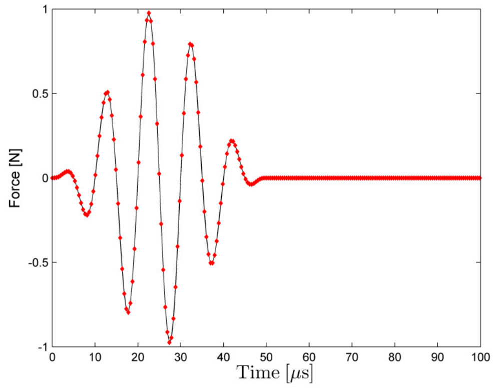


Figure 15: Discretization of input signal.

SEM – Moisture Content Modelling (Figures 15 and 16)

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = \mathbf{F}(t) + \mathbf{F}^A(t)$$

Percentage moisture content after Fick's law

$$M_c(t) = M_\infty \left[1 - \exp\left(-7.3 \left(\frac{Dt}{h^2} \right)^{0.75} \right) \right]$$

D – diffusity h – sample thickness

M_∞ – moisture content at saturation

Mass density increase

$$\hat{\rho}(M_c) = \rho(1 + M_c(t)/100)$$

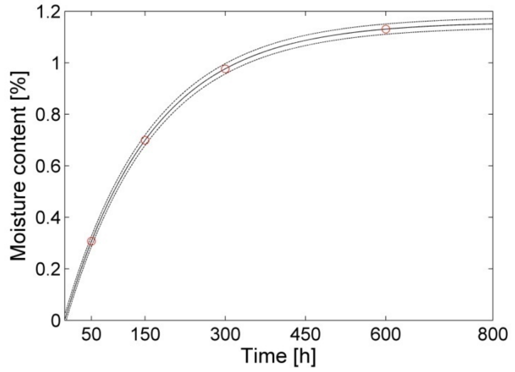
Mass matrix modification

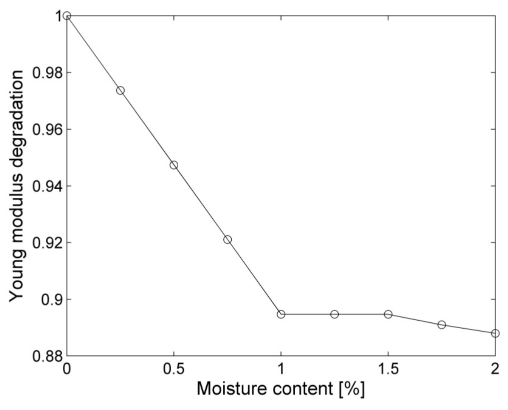
$$\mathbf{M} = \int \hat{\rho}(M_c)\mathbf{N}^T\mathbf{N} \det \mathbf{J}\, dV = \sum_{k=1}^{3}\sum_{j=1}^{6}\sum_{i=1}^{6} w_k w_j w_i \hat{\rho}_{ijk} N_{ijk}^T N_{ijk} \det J_{ijk}$$

Stiffness matrix modification

$\mathbf{D}(M_c)$ – matrix of elastic constants

$$\mathbf{K} = \int \mathbf{B}^T\mathbf{D}(M_c)\mathbf{B} \det \mathbf{J}\, dV = \sum_{k=1}^{3}\sum_{j=1}^{6}\sum_{i=1}^{6} w_k w_j w_i B_{ijk}^T D_{ijk} B_{ijk} \det J_{ijk}$$





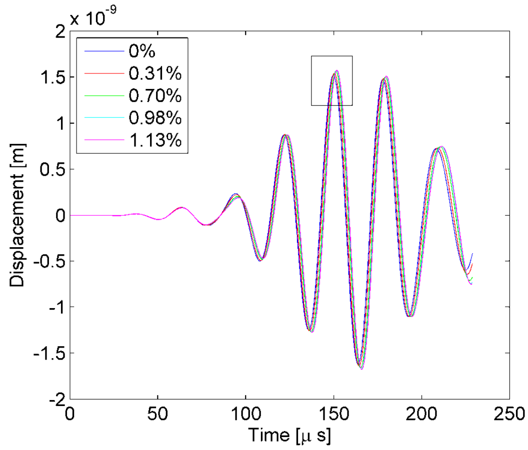


Figure 16: Simulation of the moisture content on guided wave in a composite material.

Mc=1.13% A0 mode	Amplitude decrease [%]	Time delay increase [%]	Typical signal of propagating waves at various moisture content – slight changes in amplitude and velocity
Mass modification	<0.5	<0.7	[0/0/90]S carbon – epoxy
Mass and stiffness modification	7.5–25	4.5–7	Excitation frequency 70 kHz

Moisture content influences significantly A_0 mode of propagating Lamb waves. It can be easily shown experimentally and numerically. These changes are global and can be easily detected. Both amplitude and wave velocity are affected. The S_0 mode of Lamb wave is not very sensitive to moisture changes. Numerical results show decreasing velocities with increased moisture content.

The contamination of composites by various substances has distinctive influence on wave velocity. The contamination increases or decreases a velocity depending on the contaminant.

Apart from visualisation of propagating waves also the interaction of elastic waves with various types of damage has been investigated.

4.0 REFERENCES

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