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Numerical simulation of fatigue degradation process of polymer materials using diagnostic acoustic characteristics

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Analysis and modelling

ABSTRACT

Purpose: The objective of the work was to construct the finite elements model for simulation of acoustic wave propagation process in polymer material in the aspect of diagnostic of fatigue changes.
Design/methodology/approach: Flat model was composed from finite elements with elastic properties of represented medium. Procedure of model modification corresponding with material fatigue degradation was presented. Acoustic and strength characteristics achieved as a result of numerical analysis gave the basis of numerical diagnostic of degradation process.
Findings: Structural modification possibilities of numerical model needed to obtain conformity of experimentally affirmed correlation of strength and acoustic characteristics of material have been indicated.
Research limitations/implications: Developed method allows the identification of material's residual load capacity state on the basis of given, determined in diagnostic process its acoustic characteristics. The method also enables the simulation of variable fatigue process of material in complex constructional conditions.
Practical implications: Practical utilization of the model consists in prediction possibility of material state of complex constructional elements in varied operating conditions – on the basis of failure cumulation hypothesis.
Originality/value: The value of developed model is in its practical usability in simulation diagnostic process. Simulation method with idea of diagnostic simulation is the original part of the present work.
Keywords: Numerical techniques; Acoustic characteristic; Polymer materials; Fatigue degradation

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1. Introduction

The paper presents two-dimensional model of elastic body applied to acoustic wave propagation in polymeric material to diagnostic evaluation of fatigue material degradation [1, 2]. Elaborated model, presented preliminary simulation results obtained at the model utilization as well as planned further its applications are related to research programme realized in Silesian University of Technology, Institute of Engineering Materials and Biomaterials, Division of Metallic and Polymeric Materials Processing on non-destructive methods utilization to diagnosis of the degree of strength capabilities exhaustion of polymeric composites [4, 9-14]. Among others, ultrasonic methods are extensively investigated. Ageing and fatigue are main processes leading to materials, also polymeric composites, strength capabilities decrease.

The basic task of diagnostic methods is to provide non-destructive tools with monitoring the influence of exploitation conditions on materials state. The diagnostics makes use of physical relations between evaluated characteristics or material states and achieved from used measuring techniques and registration processing parameters or diagnostic signals. The problem of diagnostic methodology lays in defining reliable fundamentals of estimation. One of the possible basics may be experimentally determined diagnostic function assigning results of acoustic testing, e.g. intensity of acoustic emission, to the characteristics of tested material state, e.g. the state of surface wears. As a source of diagnostic evaluation may be also applied by registered changes of diagnostic signal, e.g. decrease of radioactive emission from dead bone tissue may be the measure of the time elapsing between death moment and testing moment. In the case of problems with evaluation of diagnostic function, e.g. as a results of insufficient number of experiments results, it is possible to search for basis of diagnosis using system model. The known example is the problem of increase the mean Earth temperature evaluation as a result of greenhouse gasses emission. Numerical simulation methods provide convenient tools with complex physical systems modelling.

The basic and final purpose described in the paper research programme was the evaluation of the state of structural material subjected to progressing fatigue process. Phase velocity of longitudinal acoustic wave was applied as a diagnostic measure of materials strength state changes. The reason for this choice was the possibility of simple hypothesis experimental verification with the help of ultrasonic technique. In order to evaluate by simulation the ultrasounds velocity and the influence of degrading factors on this velocity, described in the following text simulation model was elaborated.

2. Simulation model

The simulation model consisting of plate-like finite elements with two freedom degrees in nodes was built [15, 16]. Rectangular domains with one dimension corresponding to the modelled composite shell thickness (length ‘l’) were assumed. It is the most often applied direction of ultrasonic diagnostic signal propagation. The second dimension (height ‘h’) arises from conventionally accepted boundaries of analyzed problem. Planned simulation of ultrasonic wave propagation demanded modelling of complex composite structure on one hand, and describing surface propagation of chosen phase of the wave (e.g. front or crest) on the other, just to evaluate wave phase velocity.

To model acoustic wave propagation process, it is necessary to choose the size of finite element properly. The size of finite element depends on shape function, describing the behaviour of physical characteristics such as displacements, velocities, accelerations and so on in element nodes. It is necessary to aim at comprising maximum finite elements in one modelled wave length. In the described research the size of finite element was chosen in such a manner that one wave length contained 20 finite elements. For elements described by the first order shape function (linear function) it is recommended to apply elements six times smaller than wave length. For elements described by the second order shape function (parabolic function) it is recommended to apply elements about three times smaller than wave length [ ].

Applied dimensions of modelled composite volume are presented in Table 1.

Table 1.
Dimensions of modelled region of elastic composite material

No	Type of modelled plate geometric property	Dimension
1.	Length *l*	2 *cm*
2.	Height *h*	1 *cm*
3.	Thickness *g*	1 *μm*

Modelled composite (Fig. 1) was divided into 40898 rectangular finite plate-like elements with two freedom degrees in every node what is equivalent to 41328 nodes. Consequently the entire model possessed 82656 degrees of freedom. The finite elements mesh was designed in such a manner that 21 nodes corresponded to one wave length, so resultant dimensions of mesh element were 69.93 μm × 69.93 μm.

It was assumed that model was loaded with harmonic force with resultant amplitude equal 1 mN acting evenly in horizontal direction on five nodes of left boundary (Fig. 2).

Evenly distributed resultant force was applied as a function of time according to the following equation:

$$F = F_0 \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi_0) \quad (1)$$

where:

F_0 – amplitude of force [*mN*],
f – frequency [*kHz*],
φ_0 – phase angle [*rad*],
t – time [*ms*].

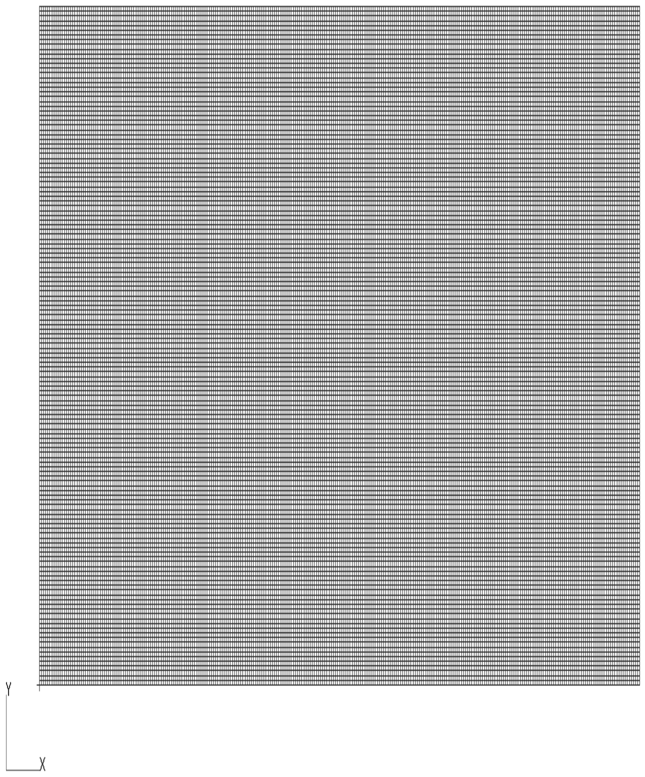

Fig. 1. Composite model divided into tetragonal plate-like finite elements

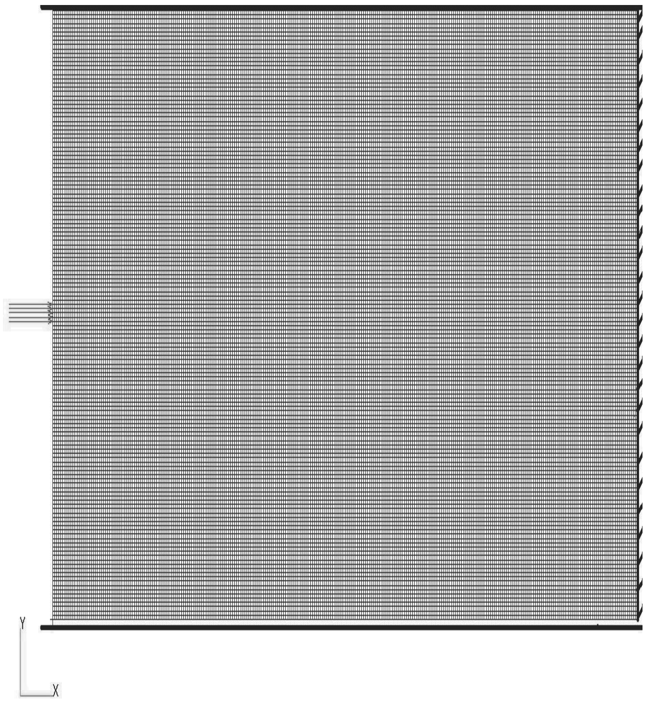

Fig. 2. Model of the composite with boundary conditions concerning loadings

The course of model force is presented in Fig. 3.

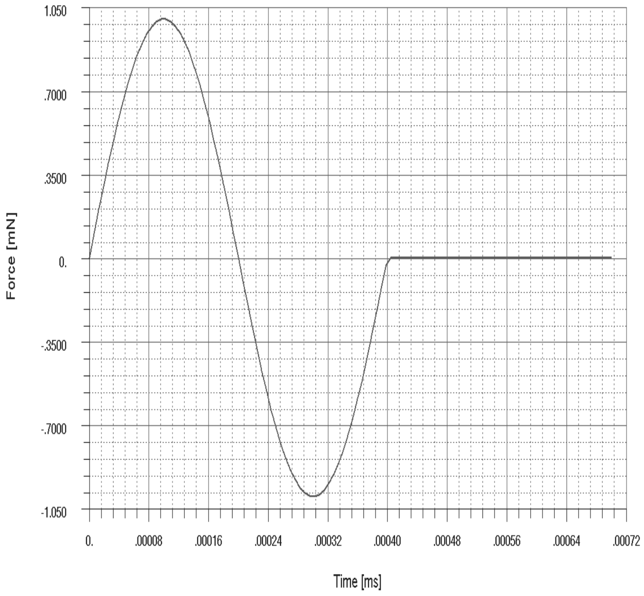

Fig. 3. The course of force as a function of time

To test strength calculations the following mean material characteristics, achieved in experimental measurements, were applied:

- Longitudinal elasticity modulus

E = 20 *GPa*,

- Poisson's ratio

$\nu = 0.4$,

- density

$\rho = 1.7 \cdot 10^{-12}\ g/\mu m^3$.

On the basis of estimated phase velocity of acoustic wave in modelled body and on the basis of the whole thickness transition time, the simulation time was assumed as 0.0075 ms.

3. Results of numerical calculations

Numerical calculations were performed using computer system MSC.Patran with calculating module MSC.Nastran, based on finite elements method. Three hundred time steps were assumed, each $\Delta t = 2.5 \cdot 10^{-5}$ ms long. Calculations were conducted for assumed time period, from starting point of time $t_p = 0$ ms to the final time $t_k = 0.0075$ ms. Results of chosen numeric calculations are presented below for three instants as maps.

3.1. Displacements maps

Figs. 4 to 9 show displacements maps for whole model in chosen instants between 5.0·10-4 ms and 4.5·10-3 ms.

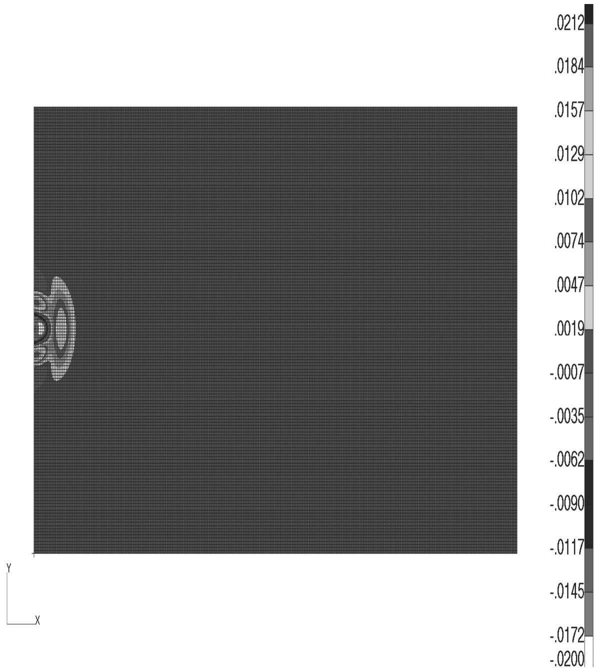

Fig. 4. Map of displacements wave propagation in x direction of modelled composite after 5.0·10^{-4} ms time

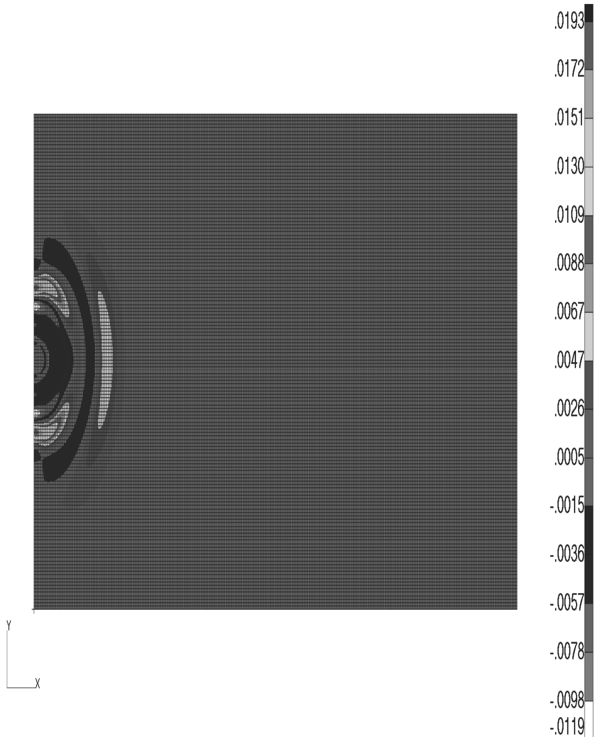

Fig. 5. Map of displacements wave propagation in x direction of modelled composite after 1.0·10^{-3} ms time

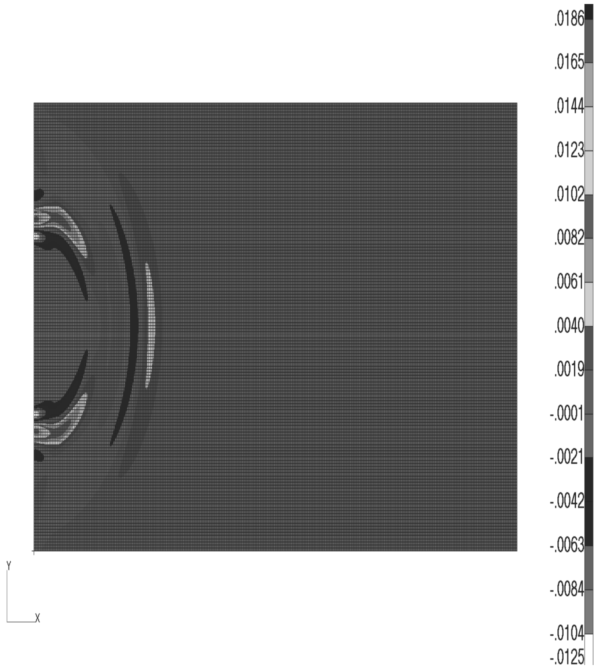

Fig. 6. Map of displacements wave propagation in x direction of modelled composite after 1.5·10^{-3} ms time

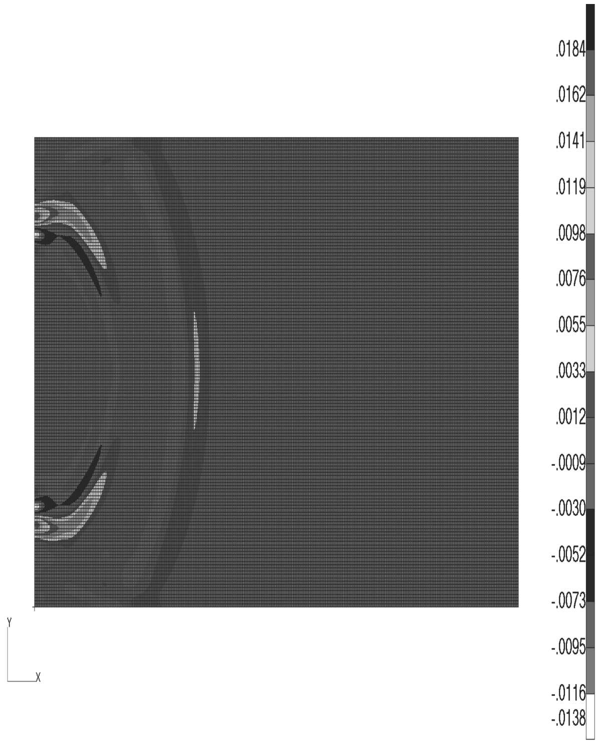

Fig. 7. Map of displacements wave propagation in x direction of modelled composite after 2.0·10^{-3} ms time

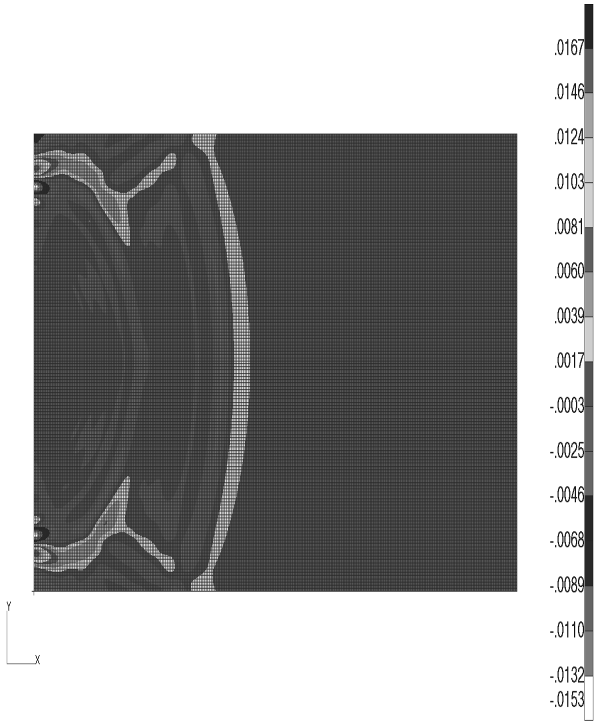

Fig. 8. Map of displacements wave propagation in x direction of modelled composite after $2.5 \cdot 10^{-3}$ ms time

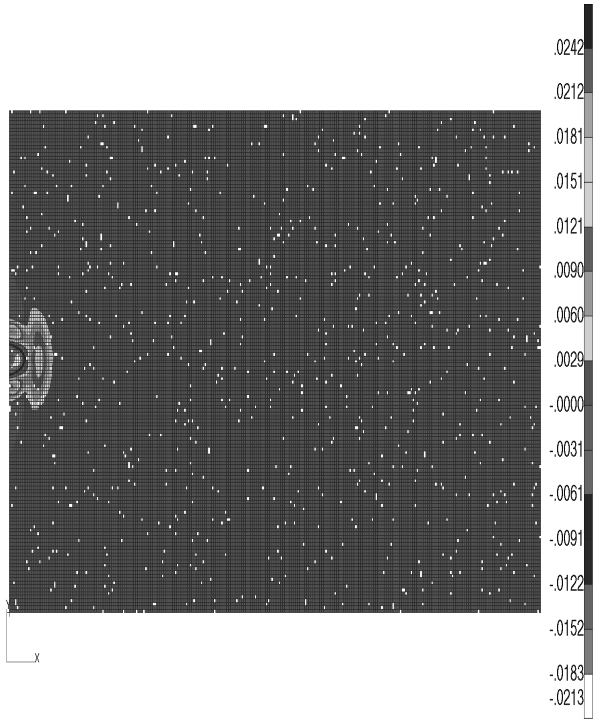

Fig. 10. Map of displacements wave propagation in x direction [μm] of modelled composite after $5.0 \cdot 10^{-4}$ ms time

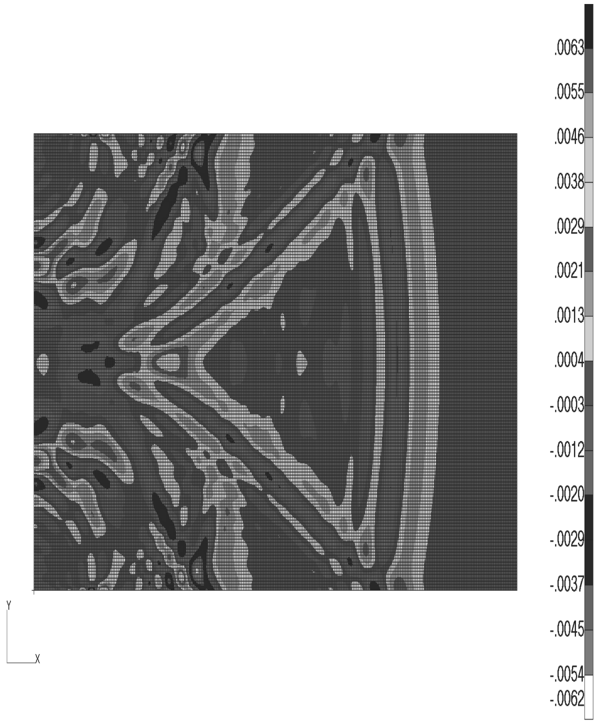

Fig. 9. Map of displacements wave propagation in x direction of modelled composite after $4.5 \cdot 10^{-3}$ ms time

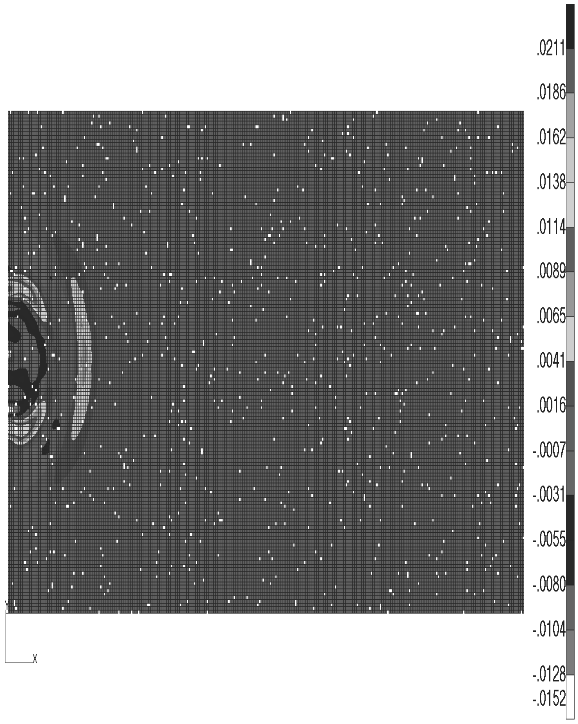

Fig. 11. Map of displacements wave propagation in x direction [μm] of modelled composite after $1.0 \cdot 10^{-3}$ ms time

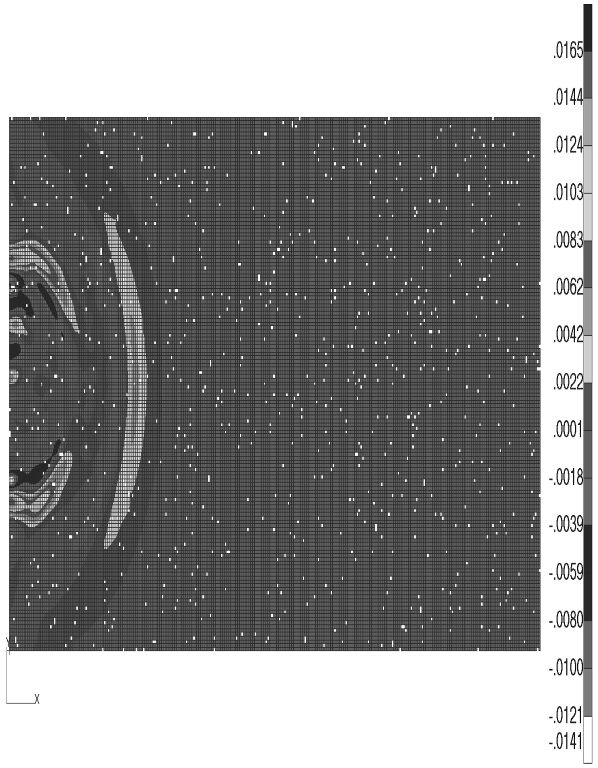

Fig. 12. Map of displacements wave propagation in x direction [μm] of modelled composite after 1.5·10^{-3} ms time

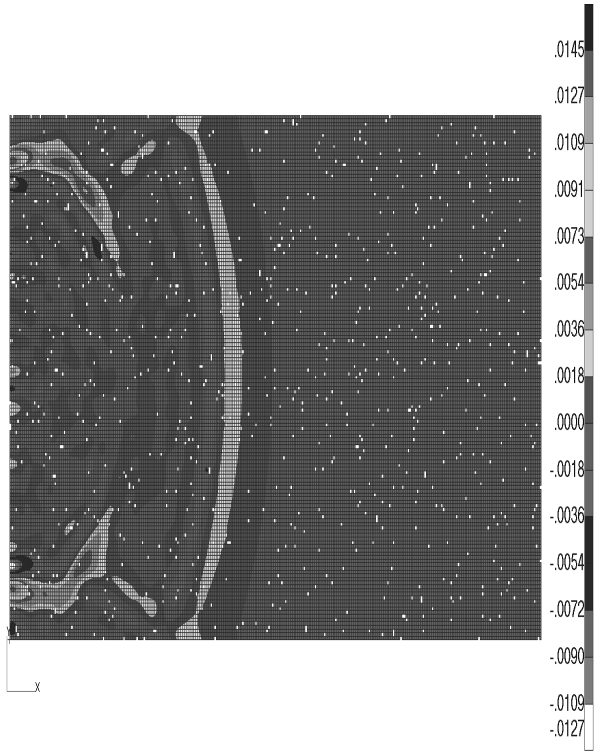

Fig. 14. Map of displacements wave propagation in x direction [μm] of modelled composite after 2.5·10^{-3} ms time

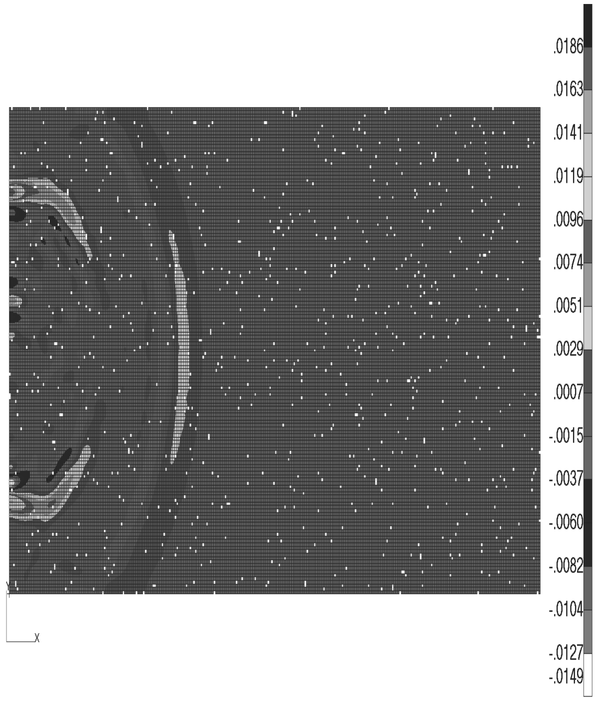

Fig. 13. Map of displacements wave propagation in x direction [μm] of modelled composite after 2.0·10^{-3} ms time

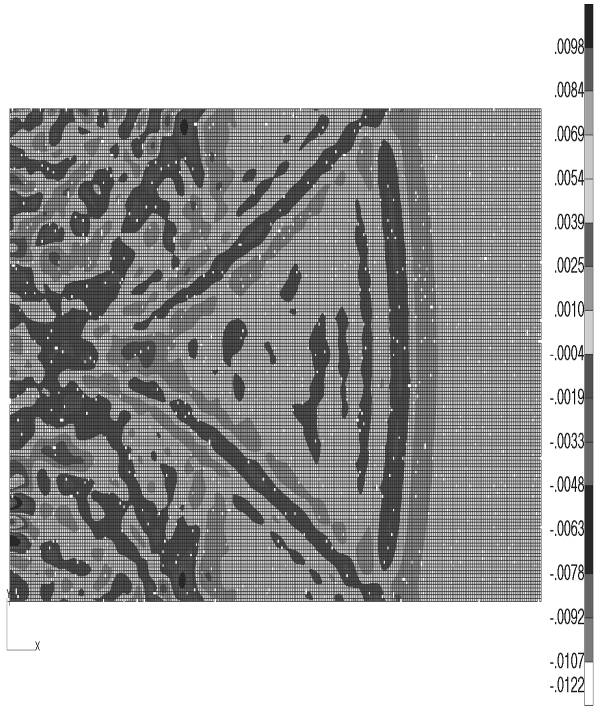

Fig. 15. Map of displacements wave propagation in x direction [μm] of modelled composite after 4.5·10^{-3} ms time

3.2. Composite degradation modelling

In order to elaborate numerical model of composite earlier subjected to fatigue our own computer software named “Random” was developed with the object programming language C++ help. Micro-cracks appearing in the composite as a result of fatigue degradation process were modelled by random removal of finite rectangular plate-like elements from starting complete continuous model.

File Mesh1.bdf generated by computer system MSC.Patran was applied as input file for our own software “Random”. Results of “Random” programme were used in dynamic calculations performed in numeric module MSC.Nastran. Author’s computer software to every finite element assigned randomly a number from <0,1> range. Next the probability (p_u) of element removal was calculated. It was assumed that in the case when assigned to element random number was equal or lesser than the calculated probability, given element will be removed. In the opposite case element will be kept in the model and taken into account in next calculations.

The next step was to generate with “Random” programme help a modified input file Mesh.bdf with removed finite elements. The modified file was transferred to “MSC.Nastran” module as input file. In the first stage the removal probability was assumed as equal p_u=0.01 and in the second stage this probability was increased to p_u=0.02. Achieved results for such removal probabilities are presented in the following text.

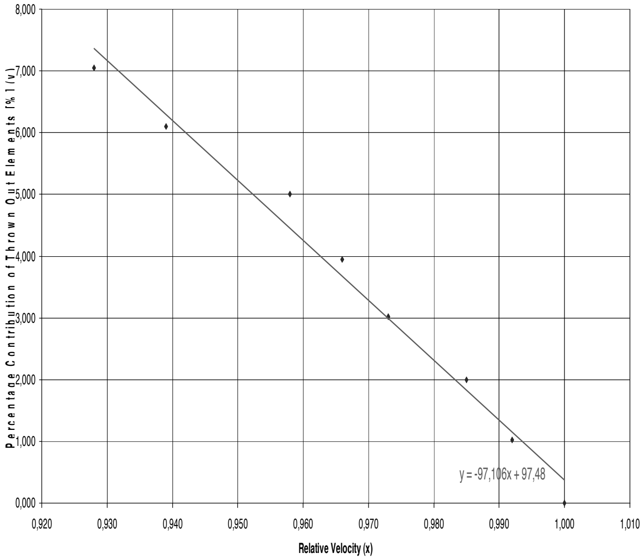

Fig. 16. Dependence of acoustic wave propagation velocity on the degree of modelled material fatigue degradation

Numerical simulation of composite undergoing degradation

Model of the composite taking degradation into account due to fatigue was developed on the basis of structure modification. Micro-cracks generated as a result of fatigue were modelled by removal of chosen finite elements. In presented examples probabilities of elements removal, p_u, were assumed as 1% and 2% respectively. As a result 411 finite rectangular elements were removed in the first case and 822 elements were removed in the second case. The density of the composite was corrected to fulfill constant composite mass condition.

Figs. 10 to 15 present exemplary maps of displacements wave propagation in x direction of modelled composite with 2% fatigue degradation after $5.0 \cdot 10^{-4}$ ms i $4.5 \cdot 10^{-3}$ ms time, respectively.

4. Conclusions

Phase velocities of ultrasound longitudinal wave front propagation in modelled body were evaluated on the basis of analysis chosen from all performed. Fig. 16 presents specification of calculated velocities for composite degraded in 1% to 7% range in the form of curve.

On the basis of performed dynamic numerical calculations of acoustic wave propagation in elastic medium, the following conclusions may be drawn:

- fatigue degradation of material may be modelled by introducing discontinuities into composite physical model through random removal of finite elements;
- the result of such procedure is the decrease acoustic wave propagation velocity, what is observed also experimentally;
- presented example proved that it is possible to adjust the “degree of degradation” of numerical model to experimentally measured acoustic characteristic – phase wave propagation velocity;
- Possibility of strength analysis of presented model forms on the basis of diagnostic simulation of searched materials.

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