Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 34
ISSUE 1
May
2009

# Numerical models of polymeric composite to simulate fatigue and ageing processes

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Received 14.01.2009; published in revised form 01.05.2009

**Materials**

## ABSTRACT

**Purpose:** of this paper was to prove the possibility of applying numeric model of polymer composite, consisting of finite elements, to simulate dynamic acoustic and thermal processes. Characteristics of these processes evaluated numerically, in comparison with experimental results, could allow to simulate complex structural processes taking place during fatigue and ageing degradation of composite. It is expected to prove relations between chosen physical properties of simulated processes and strength characteristics determining load capacity of materials.

**Design/methodology/approach:** Planar, biphase model of fibre reinforced laminate was applied. Pseudo-random procedure of model structure and physical parameters modification was used. A programme of numerical simulations was performed to evaluate sensitivity of characteristics of acoustic wave propagation and heat transport processes on model modifications.

**Findings:** Possibility of model structural and parametric modifications resulting in changes of composite physical properties, such as stiffness, acoustic wave propagation velocity and thermal conductivity, observed during degradation processes was demonstrated.

**Research limitations/implications:** It is expected that results of composite testing programme, being now realized by authors, will allow quantitative adjustment of acoustic and thermal characteristics achieved numerically and experimentally.

**Practical implications:** Complete identification of numerical model characteristics and procedure of its modification is expected to allow to estimate the degree of strength properties degradation on the basis of numerical simulations results.

**Originality/value:** Proposed numerical models for simulation of composite degradation due to fatigue and ageing processes are new and original tools supporting non-destructive evaluation of strength properties changes.

**Keywords:** Composites; Numerical models; Non-Destructive testing; Degradation

**Reference to this paper should be given in the following way:**
G. Wróbel, J. Kaczmarczyk, J. Stabik, M. Rojek, Numerical models of polymeric composite to simulate fatigue and ageing processes, Journal of Achievements in Materials and Manufacturing Engineering 34/1 (2009) 31-38.

## 1. Introduction

The problem of development of polymeric composite numerical model originated during research programme on effectiveness of chosen non-destructive diagnostic methods applied to composites state evaluation, being realized from 2005 to 2009 year in Division of Metallic and Polymeric Materials Processing, Institute of Engineering Materials and Biomaterials, Silesian University of Technology [2, 11 - 16].

Increasing interest in polymeric composite materials is the result of their qualitative differences from traditional structural materials applied in machine building, civil engineering and other industries. Basic differences concern mechanical, electrical and thermal characteristics but also technological and economical properties. Relatively simple processing technologies, lower energy consumption during processing and moderate prizes cause that in many competitive situations concerning material selection polymeric composites overcome other engineering materials.

Specific stiffness and specific strength criteria, relating traditional strength and stiffness characteristics to material density, are the most evident examples where technical reasons promote application of new polymeric materials. It especially important in car industry, astronautics and aviation applications.

Unfortunately, polymeric materials are characterized also by specific negative properties. One of the main drawbacks of these materials is low repeatability of operational characteristics. It results from high sensitivity of many properties to any changes of structure on every level – beginning from chemical structure of macromolecules and ending on macroscopic reinforcement distribution in composite volume. It is very difficult in industrial conditions to assure good repeatability in all material volume and during all production cycle. Difficulties rise substantially when nominally the same polymeric material is delivered by different suppliers or is produced from different raw materials. Only the most reputable suppliers assure repeatability of subsequent lots of raw materials and semi-finished products.

The next source of polymeric materials properties differentiation is their history, as a matter of fact the most important is history of storing and exploitation conditions, history of exposure to deteriorating factors such as high temperature, mechanical stresses, aggressive agents, high energy radiation etc.

All this factors together necessitate precision determination of all operational characteristics, especially strength properties, thermal stability thermodynamic and electrical characteristics. In laboratory conditions the kind and testing procedures are establish in appropriate standards. Specially prepared samples prepared from searched materials are subjected to testing. In most cases testing procedures irreversibly change materials state, what means , in brief, that samples are destroyed. Some of products properties, especially manufactured in continuous processes, may be continuously monitored and adjusted in technological process. It is impossible or almost impossible in many cyclic processes with significant manual work contribution. Production process monitoring is also less efficient when material characteristics change in exploitation time. Mechanical fatigue and thermal ageing are examples of processes that change material characteristics in operation period. In the case of polymeric materials additional serious problem is that degradation occurs in a dispersive way within the element area, without any visible external changes of physical or geometrical properties. In this case a classical inspection of a structures condition, very widespread for metallic structures, may not reveal any dangerous conditions.

The effective way to prolong the time of secure exploitation of systems undergoing such degrading processes is to apply suitable diagnostic procedures. The basis of these diagnostic systems is equipment allowing to evaluate tested system state, to evaluate changes of searched characteristic or characteristics. The principle of validation process is based on diagnostic relation, which allow to evaluate searched operational property, e.g. thickness of carrying shell, basing on measurable diagnostic quantity, e.g. transition time of ultrasonic wave through the shell. The diagnostic relation is determined taking into account gathered earlier experimental results, allowing to determine quantitatively parameters of this relation. In given earlier simple example, velocity of ultrasonic wave propagation in material of tested element is needed.

To apply the same methodology in the case of strength properties evaluation is much more difficult. Trials of diagnostic relations development, with ultrasonic and thermographic techniques application, are described in previous author's publications [12 - 15]. Research programmes comprised non-destructive testing and destructive testing procedures carried out on samples previously subjected to long-lasting thermal ageing and mechanical fatigue processes. This type of research programmes are very laborious and expansive in their nature. Because of this it is desirable to search shorter and cheaper ways to diagnostic relations evaluation.

The main idea of shortly described here methodology is to aid diagnostic process with computer simulation procedures. A numerical model of searched composite material was proposed. Next, the possibility of degradation processes simulation in analysed composite material model was presented. The method of modelled material state evaluation on the basis of its model numerical analysis was also indicated. Finally, conditions of numerical model diagnostic reliability achievement and means of its improvement were indicated.

## 2. Model of the composite material

Modelling methodology of material properties changes due to fatigue and ageing processes is presented here taking as an example a composite with polymeric matrix and continuous fibres (glass, carbon or graphite) as reinforcement. It is typical case, very often applied in laminate plates and shell constructions. In the described example the following assumption were accepted:

- volumetric or weight content of fibres in polymeric matrix is known;
- arrangement of fibres in the matrix is known;
- fibres are distributed evenly in the composite volume (in thickness direction and on the surface area);
- fibres lay rectilinearly and parallel in two perpendicular directions.

Described here exemplary methodology may be also applied to any other reinforcement layouts in polymeric matrix but every fibres or particles arrangement have to be taken into account in composite model.

The range of thermal or acoustic process excited in modelled plate or shell is usually local. The direction, in which thermal or acoustic process is analysed, is normal to central plane, because it is in most cases the direction available in measuring procedures. Because of this, interesting region of process registration is only central fragment of a body, limited by two boundaries, lower and upper surfaces of plate or shell. In the case of closed shells, outer and inner surfaces may be distinguished. Induced thermal or acoustic processes are often axisymmetric or symmetric in the plane. Because of this two-dimensional model with proper boundary conditions is sufficient to modelling and analysis of such processes.

In the following text described methodology will be illustrated by example corresponding to experiments with ultrasonic and thermographic diagnosis, realized in Division of Metallic and Polymeric Materials Processing of Silesian University of Technology. Tested composite samples had cuboid shape with following dimensions: 250x20x10mm or 100x100x10mm, used in ultrasonic and thermographic testing, respectively (Fig. 1.). Induced processes were axisymmetric, apart from boundary conditions concerning side boundaries. Regions of laminate excitation with ultrasonic head (in the case of acoustic process) or with IR radiator (in the case of thermal process) were distant from these side boundaries. In analysed time period, corresponding to time of signal propagation through specimen thickness, boundary conditions relating to side boundaries can be regarded as inactive. It means that these boundaries have no essential effect on course of the thermal or acoustic processes in analyzed time-space scale.

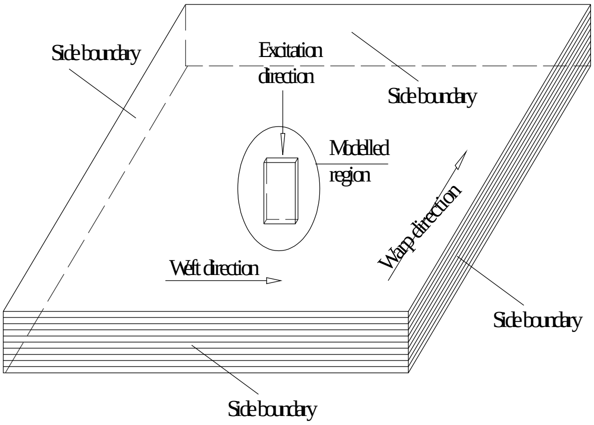

Fig. 1. Scheme of modelled composite plate

Similar conditions were assumed for physical model representing whole plate and applied as a basis for numerical modelling (Fig. 2) [9, 10]. Total model space had a shape of rectangle with shorter sides corresponding to lower and upper surfaces of the sample. Such reduction was possible due to shell symmetry conditions. Longer sides of physical model corresponded to surfaces of cross-sections parallel to two side boundaries. It is the result of reduction of analysed processes to two-dimensional model. Assumed unit thickness of finite elements defines the third dimension of analysed region. It was also assumed that in the direction of this third direction with unit thickness quantities participating in analyzed processes are constant.

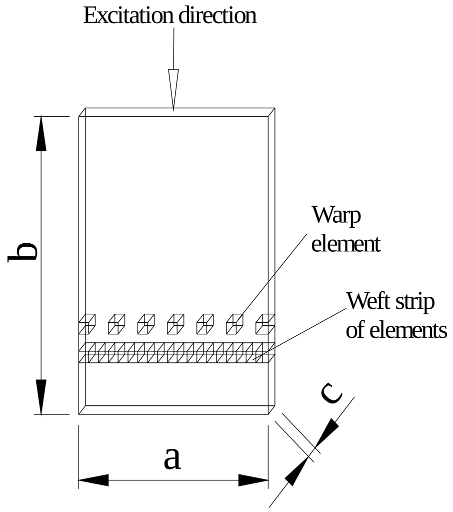

Fig. 2. Physical model of searched laminate

Numerical model, corresponding to physical model, consisting of finite elements in the form of rectangular plates was assumed for numerical simulation purposes. Entire physical model had dimensions given in Table 1. It was divided into 40898 rectangular finite platy elements, possessing two degrees of freedom in node, what gave 41328 nodes. In result model with 82656 degrees of freedom was defined. Model divided into rectangular finite elements is shown in Fig. 3.

Table 1.
Dimensions of the physical model of coposite.

| No | Dimensions of modelled composite | Value [$\mu m$] |
|---|---|---|
| 1. | Length $l$ | 20000 |
| 2. | Height $h$ | 10000 |
| 3. | Thickness $g$ | 1 |

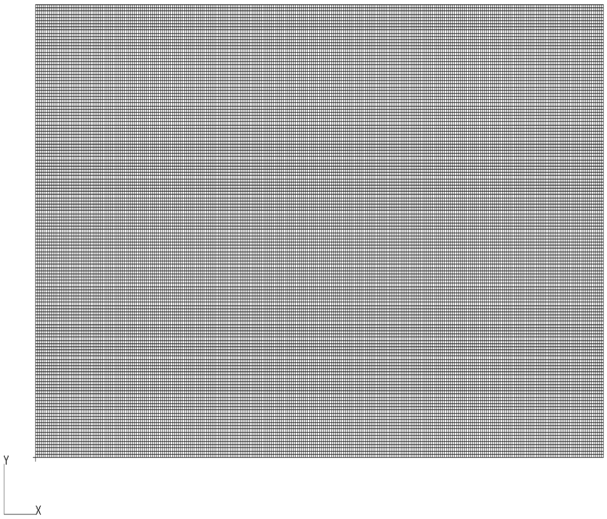

Fig. 3. Model of composite divided into tetragonal platy finite elements

Modelled composite was inhomogeneous. It was assumed that layered glass fibre fabric formed composite reinforcement. Additionally it was assumed that weft and warp fibres were arranged perpendicularly. Surface of the model was parallel to warp fibres and perpendicular to weft fibres. Warp fibres were represented by strips of finite elements, evenly distributed in the modelled plate thickness direction, parallel to the plate surface. Weft fibres, perpendicular to the model surface, were represented by individual elements possessing reduced density and stiffness, respectively to unit thickness of the model. (Fig.1 and Fig. 2). Geometrical parameters of reinforcement distribution resulted from reinforcement content in modelled composite and from weft fibres to warp fibres ratio in the reinforcing fabric weave.

Basic characteristics of polymeric matrix and glass fibres are given in Table 2. Typical properties of epoxy resin and glass fibres are accepted.

Table 2.
Basic materials properties

| Material | Polymeric matrix | Glass fibre | |
|---|---|---|---|
| Longitudinal elasticity modulus E [G Pa] | 20 | 77 | |
| Poisson's ratio **N** | 0.35 | 0,23 | |
| Density $\rho$ [kg/m$^3$] | 1200 | 2450 | |
| Volume fraction [%] | 50 | Weft | Warp |
| | | 25 | 25 |

## 3. Model of fatigue degradation process

Course of progressive material strength decrease and in this way load capacity loss as a result of repeating load cycles is known as mechanical fatigue process. Strength properties deterioration may lead to generation and propagation of material micro-discontinuities. Final effect of this process is macro-crack formation in structural elements. Degradation process during mechanical fatigue is initiated as a result of internal loadings heterogeneities. Regions of stress concentration may be an effect of external loads characteristics and also of physical and geometrical properties of structural element. Inevitable source of local stress concentrations, especially in composite materials, are material structure heterogeneities and structural defects. Concentration regions are highly dispersed in material volume. Natural consequence of stress concentrators dispersion is also dispersion of degradation process centres in structure volume. Fatigue degradation process consists of local discontinuities formation (micro-cracks initiation) in stress concentration regions and micro-cracks propagation. These processes are random in their nature. Taking into account all set of irreversible events, forming this complex process, it is reasonable to treat fatigue degradation as random process of accumulation of dispersed discontinuities. At certain stage of this process development discontinuities appear. These discontinuities play role of fatigue process attractant. Subsequent degradation process concentrates in the vicinity of such attractors and finally micro-cracks are formed.

To take into account described fatigue degradation course in elaborated model, material discontinuities were sequentially and randomly generated in fatigue simulation procedure.

Analysis of internal stresses state was performed at every stage of simulation. Internal stresses were evaluated according to external loadings resulting from structure working conditions or samples experimental conditions. Material discontinuities appearance was modelled by removal of individual finite elements. At every fatigue process stage a set of finite elements was randomly eliminated from model. Probability function of elements removal was selected taking into account materials properties and a measure of mechanical effort state. Elimination probability of elements equally stressed was the same. All quantity of removed elements was evenly distributed in the volume of the rest of elements. Stiffness modulus of remaining elements was also corrected.

For diagnostic purposes very interesting is how material structural changes manifests in strength characteristics alterations, e.g. how changes instantaneous stress concentration state or material stiffness. It is possible to evaluate numerically these characteristics by subsequent model modification at every phase of fatigue degradation process. At the same time it is possible to simulate also diagnostic processes. For example, simulation of acoustic wave excitation and propagation in conditions corresponding with measurement with ultrasonic head conditions, allow to evaluate characteristics of measuring process only with simulation help. In similar manner it is possible to simulate thermal processes in diagnostic procedures using thermography. Especially thermal analysis of material surface after thermal impulse transition through the plate or shell is possible experimentally as well as numerically. Parameters of modelled material and simulation procedure of fatigue degradation should be selected in such a way that conformity between testing characteristics of diagnostic processes and characteristics of numerically simulated processes will be achieved. All these possibilities form fundamentals for diagnostic relation development basing on simulation of degradation process. At the same time it shows the way to new diagnostic methodology, methodology based on numerical simulation procedures. These numerical procedures are able to support efficiently traditional diagnostic investigations.

In [16] numerical modelling of fatigue degradation process, applied to simulation analysis of acoustic diagnosis procedures, was presented in detail. Chosen results were also discussed. It was proved that it was possible to register wave propagation process and to observe the effect of degradation on chosen diagnostic characteristics of acoustic signal.

## 4. Model of polymeric composite ageing

Ageing process of polymeric composites is very important due to its influence on many essential structural and operational characteristics. Thermal history, aggressive environment and high energy radiation are basic sources of progressive deteriorating changes of constructional elements materials. Also in material structure are dispersed inner sources of ageing, for example thermodynamic disequilibrium, free radicals, inner stresses, dislocations and other imperfections of crystalline structure. This leads to slowly proceeding chemical, rheological and thermodynamic processes tending to equilibrium state. In polymeric matrixes it produces undesired effects such as macromolecules scission, free radicals formation, polymer oxidation, macromolecules crosslinking, crazing, micro-cracks formation and many other. In macroscopic scale elasticity decrease, free surface energy increase, material brittleness and hardness increase are observed. In composites additionally adhesion bonds between reinforcement and polymeric matrix are often destroyed or at least weakened. Also other categories of properties undergo changes, among other thermodynamic, electrical and optical.

Simultaneity of changes of different physical properties suggested authors hypothesis that it is possible to find diagnostic relation allowing to evaluate actual materials state, concerning one class of characteristics, on basis of measurements results of another class of properties. Examples of experimentally evaluated diagnostic relations occurring in ageing of polymeric composites were described in [12, 13]. It was shown that acoustic characteristics (e.g. wave propagation rate) as well as thermal characteristics (e.g. thermal conductivity or thermal diffusivity) may be applied as diagnostic relations variables.

Simulation model of composite ageing process ought to take into consideration mentioned changes of material properties. Part of altering features, especially structural, depends directly on factors determining ageing processes. Change of the rest of features is indirect result of alternation of the first group. It is necessary to chose properties in the model that will be sequentially changed by simulation program according to defined procedure. The number of distinguished in this way properties should be sufficient to achieve conformity of modelled characteristics and characteristics possible to measure experimentally for real composite. Especially results of numerical simulations should be consistent with diagnostic relation in extent possible to experimental verification.

In order to fulfil above mentioned requirements, developed model of ageing process implemented the following, independent modification procedures:

- random generation of correction of local polymeric matrix stiffness;
- random generation of correction of local thermal conductivity;
- random generation of specific heat correction;
- random generation of local discontinuities in the form of adhesion loss between polymeric matrix and reinforcing fibre.

These procedures were activated sequentially. Analysis of internal stresses state was performed in successive steps of numerical simulation. Internal stresses were evaluated according to external loadings resulting from working or experimental conditions. Additionally, temperature distribution was evaluated according to defined boundary conditions. Probability functions of stiffness, specific heat and heat conductivity corrections were chosen depending on type of material and element temperature. Probability functions of finite elements removal, adhesion between matrix and reinforcement loss were chosen in way allowing to additionally take into account a measure of mechanical effort. The change of composite state due to ageing process development determined modifications of physical properties that were interesting in diagnostics point of view. In this range it was similar to fatigue process simulation. Material state was estimated taking into account strength characteristics criteria. Diagnostic processes simulation, applying model of material subjected to ageing, indirectly provided evaluation fundamentals.

Simulation of excitation of acoustic wave propagation in conditions corresponding with ultrasonic measurements allow to model determination of measured quantity characteristics. Thermal processes simulation may be applied in similar manner. Parameters of material model selection and ageing simulation procedure choice ought provide conformance of chosen diagnostic processes characteristics, used as diagnostic criteria, with the same characteristics determined by ageing numerical simulation.

It form the basis of diagnostic relation development using numerical simulation model of ageing process. At the same time, similar to acoustic process simulation, it shows the way to new diagnostic methodology based on numerical simulation procedures. These procedures also may efficiently support traditional diagnostic investigations.

## 5. Example of simulation diagnostics of polymeric composite operational properties deterioration

Presented here results of simulation diagnostics concern material fatigue process and acoustic diagnostic method.

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. File Mesh1.bdf, generated by computer system MSC.Patran, was applied as input file for “Random” programme in order to perform dynamic calculation using MSC.Nastran calculating module.

Two dimensional model of glass fibre reinforced epoxy laminate (Fig. 2), representing tested sample (Fig. 1) was analysed. Initially continuous material structure was subjected to modification simulating fatigue degradation process. As a result a series of models, representing material degraded in different degree, were obtained. These models were subsequently utilized to simulate acoustic signal propagation in degraded composite. Precisely, propagation of ultrasonic signal was simulated.

Fig. 4 and Fig. 5 show chosen images of material deformation fields as a result of acoustic wave propagation in modelled composite. Additionally wave phase velocity was interpreted as wave front propagation in defined subsequent propagation process instants.

Phase velocity of ultrasonic wave, possible to determine in described manner, may be used as diagnostic characteristic. This velocity compared with velocity experimentally measured in real model provide information on the state of this real object. Numerical model of material degraded in defined degree allow to determine state of load characteristics which on the other hand may be used to diagnostic evaluation.

Figs. 6 to 11 show fields of instantaneous displacement in signal propagation direction (x-axis).

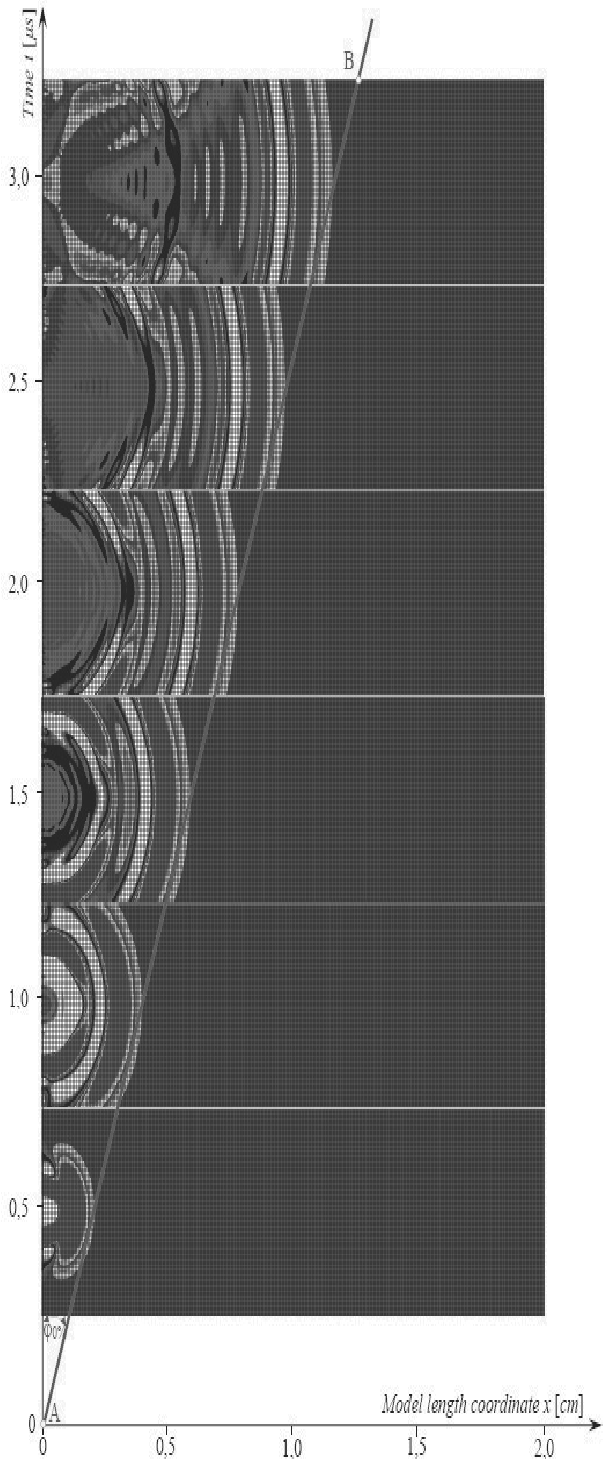

Fig. 4. Sequence of subsequent instantaneous displacements fields. Inclination of strait line connecting wave fronts corresponds to phase velocity. (Image obtained for fatigue degradation degree z = 0%)

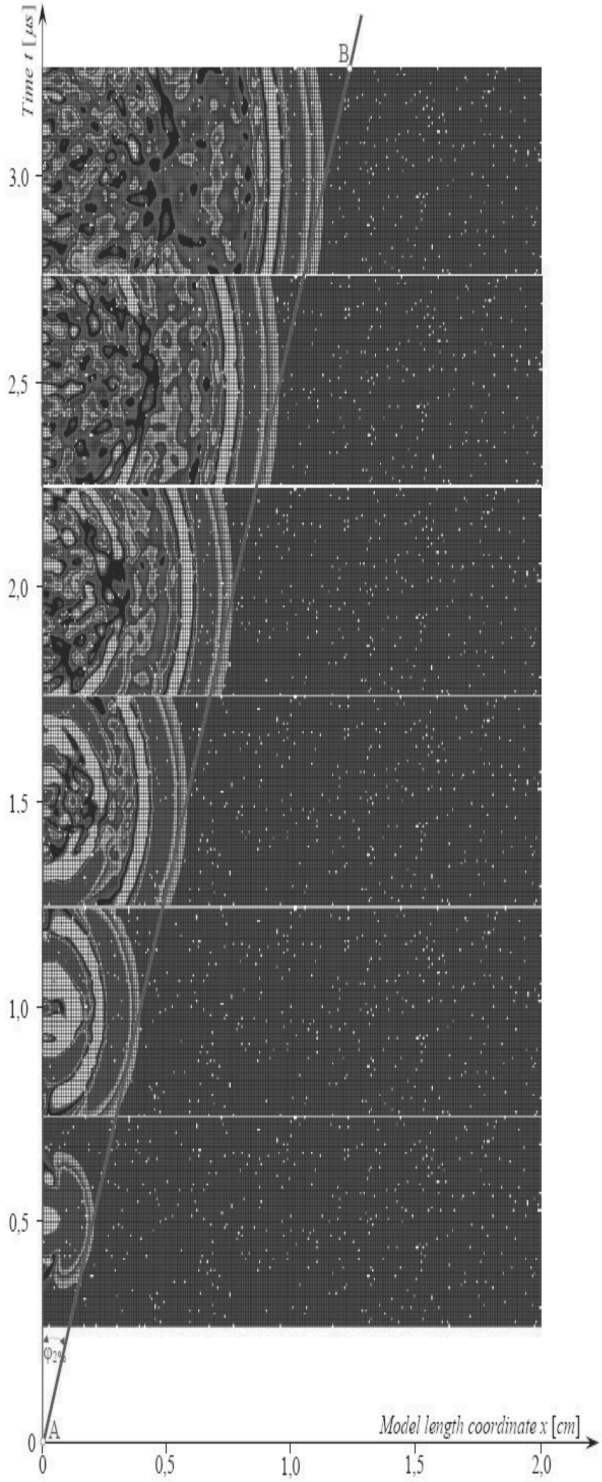

Fig. 5. Sequence of subsequent instantaneous displacements fields. Inclination of strait line connecting wave fronts corresponds to phase velocity. (Image obtained for fatigue degradation degree z = 2%)

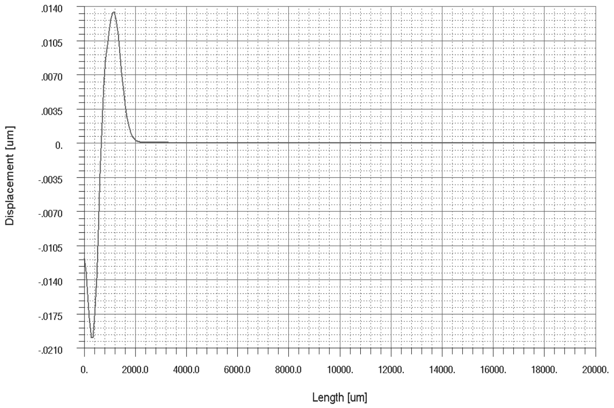

Fig. 6. Dependence of displacements wave propagation in x-axis direction (for nodes laying in horizontal axis) on position in this direction (length) in 5.0·$10^{-4}$ ms time instant

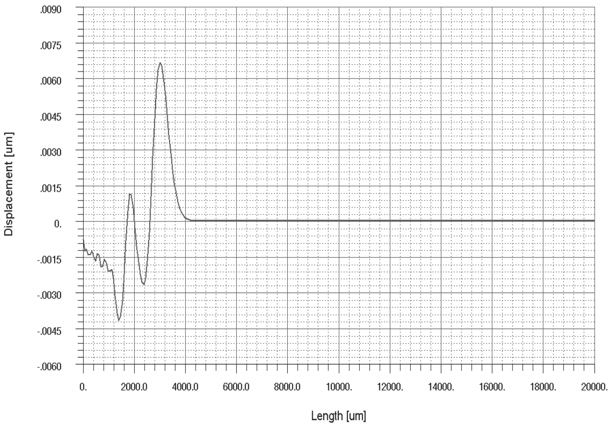

Fig. 7. Dependence of displacements wave propagation in x-axis direction (for nodes laying in horizontal axis) on position in this direction (length) in 1.0·$10^{-3}$ ms time instant

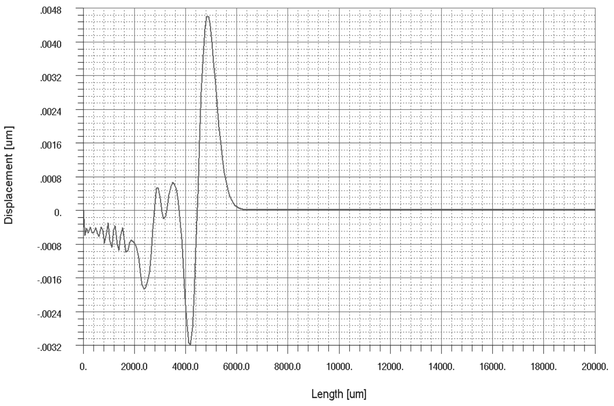

Fig. 8. Dependence of displacements wave propagation in x-axis direction (for nodes laying in horizontal axis) on position in this direction (length) in 1.5·$10^{-3}$ ms time instant

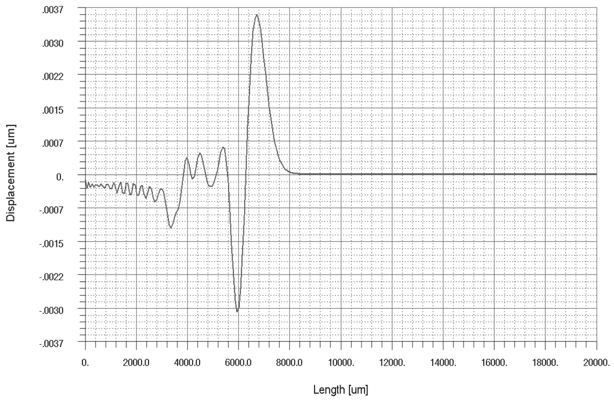

Fig. 9. Dependence of displacements wave propagation in x-axis direction (for nodes laying in horizontal axis) on position in this direction (length) in 2.0·$10^{-3}$ ms time instant

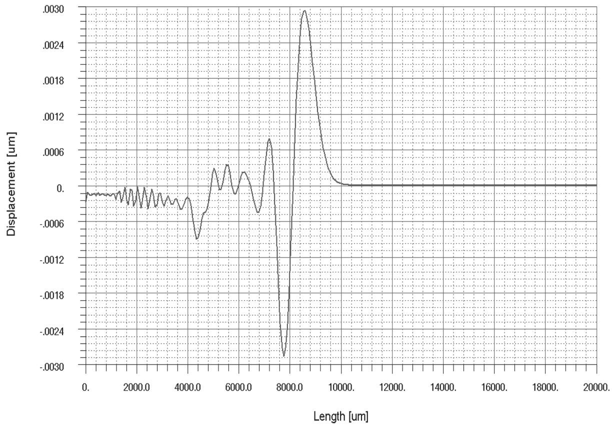

Fig. 10. Dependence of displacements wave propagation in x-axis direction (for nodes laying in horizontal axis) on position in this direction (length) in 2.5·$10^{-3}$ ms time instant

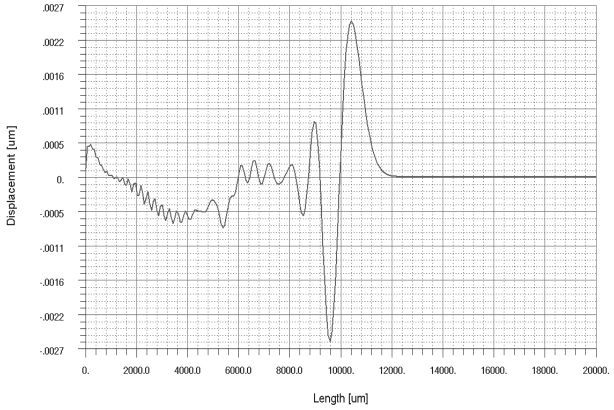

Fig. 11. Dependence of displacements wave propagation in x-axis direction (for nodes laying in horizontal axis) on position in this direction (length) in 3.0·$10^{-3}$ ms time instant

## 6. Conclusions

Presented numerical model enables computer aiding of diagnostic process.

Developed model of composite material allow to simulate ageing and fatigue degradation processes of polymeric composites.

Models parameters and simulation procedures should be adjusted to achieve conformity of chosen criteria characteristics of diagnostic processes with the same characteristics evaluated numerically.

Simulation of acoustic wave propagation excitation in conditions corresponding to that in measuring procedure allow to determine numerically characteristics of measured quantity. In similar manner simulation of thermal processes may be utilized.

In the case of ageing processes models parameters and simulation procedures should be adjusted to achieve conformity of chosen criteria characteristics of diagnostic processes with the same characteristics evaluated numerically.

Proposed methodology forms fundamentals for diagnostic relations development basing on simulation model of ageing and fatigue processes. At the same time it indicate methodological way to simulation diagnostics as an aiding tool for traditional diagnostic procedures used to evaluate the degree of strength characteristics deterioration.

## Acknowledgements

This work was financially supported by Polish Minister of Science as a part of project N501 029 32/2474 and Project No 7 T08E 007.

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