NUMERICAL ANALYSIS OF COMPOSITE STRUCTURES WITH EMBEDDED PIEZOELECTRIC ACTIVE ELEMENTS

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Abstract

The paper presents a numerical simulation of active multiple layer composite beams in bending test. Within framework of performed analysis glass-epoxy and carbon-epoxy laminates with integrated piezoelectric actuators were considered. In the research macro fiber composite (MFC) type transducers exhibiting d_{33} effect were used. The numerical models and further calculations were done in ABAQUS/Standard FEM software. Discrete models of the considered composite beam structures were formulated according to the Layup-Ply technique. In performed tests nonlinear geometric effects corresponding to large structural deflections were taken into account. The resulting state equations were solved by means of Newton-Raphson iterative method. Finally, the findings of numerical simulations were compared to the outcomes of laboratory experiments. A very good agreement of numerical and experimental results was achieved; this confirmed the assumptions made to the numerical model and further modelling technique.

Numerical model of the piezoelement, analysis of a composite beam with piezoelectric patch, numerical tests for the separated M-8503-P1 piezoelement, electric boundary conditions for the examined actuator, strain state of a glass-epoxy laminate, laboratory test-stand, numerical and laboratory experiment results are presented.

Keywords: *composite material, smart structure, piezoelectricity, numerical simulation, PZT, macro fibre composite transducer*

1. Introduction

Design of composite light-weight structures is a complex task requiring consideration of multiple material systems, plies orientations, thicknesses and their stacking sequence. Moreover, tailoring composite materials to specific tasks and specific designs result in high-effort systems. These circumstances call for advanced methods of structural analysis to enable an in-depth research of the composite system, especially with respect to its mechanical properties and load-carrying ability [3, 5]. Finite element method is a modern tool meeting fully all these requirements [4, 6, 13]. Considering new opening areas of FEM applications and integration within the CAE systems finite element methods continues to play more and more significant role in structural design and design optimisation, also regarding composite structures.

A special attention of today's engineering is given to, so called, smart structures. Apart from different definitions and problem-oriented applications structural health monitoring is one of fundamental tasks performed by these configurations. SHM actions are generally aimed at nondestructive evaluation of a current state of the system and its further performance prediction [7-9, 13]. Monitoring structural health seems to be a critical issue in case of elements made of composite materials. This arises from the fact, that the damage modes in composite laminates are completely different and much more complex than the well-known ones in conventional metal alloys. Furthermore, damage in composites usually initiates much earlier in the life cycle of the structure and often occurs inside the material where it is invisible.

One of the most promising methods of structural health monitoring is related to embedding piezoelectric sensors at crucial points of the structure. These transducers might take the form of piezoelectric wafers, patches or piezoelectric fibres set up into a widespread network monitoring state of the system in on-line mode [7-9, 11-13]. The design and analysis of smart composite systems with embedded piezoelement sensors can be aided by modern finite element software. This became possible since late 90-ties when first libraries of piezoelements were implemented into selected finite element packages. Now, the discussed technology of smart composites, is applied by all leading companies e.g. from military (McDonnell Douglas) and civil (Boeing, Airbus) aeronautic industry and still gets to be more popular.

2. Aims and scope

Within the frame of performed numerical analysis behaviour of composite structures with integrated active elements was simulated. The exemplary specimens of multi layered composite beams with transducer bonded on the beam's top surface were considered. The actuator used in simulation was exhibiting d_{33} effect – i.e. the strain was exerted along the direction of electric field loading. The verified numerical model of the piezoelement was used for the simulations of beam-actuator systems. At the final stage the results of numerical analysis of a composite-piezoelement system were discussed with reference to the laboratory test results.

3. Numerical model of the piezoelement

For numerical and laboratory tests M-8503-P1 element made by Smart Material Corp., Sarasota (FL) USA was used – see Fig. 1. This is the transducer of d_{33} effect type.

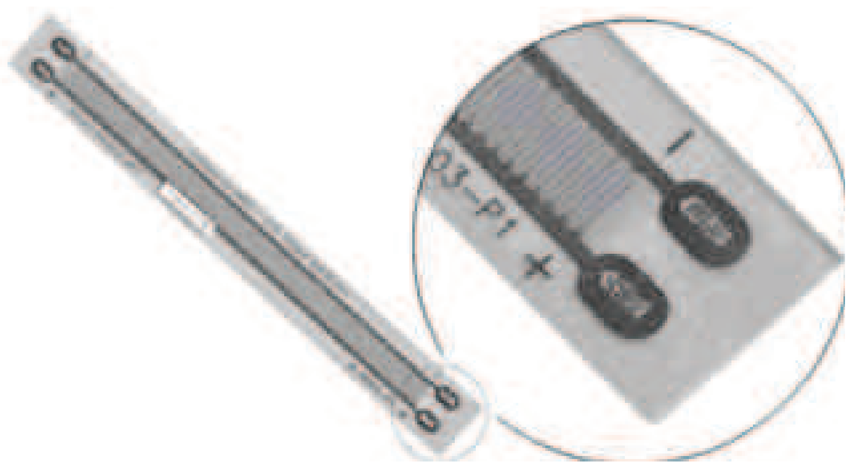

Fig. 1. Active element M-8503-P1 made by Smart Material Corp., Sarasota (FL) USA

At the initial stage of an analysis a numerical model of the separated piezoelement was developed and verified according to the data provided by the manufacturer. Despite of modular structure of the transducer under consideration (170 sections of electrocouples distant by 0.5 mm from each other – see zooming area in Fig. 1) the piezoelement was not modelled in micro scale.

Instead, in the presented approach a supplementary body made of orthotropic, homogenous piezoelectric material was proposed with voltage applied to opposite specimen faces.

The description of piezoelectric material required the elastic, piezoelectric and dielectric data to be given. According to the manufacturer catalogue the following parameters were used:

– fully elastic orthotropic material with Young's moduli $E_1 = E_2 = 15857$ MPa, $E_3 = 30336$ MPa, Kirchhoff's moduli $G_{12} = G_{13} = G_{23} = 5515$ MPa and Poisson's ratios $\nu_{12} = \nu_{13} = \nu_{23} = 0.31$,
– material with constant permittivity $D(\varepsilon) = 8 \cdot 10^{-9}$ F/m coefficients on the main diagonal; all the out-of-diagonal terms were neglected sice isotropy of ferroelectric properties was assumed,
– piezoelectric properties – according to the data provided by the manufacturer the value of strain coefficient d_{33} is not constant with respect to the electric field. For a single section of electrodes at low electric fields (i.e. $|E|$ < 1 kV/mm) the strain parameter d_{33} equals $400 \cdot 10^{-12}$ m/V, for higher magnitude fields ($|E|$ > 1 kV/mm) the d_{33} increases to $460 \cdot 10^{-12}$ m/V. Following this information the provided d_{33} values have to be multiplied by the number of 170 sections in M-8503-P1 element (Fig. 1) to get the effective value to be put into the FEM model for preliminary calculations. All the remaining strain coefficients were set to 0.

The transducer's active area (85 × 3 × 0.3 mm) was modelled in ABAQUS system and divided into 17 solid continuum elements of C3D20E type, i.e. 20-nodal second order, having at each node three translational degrees of freedom and one DOF corresponding to electric charge (related to the piezoelectric properties of the material) [1, 2, 4]. Electric load of a transducer was represented by electric potential 0 V at negative pole and 1500 V at positive one.

Series of numerical tests of the separated piezoelement were run to scale the model parameters. These comprised the axial resultant force in blocking force test and element's extension in free strain test to be compared to the catalogue data. Results of initial numerical experiments showed a serious discrepancy with respect to the manufacturer data. To get the proper agreement the correction of piezoelectric coefficient d33 was necessary.

Minimising the relative error in both tests as a function of d_{33} parameter its optimal value for the M-8503-P1 element was found to be 5.9 10^{-8} m/V. After this correction, the following final results were achieved: free strain 1040 ppm with respect to 1050 ppm given by manufacturer and 28.46 N blocking force with respect to 28 N by manufacturer. The outcomes of piezoelement analysis after model's fine-tuning are presented in Fig. 2. Results of the final simulations for the updated d_{33} parameter confirmed the sugested approach to MFC piezoelectric patch modelling to be correct.

Fig. 2. Numerical tests for the separated M-8503-P1 piezoelement: a) free strain extension, b) blocking force

4. Analysis of a composite beam with piezoelectric patch

Second stage of research comprised analysis of a clamped laminated beam with piezoelement M-8503-P1 bonded onto beam‘s top surface. Two composite materials were taken into consideration:

– unidirectional glass fibres tape with epoxy Prime 20 matrix (Sicomin 8100 + hardener 8824, fibres ratio 50±2% – manufacturer data). The subsequent layers of the composite were set in the following order: 0°/90°/+45°/-45°/+45°/90°/0° (according to axis pointing along the beam length), every single laminate with equal thickness g = 0.308 mm.
– carbon-epoxy fabric by Heatcon Composite Systems, code 985-GF3070-PW, with the plies order: +45°/90°/90°/0°/-45° (according to axis pointing along the beam length), every laminate with equal thickness g = 0.235 mm.

In both cases the length and width of the specimen were the same and equal to $l = 300$ mm and $b = 12.9$ mm respectively. The total thickness of every beam was resulting from the number of laminate layers. The placement of the actuator on every specimen was the same and is presented in Fig. 3.

Fig. 3. Placement of the actuator on the tested specimen

The ABAQUS finite element model of a beam based on shell elements and the composite material of the beam was defined as a “lamina” type one. This approach enables modelling of laminate as a set of orthotropic layers (plies) in plane-stress state, according to Layup modelling technique [1, 2]. The following data provided by the composite manufacturers was used in numerical simulations:

– glass-epoxy laminate (unidirectional tape) Young modulus along fibres $E_1 = 20\,000$ MPa, transversal Young modulus $E_2 = 2\,000$ MPa, shear moduli $G_{12} = G_{13} = G_{23} = 9\,800.7$ MPa and Poisson's ratio $\nu_{12} = 0.26$.
– carbon-epoxy laminate (fabric) Young modulus (longitudinal and transversal) $E_1 = E_2 = 56\,000$ MPa, shear moduli $G_{12} = G_{13} = G_{23} = 3910$ MPa and Poisson's ratio $\nu_{12} = 0.32$.

In performed analysis S8R elements were used i.e. second order ones with reduced integration. Finite element models of structures under consideration are presented in Fig. 4.

The previously verified model of the piezoelectric transducer body was 'glued' to master structure (beam) by TIE constraints, which resulted in joining appropriate DOF of both bodies.

According to Abaqus/Standard User’s Manual [2] the loading of the transducer was defined by means of electric potential boundary conditions defined at both actuator’s poles. Keeping the constant value of 0 V at the negative terminal the potential for positive one was changed gradually within the range of 0-1500 V; exemplary loading is given in Fig. 5.

Finally, the mechanical boundary conditions for the system were set by deactivating all translational and rotational degrees of freedom at clamping.

The deflections of a beam were calculated by reporting the vertical displacement of a point located at the edge of the piezoelement patch (located 10 mm from the edge of piezoelement active area) within the range of 0-1500 V applied to the positive terminal of the transducer. Exemplary state of strain for a glass-epoxy laminate beam is given in Fig. 6.

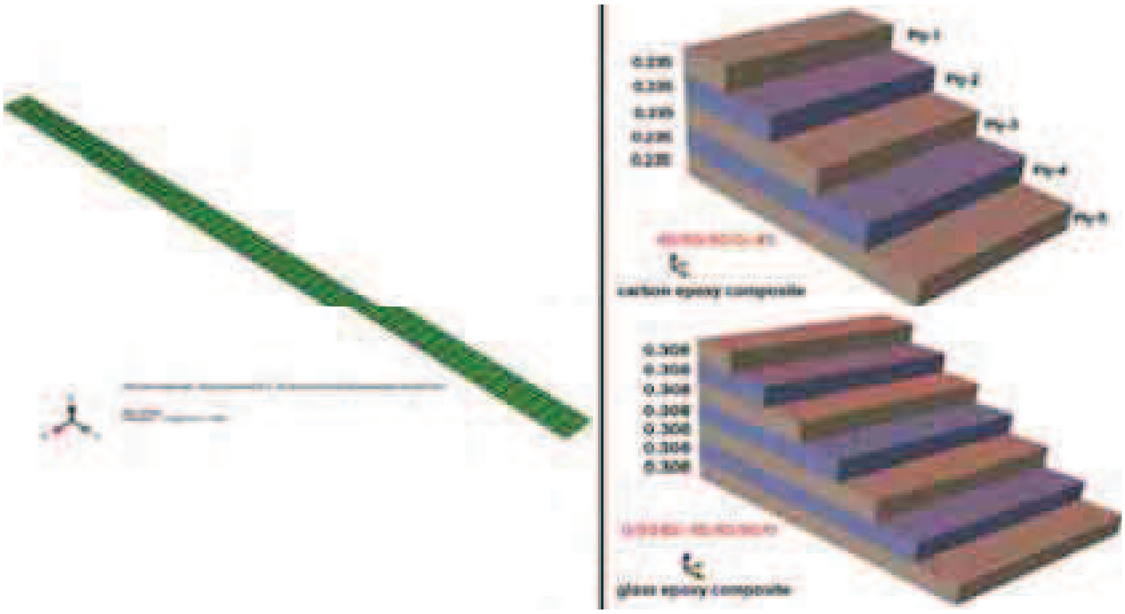

Fig. 4. Considered composites a) specimen finite element model, b) ply stacking sequence for glass-epoxy laminate c) ply stacking sequence for carbon-epoxy laminate

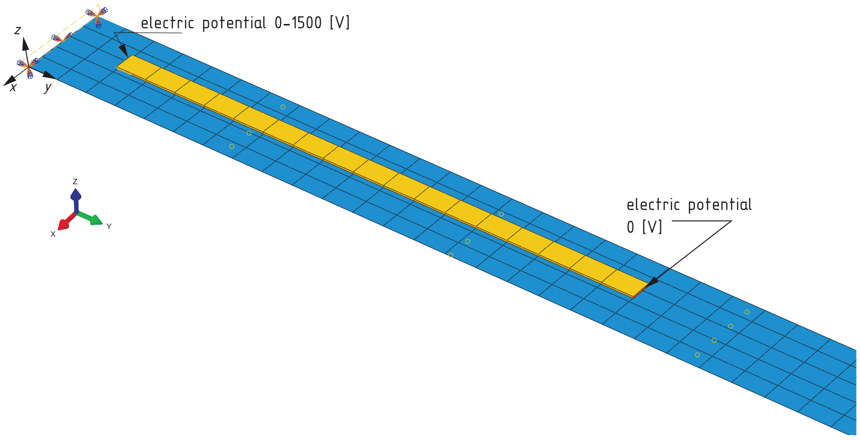

Fig. 5. Electric boundary conditions for the examined actuator

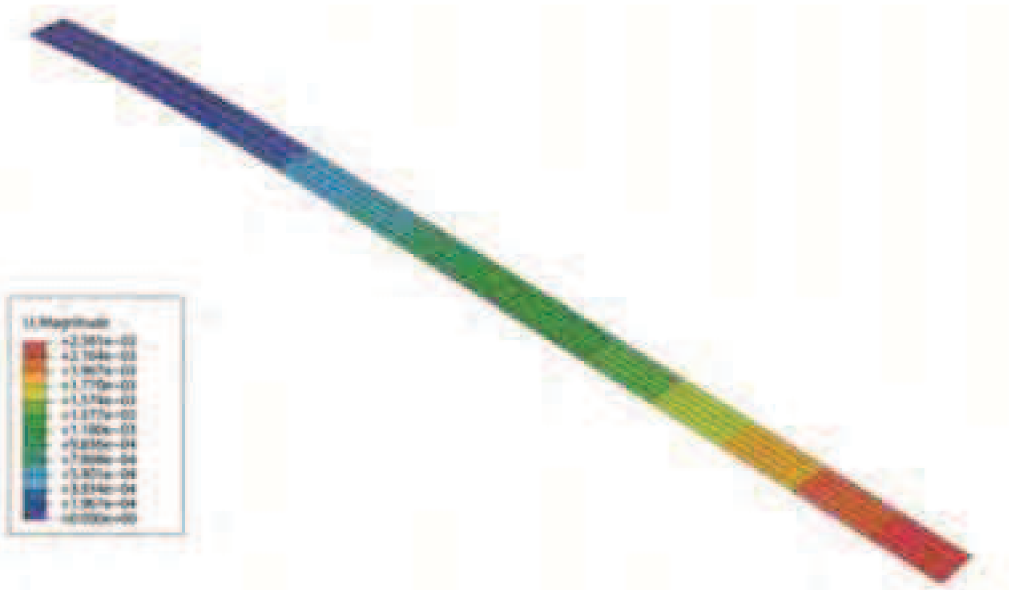

Fig. 6. Strain state of a glass-epoxy laminate at 1500 V loading

In parallel to numerical simulations the series of laboratory tests on actual specimens were performed. The setup used in experiment is shown in Fig. 7. The specimen under consideration (1) was clamped in bench vice (2). The transducer (3) bonded onto the beam was connected (4) to D.C. power unit with a controllable resistance divider. The requested driving voltages were provided by a high-voltage amplifier model PA05039 made by Smart Materials company. The vertical displacements of reference point were measured with micrometer screw (5).

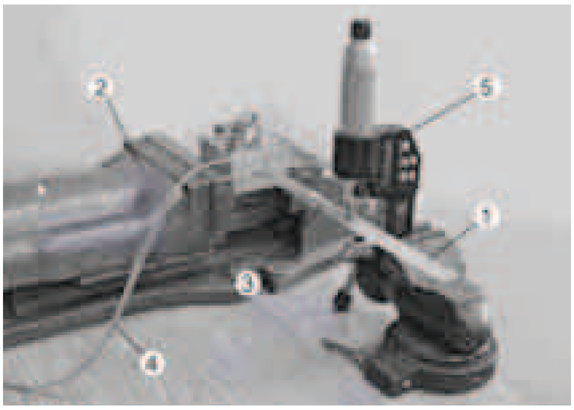

Fig. 7. Laboratory test-stand – specimen (1) under consideration with the bonded transducer (3)

5. Results

Comparison of experimental measurements and numerical simulations results are presented in Fig. 8. All measurements were done at reference point as given above.

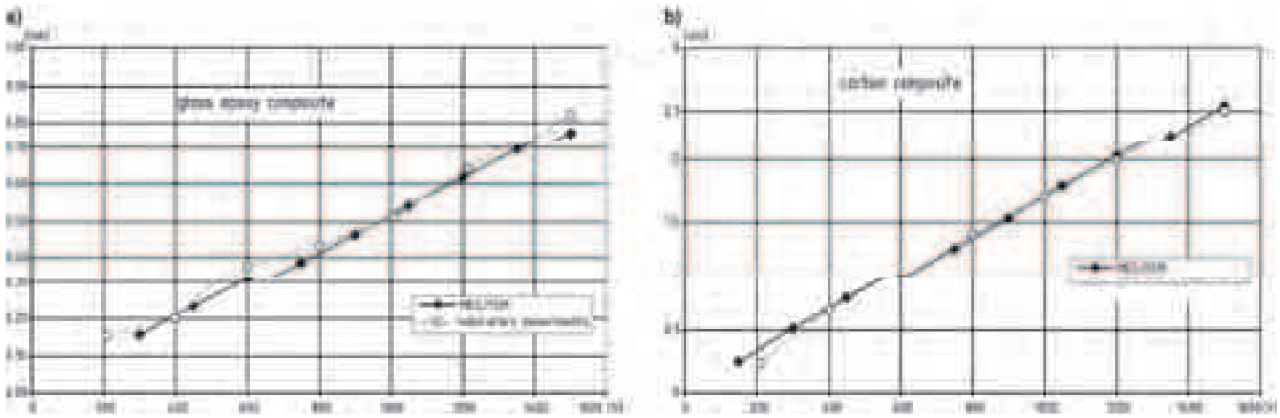

Fig. 8. Numerical and laboratory experiment results for a) glass-epoxy composite b) carbon-epoxy composite

6. Conclusions

The paper presents the possibilities of effective macroscopic modelling of macro fibre composite piezoelectric transducers embedded into composite laminates. The presented analysis falls into an area of growing interest and perspective research trends. This relates especially to lightweight aero-structures, where so-called "smart systems" are already under operation. System's ability to shape changes (or even morphing) and structural health monitoring actions are just one of most representative exemplary applications [7-9, 13].

A high correlation of numerical simulations and laboratory tests was achieved. Therefore this observation confirms the modelling technique approach to finite element representation of MFC type transducers. Moreover, a validity of suggested discretisation method of the specimen's domain is confirmed. These initial investigations encourage for further numerical simulation research in the discussed area.

Acknowledgement

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