This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Swati, R.F.; Elahi, Hassan; Wen, L.H.; Khan, A.A.; Shad, S.; Mughal, Muhammad

Investigation of tensile and in-plane shear properties of carbon fiber reinforced composites with and without piezoelectric patches for micro-crack propagation using extended finite element method

Published in:

MICROSYSTEM TECHNOLOGIES: MICRO-AND NANOSYSTEMS-INFORMATION STORAGE AND PROCESSING SYSTEMS

DOI:

[10.1007/s00542-018-4120-y](https://doi.org/10.1007/s00542-018-4120-y)

Published: 01/06/2019

Document Version

Peer reviewed version

Please cite the original version:

Swati, R. F., Elahi, H., Wen, L. H., Khan, A. A., Shad, S., & Mughal, M. (2019). Investigation of tensile and in-plane shear properties of carbon fiber reinforced composites with and without piezoelectric patches for micro-crack propagation using extended finite element method. *MICROSYSTEM TECHNOLOGIES: MICRO-AND NANOSYSTEMS-INFORMATION STORAGE AND PROCESSING SYSTEMS*, 25(6), 2361-2370.
<https://doi.org/10.1007/s00542-018-4120-y>

Microsystem Technologies

Investigation of Tensile and In-plane Shear Properties of Carbon Fiber Reinforced Composites with and without Piezoelectric patches for micro-crack propagation using Extended Finite Element Method --Manuscript Draft--

Manuscript Number:	MITE-D-18-00761
Full Title:	Investigation of Tensile and In-plane Shear Properties of Carbon Fiber Reinforced Composites with and without Piezoelectric patches for micro-crack propagation using Extended Finite Element Method
Article Type:	Original Research
Keywords:	Extended finite Element Method (XFEM); Extended Cohesive Damage Model (ECDM); Cohesive Damage Model (CDM), Laminated Composites; Fracture; Carbon Fiber Reinforced Composite.
Corresponding Author:	Hassan Elahi, Ph.D. Universita degli Studi di Roma La Sapienza Rome, Rome ITALY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Universita degli Studi di Roma La Sapienza
Corresponding Author's Secondary Institution:	
First Author:	R. F. Swati, Ph.D.
First Author Secondary Information:	
Order of Authors:	R. F. Swati, Ph.D.
	L. H. Wen, Ph.D.
	Hassan Elahi, Ph.D.
	A. A. Khan, P.hD.
	S. Shad
	M. Rizwan Mughal, P.hD.
Order of Authors Secondary Information:	
Funding Information:	
Abstract:	<p>The smart materials are capable to integrate the remarkable active functions into a traditional structure of the composites. There is a wide research possibility towards the embedded patches into a composite primary structure. This particular study aims to investigate the effect of the embedded smart materials in a conventional composite laminate. Carbon Fiber Reinforced Composite specimens with and without PZT piezo elements embedded in the structure are studied for Tensile, In-plane Shear and three point bending properties. Previously researched mechanical behaviour and the operational influence of the piezo sensors are sequentially analysed, particularly for the electric capacitance during all the categories of testing. The limitations have also been studied into the comparison of the structure with and without the piezoelectric material patches. The extended Finite Element (XFEM) modelling approach has been applied to study the sensorized damage model for the numerical and experimental study. This study also presents simplified and understandable techniques and offers a new direction for the experimental and computational modelling design for the progressive damage, based on the principles of Extended Finite Element Method (XFEM). The extensive experimentation and numerical modelling for interlaminar and intralaminar crack of Carbon Fiber Reinforced Composite CFRCs materials are studied, with and without piezoelectric patches. The experiments and simulations are designed and grouped into categories of load, boundary conditions and types arranged</p>

	<p>according-ly for fracture, delamination, fiber breakage and matrix crack towards the damage evolution. The dimensions of the specimens and the effects are also studied regarding lengths, thickness and width in multiple categories. The loading cases of tension and the inplane shear are studied for multiple cases for numerical as well as experimental investigation having different orientations and dimensions. The delaminated and fractured mode I and mode II specimen were analysed for the expected and the real time values of strength to figure out the precise values of trends to predict the composite properties.</p>
--	---

Investigation of Tensile and In-plane Shear Properties of Carbon Fiber Reinforced Composites with and without Piezoelectric patches for micro-crack propagation using Extended Finite Element Method

R.F Swati^{1,2}, L.H Wen¹, Hassan Elahi^{2,3}, A.A Khan², S. Shad¹, M. Rizwan Mughal^{2,4}

¹ School of Astronautics, Northwestern Polytechnical University, Xi'an, 710072, China

² Institute of Space Technology, Islamabad, Pakistan

³ Department of Mechanical and Aerospace Engineering, La Sapienza University of Rome, Rome, Italy.

⁴ Department of Electronics and Nanoengineering, Aalto University, Espoo, Finland

Abstract

The smart materials are capable to integrate the remarkable active functions into a traditional structure of the composites. There is a wide research possibility towards the embedded patches into a composite primary structure. This particular study aims to investigate the effect of the embedded smart materials in a conventional composite laminate. Carbon Fiber Reinforced Composite specimens with and without PZT piezo elements embedded in the structure are studied for Tensile, In-plane Shear and three point bending properties. Previously researched mechanical behaviour and the operational influence of the piezo sensors are sequentially analysed, particularly for the electric capacitance during all the categories of testing. The limitations have also been studied into the comparison of the structure with and without the piezoelectric material patches. The extended Finite Element (XFEM) modelling approach has been applied to study the sensorized damage model for the numerical and experimental study. This study also presents simplified and understandable techniques and offers a new direction for the experimental and computational modelling design for the progressive damage, based on the principles of Extended Finite Element Method (XFEM). The extensive experimentation and numerical modelling for interlaminar and intralaminar crack of Carbon Fiber Reinforced Composite CFRCs materials are studied, with and without piezoelectric patches. The experiments and simulations are designed and grouped into categories of load, boundary conditions and types arranged accordingly for fracture, delamination, fiber breakage and matrix crack towards the damage evolution. The dimensions of the specimens and the effects are also studied regarding lengths, thickness and width in multiple categories. The loading cases of tension and the inplane shear are studied for multiple cases for numerical as well as experimental investigation having different orientations and dimensions. The delaminated and fractured mode I and mode II specimen were analysed for the expected and the real time values of strength to figure out the precise values of trends to predict the composite properties.

Keywords: Extended finite Element Method (XFEM); Extended Cohesive Damage Model (ECDM); Cohesive Damage Model (CDM), Laminated Composites; Fracture; Carbon Fiber Reinforced Composite.

1. Introduction

The fracture behavior of piezoelectric materials under different loading conditions has been a focus of research recently to validate the versatility of piezoelectric patches in composite structures for applications in electromechanical. The experimentation has been carried out in different scenarios of the layered structure being replaced by fiber-reinforced composite layers to optimize the weight. The recent research revealed the importance of Lead Zirconate Titanate (PZT-5A) which is the most commonly used piezoelectric material because of its superior voltage actuation ability. The development and improvement has been constantly done for piezoelectric materials in various applications and particular design. The fracture mechanics for micro crack initiation, propagation and the failure behavior is equally critical to be known. Therefore, a

number of studies have been initiated to evaluate fracture strengths of piezoelectric materials.

For the purposes of the general scenario and methodological evolution, Table 1 lists different smart packet models analyzed and validated. Crawley and De Lois [1] developed a basic frame-and-frame research for the model of the crossbar to regularly distort the electrode of the blades on the surface, including the spots and beam axis alignment. The model calculates the bending response, including the effects of shear retardation of the adhesive layer between the bisoceramic agent and the beam. It has been shown that the transfer of voltage from the bisocerimi operator to the structure takes place in a small area near the two ends of the engine, and there is maximum effort to cut in this area. As the adhesive layer becomes thinner and / or more rigid (shear coefficient), it approaches an ideal bonding state (concentrated shear at the two

*Corresponding author. Tel.: +393276544166
E-mail address: Hassan.elahi@uniroma1.it

engine ends) and the comparison is shown in Table 1.

Table 1: Comparison of smart beam models [2]

Modeling type	Actuators	Piezoelectric coupling	Beam type
Block Force	Surface and embedded	Uncoupled	Cantilevered aluminum
Euler-Bernoulli	Surface and embedded Straight patches Skewed patches	Uncoupled	
Uniform strain	Surface and embedded Straight patches Skewed patches	Uncoupled	
Timoshenko (FSDT)	Surface and embedded	Uncoupled	Cantilever composite coupled
Vlasov with chordwise bending and shear	surface bonded Straight patches	Uncoupled	
Euler-Bernoulli coupled Layerwise shear deformation theory (LWSDT)	Surface	Coupled	Cantilevered aluminum
	Surface	Coupled	

The thick-walled and thick-walled beams were evaluated [3], [4] and assessed progress in composite modeling. By introducing the layers of the designed layers, multiple load scenarios can be observed within the whole structure with or without compressive electric spots, which regulate induced deformation procedures for various applications, especially aerospace installations. A large number of studies have been carried out for high-walled composite beams. The ceiling wall can be designed as a thick sheet or sheet, including the effect of cross shear, as well as bending distribution as developed and certified in several models as shown in Table 1.

Multipurpose and multi-layer materials systems are widely used in all vital application categories in mechanics, space, civil, biomedical, etc. Due to mechanical behavior and unique response values. Mechanical properties and damage behavior of interfaces based on laminate response were found for almost all types of applied structures, carbon fiber reinforced materials in illustrations of materials of various stages, and their own microcharacteristic system. The structure is often characterized by a complex distribution of material components, which can vary in an inevitable or even random way within a microscopic structure. Carbon fiber reinforced polymers (CFRP) have been commonly used in the aerospace, shipbuilding and automotive industries for decades. With the extensive application of CFRP, the investigation of mechanisms for damage to CFRP structures was a major concern for

the further development of CFRP in engineering structures [5] - [8]. At present, there are no reliable digital approaches that provide engineers and researchers with effective predictability of damage and failure when designing composite fiber structures. Recent developments have focused on the interlaminar interface as a special area in relation to discharge diffusion modeling. Multilayer lamination results from damage to composite plates on site most of the time, as it grows into several interlaminar interfaces. The R & D reassembling of a promising mathematical model is able to account and restores multiple failure mechanisms, including the displacement of matrix lining failure and fiber damage [9] - [11].

Assumptions and methodologies are improving; the main objective of research development is to predict numerical damage, optimal computing resources and modeling facility. The computational model for fracture cracking and structural staining is still under development, and many assumptions and techniques have been developed in this area of study to obtain accurate predictions of damage. The X-FEM method is a digital technique based on the FEM method that efficiently handles the interruptions and complex elements of the structure. The formulation and reference point was provided by Moss] N, Dolbow J and Belytschko serve as a free phenomenon network as a new approach to represent fracture surfaces and crack evolution in the standard method based on Galerkin [12]. The method began to get approaches and improvements, and began to research with the formulation of the plate where the shear block was not integrated, the limited elements approach was enriched in the next stage with intermittent functions close to the edge to allow the geometry of the cracks to be processed as an independent mesh material that greatly facilitated Simulate crack growth. XFEM has been studied for all interruptions and types to model and formulate a relatively accurate growth simulation. Disruptions can be strong or weak depending on the density and resistance values of the particular situation; in some ways, strong reflections in solution variables are addressed when managing complex structures. Displacement is the variable solution in structures. Strong interruptions are displacement of edges such as cracks and holes. Disruptions in the solution variable are mainly treated as a weak category. The method can be applied to organized and unorganized networks. The coordinated networks of material science are applied in many research works, where the properties of the unit cell of the material should be noted and appreciated, while unorganized networks tend to be widely used to analyze engineering structures and components. It is often recommended to form the grid to the outer limits of the component, That some of the methods currently under development are capable of handling complex geometric shapes even with complex networks. These methods can easily form the simplified solution for many complex cases in material modeling such as diffusion of cracks, evolution of disturbances, modeling of particle boundaries and evolution of phase boundaries [13]. When using this method, the independent morphological form of these entities and the network of finite

elements is independent. The enrichment offset fields are the main side at the near end of the fraction area and the corresponding results are analyzed and controlled for problem modeling. Similarly, the proliferation of cracks, or the fertilization function of the cracking model or the imbalance by elastic means, is estimated by a single close solution of the near field. The ability to apply the remesh method to crack growth, there are certain drafting techniques and methods to model crack propagation and relative growth parameters without rebooting. These methods without a network is not necessary for connectivity methodologies and the problem of uniqueness of nodal points, the method of replacing the arbitrary local network is a mobile network technique and divides into two different meshing problem identified in the following sections in the detailed formulation [12], [14] [15].

2. Model Description And Experimentation

2.1 Experimental setup and materials

The setup has been developed and tested by Hu kai-ming [16]. In order to simulate the effect of axial compression force piezoelectric bimorph actuator under simply supported boundary conditions, the design and customized setup of the experimental fixture is shown in Fig.1, where the left side of the drive is fixed at the end of the rotating shaft. The output shaft is the slidable at the rotary end, which is able to slide in the chute of the front base, in order to apply the axial load in the direction shown. For compression force, the sliding shaft and parallel main spindle sequentially to form a suspension effect on the suspension shaft. The magnitude of the axial force is adjusted by increasing or decreasing the weight of the blocks as indicated.

Fig. 1: Experimental platform for piezoelectric bimorph driver

Furthermore, to measure the output shaft angle of the driver, a metal strip is embedded on the output shaft as the reflector. The displacement of the distance from the center of the output shaft to a desirable height is measured by a laser position measuring instrument.

On the other hand, for direct mechanical tests, the Electronic Universal Testing Machines (DDL300) shown in Fig. 1, by Changchun machine science research institute is used in the laboratory for mechanical property testing of the Carbon Fiber

Reinforced Composites.

Fig. 2: Electronic Universal Testing Machines (DDL300)

The machine consists of a central computer, electrical connection system, data acquisition system and computer software. The program, TestExpert.NET, is used, which includes its main function group flow control and set parameters, acquisition and storage of test data, account calculation and print test report. The DDL series adopts the EDC series digital control system; the DNS series adopts the PSC-A control system. The experimental design has been inspired from numerous studies performed for testing carbon fiber/epoxy composites and a detailed available data for the properties with a number of variables were analyzed and studied for the comparison of the experiments with the calculations. The composites are made of T700S carbon fibre, based as the matrix material with the fibre varied volume fraction as shown in Table 2.

Table 2:T700/Epoxy properties

Property	T700	Epoxy
E ₁₁	156.32	3.35
E ₂₂	8.512	3.35
E ₃₃	8.512	3.35
G ₁₂	5.11	1.24
G ₁₃	5.11	1.24
G ₂₃	3.315	1.24
ν_{12}	0.284	0.35
ν_{13}	0.284	0.35
ν_{23}	0.284	0.35

Property	Tensile	Comp.	Shear	Dist.f	Control
T700	3424	-	-	Weibul	Scale 3424
Epoxy	80	120	70	-	Shape 5.022

2.2 Geometry and boundary conditions

The categories have been designated as per thicknesses of

the 5 plies layered specimens, representing the specific set of orientations and respective dimensions with the listed values of geometric tolerances. The experimental setup has been demonstrated for the different modes of tension and respective orientations of primarily [(Universal 0°), (0°, 90°, 0°, 90°), (Universal 90), (+45°, -45°)] and individual plies evaluations and pre-test investigations. The demonstration of crack propagation with the ABAQUS XFEM results of the composite carbon fiber trends was a previous trend to verify the experimental results of several studies. [17] - [19] ABAQUS uses the national definitions of physical models and interactions of carbon fiber composite samples with the multiple trends and designs described in Table 3.

Table 3: Specimen Sizing

Specimen	layers	Length	Width	Thickness
0°tensile	[0°] ₁₄	240	12.5	2.95
90°tensile	[90°] ₁₄	200	25	2.95
In-plane shear	[45 ₃ /-45 ₄ /45 ₃]	250	25	2
Laminate tensile	[0°/90°/0°/90°/0°]	250	25	3

The numerical model presented in the previous section is validated and compared to the results based on the maximum stress criterion. There is a variation in the typical dimensions of the widths and thickness of the different orientations, as shown. It provides accuracy and accuracy to verify the experimental and numerical results in terms of groups A, B and C. The material has already been defined and explained to the categories and sequences of experiments mentioned. The schematic diagram of the plates can be seen in Figure 3 with the order details.

Fig. 3: Failed specimen w.r.t orientations

Material properties of each layer are given in Table 1. The Table shows the detailed dimensions of the set of specimens corresponding to the categories A, B and C as explained.

3. Damage Model

Progressive failure defines how damage propagates through a laminate and can be caused by cyclic or monotonic loading [20]–[22]. The modeling technique that is discussed here was used to model the progressive damage of a CFRP laminate. These rules were applied in a loop until ultimate failure was achieved. The method provides a good correlation with experimental results. Modeling progressive damage of transverse cracks, delaminations, and fiber breaks is discussed in [23]. Many researchers have used cohesive zone elements to predict delaminations for a variety of experimental situations [24]–[30]

3.1 Numerical Model

A 3D numerical model of PZT having dimensions 5.8x0.5x0.12 cm is developed in commercial available software ABAQUS Standard according to the data expressed in Table 2. The numerical results are validated by the experimentation. A 3D finite element model of PZT is shown in Fig. 4.

Fig. 4: A 3D finite element model of PZT

For numerical solution in ABAQUS, Newton integration approach has been used. The meshed model has global size of 0.0003 containing 12,000 hex dominated elements. The effect of fatigue is analysed on electromechanical loading, as shown in Fig. 5.

Fig. 5: A The effect of fatigue electrical and mechanical loading

The peak to peak voltage generated by PZT patches at variable electromechanical loading is expressed numerically in Fig. 6 [31].

Fig. 6: Peak to peak voltage generated by PZT patches at variable electro-mechanical loading

3.2 Experimental model

Several laboratory methods were used to evaluate fracture characteristics, including bending tests, tensile and pressure tests, DCT, indirect voltage testing (IDT) and semi-circular flexion test (SCB). SCB engineering is irrelevant, as it is more practical to test laboratory and field samples than conventional beams [32]. In order to develop precise patterns of growth behavior of cracks, a comprehensive program of material characterization and damage should be studied and developed, taking into account the characteristics and categories, as described in [33].

Fig. 7: Failed specimen for different modes (Tensile)

Crushing and cracking are examined according to tensile loads for each case and class. Figure 6 shows failures in the case of load voltage and similar analyzes were carried out for the rest of categories A, B and C. The study was previously performed for the analytical model, which led to a similar evolution of the damage model. The composite layers and angles of CFRRC are specifically for the matrix damage standard, and the data were presented in Tables 4-6

Table 4: Experimental observations for 0° tensile specimen

0°tensile	Failure load KN	Failure strength MPa	Average modulus GPa
1	42.46	1258.06	108.75
2	43.21	1326.79	
3	52.73	1568.93	
4	47.48	1423.60	
5	41.98	1247.35	

Table 5: Experimental observations for 90° tensile specimen

90° tensile	Failure load KN	Failure strength MPa	Average modulus GPa
1	0.872	13.60	6.44
2	0.974	15.24	
3	0.914	14.63	
4	0.987	15.40	
5	0.865	13.54	

Table 6: Experimental observations for In-plane shear specimen

In-plane shear	Failure load KN	Failure strength MPa	Average modulus GPa
1	3.258	32.076	3.036
2	3.007	29.579	
3	3.512	34.059	
4	3.099	30.755	
5	3.783	36.924	

Basic tests and associated parameters are listed and graphically presented for fracture tests in the following sections, comparisons with previous experiments, how values were improved, and methods were well identified. The damage failure in the composite structure is evaluated as a complete field phenomenon for specific cases and groups where the damage to the elastic region is examined as a separate study, and the maximum load and resistivity values are shown in Table 2.

4. Experimental And Numerical Results

4.1 XFEM results without piezoelectric patches

The experimental models have been investigated for the tensile stress-strain contour plots and the comparative responses of the specimens accordingly for the listed categories and groups shown in Fig. 8–Fig. 10 and stress-strain plots are shown categorically as well in Fig. 11 – Fig. 13.

Fig. 8: Damage assessment for tensile 0°

Fig 9: Damage assessment for 90°

Fig. 10: XFEM status

Fig. 11: Group A (Tensile 0°)

Fig. 12: Group B (Tensile 0°, 90°, 0°, 90°)

Fig. 13: Group C (Tensile 90°)

The results reflect that both the tensile strength and strain capacity for the set of experiments, and the tensile strain capacity is found much more significant than the tensile strength for different orientations. It is understandable from the study by [23] that tensile strain-hardening behaviour may not exist as a first cracking may lead to failure due to an inadequate fibre bridging capacity to endure the stress. The stress-strain curve behaviour has been figured out to be zigzag by XFEM [34] and by other modelling methods; programme which are published for the damage initiation, development and growth for the crack and propagation accordingly, which is triggered by the fracture of fibers. The models depict almost uniformity for the progressive damage once the damage is initiated and moves. The trend may be observed for numerically homogenized load values against the corresponding far field strain value for the group A, B and C. Furthermore, The nominal stress-strain curve for XFEM /Weakening and cohesive elements model conforms and validates the model for all the parameters discussed in previous sections.

Based on the tensile model for mode I the damage is well defined and compared for the localization, stress intensities, delamination, fiber breakage, matrix cracking etc. for all the

categories and few results are shown in previous section for the specimens crack/fracture growth path and respective XFEM-based delamination growth models were investigated and proposed further for multi-cracking and three point bending tests. The 3D composite structure with XFEM embedded model was built in the software package of ABAQUS and employed in current and future assessment studies, the subroutines programmed for the delamination growth models were introduced into the study to validate the experimentation work shown in Table 7.

Table 7: Experimental observations for 0° tensile specimen

Type	Avg Strength	Er%	% Var
0° Tensile			
0° test	1382.45	--	10.73
RVE	1547	11.9 0	10.10
0° tensile simulation	1056.00	12.1 1	2.1
90° Tensile			
90° tensile test	15.07	--	12.40
RVE	27.94	--	6.19
90° tensile simulation	17.10	13.47	3.46
Laminate specimen			
Laminate test	1028.34	--	9.98
Laminate simulation	1374.88	19.11%	2.81

There were few bugs and data post-processing issues for one of the category for which the model was re-developed. The summary can be analysed from Table 9 for all the values of the fracture strengths for the categories and the % error and variation of the data.

4.2 Static and dynamic results with piezoelectric patches

In order to verify the statics analysis model, ANSYS software has been used to model it. The solid226 coupling field element is selected for the upper and lower two piezoelectric layers, which is a 20 node hexahedron entity list. The element has the function of coupling multiple physical fields, such as force, electricity, heat and magnetism, where only voltage and mechanical degrees of freedom are used. The solid186 structure element is adopted in the laminates and the interface between the piezoelectric layer and the intermediate matrix layer is applied for the same properties listed in the composite data. The finite element model includes the beam length of 50mm, the width of 10mm, the total thickness of 0.6mm, and the thickness of each layer being 0.2mm, repeatedly. The width of the unit cell is 1mm, and the piezoelectric layer is divided into one layer in the thickness direction. The two level, the model

contains 1000 solid 226 units, 1000 solid 186 units, and finite element modules. These types are shown in Figures 2-4. Because this analysis is geometrically nonlinear finite element analysis of electromechanical coupling field, it is Large Displacement Static solver is selected in ANSYS and divided into sub steps. The 3D model is shown in Fig. 14.

Fig. 14: A finite element model of piezoelectric bimodal sheet

The dynamic and static finite element model's size, unit, material properties and the boundary condition are the same. The half power point method for damping ratio under different axial forces is also shown in Fig. 15 for all the ranges from 0-20.3 N and the curves of first-order frequency with axial force under different load inertia mass are shown in Fig. 16.

Fig. 15: Half power point method for damping ratio under different axial forces

Fig. 16: Curves of first-order frequency with axial force under different load inertia mass

To study the material response, amplitude frequency and phase frequency characteristic curves need to be obtained. It is easier to process the amplitude frequency response data. With fast Fourier transform (FFT) and smooth processing, better amplitude and frequency response results can be obtained. The amplitude frequency response data processing program will be explained briefly at the end of this section, while the phase frequency curve is more complicated. First, the time domain response signal is measured through experimental sweep. Fig. 16 is the frequency of 20.3N at axial force. At 1~500Hz, the amplitude response is 30V linear sweep signal. The phase angle direction definition diagram is shown in Fig. 17.

Fig. 17: Phase angle direction

The analysis of Fig. 18 and Fig. 19 shows that the phase angle range of the two order oscillations can only be 0 to -180 degrees. Due to the error noise in the experimental measurement, the phase angle may lead or lag behind. In addition, the problem of defining the domain of phase angle, for example, $\psi_1 = +179$ and $\psi_2 = -179$, is actually in the four quadrant phase

coordinates. It is only 2 degrees in the system, but after initial processing, it has a delta disturbance of $\Delta\psi = \psi_1 - \psi_2$, $\Delta\psi = +358$, resulting in serious disturbance. Therefore, further data processing is needed to eliminate such disturbances, while noise errors should be retained. It is necessary to determine which circumstances are noise errors and what are the errors produced by the definition of the phase angle.

Fig. 18: 30V sine sweep time-domain response of 20.3N under axial compression force

Fig. 19: Phase frequency curve for normalized response ($\Delta\psi = \psi_1 - \psi_2$)

5. Conclusion

The extensive experimentation and numerical analysis has been carried out for the development of a flexible framework for the prediction of the damage computational model. The techniques for fracture and delamination behaviour of the crack in carbon fiber reinforced composites with and without piezoelectric patches were investigated, particularly for the different modes of loads and boundary conditions has been evaluated using XFEM. The numerical model for PZT is developed which can accurately predict the response of electro-mechanical loading on the peak to peak voltage generation of the system. The experimentation and numerical response of the framework is in a good agreement, hence conforms the proposed technique as a simplified and efficient tool for the beginners and professionals. Large deformations of smart flexible beams due to multiple loading scenarios and application of piezoelectric patches have been studied. The flexible beams having linear elastic and viscoelastic responses have been evaluated and application to bimorph wing has also studied. The effect was closely observed for the smart beams are under tensile, inplane shear and bending. The countenance for the induced moment by the piezoelectric patches is presented

by considering both linear and nonlinear electro-mechanical response of the piezoelectric material.

References

- [1] E. F. CRAWLEY and J. DE LUIS, "Use of piezoelectric actuators as elements of intelligent structures," *AIAA J.*, 1987.
- [2] I. C. (The U. of T. at A. Inderjit Chopra (University of Maryland), *Smart Structures Theory*. 2013.
- [3] S. N. Jung, V. T. Nagaraj, and I. Chopra, "Refined Structural Model for Thin- and Thick-Walled Composite Rotor Blades," *AIAA J.*, 2002.
- [4] S. N. Jung, V. T. Nagaraj, and I. Chopra, "Assessment of Composite Rotor Blade Modeling Techniques," *J. Am. Helicopter Soc.*, 1999.
- [5] R. F. Swati, W. L. Hua, H. Elahi, and A. A. Khan, "XFEM Damage Analysis of Carbon Fiber Reinforced Composites and Crack Propagation in Mixed-Mode and Implementation of the Method Using ABAQUS," *Int. J. Mater. Mech. Manuf.*, vol. 6, no. 4, pp. 286–290, 2018.
- [6] B. Stier, J. W. Simon, and S. Reese, "Comparing experimental results to a numerical meso-scale approach for woven fiber reinforced plastics," *Compos. Struct.*, vol. 122, pp. 553–560, 2015.
- [7] R. Higuchi, T. Okabe, and T. Nagashima, "Numerical simulation of progressive damage and failure in composite laminates using XFEM/CZM coupled approach," *Compos. Part A Appl. Sci. Manuf.*, vol. 95, pp. 197–207, 2017.
- [8] H. Elahi, M. Eugeni, and P. Gaudenzi, "Electromechanical Degradation of Piezoelectric Patches," in *Analysis and Modelling of Advanced Structures and Smart Systems*, Springer, Singapore, 2018, pp. 35–44.
- [9] V. F. Kirichenko, V. A. Kry's'ko, and N. S. Surova, "The Bubnov-Galerkin method in the non-linear theory of hollow, flexible multilayer orthotropic shells," *J. Appl. Math. Mech.*, 1985.
- [10] G. Geandier *et al.*, "Micromechanical Modeling of the Elastic Behavior of Multilayer Thin Films ; Comparison with In Situ Data from X-Ray Diffraction," pp. 99–108.
- [11] A. W. Hulton and P. V. Cavallaro, "Comparing Computational and Experimental Failure of Composites Using XFEM," in *Volume 9: Mechanics of Solids, Structures and Fluids; NDE, Diagnosis, and Prognosis*, 2016.
- [12] X. Zhang, P. Zhang, and L. Zhang, "A simple technique to improve computational efficiency of meshless methods," *Procedia Eng.*, vol. 31, pp. 1102–1107, 2012.
- [13] S. L. Creighton, R. A. Regueiro, K. Garikipati, P. A. Klein, E. B. Marin, and D. J. Bammann, "A variational multiscale method to incorporate strain gradients in a phenomenological plasticity model," *Comput. Methods Appl. Mech. Eng.*, vol. 193, no. 48–51, pp. 5453–5475, 2004.
- [14] X. Li, "Application of the meshless Galerkin boundary node method to potential problems with mixed boundary conditions," *Eng. Anal. Bound. Elem.*, vol. 36, no. 12, pp. 1799–1810, 2012.
- [15] R. F. Swati, A. A. Khan, and L. H. Wen, "Weight optimized main landing gears for UAV under impact loading for evaluation of explicit dynamics study," in *Advanced Materials, Structures and Mechanical Engineering*, 2016, pp. 371–375.
- [16] C. Hu Kai-ming (Northwestern Polytechnical University, "Research of Post-Buckled Precompressed Bimorph for Micro Rudder Actuator," 2015.
- [17] L. Zhao, J. Zhi, J. Zhang, Z. Liu, and N. Hu, "XFEM simulation of delamination in composite laminates," *Compos. Part A Appl. Sci. Manuf.*, vol. 80, 2016.
- [18] X. Su, Z. Yang, and G. Liu, "Finite Element Modelling of Complex 3D Static and Dynamic Crack Propagation by Embedding Cohesive Elements in Abaqus," *Acta Mech. Solida Sin.*, vol. 23, no. 3, pp. 271–282, 2010.
- [19] R. F. Swati, W. L. Hua, H. Elahi, and A. A. Khan, "Extended Finite Element Method Damage Analysis of Carbon Fiber Reinforced Composites and Crack Propagation in Mixed-Mode Using Multiscale Method and Implementation of the Method Using ABAQUS Extended Finite Element Method Damage Analysis of Carbon," in *4th International Conference on Mechanics and Mechatronics Research, Xi'an, China*, 2017.
- [20] A. P. C. Duarte, A. Díaz Sáez, and N. Silvestre, "Comparative study between XFEM and Hashin damage criterion applied to failure of composites," *Thin-Walled Struct.*, 2017.
- [21] J. Y. Wu and S. L. Xu, "An augmented multirack elastoplastic damage model for tensile cracking," *Int. J. Solids Struct.*, vol. 48, no. 18, pp. 2511–2518, 2011.
- [22] A. Bergara, J. I. Dorado, A. Martin-Meizoso, and J. M. Martínez-Esnaola, "Fatigue crack propagation in complex stress fields: Experiments and numerical simulations using the Extended Finite Element Method (XFEM)," *Int. J. Fatigue*, vol. 103, pp. 112–121, 2017.
- [23] H. W. Wang, H. W. Zhou, H. W. Ji, and X. C. Zhang, "Application of extended finite element method in damage progress simulation of fiber reinforced composites," *Mater. Des.*, 2014.
- [24] B. Van Dongen, A. Van Oostrum, and D. Zarouchas, "A blended continuum damage and fracture mechanics method for progressive damage analysis of composite structures using XFEM," *Compos. Struct.*, vol. 184, no. September 2017, pp. 512–522, 2018.
- [25] O. Giraldo-londoño, D. W. Spring, G. H. Paulino, and W. G. Buttlar, "An efficient mixed-mode rate-dependent cohesive fracture model using sigmoidal functions," *Eng. Fract. Mech.*, vol. Volume 192, pp. 307–327, 2018.
- [26] X. Li and J. Chen, "The implementation of the extended cohesive damage model for multirack evolution in laminated composites," *Compos. Struct.*, 2016.
- [27] Y. Wang and H. Waisman, "From diffuse damage to sharp cohesive cracks: A coupled XFEM framework for failure analysis of quasi-brittle materials," *Comput. Methods Appl. Mech. Eng.*, 2016.
- [28] I. G. García, M. Paggi, and V. Mantic, "Fiber-size effects on the onset of fiber-matrix debonding under transverse tension: A comparison between cohesive zone and finite fracture mechanics models," *Eng. Fract. Mech.*, 2014.

- [29] X. Li and J. Chen, "A highly efficient prediction of delamination migration in laminated composites using the extended cohesive damage model," *Compos. Struct.*, vol. 160, pp. 712–721, 2017.
- [30] H. Elahi, "Experimental Determination of Electrical Properties and Mechanical Quality Factor of Piezoelectric Material under Thermal Shocking Conditions." 2014.
- [31] H. Elahi, M. Eugeni, P. Gaudenzi, M. Gul, and R. F. Swati, "Piezoelectric thermo electromechanical energy harvester for reconnaissance satellite structure," *Microsyst. Technol.*, pp. 1–8, Jun. 2018.
- [32] I. M. Lancaster, H. A. Khalid, and I. A. Kougioumtzoglou, "Extended FEM modelling of crack propagation using the semi-circular bending test," *Constr. Build. Mater.*, vol. 48, pp. 270–277, 2013.
- [33] V. K. Goyal, E. R. Johnson, and C. G. Dávila, "Irreversible constitutive law for modeling the delamination process using interfacial surface discontinuities," *Compos. Struct.*, 2004.
- [34] L. Zhao, Y. Wang, J. Zhang, Y. Gong, N. Hu, and N. Li, "XFEM-based model for simulating zigzag delamination growth in laminated composites under mode I loading," *Compos. Struct.*, vol. 160, pp. 1155–1162, 2017.
- [35] N. A. Petrov, L. Gorbatikh, and S. V. Lomov, "A parametric study assessing performance of eXtended Finite Element Method in application to the cracking process in cross-ply composite laminates," *Compos. Struct.*, vol. 187, no. July 2017, pp. 489–497, 2018.
- [36] N. A. Abdullah, J. L. Curiel-Sosa, Z. A. Taylor, B. Tafazzolmoghaddam, J. L. Martinez Vicente, and C. Zhang, "Transversal crack and delamination of laminates using XFEM," *Compos. Struct.*, vol. 173, pp. 78–85, 2017.
- [37] M. A. Torabizadeh, "Tensile, compressive and shear properties of unidirectional glass/epoxy composites subjected to mechanical loading and low temperature services," *Indian J. Eng. Mater. Sci.*, vol. 20, no. 4, pp. 299–309, 2013.