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MULTISCALE MODEL AND EXPERIMENTAL STUDY OF DAMAGE IN PIEZOELECTRIC FIBER-BASED COMPOSITE

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ABSTRACT

The ability of piezoelectric materials to couple mechanical and electrical properties extends its role in Structural Health Monitoring (SHM) systems where it can be used both as a sensor and an actuator. Piezoelectric Fibre Composites (PFCs) offer better integrity and higher-ductility for SHM purposes of composite structures. Nevertheless, the electromechanical behaviour of PFCs remains an open topic for research. In the current study, a micromechanical model based on transformation field analysis been used to quantify the overall material properties of electrically active composite structure, where the homogenized structural properties can be calculated. After, Finite Element Method (FEM) been utilized to study the modal behaviour of a more complex structure of PFCs Bimorph (PFCBs) based on the aforementioned micromechanical model. Furthermore, the proposed multi-scale model been validated toward an experimental modal analysis of PFCBs pristine sample. Damage been introduced to the experimental samples through introducing delamination between the PFC lamina and the supporting steel strip. Shift in the natural frequencies and the corresponding electrical response due to the delamination been reported.

KEYWORDS : *Structural Health Monitoring, Piezoelectric Fiber Composites, Modal Analysis, Delamination, Transformation Field Analysis .*

INTRODUCTION

Continuous real-time Structural Health Monitoring (SHM) systems are proposed to replace conventional inspection techniques, especially with the wide use of composite materials in engineering applications [1]. SHM systems work to incorporate active in-situ damage detection along with load monitoring where a prognostic analysis can be evaluated. SHM systems typically decrease maintenance and operational cost while increasing structures reliability [2].

Smart materials that are responsive toward external stimuli can be actively utilized as sensors. Piezoelectric materials, which couple mechanical and electrical properties reversibly, could perform the role of both a sensor and an actuator in an SHM system. Piezoelectric active wafer sensors (PAWS) attached to structures or embedded within composite laminates have been subject of many studies [3, 4, 5, 6]. Where, the advancement of processing technologies helped to improve the piezoelectric materials used in SHM systems, where piezoelectric fibers can now be embedded inside the composite structure itself for SHM purposes [1]. Integrating piezoelectric fibers in polymer-based composites form electrically active composite material with enhanced properties from the brittle piezoelectric wafers [7, 8, 9]. Many studies showed great potential of Piezoelectric Fiber Composites (PFCs) in SHM applications as well as energy harvesting applications [10, 11].

One of the most prominent techniques used in SHM is modal analysis where mechanical excitation is introduced and the natural frequencies of the damaged structure are detected using embedded sensors. The shift in the natural frequencies from the pristine structure is used to identify damage. Piezoelectric materials can perform the role of both sensors and actuators, introducing the mechanical excitation and capturing the displacement as an electric signal, for similar analysis.

Many attempts were made to provide analytical or numerical models that could predict the properties of active composites. Solutions depended on expanding inactive composite materials models starting from the early Eshelby's infinite matrix with ellipsoidal inclusion [12, 13, 14, 15]. Asymptotic expansion homogenization techniques extrapolate the electro-mechanical behavior of electrically active composite using a unit cell model to characterize an idealized periodic geometry through the governing equations of local fields [16]. Bahei-El-Din expanded on this approach to compute the overall electro-mechanical response of electrically active woven composites using Transformation Field Analysis (TFA) while accounting for damage in composite lamina [17].

In this paper, the active material properties of PFC composites used to describe the composite overall electromechanical behavior are obtained from the TFA model. Accordingly, the PFC composite is treated as a single-phase homogenous structure with coupled electro-mechanical behavior. The proposed micromechanics based approach is verified through an experimental data provided by PFC manufacturer Advanced Cerametrics Inc. [18]. Furthermore, experimental dynamic analysis is conducted on Piezoelectric Fiber Composites Bimorph (PFCB) manufactured by Advanced Cerametrics to validate the numerical response. PFCB consists of two PFC layers bonded to a stainless-steel sheet. Interested in the shifting of dynamic resonance due to induced damage, pristine samples are delaminated between the PFC layer and steel sheet and tested experimentally to quantify the shift in response. Finite element method is then implemented to quantify the dynamic response of homogenous structure, and to obtain resonance frequencies of the structure.

1 MULTISCALE MODAL ANALYSIS

1.1 Transformation Field Analysis

PFC composites consist of active piezoelectric fibers surrounded by matrix material in order to provide damage tolerance for the load applied. The fibers are unidirectional aligned longitudinally inside a resin. Transformation field analysis originally described by Dvorak, G. J. [19] to compute the local fields using micro-geometry dependent concentrations factors is employed to quantify the overall effective electro-mechanical properties of active PFC composites. Transformation field analysis represents overall response of the material through separating elastic and inelastic fields. The accuracy of the two-phase representation is affected by large variations in the transformation field, thus further subdivision for constituents is conducted through a Representative Volume Element (RVE). The RVE demonstrated in Figure 1 represents a single cell repeated throughout the material, which under an idealized assumption provide periodic arrangement. The unit cell used in this transformation field analysis is Periodic Hexagonal Array (PHA) [20].

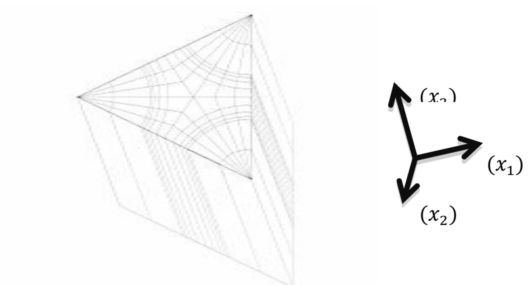


Figure 1: PHA Representative Volume element employed in TFA

Eigen stresses $[\lambda]$ and strains $[\mu]$ are used to describe transformation fields for the representative volume element. Accordingly the constitutive equations for each element in the RVE can be written to incorporate induced transformation fields due to uniform stress $[T_i]$ or strain $[S_i]$.

$$S_i = s_i^E T_i + \mu_i \tag{1}$$

$$T_i = C_i^E S_i + \lambda_i \tag{2}$$

where i represent number of elements inside the RVE [1, 2…Q]. Comparing equations with constitutive equations for PFC, the transformation fields can be attributed to an applied electric field in electrically active piezoelectric fiber-based composites.

$$\mu_i = d_i E_i \tag{3}$$

$$\lambda_i = -e_i E_i \tag{4}$$

For the RVE entity, the strains and stress caused by uniform stress or strain are super-positioned across the entire volume.

$$S_i = A_i S + \sum_{j=1,\Omega} D_{ij}\, \mu_j \tag{5}$$

$$T_i = B_i T + \sum_{j=1,\Omega} F_{ij}\, \lambda_j \tag{6}$$

where Ω is the number of elements carrying transformation fields inside the RVE, and A_i and B_i are concentration factors used to describe the volume strain and stress in terms of overall counterparts. D_{ij} and F_{ij} are constant influence functions depends mainly on the elastic moduli of each element. The TFA solution was considered for PFC composite consisting of two constituents PZT-5A and Polymer resin, the material properties of both are listed in Table 1.

Table 1: Material Properties of PZT-5A and Polymer [21, 22]

Material	E_L	v_L	d_{33}	d_{31}	d_{15}	ε_{33}
	(GPa)			$(\frac{m}{V}\, x10^{-12})$		$(\frac{C}{V.m}\, x10^{-9})$
PZT 5-A	69	0.34	374	-171	584	15000
Polymer	3.35	0.35	-	-	-	-

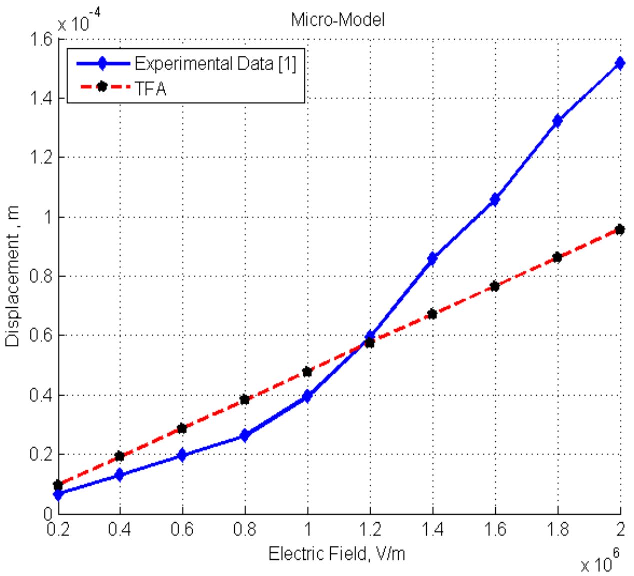


Figure 2: Experimental data compared with TFA results for mechanical deformation under applied electrical load[1]

[1]Experimental data are obtained from Advanced Ceramics Inc. data sheet for PFC-14 specimen [17]

Solving for the electromechanical behavior of PFC with d_{33} effect (where the voltage is applied along the fiber direction $[x_3]$ and the displacement is measured in the same direction for alternating voltages). As shown in Figure 2., the TFA results present purely linear behavior based on the constitutive equations for piezoelectric material, while the experimental behavior demonstrate a non-linear behavior. Both the TFA model and experimental results match well on the initial linear part of the curve with medium-high voltage applied, yet at very high voltages the experimental data starts to diverge from linear behavior.

1.2 Numerical Modal Analysis

Modal Analysis is used to predict the dynamic behavior of structures under certain loading conditions at different frequencies. At resonance frequencies the displacements become significantly higher. In the case of piezoelectric materials, the electrical output is coupled to the mechanical excitation; therefore, the mechanical resonance leads to an electrical resonance, where a higher power output can be obtained. The phenomenon is referred to in literature as electromechanical resonance where the piezoelectric impedance decreases causing a higher voltage and current output. To accurately capture both the dynamic behavior of PFCs as well as the damage effect, PFCB was modeled and validated toward the experimental results. PFCB has a d_{33} effect along the direction of the aligned fibers.

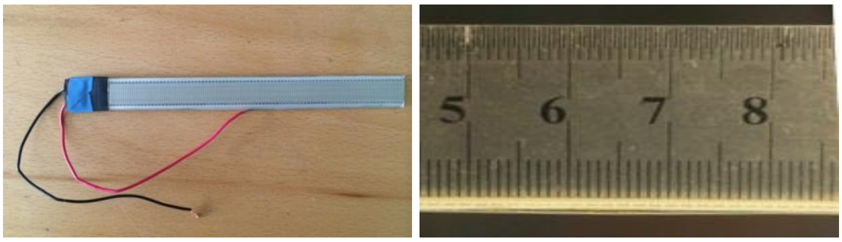
ABAQUS finite element software package [23] was used for the numerical study of the PFCB tests conducted experimentally where the FCB been treated as a single-phase homogenous structure in the finite element model. The mechanical and electrical properties of the PFCBs were extracted from the micromechanical model of the TFA presented earlier. Frequency analysis was conducted to compute the different mode shapes and natural frequencies of the PFCB at different loading and boundary conditions. The PFCB is modeled as a cantilever fully clamped from one side and free on the other sides. This is modeled as a fixed-free beam to determine numerically the mode shapes and the natural frequencies. The PFCB-14 composite is 14mm wide, 130 mm long and 1.1 mm thick, each PFC layer is 0.3 mm thick and the steel sheet is 0.5mm thick.

The natural frequencies are calculated through Lanczos eigensolver and evaluated for the first three longitudinal mode shapes. This analysis calculates the first resonance frequencies at which the electrical output will be most significant for the current study. Twenty nodes quadratic brick element was used to enhance the numerical accuracy. A mesh convergence study resulted of an optimal element size of 0.7mm and total number of elements of 11,160 to reduce the computational effort required while maintaining numerical accuracy. Numerical validation was conducted for pristine sample as presented in the next sections.

2 Experimental Analysis

In the current study, the PFCB samples were introduced to harmonic mechanical excitation that would produce output voltage to be measured. The study is limited to identifying the first three natural frequencies of electromechanical resonance for the PFCB samples. The PFCB samples were fixed to the shaker at one end leaving the other end free. This would be modeled as a fixed-free beam to determine experimentally the mode shapes and the natural frequencies by measuring spikes in the output voltage.

The experiment used the same PFCB sample obtained from Advanced Cerametrics (PFCB-14) modeled and described earlier. As shown in Figure 3, following samples were tested; first, sample in pristine condition; second, sample with a thorough delamination between the metallic strip and one of the PFC layers for; third sample with a similar delamination at both sides of the metallic strip. The mentioned delamination has a length of 28 mm and located at 50 mm distance from the tip and is introduced using a cutting device of 18 mm width and 0.5 mm thickness.



(a) **(b)**

Figure 3: (a) Pristine PFCB, damaged PFCB with one-sided delamination

A Hameg HM8150 signal generator was used with an output impedance of 50 ohms. The signal generated was used in frequency sweep mode to generate sinusoidal waves of 20 mv amplitude. The sweep range is 10-500 Hz in an incremental average of 0.25 Hz per second. The signal was amplified using Dataphysics SignalForce 100W amplifier, which was used to actuate V20 Dataphysics SignalForce shaker. The amplifier output is an AC voltage of 20 mv.

A fixture of two similar steel blocks was used (400 mm x 10 mm x 10 mm). The 2 blocks were tied together to the base of the shaker with the means of two 25 mm steel bolts. Bolts were tightened until no shift on the fundamental frequencies can be observed. The PFCB samples are held in a cantilever position leaving a distance of 130 mm from the surface of the shaker for deformation. The electric signal produced from the bimorph was directly connected to the differential analog port 1 of an NI MyDAQ kit. The output signal was viewed using the oscilloscope and the dynamic signal analysis modules of the NI ELVISMX commercial package.

3 RESULTS

3.1 Experimental Response

For the pristine PFCB sample, the electromechanical resonance were recorded at frequencies of 22.7 Hz, 150 Hz and 430 Hz; all-resulting from longitudinal vibration modes. Electrical resonances for lateral vibration modes had not been detected. Authors suggest that the twisting action has an insignificant effect to strain the piezoelectric fibers along the axis of the cantilevered PFCB samples. In other words, lateral vibrations result in a mechanical resonance without a coupled electrical resonance and will not be detected electrically.

For the one-side delaminated sample, the fundamental frequency response did not show significant shift from the pristine sample, yet, the latter natural frequencies changed significantly. Furthermore, an apparent reduction in the measured voltages at second and third natural frequencies been detected for both delaminated samples. The resonance frequencies of the one-sided delaminated sample are recorded as 22.3 Hz, 134 Hz, and 386 Hz.

The two-side delaminated sample had shown a very small frequency shifts from the single-side delaminated sample. The resonance frequencies of the PFCBs with two-side delamination are 22.3 Hz, 141 Hz, and 373 Hz. Therefore, both single and double delamination bore the same modal analysis response. The results for all samples are listed in Table 2 and presented in Figure 4.

Table 2: Results of Experimental Modal Analysis

Sample	***1st mode***		***2nd mode***		***3rd mode***	
	Frequency (Hz)	V_{rms} (v)	Frequency (Hz)	V_{rms} (v)	Frequency (Hz)	V_{rms} (v)
Pristine	22.7	8.3	22.3	7.94	22.3	8.2
One-Sided delamination	150	5.2	134	1.6	141	1.64
Two-sided delamination	430	0.56	386	0.26	373	0.25

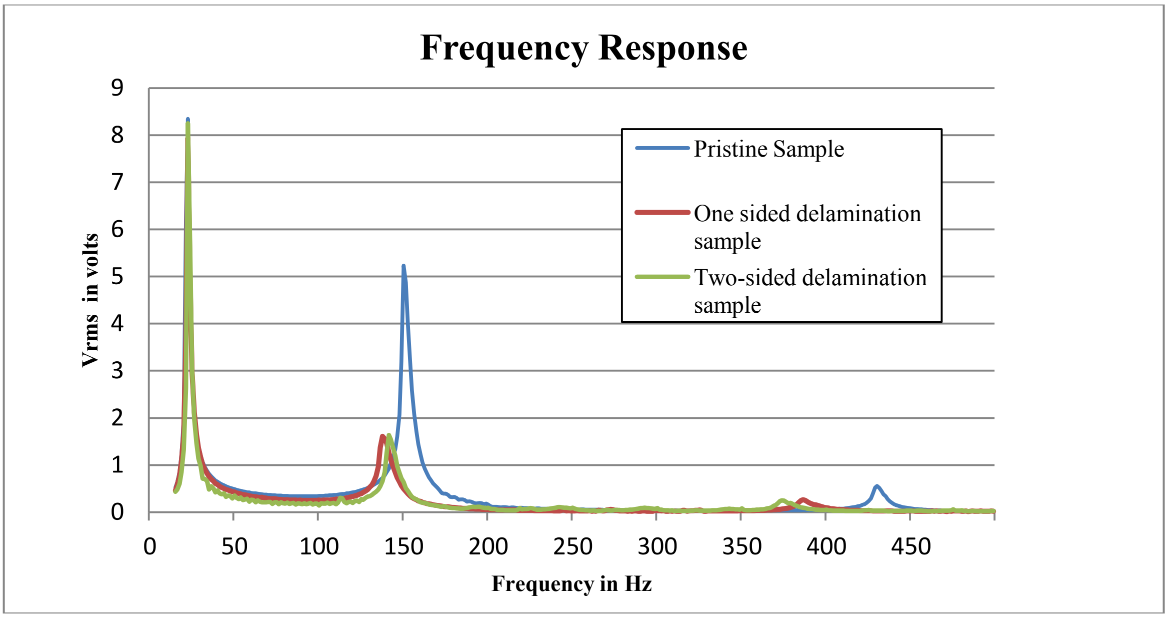


Figure 4: Frequency Response of Pristine Sample against damaged sample with both one-side and two-side delamination

3.2 Numerical response

The response calculated through the FEA frequency analysis is comparable to the experimental response shown in Section 3.1. The computed dynamic behavior of the PFCBs is demonstrated in Figure 5 for the first three longitudinal mode shapes and the corresponding resonance frequencies occurring at 25.22 Hz, 157.56 Hz and 439.67 Hz. The resonance frequency obtained from the experimental and the numerical are listed in Table 3.

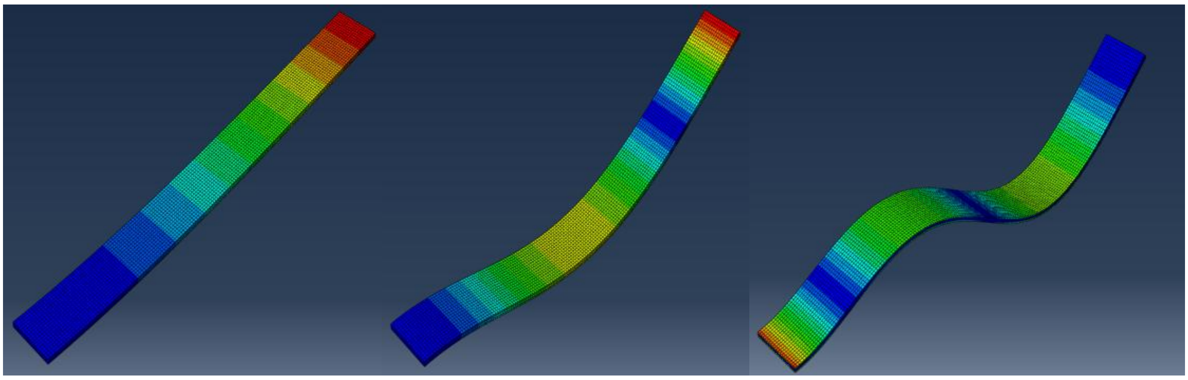


Figure 5: First three mode shapes of PFCB-14W at 25.22, 157.56 and 439.67 Hz, modeled using ABAQUS.

Table 3: Comparison between the experimental and numerical response

Mode	First	Second	Third
Experimental [Hz]	25.22	157.56	439.67
Numerical [Hz]	22.7	150	430

CONCLUSION

In the current study a multi-scale approach been utilized to extract the behavior of composite structures with electrically active fibers. The model demonstrated proper approximation of the experimental results. Both models, the micro-scale (TFA) model and macro-scale (FEM) model, been successfully utilized through a hierarchal approach; accuracy is increased substantially with fiber-fiber interaction scheme of the TFA in micro-scale and the structural response of the composite is extracted in macro-scale which allows a significant reduction in the computational cost at the macro-scale and therefore enables the modeling of more complex geometry and structures through the proposed multi-scale approach.

The experimental finding shows that delamination detection is possible using modal analysis. The shift is minimal for the first mode of vibration and increase significantly for higher modes. However, the changes in the amplitudes at later modes are significant and needs further study.

One-side and two-side delaminated PFCB samples yielded a very close frequency response. This indicated that other diagnostic methods should be employed to provide more detailed SHM database for damage identification.

The proposed multi-scale model along with other diagnostic methods can be further expanded to include damage characterization through proper implementation of Genetic Algorithms (GA) and Neural Networks (NN) algorithms for damage detection and identification [24].

REFERENCE

[1] D. Balageas, C. Fritzen and A. Güemes, Structural Health Monitoring, Wiltshire: ISTE Ltd., 2006.

[2] I. Chopra, "Review of State of Art of Smart Structures and Integrated Systems," *AIAA,* pp. 2145-2187, 2002.

[3] E. Crawley and J. de Luis, "Use of Piezoelectric actuators as elements of intelligent structures," *AIAA,* pp. 1373-1385, 1987.

[4] V. Giurgiutiu and C. Rogers, "Recent Advancements in the Electro-Mechanical (E/M) Impedance Method for Structural Health Monitoring and NDE," *Annual International Symposium on Smart Structures and Materials,* pp. 3329-3353, 1998.

[5] A. Zagrai and V. Giurgiutiu, "Electro-Mechancial Impedance Method for Crack Detection in Thin Plates," *Intelligient Materials systems and Structures,* pp. 709-718, 2001.

[6] V. Giurgiutiu and A. Zagrai, "Embedded Self Sensing Piezoelectric Active Sensors for On-line Structural identication," *Vibration and Acoustics,* pp. 116-125, 2002.

[7] W. A. Smith and B. A. Auld, "Modeling 1-3 Composite PIezoelectrics: Thickness-Mode Oscillations," *Ultrasonics, Feroelectrics, and Frequency Control,* vol. 38, pp. 40-47, 1991.

[8] A. A. Bent, N. W. Hagood and J. P. Rodgers, "Anisotropic Actuation with Piezoelectric Fiber Composites," *Intelligent Material Systems and Structures,* vol. 6, pp. 338-349, 1995.

[9] R. B. Williams, G. Park, D. J. Inman and W. K. Wilkie, "An overview of Composite Acutators with Piezoceramics," in *Proceeding of IMAC XX*, 2002.

[10] H. A. Sodano, G. Park and D. J. Inman, "An investigation into the performance of macro-fiber composites for sensing and structural vibration applications," *Mechanical Systems and Signal Processing,* no. 18, pp. 683-697, 2004.

[11] A. E. El-Etriby, M. E. Abdel-Meguid, T. M. Hatem and Y. A. Bahei-El-Din, "A Multiscale-based Model for Composite Materials with Embedded PZT filaments for energy Harvesting," in *Proc. SPIE 9058, Behavior and Mechanics of Multifunctional Materials and Composites*, San Diego, 2014.

[12] J. D. Eshelby, "The determination of the elastic field of an ellipsoidal inclusion, and related problems," *Royal Society of London,* pp. 376-396, 1957.

[13] T. Mori and K. Tanaka, "Average stress in matrix and average elastic energy of materials with misfitting inclusions," *Acta Metallurgica,* pp. 571-574, 1973.

[14] M. L. Dunn and M. Taya, "Micromechanics Predictions of the Effective Electroelastic Moduli of

Piezoelectric Composites," *International Journal of Solids and Structures,* pp. 161-175, 1993.

[15] J. Y. Li and M. L. Dunn, "Micromechanics of Magnetoelectroelastic Composite Materials: Average Fields and Effective Behavior," *Intelligent Material Systems and Structures,* pp. 404-416, 1998.

[16] S. Kari, H. Berger, R. Rodriguez-Ramos and U. Gabbert, "Numerical Evaluation of Effective Material Properties of Transversely Randomly Distributed Uniderctional Piezoelectric Fiber Composites," *Intelligent Material Systems and Structures,* pp. 361-371, 2007.

[17] Y. A. Bahei-El-Din, "Modelling electromechanical coupling in woven composites exhibiting damage," *Aerospace Engineering,* pp. 485-495, 2009.

[18] Advanced Cerametrics Inc., "PFCB Material Datasheet," [Online]. Available: http://www.advancedcerametrics.com/products/energy-harvesting/piezoelectric-fiber-composites/.

[19] G. J. Dvorak, "Transformation field analysis of inelastic composite materials," *Proceeding of Royal Society,* pp. 311-327, 1992.

[20] J. L. Teply, "Periodic Hexagonal Array Models for Plasticity Analysis of Composite Materials. Ph. D. Dissertation," University of Utah, 1984.

[21] Y. A. Bahei-El-Din, R. Khire and R. Hajela, "Multiscale transformation field analysis of progressive damage in fibrous laminates," *Multiscale Computational Engineering,* pp. 69-80, 2010.

[22] D. Berlincourt, H. H. A. Krueger and C. Near, "Technical Publications 226: mportant Properties of Morgan Electro Ceramics Piezoelectric Ceramics (PZT-4, PZT-5A, PZT-5H, PZT-8)," Morgan Electro Ceramics, 2013.

[23] Simulia, "ABAQUS 6.10 Documentation".

[24] T. M. Hatem, M. N. Abuelfoutouh and H. M. Negm, "Application of Genetic Algorithms and Neural Networks to Health Monitoring of Composite Structures," in *Proceedings of the Second European Workshop on Structural Health Monitoring*, Munich, Germany, 2004.