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Review of composite–laminated material analysis in MATLAB using Peizo – electric sensor and actuator.

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ABSTRACT

The current review covers numerical analysis using the MATLAB program for multi-layer composite materials. Which involves studies related to the intersection with fibers, between layers and piezoelectric layers or patches. It has been reported that using MATLAB program has great flexibility in analysis due to its library which includes various numerical methods. In addition to programming and developing the finite element technology to calculate the stress and strain in each layer based on different deformation methods such as (FSDT and HSDT), to obtain mechanical properties. It has been claimed that there is a deviation in results between MATLAB and Ansys for the same 20-layer composite material. Using MATLAB in dynamic analysis in various methods such as Newmark, Rayleigh damping, Timoshenko, and Euler-Bernoulli exhibit good agreement with natural frequencies and mode shapes. Moreover, MATLAB is useful for the real-time process of data acquisition to deliver a digital model of a composite material coated with a piezoelectric plate and is an ideal material for sensing, detecting, and controlling vibration inhibition.

1. Introduction

MATLAB software is already used to analyze multilayered composite material and to compute the stress and strain developed in each layer of laminated composite beam reinforced by carbon fiber, as shown in Fig. 1. Using MATLAB software to calculate the stiffness of every layer and the stress of every layer under an axial loading at the centroid of the beam shows an excellent agreement with analytical expression [1,2,3]. The normal load effects on layers with various orientations were studied by Balcı et al. [4], and a code of MATLAB was expanded to define the analysis for stresses and strains support on classical lamination. In comparison with experimental results, a great verification and correction for the stress values was achieved in the direction of loading.

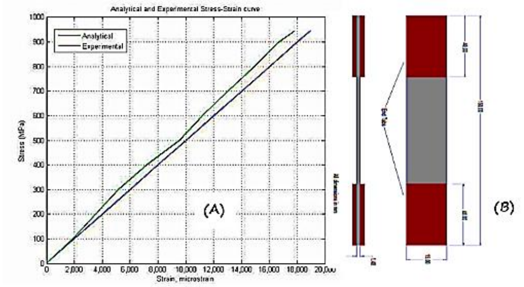

Figure 1. (A) The analytical solution results in the MATLAB approach to the experiment-logged data. (B) specimen [1]

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Currently, the combination of lightweight with high or acceptable durability structures has become a prime concern of designers because they are widely accepted by controlling the ratio of high stiffness to weight. The role of MATLAB here is useful for calculating the solution and obtaining design results that are useful in practical applications. In addition to the flexibility in performing numerical analysis under the effect of parameters with the different support conditions, laminate diagrams, and layered orientations. Using MATLAB for analysis of plate elements with four quadruple nodes and every node has 5 DOF, the model of a finite element was coded in Matlab formatting as in [5, 6] depending on the 1st degree of shear deformation theory (FSDT).

Tapered composite beam model analysis was developed by Gayen et al. [7] using the MATLAB software to compute distributions of stress (such as the stresses in the axial direction of the in-plane and the shear stresses between the laminates) in symmetric and asymmetric multi-layer composite beams with circular tapered cross-section obey to hygro-thermal loads and the compositions were validated using solutions available in the literature. The thermal loads are a linear function of the coordinates in the levels of every layer. A stress calculation was developed as shown in **Fig. 2** based on conventional lamination modification and parallel axis theories.

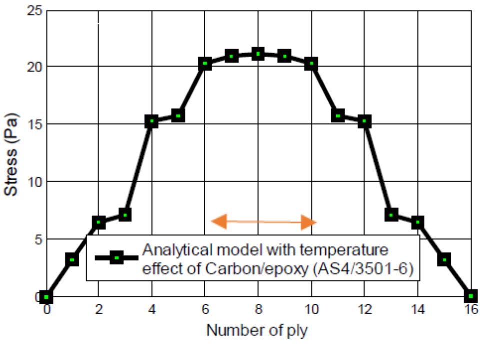

Figure 2- The researcher in [7] illustrated the behavior of shear stress distribution of the inter-laminar composite beam.

2. Dynamic Analysis

Based on the classical theory of the laminated plate, the three-dimension finite element model is used in conjunction with the integration method (Newmark) to find the damping response of the asymmetric composite beam. A Matlab code is written in [8, 9], which was developed to implement dynamic analysis (Rayleigh damping) for different damping ratios of the responses of the movable load, step, and impulse functions with which researchers tested the composed material of the beam. The dynamic beam response is formulated as a dynamic magnification operator which is got from the static and dynamic displacements in the midpoint.

The Matlab code is used to process significant factors, for example, displacement and quickness responses of the composite beam for various buckling loads with constant velocity, and the directions of the lamina, the impulse unit, and step unit reactions of the pined–pinned supports are introduced for different damping proportions and contrasted and dynamic examination of the anisotropic aluminum beam execution. The product code was created by the researcher in Lee [10] utilizing the Matlab 6.5 programming to locate the 1st and 2nd mode shapes and normal frequencies corresponding to the delamination composite beams. This code incorporates a finite element investigation of free vibration of the clamp-free boundaries also with pinned–pinned symmetric beams in various lay-up arrangements. The free vibration reactions of the laminated beams are considered utilizing the Euler-Bernoulli beam and classical lamination hypotheses. PC Matlab code was created to inspect the impacts of the width and area of the delamination, the layer direction, and the sort of limit condition on the natural frequency. While working with Miranda [11], several application tools were created in Matlab programming. Which are utilized uncovered key parts of this software and extraordinarily expanded the nature of examination time. Which is posted here for thick composite packages. For thin beams, Timoshenko and Euler-Bernoulli-based models are also provided results that are consistent with distributed logical information, and since they expend less calculation time, one can conclude that in these statuses it is not important to utilize more mind-boggling hypotheses. Concerning the expectation of dynamic conduct, the higher shear deformation hypothesis gave a few preferences to the next two speculations, particularly for higher-vibration patterns. The work in Miranda [11] comprises the improvement of three finite element models dependent on the higher-order shear deformation hypothesis for static and dynamic investigation of laminated beams. Fifteen case studies were studied for various loads and support conditions. The software Matlab has been approved computing tool, in keeping with its largest academic importance. Again, Matlab programming was constructed using a rectangular isometric plate element in Binh et al. [12] with 5 DOF per node depending on the Mindlin-plate method to obtain a numerical bending and result and analysis of vibration for the non-reinforced and rigid folded composite laminated plate by using the finite element procedure. A great arrangement was established between the results of this strategy and other distributed results reachable in the writing. The finite element technique was examined utilizing plate elements with eight-nodded isoperimetric, relying on the 1st order shear deformation technique to analyze the transient responses and vibration of the stiffened and un-stiffened folded composite plate covers by considering the various parameters. Concerning the expectation of dynamic conduct, the higher shear deformation hypothesis gave a few preferences to the next two speculations, particularly for higher-vibration patterns. The work in Miranda [11] comprises the improvement of three finite element models depending on the higher-order shear deformation hypothesis for static and dynamic investigation of laminated beams. Fifteen case studies were studied for various loads and support conditions. The software Matlab has been approved computing tool, in keeping with its largest academic importance. Again, Matlab programming was constructed using a rectangular isometric plate element in Binh et al. [12] with 5 DOF per node depending on the Mindlin-plate method to obtain a numerical bending and result and analysis of vibration for the non-reinforced and rigid folded composite laminated plate by using the finite element procedure. A great arrangement was established between the results of this strategy and other distributed results reachable in the writing. The finite element technique was examined utilizing plate elements with eight-nodded isoperimetric, relying upon the 1st order shear deformation technique to analyze the transient responses and vibration of the stiffened and un-stiffened folded composite plate covers by considering the various parameters.

Lateral shear deformation, plate rotation inertia, and stiffening techniques are known to be the most advanced in the model presented by researchers. Several examples of models in Belarbi et al. [13] have been analyzed with the expectation of complimentary vibration examination of laminar and sandwich plates to exhibit the presentation and flexibility of the finite element model created utilizing the Matlab code that is utilized to tackle the eigenvalue issue. The results of the numerical solution obtained were compared with past results of exact and finite element solutions. Al-Tabey [14] obtained the first six of the mode shapes and natural frequencies of the rectangular composite plate laminated symmetric angle-ply with simple and free boundaries (S-S-F-F) using a transition matrix of a finite-strip technique. The plate thickness is uniform on the x-axis while the thickness varied on the y-axis. It was imposed that the simply supported boundaries in the direction of the thickness that change but at the other direction approximated free. The obtained results using Matlab validate the proposed technique for the classical boundary of simply support free end (SSFF) at the plate edges. **Fig. 3** shows the mode shapes for the first two basic frequencies separated in two columns of this figure drawing, the first column shows in surface form the mode shapes and the second one shows the surface plate mode shapes as a contour.

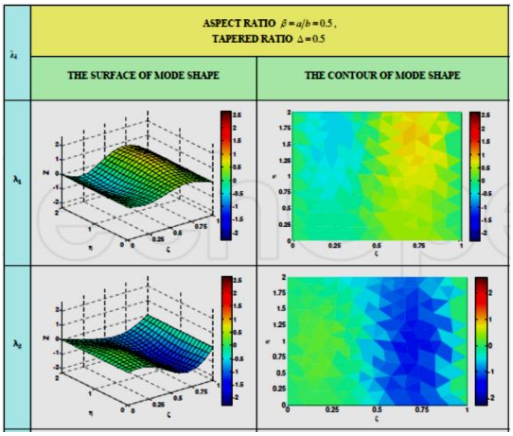

Figure 3 - The first two natural frequencies of the symmetric rectangular laminated plate and mode shapes with variable thickness of the rectangular laminated plate [14].

The plan engineers of laminate composite material under the best stacking sequence and optimum angles of the fiber in every lamina add to the number of layers (lamina) itself dependent on criteria, for example, accomplishing the highest natural frequencies or the biggest load of buckling. The composite materials analysis model is used for the estimation of the resultant properties of the material based on classical and numerical theory such as finite element techniques. The method of estimated properties is utilized for calculating the dynamic properties of the members comprised of these materials as identical isotropic members. Across this level, a graphical user interface tool in Jones [15] was created utilizing Matlab software to create an easy-to-use environment for computing the properties of total materials, where users can enter the orthotropic properties with the number of layers, and the software computes the bending, expansion, and the matrices of coupling stiffness, besides, gauges the density, in total elastic constants, and Poisson proportions. The constants results acquired from Matlab programming are approved utilizing the ANSYS program, in which the stacking of laminar sequence is built and the member is exposed to uniform strain at the end of free support, while the response of stress is normal at the fixed end.

The updated interface improves the design process to some reach. The dynamic investigation is shown regarding the fundamental natural frequency and the basic buckling load utilizing these general physical constants as a later aspect of the examination.

Furthermore, MATLAB has ideally suited for the formulation of the matrices which is extensively used to represent the mechanical behavior of composite materials. Moreover, graphic interfaces provide an efficient way to use as in article by Barton et al. [16] deals with the topics presented in a US Naval Academy course in composite mechanics and provides an overview of the MATLAB code that performs the analysis including topics of deflection analysis, stress, and strain distribution, and stiffness analysis. MATLAB provides a powerful platform for performing desired matrix calculations and provides an efficient graphical tools interface, employing menu commands, to execute the program. Using MATLAB, m-files are created to perform a specific part of the computation, basic stress analysis, for example, and then they are grouped using menu commands that provide a graphical interface. The article provides an extension of the study conducted by Sigmund Lee et al. [17] with a 99 line following the optimized command topology written in Matlab. The element stiffness matrix for the level stress problem was written with isotropic materials in lines 86-99 and was changed to the application of orthotropic and laminated composites. Matlab code was given for the matrix, representing the stiffness of the laminated composite, and numerical case study examples were provided to show the change from isotropic material to the laminated and orthotropic composite plates to improve the topology. The work in paper Ramsaroop et al. [18] manages the production of MATLAB text records that help the user in planning a composite layer to work in safe conditions. Program inputs are material properties, material cutoff points, and stacking conditions. Conditions identified with Hooke's law for the two-dimensional composites were utilized to process worldwide and neighborhood strains and weights on each layer. The structure disappointment examination was performed through the Tsai-Wu disappointment hypothesis. The program yields the ideal number of fiber layers that are needed for the composite lamina, just as the direction of every lamina. Matlab was used in the optimization theory to find the best design dimensions. The effect of force on hybrid composites was the aim of the Study by Bhingare et al. [19], using the Matlab Finite Element Analysis theory. The element used for analysis is an eight-nodded iso-parametric. At each node, five degrees of freedom are considered which are three displacements and two rotations. The fraction of glass fiber is replaced by carbon fiber to see the effect on the strength of the composite plate. Symmetric glass/epoxy and glass/carbon/epoxy composite lamina of different orientation angles like (0/0), (45/0), and (90/0) are used for analysis purposes, and stress values are found. For the study, hybrid composites are considered which is made from E-glass, Carbon, and Epoxy with different orientations to get the stress values of the plate under uniformly distributed transverse load. In other studies, such as [20, 21, 22], the resulting deflection in constructs was calculated using Matlab code to solve linear algebraic problems where the solution procedure was implemented using the generalized differential square (GDQ) technique in MATLAB code. The shear stresses and normal stresses subsequently evaluated with the present methodology agree well with the results get from semi-analytical and numerical techniques. The terms of the geometric boundaries of the plate are determined by the same agreement presented in the works. Finally, the Matlab function was used to avoid numerical instability in order to numerically evaluate the elastic geometric stiffness relationships Tornabene et al. [23].

3. Smart Composite Materials

In smart composite studies, Matlab was used to validate the results obtained with ANSYS software for the symmetrically laminated composite plates with simply supported which were subject to a uniformly distributed load and following the classical lamination theory. Where the validation of the results of the analysis was for the same plate consisting of 20-ply, in addition to this the influence of the stacking sequence on the bending stiffness was revealed in [24- 26]. It should be noted here that one of the advantages of MATLAB is also the ease and apparent flexibility of entering the material properties of each layer through the MATLAB code, as the code is entered for only five physical constants in this research, compared to the program ANSYS, which requires nine inputs for material properties at the same analysis. By focusing on the researcher publishing Adviser et al. [24], it was discovered that a major mistake proportion between the Matlab programming and ANSYS deviation results is identified with the matrices estimations of D16 and D26 don't contain zeros for the layers angles not 0º or 90º, and in this way, the covering differential equation was changed. However, the researchers in [27, 28] obtained a numerical model of a covered composite beam with piezoelectric lamina, for example, Polyvinylidene fluoride (PVDF) which from the outset was found by Kawai et al. [29]. Because of its special properties, for example, flexibility, durability, workability, and so on, PVDF is a perfect material for sensing, detecting, and damping control of vibration as in **Fig. 4** of distributed parameters, such as beams, plates, shells … etc.

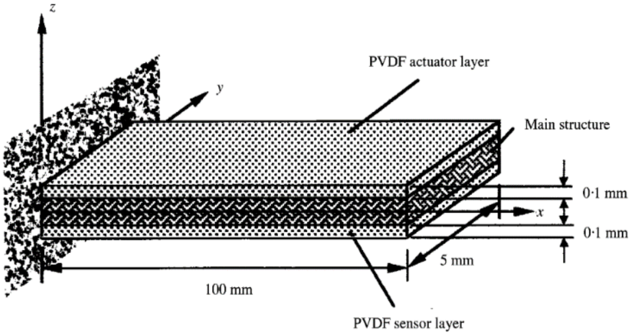

Figure 4. A composite beam stacking layer with a piezoelectric lamina for sensing and actuation [28].

The constitutive equations in [28] including the piezoelectric-electric layer concerning the plane of the laminate coordinates are

$$\{\sigma\}_k = [\bar{Q}]_k\{\varepsilon\}_k - [\bar{e}]_k\{E\}_k \quad (1)$$

$$\{D\}_k = [\bar{e}]_k\{\varepsilon\}_k - [\bar{g}]_k\{E\}_k \quad (2)$$

Where:
$\{\sigma\}$, $\{\varepsilon\}$ are stresses and strains in vector form,
$\{D\}$, $\{E\}$ are conductor vector of the electrical displacement, and electrical field vectors,
$[\bar{Q}]$, $[\ \bar{g}\ ]$ are the constants of elasticity, and permittivity matrices, respectively,
$[\bar{e}]$, $[\bar{e}]^T$ are piezoelectric constant and its transpose.

The above two equations illustrated the inverse and direct piezoelectric effects, respectively. Anisotropic properties of this model that possess the piezoelectric materials as shown in Fig. 4. The PVDF is chosen as a sensor material and at the same time actuator [30, 31]. It is possible to design a control system with a variable vibration amplitude of the beam by negative velocity feedback control gain as graphical results, using Matlab proved that the feedback control system can be used to suppress the vibration of the laminated beams and appears good control through the temporary response of the laminate beam during examination with using Matlab in the study [32, 33]. The damping of epoxy reinforced by carbon fiber of composite beams was measured experimentally by a piezoceramic (sensor and actuator type) and was compared with the theoretical estimation. Good agreement of damping ratio, and the basic frequency of the finite element modeling with those of the measured values by the piezoceramics considering that the adhesive layer has stiffness and damping impact, for example, the concentrated in [34-36]. The characteristic damping coefficient of the model structure is an important performance index to control the vibration of the structure than the damping ratio (ζ). Also in Baillargeon et al. [37], the piezoelectric embedded as a shear actuator type was used to control or to dissipate the vibration of laminated composite plates. While maximizing the controllability index to specified optimized Sitee for the actuator patch of a Macro-Fiber-Composite (MFC) type. The Linear Quadratic Regulator (LQR) approach is used in [38-39], to model the interaction between the MFC and the active substance structure as one of the laminar layers.

Finally, the software Matlab has been analyzing a smart laminated plate based on the inverse hyperbolic shear deformation theory (IHSDT) to create a finite element approach text code in Matlab software used to analyze of bending and buckling of a smart composite plate.

The approval of as of late created (IHSDT) demonstrated a smart composite structure by the examination in [40-44] and numerical problems indicating the varieties in the buckling behavior of a smart composite plate for different parametric varieties are introduced. Additionally, in this study, a numerical example of control on the deflection and buckling load capacity is introduced as an inner defect of stacking layers of composite plates. A comparison study considers portraying the viability of utilizing a piezo patch only at the center rather than piezo-layers are additionally introduced. The above-mentioned applications in this section and the preceding sections demonstrate the commitment of the current work to a useful review that clarifies the importance of the MATLAB program in analyzing stratified compounds.

Piezoelectric macro fiber composite (MFC) integration enables energy harvesting, sensing, and operation, with existing applications in space, automotive and renewable energy. There is a gap present in the literature on dynamic response modeling of piezoelectric vibration energy harvesting (PVEH) concerning real-world vibration data Jia et al. [45]. Most of the simulations were either semi-analytic MATLAB models not specific to geometry, or basic finite element simulations limited to sinusoidal analysis. However, the use of representative environment vibration data is critical to predicting the practical behavior of industrial development. The physics of piezoelectric devices that include solid mechanics and static electricity was combined with the electrical circuit defined in this finite element model. The structure was dynamically simulated using interpolated vibration data files, while the orthotic material properties of the MFC and the carbon fiber composite were individually determined for accuracy Lahoti et al. [46]. And Singh et al.[47] computed the geometric distortion of the smart jacket plate structure across the Green-Lagrange strain field including all higher-order nonlinear terms. Desired responses are evaluated mathematically using native computer code in the MATLAB environment with the help of the current top-order model and finite element steps. The nonlinear dynamic deflection values are obtained through the direct iterative method combined with Newmark integration. Besides, the accuracy of the proposed model is demonstrated by a comparative study with available published literature with and without electric field potentials.

In a study Rouzegar et al. [48], a finite element formula was developed for forced vibration analysis of viscoelastic flexible composite panels combined with a piezoelectric layer based on the four-variable redundant plate theory (RPT). Using RPT of both thick and thin plates with equality of variance of transverse shear stresses across layer thickness, the dynamic behavior of the smart flexible viscoelastic plate was studied.

Optimal designs are applied to surface pressures, where the substrate-actuator composite is robust enough to preserve shape but allow for the desired curvature under excitation. In applications where dynamic pressures are high, this trade-off restricts substrate-to-actuator thickness ratios. One way to improve actuation authority while maintaining stiffness is to use multiple piezo composite actuators. A review of the potential for new design space for multilayer actuators is presented in Wright et al. [49] which explores the benefits and drawbacks of using multilayer piezo composite actuators with a four-point loading condition, the actuators are modeled using the finite element method and are described using well-known free strain and blocked force conditions. On multilayer piezo composites with different thickness ratios, substrate content, and multiple piezo composite layers, a parametric analysis is carried out in the form of maximum curvature, work is done, by several layers, and results for the parametric analysis are provided.

Smart laminated composite structure (bonded with shape memory alloy; SMA) thermal buckling energy, numerically analyzed via a higher-order finite element analysis in combination with marching technique. The excess geometric distortion of the structure was established by Green's strain function under the elevated environment, although the material nonlinearity counted with the help of the marching procedure. The process results are values received by calculating the generalized eigenvalue equations via a customized Matlab Katariya et al. [50]. The comprehensive behavior of the present finite element implementations (least buckling load parameter) is calculated by solving an adequate number of numerical incidents, including the specified input parameter. The current numerical model is further enhanced to evaluate and report in detail the influence on the buckling temperature of different geometry parameters of the sandwich panel, including the SMA effect.

Due to their capacity to show large displacements and create complex structures, autonomous multilayer systems are the subject of recent studies. These devices have been designed with active materials that respond to diverse stimuli, including electrically active and magnetic materials, to perform useful functions and achieve a range of target shapes compared to monophonic/dichromatic structures. However, it is time-consuming and expensive to produce these tools for experimentation, ensuring that simulation is used as a means to build systems with high performance.

These systems are optimized to satisfy the specifications of applications like clutch soft robotics. A genetic algorithm developed by MATLAB for various objective functions induces a multi-objective optimizing problem and the execution of an optimization problem in a case study. In the case study Erol et al. [51], optimization outcomes are examined by analyzing the alternative designs of the optimization problem on the Pareto interaction. Different trade-offs are calculated between the thematic roles, and, depending on application demands and preferences, different feasible designs are considered to be more desirable than others.

The research study in Keshtkar et al. [52] aims to understand, by developing a theoretical model of the system, the behavior of fiber-reinforced elastomers integrated with shape memory alloy (SMA) wires. Two distinct models are derived, one to understand the SMA wire actuator dynamics and the other to describe the composite bending dynamics. Models are then combined to analyze the system behavior fully. In MATLAB / Simulink, numerical simulations of the mathematical model are performed and the simulation results are experimentally validated. To regulate the shape, deflection, and twisting of a system, the model obtained can be used to design control algorithms.

4. Conclusion

The main conclusions have been drawn from using Matlab in modeling laminated composite materials at different paraameters are the following :

It is found that creating and developing modelling programs by Matlab is not complicated. In specific areas on the smart composite plates, suppress vibrations and control both the bending and twisting of laminates of the composite plate have been done with helping of piezoelectric layers and also in sensing the deflection, bending, and stress. It is observed that composite materials can be used in advanced applications such as smart composite materials and take advantage of the Matlab program as an effective tool in real-time applications.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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