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CARBON NANOFIBER - REINFORCED MULTIFUNCTIONAL SHEET INTEGRATED WITH PIEZOELECTRIC CRYSTAL: AN OVERVIEW OF STRUCTURAL BEHAVIOR ANALYSIS METHODS

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Abstract: Most of the phenomena in life, such as heat transfer, wave propagation, thermoelectricity, sheet materials, multifunctional material properties, etc., can be expressed through mathematical equations or partial differential equations (PDEs). However, with complex differential equations, it is difficult or impossible to find solutions, especially differential equations for complex problems such as solid-liquid interactions, mechanical-thermal-electrical environments, and functional material plate environments in the multiphysics environment, etc. Since then, many numerical methods have been researched and developed to find approximate solutions to partial differential equations. Today, the finite element method (FEM) is the most widely used and effective among the commonly used numerical methods. However, with the continuous emergence of new complex problems in science and technology, especially problems in the multiphysics environment in sheet-material structures, the finite element method has revealed new challenges. There are certain limitations related to the element technique and the weak form discretization of the problem of sheet structure with many different degrees of freedom, significantly affecting the accuracy and efficiency of calculations. Therefore, it is always important to propose improvements to the traditional finite element method and the optimal method algorithm to meet the increasing requirements in the behavior analysis of sheet materials. This research direction is always topical and has received the attention of scientists around the world for many decades.
Keywords: Carbon nanofiber (CNFs), Multifunctional sheet, Piezoelectric crystal, Finite Element Method (FEM), Optimization

I. INTRODUCTION

The multiphysics environment in the sheet structure has many properties, which can be mentioned as coupling electrical and mechanical properties; material properties vary from the top surface of the sheet to the bottom of the plate along with the plate thickness, hardness, and high strength, good moisture resistance, etc. [1-3]. Common materials used in sheet structures are piezoelectric, shape memory alloys, carbon nanotubes, magnetostrictive materials, etc. In this study, it is proposed to choose two types of materials for analysis:

First, carbon nanofiber materials developed by Iijima [4] are considered materials for the 21st century [5], studied and applied in many engineering disciplines [6, 7]. Second, piezoelectric materials made by Pierre Curie and Jacques Curie are the most common materials in the smart materials layer. The most important property of piezoelectric materials is transforming mechanical energy into electrical energy under mechanical load and vice versa, i.e., converting electrical energy into mechanical energy under the act of voltage. This is known as the converse phenomenon of the piezoelectric effect. Applications of plate behaviour analysis can be found in many different fields such as aviation, energy generation, construction, marine engineering, drilling rigs, motorsports, etc., defence works or applications in biomedicine, chemical technology, etc.

Piezoelectric materials belong to the class of smart materials because of the integration of simultaneous electromechanical phenomena. The development of smart structures integrated with sensors and actuators has been widely applied in life, such as in the automotive industry, electronics industry, telecommunications, noise reduction control, structure vibration reduction, etc. Hong and Chopra [8] used the piezoelectric layer back-effect property for the multilayer plate problem for static and free vibration analysis. The influence of the mass matrix and the stiffness of the layers on the free vibration frequency and the shape of the free vibration pattern were studied by Yang and Lee [9]. Kim et al. also investigated a comparison between experimental results and numerical simulation results using FEM for the piezoelectric sheet problem [10]. The piezoelectric shell model was also studied by Pletner and Abramovich [11]. Willberg and colleagues [12] approach to model 3D piezoelectric objects using isogeometric finite elements. Wang et al. [13] used FEM to analyze the stability of piezoelectric patch composite panels, where the Lyapunov energy function [14] was used to establish the governing equations of motion of the plate. Ray and Mallik [15] used FEM to analyze piezoelectric fiber-reinforced composite panels. Besides, FEM has also been used to analyze plate and beam structures reported in [16-24].

Many theories have been developed for the class of problems controlling the vibrations of piezoelectric plates, which can be divided into two main groups: the analytical methods and the equivalent single-layer theories. As for the analytical method, Bailey et al. [25] and Shen et al. [26] studied composite beams integrated with piezoelectric layers using analytical solutions. Tzou and Tseng [27] used 3D elements to control piezoelectric shell and plate oscillation.
For equivalence class theory, the three most popular theories can be mentioned: Classical Lamination Theory (CLT), First-order Shear Deformation Theory (FSDT), and High-order Shear Deformation Theory (HSDT). In the CLT theory, based on the hypothesis of Kirchhoff plate theory, the shear strain between the layers in the composite sheet is ignored. In this theory, Hwang and Park [28] analyzed the piezoelectric plate time response using the discrete Kirchhoff quadrilateral (DKQ) element and the Newmark method under the influence of velocity feedback control. The radial point interpolation method (RPIM) incorporating CLT was used to analyze piezoelectric panel response and was reported by Liu et al. [29,30]. Suleman and Venkayya [31] used CLT based on a four-node tetragonal element incorporating an integral point reduction technique to analyze the static response of the piezoelectric plate. Victor et al. [32] have developed a high-order element formula combining analytical solutions to investigate the response of composite panels integrating sensors and actuators. Liew et al. [33] studied the post-buckling of piezoelectric panels using CLT and RPIM.

II. THEORETICAL BASIS

A. Characterisics of Material

A-1. Introduction of Composite materials

Composite materials are formed by integrating two or more materials to give outstanding mechanical properties such as high strength, good corrosion resistance, etc. [34]. Most composite materials are fiber, reinforcement, and matrix material. Composite materials can be divided into three common types as follows [34]
Type 1: fibrous composites
Type 2: particulate composites
Type 3: laminated composites
In this study, a third type is proposed, shown in Fig. 1 in the mechanical behavior analysis of the structure. In Fig. 1, symbols I, II, III, and IV represent different layers with different materials or fiber orientations.

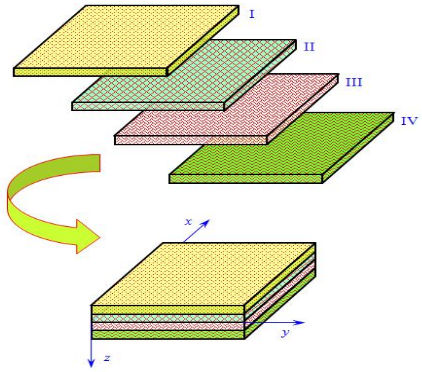

Fig. 1 Multilayer composite material structure

Hooke's law for anisotropic materials has the form:

$$\sigma_i = Q_{ij}\varepsilon_j \tag{1}$$

A-2. Carbon nanofiber reinforced functional materials

In carbon nanofiber-reinforced functional materials, four distributions of carbon nanotubes (CNTs), including UD, FG-V, FG-O, and FG-X are shown in Fig. 2.

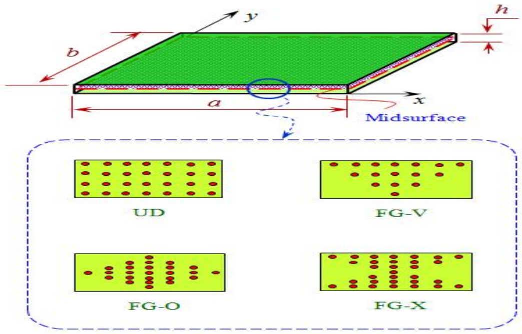

Fig. 2 Distribution of CNTs

Characterisics of Material [35]:

$$E_{11} = \eta_1 V_{CNT} E_{11}^{CNT} + V_m E^m \tag{2}$$

$$\frac{\eta_2}{E_{22}} = \frac{V_{CNT}}{E_{22}^{CNT}} + \frac{V_m}{E^m} \tag{3}$$

$$\frac{\eta_3}{G_{12}} = \frac{V_{CNT}}{G_{12}^{CNT}} + \frac{V_m}{G^m} \tag{4}$$

The distribution of CNTs along the plate thickness is determined by [36]:

$$V_{CNT} = \begin{cases} V_{CNT}^* & \text{(UD)} \\ (1+\frac{2z}{h})V_{CNT}^* & \text{(FG-V)} \\ 2(1-\frac{2|z|}{h})V_{CNT}^* & \text{(FG-O)} \\ 2(\frac{2|z|}{h})V_{CNT}^* & \text{(FG-X)} \end{cases} \tag{5}$$

A-3. Piezoelectric materials

Piezoelectric materials are considered by two laws: the law of electricity & the law of mechanics and the electrical influence is considered to be linear. Thus, in the piezoelectric problem, two variable fields will be approximated: the mechanical variable and the electrical variable. Some of the property constants of piezoelectric and composite materials include the modulus of elasticity (E), coefficient (ν), density (ρ), piezoelectric coefficient (d), and electric permittivity coefficient (p) [37]. The behavior equation of the piezoelectric plate is as follows:

$$\begin{bmatrix} \boldsymbol{\sigma} \\ \mathbf{D} \end{bmatrix} = \begin{bmatrix} \mathbf{c} & -\mathbf{e}^T \\ \mathbf{e} & \mathbf{g} \end{bmatrix} \begin{bmatrix} \boldsymbol{\varepsilon} \\ \mathbf{E} \end{bmatrix} \tag{6}$$

B. Plate theory

B-1. The classical laminated plate theory (CLPT)

In CLPT, based on the Love-Kirchhoff theory, it is assumed that [38]: The line of birth along the thickness remains perpendicular to the neutral line before and after deformation; The transverse strain and the transverse shear strains are ignored.

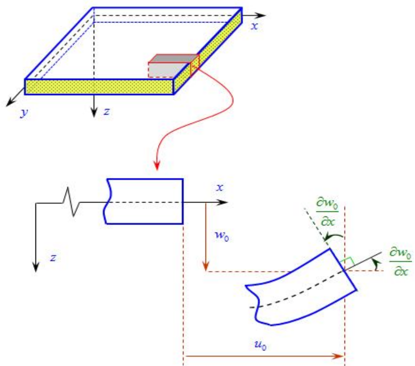

Fig. 3 Deformed and non-deformed plates in CLPT

The displacement field defined in the CLPT:

$$u(x,y,z,t) = u_0(x,y,t) + z\frac{\partial w_0}{\partial x}$$
$$v(x,y,z,t) = v_0(x,y,t) + z\frac{\partial w_0}{\partial y} \quad (7)$$
$$w(x,y,z,t) = w_0(x,y,t)$$

B-2. The first order shear deformation theory (FSDT):
In the FSDT, the shear strain is non-zero and is shown in Fig. 4. In addition, a shear correction factor is required and is discussed in detail in [41, 42].

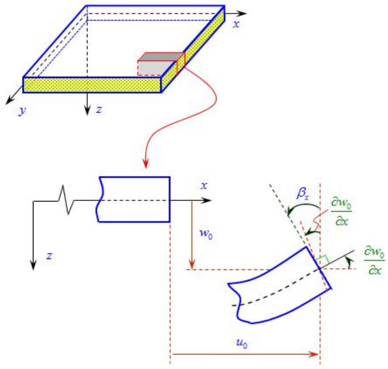

Fig. 4 Deformed and non-deformed plates in FSDT

The displacement field in the FSDT has the form [39, 40]:

$$u(x,y,z,t) = u_0(x,y,t) + z\beta_x(x,y,t)$$
$$v(x,y,z,t) = v_0(x,y,t) + z\beta_y(x,y,t) \quad (8)$$
$$w(x,y,z,t) = w_0(x,y,t)$$

B-3. The high orders shear deformation theory (HSDT):
The HSDT was developed by Reddy [43]. The displacement field is approximated to a higher-order function and is defined [43]:

$$u(x,y,z,t) = u_0(x,y,t) + z\beta_x(x,y,t) + cz^3\left(\beta_x + \frac{\partial w_0}{\partial x}\right)$$
$$v(x,y,z,t) = v_0(x,y,t) + z\beta_y(x,y,t) + cz^3\left(\beta_y + \frac{\partial w_0}{\partial x}\right) \quad (9)$$
$$w(x,y,z,t) = w_0(x,y,t)$$

Compared with the FSDT, the shear correction factor in the bid is not required [43].

III. RESEARCH APPROACH AND METHODS

This study will improve the traditional FEM, optimize the optimization methods, and develop multifunctional sheet structures and piezoelectric materials integrated plates. Research on a theoretical basis: Each issue will be analyzed and evaluated at the theoretical level and compared and contrasted with previously published results in quite a detail. Writing algorithms and programming numerical simulations: After studying the theoretical basis, write algorithms and programs with Matlab and numerically simulate common problems with exact solutions or many practical applications. Analysis of results: The numerical simulation results of the proposed method will be compared with the results of the analytical solutions, with the results published in international journals, or with the results of the sections or other software. Also, from these comparison results, the study will point out the advantages and disadvantages of each method and suggest directions for method improvement in the future.

IV. EXPECTED RESULTS

The direct product of the research is the improved finite element method to calculate the sheet structures of carbon nanofiber reinforced materials and the piezoelectric patch-integrated material sheets. Analysis of linear and nonlinear behavior of caron nanofiber-reinforced multifunctional sheet. Behavior analysis of a carbon nanofiber-reinforced multifunctional sheet with a piezoelectric patch under simultaneous mechanical, thermal, and electrical loads. Dynamic analysis and input optimization (potential difference, impact force, etc.) to find the optimal state of the structure with minimum strain energy.

V. CONCLUSIONS

The improved finite element methods have only been applied to a few problems in simple single-physics, plate problems, or two-dimensional multiphysics. Therefore, the new point of this study is the further development of the finite element methods and the improved optimization analysis method for complex problems, namely the problems of plate structures made of multifunctional material reinforced with carbon nanofibers integrated piezoelectric patch. Proposing improvements to the optimization method to meet the increasing requirements in calculating sheet structure problems in a multi-physics environment is always topical. It has received the attention of researchers worldwide for many decades. The results of this study will provide analysis and evaluation of the optimized method, which has been improved to be effectively applied in the computer calculation of complex sheet-material structural problems.

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