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Bending and buckling analysis of smart composite plates with and without internal flaw using an inverse hyperbolic shear deformation theory

V.M. Sreehari *, Linju Joseph George, D.K. Maiti

Department of Aerospace Engineering, Indian Institute of Technology, Kharagpur, WB 721302, India

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ABSTRACT

A finite element formulation based on inverse hyperbolic shear deformation theory (IHSDT) for handling bending and buckling analysis of a smart composite plates is developed. The governing equation of a piezolaminated composite plate is derived using Hamilton's variational principle. An intelligent structure with piezoelectric material perfectly bonded to the top and bottom surface of a laminated composite plate is considered for the present work. A Matlab programme has been developed using the present finite element formulation. The numerical results were obtained and compared with the available literature. Comparison of present results with those in literatures shows the effectiveness and excellent accuracy of model. The validation of recently developed IHSDT has been proved for a smart structure by this study and some numerical examples showing the variations in the buckling behaviour of a smart plate for various parametric variations are presented. Finally significant numerical examples of deflection control and enhancement of buckling load capacity is presented for composite plates with internal flaw. Comparison studies depicting the effectiveness of using a piezo patch only at centre instead of piezolayers are also presented. These specific applications proves the contribution of present work to be of realistic nature.

1. Introduction

Smart materials are interdisciplinary in nature which combines the knowledge of different science and engineering streams. Its usage helps mankind to control the environment better and increases the efficiency of devices. The subject area of smart structures has experienced a lot of research and development in the last two decades. Smart structures are those capable of correcting themselves from the external forces acting on them. Smart structure consists of multifunctional components performing sensing, control and actuation. The 'smartness' of a structure is defined on the basis of their response to stimuli and the speedy recovery of response. Since these smart materials are expected to mimic naturally occurring systems, their functions include high reliability, efficiency, sustainability, damage detection capability, self-correcting features, health and integrity monitoring, etc. Smart materials are currently used extensively in reduction of vibration and noise, aerospace and military applications, medical applications, etc. A variety of smart materials already exists, and is being researched extensively. These include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, and shape memory alloys. Piezoelectric materials are materials that exhibit the property of generating an electric potential when subjected to mechanical deformation and this phenomenon is the direct piezoelectric effect. The converse piezoelectric effect by which the material changes shape when an electric voltage is applied and widely used in actuation and control of vibration in mechanical devices. Configuring smart composite structures involves bonding piezoelectric layers (or segmented piezo patches) to the top and bottom of a multilayered composite plate which acts as distributed sensors and actuators to monitor and control the static and dynamic responses of the structure.

In the past, development of piezoelectric actuators as elements of intelligent structures was done by many investigators [1–6]. Analytical and experimental studies were done for analysing static and dynamic characteristic of laminated composite bonded with piezoelectric sensors and actuators. Pajand and Sadeghi [7] carried out bending analysis of multi-layered laminated composites, with and without piezoelectric sensor and actuator using a 12-noded triangular finite element formulation. FSDT techniques were used here for both thin and thick plates. From the obtained results they

* Corresponding author. Tel.: +91 8001581060.
E-mail address: rsvmsreehari@aero.iitkgp.ernet.in (V.M. Sreehari).

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concluded that their formulation leads to faster convergence than the similar formulations done by other researchers. Zhou [8] used three finite element models for the static and dynamic analysis of piezoelectric composite laminates and the results were compared along with varying piezoelectric lamina location and stacking sequences. Calculations were also made for transient response for a transverse disturbance on the plate. Thus they came to the conclusion that, the most effective tool for analysis of thick piezoelectric composite laminates is the third-order shear deformation theory. Maiti and Sinha [9] developed a multidirectional three dimensional finite element model in their work, with a concept of super element for formulation. The research was done on composite structures with piezopatches and piezo-fiber composites. They also concluded that, in hygrothermal conditions, the laminate stiffness reduces which can be increased with smart actuator. Samanta et al. [10] developed 8-noded iso-parametric finite element model for active vibration control of piezoelectric laminated composite plate using HSDT and found that amplitude of vibration reduces for increase in piezoelectric damping through feedback. The results also showed that, for thick plates, the damping ratio increases greater than that of thin plates. Wankhade and Bajoria [11] developed a finite element methodology for stability analysis of smart piezolaminated composite plate subjected to combined action of electrical and mechanical loading based on HSDT. They concluded that, with proper selection and placement of piezoelectric actuators, buckling characteristics of the plate could be controlled. Similar to Refs. [10,11], various other investigators [12–26] also have studied the structural response controls, but most of them considered classical or first order shear deformation theories. Carrera et al. [27] performed a detailed analysis of smart structures using fundamental principles and various advanced models. Numerous plate/shell models were made and studied. They provided both analytical and finite element solutions and the accuracy of the models were enhanced through the application of an efficient framework known as Carrera Unified Formulation (CUF).

Regarding to the shear deformation theories having non-polynomial nature, it is important to explore the recent works done in this area. Over the last few years, various shear deformation theories having non-polynomial nature and expressed in terms of shear-strain function have been proposed. Some of the nonpolynomial higher-order theories were proposed by Mantari et al. [28,29], Karama et al. [30], Meiche et al. [31], and Aydogdu [32]. Kulkarni et al. [33] has proved the accuracy and efficiency of inverse trigonometric shear deformation theory (ITSDT) in modeling and analysis of functionally graded plates (FGP). A new trigonometric zigzag shear deformation theory was developed and implemented for free vibration and buckling analysis of composite sandwich plate by Sahoo and Singh [34]. Carrera et al. [35] investigated the effects of thickness stretching in functionally graded plates (FGP) and shells and presented the significance of the transverse normal strain effects in the estimation of stresses for functionally graded structures. Neves et al. [36,37] and Ferreira et al. [38] brought remarkable progress in this area by developing a quasi-3D hybrid (trigonometric as well as polynomial) type shear deformation theory. Employing various non-polynomial displacement fields for in-plane displacements and polynomial displacement field for the out-of-plane displacement, they found out the structural responses of FGPs by means of meshless numerical technique. The CUF was extended to include non-polynomial shear strain shape function in their formulation. This is an innovative general formulation. Work shows the need of new suitable non-polynomial shear strain shape function for possible superior performance. Analysis of functionally graded structures by using new non-polynomial HSDTs was performed by Mantari and Soares [39–42]. In [41] and [42], the number of unknowns were varied to 4 and 5 respectively in addition to the incorporation of stretching effects. They observed better results of displacement and in plane normal stresses for functionally graded structures. But as we are dealing with composites with a piezo layer and not with functionally graded structures in this work and also for better computational efficiencies during FEM analysis, we are not considering the thickness effects as in above works. Also it is important to note here the excellent finite element computational efficiency and accuracy shown by inverse hyperbolic shear deformation theory (IHSDT), which is a non polynomial shear deformation theory. Grover et al. [43] developed a C^0 continuity finite element model for the flexural and stability behavioral analysis of laminated and sandwich composites implementing IHSDT. They concluded that it shows improved performance similar to all prevailing higher order shear deformation theories involving shear strain function. Rahul and Datta [44] recently studied the static and dynamic characteristics of thin plate like beam with internal flaw. Many researchers [45–48] had reported the critical buckling load of fiber reinforced composite plates. However, no work has been reported on bending and buckling of laminated composite structures equipped with piezoelectric patches using IHSDT and enhancement in buckling loads of damaged plates. The main aim of the present investigation is to study the bending and buckling analysis of smart laminated composite plates by IHSDT.

Structural analysis is becoming an important aspect in the field of designing. Structural engineering application requires an accurate prediction of system behaviour of structures. For optimum designs, the structures should be capable of withstanding maximum possible forces acting on them. Also the structure should be able to overcome the effects of small damages occurring in them. To enhance this capability we can use smart materials along with structural components in order to make them withstand more forces than what they are expected to. In the present work we concentrate more on application of piezoelectricity in strengthening structures, thereby controlling the deformations (due to external forces or caused as an effect of a flaw present in the system) and increasing the critical buckling load.

2. Mathematical modeling

2.1. Introduction

Consider a piezo laminated plate having dimensions and cross-sectional geometry as in Fig. 1, where (x, y, z) represents the rectangular Cartesian coordinate system. The plane $z = 0$ coincides with the mid-surface of the plate. The piezoelectric patches are attached firmly to top and bottom surfaces of the laminated composite plate. In the dynamic analysis, one of the layer acts as sensor and the other acts as actuator while in the static analysis both of them act as actuators. The present investigation starts with the bending analysis of a square composite plate with 2 piezo layers employing FEM. The FEM is very helpful tool for solving complex and real life problems. This method is based on variational approach. The domain is divided into number of sub-domains that are commonly known as finite elements. These elements are connected at various nodes. In the present work, geometry is discretized using an eight noded iso-parametric element as in Fig. 2. Benefit of isoparametric element is that element geometry and displacements are represented by same set of shape functions. Advantage of 8 noded element is that all the nodes are located on element sides and hence there are no internal nodes and shape functions have quadratic variation in x and y direction. The field variables are expressed in terms of shape functions N_i. Shape functions of an element in present finite element analysis is given as: