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Passive control of damaged composite laminates with optimized location of piezoelectric fiber composite patches

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This work presents a novel technique to enhance the bending, buckling, and post buckling characteristics of a damaged composite plate. This technique uses piezoelectric fiber composite patches (PFCP) for enhancing the performance and thereby reducing the effects of internal flaws. This paper discusses about the employment of PFCPs in their optimized location. Unified particle swarm optimization (UPSO) is employed for optimizing the PFCP locations for maximum critical buckling temperatures. An inverse hyperbolic shear deformation theory is used for advanced accuracy of the analysis of the smart plate. The post buckling behavior is studied with varying the number of optimally located PFCPs using modified Newton Raphson method. The obtained results are matched with those in the existing literature, wherever possible. It is observed that this is a very promising means of designing new smart material applications.

1. Introduction

Researchers have a keen interest in the area of smart structures in recent years. The main reasons behind it are the limitations in weight, space, and positioning in many applications. Currently researchers are applying optimization schemes for enhancing the performance of smart structures. Various studies were conducted in the past employing optimization analysis in smart structures. Sigmund and Torquato [1] worked on a topology optimization procedure. It was based on the finite-element analysis, sensitivity analysis, homogenization techniques, and sequential linear programming. Moheimani and Ryall [2] developed an outline to address the problem of selecting optimum locations for smart material placement used in structural vibration control. Sadri et al. [3] developed optimal actuator placement strategy for vibration control. They used genetic algorithm as their optimization tool. Genetic algorithms have also been used to obtain optimal sites for piezoelectric sensors and actuators of a smart plate based on parameter like controllability by Han and Lee [4]. Correia et al. [5] obtained the optimal location of piezoelectric actuators (PZT) and also presented the optimal fiber reinforcement angles employing simulated annealing optimization method. Finite element models using higher order shear deformation theories are used. Frecker [6] reviewed the latest works done related to optimization analysis in smart structures and drive electronics design since 1999. Quek et al. [7] used direct pattern search method for getting optimal locations of piezoelectric elements for vibration control of laminated composite plate. Sun and Tong [8] studied the design optimization of actuator patterns for static shape control of composite plates with PZT (lead zirconate titanate) actuator patches. They used a method based on energy optimization and obtained the optimal control voltages that can trigger a structure shape near to the wanted one within a specified error. Alfredo Faria [9] studied the optimization of buckling loads of a composite plate having piezoelectric actuators. The actuators maximized the buckling loads through stress stiffening effects and enhanced the plate prebuckling responses. The location of piezoelectric patches and the ply lay-up angles of laminated composite plates are considered as design variables and they are optimized simultaneously by genetic algorithm for vibration control by Honda et al. [10]. Deepak et al. [11] used genetic algorithm for placing piezoelectric actuators optimally on a plate for vibration suppression. Control effectiveness was studied using linear quadratic regulator control algorithm. As observed in above literatures, most optimization analyses in smart structures were not for buckling responses, rather conducted for shape control or vibration suppression. So in this paper, it is intended to present the effect of optimization analysis in buckling analysis under hygrothermal environment. Spallino and Thierauf [12] employed optimization scheme in thermal buckling analysis. The optimization problem was explained by means of evolution strategies, a random search method. But they

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conducted for laminated composite plates, without any smart material.

At this point it is important to note that all the above literatures considered various optimization methods. In the present work, the particle swarm optimization (PSO) algorithm is used as the optimization scheme. A few literatures relevant to the present research work are cited as follows. Parsopoulos and Vrahatis [13] presented a review of recent results concerning the PSO method. They concluded that PSO seems to be a very beneficial method and a worthy substitute in cases where other methods fail. Yet more exploration is vital to completely understand the values and limitations of this technique. Optimum actuator voltages were found by employing PSO technique in an analysis conducted using PZT by Agrawal and Shafei [14]. Montazeri et al. [15] optimized the system of a simply supported laminated thin plate for active noise and vibration control using PSO. Bargh and Sadr [16] investigated the lay-up scheme of symmetrically laminated composite plates for maximization of fundamental frequency by means of PSO algorithm. They did formulation using the classical laminated plate theory (CLPT) and the finite strip method.

Understanding the superiorities of piezoelectric fiber composites (PFC) over existing monolithic actuators, PFCs became a significant focus of a number of researchers. Broad elementary research into various aspects of PFCs like modeling, manufacturing, and physical incorporation into structures are currently going on. Some advantages of PFCs over monolithic ceramic actuators are conformability to curved surfaces, high performance, manufacturability, increased robustness to damage, etc. Specific strength and directional sensitivity of fine ceramic fibers are higher than monolithic materials. These characteristics of PFCs make them interesting components for structural control applications in various fields. PFCs were made from the researches at MIT in 1992. PFCs contain PZT fibers and epoxy resin. For the purpose of poling and to direct the electric field along the longitudinally oriented PZT fibers, interdigitated electrodes are used. Bent [17] presented work related to active fiber composites (AFC). He explained ways for manufacturing of the fiber and composite systems, progresses in the constituents and description for enhanced performance. Timothy et al. [18] developed a finite element modeling of AFC. Kerur and Ghosh [19] studied smart structures integrated with AFC layer using finite element method. Mahato and Maiti [20] had performed aeroelastic analysis of smart plates using AFC in hygrothermal environment under aerodynamic loads.

Some weaknesses may arise when we use PFC as a layer in practical applications. PFC layers are not effective when composite structure experiences moderately large deformation or when the surface of the composite structure is geometrically unconformable. In such cases fibers may break (because they are thin, brittle and continuous piezoelectric). Subsequently it will affect the actuation-capability of actuator. Studies of Newnham et al. [21], Hagood et al. [22], and Safari et al. [23] torch light into the difficulties in the fabricating of large planar PFCs for structural actuation. The problems come due to the fragility of long fibers, making their manipulation delicate, and the need for high electric fields to polarize a large planar PFC [24,25]. So by using segmented piezoelectric fiber composite patch (PFCP) at decided locations, the problem can be tackled. Indeed, the structure with PFCP has lesser density, improved fracture behavior (decreased brittleness). Moreover, the flexibility and shape variability are enhanced. So an effective method is to use these piezoelectric fiber actuators in the form of patch instead of complete layer.

Any physical system is firstly transformed into a mathematical model using some technique. The accuracy of any mathematical model depends mainly upon above transformation and solution techniques. For getting the exact responses three-dimensional (3D) elasticity methods can be employed. But 3D solutions can be used only for specific boundary and geometry conditions. Due to large ratio of elastic modulus to shear modulus in a fiber reinforced laminate, effects of shear deformation are noteworthy in composite structures and therefore it plays an important role in modeling composite structures. Many plate theories are present which combine the effects of shear deformation in distinctive ways. Most works mentioned above have taken classical, first order or third order shear deformation theories. Very few works exist using non-polynomial shear deformation theories (NPSDT). So, special attention must be given for the investigation of the composites using NPSDTs. Grover et al. [26] proposed the new non-polynomial shear deformation theories and implemented for structural responses of laminated composite and sandwich plates. They noticed that structural responses with new nonpolynomial shear deformation theories shown improved performance alike all prevailing higher order shear deformation theories comprising shear strain function. The authors had explained the buckling of composite structures using inverse hyperbolic shear deformation theory (IHSDT) in their earlier published works [27,28].

As seen in the observations made in the literature survey, certain gaps exist for the structural analysis of laminated composite plates. The limited studies on the bending, buckling, and postbuckling behavior of damaged composite structures provides a scope for such investigation considering more realistic shear deformation. To the best of authors knowledge, the particle swarm optimization algorithm and segmented PFCPs has not been used so far. Finding the optimum location of PFCPs to obtain maximum buckling load of a damaged composite plate is an interesting problem. It is significant to optimize the location of PFCPs to obtain maximum critical buckling temperature of laminated plate by employing the unified particle swarm optimization (UPSO) algorithm. PFCPs are employed in their optimized location using UPSO for enhancing the performance and thereby reducing the effect of internal flaws in composite plates in the current work. Finally path of post buckling response of an optimized smart plate with and without damage is traced. Next section presents the thorough mathematical formulation of the present research followed by some important results and discussion.

2. Mathematical modeling

2.1. Introduction

A laminated composite plate with dimensions and geometry as shown in Fig. 1 is considered, where (x, y, z) denotes the rectangular Cartesian coordinate system. The plane $z = 0$ corresponds with the mid-surface of the composite plate. A finite element formulation is developed for the present analysis of laminated composite plates with damage. The essential idea of finite elements is that the structure is considered as an assembly of elements linked at nodes. An isoparametric element has a benefit that element geometry as well as displacements are characterized by same set of shape functions. In the present analysis 8-noded isoparametric plate element is used

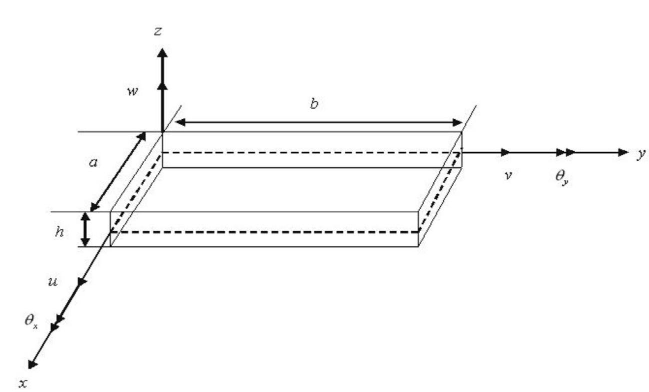

Fig. 1. Dimensions of plate.