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Vibration analysis and control of smart composite plates with delamination and under hygrothermal environment

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ABSTRACT

An analysis of delaminated composite plates with integrated active fibre composite (AFC) actuators and sensor under hygrothermal environment has been undertaken in the present work. The top and bottom plies of the laminate constitute AFC actuators and sensors. In the present investigation, hygrothermal loading is taken into consideration, and the effect of moisture and temperature on the delaminated plate structures is analysed. The minimum total potential energy approach is used for arriving at the governing equation. A finite element model for centrally located delamination is developed on the basis of first order shear deformation theory. An eight noded serendipity element with five degrees of freedom per node is considered for the finite element formulation. A parametric study on the effect of stacking sequence, boundary conditions and environmental conditions in the presence of delamination on the laminated plate is studied. The key observations from the parametric study are: there will be reduction in natural frequencies in the presence of delamination and/or hygrothermal loading, and reduction in structural stiffness due to the presence of delamination can be negated by applying voltage to the active fibre actuator layer.

1. Introduction

Composite materials are extensively used in many engineering applications like aircrafts, civil structures, satellite launch vehicles, automobiles and other engineering applications due to their high strength to density, and stiffness to density ratios. During the service period of composite structures, they may be exposed to hot and/or humid environmental conditions, in such conditions the strength and stiffness of composite degrades; because of moisture diffusion, thermal spikes and thermal oxidation. In recent times, if the composite structure constitutes the primary load carrying member, or if the composite structure is expected to perform active function, then, active fibre laminae are embedded in these structures. The purpose of these active fibre layers may be either to sense the strains (for structural health monitoring purpose), or to provide actuation to the system or structure under consideration. An active fibre composite (AFC) is a kind of piezoelectric fibre, which was originally developed by Hagood and Bent [1]. The key features of AFC over conventional piezoceramics actuators are high strength, conformability, directional actuation and low insertion cost [2,3]. AFCs contribute to a large scale of actuation and sensing capability in active structures. Hence, AFC are used in controllable structures, to get required strength and/or stiffness, and to perform the required tasks.

Laminated composite structures are highly affected by the environmental factors, such as temperature and moisture. An adverse environmental condition leads to the degradation of mechanical properties, like stiffness and strength of the structures [4]. Many scholarly articles are available which focus on hygrothermal effect on the composite laminates. Laminated structures when subjected to higher temperature or under humid conditions, laminated structures develop residual stresses. In 1989, Bouadi and Sun [5] studied the effect of hygrothermal conditions on the stress fields for a cross-ply laminated composite, using a three dimensional finite element model. Whereas, Ram and Sinha [6,7] conducted stress behaviour [6] and free vibration [7] numerical studies for cross-ply and angle-ply laminated plate, subjected to hygrothermal environment. For these studies, Ram and Sinha [6,7] used quadratic isoparametric plate bending finite element model. The static and dynamic analysis of the thick laminates, based on higher-order shear deformation theory, and subjected to hygrothermal environment, was carried out by Patel et al. [8], they concluded that for thick laminates considering shear stress alone and neglecting thickness stretching would be inadequate. Free vibration analyses of sandwich plate with laminated anisotropic face sheets under thermal environment for different parameters such as aspect ratio, stacking sequences

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are discussed by Fiorenzo and Carrera [9], they have employed hierarchical trigonometric Ritz formulation for their study. Similarly, a functionally graded carbon nanotube reinforced composite plate is analysed for free vibration under thermal environment with Kp-Ritz formulation by Lei et al. [10]. The effect of steady state hygrothermal environment on free and forced vibration of laminated composite plate is studied by Chen and Chen [11]. The numerical and experimental free vibration studies on the effect of hygrothermal environment in woven fabric (glass/epoxy) laminated composites is carried out by Rath and Sahu [12]. Whereas, Pandey and Pradyumna [13] have studied the free vibration behaviour of functionally graded sandwich plate in thermal environment. Buckling and post buckling analysis under elevated temperature and moisture conditions is carried out by Sreehari and Maiti [14].

The previous paragraph concentrated on the literature review of laminated, sandwich and functionally graded plates subjected to hygrothermal environment. This paragraph will briefly review the literature on active composite. Piezoelectric actuators and sensors have been used in many applications to make a structure smart and controllable [15], when subjected to undesirable oscillations. These intelligent structures have integrated piezoelectric actuators, sensors and controller to effectively control the undesirable responses of the structures [16,17]. There are many research articles available to determine feasibility of smart structures. AFC is a special type of piezoelectric material with interdigitated electrode embedded on its surface. It has high value of piezoelectric charge constant. Static and dynamic analysis of laminated composite plates with integrated piezoelectric actuators and sensors has been carried out by Liu et al. [18] and Zhang and Shen [19]. A finite element model of piezo laminated plate was developed by Chien-Chang et al. [20]. Medeiros et al. [21] used asymptotic homogenization method and finite element analysis for AFC made of circular and square cross-section fibres. Mahato and Maiti [22,23] investigated flutter control analysis of AFC laminate subjected to hygrothermal environment. Brunner et al. [24] discussed the capability of AFC in structural health monitoring. Guruprasad et al. [25] have modelled the AFC as a sensing device for detecting the damage and delamination in structure. Martinez and Artemev [26] studied the actuation degradation of AFC in presence of fibre damage. Han and Lee [27] have used a layer-wise theory for active laminated plates.

The main aim of the present article is to study the behaviour of active laminated composite plate subjected to hygrothermal environment and with inbuilt delamination. Hence, a brief review on delamination and the available delamination model for plate structures is reviewed in this paragraph. Delamination refers to a defect associated with the laminated structures. The cause of delamination may be either due to imperfect fabrication techniques (air entrapment or residual stresses), or due to fatigue loads during the service period of the structure. Due to delamination in composite structures, structural stiffness degrades. The study of delamination is mainly categorized into two approaches [28].

i. Region wise approach: In this approach laminate is divided into sublaminates i.e. healthy laminated region and delaminated region. The continuity condition is applied at the interface of healthy and delaminated sublaminates [28].
ii. Layer wise model approach: This approach is based on layer wise theory in which layer-by-layer approximation of displacement fields in thickness direction is considered [28]. At the delamination interface, the displacement continuity conditions are not enforced.

Region wise delamination modelling is further divided into free mode and constrained mode delamination. The study on delaminated structures started in early 1990s. Wang et al.[29], while considering an isotropic split beam and applying the classical beam theory, assumed that the delaminated layers deformed freely without intersecting each other. They categorized the beam into split and un-split regions according to the delamination interface, and they offered a general solution. Babu and Hanagud [30] applied the minimum potential energy approach to derive an equation of motion for a beam and employed free mode assumption for delamination analysis. Whereas, Majumdar and Suryanarayan [31] discussed that in case of off-mid-plane delamination free mode modelling does not yield physically admissible mode shape, because delaminated layers may have different transverse deformation and may penetrate each other for few mode cases. Hence, Majumdar and Suryanarayan [31] proposed a constrained mode delamination modelling in which identical transverse deformation is considered for delaminated layers. Modal analysis of delaminated composite laminate was carried out by number of researchers. Ju et al. [32] developed a finite element model for delaminated composite plates based on Mindlin plate theory, they divided the plates into two sub-parts, i.e. delaminated and none delaminated region and derived the Stiffness and mass matrices by the finite element method, using minimum potential energy approach, they imposed the displacement and slope continuity condition at the delaminated junction. Campanelli and Engblom [33] developed an eight noded shear deformable plate, finite element based model to study the behaviour of AS4/PEEK delaminated composite plates. The authors divided the plates into upper and lower sub-laminates according to the extent of delamination, and applied the penalty parameter approach to connect the upper and lower sub-laminates, they validated their numerical model results with experimental results. Barbero et al. [34] applied the jump discontinuity condition at the delaminated interface. Lee [35] conducted a free vibration analysis of the delaminated beam for different aspect ratio, using layerwise model. A three dimensional finite element model of delaminated composite plate is studied by Alnefaie [36]. Yam et al. [37] have considered a virtual element in delaminated region to avoid the inter-penetration of displacement field. Free vibration analyses of delaminated glass/epoxy plate including various parametric studies were presented by Mohanty et al. [38], they have validated the numerical results with experimental data. Lachaud et al. [39] simulated the matrix cracking and delamination propagation in laminates for various load. A detailed review article on delamination modelling in beam and plate type of structures is documented by Della and Shu [28].

There are many studies available on modelling of laminated plates. They can be broadly classified into equivalent single layer (ESL) theories [40] and layerwise theory (LW) [41,42]. ESL theories can further be classified into classical plate theory (CPT) [43], first order shear deformation theory (FSDT) [44], higher order shear deformation theory (HSDT) [45], and zigzag theory [46]. A detailed review on different types of plate theories with their applicability is presented by Khandan et al. [47].

The effect of hygrothermal loading on delaminated structures was presented by Parhi et al. [48], they used Newmark's integration technique for the transient analysis of the multiple delaminated structures in enhanced temperatures and moisture concentration conditions. Buckling behaviour of the delaminated structures through three dimensional theories has been noted in reference [49]. Recently, an analytical model of damaged isotropic rectangular plates for the purpose of free vibration analysis in thermal environment has been presented by Joshi et al. [50]. A numerical and experimental study of delaminated woven fabric glass/epoxy laminate under hygrothermal environment is presented by Panda et al. [51], they have carried out numerical FE-model studies for 6.25%, 25% and 56.25% area delaminated plate, subjected to hygrothermal environment and they validated numerical results experimentally. The vibration analysis of doubly curved panel with delamination and under elevated moisture concentration is studied by Panda et al. [52].

It can be observed from the literature survey that the researchers have mainly concentrated on vibration studies of delaminated plates. There are very few analyses available on hygrothermal study of the delaminated active plates. The study on the effect of hygrothermal