Chapter 1

Introduction

This chapter is concerned with the introduction and the review of literature on the analyses of smart structures. The literature pertaining to the use of piezoelectric composite (**PZC**) materials and the active constrained layer damping (**ACLD**) of smart structures have been reviewed next. Based on the review of literature, the scope of research for this thesis has been identified and the objectives of this dissertation have been presented. Also, the contributions in the field of smart structures while preparing this dissertation have been delineated. In the end, organization of the chapters has been outlined.

1.1 Smart Structures

Due to stringent constraint on the saving of energy, lightweight flexible structures have attained the growing demand for the design of space structures, robotic manipulators, aerospace structures and the like. These lightweight structures are susceptible to large vibrations with long decay time because of their low internal damping. This often leads to the structural fatigue and instability which result in the serious deterioration of the structural performance. Such possibilities of failure can be mitigated by the integration of an active control system onto the host structure and the performance of the overall structure under operation can be enhanced.

In the quest for developing such very lightweight high performance flexible structures, a concept was emerged for developing the structures with self-controlling and/or self-monitoring capabilities. Expediently, utilizing the

phenomenon that in a piezoelectric material coupling of electric and elastic fields takes place [1], Forward [2] first attempted to demonstrate the feasibility of the effectiveness of the piezoelectric actuators to damp out two closely spaced orthogonal bending modes in a cylindrical fiberglass mast employing a simple rate damping control law. Another pioneering work showing the effectiveness of the use of distributed piezoelectric actuator in controlling the deformable mirror surface is due to Chiarappa and Claysmith [3]. Next, using the piezoelectric materials, the design and analysis of an active distributed damper for the control of a thin cantilever beam was presented by Baily and Hubbard [4], Bruke and Hubbard [5], Crawley and Luis [6] and Im and Atluri [7]. Miller and Hubbard [8] first demonstrated the use of piezoelectric materials as distributed sensors. Subsequently, Tzou and Panditha [9] used these materials for tactile sensors of robot manipulators and Crawley et al. [10] demonstrated the use of piezoelectric technology for control of intelligent structures.

The flexible structures coupled with distributed actuators and/or sensors made of piezoelectric materials are able to achieve self-controlling and self-sensing capabilities. Such structure is customarily known as "Smart Structure" [11] and is schematically illustrated in Fig. 1.1. Such a structure is capable of adapting or taking corrective action to changing operating conditions. The passive part of a smart structure is the load bearing part i.e. the host structure and the active parts of the same are the layers/patches of piezoelectric materials which perform the operations of sensing and actuation. Piezoelectric materials can easily be integrated with the load bearing structures by surface bonding or embedding into it and do not significantly alter the passive stiffness characteristics of the host structures [10]. The load bearing part or the passive part of the smart structure is generally called as the substrate which can be beam, plate or shell. A great deal of research on smart structures has already been

reported on the exact solutions [11-20], analytical solutions [21-25], finite element analyses [26-46] and active control analyses [47-73]. The concept of smart structures has also been implemented for active control of rotor dynamic systems [74], aerospace structures [75-77], international space station [78] and sound radiated from vibrating structures [79-81]. Furthermore this concept has also been used for the structural health monitoring as a nondestructive evaluation technique [82-86] and the active control of smart hull structure [87].

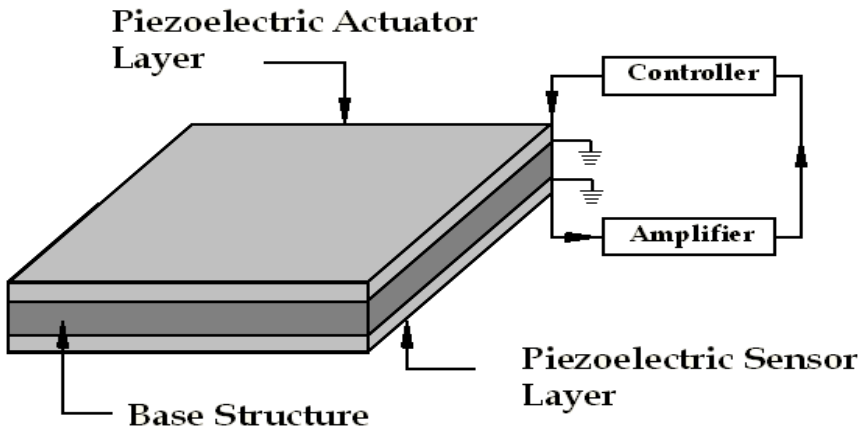


Fig. 1.1 Schematic representation of a smart structure

1.2 Active constrained layer damping treatment

The main drawback of the existing monolithic piezoelectric materials is that the magnitudes of their piezoelectric coefficients are very small. Thus, the distributed actuators made of monolithic piezoelectric materials possess very low control authority and require large voltage for achieving appreciable results. Further investigation on the efficient use of these monolithic piezoelectric materials for active control of flexible structures led to the development of the active constrained layer damping (**ACLD**) treatment [88, 89]. The **ACLD** treatment consists of a layer of the viscoelastic material constrained between the host structure and an active constraining layer made of the piezoelectric material.

When the host structure undergoes vibrations, the active constraining layer not only restrains the constrained soft viscoelastic layer to undergo transverse shear deformations but also controls its transverse shear deformations to cause improved damping characteristics of the overall structure over the passive damping. If the constraining layer is not subjected to applied voltage, the treatment turns out to be the conventional passive constrained layer damping (**PCLD**) treatment. Thus, the **ACLD** treatment provides the attributes of both active and passive damping. Also, the task of controlling the transverse shear deformations of soft viscoelastic layer is compatible with the low control authority of the piezoelectric actuators. Hence, the **ACLD** treatment has earned wide acceptability for efficient and reliable active control of flexible structures [90-93].

As an important study, optimization of energy dissipation characteristics of beams and plates integrated with the **ACLD** treatment have been studied by Baz [94] and Ray and Baz [95]. In these analyses, a globally stable boundary control strategy is employed to control the strains of the active piezoelectric layers caused by the structural vibrations. Baz [96] developed a globally stable boundary control strategy to damp out the vibrations of beams fully treated with the **ACLD** treatment and also studied [97] robust control of beam using **ACLD** treatment. Crassidis et al. [98] carried out the analysis for $\boldsymbol{H}_\infty$ control of a beam integrated with the **ACLD** treatment. Baz [99] also carried out the spectral **FE** analysis for controlling longitudinal wave propagation in rods treated with the **ACLD** treatment. Lam et al. [100] showed that the control effort needed to damp out the vibrations of structures using the **ACLD** treatment can be significantly higher than that using purely active control. They modeled the constrained viscoelastic layer using Golla-Hughes-McTavish (**GHM**) method. Park and Baz [101] investigated the comparison between the **FE** analysis of **ACLD** using

classical and layer-wise laminated theories. Ray et al. [102] theoretically and experimentally demonstrated the use of the **ACLD** treatment for significant control of linear vibrations of thin cylindrical shells. Jeung and Shen [103] developed a generalized **FE** model of plates and shells integrated with the **ACLD** treatment. Chantalakhana and Stanway [104] numerically and experimentally investigated the **ACLD** of the linear vibrations of the clamped-clamped plate. Chattopadhyay et al. [105] studied the influence of number of segments of the **ACLD** treatments along with their placements on the vibration control of composite plates. Balamurugan and Narayanan [106] presented an analysis for active vibration control of beams with smart constrained layer damping (**SCLD**) treatment. They investigated the effects of the **SCLD** on the vibration suppression performance and the control effort requirements using the linear quadratic regulator (LQR) optimal control theory. Liu and Wang [107] demonstrated the enhanced **ACLD** for broadband vibration suppression. Batra and Geng [108] studied the comparison of damping augmentation mechanism for **ACLD** treatment.

As an important application, Chattopadhyay et al. [109] used the **ACLD** treatment to enhance the aeromechanical stability and the control of smart composite rotor blades. Ro and Baz [110] investigated vibration control of plates using the self-sensing **ACLD** networks and also determined the optimal placement of the **ACLD** patches using the modal strain energy approach [111]. As an important study, the effect of debonding in the **ACLD** patches on the control of smart beams has been investigated by Sung and Tong [112]. Ray and Reddy [113] investigated the optimal control of thin circular cylindrical laminated composite shells using the **ACLD** treatment. They [114] also investigated the effect of delamination on the **ACLD** of substrate composite beams. Shi et al. [115] presented the experimental study of the **ACLD** of beams.

They also developed a **FE** model in which the constrained viscoelastic material is modeled by the Golla-Hughes-McTavish (**GHM**) method. Badre-Alam et al. [116] presented an analysis of the interlaminar stresses in the **ACLD** treatments. The primary objective of this study is to provide an in-depth understanding of the delamination of the **ACLD** treatment and to establish guidelines to lower the risk of delamination without sacrificing the performance. Langote and Seshu [117] carried out experimental investigation on the active vibration control of a beam using the hybrid active/passive constrained layer damping treatment. Pradeep and Ganesan [118] studied the vibration behavior of the **ACLD** treated beam in the presence of a thermal environment. Recently, Kumar and Singh [119, 120] presented experimental results for the vibration and damping characteristics of **ACLD/PCLD** treated beams and curved panels. Most recently, Zheng et al. [121] investigated the vibration and damping characteristics of the cylindrical shells with the **ACLD** treatments.

1.3 Piezoelectric composites

It is known that brittle fibers are efficiently exploited to form polymer matrix composites with improved properties suitable for structural applications. Probably, this motivated the researchers to develop the piezoelectric composites (**PZC**s) with brittle piezoceramic fibers. **PZC**s are usually composed of an epoxy matrix reinforced with fibers of monolithic piezoceramic materials such as **PZT**, **PZT5H** etc, provide a wide range of effective material properties not offered by the existing monolithic piezoelectric materials and are characterized by good conformability and strength. Being a composite material, the **PZC**s have the ability to cause anisotropic actuations.

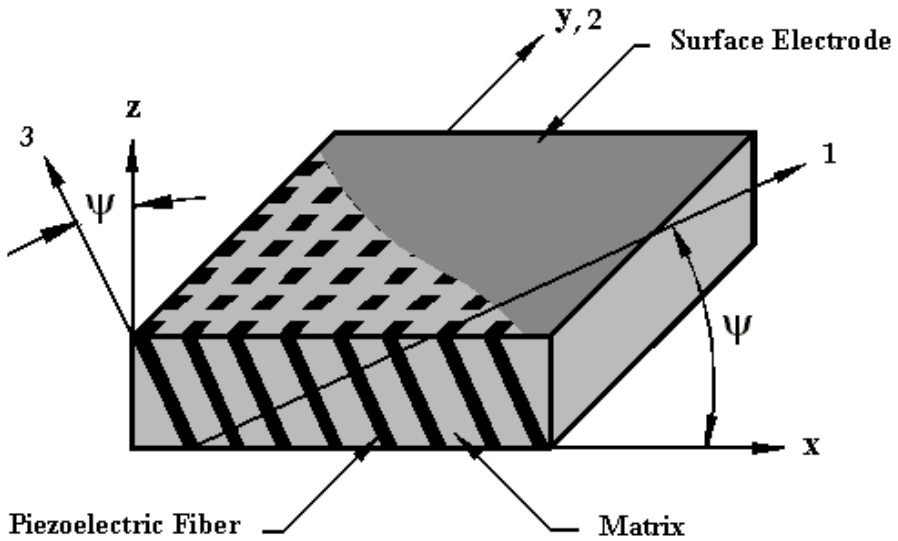
Various micromechanics models were proposed to predict the effective properties of the **PZC**s from the properties of their constituents. For example, Chan and Unsworth [122] derived a simple micromechanics model for the

analysis of piezoelectric ceramic/polymer 1-3 composites. Mallik and Ray [123] proposed the concept of a new horizontally reinforced 1-3 **PZC** material and predicted the effective mechanical and piezoelectric properties of these composites. The main concern of this investigation was to determine the effective piezoelectric coefficient ($\boldsymbol{e_{31}}$) of this 1-3 **PZC** material, which quantifies the induced normal stress in the fiber direction due to the applied electric field in the direction transverse to the fiber direction. They predicted that this effective piezoelectric coefficient becomes significantly larger than the corresponding coefficient of the monolithic piezoelectric material of the fibers. Smith and Auld [124] predicted the effective properties of the vertically reinforced 1-3 **PZC** materials using the strength of material approach of micromechanics. These materials have improved mechanical performance and electro-mechanical coupling and are useful for studying the thickness mode oscillations of structures. Ray and Pradhan [125] derived a three dimensional micromechanics model of the vertically reinforced 1-3 **PZC** and presented its effective elastic and piezoelectric coefficients for subsequent analysis of smart laminated composite plates. Subsequently, Kumar and Chakraborty [126] presented a micromechanics model to predict the material properties of the horizontally reinforced 1-3 **PZC** material. Their work is concerned with the prediction of thermal, mechanical and electrical properties of this 1-3 **PZC** material. In order to attain the in-plane actuation by the **PZC** material, Bent et al. [127] developed Active Fiber Composites (**AFC**). Subsequently, Bent and Hagood [128] used interdigitated electrodes which create the electric field along the length of the piezoelectric fibers. Kar-Gupta and Venkatesh [129] developed an analytical model to investigate the electromechanical responses of these **AFC**s. Zhang and Shen [130] investigated the performance of the **AFC**s for vibration suppression of laminated plates. Recently, Ivanov [131] carried out the finite element analysis and

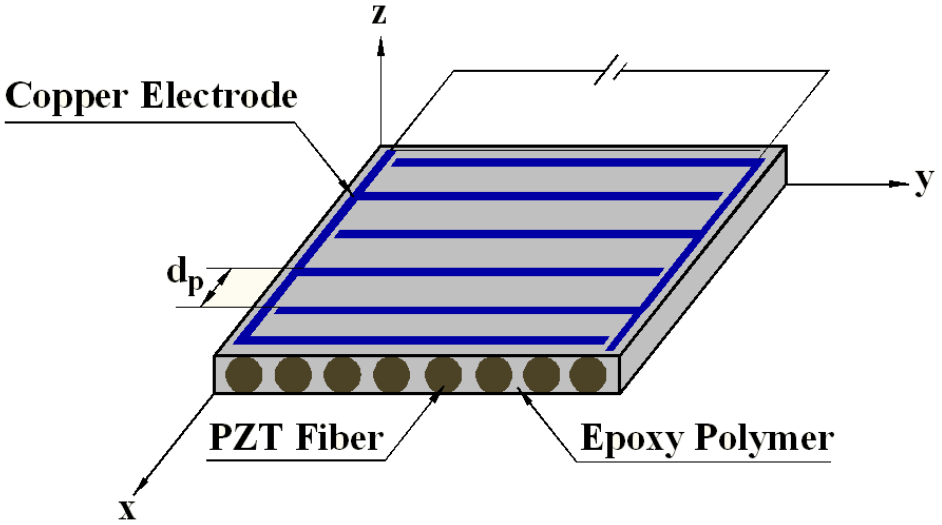
modeling of **AFC**s including damages.

The constructional feature of the laminae made of the vertically/obliquely reinforced 1-3 **PZC** [124, 125] and the **AFC** [128] are schematically illustrated in Figs. 1.2 (a) and 1.2 (b), respectively. As shown in Fig. 1.2 (a), the piezoelectric fibers are uniformly aligned and coplanar with the vertical $\boldsymbol{xz}$-plane across the thickness of the lamina while the fibers are oriented at an angle ($\boldsymbol{\Psi}$) with the transverse ($\boldsymbol{z}$) direction. Also, the fibers can be coplanar with the vertical $\boldsymbol{yz}$-plane. The top and the bottom surfaces of the lamina are coated with surface electrodes and the fibers are poled along their length with their ends being in contact with the surface electrodes. In case of the vertically reinforced 1-3 **PZC**, the orientation angle ($\boldsymbol{\Psi}$) is zero while it is nonzero for the obliquely reinforced 1-3 **PZC**. A lamina of the **AFC** (Fig. 1.2(b)) is composed of piezoceramic (**PZT**) fibers horizontally aligned in the plane of the lamina while the fibers are poled along their length. The top and the bottom surfaces of the lamina are equipped with the patterns of the interdigitated electrode fingers which are mirror images of each other. Each pattern consists of alternatively aligned positive and negative electrode fingers and is placed transverse to the fibers such that the electric field is created along the length of the fibers. The distance ($\boldsymbol{d_p}$) between a positive electrode and a negative electrode controls the measure of the electric field. Such an arrangement of electrodes in **AFC** attributes the distributed actuator made of **AFC** with high in-plane actuation authority along the fiber direction.

Extensive research has been carried out to demonstrate the performance of the **PZC** materials as the materials of the distributed actuators or constraining layer of the **ACLD** treatment for active control of linear deformations and vibrations of laminated structures [132-136]. Recently, Ray and Pradhan [137] investigated the use of vertically/obliquely reinforced 1-3 **PZC**s for active damping of linear vibrations of thin laminated composite cylindrical panels.



(a)



(b)

Fig. 1.2. Schematic diagram of the laminae of (a) Vertically (Ψ =0) /obliquely (Ψ≠0) reinforced 1-3 PZC (b) Active fiber composite.

1.4 Nonlinear analysis of smart structures

In the preceding sections, a brief review of literature on the linear analysis of smart structures has been presented. Considerable interest has also been placed on the geometrically nonlinear analysis of smart structures. For example, a nonlinear theory for dynamics and active control of composite plates integrated with piezoelectric sensors and actuators was developed by Pai et al. [138]. Tzou and Zhou [139] investigated the dynamic control of nonlinear circular plates composed of two surface piezoelectric layers and one isotropic elastic layer. Icardi and Sciuva [140] analyzed large deformations of multilayered plates with induced strain actuators. Reddy [141] analyzed large deformations of laminated composite plates integrated with piezoelectric sensors and actuators. Yi et al. [142] presented a nonlinear dynamic analysis of structures integrated with piezoelectric sensors/actuators. Oh et al. [143] investigated postbuckling and vibration characteristics of piezolaminated composite plates subjected to thermo-piezoelectric loads and also studied the thermo-piezo-elastic snapping of piezolaminated plates using layer-wise nonlinear finite elements [144]. Ray and Baz [145] developed a variational model to investigate the control of nonlinear vibrations of beams using the **ACLD** treatment. Moita et al. [146] developed a **FE** model based on the classical plate theory for the geometrically nonlinear analysis of piezolaminated plates and shells. Mukherjee and Choudhuri [147] analyzed the large deformations of piezoelectric structures. Next, Ishihara and Noda [148] presented the nonlinear dynamic behavior of a piezo-thermo-elastic laminated plate with anisotropic material properties and Gao and Shen [149] showed by **FE** analysis that the piezoelectric actuators can significantly suppress the geometrically nonlinear transient vibrations of composite plates. Shen [150] presented a nonlinear bending analysis for simply-supported, shear deformable un-symmetric cross-ply laminated plates integrated with piezoelectric actuators

and subjected to combined action of mechanical, electrical and thermal loads. Lentzen and Schmidt [151] developed a **FE** model for geometrically nonlinear static and dynamic analyses of smart composite structures. Huang et al. [152] analyzed nonlinear dynamic responses of simply-supported shear deformable cross-ply laminated plates integrated with the piezoelectric actuators. Kulkarni and Bajoria [153] derived a **FE** model based on the higher order shear deformation theory for the geometrically nonlinear analysis of smart thin and sandwich plates. Kundu et al. [154] presented the geometrically nonlinear post buckling of laminated doubly curved shells integrated with piezoelectric actuators. Butz et al. [155] developed a geometrically and materially nonlinear piezoelectric three dimensional beam finite element including the warping effect. Schmidt and Vu [156] presented nonlinear dynamic finite element simulation of smart piezolaminated structures. Their work is based on the first- and the third-order transverse shear deformation theories. Recently, Yiming et al. [157] developed a nonlinear active vibration control model for piezoelastic laminated plates considering interfacial damage effects. Subsequently, Tanveer and Singh [158] presented a numerical approach for linear and geometrically nonlinear forced vibrations of laminated composite plates with piezoelectric materials. Most recently, Fakhari and Ohadi [159] investigated the large amplitude vibration control of functionally graded material plates under thermal gradient and transverse mechanical loads using integrated piezoelectric sensor/actuator layers.

1.5 Scope and objectives of the present work

Due to the stringent consideration of weight, very lightweight high performance smart structures with high stiffness to weight ratio can be developed if the base structure of the smart structures is made of thin laminated composite structures which can be tailored to meet the design stiffness to weight ratio for a particular

need. The thin walled very light weight flexible structures are prone to large vibrations with long decay time leading to failure caused by the structural fatigue and instability. Hence, the active control of vibrations of these structures is necessary. The **ACLD** treatment has gained its credential to become the most efficient means of exploiting the piezoelectric materials for achieving active control of thin walled structures. Thus, the high performance smart structures may be built utilizing the concept of **ACLD** treatment so as to keep the host structures away from the deleterious effect of large vibrations. The review of literature indicates that the 1-3 **PZC** materials provide wide range of material properties which the monolithic piezoelectric materials cannot. Hence, in order to tailor the damping characteristics of the host structures, commercially available **PZC** materials like the vertically/obliquely reinforced 1-3 **PZC**s and the **AFC**s may be used as the materials of the constraining layer of the **ACLD** treatment. However, the research on the **ACLD** of geometrically nonlinear vibrations of thin laminated composite beams, plates and shells using these vertically/obliquely reinforced 1-3 **PZC** and **AFC** materials is still not available in the open literature. Hence, it is not known if the vertical actuation by the constraining layer of the **ACLD** treatment can cause the active damping of geometrically nonlinear vibrations of laminated composite structures. This lacking provides an ample scope for further work.

Conventional laminated composite structures are characterized by high strength to weight and high stiffness to weight ratios. But, the mismatch of material properties at the interface of two adjacent laminae may cause initiation of delamination in the laminated composite structures. The lamina of conventional unidirectional fiber-reinforced composite material may be tailored in such a way that the fibers are longitudinally aligned in the plane parallel to its top or bottom surface but the fiber orientation angle varies along the thickness of

the lamina according to some power-law [160-162] such that the graded material properties along the thickness direction can be attained. The resulting lamina becomes a functionally graded (**FG**) generally orthotropic layer and its properties at any point can be determined from the nine independent material properties of the orthotropic unidirectional fiber-reinforced composite material. If such laminae are stacked according to a designed stacking sequence such that the fiber orientation angles at the interface between any two adjacent layers are identical then the material properties of the resulting laminated composite structure vary along the thickness direction in a continuous manner and thereby the initiation of delamination may be avoided. This laminated composite structure may be called as an orthotropic **FG** laminated composite structure. However, the research in line with this new concept of developing advanced laminated composite structures is very limited. Recently, Panda and Ray [163] carried out investigations on the active control of **FG** laminated composite plates using piezoelectric fiber reinforced composite material as the material of the constraining layer of the **ACLD** treatment. But the study on the **FG** laminated composite shells has not yet been reported.

Considering the above mentioned aspects into account, the main objective of the present research is directed to investigate the performance of the vertically/obliquely reinforced 1-3 **PZC** and **AFC** materials as the candidate materials of the constraining layer of the **ACLD** treatment for controlling the geometrically nonlinear vibrations of the substrate beams, plates and shells. In order to fulfill this objective the following theoretical analyzes have been carried out:

1. **ACLD** of geometrically nonlinear vibrations of laminated composite beams, plates and shells using the vertically/obliquely reinforced 1-3 **PZC** materials [164 - 167].

2. Performance of the active fiber composite (**AFC**) as the material of the constraining layer of the **ACLD** treatment for controlling the geometrically nonlinear vibrations of laminated composite shells.
3. Active control of geometrically nonlinear vibrations of the doubly curved **FG** laminated composite shells under a thermal environment using the vertically/obliquely reinforced 1-3 **PZC** and the **AFC** materials.

1.6 Contributions

The following contributions in the field of smart structures have been made towards the preparation of the dissertation:

1. Three dimensional **FE** models are developed to study the **ACLD** of geometrically nonlinear vibrations of the smart laminated composite beams, plates and shells. The constrained layer of the **ACLD** treatment is considered to be composed of either the vertically/obliquely reinforced 1-3 **PZC** or the **AFC** material.
2. For time domain analysis of **ACLD** of geometrically nonlinear vibrations of laminated composite structures, the constrained viscoelastic layer of the **ACLD** treatment has been modeled by the **GHM** method.
3. In order to exploit the transverse actuation by the constraining 1-3 **PZC** layer of the **ACLD** treatment, transverse normal deformation in all layers of the overall laminated structures are considered. Emphasis has been placed on investigating the effects of variation of the piezoelectric fiber orientation angle.
4. A novel concept of orthotropic **FG** laminated composite shell has been proposed. **ACLD** of geometrically nonlinear vibrations of such **FG** shells under a thermal environment using 1-3 **PZC** and **AFC** materials has been investigated by developing three dimensional **FE** models.

1.7 Organization of the thesis

A brief introduction and review of literature on the linear and nonlinear analyses of smart structures have been presented in Chapter 1. The research on **PZC** materials and the **ACLD** treatment has also been reviewed in this chapter. Subsequently, the scope and objectives of the present research are outlined.

Chapter 2 is concerned with the **ACLD** of geometrically nonlinear vibrations of the laminated composite beams. The constraining layer of the **ACLD** treatment is made of the vertically reinforced 1-3 **PZC** material. The performance of this **ACLD** treatment for controlling the nonlinear vibrations of the laminated beams has been demonstrated by the **FE** analysis.

The performance of the vertically/obliquely reinforced 1-3 **PZC** material as the material of the constraining layer of the **ACLD** treatment for controlling the geometrically nonlinear vibrations of the laminated composite plates has been demonstrated in Chapter 3 by the **FE** analysis.

Three dimensional **FE** model for the analysis of **ACLD** of geometrically nonlinear vibrations of the doubly curved laminated composite shells using the vertically/obliquely reinforced 1-3 **PZC** and the **AFC** material has been developed in Chapter 4. The effect of piezoelectric fiber orientation angle in the 1-3 **PZC / AFC** constraining layer on the performance of the **ACLD** treatment for controlling nonlinear vibrations of the shells has been studied.

Chapter 5 deals with the **ACLD** of geometrically nonlinear vibrations of the orthotropic **FG** laminated composite doubly curved shells under a thermal environment using vertically/obliquely reinforced 1-3 **PZC / AFC** material. The effect of piezoelectric fiber orientation angle in the obliquely reinforced 1-3 **PZC** and the **AFC** constraining layer on the performance of **ACLD** treatment for controlling nonlinear vibrations of the orthotropic **FG** laminated composite shells has also been studied.

Finally, the major conclusions from the work carried out and the future scopes for further research are outlined in Chapter 6. The list of references and the appendix are provided at the end of the dissertation.