Efficient Multifield Finite Element Formulation with Layerwise Mechanics for Smart Piezolaminated Shells Featuring Delaminations and Debonding

Abstract

Anisotropic fiber-reinforced composite and soft-core sandwich laminates are finding increased usage in modern structures such as aircrafts, spaceships, automobiles, marine propellers, wind turbine blades and bridges. For their improved performance and reliability, it is often required to have inbuilt advanced features like active vibration control, adaptive shape control and real time structural health monitoring (SHM), by equipping them with surface-bonded or embedded piezoelectric patch sensors and actuators. Such smart laminated structures are, however, prone to delamination damages in the host laminate and debonding of transducers. Computationally efficient and accurate models for these structures are essential particularly for problems involving their dynamics, vibration control and wave propagation analysis, and for the inverse problem of damage detection in model-based SHM methods.

In this thesis, a new efficient multifield finite element (FE) formulation with layerwise mechanics is presented for the analysis of smart piezolaminated shells featuring multiple delaminations and transducer debondings. It represents the first two-dimensional (2D) model presented for this purpose. The laminate theory is based on the efficient coupled zigzag theory (ZIGT) considering a layerwise description of the inplane displacements and the normal deformation in the piezoelectric layers due to the transverse piezoelectric coefficient (d_{33}-effect), without introducing any additional dispacement variables beyond the smeared third order theory. A piecewise quadratic through-thickness variation of the electric potential along with the provision of satisfying the equipotential condition of electroded surfaces is adopted. A quadrilateral facet shell element is developed having four kinetic nodes and one electric node which allows equipotential condition over a number of elements under an electrode resulting in a significant reduction in the number of electric degrees of freedom (DOFs). The local axes of the facet shell element are taken in such a way that they are optimally parallel to either set of its opposite sides. The delaminations and debondings are modeled using the region approach based on the free mode assumption. A novel hybrid point-least squares (HPLS) method is proposed for satisfying the continuity of the nonlinear displacement field at the delamination, debonding and patch fronts. The conti-

nuity conditions are imposed exactly by relating the nodal DOFs of the adjacent elements at these fronts through a transformation matrix. Before imposing the continuity conditions, the nodal DOFs of the elements in the secondary segment are transformed to the local coordinate system of the respective adjacent elements in the intact/primary segment. The methodology is generic for multiple patch transducers, delaminations and debondings, occuring at any arbitrary interface and inplane locations. For active vibration control, the FE model is transformed to the reduced order modal space considering the first few modes, and is expressed in the state space format. The output feedback linear quadratic Gaussian (LQG) optimal controller is adopted for the vibration control.

The developed element is made to pass through the three-problem standard obstacle course test and is found to be among the best performers. By analyzing ultra thin shells, it is also established that the element is free of shear and membrane locking problems. Next, the element is critically assessed for its accuracy for the static and free vibration response of elastic singly and doubly curved composite and highly inhomogenous sandwich deep shells. The multiphysics element is also assessed for the stress analysis under mechanical and electric potential loadings, and for the free vibration response of various smart piezolaminated deep shells with different boundary conditions, covering both actuator and sensory roles of the piezoelectric layers. The results of all the problems considered are shown to be very accurate in comparison with the analytical 3D piezoelasticity solutions or full-field 3D FE solutions for both the elastic and piezolaminated smart shells. The performance of the element is then assessed for the free vibration analysis of beams, plates and shells with multiple delaminations in comparison with available theoretical and experimental results, and newly obtained 3D FE solutions. The relative performance of the proposed HPLS method and the other available methods of satisfying continuity is also studied. The accuracy of the element is then examined for the free vibration response of smart laminated plates and shells with delaminations and debondings of patch transducers. Finally, the effect of delaminations and transducer debondings on the active vibration control behavior of smart laminated plates and shells is studied. The results have shown that the developed coupled-field FE provides a simple, computationally efficient, robust and accurate tool for dynamics and control of moderately thick to thin multilayered smart plates and shells featuring delaminations and transducer debondings.