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Thermomechanical Extended Layerwise Method for laminated composite plates with multiple delaminations and transverse cracks

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ABSTRACT

A Thermomechanical Extended Layerwise Method (TELM) is developed for the laminated composite plates with multiple delaminations and transverse cracks. The discontinuity of displacements and temperature induced by multiple delaminations is simulated by strong discontinuous function while the discontinuity of strain and temperature gradient between dissimilar layers is modeled by a weak discontinuous function. Transverse cracks are modeled using classical Extended Finite Element Method (XFEM). The coupled thermomechanical variational principle is employed to derive the Euler equations and the discrete forms. Since the displacement and temperature fields are solved simultaneously, a fully coupled time integration method is developed based on the Newmark integration algorithm and Crank-Nicolson scheme. The strain energy release rate for multiple delamination fronts and stress intensity factors for transverse cracks are calculated by the Virtual Crack Closure Technique and the Interaction Integral Method, respectively. The proposed method is applied to the steady-state thermomechanical problems, elastic and thermomechanical dynamic problems for isotropic and composite plates with transverse cracks and multiple delaminations.

1. Introduction

With accelerating use of aeronautic and aerospace composite structures in the high-temperature operating conditions, numerous research works were published on heat transfer and thermal stress analysis of laminated composite plates and shells during the last three decades [1–3]. In order to uncouple heat transfer and thermal stress analyses, the thermomechanical dissipation was neglected in most of the existing analytical and numerical models [4,5]. In addition, considerable research works were carried out under the steady-state assumption by considering the thermal effect as an additional term in the constitutive relationship. However, when the dynamic disturbances resulting from the heat flow are considered, the thermomechanical dissipation is of primary interest. Daneshjo and Ramezani [6] proposed a new mixed finite element formulation to analyze transient coupled dynamic thermomechanical problems for laminated composites and homogeneous isotropic plates by using the third-order shear deformation theory (TSDT). Based on the Reissner's mixed variational principle, Benjeddou and Andrianarison [7] developed a new heat mixed variational theorem, which is suited for the analytical and numerical analyses of fully coupled thermomechanical analysis of multilayered composites.

During the last three decades, numerous mathematical models for thermal analysis of laminated composite plates were formulated by using analysis theories of composite plates and shells, such as the three-dimensional theory of elasticity [8], Equivalent Single Layer Theories (ESLT) [9–12], Layerwise Theories (LWT) [5,13–16], Zig-Zag Theories (ZZT) [17,18] and so-called Carrera's Unified Formulation (CUF) [4,19]. Thermal stresses in laminated composite plates are induced during fabrication and service life. Due to the layerwise inhomogeneity, thermal stresses usually occur at interfaces with different fiber orientation (due to mismatch in thermal expansion coefficients). Although the ESLT is sufficiently accurate for predicting global elastic and thermal responses and is computationally less expensive compared to other higher order theories, it may exhibit considerable errors in local behavior at a ply level [20]. In such cases, refined analysis methods have been proposed to overcome some of the shortcomings of ESLT, such as the LWT [5].

The internal damage of laminated composites induced during fabrication and service life could reduce the strength significantly, but the resulting internal damages may not be detectable. If the internal damage is not detected and repaired on time, it may continuously grow and lead to complete structural collapse. The fracture problems of

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plates and shells has long been a research focus, and many analysis methods had been developed, such as the finite element method (FEM), extended finite element method (XFEM), phase-field model [21,22], meshfree methods [23], extended meshfree methods [24–26], peridynamics [27] and efficient remeshing techniques [28,29]. Rabczuk et al. [24–26] extended the meshfree methods for the arbitrary evolving through-the-thickness cracks in thin shells based on an intrinsic basis of third order completeness. Amiri and Areias [21,22] developed a phase-field analysis model for the Kirchhoff–love thin shells. The correct fracture behavior in bending were considered by two independent phase-fields of the lower and upper faces. Areias and Rabczuk [28] established a simple and efficient algorithm for the fracture analysis of plates and shells based on FEM, and it has algorithmic and generality advantages compared XFEM and classical tip remeshing schemes. Chau-Dinh et al. [30] presented a phantom-node method to simulate the cracks of shells. In this approach, since three-nodes elements were overlapped on the crack, the arbitrary shape cracks were independent on the meshing. Nguyen et al. [31] developed an extended isogeometric element method (XIGA) for the through-the-thickness cracks in thin shell by using the Non-Uniform Rational B-Splines (NURBS) and Kirchhoff–Love theory. Silani et al. [32–34] proposed a concurrent multiscale methods to model damage in clay/epoxy nanocomposites based on the Arlequin method which couples two overlapping scales. In addition, a detailed reviews of crack tracking techniques can be found in Ref. [35], especially the meshfree methods. Ren et al. [27] developed a dual-horizon peridynamics formulation, and the concept of dual horizon was introduced to consider the unbalanced interactions between the particles with different horizon sizes.

Due to layered and orthotropic characteristics, laminated composites may fail in various modes, such as delaminations, transverse cracks, matrix cracks, fibre breakage and fibre/matrix debonding. The first two modes are dominant, especially for failure induced by a low-velocity impacts. Considerable research works focused on transverse cracking [36,37], delamination [38–46] and interaction between the two [47–53] under static and dynamic loads, but consideration of the thermal shock is quite rare. Clearly, there is a need for fully coupled fracture analysis models capable of resolving the onset and growth mechanisms of the composite damage under combined thermal and mechanical loads.

For the transverse cracks, Kim et al. [54] calculated the stress intensity factor (SIF) based on the thermal weight function method and the finite element method for vessels and pipes with cracks subjected to thermal shock. Jin and Batra [55] analyzed thermal stresses and SIF in an edge-cracked strip of functionally graded material subjected to a thermal shock at the cracked edge. Hosseini-Tehrani et al. [56] developed boundary element method using Laplace transform in time domain for the cracked strip under coupled thermomechanical loading. Takeda et al. [57] studied the thermomechanical behavior of cracked woven glass/epoxy laminates with temperature-dependent material properties based on three-dimensional finite elements models. Duflot [58] applied the XFEM to the thermal stress analysis. Both thermal and mechanical fields were enriched by the XFEM to represent discontinuous temperature, heat flux, displacement and traction across the crack surface, as well as singular heat flux and stress at crack tips. Zamani and Eslami [59,60] applied XFEM to the cracked body under mechanical and thermal shocks. The Newmark and the Crank-Nicolson time integration schemes were used to integrate discrete elastic and thermal equations, respectively.

Yin [61] studied the thermomechanical postbuckling of a delaminated strip. Panda and Pradhan [62] presented two sets of three-dimensional finite element models for the superimposed thermomechanical loaded composite laminates with embedded interfacial elliptical delaminations. Shu [63] developed an analysis model for the thermomechanical response of composite laminates with weak interfaces. The discontinuity of interfacial displacements and temperature was depicted by the interfacial constitutive relations and a thin thermally conducting layer between two weakly bonded layers, respectively. Tahani and Yousefsani [64] analyzed adhesively bonded composite joints with structural imperfection in the adhesive layer based on the Reddy's LWT. The multilayer thermal barrier coatings (TBCs) are susceptible to delamination, thermal mechanisms of delamination in TBCs has been an area of intensive research during the last three decades. Various analytical, numerical and experimental methods were developed to predict the onset and growth mechanisms of the delamination at the TBCs/substrate interface [65–67].

Existing works mainly focus on the thermomechanical fracture problem of delamination or transverse cracking, but only few studies have been conducted on multiple delaminations and problems in which the delamination and transverse cracks interact. In the present work, the thermomechanical fracture problem of the laminated composite plate with multiple delaminations and transverse cracking is studied based on the Extended Layerwise Method (XLWM) [48–53]. Fully coupled thermomechanical dynamic governing equations are developed, together with the time integration scheme. The remainder of this manuscript is organized as follows. Section 2 presents the displacement and temperature fields assumptions along the thickness direction of a laminated composite plate. The strong discontinuous functions are employed to represent the displacement and temperature discontinuity induced by multiple delaminations, and weak discontinuous functions are introduced to model the strain and temperature gradient discontinuity at the interface. The variational form is presented in Section 3, together with the Euler equations and natural boundary conditions. The constitutive equations and finite element formulations are formulated in Sections 4 and 5, respectively. In Section 6, the time integration, interaction integral of SIF and Virtual Crack Closure Technique (VCCT) are detailed. For the fully coupled governing equation, the time integration algorithm is developed based on the Newmark integration and the Crank-Nicolson schemes. Section 7 presents several numerical examples to verify the proposed method for the steady-state and time-dependent thermomechanical problems of isotropic and composite plates. Finally, conclusions are drawn in Section 8.

2. Displacement field of the XLWM for thermomechanical problems

In our previous studies, an XLWM was developed for the composite laminated beams, plates and shells with multiple delaminations and transverse cracks [48,53,52,50,51]. The displacement field was discretized with linear Lagrange interpolation functions, one-dimensional weak and strong discontinuous functions. The strong and weak discontinuous functions were introduced in the displacement field along the thickness direction to model the displacement discontinuity induced by delaminations and strain discontinuity due to dissimilar layer, respectively. The transverse cracks were introduced in the in-plane displacements based on the classical XFEM. In the proposed Thermomechanical Extended Layerwise Method (TELM), the displacements and temperature at a point (x,y,z) in the laminated composite plates with multiple delaminations is expressed as

$$\begin{aligned} u_\alpha(x,y,z,t) &= \sum_{[k=1]}^{N+2} \phi_k(z) u_{\alpha ik}(x,y,t) + \sum_{[k=1]}^{N_D} \Xi_k(z) u_{\alpha lk}(x,y,t) \\ &\quad + \sum_{[k=1]}^{N} \Theta_k(z) u_{\alpha rk}(x,y,t) \\ \theta(x,y,z,t) &= \sum_{[k=1]}^{N+2} \phi_k(z) \theta_{ik}(x,y,t) + \sum_{[k=1]}^{N_D} \Xi_k(z) \theta_{lk}(x,y,t) \\ &\quad + \sum_{[k=1]}^{N} \Theta_k(z) \theta_{rk}(x,y,t) \end{aligned} \tag{1}$$

where $\alpha = 1,2,3$ denotes components in x,y and z directions, where z denotes the thickness direction of composite plates. $u_{\alpha ik}$,$u_{\alpha lk}$ and $u_{\alpha rk}$ are the nodal degrees-of-freedom, nodal degree-of-freedom representing