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Improved finite element viscoelastic analysis of laminated structures via the enhanced first-order shear deformation theory

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ABSTRACT

In this paper, a new finite element formulation based on the enhanced first-order shear deformation theory (EFSDT) is developed for the efficient and accurate viscoelastic analysis of multilayered composite and sandwich plates. The main objective herein is to systematically establish the relationship between two independent theories (i.e., third order zigzag model and conventional FSDT) in the Laplace domain via the strain energy transformation. For viscoelastic problems, the complexity of dealing with viscoelastic materials can be simplified by introducing the concept of Laplace transform. Based on the predefined relationship, the proposed finite element model has the same computational advantage as that of the conventional FSDT (5-DOFs), while allowing the improved local layer-wise distributions of viscoelastic responses via the recovery procedure. In the model, a simple eight-noded isoparametric plate element is employed to analyze the viscoelastic response of multilayered composite and sandwich plates. Furthermore, for the isotropic material, a reference solution based on the three-dimensional finite element model is newly introduced to evaluate the accuracy of the viscoelastic behavior. To demonstrate the perforance of the proposed finite element model, the results obtained are compared to those of the conventional FSDT and three-dimensional finite elements with commercial software (i.e., ABAQUS).

1. Introduction

In the recent past, lightweight and high specific strength materials have increasingly been demanded in high-performance industrial facilities, especially in the automotive and aerospace fields. Because advanced structures made of laminated composite panels have considerable advantages such as high stiffness-to-weight ratio as well as design flexibility, they have attracted considerable attention in various fields of engineering. Based on their sequentially stacked nature, laminated structures inevitably exhibit a relatively weak transverse stiffness. Thus, thorough consideration is needed to accurately predict the through-the-thickness distributions of the transverse stresses that induce structural failures such as layer delamination.

In order to accurately predict the transverse behaviors of laminated structures, various equivalent single-layer models (i.e., polynomial-based and zigzag theories) have been developed over the last three decades [1–46]. Among them, polynomial-based theories (i.e., conventional FSDT and HSDT) have a major drawback in predicting inter-laminar local stress distributions because the transverse shear stress conditions at the surfaces as well as layer interfaces are not enforced in the polynomial-based model [1–7]. To mitigate this problem, some analysis models based on zigzag displacement field (i.e., EHOPT and RHSDT) have been developed [8–22]. Especially, the efficient higher-order plate theory (EHOPT) shows excellent performance in predicting the behavior of the laminated structures [11–18]. However, these zigzag analysis models require the non-conventional C^1 shape function (slope continuity condition along the boundary of the element) for the finite element (FE) implementation, which is not available in commercial FE software

There have been many efforts to circumvent the C^1-class problem by employing sophisticated approaches [23–41]. As one of most attractive schemes, refined first-order shear deformation theories have been proposed based on the intuitive manners [23–30] or more rigorous approaches [31–37]. Kim and Cho suggested the enhanced first-order shear deformation theory (EFSDT) to take advantage of both the simplicity of the conventional FSDT and the accuracy of the EHOPT [31–33]. They systematically bridged the conventional FSDT and EHOPT by transforming the strain

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energy of the EHOPT into FSDT-like strain energy. According to the relationship between them, the EFSDT can implement C^0-based finite element analysis (FEA) to improve its compatibility with commercial FE software. In addition, the accuracy of the results can be further improved by employing the EHOPT displacement field as the recovery procedure. More recently, C^0-based higher-order zigzag theories have also been developed to address the aforementioned numerical problem [38–41]. In the C^0-based zigzag model, derivatives of the transverse displacement field are systematically eliminated by the transverse shear stress conditions. Therefore, these analysis models can improve the computational efficiency because the C^0-continuous kinematic interpolation functions are only required in the FE implementation.

Meanwhile, all of the aforementioned analysis models (FSDT, EHOPT, RHSDT, and EFSDT) are bounded by the linear elastic analysis of laminated structures. However, fiber-reinforced composite materials have anisotropic viscoelastic characteristics because they are made of elastic carbon fiber and temperature-sensitive viscoelastic epoxy materials. These viscoelastic behaviors (creep strain and stress relaxation) can lead to significant time-dependent failures when the composite structures are located in a severe engineering environment such as in high hygrothermal conditions. Therefore, the viscoelastic behaviors of laminated composite and sandwich structures need to be considered comprehensively in order to provide reliable solutions in high temperature environments [47–49].

To reflect the viscoelastic effects on laminated composite and sandwich plates, numerous approaches have been made over the past three decades. Numerical procedures, based on the Taylor and trapezoidal time integration method, were suggested to solve the viscoelastic Boltzmann superposition equation which is expressed as a time-integral form [50–55]. However, these numerical methods require massive computational resources because their accuracies depend on each time step, Δt. Especially, the error rate of the solution becomes significant for long-term viscoelastic problems.

To overcome these limitations, other efficient methods based on the Laplace or Fourier transform have been introduced in order to examine the linear viscoelastic behaviors of laminated composite structures [56–62]. On the basis of domain transformation, a linear viscoelastic problem can be solved in the Laplace domain. Further, the solutions in the real-time domain are obtained by applying numerical techniques for inverse Laplace transform. These effective techniques can provide a reliable solution for long-term viscoelastic problems because their calculation process is independent of the time integration. Recently, Nguyen et al. applied the concept of Laplace transform to a number of analysis models (FSDT, HSDT, and EHOPT) for the reliable viscoelastic analysis of laminated composite and sandwich plates [60,61]. In the EHOPT for the viscoelastic problem, applying the transverse shear stress continuity conditions at the layer interfaces and stress-free condition at top and bottom surfaces of the laminates are extremely complicated since the linear viscoelastic materials include a time integration process in the constitutive relation. In terms of computational efficiency, the scheme of Laplace transform provides an important benefit for enforcing the transverse shear stress continuity conditions as well as transverse shear stress surface free conditions in viscoelastic problems.

In order to develop a simple yet accurate viscoelastic analysis model, an analytical model of EFSDT for viscoelastic composite and sandwich plates has been suggested [58]. By systematically establishing the relationships between the two independent theories (conventional FSDT and EHOPT) in the Laplace domain, this enhanced analysis model can provide reasonable viscoelastic solutions that take advantage of the accuracy of EHOPT and the efficiency of FSDT.

For the viscoelastic FEA, a number of numerical approaches have been proposed to analyze the static and dynamic behaviors of viscoelastic composite structures [62–66]. Further, Nguyen et al. extended the EHOPT in the Laplace domain to the three-noded Specht's element formulation for the viscoelastic analysis of laminated structures with arbitrary boundaries and loading conditions [62]. This FE model can provide accurate layer-wise distributions of viscoelastic behavior. However, its usability is limited because technical problems occur with the nonconforming element based on the Specht's shape functions when linking with commercial FE software. Moreover, in the bending problem, the three-noded triangular element gives a relatively stiffer solution compared to a quadrilateral element. In other words, accurately predicting the viscoelastic behavior of laminated structures with a simple FE model is still a challenging issue.

In this paper, as further work to improve the applicability of the viscoelastic numerical model, a simple FE formulation based on the viscoelastic EFSDT is developed and tested numerically. By applying the concept of Laplace transform, transverse shear stress conditions at the surfaces and the layer interfaces can be easily enforced because the time integral form of the Boltzmann superposition equation can be simplified in the Laplace domain. Hence, the computational efficiency of the proposed FE model can be further improved compared to the linear elastic EFSDT counterpart in the process of viscoelastic FEA. Furthermore, based on the scheme of strain energy transformation, the proposed FE model can embrace the characteristics of both EHOPT and the conventional FSDT. The main technical contributions of the present work can be summarized as follows:

- A finite element realization, which is a simple eight-noded isoparametric quadrilateral plate element, is employed to accurately analyze the viscoelastic behavior of laminated structures with arbitrary boundary and loading conditions.
- For the case of laminated isotropic plates, three-dimensional (3-D) viscoelastic FEA is performed to provide a reference solution for the viscoelastic behavior.

In order to evaluate the viscoelastic behavior, laminated structures with two types of boundaries and loading conditions were considered as numerical examples. The numerical performance of the proposed FE model was demonstrated by comparing its results with the 3-D FEM solutions based on the commercial FE software (i.e., ABAQUS) as well as the results of conventional FSDT.

2. Theoretical formulation

Rectangular laminated composite and sandwich plates made of carbon fiber reinforced orthotropic materials were considered as a viscoelastic numerical model. The geometry and coordinates of the laminated structures are given in Fig. 1. Unless otherwise noted,

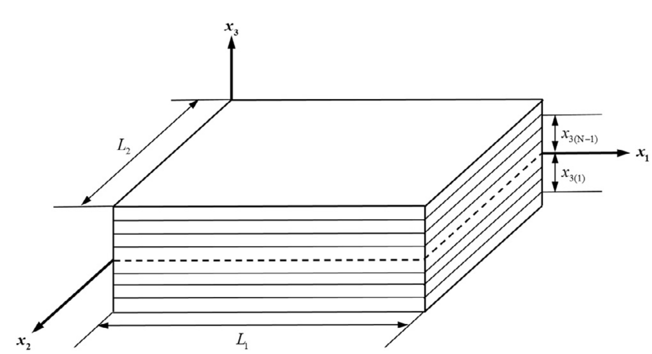

Fig. 1. Geometry and coordinates of the laminated composite plates.