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Mixed integer multi-objective optimization of composite structures with frequency-dependent interleaved viscoelastic damping layers

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ABSTRACT

The optimal design of composite structures with frequency-dependent interleaved viscoelastic damping layers is addressed in this paper. The design objective of simultaneously maximizing structural modal damping and frequency and minimizing weight is considered. The design problem is formulated as a mixed integer multi-objective optimization problem and solved by evolutionary algorithm. A layerwise finite element model is used. The Pareto-optimal solutions are obtained for two applications. The results show that the approach is quite useful in integrally designing such kind of composite structures. In particular, it is shown that the inserting position and the material type are two important design parameters.

1. Introduction

Fiber reinforced composites are extensively used in aerospace, civil and automotive industries due to their high specific stiffness, high specific strengths and tailorable anisotropic elastic properties. Although fiber-reinforced composites exhibit higher energy dissipation capacity than common metals, the amount of damping is still not sufficient for many applications especially under severe vibration circumstances [1]. In past decades, a number of works [2–6] to improve the damping of composite structures have been concentrated on inserting viscoelastic damping layers between the base composite laminate. By this hybrid technique, the damping capacity of composite laminate can be increased many times by the shear deformation induced between the soft damping layer and the stiff constraining layer. However, due to interleaving soft material layers within stiff laminate, the mechanical analysis and design optimization of these structures becomes difficult and challenging.

Many works have been done on dynamic analysis of viscoelastic laminated composite structures. For example, DiTaranto and Blasingame [7] proposed analytical solutions for composite viscoelastic beams. Rao et al. [8] presented closed-form solutions for resonance frequencies and modal loss factors of laminated composite beams with multiple viscoelastic layers by the energy formulation and Ritz method. Zhou et al. [9] analytically studied the effects of various geometry and physical parameters on the resonance frequencies and modal loss factors of a composite tube with embedded viscoelastic layers. Finite element method is also used for analyzing viscoelastic sandwich structures by many researchers. Lu et al. [10] compared finite element to experimental results for three layered damped viscoelastic composite plates. Rikards et al. [11] studied the damping features of laminated visco-elastic sandwich beams using finite elements. Rao et al. [12] proposed a finite element based modal strain energy method to analyze laminated composite beams with embedded multiple damping layers. Three dimensional solid elements were used to model the viscoelastic material (VEM) and shell elements to discretize the elastic layers in their study. Akoussan et al. [13] elaborated a model for multilayered laminated viscoelastic sandwich plates and proposed a new solution procedure to perform parametric studies of damping characteristics of these structures. Zhang et al. [14] developed a detailed 3D finite element model for predicting the modal loss factor of laminated composite beams with integral viscoelastic layers. The frequency dependence of viscoelastic damping materials was considered. It is concluded that to accurately represent the strain energy induced by the shear of the viscoelastic layer, a full 3-D solid finite element model or a mixed solid/shell composite element model is generally necessary. Although those full 3D or mixed solid/shell finite element models can effectively describe the shear deformation inside the viscoelastic layer, a cumbersome and time consuming mesh generation process are commonly required. Moreover, the developed FE model is not well suited for the optimal design procedure due to the need to completely regenerate three dimensional FE mesh when changing the geometric parameters of damping treatment.

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In recent years, Reddy's layerwise theory [15], which is based on a piece-wise description of displacement field, has been applied to develop finite element beam/plate/shell formulations for analyzing viscoelastic laminated structures. Zapfe et al. [16] presented a discrete layer finite element for the dynamics analysis of viscoelastic laminated beams. A discrete layer annular finite element was proposed by Wang et al. [17] for vibration and damping analysis of a three-layered composite annular plate with a viscoelastic mid-layer. Moreira et al. [18] developed a generalized layerwise plate finite element for multi-layer viscoelastic damped structures. A full layerwise shell finite element considering frequency dependent material properties was proposed by Oh et al. [19] for cylindrical laminates with viscoelastic layer. Araujo et al. [20] presented a finite element model for composite laminates with frequency dependent viscoelastic core using mixed layerwise approach, by considering a high order shear deformation theory to represent the displacement field of viscoelastic layer and a first order shear deformation theory for the displacement files of adjacent laminated face layers. Ferreira et al. [21] presented a layerwise finite element model based on Carrera's Unified Formulation for the analysis of composite laminated plates with a viscoelastic core.

It can be found that a significant simplification in the spatial finite element modeling of multilayer structures can be achieved by using a layerwise finite element model since it maintains a 2-D type data structure. In addition, the element stiffness matrix can be computed much faster for layerwise element by performing in-plane and out-of-plane integration separately [22]. In this paper, to simplify the modeling and optimization process, a quadrilateral plate finite element based on the layerwise theory is developed for modeling hybrid composite laminates with interleaving viscoelastic layers.

Design optimization is an important procedure to ensure achieving desired structural mechanical and damping capacities for hybrid viscoelastic composite laminates. Some researchers formulate this design problem as a single-objective optimization problem. Araújo et al. [20,23] conducted a single objective constrained optimization for the maximization of modal loss factor of viscoelastic laminated composite structures, using a gradient based algorithm and mixed layerwise finite element model. Montemurro et al. [24] presented a genetic algorithm based optimization technique for the design of damping properties of hybrid elastomer/composite laminates. The only optimization objective was to maximize the first N modal loss factors. Le Maout et al. [25] maximized damping loss factors of a hybrid elastomer/composite sandwich plate taking the total number of layers, their respective thicknesses, their fiber orientations, and the position of the visco-elastic core, and the stacking sentence as design variables. A layerwise optimization method was proposed by Li et al. [26] to design the damping capacity of laminated rectangular plates under general edge conditions using the analytical optimization technique. Montemurro et al. [27] proposed a two-level procedure for the global optimization of the damping behavior of composite laminated plates with elastomer patches.

The presence of soft viscoelastic layers in composite laminate increases the structural damping capacity, while it changes the overall mechanical properties of the composite structure and increases the weight [28]. In real engineering practice, these conflicting design performances need to be considered simultaneously. Therefore, it is natural to formulate a multi-objective optimization problem instead because multi-objective optimization can balance all aspects of design performance and output a set of flexible solutions [29]. Recently, the multi-objective optimization of viscoelastic laminated structures gradually attracts some attention. Multi-objective optimization of viscoelastic laminated composite structures based on genetic algorithm and ABAQUS finite element model was presented by Araújo et al. [23]. Madeira et al. [30,31] presented a multi-objective method for optimization of viscoelastic laminated sandwich structures for minimizing weight and material cost and maximizing the modal loss factors. The new developed derivative-free algorithm, called direct multi-search (DMS) [50] are used as the optimization tool in their work. Xu et al. [32] proposed a multi-objective optimization model for constrained layer damping structures, and only frequency-independent material properties were considered. Hamdaoui et al. [33] presented a multi-objective optimization approach to choose the most appropriate frequency dependent viscoelastic material for a three-layered rectangular composite beam for low mass and high damping.

In this paper, we present an optimal design method for hybrid composite laminates with interleaved viscoelastic damping layers under general edge conditions using a mixed integer multi-objective optimization method. A quadrangular plate finite element based on the layer-wise theory is developed to model multi-layered hybrid composite laminates under general edge conditions. Frequency-dependent material properties are considered. An evolutionary multi-objective algorithm handling discrete design variables is implemented to find a global optimum. The aim is to obtain designs that give simultaneously low mass, high natural frequency and high modal loss factors. In Section 2, the layer-wise plate finite element model is presented and validated. The optimal design formulation and implementation of the evolutionary multi-objective algorithm are presented in Section 3. In Section 4, the optimization cases are presented. The results are given and discussed in Section 5.

2. Layerwise finite element modeling

2.1. Layerwise plate finite element

A quadrilateral layerwise plate element is developed and applied to model viscoelastic hybrid multilayered composite laminates. The kinematics is described by the layerwise theory based on the first-order shear deformation assumption in each layer, which was also used in Ref. [34]. Fig. 1 represents a section of an n-layer hybrid composite laminate. According to the layerwise theory, each layer is modeled as a thick plate fulfilled to the first-order shear deformation theory. The middle surface of the bottom layer is chosen as the reference plane and its displacement components are the reference displacement components. The displacement of the other points on the plate is defined with reference to the displacement of the reference plane.

Since the first-order shear deformation is assumed in each layer, the in-plane displacement components show a zig-zag

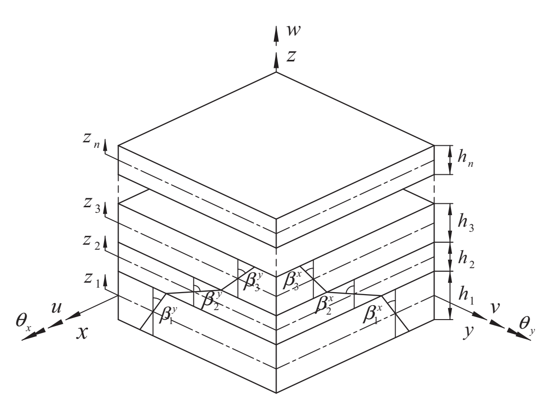

Fig. 1. Kinematic model of the layer-wise theory.