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Simplification of finite element modeling for plates structures with constrained layer damping by using single-layer equivalent material properties

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ABSTRACT

As an effective approach of suppressing vibrations, the constrained layer damping (CLD) has drawn wide attention from the automotive and aerospace industries. However, most of the existing investigations focus on the beam structures with CLD and few studies have been done on the plate structures with CLD. Considering the practical applications, this work studies the finite element (FE) modeling of plate structures with CLD by considering the shear and extension strains in all of three layers. To reduce the computational cost and ensure the accuracy, a simplified single-layer equivalent method is originally proposed to model the plate structure with CLD based on the equivalent material properties. In this method, the equivalent material properties are obtained by defining a new equation which includes the equivalent bending stiffness. By nonlinear regression of these responses at resonance frequencies, the equivalent bending stiffness can be obtained, and the plate structure with CLD can be regarded as a regular single-layer plate for modeling. The simulation result shows that the proposed simplified single-layer equivalent method using single-layer equivalent material properties is efficient and accurate for modeling plate structures with CLD.

1. Introduction

In recent decades, the vibration control has been an active topic with the effective solution of constrained layer damping (CLD) in both automotive and aerospace industries [1–8]. The CLD structure consists of three layers. The constraining layer and base layer with the elastic material sandwich a damping layer which is made up of viscoelastic material [9–11]. With the relative motion of the constraining layer and base layer, a deformation of the damping layer is generated to consume a portion of the strain energy, thus achieving the vibration damping [12–14]. Considering the complexity and geometry properties of the material, it is a challenge to model the CLD structure.

Recently, various researches have been done on the study of CLD structures. Panda et al. [15] studied the performance of the active CLD for beam structures. Özer [16] conducted the modeling and controlling of a fully dynamic three-layer cantilever beam with active constrained layer by using the vibrational approach. Hujare and Sahasrabudhe [17] investigated the damping performance of different viscoelastic material for beams experimentally using CLD treatment. Even though these research facilitates the development of CLD structures, existing studies mainly focus on beam structures, and only few attention has been paid on the modeling of plate structures. Considering the widespread application of plate structures in various fields of engineering, this work tries to investigate the modeling of plate structures with CLD.

As for the numerical analysis of the structural vibrations, the finite element modeling is a good method which has been extensively and efficiently applied to investigate the vibrational behavior of structures including the viscoelastic material [1,10,18,19]. When modeling this plate structure using finite element method, the plate is meshed into many finite elements. Meanwhile, the degrees of freedom should be well defined with fully consideration of the shear, compression and extensional damping. With three layers, the FE modeling of plate structures with CLD is very complicated due to the involved overwhelming degrees of freedom, especially for the plate structure with a

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quite thin damping layer. As a result, the FE modeling of plate structures with CLD cannot be well applied in engineering design. However, the precise results might not be obtained when reducing the degrees of freedom and meshed elements. To solve this problem, a simplified method should be developed to reduce the computational cost and ensure high accuracy. In Ref. [20], a simplified FE modeling for beam structures with CLD is presented by using single-layer equivalent finite element method. The equivalent material properties are calculated and then a regular beam is constructed. Considering the simplicity and accuracy, this work also attempts to develop a simplified equivalent single-layer modeling for plate structures with CLD using single-layer equivalent material properties.

In this research, a simplified single-layer equivalent method is proposed to model the plate structure with CLD based on the equivalent material properties for achieving low computational cost and high accuracy. The rest of this paper is organized as follows. Section 2 presents the FE modeling for the plate structure with CLD. Subsequently, the simplified single-layer equivalent model of the plate structure with CLD is described in Section 3. Finally, conclusions are given in Section 4.

2. Finite element modeling of plate structures with CLD

This section presents the FE modeling of the plate structure with CLD. First, some assumptions are made, and then the modeling process is presented. Finally, the model developed is evaluated by simulation results.

2.1. Assumptions

Before introducing the finite element modeling for plate structures with CLD, the following assumptions are made [21–24]:

(1) The transverse displacement of each layer is identical at the same position;
(2) The longitudinal displacement caused by the shear or extension strain is linearly distributed across the thickness of each layer;
(3) The slip does not occur among the layers.

2.2. Finite element modeling process

The plate structure is shown in Fig. 1. Layer 1, layer 2 and layer 3 are the constraining layer, damping layer and base layer, respectively. The transverse displacement is along with the z-axis, while the longitudinal displacements caused by the shear and extension strain are along with the x-axis and y-axis, respectively.

When modeling this plate structure using finite element method, the plate is meshed into many finite elements first. When meshing these

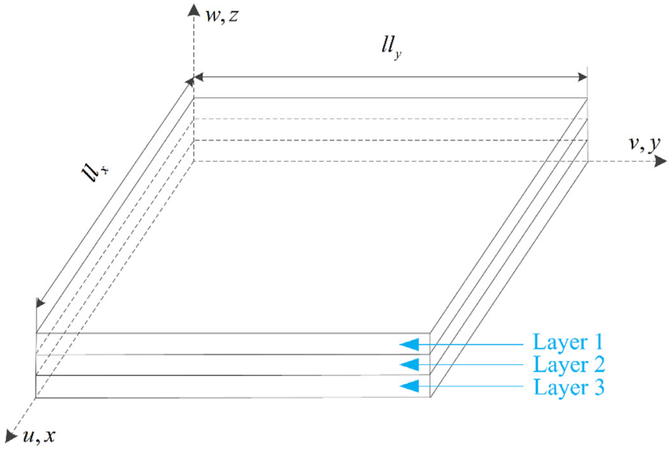

Fig. 1. Plate structure with CLD.

finite elements, n_x and n_y nodes are used in the directions of the x-axis and y-axis, respectively. As a result, $(n_x - 1) \times (n_y - 1)$ finite elements can be obtained for the plate structure with CLD. One finite element in the plate structure with CLD is shown in Fig. 2 based on the Zapfe's element in dealing with the beam structure [25]. In this plate finite element, both the shear strain and extension strain are considered with a high accuracy. To fully characterize the shear strain and extension strain and clearly represent the transverse displacement at each location of the plate, 25 degrees of freedom (DOFs) are defined for the plate finite element with one layer. Since there are three layers, the plate finite element with CLD has 41 DOFs. The DOF vectors can be expressed in the following equations [26,27],

$$\text{For } i^{th} \text{ layer } (i = 1,2,3):$$
$$\mathbf{U_i} = [u_{mi}, u_{m(i+1)}, v_{mi}, v_{m(i+1)}, w_m, w_1, u_{ki}, u_{k(i+1)}, v_{ki}, v_{k(i+1)}, w_k, w_2, w_3, w_4, u_{pi}, u_{p(i+1)}, v_{pi}, v_{p(i+1)}, w_p, w_5, u_{qi}, u_{q(i+1)}, v_{qi}, v_{q(i+1)}, w_q]$$
$$\text{For three layers}:$$
$$\mathbf{U} = [u_{m1}, u_{m2}, u_{m3}, u_{m4}, v_{m1}, v_{m2}, v_{m3}, v_{m4}, w_m, w_1, u_{k1}, u_{k2}, u_{k3}, u_{k4}, v_{k1}, v_{k2}, v_{k3}, v_{k4}, w_k, w_2, w_3, w_4, u_{p1}, u_{p2}, u_{p3}, u_{p4}, v_{p1}, v_{p2}, v_{p3}, v_{p4}, w_p, w_5, u_{q1}, u_{q2}, u_{q3}, u_{q4}, v_{q1}, v_{q2}, v_{q3}, v_{q4}, w_q] \tag{1}$$

where u_{ji} and $u_{j(i+1)}$ are the longitudinal displacements at the jth point ($j = m, k, p, q$) of the ith layer along with the x-axis; v_{ji} and $v_{j(i+1)}$ are the longitudinal displacements at the jth point of the ith layer along with the y-axis; and w_n is the transverse displacement at the nth point ($n = m, k, p, q, 1,2,3,4,5$). Based on the above definition of DOFs, the DOF in the plate structure can be expressed as,

$$n_{DOF} = 9n_xn_y + (3n_x - 2)(n_y - 1) + n_x - 1. \tag{2}$$

Given displacement field, the elastic strain energy and kinetic energy of the ith layer in the plate can be represented as [28–35],

$$V_i = \frac{1}{6}\iiint_{V_i} E_i\left(\left(\frac{\partial u_i}{\partial x}\right)^2 + \frac{\partial u_i}{\partial x}\frac{\partial u_{i+1}}{\partial x} + \left(\frac{\partial u_{i+1}}{\partial x}\right)^2\right) + 3G_i\left(\frac{\partial w_i}{\partial x} - \frac{u_i - u_{i+1}}{2H_i}\right)^2 + 3E_iI_i\frac{\partial^2 w}{\partial x^2} + E_i\left(\left(\frac{\partial v_i}{\partial x}\right)^2 + \frac{\partial v_i}{\partial x}\frac{\partial v_{i+1}}{\partial x} + \left(\frac{\partial v_{i+1}}{\partial x}\right)^2\right) + 3G_i\left(\frac{\partial w_i}{\partial x} - \frac{v_i - v_{i+1}}{2H_i}\right)^2\Bigg)dv, \tag{3}$$

$$T_i = \frac{1}{2}\rho_i\iiint_{V_i}(\dot{u}_i^2 + \dot{v}_i^2 + \dot{w}_i^2)dv, \tag{4}$$

where H_i is the thickness of the ith layer; and G_i are the Young's modulus and shear modulus of the ith layer, respectively; I_i stands for the second moment of area of the plate cross section; and ρ_i is the density of the ith layer.

For the ith layer of the plate finite element, the proposed displacement field can be organized as [30,36–39],

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \mathbf{B}\begin{bmatrix} u_i \\ u_{i+1} \\ v_i \\ v_{i+1} \\ w \end{bmatrix} = \mathbf{B}\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{bmatrix}\mathbf{U_i} = \mathbf{BFU_i} = \mathbf{NU_i} \tag{5}$$

where $\mathbf{B} \in R^{3\times5}$ and $\mathbf{F} \in R^{5\times25}$ are shape function matrices. The matrices $\mathbf{B}$ and $\mathbf{F}$ can be represented as,

$$\mathbf{B_1} = \begin{bmatrix} \frac{z-(H_2+H_3)}{H_1} & 1 - \frac{z-(H_2+H_3)}{H_1} & 0 & 0 & 0 \\ 0 & 0 & \frac{z-(H_2+H_3)}{H_1} & 1 - \frac{z-(H_2+H_3)}{H_1} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$