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Vibration of delaminated multilayer beams

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Abstract

The free vibration of delaminated multilayer beams is analyzed. Both the 'free mode' and 'constrained mode' analyses in the study of delamination vibration are used. Two parameters are introduced, namely, the normalized axial stiffness and the normalized bending stiffness. These parameters provide a better insight on the vibration behavior of the delaminated beam. A relative slenderness ratio specific for delamination vibration is further introduced, which is shown to influence the vibration behavior of the beam. Global, mixed and local vibration modes occur depending upon the relative slenderness ratio of the beam. In addition, for three-layer beams with double delaminations, the lower and upper bounds of the natural frequency are obtained by assuming a totally 'free' and totally 'constrained' deformations of the delaminated layers. These bounds are easy to compute and provide useful approximations.
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1. Introduction

Delamination is a common failure mode in layered structures. It may arise from loss of adhesion between two layers of the structure, from interlaminar stresses arising from geometric or material discontinuities, or from mechanical loadings. The presence of delamination may significantly reduce the stiffness and strength of the structures. A reduction in the stiffness will affect the vibration characteristics of the structures, such as the natural frequency and mode shape. The natural frequency reduces, as a direct result of the reduction of stiffness, which may cause resonance if the reduced frequency is close to the working frequency.

To study the free vibration of a composite beam with a through-width delamination, Ramkumar et al. [1] presented an analytical solution by treating the delaminated beam as four Timoshenko beams that are connected at the delamination edges. The natural frequencies and the mode shapes were solved by a boundary eigenvalue solution. However, the predicted frequencies were much lower than the experimental values. Similarly, Wang et al. [2] presented an analytical model using the Euler–Bernoulli beam theory. They assumed the delaminated layers deform 'freely' without touching each other and have different transverse deformations ('free mode'). The coupling between the bending and axial vibrations was included in their analysis. Their study showed that for short and midplane delaminations, the predicted frequencies were close to the experimental values. Mujumdar and Suryanarayan [3] proposed a model based on the assumption that the delaminated layers are 'constrained' to have identical transverse deformations ('constrained mode') but are free to slide over each other in the axial direction except at their ends. The coupling between the bending and axial vibrations was considered by including the effect of the differential stretching between the delaminated layers. Similar 'constrained mode' models were presented by Tracy and Pardoen [4] for composite beams, Hu and Hwu [5] for sandwich beams, Shu and Fan [6] for bimaterial beams and Valoor and Chandrashekhara [7] for thick composite beams. However, the 'constrained mode' model, failed to predict the opening in the mode shapes found in the experiments by Shen and Grady [8]. To simulate the 'open' and 'closed' behavior between the delaminated layers, Luo and Hanagud [9] presented an analytical model based on the Timoshenko beam theory by using piecewise-linear springs. Saravanos and Hopkins [10] developed an analytical

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solution for predicting the natural frequency, mode shape and modal damping of a delaminated composite beam based on a general laminate theory which involves kinematic assumptions representing the discontinuities in the in-plane and through-the-thickness displacements across each delamination crack. Krawczuk et al. [11] and Chakraborty et al. [12] presented finite element models using the first-order shear deformation theory (FSDT).

The above works are on one-dimensional beam-plates with a single delamination. Two- dimensional plates with a single delamination have mostly been numerically investigated. Zak et al. [13,14] presented finite element models using the FSDT. They modeled the delaminated region by using additional boundary conditions at the delamination fronts. Chattopadhyay et al. [15], Radu and Chattopadhyay [16] and Hu et al. [17] presented finite element models using higher-order shear deformation theories.

Several works have been presented for multiple delaminations. Shu [18] presented an analytical solution to study a sandwich beam with double delaminations. His study emphasized on the influence of the contact mode, 'free' and 'constrained', between the delaminated layers and the local deformation at the delamination fronts. Della and Shu [19] further investigated the beam with double delaminations by using 'free mode', 'partially constrained mode' and 'constrained mode' models. Lestari and Hanagud [20] studied a composite beam with multiple delaminations using the Euler–Bernoulli beam theory with piecewise-linear springs to simulate the 'open' and 'closed' behavior between the delaminated surfaces. Lee et al. [21] studied a composite beam with arbitrary lateral and longitudinal multiple delaminations by using a 'free mode' model and assumed a constant curvature at the multiple-delamination tip. Shu and Della [22,23] and Della and Shu [24] presented 'free mode' and 'constrained mode' models to study composite beams with multiple delaminations. Their study emphasized on the influence of a second short delamination on the first and second bending frequencies and the corresponding mode shapes of the beam. Finite element models have been presented by Ju et al. [25] using the Timoshenko beam theory and Lee [26] using the layerwise theory.

Similarly with the single delamination case, composite plates with multiple delaminations have been numerically investigated. Finite element models have been presented by Ju et al. [27] using the Mindlin plate theory, Kim et al. [28,29] using the first-order zig-zag theory and Cho and Kim [30] using the higher-order zig-zag theory. Three-dimensional finite element models were presented by Tenek et al. [31] and Yam et al. [32].

In this research, we examine the free vibration of delaminated multilayer beams. The 'free mode' and 'constrained mode' models are used. Two parameters are introduced, namely, the normalized axial stiffness and normalized bending stiffness, which provides a better understanding on the vibration of delaminated beams. A new slenderness ratio specific for vibration is further introduced, which is shown to influence the vibration behavior of the beam. This relative slenderness ratio can be used to predict the delamination opening and to characterize the vibration mode shape of the beam. In addition, the vibration of a three-layer beam with double delaminations is investigated using the introduced parameters. Lower and upper bounds of the natural frequency are obtained by assuming a totally 'free' and totally 'constrained' deformations of the delaminated layers.

The research is presented as follows: first, the analytical solution for a two-layer beam with a single delamination is presented, and the new parameters are introduced. Second, the free vibration of a two-layer beam with a single delamination is examined using the new parameters. In addition, the influence of the new relative slenderness ratio on the natural frequency and mode shape of the delaminated beam is shown. Finally, the vibration of a three-layer beam with double delaminations is solved.

2. Two-layer beam with a single delamination

The analytical solutions reported by Shu and Fan [6] on a 'constrained mode' and Shu [18] on a 'free mode' are used in the present study. Their solutions are presented here for convenience. The analyses include the effect of the differential stretching between the delaminated layers. Fig. 1 shows a beam with length L and thickness H_1. The beam is made of two distinct layers, with Young's modulus E_2 and E_3, and thickness H_2 and H_3. The beam is separated along the interface by a delamination with length a and located at a distance d from the center of the beam.

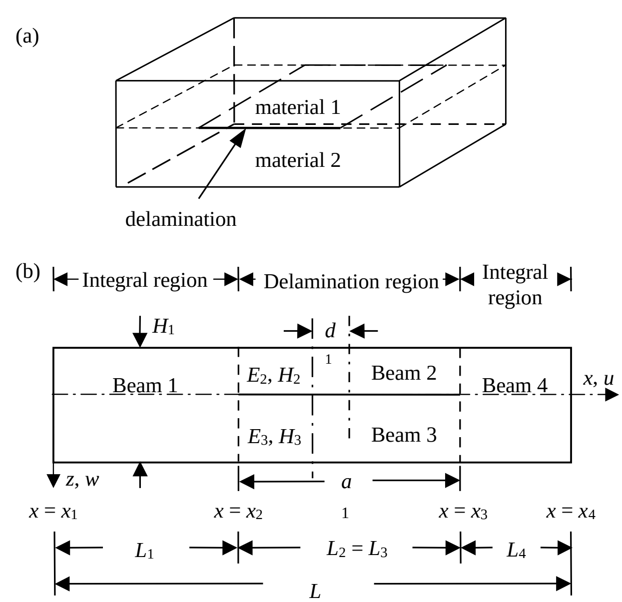

Fig. 1. (a) A beam consisting of two distinctive layers is delaminated along the interface; (b) Beams 2 and 3 are connected at their ends to the integral beams 1 and 4.

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