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Interface profile optimization for planar stress wave attenuation in bi-layered plates

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ABSTRACT

Stress waves scatter upon entering a new medium. This occurs due to the reflection and transmission of the waves, which depends on the impedance mismatch between the two materials and the angle of incidence. For a bi-layered structure with finite dimensions and constant impedance ratio, the scattering and intensity of the stress waves may be varied by changing the interface profile between the two layers. In this paper, a methodology is proposed for optimizing the interface profile between the layers of a finite bi-layered plate for the objective of planar stress wave attenuation. The bi-layered plates are subjected at one end to highly impulsive loadings with various durations, and the geometry of the internal interface is optimized for the purpose of minimizing the amplitude of the maximum reaction force at the opposite fixed end. The optimization methodology is based on a genetic algorithm, which is coupled with a finite element method for analyzing the wave propagation behavior of the plates. It is observed that the interface profile and the amount of stress wave attenuation depend on the duration of the applied impulsive loading, with higher amounts of attenuation obtained when the wavelength associated with the impulsive load is small compared to the dimensions of the bi-layered plates.

1. Introduction

Over the past few decades, layered structures have been used extensively in a broad range of engineering applications. Many of these applications are related to designing structures that are subjected to dynamic loadings. For example, in military applications, laminated composites are exploited broadly for mitigating the effects of impulsive loadings. As another example, various numbers of layered and sandwich composites have been developed for protecting structures against blast and high velocity impact. The behavior of the layered structures under dynamic loadings and their attenuation capacity depends on the material properties and impedance mismatch between the layers. Due to the existence of impedance mismatch, reflection and transmission of the incident waves take place at the interface between the two materials. This results in scattering of the waves and altering the wave propagation behavior of the layered systems. Considering the impedance mismatch phenomenon, the material properties of layered systems can be tuned for attenuating the intensity of the dynamic loadings.

The wave propagation behavior of layered structures has been explored by many researchers. In one of the early works, Lindholm and Doshi [1] studied the wave propagation in a nonhomogeneous finite elastic bar with varying modulus of elasticity, which is subjected to a transient pressure pulse. Anfinsen [2] provided a design approach for maximizing and minimizing the amplitude of a stress pulse in layered one-dimensional elastic structures. Lee et al. [3] explored the efficiency of layered plates with discontinuous and continuous changes in material properties for the objective of impact resistance. Chiu and Erdogan [4] demonstrated the one-dimensional wave propagation in elastic slabs with functionally graded materials (FGMs). Sudden changes in the material properties have many disadvantages because of the high amount of stress concentration. To overcome this problem, FGMs are usually employed in engineering applications, because the material properties of these structures are gradually changing. Wave propagation in FGMs are extensively studied in the literature. Some examples include the works by Li et al. [5], Velo and Gazonas [6], Naik et al. [7], Aksoy and Şenocak [8], Sun and Luo [9], Hui and Dutta [10], and Pandya et al. [11]. In addition, some research has been done on the optimal design of the FGMs and layered systems for the purpose of stress wave attenuation (Taha et al. [12], Luo et al. [13] and [14], Rafiee-Dehkharghani et al. [15], and Rafiee-Dehkharghani [16]).

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By reviewing the literature, it is demonstrable that most of the research on wave propagation in layered structures has focused on the effect of impedance mismatch between the layers and the way that the change in the material properties occurs, i.e., graded or abrupt. This means that the major parameter, which is explored in the literature is the material effect and it is discussed by several researchers (Liu et al. [17]; Banks-Sills et al. [18]; Nwosu et al. [19]; Hong and Lee [20]). For this reason, many of these studies (Chiu and Erdogan [4]; Bruck [21]; Samadhiya et al. [22]; Chen et al. [23]) are based on one-dimensional wave propagation, even in two-dimensional structures, such as plates. In fact, in many practical applications, the structures have more than one dimension and their wave propagation behavior depends on the geometric specifications in addition to the material properties. For layered systems, the geometric properties can be attributed to the global shape of the structure and the interface profile between the layers. To the best of our knowledge, no research has been done on the effect of the interface profile between the layers.

This paper describes a study that aimed at investigating the effect of the interface profile between two media in layered structures and illustrates the development of a methodology for optimizing the shape of this profile for the objective of stress wave attenuation. The developed methodology is used for optimal design of the interface profile between the layers of free-fixed rectangular bi-layered plates, which are subjected to in-plane transient dynamic loadings with different durations. It is assumed that the interface between the layers is composed of various straight line segments that are connected to each other to make a jagged path. An optimization methodology is then used to find the optimal shape of this jagged path for minimizing the intensity of the transient load, as it reaches the fixed boundary. Since the amount of attenuation and scattering of the waves depends on the inclination angle of the incident waves at the jagged interface, the theory of the reflection and transmission for an incident wave with oblique angle is explained in detail.

The dynamic behavior of the bi-layered plates is analyzed using two-dimensional plane stress wave propagation theory. The finite element (FE) method is employed for this purpose due to the limitations of finding closed-form solutions for the problem of wave propagation in finite plates with a complex jagged interface. A genetic algorithm (GA) optimization approach is utilized for the problems under consideration. This optimization approach is a robust heuristic optimization methodology, which is appropriate for solving the problems stated in this paper. In particular, GAs resolve the difficulty of obtaining gradient information with respect to the design variables, and are well-suited for the highly nonlinear nature of the problem at hand. For finding the fitness value, the GA is coupled with an FE code. The coupled GA-FE optimization methodology is utilized for designing the bi-layered plates with jagged interfaces subjected to in-plane half-sine transient loadings with different durations. The efficiency of this coupled GA-FE optimization methodology is examined for layered systems with straight interfaces and for plates with circular inclusions in Rafiee-Dehkharghani et al. [15] and [24], respectively.

The theory and background of the problem, details of the coupled GA-FE optimization methodology, and the results of the optimal designs are explained comprehensively in the following sections.

2. Theory and background

Discontinuity in material and geometric properties lead to wave scattering in elastic media and thus provide the potential for stress wave attenuation. For example, for longitudinal wave propagation in one-dimensional bi-material bars with equal cross section areas, the stress amplitude ratio of a transmitted wave (σ_t) to an incident wave (σ_i) is given by $\sigma_t/\sigma_i = (2Z_2/Z_1)/(1+Z_2/Z_1)$, where Z_1 and Z_2 represent the impedances of the first and second layers, respectively, as the wave propagates (Graff [25]). Consequently, stress wave attenuation will occur when a wave passes from a high impedance to a low impedance material (i.e., $Z_1/Z_2>1$). However, in practice, the overall response is complicated due to multiple reflections in finite length bars and to oblique incidences.

The more general case of wave scattering occurs for an incident wave at an oblique angle associated with the interface of two different materials, as shown in Fig. 1. The two materials can be solid, fluid, vacuum, or any other combination. The continuity in displacement and stress at an interface results in wave scattering through reflection and transmission in the two media at different angles. Solids can sustain both dilatational and shear waves, and each of these waves generates dilatational plus shear waves at an interface. Thus, for dilatational and shear wave incident on an interface at an oblique angle, eight new waves will be generated, as shown in Fig. 1. However, in fluids and vacuum, less number of waves will be generated because shear waves do not travel in non-viscous fluids, and longitudinal and shear waves do not propagate in vacuum.

Fig. 1 shows the scattering of stress waves at the interface of two solid materials. In this figure, I_D and I_s represent displacement amplitudes of incident dilatational and shear waves and R_{D-S}, R_{D-D}, T_{D-S} and T_{D-D} correspond to the displacement amplitude of reflected shear, reflected dilatational, transmitted shear, and transmitted dilatational waves for a dilatation incident wave (I_D), respectively. Similar notations are used for a shear incident wave (I_S) by converting the first index from D to S, i.e., R_{S-S}, R_{S-D}, T_{S-S} and T_{S-D}.

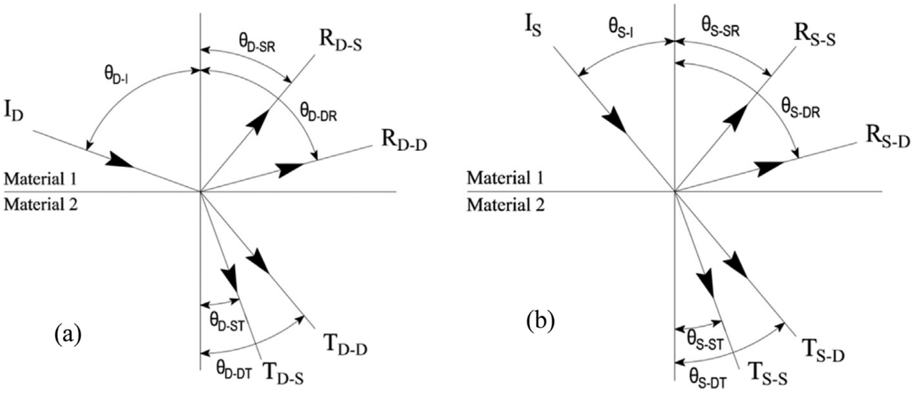

Fig. 1. Reflection and transmission of waves at the interface of two solids, (a) dilatational incident wave, (b) shear incident wave.