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Optimization of transparent laminates for specific energy dissipation under low velocity impact using genetic algorithm

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ABSTRACT

We employ a genetic algorithm to maximize the energy dissipated per unit areal density in laminates composed of layers of poly-methyl-metha-acrylate (PMMA), adhesive and polycarbonate (PC) impacted at low velocity by a rigid hemi-spherical nosed cylinder. Sources of energy dissipation considered are plastic deformations of the PC and the PMMA, cracking of the PMMA, viscous deformations of the adhesive, and the energy used to deform failed elements that are deleted from the analysis domain. Some of the challenging issues are appropriate constitutive relations for the three materials, failure criteria, and numerical techniques to accurately analyze finite deformations of different constituents. We model the PC and the PMMA as thermo-elasto-visco-plastic materials with constitutive relations proposed by Mulliken and Boyce and modified by Varghese and Batra, the adhesive as a visco-elastic material, and use the commercial finite element software LS-DYNA in which these material models have been implemented as user defined subroutines. This software is coupled with a genetic algorithm to optimize the layup of the PC, the PMMA and the adhesive layers of the same thickness under the constraints that the top and the bottom layers are not adhesive, the PC and the PMMA layers must have an adhesive layer between them, and the total number of layers is fixed.

1. Introduction

Optimizing the impact performance of laminated structures can save mass and hence cost. Furthermore, using a computational algorithm to optimize the design can minimize the number of prototypes to be built and tested. Florence [1] gave an analytical expression for estimating the ballistic limit of a two-component ceramic-faced armor as a function of the impactor mass and radius, and of the ply thicknesses, mass densities, failure strains and the ultimate tensile strength of the armor materials. Ben-Dor et al. [2] modified the expression by scaling the predicted ballistic limit with a parameter that is determined from the available experimental data and formulated a condition of optimality for the armor design for constant areal density but the thicknesses of the two plates as variables. Ben-Dor et al. [3] used the modified expression to optimally design armor, provided closed-form simple solutions to the optimization problem and showed that the range of possible designs giving almost identical ballistic performance is broad. Hetherington [4] used Florence's [1] expression to optimally design a ceramic/aluminum armor by keeping the areal density constant and analytically finding the range of thickness ratios for the highest ballistic limit of the armor. Hetherington found that the impact performance is better when the ceramic tile is thicker than the backing plate, and verified the optimal design through physical tests.

Here we use a genetic algorithm (GA) to maximize the energy dissipated during the low-velocity impact (below the perforation limit) of a clamped rectangular laminate of a given areal density. The laminate is composed of different layers of poly-methyl-metha-acrylate (PMMA), adhesive and polycarbonate (PC). Since the mass density of the three materials is nearly the same, the design variables are the arrangement of layers under the constraint that the adhesive layer cannot be one of the major surfaces and the PMMA and the PC layers must have an adhesive layer between them. The problem has been simplified by assuming that each layer is of the same thickness, and the adjacent layers are perfectly bonded to each other. Thus only the arrangement (or the layup) of layers is to be determined. This optimization problem is similar to that of a fiber-reinforced laminate with the fiber orientation angle in each layer as the design variable; e.g. see Batra and Jin [5]. Qian and Batra [6], Goupee and Vel [7] and Batra [8] studied the spatial variation of elastic moduli to optimize either the fundamental frequency or the stress distribution in a structure. The optimization problem of minimizing a laminate weight while fulfilling

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requirements of the strength, fundamental frequency, buckling load and/or strain limit have been studied, amongst others, by Nagendra et al. [9,10], Gantovnik et al. [11], Nagendra et al. [12], Kogiso et al. [13], Gantovnik et al. [14], and Malott et al. [15]. Another class of problems is to maximize a structural property, typically the buckling load, while keeping the number of plies or the weight constant; e.g. see Soremekun et al. [16].

Punch et al. [17] and Punch et al. [18] used a GA to optimally design a laminated beam for the maximum energy absorption when a point load is suddenly applied at the center of the top surface. Poirier et al. [19] used the GA to analyze a multi-objective problem for a laser welded steel beam.

The major contribution of the present work is in applying the GA technique to a transient coupled thermo-elasto-visco-plastic problem involving finite deformations, material failure, cracking and significant plastic deformations.

2. Problem definition and method

2.1. Initial-boundary-value problem

A schematic sketch of the impact problem studied is depicted in Fig. 1. A $L_1 \times L_2$ rectangular clamped laminated plate made of n layers of thickness h_1 through h_n and total thickness $h = \Sigma h_i$ is impacted at normal incidence by a hemispherical nosed rigid impactor of mass m moving at velocity v_0. The layers are made of PMMA, PC, DFA4700 or IM800A. The PMMA and the PC are glassy transparent polymers, while the DFA4700 and the IM800A are transparent viscous adhesives. The thermo-elasto-visco-plastic material model developed by Mulliken and Boyce [20] and modified by Varghese and Batra [21] is used for the PMMA and the PC. The DFA4700 and the IM800A are modeled as nearly incompressible viscous rubbery materials with the elastic response represented by the Ogden energy potential and the viscoelastic response by a hereditary type integral e.g., see [30]. Effects of both geometric and material nonlinearities are considered. The different layers are assumed to be perfectly bonded and the continuity of displacements and surface tractions is imposed between adjacent layers. Thus successive layers made of the same material are equivalent to one thick layer. The mass densities of the PMMA, the PC, the DFA4700 and the IM800A are taken to equal 1.2, 1.2, 1.1 and 1.04 g/cm^3. The constitutive relations and values of material parameters for these materials are given in [20–22]. Similarly, partial differential equations governing deformations of the system, and the initial and the boundary conditions are summarized in [22]. In the present work we take $L_1 = L_2 = 120$ mm, $h = 4.0$ mm, $n = 12$ and h_1 through $h_n = 0.33$ mm. The spherical rigid impactor of radius $R = 5$ mm and mass $m = 35$ g impacts the plate center at $v_0 = 20$ m/s.

2.2. Optimization problem

Our goal is to find the material of the 12 layers that will maximize the energy dissipated during the impact. Whereas one usually considers the constraint of constant areal density (e.g., see [2–4]), here the layers are assumed to have fixed thickness. Since mass densities of the materials vary between 1.04 and 1.20 g/cm^3, variations in the areal density among the layers are small. We impose the constraint that layers 1 and 12 are made of either PMMA or PC and that the PMMA and the PC layers within the laminated plate cannot have common interfaces but must be bonded with an adhesive layer.

We assign each material an integer between 1 and 4 as listed in Table 1 and denote the energy dissipation by the function f. Thus f is a function of x_1 through x_{12}, where the x_i is the material of the ith layer, and the optimization problem is:

$$\text{maximize} \quad f(x_1, x_2, \ldots, x_{12}) \tag{1a}$$
$$\text{subject to} \quad x_1 = 1 \quad \text{or} \quad x_1 = 4 \tag{1b}$$
$$x_{12} = 1 \quad \text{or} \quad x_{12} = 4 \tag{1c}$$
$$|x_{i+1} - x_i| \le 2 \quad \text{for } 1 \le i \le 11 \tag{1d}$$

With constraints defined by Eq. (1b)–(1d) there is a total of 885,922 admissible designs. The computational cost of evaluating the fitness of each design is unrealistically high which motivates the use of an optimization algorithm to explore the design space.

2.3. Genetic algorithm

The optimization problem described by Eq. (1a)–(1d) is solved by using a GA. A GA is a direct search method that uses ideas based on natural selection to explore the search space for finding a global optimum. Population initialization, parent selection, crossover, mutation and selection of the fittest are common elements in most GAs, e.g. see [16] and [23]. A GA generally involves the following steps: (i) generate an initial population of individuals, (ii) develop a scheme to select members for mating in the existing population with preference given to the fittest individuals (individuals with the highest objective function value), (iii) create children through mating, and (iv) replace the existing population. We follow guidelines presented in Refs. [16,23] for selecting individuals for mating, generating children, and enforcing the constraints. A random number generator is used to simulate approximate uniform distribution where evolution is directed by random numbers. The function of the GA is schematically depicted in Fig. 2.

2.3.1. Selection strategy for new parents

In a typical GA after a new population is formed the previous population is killed and is replaced by the new one. However, there is no guarantee that an individual in the new generation has higher fitness than that of the best individual in the previous one. In other

Table 1
Coding of the materials.

Material	PMMA	DFA4700	IM800A	PC
Code (value of the variable x_i)	1	2	3	4

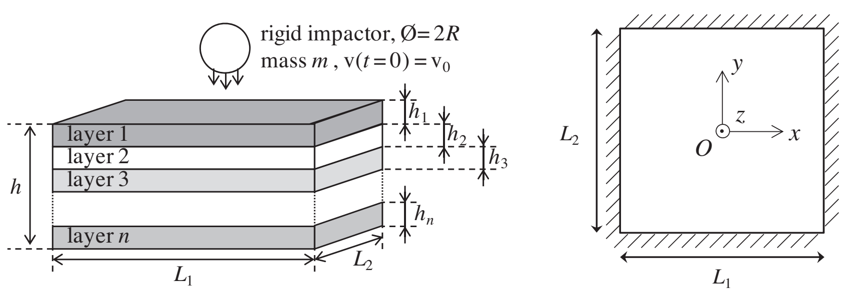

Fig. 1. Sketch of the impact problem studied.