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Sensitivity analysis of low-velocity impact response of laminated plates

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ABSTRACT

We analyze the sensitivity to values of material parameters, layer thickness and impact speed of the plate deflection, the contact force between the impactor and the plate, the maximum length of a crack, and the energy dissipated during the low velocity impact at normal incidence of a clamped rectangular laminate by a rigid hemispherical-nosed cylinder. The laminate is comprised of layers of polymethylmethacrylate (PMMA) and polycarbonate (PC) bonded by an adhesive, and its deformations are analyzed by the finite element method. The mathematical and computational models of the system have been described in our previous work, and their predictions compared with test data (*Composite Structures*, 116, 193-210, 2014). The thermo-elasto-viscoplastic materials of the PMMA and the PC and the viscoelastic material of the adhesive involve a large number of material parameters whose precise values are unknown. Here we consider values of eleven material parameters – five for the PMMA, five for the PC and one for the adhesive. It is found that values of Young's moduli and Poisson's ratios of the PMMA and the PC, and the shear modulus of the adhesive strongly influence the plate deflection and the crack length. Values of material parameters of the PC that noticeably affect its plastic deformations also determine the energy dissipation whose correlation with the second peak in the contact force between the impactor and the laminate is exhibited. The PMMA layer thickness is found to influence the crack length and the PC layer thickness the energy dissipated.

1. Introduction

Mathematical models of engineering structures generally involve a system of either ordinary or partial differential equations whose coefficients depend upon values of numerous material parameters. For a fixed set of initial and boundary conditions, the structural response depends upon materials of structural components. A goal of sensitivity analysis is to explore the effect on the structural response of variability or uncertainty in the knowledge of values of material and geometric parameters of the structure.

While studying the response of glass targets to hypervelocity impact by small impactors, Anderson and Holmquist [1,2] analyzed the sensitivity of the computed results to small variations in the impact speed. They considered impact velocities of 2238, 2238.0001, 2238.0002, 2066 and 2066.0001 m/s, and found that a small variation in the impact speed noticeably affected the propagation of the penetration and failure fronts. In particular, the final depth of the failure and the penetration fronts increased by about 20% and more than 10%, respectively, with a 0.0001 m/s or 5×10^{-5} % increase in the impact velocity, showing the high sensitivity of their computational model upon the impact speed. Poteet and Blosser [3] used sensitivity analysis to find the design factor with the greatest effect in the hypervelocity impact resistance of a bumper metallic protection system comprised of three metallic layers with spacing between them. Taking the layer thickness and the spacing between two adjacent layers as design variables, and the damage to the substructure and the debris dispersion as measures of the structure performance, the parameters with the largest effect on structure's integrity were found to be the thickness of the first layer and the spacing between the layers.

Here we determine material and geometric parameters that significantly affect the laminate deflection, the energy dissipated, the contact force between the impactor and the laminate, and lengths of cracks, if any, formed in a layer. The laminate comprised of polymethylmethacrylate (PMMA)/adhesive/polycarbonate (PC) is impacted at normal incidence by a low-velocity smooth hemispherical-nosed rigid cylinder. The constitutive equations used to model the thermoviscoplastic response of the PMMA and

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the PC involve 30 material parameters whose values cannot be precisely determined. Here we first screen values of material parameters to find 5 material parameters each for the PMMA and the PC that significantly affect the system response. Subsequently, we use the sampling-based sensitivity method to ascertain the influence of these parameters on the system response by considering either 10% or 30% variation in the values of these parameters. We note that the uncertainty in the values of material parameters is *a priori* unknown and requires data from numerous experiments performed under controlled conditions. In the absence of this data, the assumed 30% variability in the values of material parameters is probably an upper limit.

The rest of the paper is organized as follows. We briefly describe the impact problem studied in Section 2 and provide a comparison of the computed and the test results. The screening method and the selection of five important material parameters for the PMMA and the PC are discussed in Section 3. The details of the sensitivity analysis for the impact problem are given in Section 4, and conclusions of the work are summarized in Section 5.

2. Problem description

2.1. Initial-boundary-value problem

We perform sensitivity analysis of the impact problem schematically sketched in Fig. 1 and described in Antoine and Batra [4]. The smooth hemispherical nosed rigid impactor of mass 28.5 g and 6.9 J initial kinetic energy impacts at normal incidence a clamped flat $L_1 \times L_2 \times h$ ($= h_1 + h_2 + h_3$) rectangular plate. We refer the reader to [4] for details of the analysis of deformations of the laminate by the finite element method (FEM) using the commercial FE software, LS-DYNA, in which material models for the PC, the PMMA and the adhesive have been implemented as user defined subroutines. The convergence of results with the refinement of the FE mesh and other details of the computational work (e.g., energy of hour-glass control algorithms) are described in Ref. [4]. In the present analysis a fixed FE mesh comprised of 8-node brick elements has been employed, and deformations of only a quarter of the laminate have been analyzed due to the symmetry of the problem geometry, and initial and boundary conditions. This FE mesh gave a converged solution of the impact problem, e.g., see Ref. [4]. Results have been computed for $L_1 = L_2 = 127$ mm, $h_1 = h_3 = 1.5875$ mm and $h_2 = 0.635$ mm.

2.2. Validation of the model

For the sake of completeness we describe below a few salient features of the model and give some results.

Constitutive equations proposed by Mulliken and Boyce [5] and modified by Varghese and Batra [6] used to model the PMMA and the PC materials are given in the Appendix. Values of the material parameters and methods to find them can be found in Refs. [5–7]. These references also show that the predicted and the experimental stress-strain curves for the PMMA and the PC deformed in uniaxial compression compare well with each other from at low and high strain rates thereby establishing the appropriateness of their values and the material model.

The failure criteria for the PMMA and the PC adopted from the literature are given in Ref. [4]. The brittle failure of the PMMA is modeled using a maximum threshold for the principal stresses (Fleck et al. [8]), and its ductile failure is assumed to occur when the accumulated equivalent plastic strain reaches 5% (Stickle and Schultz [9]). The PC is assumed to have only ductile failure when the maximum effective plastic strain at a point equals 3 (similar to

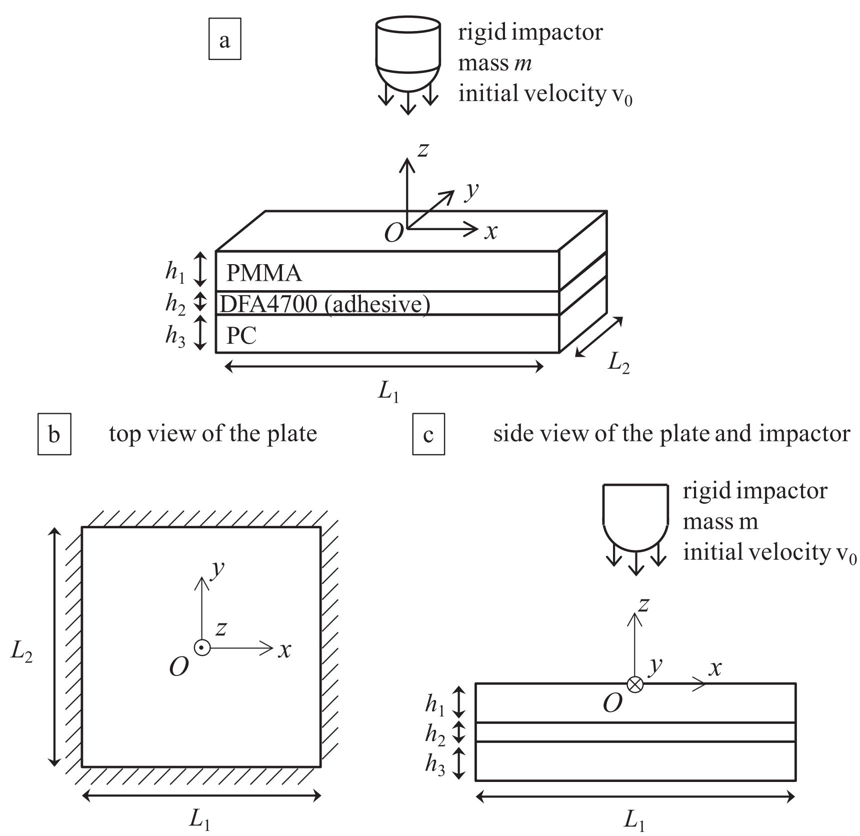

Fig. 1. Schematic sketch of the impact problem studied.