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Experimental and numerical investigation of contact laws for the rapid simulation of low-energy impacts on laminated composite plates

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ABSTRACT

A computationally efficient model for the impact simulation of low energy impacts on composite laminated plate structures is developed, which combines a contact law with a new time domain spectral shear plate finite element. Various contact laws are numerically and experimentally investigated based on elastoplastic and fully-plastic indentation theory. The contact laws are correlated with quasi-static indentation test data performed on carbon/epoxy cross-ply laminates and with numerical results of a 3-D finite element analysis (FEA) indentation model with Hill failure criterion. The extracted contact laws are combined with a first-order shear plate time domain spectral finite element with explicit time integration. Obtained impact simulation results are compared with a 3-D continuum explicit FEA model and experimental results. The results demonstrate excellent accuracy of the present method, and drastically improved numerical simulation speed.

1. Introduction

Advanced fiber composites offer high weight-to-stiffness and strength ratios, and better resistance to fatigue and environmental degradation, compared to traditional materials, such as metals. In spite of the many attractive characteristics, laminated composite materials suffer some serious limitations. Perhaps the most significant among these, is their response to localized impacts such as small hail stones, tool drop, other manufacturing or handling accidents, runway debris [1], and so forth. This is due to the fact that the impact damage caused by foreign objects may significantly reduce the load carrying capacity of composite structures [2].

As it is well known, impact is a complex event, involving several phenomena and many parameters; from capturing the essential dynamics experimentally to the computational difficulties required to acquire converged results. In order to develop a reliable analytical, experimental or computational method for studying an impact event, it is required a priori knowledge of the impact dynamics that includes phenomena such as contact, damage, wave propagation and vibrations. Consequently, the characterization of impact events is very critical for facilitating the prediction of impact response and for scaling impact among similar or dissimilar structures, in order to optimize the resources for parametric and experimental studies [3,4]. More specifically, the proposed characterization diagram by Christoforou and Yigit can be used to provide a priori knowledge of the impact dynamics and choose adequate simple lumped-parameter models for any impact case [5,6].

A second step in gaining some understanding of the impact problem is the accurate knowledge of impact/contact force. Two approaches are typically used to solve the impact problem. The first employs detailed 3-D continuum finite element models for the composite structure and the impactor, which results in computationally intense explicit time integration solutions. The second employs simplified models for the target structure usually assuming a single-layer laminate theory in the context of a global Ritz, or finite element discretization, and treat the impactor as a concentrated mass with one degree of freedom. It is further hypothesized, that a contact law expressing the static indentation of the impactor on a semi-infinite elastic body is sufficient [7–9] to provide the nonlinear interaction between impactor and target structure. Hence, reasonable compromises between computational speed and accuracy have been obtained.

The first attempt of extracting a contact law that is based on the indentation theory was done by Hertz [10], where the contact law was obtained by the elasto-static analysis of the contact between a spherical impactor and an elastic half-space, where permanent deformations due to damage and plasticity were inconsequential. The contact theory proposed by Hertz has been used extensively by many researchers to study contact/impact for isotropic and composite structures [7,11,12]. During the initial loading,

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Hertzian-type contact laws could give satisfying results. However, it has been shown that even at low impact energies, this model is not adequate, as some energy is dissipated due to plastic deformation, wave propagation, and other effects, indicating that the contact law should be modified accordingly. Tan and Sun [13] developed an empirical contact law based on indentation experiments on glass/epoxy and graphite/epoxy composites that accounts for permanent indentation after unloading cycles. Many researchers have studied the low-velocity impact problem on composite laminates following this approach [14–16]. Because permanent deformation is not taken into account in the formulation, validity occurs only during the initial stages of the impact event. In order to account for permanent deformation, an elasto-plastic contact law [17,18] may be used to obtain the impact force. Sutherland and Soares [19] performed quasi-static indentation tests on marine laminates and they found out that the Hertzian contact law described well the initial response, and predicted the contact stiffness using a larger diameter indenter. However, at higher loads the response became linear as damage became significant. Recently, the response of half-space and thin supported composite laminates in contact with spherical objects using effective isotropic properties and based on elasto–plastic and fully plastic indentation theory, was investigated [20]. The proposed contact model agreed very well with the FE simulation and limited experimental data.

In this paper we present a rapid impact simulation model which yields enhanced combinations of accuracy and computational speed through the integration of improved and experimentally validated contact laws and a novel time domain spectral finite element for the structural dynamics of composite plate structures. In the following sections, the theoretical framework and governing equations of the developed impact model is outlined. Bilinear and elastoplastic contact laws are formulated and their performance is validated with measured data from quasi-static indentation tests performed on thick carbon fiber-reinforced epoxy cross-ply laminates, and subsequently simulated with 3-D solid explicit finite element models with damage capabilities based on the Hill failure criterion. The development and basic features of a time domain spectral finite element (TDSFE) [21] based on first order shear theory (FSDT) is presented. Finally, the extracted contact laws and the TDSFE are integrated in the framework of an explicit time integration scheme, to provide the rapid impact prediction model. Numerical predictions of the present model are presented and compared, in terms of accuracy and computational speed, with results obtained by explicit 3-D FEA analysis models for select impact cases on carbon/epoxy plates, and also with experimental results.

2. Theoretical background

2.1. Derivation of the governing equations

In the case of impact of a spherical object having an initial velocity v_0, termed thereafter as impactor, on a composite laminate, termed as target structure, the motion of the structure and the impactor is described by the following differential equations as,

$$\mathbf{M}_s\ddot{\boldsymbol{w}}_s(t) + \mathbf{K}_s\boldsymbol{w}_s(t) = \boldsymbol{F}(t) \tag{1}$$

$$\mathbf{M}_i\ddot{\boldsymbol{w}}_i(t) + \mathbf{K}_i\boldsymbol{w}_i(t) = -\boldsymbol{F}(t) \tag{2}$$

where $\mathbf{M}$ and $\mathbf{K}$ are the mass and stiffness matrices of the two contacting bodies respectively, $\boldsymbol{w}$ is the generalized nodal or modal coordinate vector and $\boldsymbol{F}$ is the impact force vector. An important equation which couples the previous equations and relates the impact force to local indentation is the contact law or indentation law, which usually takes the form,

$$F = \left\{ \begin{array}{ll} f(\alpha,t) & \text{if } \alpha > 0 \\ 0 & \text{if } \alpha \leqslant 0 \end{array} \right\} \tag{3}$$

where α is the relative approach (indentation) between the impactor and the structure at the contact point (shown in Fig. 1) given as,

$$\alpha(t) = w_{ic}(t) - w_{sc}(t) \tag{4}$$

where w_{ic} is the normal displacement of the impactor, while w_{sc} is the deflection of the structure, both at the impact point. The initial conditions can be expressed as

$$\boldsymbol{w}_s(0) = \dot{\boldsymbol{w}}_s(0) = 0, \dot{\boldsymbol{w}}_i(0) = v_0 \tag{5}$$

2.2. Contact laws

Three different types of contact laws, the elastic Hertzian, an elastoplastic and a bilinear contact law are considered below.

2.2.1. Hertzian contact law

The relationship between the contact force and local deformation between an elastic sphere and an elastic half-space is defined by Goldsmith [10] as,

$$F = K_h\alpha^{3/2} \tag{6}$$

The Hertzian contact stiffness K_h depends on the material properties and the contact geometry and in the case of a spherical body of radius R in contact with a flat surface is given as,

$$K_h = \frac{4}{3}\sqrt{R}E^* \tag{7}$$

where E^* being the effective contact modulus determined as follows,

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \tag{8}$$

and v_i and E_i are the Poisson‘s Ratio and Elastic Modulus of the two contacting bodies, respectively.

2.2.2. Elastoplastic contact law

Experimental evidence suggests that after an initial elastic indentation limit, the contact stresses are high enough to cause permanent indentation in the composite laminate [11,12,22]. Hence, a general elastoplastic contact law for a transversely isotropic composite half-space in contact with a spherical indenter was proposed by Christoforou and Yigit [17], by combining the classical Hertzian contact theory [10] and the elastic–plastic indentation theory given in [12]. The term “plastic” denotes a combination of failure modes such as matrix cracking/crushing and fiber breaking/kinking/micro-buckling. The slope of the load-indentation curve after the critical indentation can be shown to be approximately a constant, i.e., a nearly linear relationship exists between force and indentation [7,18,19]. The contact law is given as follows,

Phase I: Elastic Loading

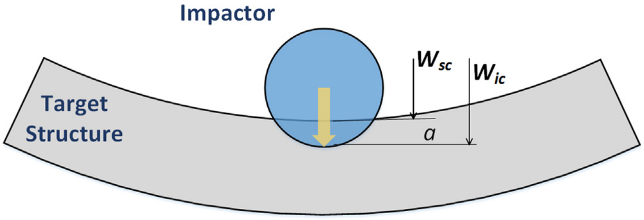

Fig. 1. Schematic impactor-structure indentation: structure deflection (w_{sc}), impactor displacement (w_{ic}), indentation (α).

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