DAMAGE EVOLUTION IN PLANE STRAIN DEFORMATIONS OF IMPACT LOADED SANDWICH PLATES

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Abstract

Plane strain thermomechanical deformations of a sandwich plate impact loaded by a cylinder are analyzed by the finite element method. The materials of the bottom and the top face sheets and the intervening soft core are modeled as isotropic, homogeneous, microporous and thermoelastoviscoplastic. Contact surfaces are assumed to be smooth and the material of the impacting cylinder much stiffer than that of the face sheets. Two measures of damage, namely the effective plastic strain and the porosity, are considered. Results have been computed for two impact speeds. It is found that in each case the damage stays localized in a small region surrounding the point of impact and is essentially independent of the boundary conditions at the edges. For the sandwich plate comprised of thin steel face sheets bonded to thick steel foam the maximum temperature rise equals approximately 700 K.

1 INTRODUCTION

Advanced engineering applications require that structures be designed optimally making full use of material's strength and its directional dependent properties. Sandwich structures are ideally suited for marine applications requiring high strength and low weight thereby increasing the payload. These structures are frequently subjected to time-dependent loads and may be exposed to blast loads because of storms, underwater explosions, wave slamming and/or impact by hard objects. Whereas static behavior of sandwich structures has been extensively studied, their response to transient and especially rapidly varying thermomechanical loads has not been thoroughly scrutinized.

Sandwich structures are rather complex three-dimensional systems. Their deformations can be analyzed either by the finite element method (FEM) or by finding a suitable equivalent laminated structure and studying deformations of the laminated structure either by the FEM or by using a plate theory coupled with a numerical technique. The transient deformations of a structure can be analyzed either in the time domain or in the frequency domain. However, when deformations are large and thus the governing equations are nonlinear, then the analysis in the time domain is more suitable.

Sandwich structures with honeycomb and other types of cores have been discussed in [1,2]. It is generally agreed upon that the response of materials under dynamic loads is quite different from that under static loads [3]. Under high loading rates, materials exhibit strain hardening, strain-rate hardening, and thermal softening. For composites, different damage mechanisms must be identified in addition to representing the effective stress as a function of the effective strain, effective strain-rate and the temperature. Vinson and Rajapakse [4] have discussed in considerable detail high strain rate effects on polymers, metals and ceramic matrix composites. Chun and Lam [5] have investigated the dynamic response of clamped laminated and curved panels subjected to step, triangular and explosive loadings. The initiation and propagation of cracks in composites under dynamic loads is a multiscale phenomenon due to differences in geometries of the matrix, reinforcements in the face sheets and the core. The penetration of moisture and other agents into crack systems interferes with crack opening and closing under cyclic loading, degrades their endurance and contributes to the reduction in the load carrying capacity of the structure. Hygrothermal response of polymeric composites under quasistatic conditions has been studied by Weitsman [6].

Here we study their transient plane strain thermomechanical elastic/plastic deformations under impact loads by the FEM. The face sheets and the core are made of steel and steel foam respectively with each modeled as isotropic and homogeneous material. Work on delineating the effect of material anisotropy and moisture is in progress and will be reported at the conference.

2 PROBLEM FORMULATION

Figure 1 depicts a schematic sketch of the problem studied. The sandwich plate is comprised of two 1 mm thick steel face sheets enclosing a 10 mm thick steel foam plate. The edges of the composite plate are either simply supported or rigidly clamped. It is assumed that the plate is very long in the third direction so that a plane strain state of deformation prevails in the plate. The top surface of the plate is impacted by a 1 mm diameter rigid cylinder with axis along the longest side of the plate and mass density equal to that of steel.

The balance laws for mass, linear momentum, moment of momentum, and the internal energy, are written in the Lagrangean or the referential description of motion. Elastic deformations, heat conduction and stresses due to thermal expansion are considered. Following assumptions are made in the analysis of the problem: (i) the strain rate tensor is additively decomposed into an elastic part, a plastic part and a thermal part; (ii) the Jaumann rate of the Cauchy stress tensor is a linear function of the elastic part of the strain rate tensor; (iii) Young's modulus and the shear modulus decrease affinely to zero as the porosity approaches one; (iv) the porosity represents damage induced in the body; (v) the specific heat and the thermal conductivity are affine functions of porosity; (vi) a material point deforms plastically when the stress state satisfies Gurson's flow potential modified for its dependence upon the porosity and the dependence of the flow stress upon the plastic strain, plastic strain rate and temperature; the latter is assumed to be given by the Johnson-Cook relation; (vii) the associative rule of plasticity gives the plastic part of the strain rate tensor; (viii) Chu and Needleman's expression for the evolution of porosity applies; (ix) the rate of change of internal energy is a linear function of the first and the second time derivatives of temperature thereby resulting in a hyperbolic heat equation, and (x) face sheets are perfectly bonded to the core. Thus, both mechanical and thermal disturbances propagate at a finite speed. A complete set of equations and values of material parameters used in computing results are given in [7]. The impacting cylinder is modeled as essentially rigid by assigning very high values to its Young's modulus and the quasistatic yield stress. A slideline contact algorithm is employed to ensure the non-interpenetration of the impacting cylinder and the sandwich particles.

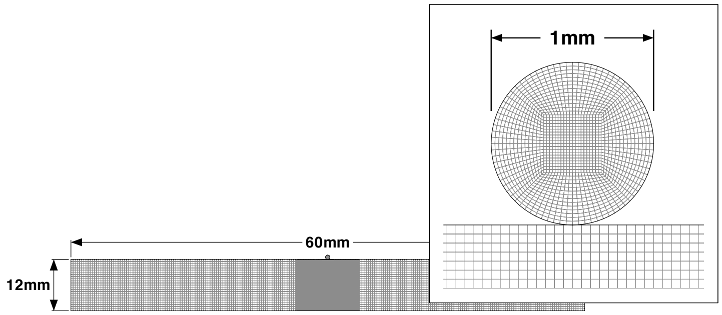

Figure 1 Schematic sketch of the problem studied, and discretization of the domain of study into finie elements.

3 WEAK FORMULATION OF THE PROBLEM

The constitutive assumptions identically satisfy the balance of moment of momentum. Galerkin's method is used to derive a weak form of the balance of linear momentum, the balance of internal energy, equations expressing the Jaumann rate of the Cauchy stress tensor in terms of the elastic part of the strain rate tensor, and evolution equations for the effective plastic strain rate and the porosity, and of the velocity equaling the time rate of change of the present position. The Johnson-Cook relation is rewritten to express the effective plastic strain rate in terms of the effective stress, the effective plastic strain and the temperature. Also, an auxiliary variable equal to the time rate of change of temperature is introduced. Thus at each node there are thirteen unknowns, namely two components of the position vector, two components of velocity, four components of Cauchy's stress tensor, porosity, temperature, its rate of change, the effective plastic strain, and mass density. Galerkin's approximation incorporates natural boundary conditions and results in a system of coupled nonlinear ODEs for the unknowns. These ODEs are integrated by using the subroutine LSODE. During this integration process, essential boundary conditions are imposed. The subroutine adjusts the time step adaptively to compute the solution within the prescribed accuracy.

4 COMPUTATION AND DISCUSSION OF RESULTS

Figure 1 also depicts discretization into 4-node isoparametric quadrilateral elements of the sandwich plate and of the cross-section of the impacting cylinder. The FE mesh is fine in the impacted region and gradually becomes coarser at points away from it. There are 21,504 elements and 21,861 nodes in the sandwich plate, and 1,561 nodes and 1,520 elements in the impactor. Literature values of material parameters for steel used in this study are given in [7]. Young's modulus E, mass density ρ, thermal conductivity, specific heat, and quasistatic yield stress of the steel foam are taken to equal one-tenth of their values for the steel face sheets. The quasistatic yield stress of the impacting cylinder is set equal to ten times that of steel so as to model it as essentially rigid. Upon impact elastic and plastic waves emanate from the contact point and propagate outwards. These are reflected from the free and the clamped surfaces, and reflected and refracted from the interfaces between the stiff face sheets and the soft foam. Note that the bar wave speed, $\sqrt{E/\rho}$, in the face sheets and the foam are the same. For impact speeds, V_0, of 100 and 200 m/s, Figures 2a,b and 3a,b exhibit, at time $t \simeq 1\,\mu s$ after impact, contours of the effective plastic strain and the temperature rise in a small region surrounding the impact point. It is clear that the extensive damage as indicated by large values of the effective plastic strain occurs in the vicinity of the impact point in the face sheet and directly below the impact point on the interface between the face sheet and the core. The damage propagates laterally along the interface to a distance of about 1.4 mm in either direction.

A comparison of the contours of the effective plastic strain in Figures 2a and 2b reveals that the maximum effective plastic strain in the face sheet equals approximately 0.16 and 0.60 for V_0=100 and 200 m/s respectively. Whereas damage tends to propagate vertically at V_0=100 m/s, it spreads laterally in the face sheet at V_0=200 m/s but is localized at the interface between the top face sheet and the core. At points near the interface plastic deformations spread farther into the soft core than into the steel face sheet. Fringe plots of the temperature rise in Figures 3a and 3b reveal that the maximum temeprature rise at V_0=200 m/s equals 700°C and occurs at points of the face sheet that are near the impact point and at points of the steel foam underneath the impacted region. Because of very small times involved, not much heat has been conducted away from the intensely deformed regions. Unless the face sheet is welded to the foam, the adhesive is likely to melt and result in delamination between the two; the delamination has not been modeled. Note that the temperature rise in white broken regions in Figure 3a,b is less than 40 K.

5 CONCLUSIONS

We have analyzed transient plane strain coupled thermomechanical deformations of a sandwich plate impacted by an essentially rigid cylinder. It simulates the impact of a tiny fragment onto a structure. At an impact speed of 200 m/s, the maximum effective plastic strain and the temperature rise equal respectively 0.6 and 700 K.

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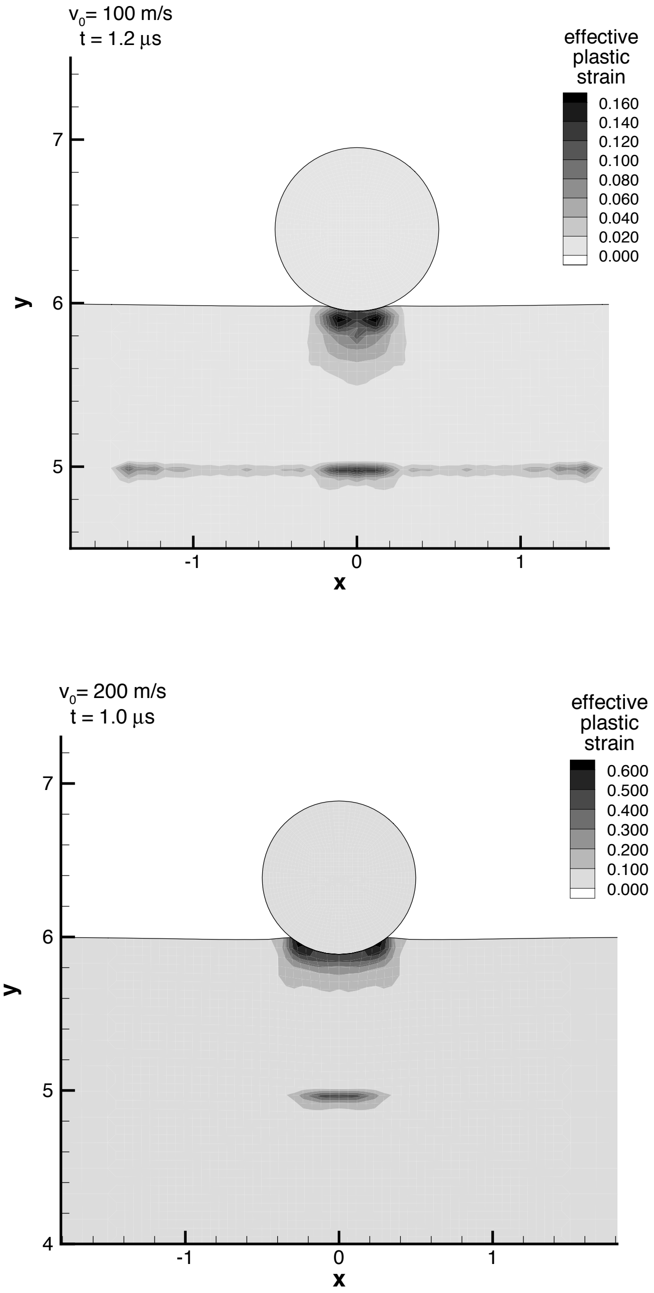
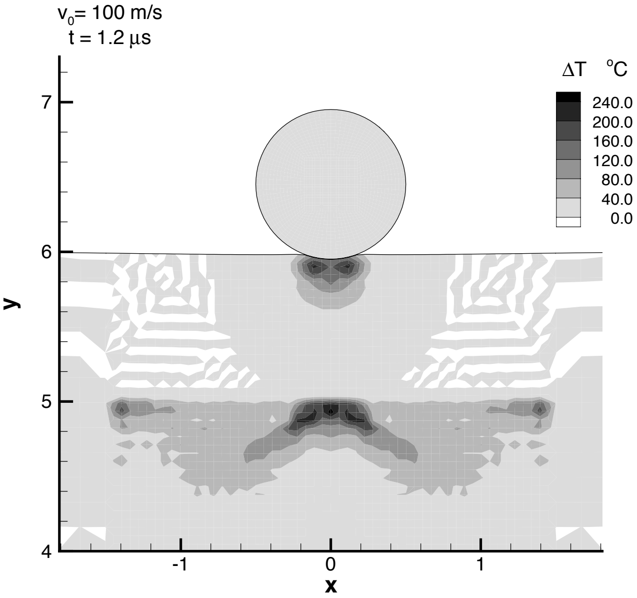


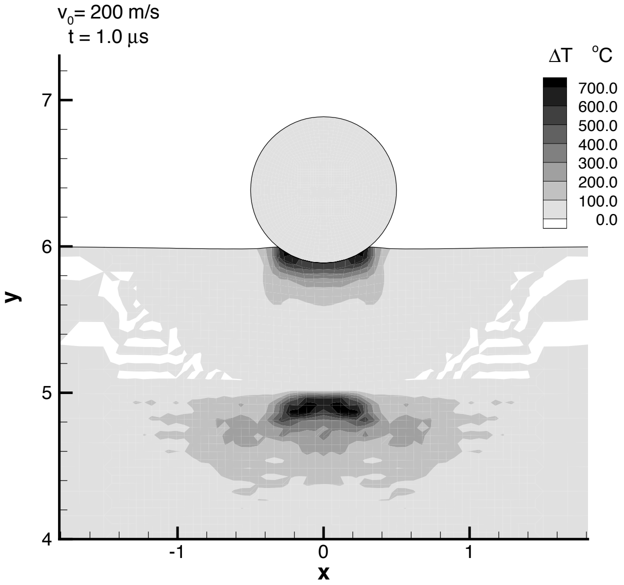
(2a)

(2b)

Figure 2. Fringe plots of the effective plastic strain (a) t = 1.2 μs, impact speed = 100 m/s; (b) t = 1 μs, impact speed = 100 m/s.



(3a)



(3b)

Figure 3. Fringe plots of the temperature rise; (a) t = 1.2 μs, impact speed = 100 m/s; (b) t = 1 μs, impact speed = 200 m/s.