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Blast response of double curvature, composite sandwich shallow shells

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ABSTRACT

An analytical model was developed for predicting the blast response of a double-curvature, composite sandwich shallow shell with PVC foam core. Based on Donnell's nonlinear shallow shell formulation, the PVC foam core was modeled with isotropic and transversely isotropic elastic–plastic properties. The predicted transient response was shown to be in good agreement with Finite Elements (ABAQUS Explicit) when assuming isotropic foam crushing. For sandwich shells with higher curvature and in-plane membrane resistance, lower blast resistance was found with transversely isotropic than isotropic core crushing. This indicated that modeling the core of the sandwich shell as isotropic instead of transversely isotropic would give non-conservative estimates of the structure's ability to resist blast loading for some sandwich shell geometries.

1. Introduction

Composite sandwich shells consisting of fiber-reinforced polymer skins and crushable polymeric foam cores are used in naval, aerospace, civil infrastructure and transportation industries. The curved, composite sandwich panels not only provide high specific stiffness and strength but are corrosion-free and low-cost alternatives to their existing metal counterparts. In some cases, these sandwich shells may be exposed to blast or pressure pulse loading. The subsequent response of the sandwich shell can involve transient deformations and vibrations, instability, and/or failure of core and facesheets of the sandwich. Porfiri and Gupta [1] have reviewed some recent work on marine composites subjected to this type of loading. Specialized continuum damage models have been developed by Batra and Hassan [2] to address damage initiation and evolution of fiber-reinforced laminates under blast using finite element analysis. Several multi-layered sandwich shell theories that incorporate higher-order shell kinematics to address transverse core compressibility and shear deformations have been proposed over the last decade to address this problem [3–6]. However, these solutions are restricted to elastic core behavior. In this paper we examine the blast response of composite sandwich shells with crushable foam cores that exhibit elastic–plastic response.

Recent blast experiments both in the laboratory [7,8] and in the field [9,10], have indicated that an elastic–plastic core is more representative of the blast behavior of foams used nowadays in composite sandwich construction. While the current design of a sandwich panel under quasi-static loads prohibits plastic crushing of the core, plastic core crushing is inevitable under very high intensity loading, such as one due to a nearby explosion. Plastic core crushing is a desirable feature in blast mitigation. Wang et al. [11] have conducted shock-tube tests on step-wise graded cores with different foam core crushing abilities to show that the blast resistance of a composite sandwich panel can be improved by staggering the foams such that the softest core, which would experience significant core crushing and plasticity, is the first incident layer during transmission of the through-thickness shock wave from a blast. The blast resistance and energy absorption of the composite sandwich panel with step-wise graded cores can be even further enhanced with polyurea interlayers [12].

This paper is concerned with the blast response of a composite sandwich shell with elastic–plastic core. Specifically, an analytical model for the transient response and failure of a fully-clamped, double-curvature, composite sandwich panel with a crushable, elastic–plastic polymeric foam core when it is subjected to uniformly-distributed pressure pulse loading is developed. This model follows from previous work by the authors on cylindrical, flat and single curvature sandwich panels [13–15]. Finite element analysis using ABAQUS Explicit is performed to compare model predictions with more refined three-dimensional numerical predictions. This analytical study shall elucidate the effect of core crushing as the sandwich shell undergoes transient deformation under blast loading.

Although many foams are transversely isotropic, they are often assumed to behave in an isotropic manner. In a flat sandwich panel subjected to lateral pressure loading, the foam core resists

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primarily transverse shear and compression. Modeling the core as an isotropic material with transverse or out-of-plane compression and shear properties is adequate for analysis of flat sandwich panels and often produces accurate solutions. However, in a curved sandwich panel or shell subjected to outer lateral pressure loading, the foam core must resist in-plane compression in addition to transverse shear and compression because of shell curvature. Such in-plane or membrane compression may be responsible for local facesheet buckling if the sandwich shell has thin facesheets and a strong core [16]. In Ref. [17], it was shown that both in-plane and out-of-plane compressive normal stresses are about the same magnitude in the elastic core of a composite sandwich shell that is externally loaded by a pressure pulse. Since most structural foams are transversely isotropic [18,19], this indicates that the in-plane foam properties would be needed to accurately determine the response of a composite sandwich shell, which carries much of the lateral blast load in membrane compression. Solutions for the blast response of a composite sandwich shell with isotropic core crushing as well as a transversely isotropic core crushing are given and compared in this paper.

2. Problem formulation

The double-curvature, composite sandwich shell is defined in Fig. 1 with facesheet thickness h and core thickness H. The mid-surfaces of the composite facesheets are defined with radius $R_{x_1}, R_{y_1}, R_{x_2}$ and R_{y_2}. Curvilinear coordinates x_1, y_1, z_1 and x_2, y_2, z_2 are defined with respect to the outer and inner facesheets, respectively. The sandwich shell is fully clamped along all edges, and is considered to be shallow; i.e., a shell with a rise-to-span ratio of less than approximately 1/5 [20–22]. This sandwich shell is subjected to uniformly-distributed pressure pulse of amplitude p_o and duration ΔT,which is given by

$$p(t) = \begin{cases} p_0\left(1 - \frac{t}{\Delta T}\right), & 0 \leqslant t \leqslant \Delta T \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

The above triangular pulse load is a simplification of the blast loading on a structure. In an actual explosion, charge weight, stand-off distance and reflected pressure waves affect the actual pressure distribution on the surface of the structure. An exponentially-decaying pressure time history is usually what is measured in blast experiments, but triangular pulse load is a good approximation of the initial stages of this loading history. It should be noted that this paper does not model an actual explosion, but rather gives a solution methodology that one can use to model blast response of a sandwich shell with an elastic–plastic core.

The composite sandwich shells considered in this paper are composed of fiber-reinforced polymeric facesheets and PVC foam cores. The mass density of facesheets and core are ρ_f and ρ_c, respectively. The facesheets are considered to be orthotropic, linear elastic-brittle material, while the core is idealized as an elastic, perfectly-plastic material. As in our previous work [13–15,17], the following assumptions concerning sandwich material behaviors are made:

1. Foam cores do not experience appreciable crushing (core compression) before facesheet fracture so that they can be described as an elastic, perfectly-plastic material. This assumption is generally applicable to uniformly-loaded composite sandwich panels with fiber-reinforced polymeric facesheets that are brittle (fracture strains less than 5% [23]) because the facesheet would fracture long before core densification. It may not be true for more localized loading, however.
2. There is perfect bonding between facesheet and core. The validity of this assumption depends on adhesion between facesheet and core. In many cases a good choice of adhesive and bonding practice ensures that there is perfect adhesion between core and facesheets. Gdoutos and Daniel [24] have examined failure modes of composite sandwich beam that were perfectly bonded and subjected to four-point bend tests. They have documented core failure due to transverse shear cracking along lines approximately 45° to a transverse cross-sectional plane; this was followed by cracking just under and parallel to the bond line between facesheet and core [24]. Post-mortem sectioning of fully clamped composite sandwich panels subjected to air-blast in Ref. [10] also indicates similar shear cracking patterns in the core.
3. Strain rate effects in both facesheet and core material behavior are neglected. Under blast loading, facesheet and core materials experience high strain rates. Fiber-reinforced polymer and polymer foam materials are best described by dynamic constitutive relations since experiments indicate that they exhibit rate-dependent behaviors [25,26].

2.1. Facesheet kinematics

Donnell's nonlinear shallow shell theory is used to obtain the strain–displacement relations in the outer facesheet ($i = 1$) and inner facesheet ($i = 2$):

$$\varepsilon_{x_i} = \varepsilon_{x_i,m} + z_i \kappa_{x_i} \tag{2}$$

$$\varepsilon_{y_i} = \varepsilon_{y_i,m} + z_i \kappa_{y_i} \tag{3}$$

$$\gamma_{x_i y_i} = \gamma_{x_i y_i,m} + z_i \kappa_{x_i y_i} \tag{4}$$

where the mid-surface strain and the change in curvature in the outer and inner facesheets are

$$\varepsilon_{x_i,m} = \frac{\partial u_i}{\partial x_i} + \frac{w_i}{R_{x_i}} + \frac{1}{2}\left(\frac{\partial w_i}{\partial x_i}\right)^2 \tag{5}$$

$$\varepsilon_{y_i,m} = \frac{\partial v_i}{\partial y_i} + \frac{w_i}{R_{y_i}} + \frac{1}{2}\left(\frac{\partial w_i}{\partial y_i}\right)^2 \tag{6}$$

$$\gamma_{x_i y_i,m} = \frac{\partial u_i}{\partial y_i} + \frac{\partial v_i}{\partial x_i} + \frac{\partial w_i}{\partial x_i}\frac{\partial w_i}{\partial y_i} \tag{7}$$

$$\kappa_{x_i} = -\frac{\partial^2 w_i}{\partial x_i^2} \tag{8}$$

$$\kappa_{y_i} = -\frac{\partial^2 w_i}{\partial y_i^2} \tag{9}$$

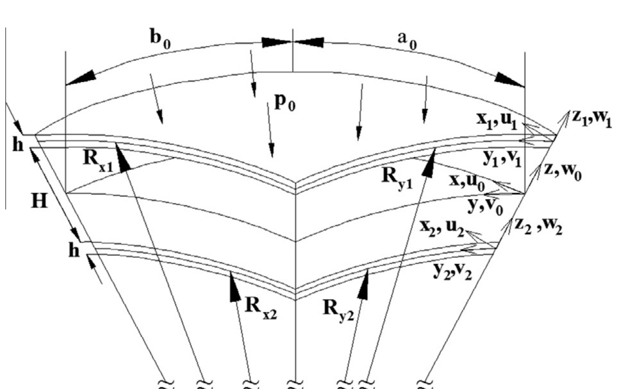

Fig. 1. Geometry and loading of double curvature sandwich shell.