Composite Structures 94 (2011) 15–23

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

# Hybrid approach in bird strike damage prediction on aeronautical composite structures

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ARTICLE INFO

*Article history:*
Available online 10 August 2011

*Keywords:*
Composite structures
Impact damage
Bird strike
Aeronautical structures

ABSTRACT

This paper deals with the problem of numerical prediction of bird strike induced damage on aeronautical structures. The problem of soft body impacts has been tackled by applying a hybrid Eulerian Lagrangian technique, thereby avoiding numerical difficulties associated with extensive mesh distortion. Eulerian modeling of the bird impactor resulted in a more realistic behavior of bird material during impact, which has lead to an enhanced response of the impacted structure. The work presented in this paper is focused on damage modeling in composite items of aeronautical structures. The bird impactor model and damage modeling approaches have been validated by comparison with experimental gas gun results available in the open literature, while the complete damage prediction procedure has been demonstrated on a complex airplane flap structure finite element model.



## 1. Introduction

The work presented in this paper presents improvements in the constitutive and damage modeling of the bird strike simulation presented in [1–3]. Lagrangian impactor modeling presents an efficient technique for numerical modeling of bird deformation behavior as demonstrated in [1]. Excessive distortion of Lagrangian finite elements can in some impact conditions lead to numerical difficulties, as stated in [2], where the Lagrangian bird model has been replaced by a hybrid Lagrangian Eulerian technique. The application of hybrid methods in bird strike analyzes allows the bird to be modeled as Eulerian material, while the impacted structure is represented by traditional Lagrangian finite elements. Eulerian material motion is independent of finite element motion, thereby avoiding numerical difficulties associated with extreme mesh distortion. Application of hybrid techniques is particularly suited to bird strike modeling as very large deformation of the impactor is expected.

The explicit dynamic finite element analyzes illustrated in this work have been performed using Abaqus/Explicit and the hybrid Coupled Eulerian Lagrangian (CEL) method. The Eulerian model in CEL analyzes is usually represented by a stationary cube containing Eulerian finite elements. Abaqus provides multi-material EC3D8R volume elements to model Eulerian problems, which may be completely or partially occupied by the Eulerian material [4]. In addition to numerical stability, an important outcome of CEL application is the improved realistic behavior of the bird impactor upon impact, since large deformation and even disintegration of the material is possible without causing numerical difficulties, as stated in [2].

The Eulerian material of the bird model is able to interact with the Lagrangian finite element model, which in this work presents a large airliner flap structure. The bird material boundary does not have to match element geometry at any time during the analysis and has to be recomputed in each time increment as the material flows through the mesh. Coupling between Eulerian and Lagrangian meshes is introduced by an extension of the general contact algorithm. The contact is created between Lagrangian mesh surfaces and Eulerian material surfaces, which are automatically computed and tracked during the analysis. Abaqus, like most of the commercial FE codes, uses penalty contact algorithms to introduce coupling between Eulerian and Lagrangian instances, as this approach uses the simplest computational level and increases robustness, as described in [5].

The size of the volume enclosing Eulerian elements must be sufficiently large to prevent loss of material during the analysis. The loss of material leads to a loss of kinetic energy and could under some conditions lead to numerical instabilities. An important restriction is placed on the mesh size of the Eulerian finite element model. A very fine mesh of the Eulerian grid is necessary to efficiently capture the contact between Eulerian material surfaces and Lagrangian elements in order to prevent physically unacceptable penetration of the bird impactor through the Lagrangian finite element mesh.

The capability of the described damage prediction procedure introduced in [1–3] has been extended by employing new material

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doi:10.1016/j.compstruct.2011.07.028

and damage models using the Abaqus user material subroutine VUMAT. The application of this subroutine enabled implementation of strain rate effects for Aluminum alloys and Puck's phenomenological damage model for composite materials. Additionally, the Mie–Grüneisen equation of state has been replaced by the polynomial equation of state consequently enabling inclusion of porosity effects for the bird impactor.

## 2. Bird modeling

Theoretical analysis of the bird strike introduces some assumptions on the bird material constitutive behavior which allow hydrodynamic theory to be applied for the bird impact [6]. As the strength and viscosity in this approach are neglected, a simple pressure vs. density equation of state can be used to describe the constitutive behavior of the bird material in numerical analyzes. Theoretical and numerical validations of bird impactor geometry suggest that a hemispherical cylinder with a length to diameter ratio equal to two, enclosing a material having the density of 950 kg/$m^3$, best resembles a real bird during impact [6,7].

Numerical bird material models have the properties of a water and air mixture, as real birds mostly consist of water and trapped air inside internal cavities. The constitutive behavior of fluid-like materials is governed by hydrodynamic material models, whose volumetric strength is calculated using equations of state (EOS). An incomplete equation of state, which does not cover heat conduction effects, determines values of the hydrostatic pressure depending on a combination of two internal variables: density ($\rho$) and specific internal energy ($e$); volume ($V$) and temperature ($T$); or volume and specific internal energy, after [8]

$$p = p(\rho, e) \vee p(V, T) \vee p(V, e). \tag{1}$$

Experimental study of soft body impactors [6] illustrates that the time-dependence of the pressure values at the impacted plate shows a recognizable pattern with three distinct regions. Immediately after the initial contact very high values of pressure arise. The peak pressure value (also called Hugoniot pressure) has the theoretical value [6]

$$p_H = \rho_0 U_S(U_0) U_0. \tag{2}$$

The second stage is characterized by release waves which decrease pressure values [6]. After several reflections of release waves, a region of stable and constant pressure is established. The steady flow stage is characterized by the stagnation pressure

$$p_{stag} = \frac{1}{2}\rho_0 U_0^2. \tag{3}$$

In order to improve the time dependent pressure response at the impact, porosity effects of water to air mixtures have been taken into account by programming the polynomial equation of state using Abaqus/Explicit user material subroutine VUMAT. According to [6], porosity has a significant effect on the shock velocity and compressibility of soft body impactors and, consequently, needs to be considered in order to realistically replicate the forces generated at an impact of real bird. Porosity decreases the shock velocity in the material, resulting in the lower Hugoniot and stagnation pressures, although the effect on stagnation pressures is not as pronounced. According to [6] the effect of porosity ($\alpha$) on the pressure to density relation is accounted for by the relation

$$\frac{\rho_0}{\rho} = (1-\alpha)\left(\frac{p}{A}+1\right)^{-\frac{1}{B}} + \alpha\left(\frac{p}{p_0}\right)^{-\frac{1}{\gamma}} \tag{4}$$

where $\rho_0$ and $p_0$ are the initial density and pressure, respectively, while $\gamma$ is the ratio of specific heats of the air. The empirical constants $A$ and $B$ are defined by Eqs. (5) and (6), where $s$ is the coefficient which relates impacting and shock velocities, while $c_0$ is the speed of sound in the material

$$A = \frac{\rho_0 c_0^2}{(4s-1)}, \tag{5}$$

$$B = 4s - 1. \tag{6}$$

The effect of porosity on the pressure vs. relative specific volume relation (Hugoniot curves), after Eq. (4), is shown by Fig. 1. The polynomial equation of state which has been programmed in VUMAT has the form

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3, \tag{7}$$

where $\mu$ is a dimensionless parameter which is defined in terms of the ratio of initial to current density

$$\mu = \frac{\rho}{\rho_0} - 1. \tag{8}$$

The polynomial EOS has been used as bird material in [7,9–11]. As in [7], the coefficients $C_0$–$C_3$ in the polynomial EOS (Eq. (7)) have been varied in order to achieve a reasonable fit of the Hugoniot curves of the homogenized materials with 10% porosity. The Hugoniot curves of the approximated material properties (after Eq. (7) for 10% porosity) along with the ones for water with various porosity, after Eq. (4), have been plotted in Fig. 1.

The porous EOS material has been validated in an impact on a rigid plate as to compare the impact pressures with experimental values [6]. An Eulerian model containing 500,000 finite elements has been used to discretize bird material motion in this analysis. The results of the bird material validation are shown on Fig. 2 in which the pressure values have been normalized by the stagnation pressure in order to compare the values with experimental results. It can be concluded that the pressure temporal response follows the general trend observed in experimental results with distinct Hugoniot, pressure release and stagnation pressure stages. The theoretical Hugoniot pressure value for an impact at 116 m/s is 93.6 MPa, after [12], which has given normalized value of 14.9. Experimental results for real birds show significantly lower peak pressure values, reaching normalized pressure value of 3.5. Fig. 2 shows that the EOS with approximated material properties shows significantly higher Hugoniot pressure values than the experimental values reported in [6], reaching normalized pressure value of

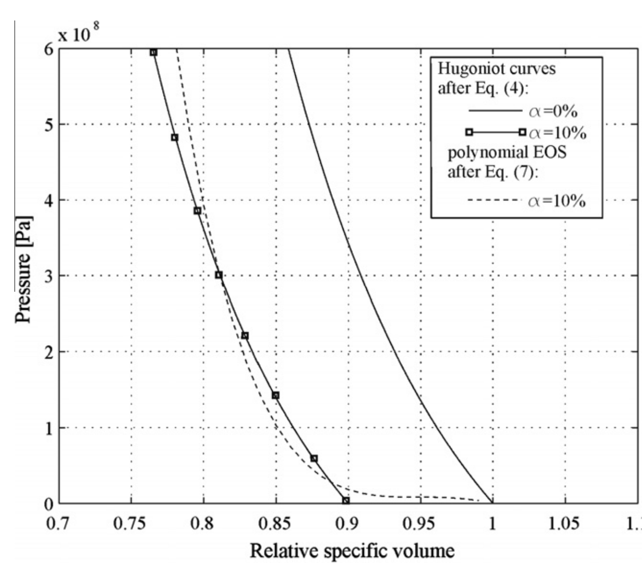


**Fig. 1.** Hugoniot curves of porous water and approximated homogenized bird material with 10% porosity.