A NUMERICAL MODEL FOR BIRD STRIKE SIMULATIONS IN COMPOSITE AEROSTRUCTURES

Maurício V. Donadon, Mariano A. Arbelo, Sérgio Frascino M. de Almeida
Instituto Tecnológico de Aeronáutica, ITA-CTA-IEM
Praça Mal. Eduardo Gomes, No. 50, São José dos Campos-SP, Brazil
Email: donadon@ita.br

ABSTRACT

The present paper describes the implementation of an improved damage mechanics based material model combined with an equation of state to simulate the progressive failure in composite aerostructures subjected to bird strike loading. A series of bird strike impacts on flat panels fabricated from low cost woven glass composite materials are used to validate the material model for practical composite component applications. The panels are modelled with shell elements only. The proposed material model can capture the strain rate enhancement to strength and strain in shear observed in composite materials.

A hydrodynamic model for the bird, based on 90% water and 10% air, is derived to represent the behaviour of the bird for all impact scenarios considered. The bird is heterogeneous in nature. However, a uniform material behaviour is assumed with a geometry based on a 2:1 length to diameter ratio with a cylindrical body and spherical end caps using Lagragian mesh. Appropriate contact definitions are used between the bird and the composite panel. The simulations results are compared to experimental results and conclusions drawn.

Keywords: Composites, impact, damage mechanics, finite elements

INTRODUCTION

The rapid increase in the use of advanced composite materials in the design of aircraft, helicopters, boats, cars, etc. requires a detailed understanding of the behaviour of the composite component or structure to a wide range of potential external loadings, some of which may be severe. In particular in the aerospace industry, impact damage in laminated composite materials continues to be a major cause of concern. Typically impact damage can be generated from low velocity tool drop or runway debris, to high velocity impacts from birds or ballistic damage from missiles or shell fragments. The bird strike impact problem is an increasing concern to the composite aerospace designer because a growing number of aerospace components are being manufactured from composite materials. Non-linear finite elements codes such as ABAQUS® and LSDYNA® are often used to model such an event as they can accurately represent the bird material behaviour, contact between the bird and the structure and the constitutive behaviour of composites by means of user-defined material models. Numerical simulations are usually accompanied by a parallel testing programme to validate the numerical simulations for some of these impact scenarios. The fabrication, test and certification of composite components and structures can be very expensive. However, advanced simulations will never eliminate the need for these expensive impact tests. In practise, they will require more detailed experimental tests to validate the advanced algorithms used within the Finite Element (FE) formulation. The major advantage of FE modelling is that they can study the effects of new and different structural and material concepts, without an extensive fabrication and testing programme.

In the current paper an improved damage mechanics based material model combined with an equation of state to simulate the progressive failure in composite aerostructures subjected to bird strike loading is presented. The proposed material model can capture the strain rate enhancement to strength and strain in shear observed in composite materials. A series of bird strike impacts on rigid and flexible flat panels fabricated from low cost woven glass composite materials are used to validate the proposed material model.

HYDRODYNAMIC MODEL FOR THE BIRD

Extensive databases of bird modelling strategies are currently available in the open literature. A summary of these strategies are presented in the GARTEUR AG23 final report [1]. Based on these previous works a hydrodynamic model based on a rule of mixtures using 90% by volume of water with remainder of air has been proposed to describe the bird behaviour. The model development is based on the following assumptions:

- The components of the stress tensor are split into deviatoric and hydrostatic stresses
- In order to assign a fluid like behaviour for the bird the deviatoric stresses are assumed to be equal to zero
- Equations of state are defined for each constituent separately and a rule of mixture is proposed to derive an equation of state for the bird
- The hydrostatic stresses are defined in terms of the equation of state (EOS) for the bird
- Temperature effects are not taken into account in the derivation of the equation of state for the bird

The compressibility effects on the water can be described by an equation of state given in the following form,

$$P(\mu) = P_0 + c^2 \rho_0 (\mu - 1) \tag{1}$$

where $\mu = \rho_o / \rho$. ρ_o is the initial or reference density defined at reference pressure P_o and ρ is the current density for a given pressure level P . c is the sound speed in the water. By assuming the air as an ideal gas under isoentropic flow the increase in pressure due to increasing density can be related by

$$P(\mu) = P_o(\mu)^k \tag{2}$$

where $\mu = \rho / \rho$ and k=1.4 . In the equations above $_0\rho$ is the initial or reference density of each component defined at reference pressure P_0 and ρ is the current density for a given pressure level P The bird is assumed to be composed by water and air. Thus, the total volume of the bird is given by

$$V = V_{water} + V_{air} = m_{water} / \rho_{water} + m_{air} / \rho_{air}$$

where m_{water} and ρ_{water} are the mass and density of the water and m_{air} and ρ_{air} are the mass and density of air, respectively. Defining f_{water} and f_{air} as mass fractions of water and air, respectively, one can show that the equivalent density and density ratio for the mixture can be respectively written as follow,

$$\bar{\rho} = \frac{\rho_{water} \rho_{air}}{\rho_{air} f_{water} + \rho_{water} f_{air}} \tag{4}$$

$$\bar{\mu} = \frac{\mu_{water} \mu_{air}}{\mu_{air} f_{water} + \mu_{water} f_{air}} \tag{5}$$

As the mixture is thermodynamically under equilibrium and its components are subjected to the same pressure level, a compressibility curve as the one shown in Figure 1 can be obtained.

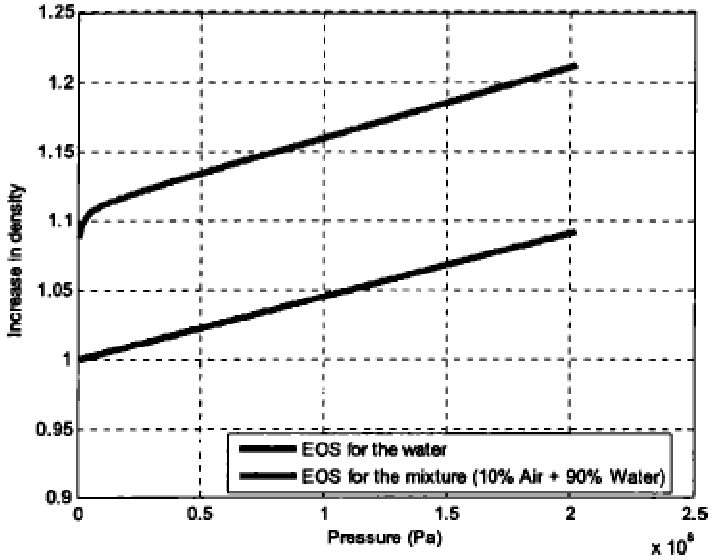

Figura 1. Equation of State for bird material in relation to the EOS of water

It can be seen from Figure 1 that a small percentage air (10%) dramatically affects the compressibility at low pressures, and hence must be included in the model. The stress-strain relationship for the bird is given by

$$S = S^{Dev} + S^{Hyd}$$
$$S^{Dev} = 0 \tag{6}$$
$$S^{Hyd} = -p(\bar{\mu})$$

where S^{Dev} and S^{Hyd} are the deviatoric and hydrostatic components of the stress tensor. The hydrostatic stresses are defined in terms of pressure p and volumetric strain. The volumetric strain for the bird can be written in terms of the density ratio for the mixture as follows,

$$\varepsilon^{vol} = \frac{\Delta V}{V} = 1 - \bar{\mu} \tag{7}$$

Within the nonlinear finite element context and based on the updated Lagrangean formulation, the volumetric strain for the bird can be written in terms of the deformation gradient as follows,

$$\varepsilon^{vol} = 1 - \frac{J_0}{J} \tag{8}$$

where $J = \det(F)$ and $F = \nabla_0 \mathbf{x}(x, y, z)$ is the deformation gradient. The proposed hydrodynamic model has been implemented into ABAQUS/Explicit finite element code.

COMPOSITE FAILURE MODEL

The formulation proposed to model progressive failure in composites is based on the smeared cracking approach [2,3]. The smeared cracking formulation relates the specific or volumetric energy, which is defined by the area underneath the stress-strain curve, with the strain energy release rate of the material. The method assumes a strain softening constitutive law for modeling the gradual stiffness reduction due to the micro-cracking process within the cohesive or process zone of the material. In order to avoid pathological problem associated with strain localization and mesh dependence during softening, the softening portion of a stress-strain curve is adjusted according to the element topology and cracking direction for each failure mode using an advanced objectivity algorithm [2,3].

Failure criteria

The failure criteria used to detect damage initiation for all in-plane failure modes are all based on the maximum stress criteria and they are given in the general form as follows,

$$F_{ij}^{k}(\sigma_{ij}) = \frac{\sigma_{ij}}{S_{ij}^{k}} - 1 \geq 0 \tag{9}$$

where $F_{ij}^{k}(\sigma_{ij})$ is the failure index associated with the failure mode k, where $k = t$ for failure in tension, $k = c$ for failure in compression and $k = s$ for failure in shear. σ_{ij} are the stresses acting on each layer at the local material coordinate system, where the subscripts $i = j = 1$ and $i = j = 2$ refer to the fibre and matrix directions, respectively and $i \neq j$ refer to inplane shear direction. S_{ij}^{k} is the material strength associated with the failure mode k in the local direction defined by the subscripts ij

Damage evolution laws

Damage evolution law for fibre failure and matrix cracking

The general expression proposed for the damage evolution laws in the fibre and matrix directions is given as follows,

$$d_{ii}(\lambda_{i,1}, \lambda_{i,2}) = \lambda_{i,1} + \lambda_{i,2} - \lambda_{i,1}\lambda_{i,2} \tag{10}$$

with

$$\lambda_{i,1} = \frac{2G_{ii}^{t}}{2G_{ii}^{t} - S_{ii}^{t} l^{*} \varepsilon_{i,0}^{t}} \left(\frac{\varepsilon_{ii}^{t} - \varepsilon_{i,0}^{t}}{\varepsilon_{ii}^{t}} \right) \tag{11}$$

$$\lambda_{i,2} = \frac{2G_{ii}^{c}}{2G_{ii}^{c} - S_{ii}^{c} l^{*} \varepsilon_{i,0}^{c}} \left(\frac{\varepsilon_{ii}^{c} - \varepsilon_{i,0}^{c}}{\varepsilon_{ii}^{c}} \right) \tag{12}$$

where i assumes value equals to one for fibre failure and two for matrix cracking. The values for both functions $\lambda_{i,1}, \lambda_{i,2} \in [0,1]$. G_{ii}^{t} and G_{ii}^{c} are the intralaminar fracture toughnesses in tension and compression, respectively. $\varepsilon_{i,0}^{t}$ and $\varepsilon_{i,0}^{c}$ are maximum strains prior to catastrophic failure in tension and compression, respectively. In order to account for damage irreversibility effects $\varepsilon_{ii}^{k} = \max\left[\left|\varepsilon_{ii}^{\max}(t)\right|, \varepsilon_{i,0}^{k}\right]$ where $\varepsilon_{ii}^{\max}(t)$ is the maximum achieved strain in the strain versus time history. The superscript k refers to the fibre failure mode, that is, $k = t$ for failure in tension and $k = c$ for failure in compression. The characteristic length l^{*} is used for mapping the material process (or microcracking) zone into the finite element mesh. For fibre failure modes l^{*} is computed in terms of the isoparametric coordinates (ξ_{l}, η_{m}) for each integration point m according to the following expression,

$$l^{*}(\xi_{m}, \eta_{m}) = \left(\sum_{l=1}^{n_{e}} \left[\frac{\partial N_{l}(\xi_{m}, \eta_{m})}{\partial x} \cos(\theta_{m}) + \frac{\partial N_{l}(\xi_{m}, \eta_{m})}{\partial y} \sin(\theta_{m}) \right] \phi_{l} \right)^{-1} \tag{13}$$

where $\theta_m = \theta_{fibre}$ being θ_{fibre} the fibre orientation angle for each integration point for fibre failure and $\theta_m = \theta_{fibre} + 90^0$ for failure in the matrix direction. For four nodes shell elements $n_c = 4$, $N_I(\xi_m, \eta_m)$ are bi-linear interpolation functions and φ is defined as crack band discontinuity function. Details about the derivation of the expression for the characteristic length for orthotropic smeared cracking modes can be found in Ref [3].

Damage evolution law for in-plane shear failure

The damage evolution for in-plane shear failure is given by

$$d_{12}(\gamma_{12}) = \frac{\gamma_{12,f}\left[2\left(\gamma_{12} - \gamma_{12,0}^{in}\right) - \gamma_{12,f}\right]}{\left(\gamma_{12,f} + \gamma_{12,0}^{in} - \gamma_{12}\right)\left(\gamma_{12} - \gamma_{12,0}^{in}\right)} \tag{14}$$

with

$$\gamma_{12,f} = \frac{2G_s}{S_{12} l^*} \tag{15}$$

where $\gamma_{12,0}^{in}$ is the inelastic strain at failure and G_s is the in-plane shear intralaminar fracture toughness. The characteristic length l^* for in-plane shear failure is assumed to be the same as the one used for fibre failure modes.

Non-linear rate dependent in-plane shear model

The observed behaviour of glass and carbon fibres laminates generally shows marked rate dependence in matrix dominated shear failure modes and for this reason a rate dependent constitutive model has been used to model the in-plane shear behaviour. The constitutive model formulation is based on previous work carried out by Donadon and co-authors [4], and it accounts for shear non-lineatities, irreversible strains and damage within the Representative Volume Element (RVE) of the material. The stress-strain behaviour for in-plane shear failure is defined as follows,

$$\tau_{12} = \alpha G_{12} \gamma_{12} \tag{16}$$

with

$$G_{12} = G_{12}^0 + c_1\left(e^{-c_2\gamma_{12}} - 1\right) \tag{17}$$

where G_{12}^0 is the initial shear modulus and c_1 and c_2 are material constants obtained from in-plane shear tests. α is the strain rate enhancement given by the following law,

$$\alpha = 1 + e^{\frac{\dot{\gamma}_{12}}{c_3}} \tag{18}$$

where c_3 is a material constant obtained from dynamic in-plane shear tests. By decomposing the total shear-strain into inelastic γ_{12}^{in} and γ_{12}^{e} elastic components, the inelastic shear strain can be written in terms of the elastic and total strain components as follows,

$$\gamma_{12}^{in} = \gamma_{12} - \gamma_{12}^{e} = \gamma_{12} - \frac{\tau_{12}(\gamma_{12})}{G_{12}^0} \tag{19}$$

Stress degradation procedure

The resultant degraded stresses at ply level are given by

$$\begin{Bmatrix} \sigma_{11}^d \\ \sigma_{22}^d \\ \tau_{12}^d \end{Bmatrix} = \begin{bmatrix} (1-d_{11}(\lambda_1^f,\lambda_2^f)) & 0 & 0 \\ 0 & (1-d_{11}(\lambda_1^f,\lambda_2^f))(1-d_{22}(\lambda_1^m,\lambda_2^m)) & 0 \\ 0 & 0 & (1-d_{12}(\gamma_{12})) \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} \qquad (20)$$

where

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} = \frac{1}{(1-\nu_{12}\nu_{21})} \begin{bmatrix} E_{11} & \nu_{12}E_{22} & 0 \\ \nu_{21}E_{11} & E_{22} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix} \qquad (21)$$

NUMERICAL SIMULATIONS

Single element validation

Simulations at element level were carried out to validate the proposed hydrodynamic model for the bird. The single element model consists of an element subjected to a pure hydrostatic stress state. Figure 2 compares the numerical response in terms of pressure versus volumetric strain for a single finite element subjected to hydrostatic pressure only with the proposed analytical EOS for the bird.

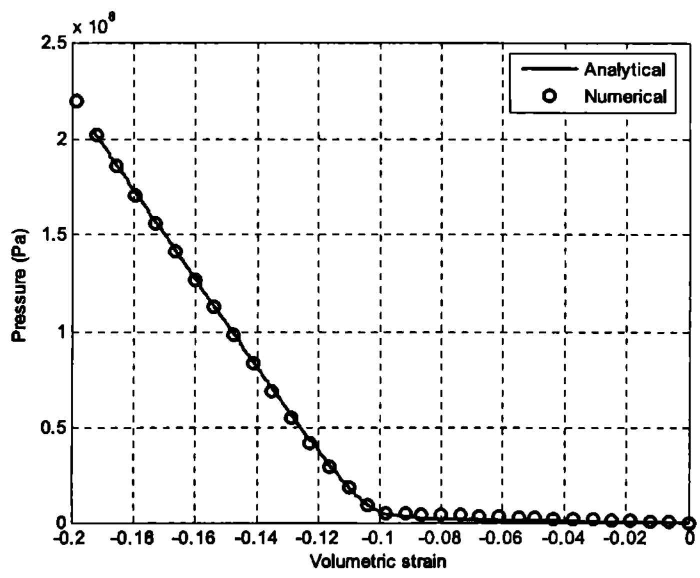

Figura 2. Single element validation

Bird strike onto rigid targets

According to Ref [1] the bird model should have a length to breadth ratio of 2 and should consist of a cylindrical type structure with rounded ends. Figure 3 illustrates the recommended 1.82 kg (4lbs) bird geometry.

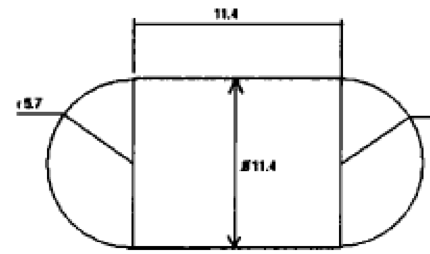

Figura 3. Bird Model Geometry (all dimensions are in cm)

Figure 4 shows the deformation of the bird mesh when impacting the rigid target at 225 m/s. The figures clearly illustrate the Lagrangian bird flowing over the rigid surface. Also, the peak Hugoniot pressures occur at approximately 100 ∝sec and 60 ∝sec into the impact events at 116 m/s and 225 m/s, respectively. Hence the percentage of water and air within the bird EOS are critical in determining the peak Hugoniot pressures. Hugoniot pressures calculated using the proposed hydrodynamic model are shown to occur within the scatter of experimentally measured values reported in Refs [5,6].

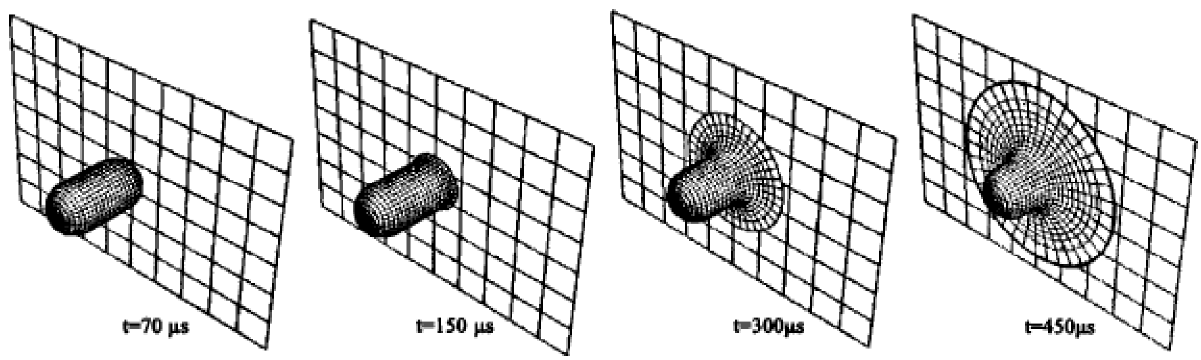

Figura 4. Rigid wall bird strike at 225 m/s

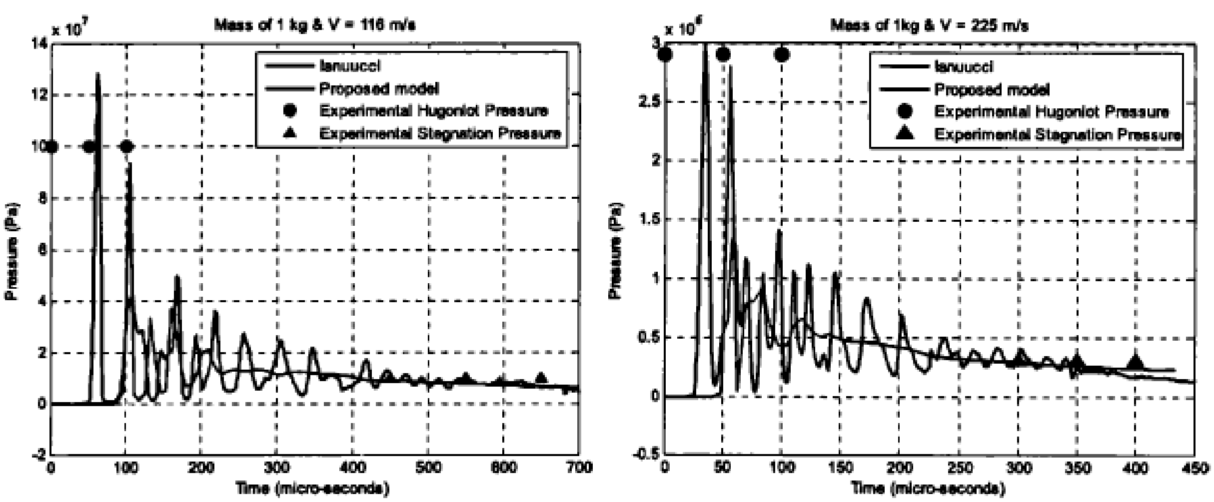

Figura 5. Pressure vs. time history for centre-line element of bird: 116 m/s (left), 225 m/s (right)

The numerically calculated pressure-time plots for a 1 kg impact at 116 m/s and 225m/s are shown in Figure 5. The Hugoniot and the stagnation pressures for both cases, are within the experimental scatter given in Barber et al [5]. Comparisons between numerical predictions for the Hugoniot and the stagnation pressures obtained using the proposed model and a previous model proposed by Iannucci [4] are also shown in Figure 5. The hydrodynamic model proposed here clearly gives better correlation with experimental compared with the model presented in Ref [4] for both impact cases.

Bird strike onto composite plates

Two 6 ply (3mm thick) flat panels made of glass fibre embedded into an epoxy resin system with a lay-up 0/90/0/90/0/90 and dimensions 750mmx500mm taken from Ref [4] were analysed. Both panels are bolted via a clamping plate to distance of 50mm from the free panel edges. Normal incident impact of a 1kg bird projected using 6-inch gas gun. In the first case the bird strike impact occurred at 147 m/s. No bird penetration, but extensive (between 40% - 50% of edges) bearing damage at support locations with damage symmetrical in nature was observed. Comparisons between predicted and experimental damaged zones are shown in Figure 6. The failed elements have been removed from the mesh. The second case analysed consisted of a bird strike impact at 245 m/s. For this case the bird penetrates the panel with extensive damage in the impact zone. The fracture surface had extensive fibre/filament pullout. Bearing damage substantially reduced, however, perforation outline not symmetrical. Comparisons between predicted and experimental damaged zones are shown in Figure 7. The predicted damaged zone is indicated by the failed elements which have been removed from the mesh.

Figura 6. Comparison between numerical and predicted damage extension for bird impact at 147 m/s

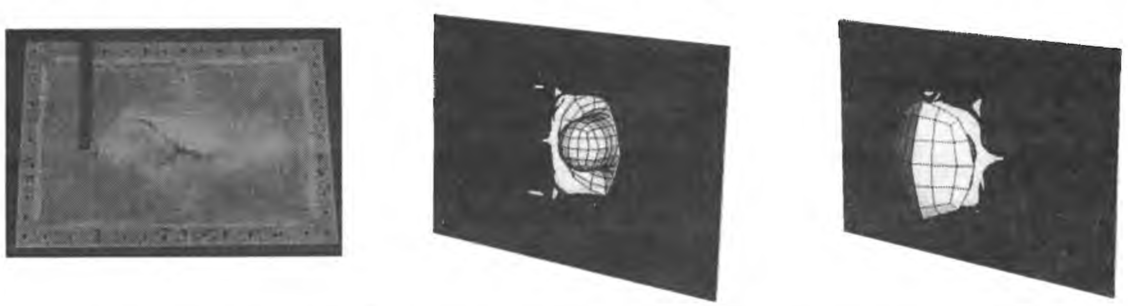

Figura 7. Comparison between numerical and predicted damage extension for bird impact at 245 m/s

CONCLUSIONS

In the present study the overall agreement between the experimentally observed and numerically calculated damage is found to be very good, considering the wide variability present in bird shape/properties and the extrapolation of dynamic properties. Very good correlation between numerical predictions and experimental results for rigid wall bird strike was obtained using the proposed hydrodynamic model. The use of a hybrid modeling approach combining stress based failure criteria, damage mechanics and fracture mechanics approaches appears to yield reliable predictions for the behaviour of woven glass composites. The shell model implementation could be coupled to solid elements to realistic predict the delamination extent.

REFERENCES

1. Willows, M. L., Final report on the European Aerospace GARTEUR group on bird strike (AG23), QinetiQ, 2005.

2. Donadon, M.V., "The impact behaviour of composite structures manufactured using resin infusion under flexible tooling", Ph.D Thesis, Department of Aeronautics, Imperial College London, England, UK, 2005, 375 p.
3. Donadon, M.V., Iannucci L., Falzon B. G., Hodgkinson J. M., Almeida S.F.M., 2008, "A progressive failure model for composite laminates subjected to low velocity impact damage", Computers & Structures, 2008, Vol. 86, pp 1232-1252.
4. Donadon, M. V. and Iannucci L., "Bird strike modelling using a new woven glass failure model", Proceedings of the LS-DYNA International Conference, Michigan, Dearborn, USA, 2006.
5. Barber, H. R. Taylor and Wilbeck, J. S., Bird Impact Forces and Pressures on Rigid and Compliant Targets, NASA AFFDL-TR-77-60, University of Dayton Research Institute Ohio, May 1978.
6. Iannucci, L., Bird strike impact modelling, Foreign Object Impact and Energy Absorbing Structure, IMechE HQ, March 1998.