NUMERICAL SIMULATION OF BIRD STRIKE IMPACT AGAINST BALANCED FIBERGLASS/EPOXY COMPOSITE PLATES

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Abstract. *Bird strike events are a potential dangerous problem faced by flight safety nowadays. These events are usually simulated through numerical approaches due mainly to the technical difficulties and high costs associated with experimental tests. In this work, bird strike like phenomenon and correlated aspects such as contact, perforation and failure occurrence are addressed by using LS-DYNA3D finite element explicit code. Medium to high impact velocities of 'dummy birds' over balanced S2-glass/epoxy laminate composites are simulated in the tests. Material modeling issues of both impacted plates and soft body are stressed, being employed a polynomial equation of state to describe the fluid-like behavior of the jelly-bird. An investigation on the accuracy, merits and limitations of a finite element approach to this kind of problem is presented as well as comparisons with gas gun tests.*

Keywords: *composite laminate, impact, bird strike, finite element, explicit analysis.*

1. INTRODUCTION

Due to the appreciable presence of birds in the vicinity of airport, hundreds of occurrences of bird strike onto aircrafts have been verified every year in Brazil. Financial damages originated by this kind of event are of the order of some million of dollars (Cenipa, 2006), although most of times it has no tragic consequences. High strain rates, large deformations and inelastic strains associated to this phenomenon, among other factors, restrict the use of analytical procedures. Abrate (2001) presented a comprehensive review of modeling of impact on composites structures based mainly on such analytical approaches.

In the last two decades a significant expansion of the use of composite materials in aeronautical industry has been verified, aiming to obtain structures with advantageous strength-to-weight relations. However, the impact induced damage in composite materials is an aspect that inhibits the application of this kind of material, since it is well known that composites are very susceptible to transverse impact. The impact response of laminates to distinct impact velocities differs considerably: to low velocities there is a predominance of elastic absorption of impact energy, whereas to high velocities the contact time is shorter and the main issue is the occurrence of partial or total penetration, i.e. perforation.

Damage and failure mechanisms related to laminated composite materials under impact loading are very complex, depending on several parameters, which must be well understood in order to ensure a safety use of composite laminate structures.

Experimental tests using projectile launchers have been often used to approach the problem (Antoun et al., 1992; Jackson and Fasanella, 2000; Fasanella, Jackson and Lyle, 2000; Johnson and Holzapfel, 2003), but this methodology is expensive and difficult to perform. With the development of reliable non-linear explicit codes in the late eighties, based mainly on the Finite Element Method (FEM), the numerical treatment became possible and since then numerical analysis have been increasingly adopted to solve this kind of problem, allowing to reduce certification and development costs. However, comparison with available experimental results continues being welcome and necessary to verify the accuracy of the computational methodology.

The LS-DYNA3D code (Hallquist, 2006) was developed in the end of the seventies by the North American laboratory 'Lawrence Livermore National Laboratory (LLNL). The current version is a general purpose finite element code for non-linear structural dynamics connected to problems of heat and/or fluids, that makes use of sophisticated algorithms for treatment of contact-impact problems. A large number of impact analysis by using this software has been published in the literature in the last years. Schweizerhof et al. (1998) presented a critical review of several composite material in LS-DYNA3D. Hou et al. (2000) proposed improved failure criteria, which consider the interactions between different damage mechanisms. The work of Johnson and Holzapfel (2003) considered the numerical simulation of gas gun impact tests performed with gelatine projectiles and glass fasbric/epoxy targets. More recently, Airoldi and Cacchione (2006) compared different bird characterizations, focusing the study on the pressure distribution on the impacted targets. Recent progress on material modeling and numerical simulation of soft body impact damage in fibre reinforced composite aircraft structures can be found in the work of Johnson and Holzapfel (2006).

In this work, a numerical analysis of the impact of soft bodies onto S2-Glass/Epoxy composite plates is carried out by using the LS-DYNA3D code. Material modeling of soft body and composite plates, contact aspects and numerical issues concerning to the simulation are addressed and the numerical results obtained are compared with experimental gas gun projectile launcher tests conducted at authort's institution.

2. IMPACT SIMULATION

2.1 Problem overview

The governing equations of motion of a continuous medium, i.e. conservation of mass, *momentum* and energy, can be found in textbooks of Continuum Mechanics (see for instance Malvern,1969). The classical theories of beams, plates and shells are not suitable for the problem in focus since they assume transversal inextensibility of the structure, as observed by Abrate (2001).

The impact of a cylindrical soft body horizontally launched and normally incident on a circular clamped composite plate is considered. The problem was modeled and solved with LS-DYNA3D explicit finite element code, using 8-nodes underintegrated solid elements to both cylinder (projectile) and plate (target). Simulation aspects such as contact, material modeling and description of the motion are described in the next sections.

2.2 Contact

The most basic level of a contact algorithm refers to the impediment of all and any node to penetrate a surface. The three-dimensional LS-DYNA3D algorithm can be summarized in the following stages:

- to define 'master' and an 'slave' surface in the bodies for which the contact occurrence will be investigated;
- the surfaces cited in the previous item are automatically approximated by a polyhedral representation;
- nodes pertaining to each surface are labeled as slaves or masters in accordance with the type of surface that belongs;
- according to the modality of contact, the code logical treatment is performed and updated in each time step.

In this work it was employed the ERODING_NODES_TO_SURFACE and ERODING_SURFACE_TO_SURFACE code's contact options (Hallquist, 2006), in which the contact of a set of nodes or elements in the surface of the body is verified with regard to the elements of the surface of the impacted body. When the elements of both impactor and impacted body part are deleted by some failure criterion, this simulates the erosion process that results from the impact.

2.3 Constitutive models

2.3.1 Composite plate

This work used S2-glass/epoxy composite laminates to which were added nanoclays (Fig. 1), manufactured and furnished by the Mechanics of Composites Laboratory of Federal University of Minas Gerais (UFMG) (Ávila et al., 2005). The plates had size 350 x 350 mm and a thickness of 4 mm. The studied fiber configuration is of the plain weave balanced type, i.e. formed by equal fractions of fibers in the longitudinal and transversal directions at each layer. The process of manufacture of these plates is detailed in the work of Morais (2003).

Previous computational tests with LS-DINA3D constitutive models **MAT22**, **MAT54**, **MAT55** and **MAT59** (Hallquist, 2006) had led to the choice of the later one after a comparative cost-benefit analysis. This model presents the option of definition of the associated system of co-ordinates to the material, either local or globally orthotropic in cartesian or cylindrical coordinates. It has control of automatic elimination of elements values in accordance with a specified time step and a softening process for reduction of the properties. Another important characteristic of this material model is the possibility of adoption of a failure theory with faceted or ellipsoidal surfaces.

The failure surface associated with MAT59 when hexahedral elements are used is similar with the Tsai-Wu interactive criterion (Tsai and Wu, 1971). Elastic properties, as well as tensile, compressive and shear strengths at the three

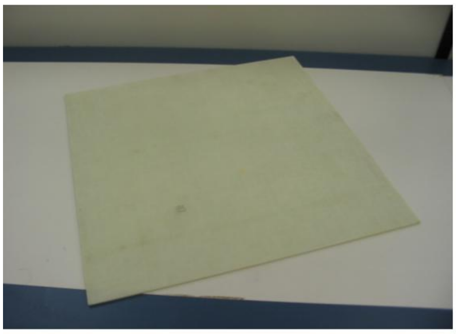

Figure 1. Composite laminate view.

principal directions are required by this model. It is worthwhile to mention that all available material data resulting from mechanical characterization tests were used to a better representation of the material properties. However, as observed by Yen (2002), not all experimental values for S2-Glass/Epoxy are currently available, leading to the need of simplifications and estimations, which were also adopted in the present work in order to complete the model material data requirements. Previously performed quasi-static tests and symmetry consideration had lead to the values specified in Tab. 1.

Table 1. Lamina's mechanical properties of the analyzed composite.

Elastic modulus at in-plane fill direction, E_1	17 GPa
Elastic modulus at in-plane warp direction, E_2	17 GPa
Elastic modulus at out-of-plane direction, E_3	17 GPa
Poisson's ratio (in-plane), ν_{21}	0.12
Poisson's ratio (out-of-plane), ν_{31}	0.4
Poisson's ratio (out-of-plane), ν_{32}	0.4
Shear modulus (in-plane), G_{12}	6.1 GPa
Shear modulus (out-of-plane), G_{23}	6.1 GPa
Shear modulus (out-of-plane), G_{31}	6.1 GPa
Shear strength (in-plane), S	60 MPa
Shear strength at plane $1-3$, $S1$	60 MPa
Shear strength at plane $2-3$, $S2$	60 MPa
Compressive strength at in-plane fill direction, XXC	325 MPa
Compressive strength at in-plane warp direction, YYC	325 MPa
Compressive strength at out-of-plane direction, ZZC	325 MPa
Tensile strength at in-plane fill direction, XXT	325 MPa
Tensile strength at in-plane warp direction, YYT	325 MPa
Tensile strength at out-of-plane direction, ZZT	325 MPa

2.3.2 Soft body

Impact of bodies with low rigidity and hardness, as those considered in the present analysis, has been treated in the aeronautical industry and research centers through the so-called 'substitute birds' (Airoldi and Cacchione, 2006; Johnson and Holzapfel, 2006), materials whose mechanical behavior resembles real birds, with advantages in what it refers to the systematization of the experimental essays. These materials, e.g. ballistic gelatin, flow as a fluid when shocking itself with the impacted surface, significantly increasing the damaged area. Another important difference between the impact of soft bodies and of bodies with high rigidity/hardness is the reduced level of penetration verified as resulted of this type of shock.

For numerical simulation of this type of impact, one of the main approaches consists of considering the pressure-dependent character of the material behavior (Johnson, 2003): at lower pressures the material behaves as isotropic elasto-plastic and at higher pressures as a hydrodynamic material, for which an equation of state relating the thermodynamic properties of pressure, p, and volume is adopted (Meyers, 1994). An example of equation of state that has been largely used is the polynomial one, which was adopted in this work and has the following mathematical expression:

$$p = C_0 + C_1\mu + C_2(\mu)^2 + C_3(\mu)^3, \quad \mu = \rho/\rho_0 - 1 \tag{1}$$

where C_0, C_1, C_2 and C_3 are material constants, ρ is the current density and ρ_0 is the reference initial density. Difficulties in the measurement of these constants have motivated to adopt a material behavior similar to water, such that:

$$C_0 = 0, \quad C_1 = \rho_0(c_0)^2, \quad C_2 = (2k-1)C_1, \quad C_3 = (k-1)(3k-1)C_1 \tag{2}$$

where C_1 is the bulk modulus, k a constant from the Hugoniot relation (Meyers, 1994), c_0 is the sound speed in the material. As recommended by Johnson (2003), material constants representing a water mixture with 10% of incorporated air were employed, aiming to reduce the specific mass and the module of compressibility of this resultant material, as well as the speed of the sound. Introducing the values of specific mass, sound speed and constant of Hugoniot for water into expression 2, one finally obtains the following results:

$$C_0 = 0, \quad C_1 = 2.1 \text{ GPa}, \quad C_2 = 2.1 \text{ GPa}, \quad C_3 = 10 \text{ GPa} \tag{3}$$

2.4 Description of the motion

To describe the movement of a continuous medium the Eulerian and Lagrangian referential can be used. The Eulerian description, adopted normally in problems of Fluid Dynamics, has the capability of handling severe distortions but it presents difficulties to consider free surfaces. The Lagrangian description, used currently in Solids Dynamics, has limitations to contemplate severe distortions of the mesh. Hence, an alternative to treat impact problems of soft bodies with deformable surfaces is the so called Arbitrary Lagrangian-Eulerian (ALE) description, which avoids the premature interruption of the analysis through an automatic remeshing, i.e. without topological changes. The steps followed by the code to advance the solution in time with an ALE description are (Hallquist, 2006):

1. Lagrangian advance of the solution in time;

2. Advective step

  - selection of the nodes to be moved;
  - boundary nodes movement;
  - internal nodes movement;
  - transport of the solution variables to the new nodes;
  - velocities update.

3. NUMERICAL RESULTS AND COMPARISON WITH GAS GUN IMPACT TESTS

The complete impact system was modeled with 8-node brick elements with single integration point and control of spurious modes. The plate was placed over a rigid circular ring, i.e. clamped boundary condition was assumed and an initial velocity was provided to the impactor to start the analysis. The circular cylinder with 50 mm of diameter and 100 mm of height is made of a plasticine compound (Fig. 2) and fired by the gas gun (Fig. 3). The soft body element erosion criterion was given by a combination of LS-DYNA material card **MAT_NULL** and the equation of state **EOS_LINEAR_POLYNOMIAL** (Hallquist, 2006) as indicated to this kind of projectile.

Figure 2. Modeling compound circular cylinder.

Figure 3. GMSIE's gas gun projectile launcher.

Three different finite element meshes were adopted in the simulations. The second and the third meshes were obtained from the first one by division of the plate thickness in two and four element layers, respectively. Table 2 below resumes mesh characteristics and Fig. 4 shows the plate finite element mesh #3. A regular mesh (not shown) was adopted to the circular cylinder in all numerical tests. This mesh was generated in order to obtain a compatibility between element sizes in both the impact area and discretized projectile.

Table 2. Impact test simulation parameters.

Mesh number	Layers	NNOS	NEL	LS-DYNA contact card
1	1	7454	3678	ERODING_SURFACE_TO_SURFACE
2	2	11181	7356	ERODING_SURFACE_TO_SURFACE
3	4	18635	14712	ERODING_SURFACE_TO_SURFACE

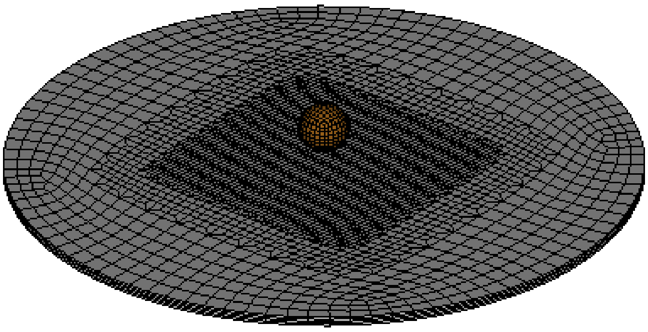

Figure 4. Mesh#3: 18635 nodes, 14712 elements.

Figures 5 to 8 illustrate the sequence of impact simulated with the projectile's properties estimated as described above. Similar procedure was adopted by Airoldi and Cacchione (2006). Mesh #3 was adopted to the plate, the impact velocities in the numerical tests was kept constant and equal to 115 m/s. The total time of the phenomenon was 5 ms and the timestep, updated automatically by the program, varied between O(10^{-7} s) to O(10^{-9} s) as the simulation advanced to the end.

As expected, the impact is propagated in a quite significant area along the plate, like the stress field represented in the Figure 9 allows to check. Besides, the agreement in qualitative terms with the experimental results, showed in Figures 10, 11 and 12, can be considered quite reasonable, taking into account the approximations that were done in the computational model, mainly to the lack of more accurate material data.

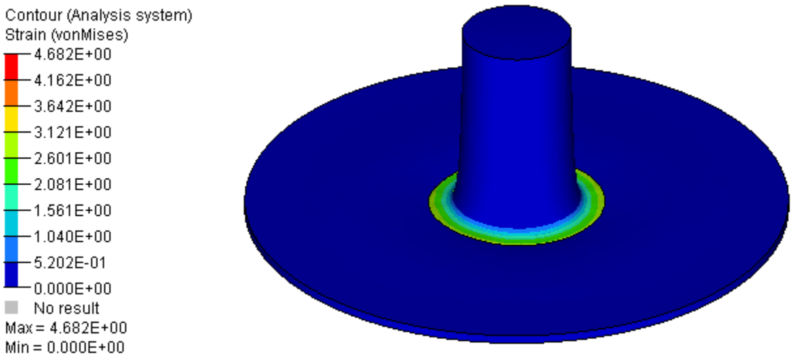

Figure 5. Soft body impact simulation. Strain state at t= 0.08 ms.

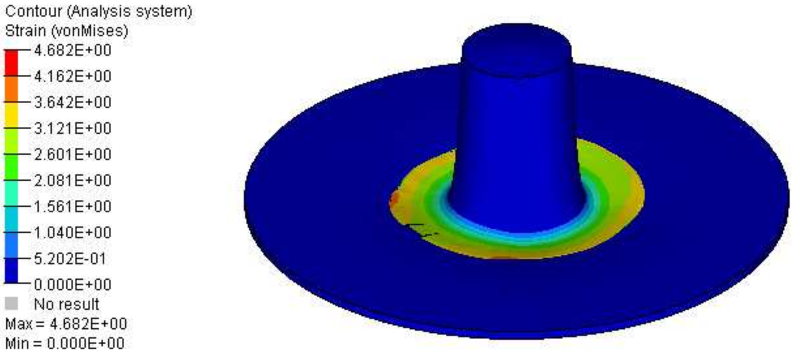

Figure 6. Soft body impact simulation. Strain state at t= 0.15 ms.

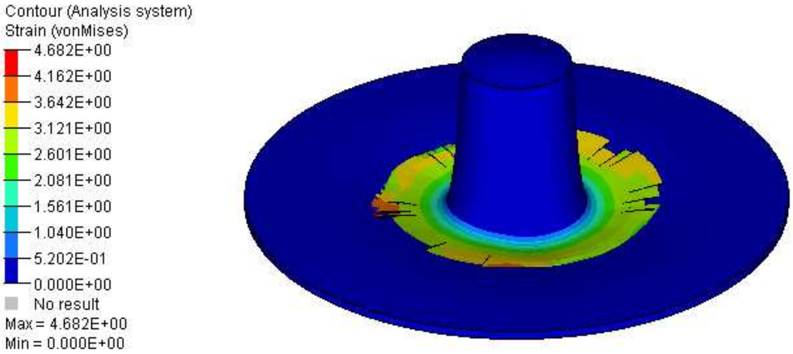

Figure 7. Soft body impact simulation. Strain state at t= 0.25 ms.

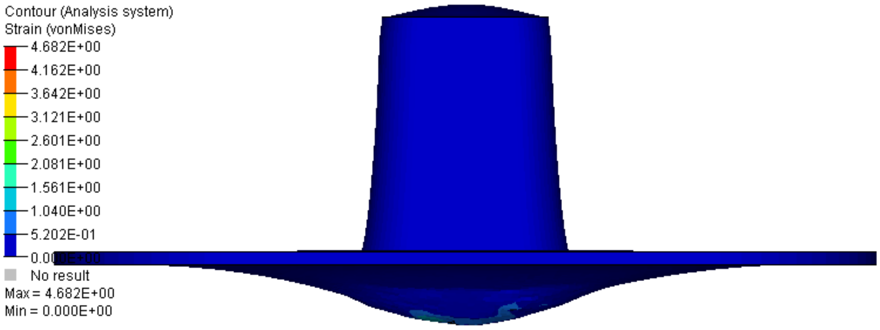

Figure 8. Soft body impact simulation. Side view of deformed configuration at t= 0.25 ms.

4. CONCLUSIONS

It is shown in the present work some aspects of the simulation of the impact of a soft body in a composite circular plate. The problem is solved with a FE code and some qualitative comparisons are made with experiments performed in Brazil.

It is clear that the LS-DYNA3D can handle such a complex problem provided material data are available, which is a

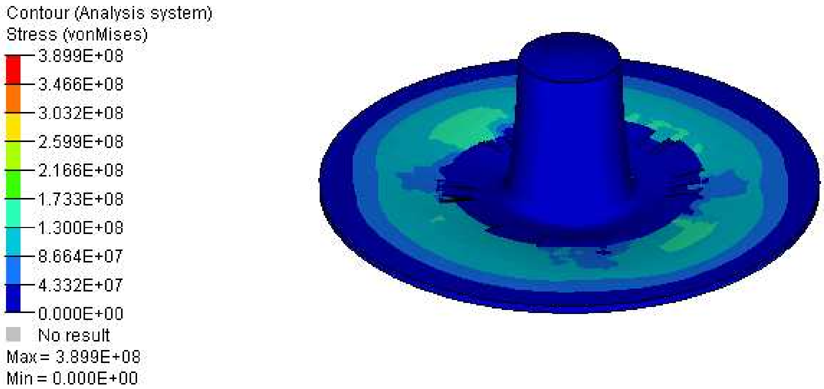

Figure 9. Soft body impact simulation. Stress state at t= 0.25 ms.

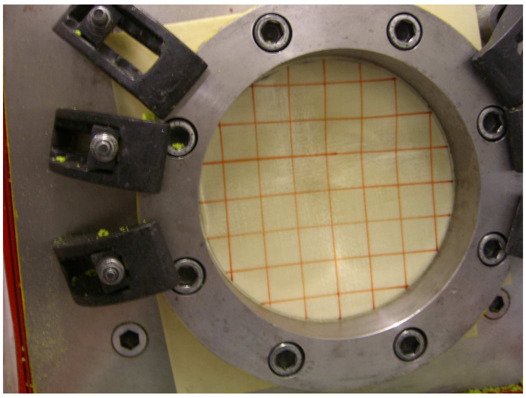

Figure 10. Picture #3: final configuration after soft body impact.

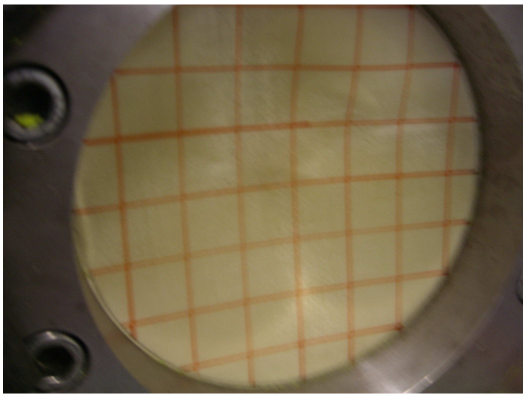

Figure 11. Picture #4: final configuration after soft body impact.

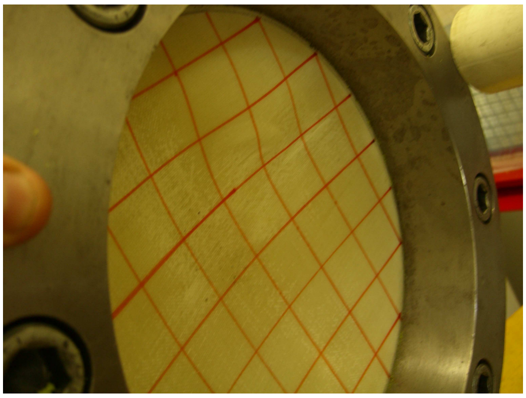

Figure 12. Picture #5: final configuration after soft body impact.

difficult and important issue. It should be emphasised that the composite plates are made of an advanced material in the sense that it has nano-particle inclusions. In this sense, it can be considered that the analyses is quite troublesome and yet performed successfully under the present restrictions. Some issues like a better mechanical characterization of the materials and additional instrumentation of the experimental tests with gas gun, allowing quantitative comparisons and aiming more integrated (numerical-experimental) analysis still remain open to be addressed in future works.

Moreover, the limits of the ALE description of motion to problems with large deformations and the need of meshless formulations, such as Smooth Particle Hydrodynamics (SPH), also available in LS-DYNA3D, are also subjects to be addressed by future works in this area.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Abrate, S.,2001, "Modeling of Impact on Composite Structures", Composite Structures, Vol.51, pp. 129-138.

Airoldi, A. and Cacchione,B.,2006, "Modelling of impact forces and pressures in Lagrangian bird strike analyses", International Journal of Impact Engineering, Vol.32, pp. 1651-1677.

Antoun, T.H.,Gekfen, P.R., Holmes, B.S. and Kirkpatrick, S.W,1992, ""Description of a Six-Inch Gas Gun Facility for Soft Body Impact", Proceedings 43rd Annual Meeting of the Aeroballistic Range Association (ARA), Paper No. 50 (http://www.sri.com/poulter/composites/bird.html).

Ávila, A.F., Soares, M.I., Silva Neto, A., 2005, "An experimental investigation on nanocomposites under impact loading", WIT Transactions on Engineering Sciences, Impact Loading of Lightweight Structures, Ed. M. Alves and N. Jones, pp. 89-102.

CENIPA,2006,http://www.cenipa.aer.mil.br.

Chang, F.K.,Chang and K.Y.,1987, "A Progressive Damage Model for Laminated Composites Containing Stress Concentrations", Journal of Composite Materials, Vol.21, pp. 834-855.

Fasanella, E. L., Jackson, K.E., Lyle, K.H., 2000, "Finite Element Simulation of a Full-Scale Crash Test of a Cmposite Helicopter", American Helicopter Society 56th Annual Forum, Virginia Beach, Virginia, May 2-4.

Hallquist, J.,2006, "LS-DYNA3D Theoretical Manual", Livermore Software Technology Corporation (LSTC), Livermore.

Hashin, Z.,1980, "Failure Criteria for Unidirectional Fiber Composites", Journal of Applied Mechanics, Vol.47, pp. 329-334.

Hou, J.P., Petrinic, N., Ruiz, C., Hallett, S.R., 2000, "Prediction of Impact Damage in Composite Plates", Composites Science and Technology 60, pp. 273-281.

Jackson, K., Fasanella, E.,2000, "Impact Testing and Simulation of a Crashworthy Composite Fuselage", American Helicopter Society 56th Annual Forum, Virginia Beach, Virginia, May 2-4.

Johnson, A. and Holzapfel,M.,2003, "Modelling Soft Body Impact on Composite Structures", Composite Structures, Vol.61, pp. 103-113.

Johnson, A. and Holzapfel,M.,2006, "Numerical Prediction of Damage in Composite Structures from Soft Body Impacts", Journal of Material Science, Vol.41, pp. 6622-6630.

Malvern, L.E., 1969, "Introduction to the Mechanics of a Continuum Medium", Prentice-Hall.

Meyers, M.A., 1994, "Dynamic Behavior of materials", John Wiley and Sons, Inc..

Morais, D.T.S., 2003, "Avaliação dos Processos de Manufatura de Compósitos Laminados e Determinação do Coeficiente de Correlação Yoke Ratio", Dissertação de Mestrado, Programa de Pós-Graduação em Engenharia Mecânica, Universidade Federal de Minas Gerais (UFMG).

Schweizerhof, K., Weimar, K., Munz, Th., and Rotter, Th.,1998, "Crashworthiness Analysis with Enhanced Composite Material Models in LS-DYNA - Merits and Limits", Proceedings of the 5th International LS-DYNA Users Conference.

Tsai,S.W. and Wu, E.M., 1971, "A general theory of strength for anisotropic materials", Journal of Composite Materials, Vol. 5, pp. 58-80.

Yen,C-. F.,2002, "Ballistic impact modeling of composite materials", Proceedings of the 7th International LS-DYNA Users Conference.

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