

Final title of paper:

BALLISTIC SIMULATION OF IMPACT ON COMPOSITE LAMINATES

Authors:

1. M.A. Gonçalves da Silva

Professor Catedrático

Centro de Investigação em Estruturas-UNIC, Faculdade de Ciências e Tecnologia,
Universidade Nova de Lisboa, Quinta da Torre, 2829-516, Monte de Caparica,
Portugal

e-mail: mgs@fct.unl.pt

2. Cosmin G. Chiorean

Lecturer

Faculty of Civil Engineering, Technical University of Cluj-Napoca, 15 C.
Daicoviciu Str., 3400 Cluj-Napoca, Romania

e-mail: cosmin.chiorean@mecon.utcluj.ro

3. Corneliu Cismasiu

Professor Auxiliar

Centro de Investigação em Estruturas-UNIC, Faculdade de Ciências e Tecnologia,
Universidade Nova de Lisboa, Quinta da Torre, 2829-516, Monte de Caparica,
Portugal

e-mail: cornel@fct.unl.pt

For correspondence purpose:

Prof. Corneliu Cismasiu, Faculdade de Ciências e Tecnologia, Universidade Nova de
Lisboa, Quinta da Torre, 2829-516, Monte de Caparica, Portugal, e-mail: cornel@fct.unl.pt

ABSTRACT. The paper reports on numerical simulation of impact problems on fiber reinforced plastic composite laminated plates reinforced with Kevlar 29. The ballistic impact caused by STANAG-2920 projectile is analyzed to obtain an estimate for the V_{50} and the global damage. All estimates have been carried out using the finite difference numerical code AUTODYN-3D, are compared with the experimental data to illustrate the performance of the simulation. Good correlation between resulting simulations and experimental results is demonstrated both in terms of deformation and damage of the laminates and ballistic performance.

Keywords : Non-Linear Transient Dynamics, Ballistic Impact, Composite Materials.

Professor M.A. Gonçalves da Silva is Full Professor of structures in the Universidade Nova de Lisboa, Portugal. His research interests are mainly on composites for strengthening of structures and on dynamic analysis and modeling.

e-mail: mgs@fct.unl.pt

Dr. Cosmin G. Chiorean is a lecturer of civil engineering in the Technical University of Cluj-Napoca, Romania. His research interests focus on nonlinear inelastic analysis methods and numerical models for laminated composite materials.

e-mail : cosmin.chiorean@mecon.utcluj.ro

Dr. Corneliu Cismasiu is a lecturer of civil engineering in the Universidade Nova de Lisboa, Portugal. His research interests focus on: hybrid-Trefftz elements, p-adaptive methods, dynamic analysis, numerical models.

e-mail: cornel@fct.unl.pt

INTRODUCTION

The complexity of impact problems [1] caused by the high number of intervening parameters like relative velocity, shape of colliding objects, relative stiffnesses and masses, location of contact, dimensions and boundary conditions, material characteristics, etc., increases when composite materials are involved, due to the orthotropic properties and distinct failure modes that may occur. Designing composite material ballistic armour requires thus a very large number of experimental tests, which are time and resources consuming.

The recent advances toward understanding damage mechanisms and mechanics of laminated composites [2,3,4,5] coupled with the development of advanced anisotropic material models [6,7,8] offer the possibility of avoiding many of the experimental tests by using impact simulation. However, the numerical results should be used with precaution and must always be validated by experimental tests.

The objective of this paper is to report on experimental work and corresponding numerical simulation of impact problems on composite laminate plates reinforced with Kevlar 29 and to illustrate the performance of the simulation, laying ground for predictions solely based on numerical models.

All the simulations presented in the paper have been carried out by using the hydrocode AUTODYN [9], specially designed for non-linear transient dynamic events such as ballistic impact, penetration and blast problems. The software is based on explicit finite difference, finite volume and finite element techniques, which use both grid based and gridless numerical methods. A new material model, specifically designed for the shock response of anisotropic material [8], has been implemented and couples non-linear anisotropic constitutive relations with a Mie-Grüneisen equation of state.

A set of partial differential equations for conservation of mass, momentum and energy is solved together with the constitutive equations using an explicit time integration scheme. An additional relationship between pressure, volume and energy from an equation of state specific to the material provides a solvable set describing the purely hydrodynamic portions of stresses and strains. These, together with a material model and a set of initial and boundary conditions, define the complete solution of the problem. The impact is controlled by a so-called impact/slidelines procedure, allowing impacted material to *erode*, so that deep penetrations can be accounted for. The erosion is a numerical procedure, which allows automatic removal of elements when they become heavily distorted.

MATERIAL MODEL

The most important characteristics and phenomena governing the behaviour of composite materials under ballistic impact are: material anisotropy, shock response, coupling of volumetric and deviatoric behaviour, anisotropic strength degradation, material compaction, phase changes. In the case of anisotropic materials, there is a strong coupling between the equation of state and the constitutive relations, as volumetric strain leads to deviatoric stress and similarly, deviatoric strain leads to spherical stress. An advanced material model [7,8], specially designed to simulate the shock response of anisotropic materials has recently been implemented, as mentioned above, and couples the non-linear constitutive relations with the equation of state. The coupling is based on the methodology proposed by Anderson

et.al [10]. The model can additionally include compaction and orthotropic brittle failure criteria to detect directional failure such as delamination.

Composite materials of polymeric matrix subject to impact exhibit complex behaviour. Experimentally, the dominant tensile material failure modes were identified as extensive delamination, due to matrix cracking and/or matrix-fibre debonding, in-plane fibre failure and punching shear failure caused by a combination of delamination and fibre failure leading to bulk failure. In the numerical model the composite material is considered to be homogeneous. Kevlar fibres and epoxy matrix are not separately modelled and the main phenomena of relevance are accounted for in a macro-mechanical model.

Delamination is assumed to result from excessive through-thickness tensile stresses or strains and/or from excessive shear stresses or strains in the matrix material. In the incremental constitutive relation

$$\begin{bmatrix} \Delta\sigma_1 \\ \Delta\sigma_2 \\ \Delta\sigma_3 \\ \Delta\sigma_{23} \\ \Delta\sigma_{31} \\ \Delta\sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \alpha C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \alpha C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha C_{66} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{11} \\ \Delta\varepsilon_{22} \\ \Delta\varepsilon_{33} \\ \Delta\varepsilon_{23} \\ \Delta\varepsilon_{31} \\ \Delta\varepsilon_{12} \end{bmatrix} \quad (1)$$

the stress $\Delta\sigma_{11}$ normal to the laminate and the corresponding orthotropic stiffness coefficients C_{ij} are instantaneously set to zero, whenever the failure is initiated in either of those two modes, $j=1$ in equation(2):

$$\Delta\sigma_{jj} = 0 \text{ and } C_{ij} = C_{ji} = 0 \text{ for } i=1,3 \quad (2)$$

Delamination may also result from reduction in shear stiffness of the composite, via parameter α in equation (1). In-plane fibre failure is assumed to result from excessive stresses and/or strains in the 22 or 33 directions, $j=2$ or $j=3$ in equation (2).

The combined effect of failure in all three material directions is represented changing the material stiffness and strength to isotropic characterisation, with no stress deviators or material tensile stresses. A fractional residual shear stiffness is maintained through the parameter α , whose value is obtained by experimental tests.

Composite material cell failure initiation criteria is assumed to be based on a combination of material stress and strain failure. Subsequent to failure initiation, the cell stiffness and strength properties are modified in agreement with the failure initiation modes.

The volumetric response of the material is defined through the solid equation of state. The polynomial sub-equation of state used in the numerical simulation, allows non-linear shock effects to be coupled with the orthotropic material stiffness.

All the reported tests were performed on Kevlar 29/Epoxy composite target. The 4340 steel was represented using the Johnson-Cook strength model, which include strain and strain rate hardening and thermal softening effects. Material data for Kevlar/Epoxy target and 4340 stell impactor are shown in Table 1.

Table 1. Material Data

KEVLAR/EPOXY	
Equation of states : <i>Orthotropic</i>	Tensile failure Stress 11 (kPa) $5.00E+04$
Sub-Equation of States : <i>Polynomial</i>	Maximum Shear Stress 12 (kpa) $1.00E+05$
Reference density (g/cm ³) 1.40	Tensile Failure Strain 11 0.01
Young modulus 11 (kPa) $2.392E+05$	Tensile Failure Strain 22 0.08
Young modulus 22 (kPa) $6.311E+06$	Tensile Failure Strain 33 0.08
Young modulus 33 (kPa) $6.311E+06$	Post Failure Response <i>Orthotropic</i>
Poisons ratio 12 0.115	Fail 11 & 11 Only
Poisons ratio 23 0.216	Fail 22 &22 Only
Poisons ratio 31 3.034	Fail 33 & 33 Only
Strength : <i>Elastic</i>	Fail 12 & 12 and 11 Only
Shear modulus (kPa) $1.54E+06$	Fail 23 & 23 and 11 Only
Failure : <i>Material Stress/Strain</i>	Fail 31 & 31 and 11 Only
	Residual shear Stiff. Frac. 0.20
4340 Steel	
Equation of States : <i>Linear</i>	Yield Stress (kPa) $7.92E+05$
Reference density (g/cm ³) 7.83	Hardening constant (kPa) $5.10E+05$
Bulk modulus (kPa) $1.59E+07$	Hardening exponent 0.34
Reference temperature (K) 300	Strain rate constant 0.014
Specific heat capacity (J/kgK) 477	Thermal softening exponent 1.03
Strength : <i>Johnson-Cook</i>	Melting temperature (K) 1793
Shear modulus (kPa) $8.18E+07$	Failure model : <i>None</i>

The values characterising the orthotropic strength of the target were obtained in experimental tests carried out at Ernst-Mach-Institut in Germany. Quasi-static tensile tests were used to provide data on in-plane stiffness and failure strains. The through thickness stiffness was obtained in quasi-static compression tests. However, due to the fact that the sample thickness was less than 2 mm and because of instantaneous through thickness delamination, it was not possible to determine the Poisson's ratio, ν_{12} . The positiveness of the stiffness C and the compliance $S=C^{-1}$ tensors in anisotropic materials is imposed by thermodynamic principles based on the fact that the elastic potential should remain always a positive quantity. The positive definiteness of these two tensors for the transversely isotropic materials implies that the following system of relations must hold [14] :

$$|\nu_{12}| = |\nu_{13}| < \left(\frac{E_{11}}{E_{22}} \right)^{1/2}, \quad |\nu_{23}| < 1 \quad (3)$$

and

$$\nu_{12}^2 \nu_{23} < \left(1 - \nu_{23}^2 \right) \frac{E_{11}}{2E_{22}} - \nu_{12}^2 \quad (4)$$

It can readily be derived from these relations in conjunction with the material data depicted in table 1, that the extreme positive limit of ν_{12} Poisson's ratio is $\nu_{12}^{\max} = 0.1219$. The value in the Table was derived iteratively through numerically low speed impact calibration, using several values for ν_{12} Poisson's ratio between 0 and ν_{12}^{\max} .

BALLISTIC IMPACT ON KEVLAR/EPOXY PLATE

In the following set of tests the numerical simulation estimates are used to predict the V_{50} number, i.e. the velocity at which a projectile has a 50 percent chance of penetrating a given piece of armour. The results of the simulation are compared with data from ballistic experiments conducted at the Navy School in Lisbon. The ballistic limit, defined as the highest striking velocity for which the residual velocity equals zero, is also predicted and compared with the experimental data reported in [12].

Experimental Tests

In the ballistic experimental tests, the target was a square Kevlar 29/Epoxy plate firmly clamped on the edges. The dimensions of the plate are 400 x 400 mm and 2 mm thickness. The fragment simulating projectile, defined by STANAG-2920 and US MIL-P-46593, was used to determine the V_{50} and the ballistic limit. This V_{50} number is arrived at by shooting the armour numerous times, with the same type of projectile, across a broad range of velocities associated with different amounts of loaded explosives.

Numerical Model

As the high velocity impact phenomenon is of localised nature, the boundary conditions do not influence the results and therefore only a square region of 100 x 100 mm was modelled. This region, of 2 mm thickness was firmly clamped on the edges. Both the target and the projectile were modelled using TrueGrid [11], taking into account the symmetry of the problem. The analysis starts with the impactor and plate in contact. The modelled geometry and the initial grid are illustrated in Figure 1.

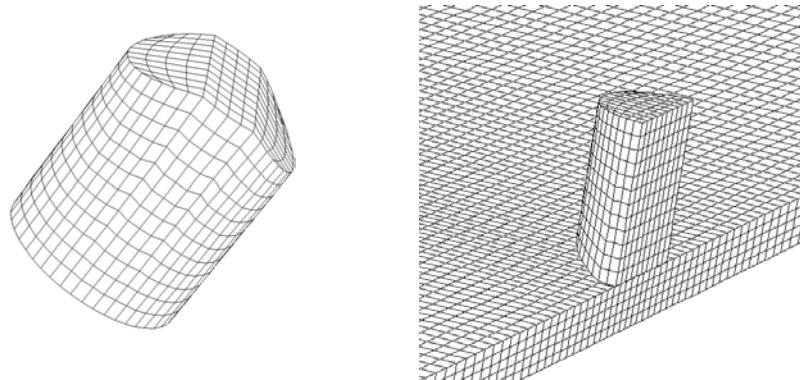


Figure 1. Projectile view and contact at initial step

The Lagrange processor was used to represent both projectile and composite target. This processor attaches the mesh to the material and they deform together. Uniform cells of side 0.4 mm were used to discretise the target and projectile in the central impact area. Cells dimension gradually increased to the outer edges. Degenerate cells were *eroded* at an instantaneous geometric strain equal to 1.0. Interaction between the projectile and the laminate target was handled by the impact logic, using a gap size 0.014 mm. A broad range of impact velocities was tested in order to determine the ballistic limit and V_{50} .

Comparison of Results

Results reported in [12] indicate a ballistic limit of 320 m/s. Analysing the impacted plate, see Figure 2, one can see that the plate was not penetrated nor was the projectile retained in the plate. If the ballistic limit is defined as the maximum velocity at which the projectile can be stopped [13], the ballistic limit must be higher, and the projectile retained in the plate.

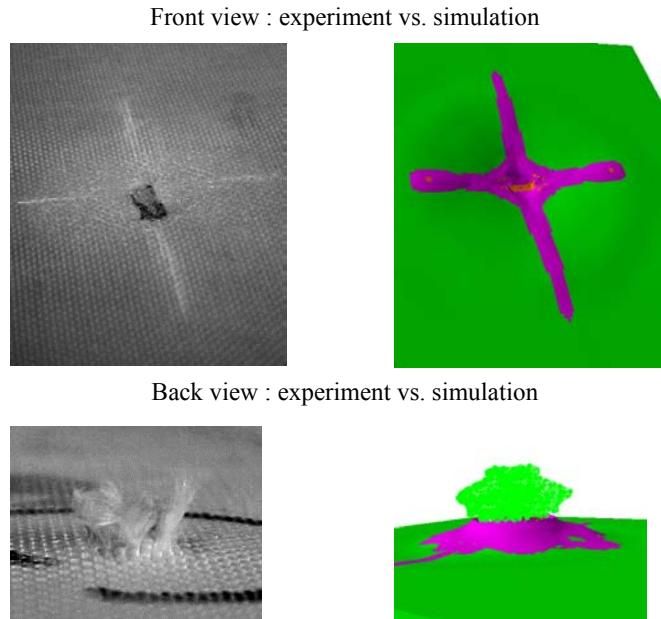


Figure 2. Impact at 320 m/s – total damage

The total damage obtained from numerical simulations for impact velocity of 320 m/s is also compared with the one reported in [12]. In the experimental tests, delamination shows an elliptical shape, with axis of 7.10 cm x 5.00 cm. The numerical simulation exhibits the same shape with an extension of 7.35 cm x 5.15 cm. These results are illustrated in Figure 2.

A sequence of material status plots, showing the damage development in the Kevlar/Epoxy plate, is presented in Figure 3. Significant evolution of the delamination, caused by excessive shear tensile stresses through thickness, can be observed.

In order to predict V_{50} , the impact velocity was gradually increased until perforation occurs. According to the numerical tests, V_{50} equals 380 m/s, while the experimental V_{50} found in the tests performed in the Navy School was 375.8 m/s.

The total damage of the plate is depicted in Figure 4, for both experimental tests and numerical simulation. The delamination exhibits this time a circular shape with 5.5 cm of radius in the case of experimental tests, and 6.0 cm in the numerical simulation.

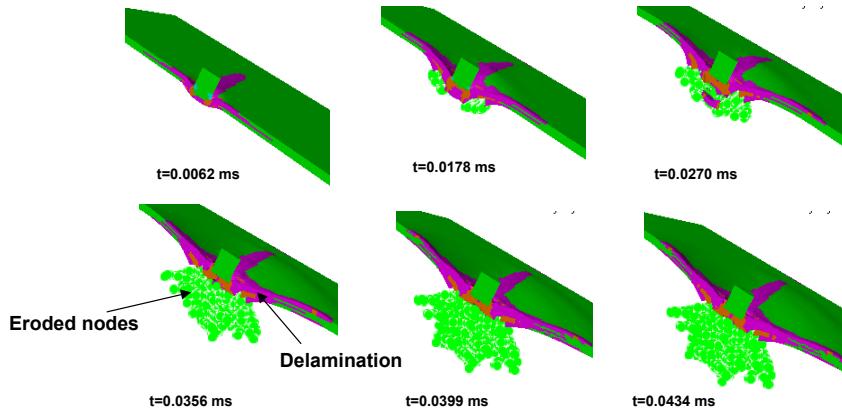
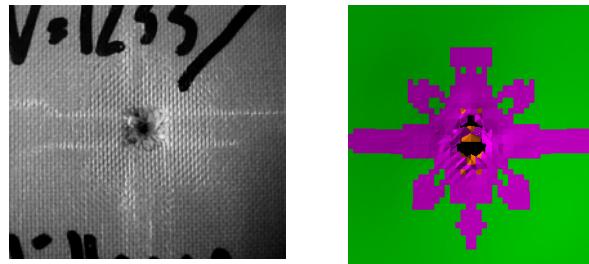


Figure 3. Ballistic limit – simulated damage development

Front view : experiment vs. simulation



Back view : experiment vs. simulation

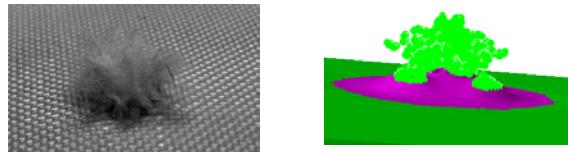


Figure 4. V_{50} – total damage

CONCLUSIONS

The ballistic performance of the composite laminate plates reinforced with Kevlar 29 was examined using the finite difference numerical code AUTODYN, based on an advanced model for orthotropic materials [8]. Its main draw is the ability to take into account the typical damage mechanisms for composite materials under impact loading, such as : extensive delamination due to matrix cracking and/or matrix-fibre debonding, fibre failure and combined delamination and fibre failure.

Ballistic impact of a simulated fragment on Kevlar fibre reinforced panel was modelled in order to predict V_{50} and the global damage. The estimate for V_{50} was very accurate, differing from the experimental value by only 1%. Similar global damage and delamination patterns were observed in both simulated and experimental tests, with an area of delamination of 113 cm^2 and 95 cm^2 , respectively.

These results encourage the use of computer simulation in the design of ballistic light armours in order to avoid expensive and time consuming experiments.

Future work is envisaged considering the interposition of a ceramic type layer and oblique impact.

Acknowledgement

This work is part of the research developed at DEC, Faculdade de Ciências e Tecnologia, supported by contract 43228/EME/2001 with Fundação para a Ciência e Tecnologia. Cooperation with colleagues from INEGI, Porto and Comd. F. Neto from Navy School of Lisbon is gratefully acknowledged.

REFERENCES

1. SMITH, P.D., HETHERINGTON, J.G., *Blast and Ballistic Loading of Structures*, Butterworth-Heinemann Ltd., 1994.
2. ABRATE, S., *Impact on Composite Structures*, Cambridge University Press, 1998.
3. CHOI, H., CHANG, F., A model for predicting damage in graphite/epoxy laminated composites resulting from low-velocity point impact, *Journal of Composite Materials* 26(14), 1992, pp. 2134-2169.
4. CHOI, H., DOWNS, F., CHANG, F., A new approach toward understanding damage mechanisms and mechanics of laminated composites due to low-velocity impact: Part I, and Part II, *Journal of Composite Materials*, 25, 1991, 992-1038.
5. SILVA, M.A.G., Low speed impact on polyethylene and aramidic FRP laminates in: *Proceedings of Conference on Integrity, Reliability and Failure*, Porto, 1999.
6. CLEGG, R., HAYHURST, C., LEAHYJ., DEUTEKOM, M., Application of coupled anisotropic material model to high velocity impact response of composite textile armour, in 18th Int. Symposium and Exhibition on Ballistics, san Antonio, Texas USA, 1999.
7. HAYHURST C., HIERMAIER, S., CLEGG, R., RIEDEL, W., LAMBERT, M., Development of material models for Nextel and Kevlar epoxy for high pressures and strain rates, in: *Hypervelocity Impact Symposium*, Huntsville, AL, 1999.
8. HIERMAIER, S., RIEDEL, W., CLEGG, R., HAYHURST, C., Advanced material models for hypervelocity impact simulations, Tech., rep., ESA/ESTEC Contract No. 12400/97/NL/PA(SC), 1999.
9. Century Dynamics, Inc., *AUTODYN*. Interactive Non-Linear Dynamic Analysis Software, 1997.
10. ANDERSON, C., COX, P., JOHNSON, G.R., MAUDLIN, P, A constitutive formulation for anisotropic materials suitable for wave propagation computer program, *Computational Mechanics* 15, 1994, pp. 201-223.
11. XYZ Scientific Applications, Inc., *TrueGrid*, 2000.
12. JUSTO, J., MARQUES, T., Design and testing of composite panels for ballistic protection, in 2nd International Symposium on Impact Engineering, Pequim, China, 1996.
13. AKZO, Twaron in Soft Body Armour, 1993.
14. JONES, R.M., *Mechanics of composite materials*. Washington: Scripta Book Co. 1975.