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Finite Element Simulation of Ballistic Impact on Composite Plates

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Abstract: In this study, effect of reinforcement type and different numerical composite damage material models are investigated in high velocity impact applications. Aramid and carbon-aramid hybrid fibers are used as a reinforcement material and epoxy is used as matrix in the composite plate. Numerical methods are performed for understanding energy absorption mechanisms. For numerical study, ANSYS is used as pre-processor and LS-Dyna is used as solver. Two failure models are used for composite materials which are MAT 22 (Mat_Composite_Damage) and MAT 59 (Mat_Composite_Failure_Solid_Model). Three different numerical models are created; MAT 22 with layered composite which is modeled as solid plies, MAT 59 with a layered composite which is modeled as solid plies and MAT 59 with single layer. Layered modeling technique is preferred because of weave style of composites. For modeling delamination, contact with tie-break option is used between composite layers. Experiment results are used for comparison of numerical results. 7.62 M61 type AP (Armor Piercing) projectiles were used in experimental procedure as strikers. Residual velocities were measured by velocity measurement traps. Six different velocities were used for both composites which have different reinforcements. After performing numerical procedure, comparison is done with experimental results and good agreement is obtained in terms of ballistic limit velocities and residual velocities of projectile between experimental and numerical methods.

Keywords: Ballistic Impact, 7.62 AP, Aramid/Epoxy, Carbon-Aramid/Epoxy, LS- Dyna, Numerical Simulation

I. INTRODUCTION

Composite materials have become important recently in defence, aerospace and naval industry. The importance of composite materials appeared because of high strength, lightness, thermal insulation and corrosion resistance. It is not always possible to combine all advantages in a product so working conditions of the product should be considered well.

Ballistic impact of the materials is one of the most popular topics over last years. Penetration mechanisms continue to be developed by the experts. Besides the analytical approaches, numerical codes are widely used. Finite element and finite difference methods are used popularly. Materials show different behaviors depending on strain rate and temperature. Two different approaches are mostly used for solving dynamic applications which are known as implicit and explicit solvers. There are three different phases which are known as static, quasi-static and dynamic. General engineering materials are used for low strain applications and subjected to static equilibrium. These materials show static responses and strain rate effects are mostly excluded. Quasi- static phase is between static and dynamic phases and internal and external forces difference is nearly zero. Dynamic phase includes impact, metal forming and explosion events. For providing true behavior of materials, strain rate effects should be included.

Explicit dynamics theory has some advantages which are non-convergence issues and time over implicit dynamics theory. It is known that different approaches are used in explicit finite elements method. Four formulations are popularly used which are known as Lagrangian, Eulerian, ALE (Arbitrary Lagrangian-Eulerian) and a mesh free method called as SPH (Smoothed Particle Hydrodynamics). Explicit Dynamics solvers usually use central difference integration theme. This integration has advantages such as not having convergence checks, not requiring any iteration and no inversion of global stiffness matrix. Lagrangian approach is chosen for corresponding numerical simulations. The method uses material coordinates which is also known as Lagrangian coordinates. Nodes of mesh move and distort with material and no material transfer between elements. With this method, less computational time may be provided than other approaches.

II. MATERIAL MODELS FOR COMPOSITE MATERIALS IN NUMERICAL SIMULATIONS

MAT 22 (Mat_Composite_Damage) which is also known as Chang-Chang failure model and MAT 59 material model (Mat_Composite_Failure_Solid_Model) are preferred for modeling composite failure in numerical simulations.

Corresponding relationships for MAT 22 (Mat_Composite_Damage) failure model are as follows (Hallquist, 2006). When any corresponding failure criteria exceed 1, it is considered that this element is failed for this mode.

Longitudinal tension :

$$\left(\frac{\sigma_1}{X_t}\right)^2 + \bar{\tau} > 1, \quad \sigma_1 > 0$$

$$\bar{\tau} = \frac{\frac{\tau_{12}{}^2}{2G_{12}} + \frac{3}{4}\alpha\tau_{12}{}^4}{\frac{S_{12}{}^2}{2G_{12}} + \frac{3}{4}\alpha\tau_{12}{}^4}$$

Transverse tension :

$$\left(\frac{\sigma_2}{Y_t}\right)^2 + \bar{\tau} > 1, \quad \sigma_1 > 0$$

Transverse compression :

$$\left(\frac{\sigma_2}{2S_{12}}\right)^2 + \left[\left(\frac{Y_c}{2S_{12}}\right)^2 - 1\right]\frac{\sigma_2}{Y_c} + \bar{\tau} > 1$$

where σ_1 is stress in fiber direction, X_t is longitudinal tensile strength. τ is fiber matrix shearing term. σ_2 is stress in matrix in matrix direction Y_t is transverse tensile strength, S_{12} is in-plane shear strength and Y_c is transverse compressive strength. τ_{12} is in-plane shear stress, G_{12} is in-plane shear modulus and α is nonlinear shear stress parameter.

Corresponding relationships for MAT 59 are as follows. When any corresponding failure criteria exceed 1, it is considered that this element is failed for this mode (Davis, 2012).

- Longitudinal tension :

$$\frac{\sigma_1{}^2}{X_t{}^2} + \frac{\tau_{12}{}^2}{S_{12}{}^2} + \frac{\tau_{31}{}^2}{S_{31}{}^2} > 1, \quad \sigma_1 > 0$$

- Transverse tension (with longitudinal tension) :

$$\frac{\sigma_2{}^2}{Y_t{}^2} + \frac{\tau_{12}{}^2}{S_{12}{}^2} + \frac{\tau_{23}{}^2}{S_{23}{}^2} > 1, \quad \sigma_2 > 0$$

- Through-thickness shear (with transverse tension) :

$$\frac{\sigma_2{}^2}{Y_t{}^2} + \frac{\tau_{23}{}^2}{S_{23}{}^2} > 1, \quad \sigma_2 > 0$$

- Longitudinal compression :

$$\frac{\sigma_1{}^2}{X_c{}^2} > 1, \quad \sigma_1 < 0$$

- Through-thickness shear :

$$\frac{\sigma_1{}^2}{X_t{}^2} + \frac{\tau_{31}{}^2}{S_{31}{}^2} > 1, \quad \sigma_1 > 0$$

- Through-thickness tension (delamination) :

$$\frac{\sigma_3{}^2}{Z_t{}^2} + \frac{\tau_{23}{}^2}{S_{23}{}^2} + \frac{\tau_{31}{}^2}{S_{31}{}^2} > 1, \quad \sigma_3 > 0$$

- Transverse compression :

$$\frac{\sigma_2{}^2}{(S_{12}+S_{23})^2} + \frac{\sigma_2}{Y_c}\left[\left(\frac{Y_c{}^2}{(S_{12}+S_{23})^2}\right) - 1\right] + \frac{\tau_{12}{}^2}{S_{12}{}^2} + \frac{\tau_{31}{}^2}{S_{31}{}^2} > 1, \quad \sigma_2 < 0$$

- Through-thickness compression :

$$\frac{\sigma_3{}^2}{(S_{31}+S_{23})^2} + \frac{\sigma_3}{Z_c}\left[\left(\frac{Z_c{}^2}{(S_{31}+S_{23})^2}\right) - 1\right] + \frac{\tau_{31}{}^2}{S_{31}{}^2} + \frac{\tau_{23}{}^2}{S_{23}{}^2} > 1, \quad \sigma_3 < 0$$

III. MODELING

In this study, two type of composite materials and projectile system simulated by initial velocity conditions, residual velocities are observed and compared with experimental data. LS-Dyna 3D is used for solving these simulations. Lagrangian approach is preferred because of the advantage of saving computational time. Solid modeling technique is preferred.

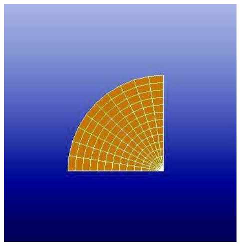
Three different numerical models are created which are combinations of,

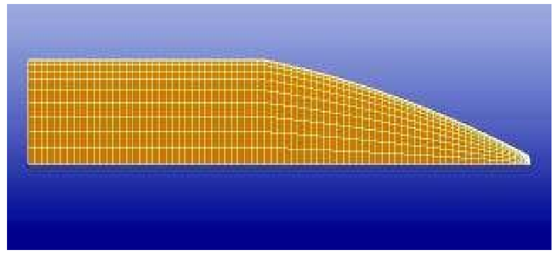
MAT 22 and layered composite which is modeled as solid plies,

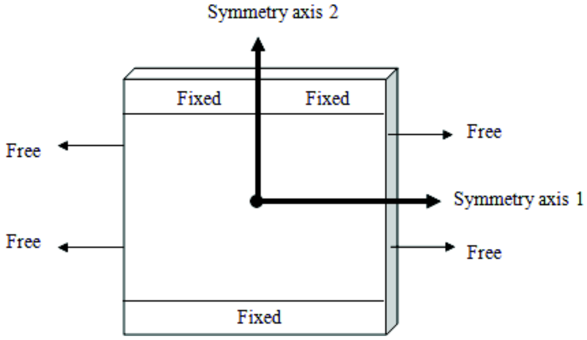
MAT 59 with a layered composite which is modeled as solid plies and

MAT 59 with single layer.

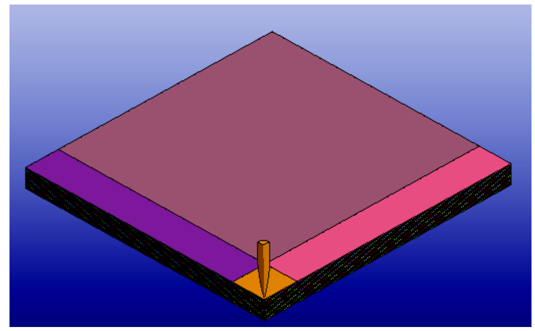
After considering boundary conditions, it is apparent that composite and projectile have two symmetry planes. Because of symmetry planes, 1/4 of model is used for corresponding simulations.







Boundary conditions



Simulation start-up

IV. BALLISTIC LIMIT VELOCITY

Ballistic limit velocity is the lowest velocity in order to provide total penetration of laminate (Abrate, 2007). Ballistic limit velocity (V_b) is also known as V_{50} and V_{50} means the velocity which is required to penetrate probability at least 50 % of all tests.

$V_b = \sqrt{V_i^2 - V_r^2}$ where V_b is ballistic limit velocity, V_i is initial velocity of projectile and V_r is residual velocity of projectile.

V. EXPERIMENTAL RESULTS

Table 5.1 Experimental initial, residual and ballistic limit velocities for aramid/epoxy composites [1]

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
852	817	241.69
790	742	271.17
713	657	276.98
619	579	218.90
543	498	216.43
333	259	209.30
		Average ballistic limit velocity V_b = 237.05 m/s

Table 5.2 Experimental initial, residual and ballistic limit velocities for carbon-aramid/epoxy composites [1]

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
850	820	223.83
841	805	243.43
764	724	243.97
652	626	182.29
540	489	229.08
381	353	143.36
		Average ballistic limit velocity V_b = 219.79 m/s

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VI. NUMERICAL RESULTS

A. *Numerical Results of Layered Composites with MAT 22*

Table 6.1 Initial, residual and ballistic limit velocities of layered aramid/epoxy composite with MAT 22 after simulations

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
852	789	321.53
790	729	304.40
713	662	264.81
619	575	229.21
543	506	197.01
333	314	110.87
		Average ballistic limit velocity V_b = 248.85 m/s

Table 6.2 Initial, residual and ballistic limit velocities of layered carbon-aramid/epoxy composite with MAT 22 after simulations

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
850	826	200.56
841	816	203.53
764	745	169.32
652	633	156.25
540	525	126.39
381	369	94.87
		Average ballistic limit velocity V_b = 163.13 m/s

B. *Numerical Results of Layered Composites with MAT 59*

Table 6.3 Initial, residual and ballistic limit velocities of layered aramid/epoxy composite with MAT 59 after simulations

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
852	788	321.53
790	730	304.40
713	655	264.81
619	575	229.21
543	506	197.01
333	314	110.87
		Average ballistic limit velocity V_b = 252.47 m/s

Table 6.4 Initial, residual and ballistic limit velocities of layered carbon-aramid/epoxy composite with MAT 59 after simulations

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
850	804	275.83
841	796	271.41
764	726	237.95
652	621	198.65
540	516	159.20
381	366	105.85
		Average ballistic limit velocity V_b = 216.80 m/s

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C. Numerical Results of Single Layer Composite with MAT 59

Table 6.5 Initial, residual and ballistic limit velocities of single layer aramid/epoxy composite with MAT 59 after simulations

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
852	778	347.30
790	725	313.80
713	651	290.80
619	569	243.72
543	496	220.98
333	310	121.61
		Average ballistic limit velocity V_b = 267.33 m/s

Table 6.6 Initial, residual and ballistic limit velocities of single layer carbon-aramid/epoxy composite with MAT 59 after simulations

Initial velocity V_i (m/s)	Residual velocity V_r (m/s)	Ballistic limit velocity V_b (m/s)
850	787	321.14
841	778	319.37
764	710	282.13
652	608	235.46
540	506	188.58
381	361	121.82
		Average ballistic limit velocity V_b = 256.38 m/s

VII. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

Table 7.1 Error percentages of numerical methods for aramid/epoxy composite considering ballistic limit velocities

	Ballistic limit velocity (m/s)	Error (%)
Experimental	237.05	-
Layered composite with MAT 22	248.85	4.98
Layered composite with MAT 59	252.47	6.5
Single layer composite with MAT 59	267.33	12.78

Table 7.2 Error percentages of numerical methods for carbon-aramid/epoxy composite considering ballistic limit velocities

	Ballistic limit velocity (m/s)	Error (%)
Experimental	219.79	-
Layered composite with MAT 22	163.13	25.78
Layered composite with MAT 59	216.80	1.36
Single layer composite with MAT 59	256.38	16.64

VIII. CONCLUSION

A. For aramid/epoxy composite, all numerical models showed similar behaviors in terms of projectile residual velocity.

B. It was thought that in-plane stiffness has more importance than through-thickness stiffness for aramid/epoxy composite. But layered composites with MAT 22 and MAT 59 showed better performance than single layer MAT 59 in terms of ballistic limit velocity.

C. For carbon-aramid/epoxy composite, differences are observed between numerical models. Layered composite with MAT 22 showed a good performance for the highest two velocities and single layer composite with MAT 59 showed better performance than other methods for the lowest two velocities. Layered composite with MAT 59 showed better performance and results occurred with a very low margin of error than other two methods in terms of residual and ballistic limit velocities.

D. For aramid/epoxy layered composite with MAT 22 and MAT 59, for carbon- aramid/epoxy composites layered composite with MAT 59 showed better performance over other methods. In line with these results, it is observed that choosing true material model or technique is also dependent on material mechanical properties.

E. Aramid/epoxy absorbed more energy than carbon-aramid/epoxy composites both experimentally and numerically as expected. But these energy differences are not too high and even can be said as close, hybrid composite can also be preferred because of lower areal density advantage.

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