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Experimental and Numerical Simulation of Energy Absorption on Composite Kevlar29/Polyester Under High Velocity Impact

A.A. Ramadhan[a], A.R. Abu Talib, A. S. Mohd Rafie, R. Zahari
Department of Aerospace Engineering, University Putra Malaysia, Malaysia
[a]ayad_almuhndis@yahoo.com

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ABSTRACT

This paper presents the results of the energy absorbed due to impact of 7.62mm steel bullet on composite materials targets. The energy absorbed due to impact of conical nose projectiles on composite Kevlar-29/Polyester laminates are investigated experimentally. The impact on Kevlar 29/Polyester thin plate laminated has been subjected to a high velocity range of 160-400m/s. The results obtained via simulation by ANSYS AUTODYN 3D-v.12.1 Software programs were compared with the experimental work for different thickness of specimens. The results shown in this work are in terms of varying plate thickness and the amount of energy absorbed by the laminated plates meanwhile we obtained that the 20mm thickness of composite plate suitable for impact loading up to 320m/s impact velocity. The results obtained the maximum error observed and computed values on the ballistic limit were 3.6 % so, these results were reasonably well with the experimental result.

Keywords: **High velocity impact, Energy absorption, AUTODYN 3D simulation, Composite materials, Kevlar-29/Polyester.**

Nomenclature

ρ	Density (g/cm^3)	V_i	Initial velocity (m/s)
ν	Poisson's ratio	V_r	Residual velocity (m/s)
E_1	Longitudinal Young's Modulus (GN/m^2)	E_{Abs}	Energy Absorption by the specimen (J)
E_2	Transverse Young's Modulus (GN/m^2)	m_p	Mass of bullet (Kg)
V_f	Volume fraction of fiber (N/m)	V_b	Ballistic limit velocity (m/s)

1. Introduction

Composite materials are used increasingly in many military, civil and spacecraft applications. Spacecraft encounter various impacts phenomena in space, among which orbital debris impacts are of most concern. These impacts occur at a wide range of velocities. Impact velocities from a few hundred m/s to more the one km/s are common in geostationary orbit and even occur in low Earth orbit. Composites materials that are used in aerospace and land based structural components are often subjected to high velocity impact threats, such as broken engine parts, pebbles, fragments from bombs, shells and mortars. These applications have excellent mechanical properties as high specific strength, specific stiffness, resistance to corrosion and increased fatigue life. However, one of the main concerns in the use of advanced composites is their poor properties, which become critical under situations like impact loading (Cantwell and Morton, 1991). Composites exhibited limited ability to undergo plastic deformation. As a result, energy is absorbed through the creation of large areas of fracture, which are generally complex in nature and difficult to characterize (Naik and Shrirao, 2004). The high velocity (ballistic) impact with more than 100 m/s is usually a result of small arms fire or explosive warhead fragments. In hyper velocity impact, projectiles are moving at very high velocities in the range of 2-15 km/s. In this case, the target materials behave like fluids. The energy absorption of targets subjected to high velocity impact has been studied analytically under small mass with high velocity impact. Damage is more localized demonstrating that the impact duration plays a significant role (Lee et al., 2001).

The energy absorption in composite laminates differs from impact on high strength textile laminates such as those used in soft (flexible) body armor. The matrix in laminated composites inhibits yarn slippage allowing a greater number of primary yarns to carry the load and absorb energy through strain (Goldsmith & Chang, 1995). There are currently several analytical models available for predicting the ballistic limit, energy absorption, or damage mechanisms in composite materials. These models take into account some form of the laminate mechanical and physical properties, and penetrator size and shape. The two known approaches use a static punch curve of load versus displacement for a given penetrator (Sun and Potti, 1996), (Naik et al., 2005) .There are few studies into the impact on fabric structures by projectiles travelling at energy absorption (Morye et al., 2000). Most of these work involved in the form of derive the equations on energy absorption on structures consisting either of a single fabric layer or of a collection of multiple layers of fabric where all of the fabric layers consisted of the same material (Goldsmith & Chang, 1995). There are also correlations developed to evaluate the energy absorption through elastic deformation of the secondary Yarns strain which is equal to the strain in the primary Yarns (Goldsmith & Chang, 1995) and (Naik et al., 2005) developed secondary yarns to obtain the energy absorbed through the deformation of integration in Eq.(1). The derivation for Eq. 1 is detailed in (Naik et al., 2005) as shown below:

$$E_{Di} = \int_{d/\sqrt{2}}^{r_{ti}} \left(\int_0^{\varepsilon_{syi}} \sigma_{sy}(\varepsilon_{sy}) \mathrm{d}\varepsilon_{sy} \right) h \left\{ 2\pi r - 8r \sin^{-1}\left(d/2r \right) \right\} \mathrm{d}r \qquad (1)$$

The work done by other researchers focuses on the prediction on the energy absorption of generic composite materials. However, there is a lack of information in the existing literature on the method of energy absorption prediction specifically on Kevlar -29/polyester materials. This research can be contributed in many applications like Vehicle, body Armour, aerospace and military applications. The high velocity impact response of fiber (12mm, 16mm and 20mm) thicknesses of this composite material presented in this work by using nosel bullets type 4340 steel projectiles. Effects of projectile velocity, thickness of plates on the ballistic impact and energy absorption behavior of the targets are investigated experimentally and numerically simulation. The simulations are carried out using ANSYS AUTODYN 3D- v.12 software.

2. Experimental Methodology

2.1. Materials used, properties and fabricating the specimens

The materials used in this work were Woven fiber Kevlar-29 and Polyester. The mechanical properties of these materials have been specified in table 1 as bellow The volume fraction of fiber V_f (fiber volume/total volume) in composites is very often significantly less than 100%, and it was tested by (Amotz and Schwartz, 1987) as shown in table 2, so the volume fraction was selected 55% in this work, it was a optimum value compared with others volume fraction for fabricating the specimens. The advancement in designing a new composite constructor is embodied in the composite compounds arrangement and the tactical ways that are depended on the assembled layers. Meanwhile, the target geometry is a sensitive point in this investigation, and the adjacent panels have the responsibility to increase energy absorption by the targets. The target preparation processes include composite preparation and geometry of the target. Hence, the composite was constructed from the Kevlar29 and polyester resin, since the target area was 100 × 100 mm, as illustrated in Fig.1

Fig.1. Kevlar29/polyester laminated plate

Three thicknesses (12, 16 and 20 mm) of specimens were fabricated by using Hand lay-up method of all the specimens. Woven roving Kevlar-29 fibre is wound manually in the open mold of glass, which was coated with wax to easily remove the specimen later, and polyester resin mixed by mixer until homogenous occurred the ratio of polyester, then brushed over and into the woven roving Kevlar-29 fibre, The time of solidification is about 72 hours to provide optimum blend. The tensile test shown in Fig. 2 with the mechanical properties of Kevlar-29 and polyester as shown in table 1

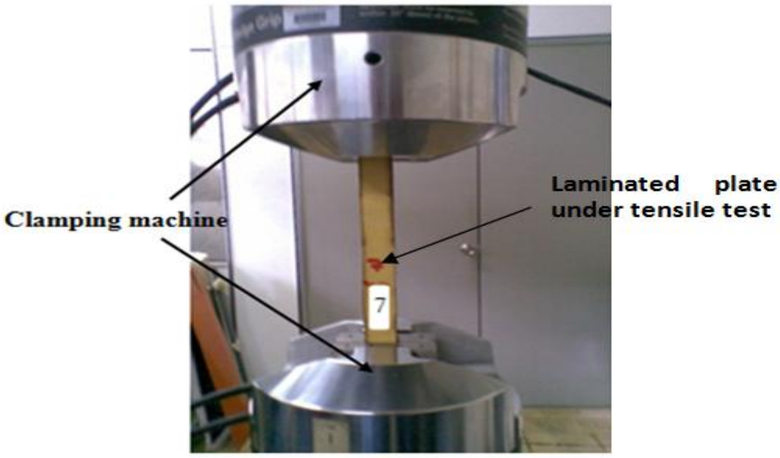


Fig.2.Specimens under tensile test

Table 1: Mechanical properties of Kevlar-29 and polyester

Properties	Fiber Kevlar-29	Polyester
Density (g/cm3)	1.4	2.7
Ultimate Tensile strength(MPa)	58.9	310
Tensile Yield Strength (MPa)	2758	276
Modulus of Elasticity (GPa)	62	68.9
Poisson's Ratio	0.44	0.33
Fatigue Strength (MPa)		96.5
Shear Strength (MPa)		207

Compression test also achieved in this work to obtain the basic mechanical properties to obtain the result of stress strain curve as shown in Fig. 3 of tensile and compression test for this laminated plate which it used later in simulation work, but the main objective in this work was fabricated novel sandwich structure and tested it under high impact loading.

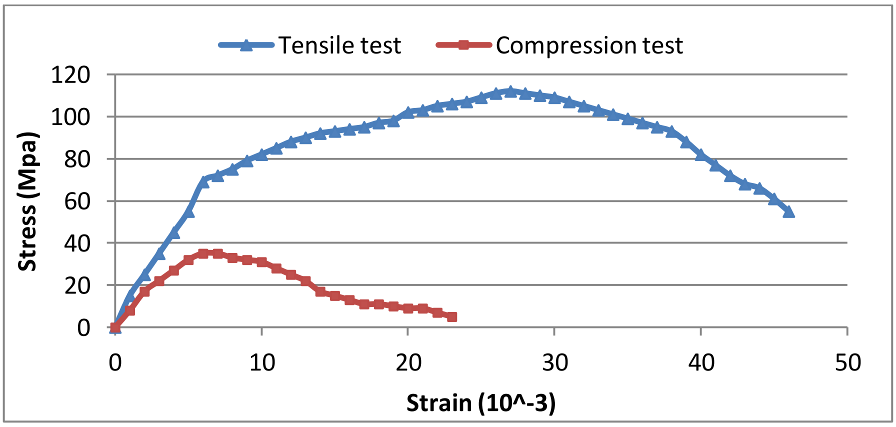


Fig.3. Stress-strain curve for tensile and compression test loading of Kevlar29/polyester laminated plate

The volume fraction used in all specimens fabricated is 55% and the total specimens were tested in this work 27 laminated plates; for compression and tensile test 6 and for high velocity impact test 21 specimens were subjected to cylindrical bullet with different initial velocity impact as shown in table 2.

Table 2: The volume fraction and number of specimens used in experimental work.

Thickness (4mm)	No. of Kevlar-29 layers	Volume fraction (V_f)	Initial Velocity impact m/s	No. of specimens
12	22	55%	160, 200,240,280,320,360,400	7
16	28	55%	160, 200,240,280,320,360,400	7
20	33	55%	160, 200,240,280,320,360,400	7

2.2. Gas Gun and Bullet selection

The instrumented impact test equipment used in this study was a gas gun impact tester M. T. H. Sultan shown in Fig.4. The general features of the testing apparatus are shown in Fig. 5 has been designed in order to launch the projectile. The main components of the gas gun are the 2200 Psi pressure tank, the purpose-built ring section for compressed gas, the 4 m long smooth barrel and (60, 60 and 40 cm) dimensions of box chamber to hold the specimen inside this box which it has (60 x 60 cm) framing window to observe the behavior of target and bullet by photography high speed camera (200,000 fps) for this work.

Fig. 4.Gas gun tunnel to test the specimens

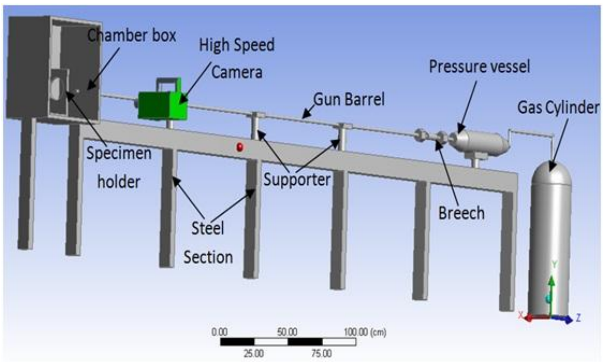


Fig.5.Gas gun tunnel (instrument impact tester)

The specimen mounted by (25 x 25cm) two frames to prevent the movement during the impact test as shown in Fig. 6.

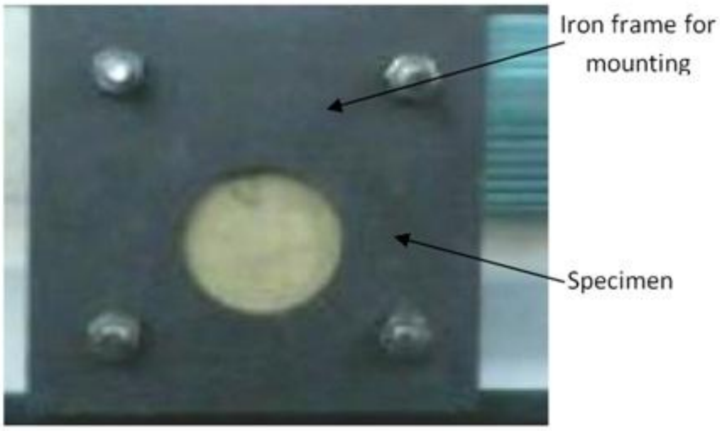


Fig.6.The target mounted with holding frame.

The gas gun is capable of launching three (cylindrical, spherical and nose tip) but in this work used cylindrical shape of 7.62mm diameter steel projectile and 5g of 4340 steel bullet (as shown in Fig.7) package to a range of velocity of 160-400 m/s when helium is used as a propellant gas.

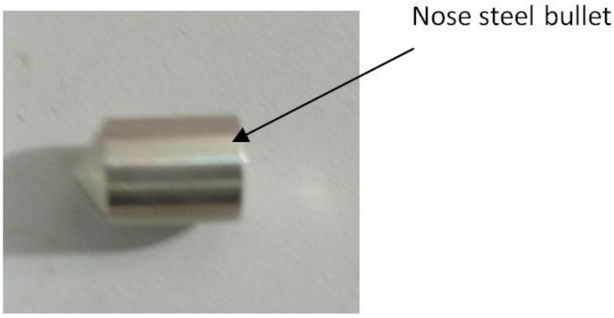


Fig.7. Cylindrical steel 4340 bullet

2.3. Impact Testing

The impact testing was Installed the composite of woven Kevlar-29/polyester laminated plates of square shape (100 x 100 mm) with different (12, 16 and 20 mm) thicknesses dimensions inside the specimen holder and focused the high speed camera with suitable resolution (200,000 fps) and adjusted the lights to get optimum conditions before test. However, both the aligning of the system and the luminance during testing are crucial parameters in order to have good, reliable images. As indicated above, the high-speed camera system is used for measuring the velocity of projectiles. This is made possible by advanced image processing of the digital pictures which it's connected with P.C. to calculate the time of bullet before impact and after penetration if accrued of specimens as shown in Fig. 8 an example of 280 m/s velocity impact of 12mm thickness of plate. The most important feature is the possibility to obtain the initial and residual velocity by the following equations:

$$v_i = \frac{\Delta S_1}{\Delta t_1} \quad (2)$$

and

$$V_r = \frac{\Delta S_2}{\Delta t_2} \quad (3)$$

Where

V_i and V_r initial and residual velocity (m/s) respectively.

While S_1, S_2 displacement before and after penetration respectively andt_1, t_2 time before and after penetration (s) respectively.

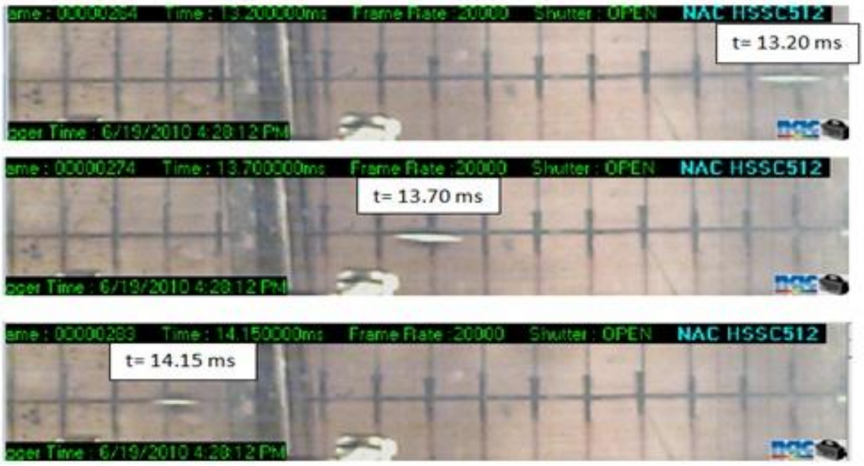


Fig.8. Frames record history by high velocity impact during impact test of specimen.

3. Mathematical and Numerical Model for the Energy Absorption

The determination of energy absorption is important in the design of protective structures, evaluation of the effectiveness on military armour vehicle, aircraft vulnerability analysis and in other situation where an impact can cause damage. The energy absorption is determined from physical principles (the conservation laws and material constitutive relations). However due to the complexity of a problem, the choice of probabilistic technique is made. In this technique, a statistical approach is employed. The complete penetration occurs by target whenever a fragment or fragments from either the impacting projectile or the armour are caused to be expelled from the back of the armour material with sufficient remaining energy to pierce a thin sheet of composite Kevlar-29/polyester.

Three different thicknesses of target plates (12, 16 and 20 mm) where included in this work for case study. According to the Navy Ballistic Limit (NBL) criterion (Beckmann and Goldsmith, 1978), for a complete penetration, it requires that the projectile or a major portion of a projectile passes through the plate. On the basis of the procedure explained in determination of ballistic limit, the value of ballistic limit for carbon fiber composite panel of different thicknesses namely 4.5, 6.5, 7.5, 8.5 and 10.5 mm against a 7.62 mm projectile at normal obliquity has been experimentally determined by Beckmann and Goldsmith, (1978).

The projectile has a dimension of 7.62 mm diameter with a conical shape. The mathematical expression for ballistic velocity of projectile that penetrate at 50% of plate thickness target (V_{50}) will depend upon the density, thickness (number of layers), mechanical properties and shock wave velocity in the target plate, and angle of impact, presented area, weight and shape of the projectile.

$V_{50} = f(\rho_t, \alpha, A_p, w, t, s, a)$ (4)

where,

ρ_t = density of the target (g/cm^3)

α=Angle of impact (degree),

A_p = presented area of the projectile (mm^2),

t = thickness of the target (mm),

w = weight of the projectile (g),

s = strength of the target (g/cm^2) and

a = velocity of sound in the target m/s.

The dimensional analysis (Beckmann and Goldsmith, 1978) provide the solution in the following form

$\Psi_1 = \Phi(\Psi_2, \Psi_3, \Psi_4)$ (5)

If we assume $\Psi_1$to be non dimensional group with V_{50} , Ψ_2, and Ψ_3 with s and a,

$\Psi_4 = \frac{\rho_t A_t t}{w}$, then the experimental simulation of equation (3) gives,

$V_{50} = 2106.83(\frac{\rho_t A_t t}{w})^{0.763}$ (6)

The mechanical properties have been submerged in the values of constants. Therefore to determine the remaining velocity, the relation of striking velocity and ballistic limit/critical velocity of 7.62 mm projectile against composite plate has been formulated and given below. Equation (4) can be re-written in a general form [13] as follows:

$V_r = \lambda\left(V_s^p - V_l^p\right)^{\frac{1}{p}}$, $V_s > V_l$ (7)

Where,

V_r = penetrator residual velocity (m/s),

V_s = penetration striking velocity (m/s),

V_l = limit velocity, material parameter (m/s) and

λ , p = empirical constants

h= thickness of plat

The general form listed above is actually a modification of energy balance equation, so the total energy absorption (E_T) by the target can be written as:

$$E_T = \frac{1}{2}mV_s^2 - \frac{2}{2}mV_r^2$$

or

$E_T = \frac{1}{2}m(V_s^2 - V_r^2)$ (8)

The maximum energy that the material dissipates, (E_{max}), can be written as:

$E_{max} = \frac{1}{2}mV_l^2$ (9)

Equating the two energy expression, E_T , E_{max}, the residual velocity can be expressed as:

$$V_r = \sqrt[2]{V_s^2 - V_l^2} \qquad (10)$$

From the above equations 6 can extract the magnitude of energy absorption residual and equation 8 for residual velocity, this model simply represents the composite laminate, it is possible to obtain the ballistic limit, equaling the residual velocity [10].
The total energy absorption by the specimen according to the following equation:

$$E_{Abs} = \frac{1}{2} m_p (V_i^2 - V_r^2) \quad \text{or} \quad E_{Abs} = \frac{1}{2} m_p V_b^2 \qquad (11)$$

$$V_b = \sqrt{V_i^2 - V_r^2}$$

Where

E_{Abs}= Energy Absorption by the specimen (J), m_p = mass of bullet (Kg) and V_b= ballistic velocity (m/s).

3.1 Description of the Numerical Model

3.1.1 Material Modeling

The main properties of fiber Kevlar29/polyester and Steel 4340 were used in this simulation at room temperature condition shown in tables 3 and the Johnson-Cook failure model has been used for projectile material, deformations were observed in the cylindrical steel 4340 bullet as shown in table 4.

Table 3: Kevlar29/polyester (orthotropic)

E_{11} (Kpa)	E_{22}(Kpa)	E_{33}(Kpa)	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY Pa	Shear Modulus YZ Pa	Shear Modulus XZ Pa
1.15e+7	1.15e+7	1.15e+6	0.08	0.7	0.075	1.e-004	1.e-004	1.e-004

Table 4: Steel 4340 impactor (Johnson Cook Strength)

Initial Yield Stress Pa	Density Kg/m3	Bulk Modulus (Pa)	Strain Rate Constant	Thermal Softening Exponent	Melting Temperature C	Reference Strain Rate (/sec)
7.92e+008	7830	1.59e+011	1.4e-002	1.03	1519.8	1

3.1.2 Finite Element Mesh and Autodyn Simulation

The finite element model by Lagrange model using ANSYS v12.1, where a sandwich plate is idealized using the same conditions in experimental work like fixed ended of plate thickness of plates mechanical properties, initial velocity of bullet and the properties of bullet as shown in Figures 9 and 10-a. Explicit mesh element of 18551 nodes and 15266 elements for 20mm, 13349 nodes and 10266 elements for 16mm, 7803 nodes 5000 elements for 12mm target thickness, while for the bullet 344 nodes and 266 elements was used to simulate the target and the impactor by Academic Autodyn 3D version 12.1 as illustrated in figures 10, and 11 that show also the damage view occurring during different time . Each layer of the plate was modeled using two solid elements through the thickness, and the minimal element size was 0.2 x 0.2 mm at the plate, which was the point of impact.

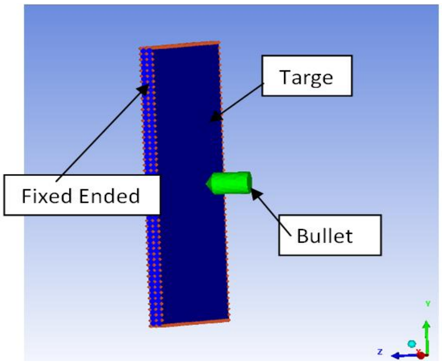


Fig.9.12mm target of Kevlar29/polyester fixed ended subjected to cylindrical steel bullet at time 0 ms and cycle 0.

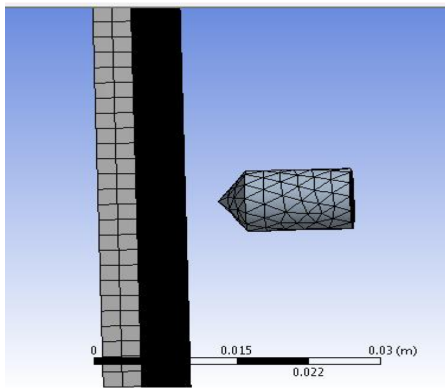
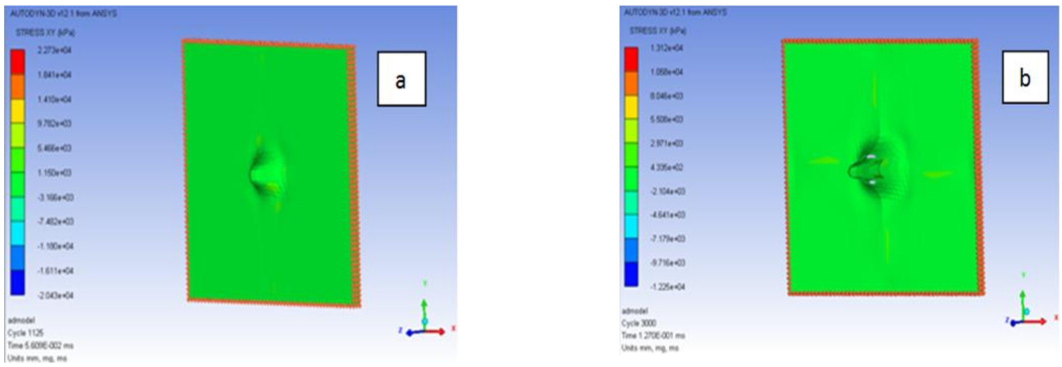


Fig.10. 12mm target of Kevlar29/polyester subjected to 350m/s cylindrical steel bullet a- explicit mesh and b



(a) (b)

Fig.11. Back view stress damage of 12mm target of Kevlar29/polyester subjected to 320m/s cylindrical steel bullet (a) at time 6.5 ms and (b) at time 12 ms.

4. Results and discussion

Measurements of velocity in ballistic experiments are not easy and reliable. In most experiments, the residual velocity of the projectile after the perforation of the target is quantified. The experimental work by (Patel et al., 2004; Backman & Goldsmith, 1978) is explained the effect of initial velocity is carried out by keeping the initial kinetic energy constant at 578 J. Fig.-12 shows that the ballistic limit increases with the initial velocity for same initial kinetic energy and it follows a linear relationship with initial velocity of impact.

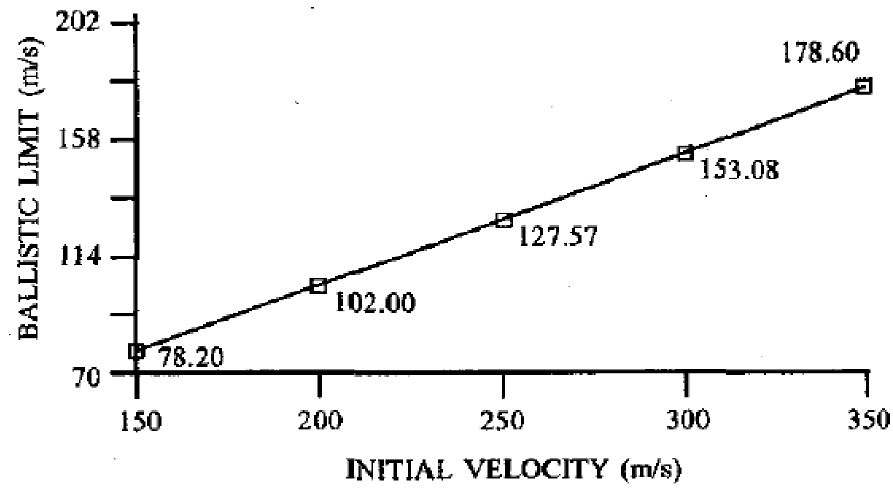


Fig.12. Variation of ballistic limit with initial velocities (Patel et al., 2004; Backman & Goldsmith, 1978)

It can be noticed from Fig.13 that at low initial velocities near the ballistic limit, the plate vibrates with higher amplitude and for longer time period and the response of the plate changes with increase in impact velocity.

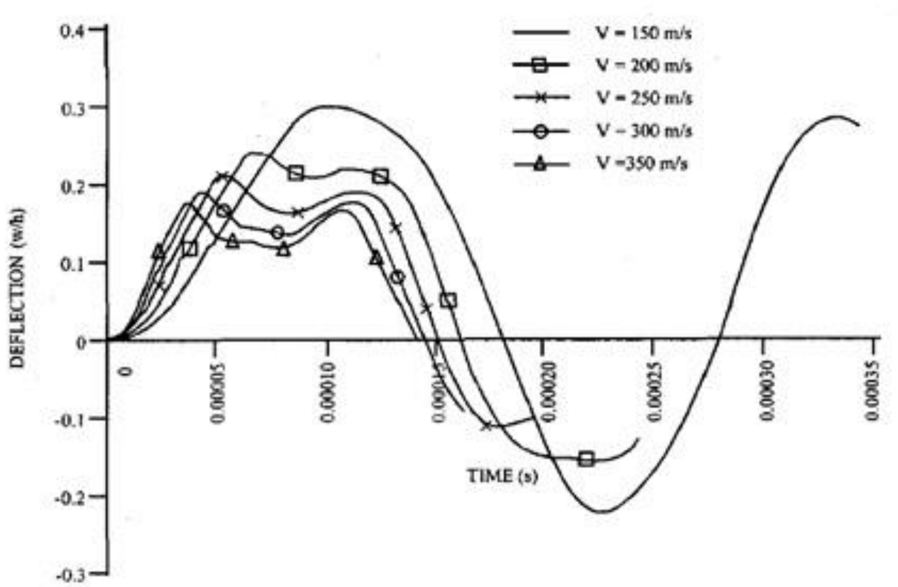


Fig.13. Plate deflection history for different initial velocities (Patel et al., 2004; Backman & Goldsmith, 1978)

The predicted damages by Autodyn-3D v12.1 software of the composite Kevlar29/polyester laminated plates perforating listed in table 4 with different (12, 16 and 20mm) thicknesses at range of (160 - 400 m/s) strike velocities of steel 4340 bullet, an example of (100 x 100 x 12mm) target under 320 m/s shown in Fig. 14 at different history cycles, this figure shows the stress and strain distribution which it results by the damage occurred in the specimen, hence the simulation was done as the same conditions in experimental work so as to obtain good comparison. .

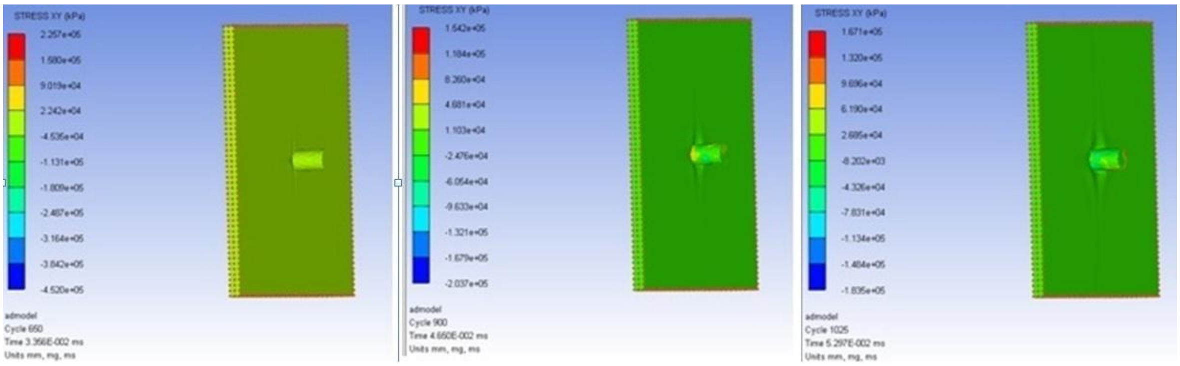


Fig.14. The stress and strain of (100 x 100 x 12 mm) Kevlar29/polyester and subjected to 320 m/s of tip nose steel 4340 bullet at different times

To comparison the damage occurred during this simulation with experimental test Fig.15 shows the specimen tested of 12mm thickness of laminated plate. The damage occurred for experimental work of tip nose Steel4340 bullet at 320m/s velocity on 12mm thickness of target shown in Fig. 16

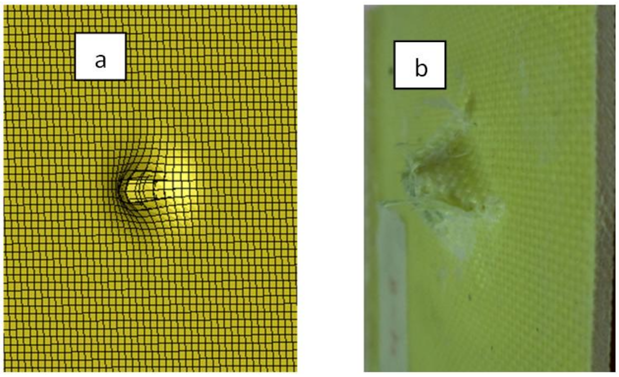


Fig.15. Comparison of the perforated damage in the fabric target in the experimental and theoretical analyses: (a) simulated and (b) observed

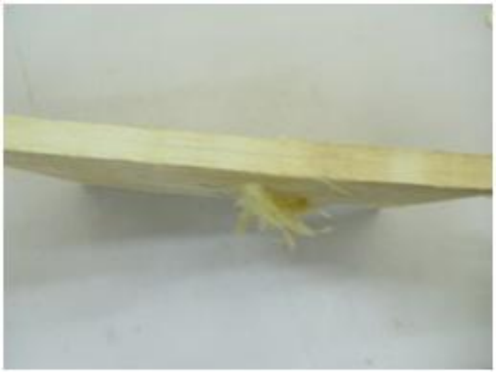


Fig.16. The damage occurred of tip nose Steel4340 bullet at 320m/s velocity on 12mm thickness of target.

The initial velocity versus residual velocity of (12, 16 and 20mm) laminated plated thicknesses subjected to rang of impact velocity (160-400 m/s) steel bullet was presented in Fig.17 which it shows decreasing the residual velocities with increasing thickness of targets until no penetration occurred via 20mm thickness of laminated plate especially at initial velocity less than 320 m/s. Figures 18 and 19 presented the experimental and simulation results respectively of initial velocity versus energy absorption of (12, 16 and 20mm) thicknesses of kevlar29/polyester laminated plates. The numerical simulation by using Autodyn-3D v12.1 obtained a good approximation to the experimental results.

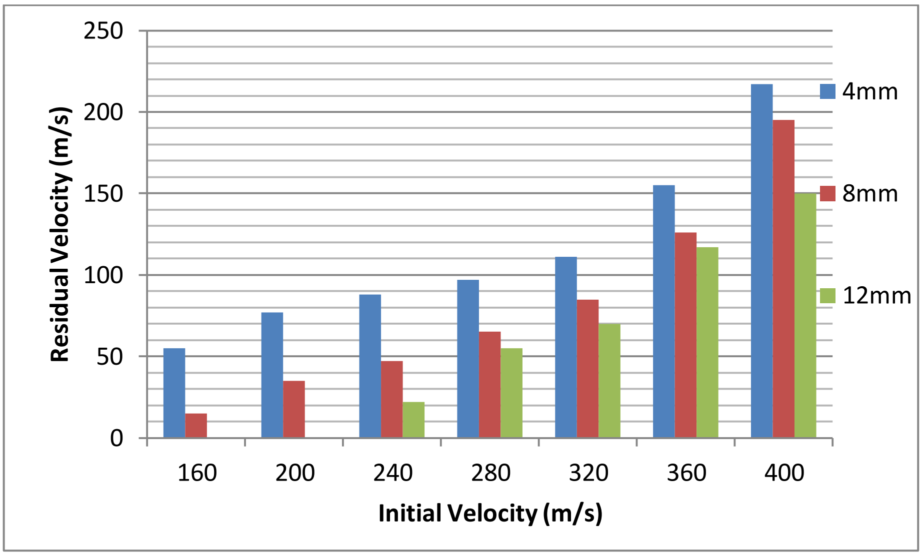


Fig.17. Initial velocity versus residual velocity of 12, 16 and 20mm thickness of laminated plates

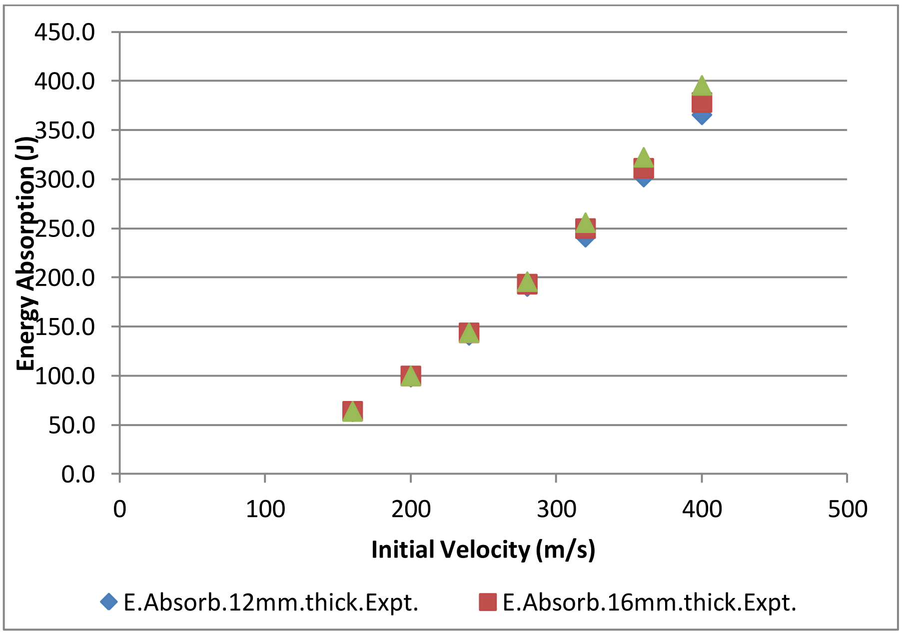


Fig.18. Experimental work of initial velocity versus energy absorption of 12mm, 16mm and 20mm targets laminated plate subjected to range (160-400 m/s) steel bullet .

The velocity history during impact also dependent on the thickness of plate as shown in Fig.20 , that shows an example of 320m/s of initial velocity for different thickness of kevlar29/polyester laminated plates, the time of drop slop increase with the thickness of plate.

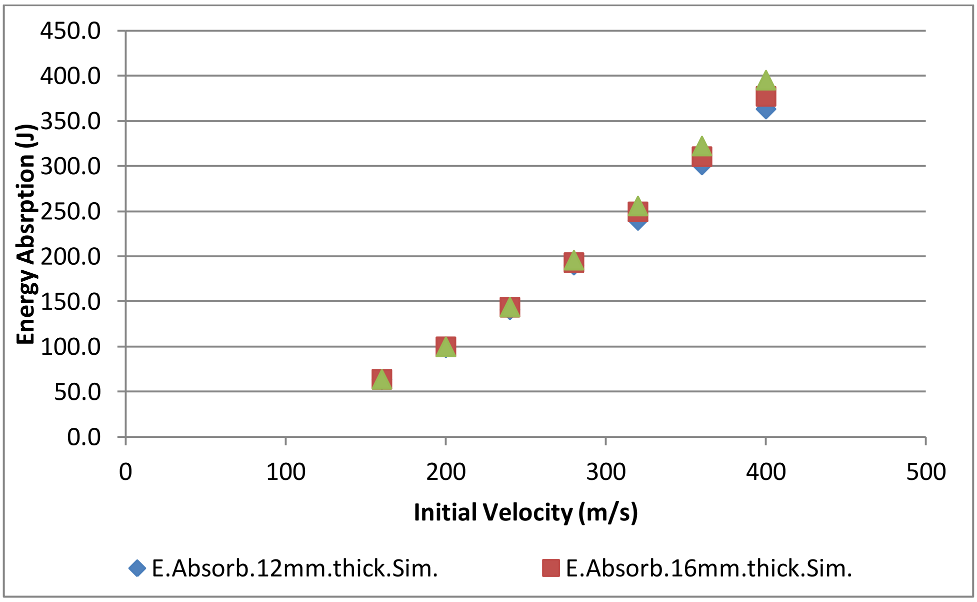


Fig. 19. Simulation of initial velocity versus energy absorption of 12mm, 16mm and 20mm targets laminated plate subjected to range (160-400 m/s) steel bullet

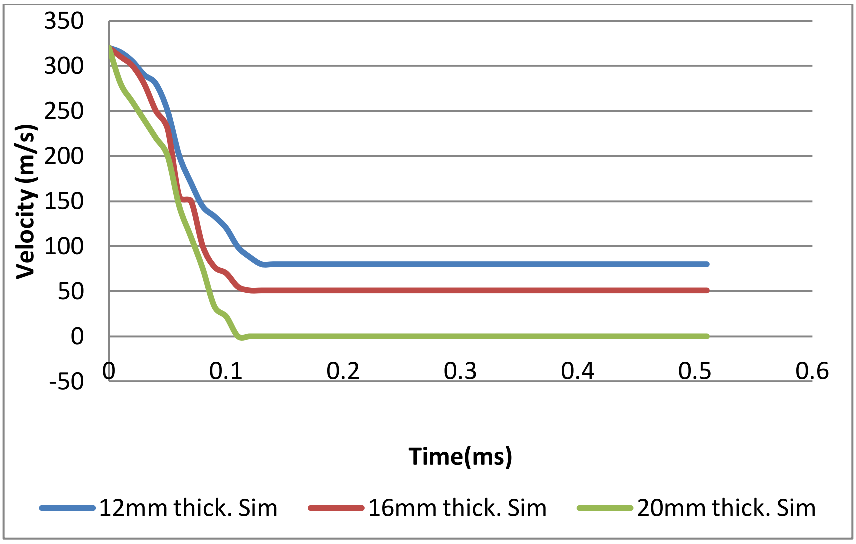


Fig.20. Simulation of velocity behavior with time of 12mm, 16mm and 20mm targets laminated plate subjected at 320m/s steel bullet

The energy absorption was studied in this work to obtain the optimum results value and it were found the maximum relative error of energy absorption between simulation and experimental values is 3.6 % for overall results obtained with different thickness and initial velocity of composite laminated plates.

5. Conclusions

The proposed correlation on the energy absorption for Kevlar-29/polyester materials is well to predict the behavior of energy impact for the composite material. The results inferred from the work presented described formulation of the energy absorption for composite material plate target against 7.62 mm of conical nose projectiles are suitable to compute accurate result within an error of maximum 3.6% of experimental work. The energy absorption of the composites were increased as the initial velocity increases and the numerical simulation was developed and combined with academic 3D-AUTODYN v.12.1software by explicit mesh to calculate time vs. velocity curves and energy absorption of kevlar29/polyester composite laminated plates. The impact energy absorptions of numerical simulation compared with experimental work which it was calculated by using equation (11).

The good agreements of the comparisons with maximum errors were 3.6%
The increasing of thickness of plate affected on the behavior of energy absorption and ballistic limit for the projectile that the structure obtained of 20mm thickness was optimum structure to resist the impact loading under 320m/s impact velocity as armor application.

Acknowledgement
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