Impact Stress Analysis of Carbon/Epoxy Composite Plate

تحليل إجهاد ألصدمه للصفائح ألمركبه كربون\ايبوكسي

Asst. Prof. Dr. Abdukareem Abdulrazzaq Al-Humdany, Asst. Prof. Dr. Jawad Talib Abodi and Salah Mahdi Ali
Mechanical Engineering Department, University of Karbala

Abstract

The composite materials are widely used in the manufacturing of the military protection equipments such as body armors, helmets, vehicles body and other engineering applications because of the light weight and the high performance as compared to the metals. With the progress made in the manufacture of arms and ammunition it has become important to develop armors to become lighter and more effective in resisting fire arms and this represents a great challenge to the researchers.

In this work finite element ANSYS program is used to analyze the impact stresses of 9mm bullet impact on composite plate using explicit dynamic and autodyne code. The material used in this work is unidirectional carbon fibers and epoxy. The experimental work including manufacturing composite plates made from Carbon/Epoxy with different thicknesses and subjects these plates to impact by 9mm bullets at speed of 371m/s from 5m distance. The numerical results were validated by comparing the bullets residual velocity and the ballistic limit with the results from the experiment work. The results show that the shear and strain are maximum in the front layers while the tensile stress is maximum at the rear layers and the ballistic limit for the Carbon/Epoxy plate with 5mm thickness is 371m/s.

ألخلاصه

الصفائح ألمركبه أصبحت تستخدم بشكل واسع في صناعه المعدات ألعسكريه الخاصة بالحماية مثل الدروع والخوذ والسيارات وتطبيقات اخرى كثيرة بسبب خفه الوزن والأداء العالي مقارنةً بالمعادن. مع التقدم الحاصل في صناعه الاسلحه والذخائر أصبح من الضروري تطوير الدروع لتصبح اخف وزنا وأكثر فاعليه في التصدي للأسلحة ألناريه وهذا مثل تحدي كبير للباحثين. في هذا البحث تم استخدام برنامج الانسز لتحليل الاجهادات الناتجة عن اصطدام رصاصه عيار 9ملم بالصفائح ألمركبه. المواد ألمستخدمه في هذا البحث هي ألياف كربونية ذات اتجاه واحد مع الايبوكسي. التجارب ألعمليه في هذا البحث تتضمن تصنيع صفائح من الألياف الكربونية والايبوكسي بسمك مختلف وإطلاق الرصاص عليها بسرعه 371 م\ث ومن مسافة 5 م. لإثبات النتائج المتحصل عليها من برنامج الانسز تم مقارنه سرعه خروج ألرصاصه واقل سرعه لازمه لاختراق هذه الألواح مع النتائج ألعمليه. وقد بينت النتائج أن إجهاد القص والانفعال يكون في أعلى قيمه في الطبقات الأولى بينما إجهاد الشد يكون في أعلى قيمه له في الطبقات الأخيره وان اقل سرعه لازمه لاختراق لوح من الالياف الكربونيه والايبوكسي بسمك 5ملم هو 371م\ث.

1. Introduction

Impact studies are so important in many fields like military, airspace and motivate the researchers to conducted more experiments and studies to get clear picture to the impact behavior. This search analyze and study the impact stresses of striking bullets on composite plate, and a unidirectional Carbon Fiber Reinforced polymer (CFRP) with epoxy is used in this work. The high mechanical properties of composite material such as the high strength and low density compared to conventional material gave it important role in aerospace, automotive, and military manufacturing such as helmets and body armor. Harpreet et al [1] conducted numerical and experiment analysis to find the impact damage of the composite materials using ABAQUS/Explicit. The material used in there work is graphite/epoxy and 6.5g steel bullet with different speeds. The authors concluded that the numerical result in prediction the composite damage is matches well with the experiment results. V. Narayanamurthy et al [2] performed numerical simulation to analyze the impact of steel bullets on steel target using ANSYS LS DYNA software and the authors proved this software can efficiently calculated the impact parameter such as the damage, bullet residual velocity, bullet displacement. Rimantas et al [3] conducted a series of numerical analysis to prove that by using LS-DYNA software the bullet residual velocity can be accurately calculated. The authors have used twaron textile in modeling the target and lead in modeling the bullet. The authors concluded that the residual velocity can be accurately calculated by using LS-DYNA software.

In this work impact stress analysis of Carbon/Epoxy composite plate is performed using ANSYS 16.1 software and validated by comparing the bullets residual velocity and the ballistic limit with the experiment work.

2. Three- Dimensional stress and strain:-

In the stress analysis of general three- dimensional bodies it's considered that the three-dimensional infinitesimal element in Cartesian coordinates with dimensions dx, dy, and dz subjected to normal and shear stresses. This element is subjected to three-dimensional stress, the normal stresses are represented by$\sigma x, \sigma y,$ andσz. Shear stresses are represented by $\tau_{xy}, \tau_{yz},$ andτ_{zx}.

From the element equilibrium get [8]:

$$\tau_{xy} = \tau_{yx} \ , \qquad \tau_{yz} = \tau_{zy} \ , \qquad \tau_{zx} = \tau_{xz}$$

The element strain/displacement relationship is:

$$\varepsilon_x = \frac{\partial u}{\partial x} \ , \qquad \varepsilon_y = \frac{\partial v}{\partial y} \ , \qquad \varepsilon_z = \frac{\partial w}{\partial z} \qquad (1)$$

The shear strain relationship is:

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \gamma_{yx}$$

$$\gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} = \gamma_{zy}$$

$$\gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} = \gamma_{xy} \qquad (2)$$

By representing the stresses and strains by column matrix get:

$$[\sigma] = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix} \qquad [\varepsilon] = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{bmatrix} \qquad (3)$$

The stress/strain relationship is:

$$[\sigma] = [D][\varepsilon] \qquad (4)$$

Where $[D]$ is given by equation (20):

$$D = \frac{E}{(1+v)(1-2v)} \begin{bmatrix} 1-v & v & v & 0 & 0 & 0 \\ & 1-v & v & 0 & 0 & 0 \\ & & 1-v & 0 & 0 & 0 \\ & & & \frac{1-2v}{2} & 0 & 0 \\ & & & & \frac{1-2v}{2} & 0 \\ & & & & & \frac{1-2v}{2} \end{bmatrix} \qquad (5)$$

3. Carbon Fibers Fabrication:-

The Carbon/Epoxy laminates were fabricated using the unidirectional carbon fibers type sikawrap-230C which have areal density of 230g/m^2, and the epoxy type sikadur-330 which it has density of 1310 kg/m^3. The epoxy was mixed with the hardener in weight ratio of 80% epoxy and 20% hardener this ratio was used according to the manufacture instruction. The Carbon/Epoxy laminates were fabricated in ($0^\circ/90^\circ$) orientation because according to [9] the ballistic limit is maximum for ($0^\circ/90^\circ$) lay-up laminates and for all thickness, and the volume fraction was 40% carbon fibers and 60% epoxy with dimension of 15cm $\times$ 15cm and in different thicknesses.

4. Impact Testing:-

The experimental test was created according to the guidelines given by the National Institute of Justice (NIJ) standards (MIL-STD-662E, NIJ standard 0108.01) which is the most reliable test that widely used by government agencies and armor manufacturers for product acceptance test [10]. The schematic of ballistic setup of (NIJ) test are shown in figure (1). The test weapon used was 9mm handgun made in IRAQ and fixed on stand to insure that the bullets are fired in strait line with the target and the chronograph also laser beam is used to help in aiming as shown in figure (2), and in order to determine the velocity of the bullet a Caldwell chronograph was used which is shown in figure (3). The test procedure used to test the composite plates was done using specimens of

Carbon /Epoxy with different thicknesses. The test specimens were perpendicular to the line of bullet flight at the point of impact, and one bullet was fired on each specimen. The bullet used in this test has flat ended and conical nose, the core was made from lead and the jacket from copper, the bullet length was 15.38mm and the diameter 9mm, and its weight 8g.

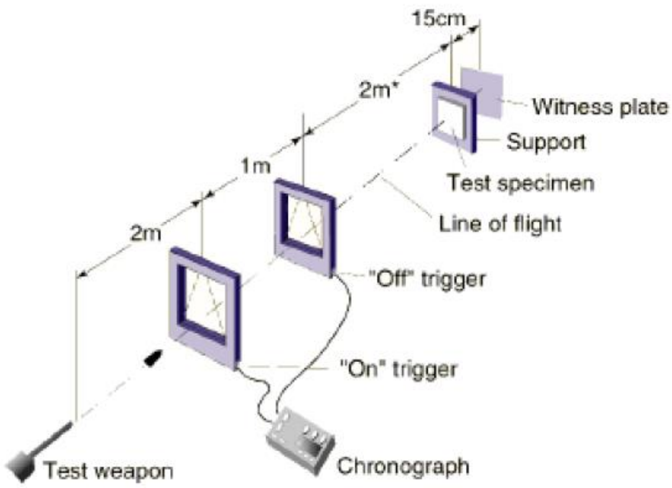

Figure (1): Ballistic testing {National Institute of Justice (NIJ) Standard} [10]

Figure (2): Gun fixing mechanism

Figure (3): The ballistic chronograph

5. Projectile modeling:-

To modeling the 9 mm bullet it has been used the lead metal as core and copper metal to incase the lead core as in figure (4). Jonson cook failure low is used in modeling the lead and copper metal [11]. The lead and copper metal properties are taken from ANSYS 16.1 engineering data sources-explicit materials. The projectile was modeled in detail according to the projectiles used in the experiments and in order to save computation time the planer symmetry condition in a quarter models is used as in figure (5), and in meshing the projectile a mesh of size 1 mm is used as in figure (6). The numerical analyzes is done by setting the bullet initial velocity of 371 m/s as it obtained from the experiments and due to the lack of thermal material data for the target material the heat generated during the impact is neglected.

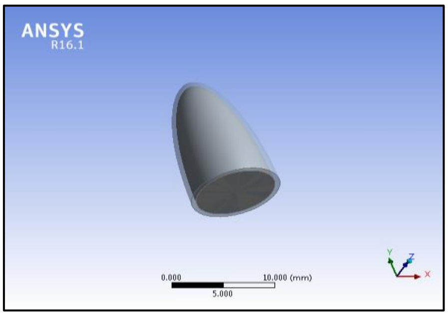

Figure (4): Bullet modeling in ANSYS.

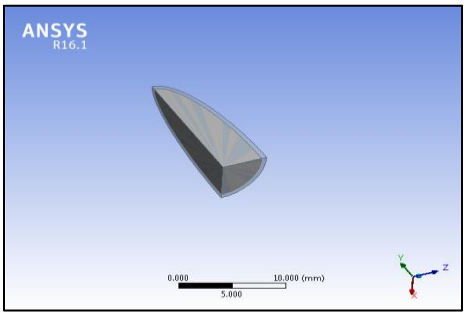

Figure (5): Bullet symmetry

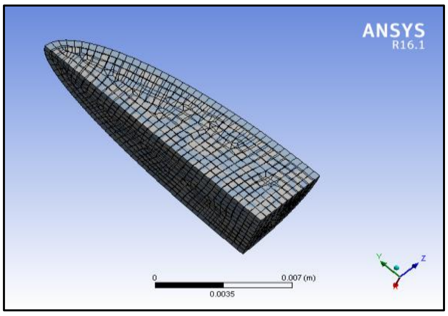

Figure (6): Bullet meshing

6. Composite modeling:-

In modeling of Carbon/Epoxy composite plate the plies are layup in alternating 0° and 90° orientation, and the Carbon/Epoxy properties are calculated according to the manufacturer data sheet and the lamination theory as shown in table (1). Ply to ply contact for the composite are defined using automatic contact with friction equal to (0.2) [12]. All the plates are modeled in the same size and details as in experiment with long 15cm, width 15cm, and with different thicknesses, and meshed with size of 1mm. The boundary condition that has been used is fixing the four ages of the plate.

Table (1): Carbon/Epoxy properties

Density	1.49 g/cm^3
E_{11}	97.9 GPa
E_{22}	7.4 GPa
E_{33}	7.4 GPa
G_{12}	2848.71 MPa
G_{23}	2607.971 MPa
G_{13}	2848.71 MPa
ν_{12}	0.27
σ_T	1768.6 MPa
ε_T	0.018

In this work the analyzing of the stresses of the impact is made using ANSYS 16.1 and validated by comparing of this result with the experimental work. Symmetry boundary condition of $X = 0$ and $Y = 0$ are used to in order to save time as shown in figure (7).

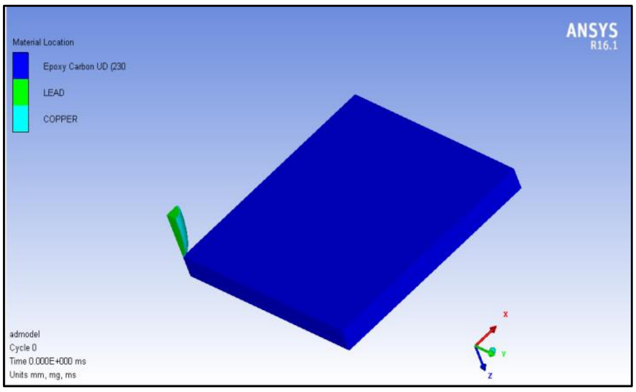

Figure (7): Quarter model with symmetry condition X=Y=0.

7. Validation of Carbon/Epoxy Model:-

Case (1) 4mm thick:-

Figure(8) shows directional deformation of 4mm Carbon/Epoxy plate impacted by 9mm bullet and shows complete penetration to the bullet, also it's observed conoid formation . Figure (9) shows the change in the directional deformation with time, this figure also shows that the maximum directional deformation is increasing with time to reach maximum 0.0361m at 0.0001 second, while the minimum directional deformation is decreasing with time to reach -2.06$\times 10^{-3}$ at the end of the setting time.

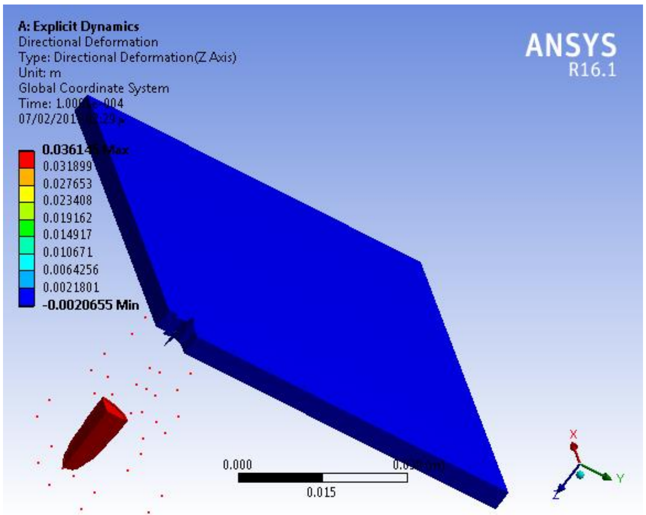

Figure (8): Directional deformation of 4mm carbon/epoxy
Plate impacted by 9mm bullet at speed of 371m/s.

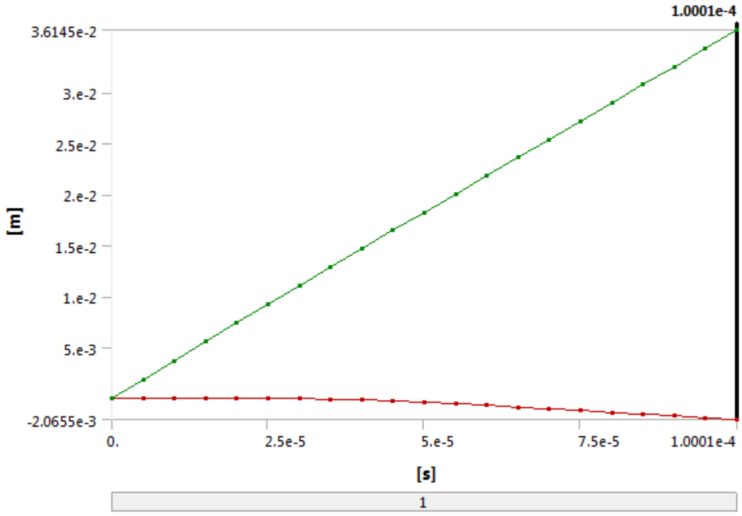

Figure (9): The change in the directional deformation with time
For the Carbon/Epoxy plate 4mm thick impacted by 9mm bullet.

Figure (10) shows the stress distribution in the composite plate using maximum principal stress at 0.0001 Second and it's observed that the maximum stress in the composite is located in the impact area which take red color, and figure (11) shows the change in the maximum and minimum stress with time. From these two figures it's observed that the maximum stress happen at 1×10^{-8} second at this time the material fails to resist the bullet and therefore the penetration happen. After that time the stress are decreasing with time until the end of the setting time. The vibration in stress curve is due to the tensile and compressive stress wave that happens during the impact.

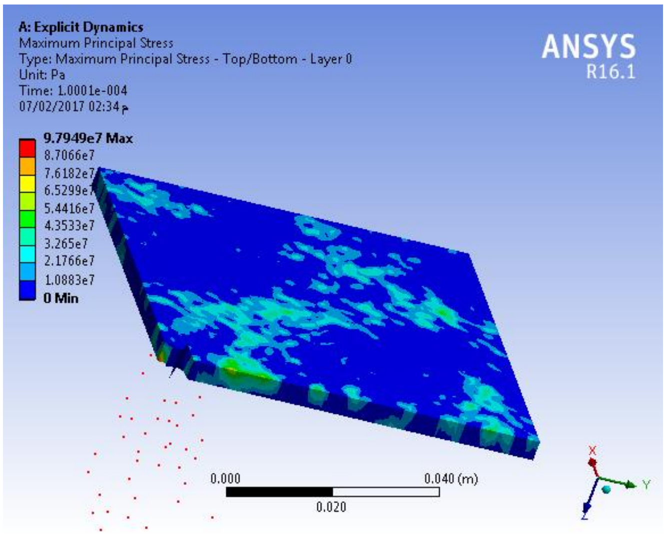

Figure (10): The maximum principal stress with time for the
Carbon/Epoxy plate 4mm thick impacted by 9mm bullet.

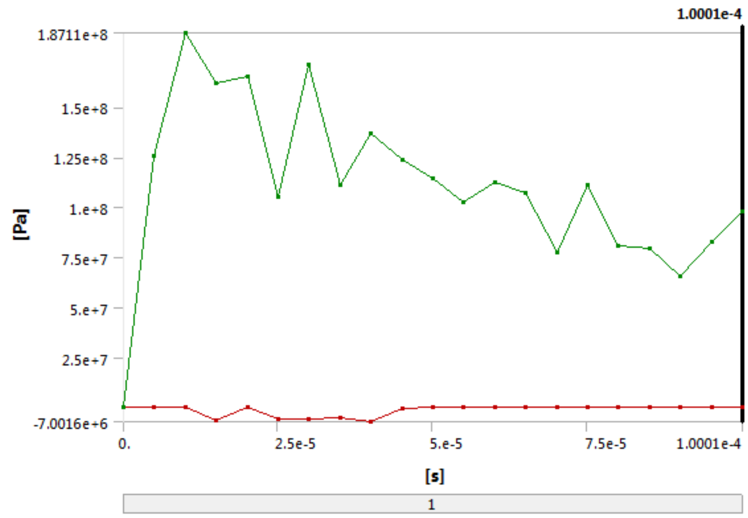

Figure (11): The change in the maximum principal stress with time for the Carbon/Epoxy plate 4mm thick.

Figure (12) shows the maximum principal stress in the bullet at 0.0001 second using maximum principal stress and it's observed that the bullet tip is deformed and the maximum stresses concentrate in tip of the bullet and the copper jacket has slide backward. Figure (13) shows the change in the maximum and minimum stress with time. From these two figures it's noticed that the maximum stress on the bullet reach 4.969×10^{8} after 0.5×10^{-5} second and that is higher than the stress on the composite plate that because the surface area of the bullet is smaller therefore the stress is higher.

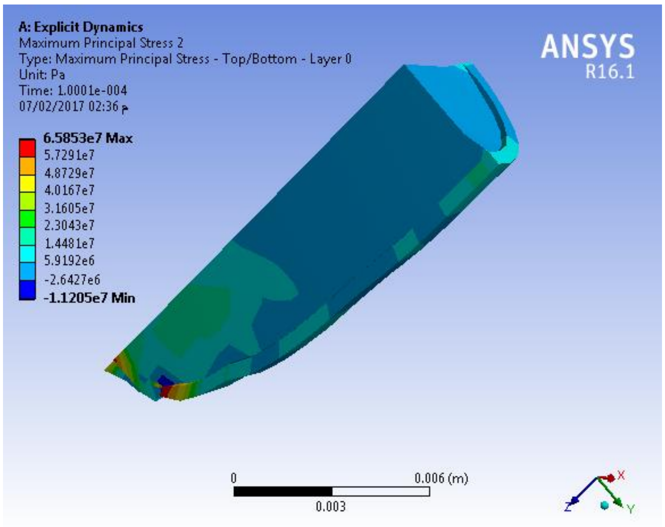

Figure (12): The maximum principal stress in the 9mm bullet impact Carbon/Epoxy plate 4mm thick at speed of 371m/s.

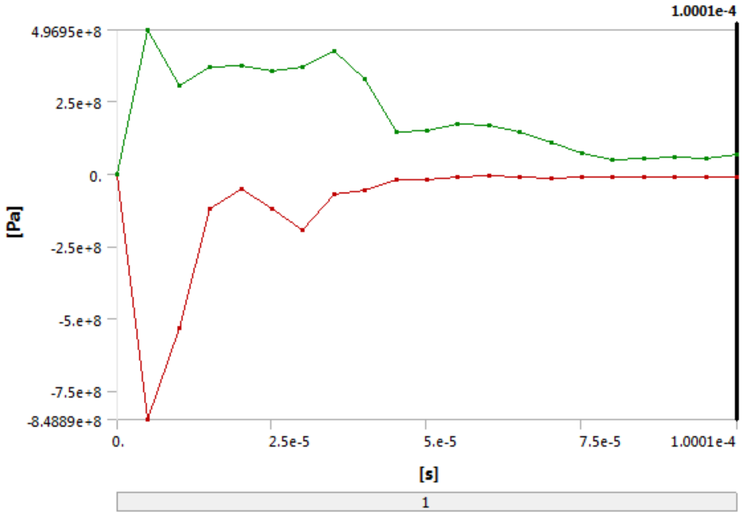

Figure (13): The change in the maximum principal stress with time for the 9mm bullet impact Carbon/Epoxy plate at speed of 371m/s.

Figure (14) shows the distribution of the shear stress in the composite plate using maximum shear stress and it's noticed that the maximum shear stress located in the in the area of impact area and all the composite layers failed by shear. Figure (15) shows the change in shear stress with time and it's noticed that the maximum shear stress value is 1.898×10^{8} at time of 1×10^{-5} second in this value is higher than shear stress limit for the Carbon/Epoxy composite.

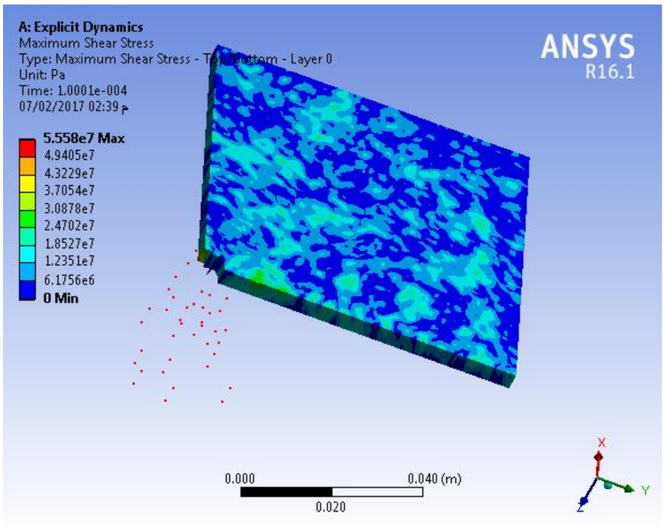

Figure (14): The change in the maximum shear stress in the Carbon/Epoxy plate impacted by 9mm bullet.

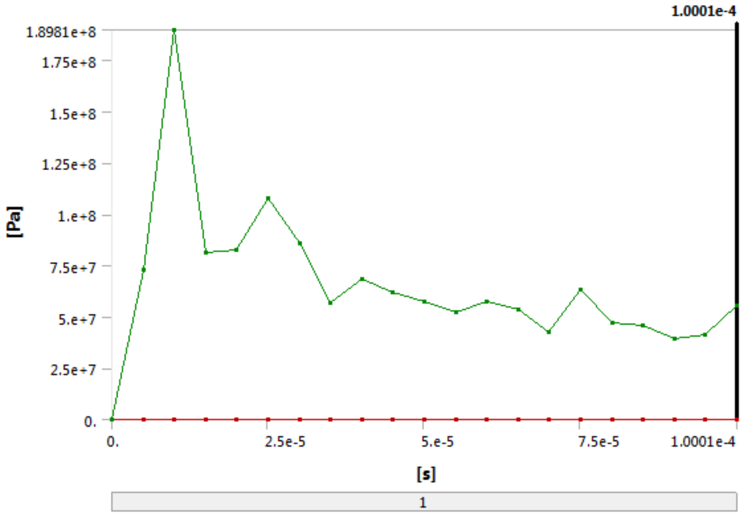

Figure (15): The change in the maximum shear stress with time for the Carbon/Epoxy plate 4mm thick.

Figure (16) shows the elastic strain in the composite plate using maximum principal elastic strain and it's observed that the area under the impact has failed by strain. Figure (17) shows the change in elastic strain with time and its reach maximum 3.645% after 4.5×10^{-5} second. This value of strain is higher than the strain limit of the Carbon/Epoxy composite and indicates that all layers have failed in strain.

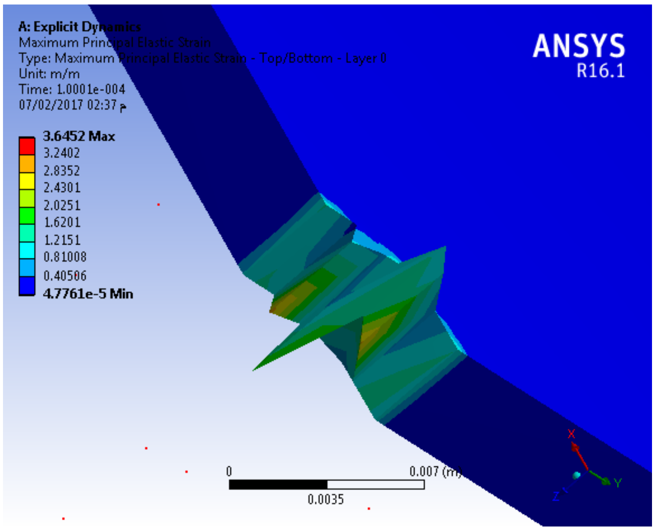

Figure (16): The maximum principal elastic strain in the Carbon/Epoxy plate 4mm thick impacted by 9mm bullet.

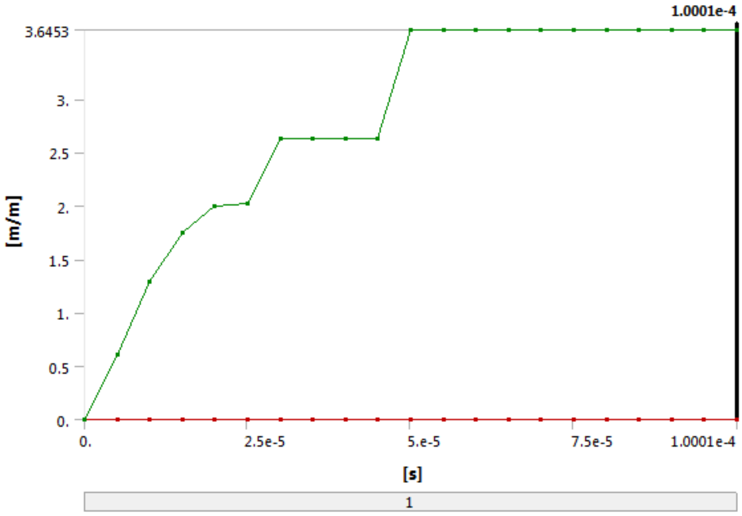

Figure (17): The change in the maximum principal elastic Strain with time for the Carbon/Epoxy plate 4mm thick.

Figure (18) shows the change in internal energy with time. The curve of composite plate internal energy shows increasing with time because the energy lost by the bullet during the impact is gained by the composite plate. After the penetration the internal energy starts decreasing until the end of the time setting.

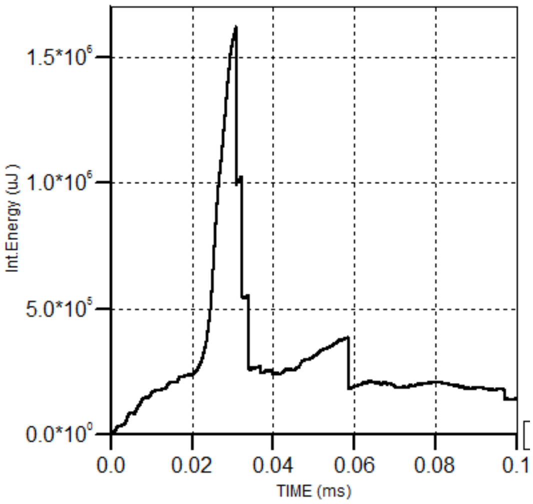

Figure (18) shows the change in the average velocity with time for the lead and copper metal with time in Z direction.

Case (2) 8mm thick:-

Figure (19) shows the directional deformation of 8mm of Carbon/Epoxy plate and figure (20) shows the change in the directional deformation with time. These two figure shows that the bullet has failed to penetrate the composite plate and the maximum directional deformation was 6.6318×10^{-3} at the end of the setting time.

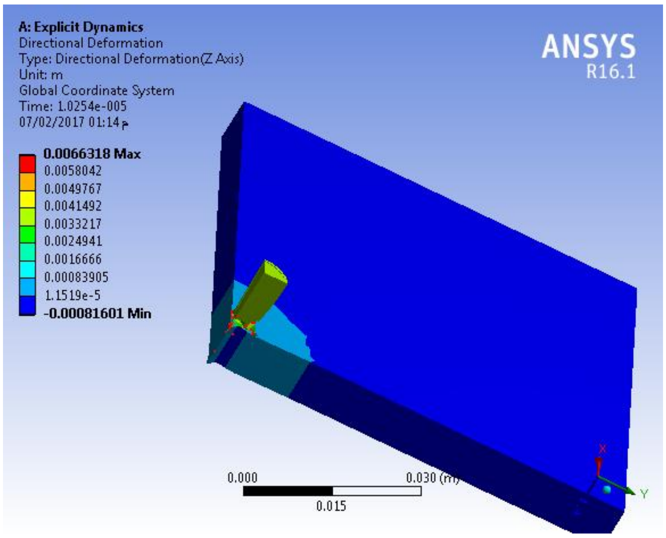

Figure (19): The directional deformation in Z-direction for the Carbon/Epoxy plate 8mm thick impacted by 9mm bullet.

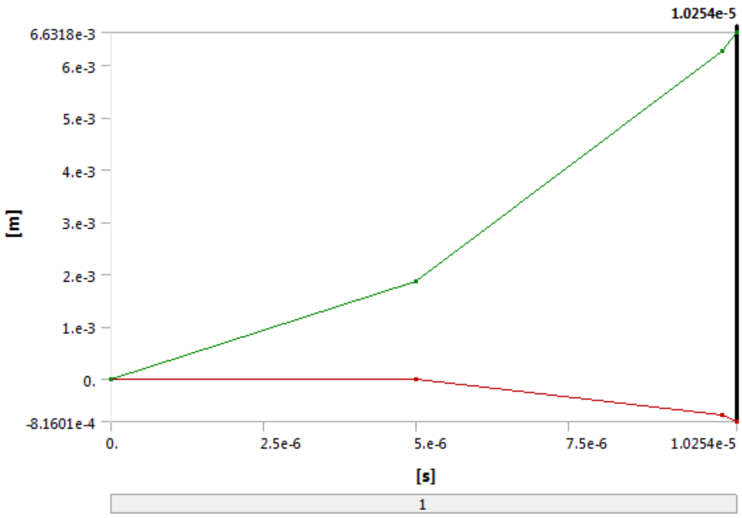

Figure (20): The change in directional deformation with time for the Carbon/Epoxy plate 8mm thick.

Figure (21) shows the stress distribution in the composite plate using maximum principal stress at 0.0001 second and figure (22) shows the change in maximum and minimum stress with time. These two figure shows that maximum stress value is 2.054×10^{11} at 1.025×10^{-5} second and it's concentrated in the impact area and it's higher than the stress in case (1) because the plate is stronger therefore the bullet energy lost in fiber deformation is less.

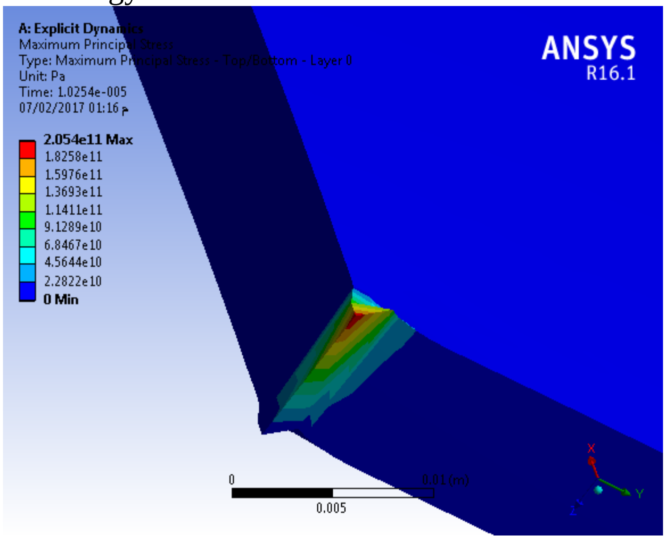

Figure (21): The maximum principal stress in the Carbon/Epoxy plate 8mm thick impacted by 9mm bullet.

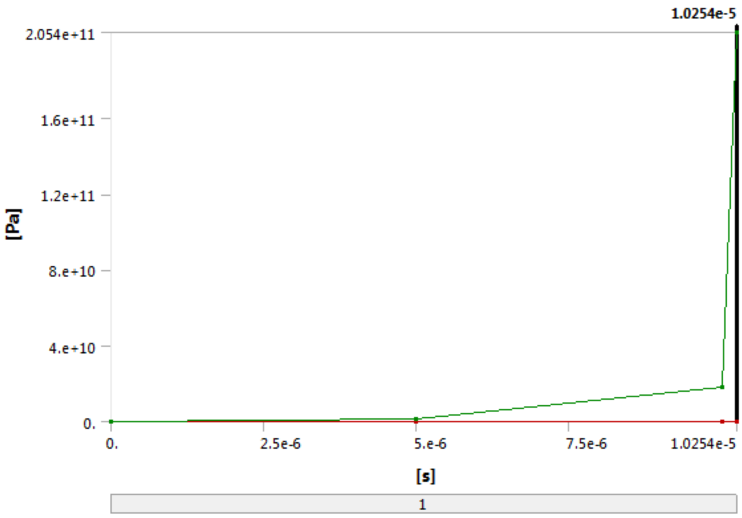

Figure (22): The change in the maximum principal stress with time for the Carbon/Epoxy plate 8mm thick.

Figure (23) shows the stress distribution in the bullet and it's observed that the bullet tip is severely deformed and maximum principal stress is 1.173×10^{11} which is higher than stress in case (1). Figure (24) shows the change in maximum and minimum principal stress with time and the maximum stress curve reach maximum at 1.544×10^{-5} s and the minimum stress curve reach -5.323×10^{12} at 1.544×10^{-5} s.

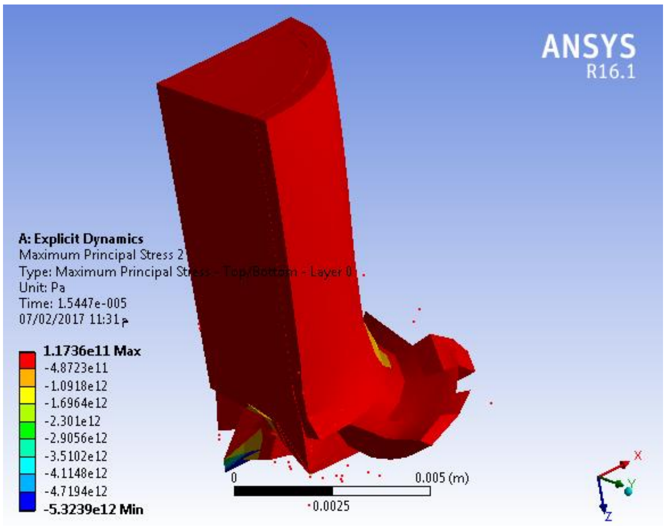

Figure (23): The maximum principal stress in the 9mm bullet Impact Carbon/Epoxy plate 8mm thick at speed of 371m/s.

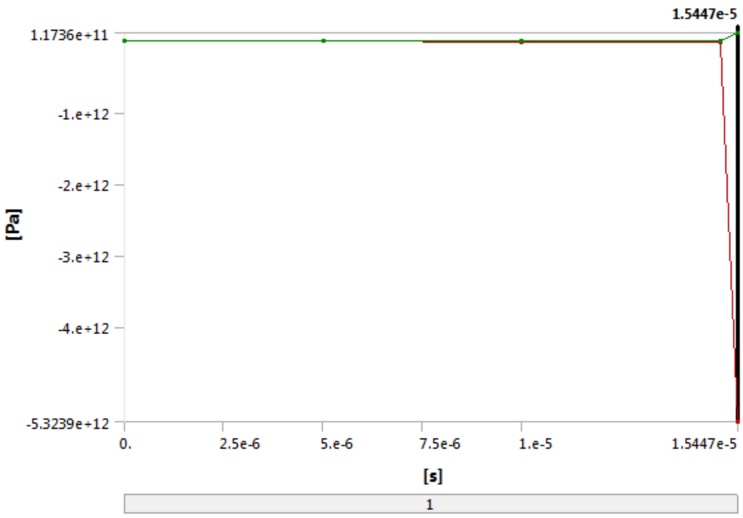

Figure (24): The change in the maximum principal stress with time for the 9mm bullet impact Carbon/Epoxy plate 8mm thick.

Figure (25) shows the shear stress distribution in the composite plate using maximum shear stress and it's observed that maximum shear stress is 1.08×10^{11} and concentrate in the front layers that is mean that the front plate layers has failed in shear also it's higher than shear stress in case (1). Figure (26) the change in the shear stress with time and the shear stress curve shows increasing with time to reach maximum at 1.025×10^{-5}.

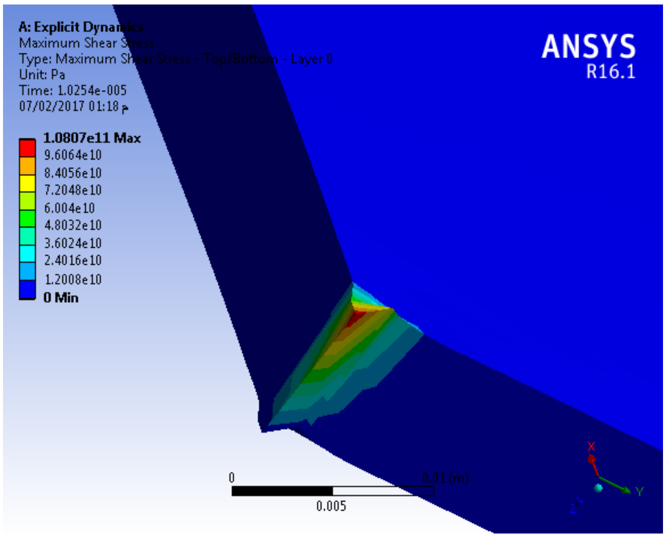

Figure (25): The maximum shear stress in the Carbon/Epoxy plate 8mm thick impacted by 9mm bullet.

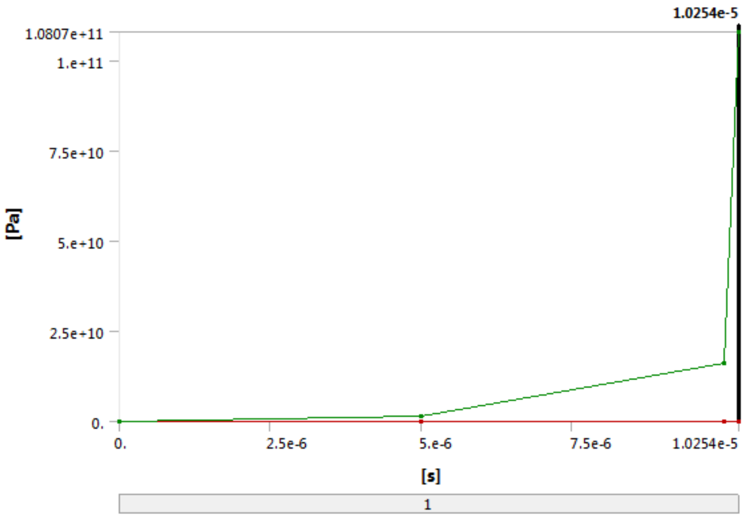

Figure (26): The change in the maximum shear stress with time For the Carbon/Epoxy plate 8mm thick impacted by 9mm bullet.

Figure (27) shows the elastic strain in composite plate using maximum principal elastic strain and it's observed that the maximum strain value is 1.56% and concentrate in the top layers this value of strain is lower than the strain limit of the Carbon/Epoxy composite and indicate that the plate has not failed in strain. Figure (28) shows the change in elastic strain with time and it's observed that the elastic strain curve shows increasing with time and reach maximum at 1.025× 5 s.

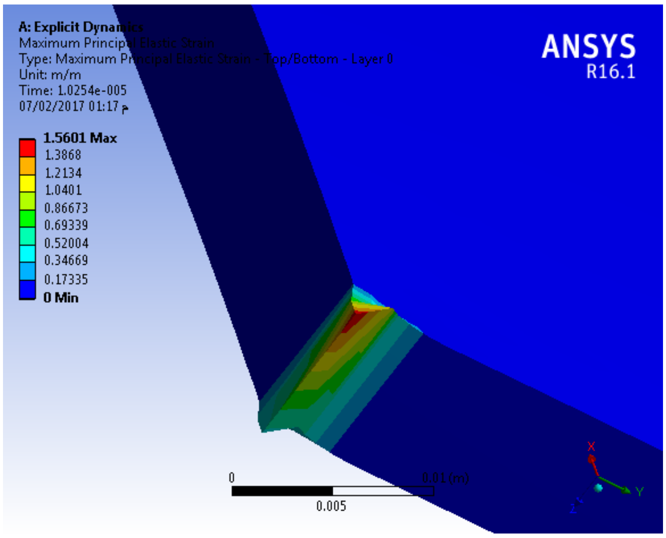

Figure (27): Maximum principal elastic strain in Carbon/Epoxy plate 8mm thick impacted by 9mm bullet.

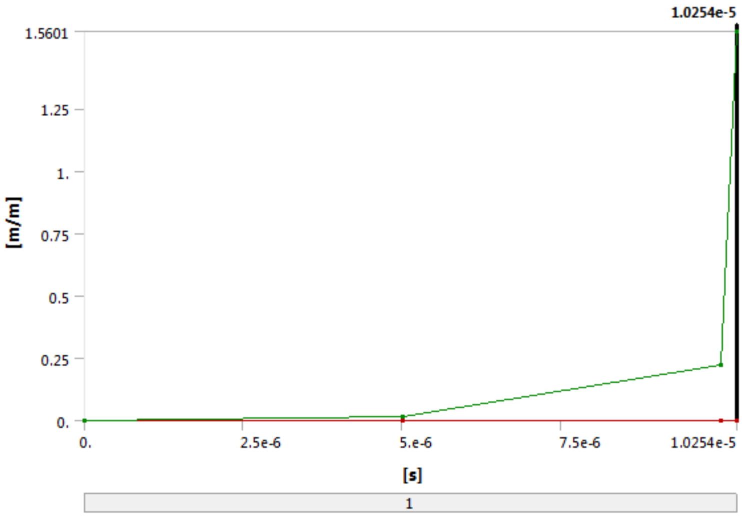

Figure (28): The change in elastic strain with time for the Carbon/Epoxy plate 8mm thick.

Figure (29) shows the change in internal energy with time for the composite plate. The internal energy curve shows increasing with time to reach 1.3255×10^{5}uJ at 5.455×10^{-3}ms this internal energy value is less than internal energy value in case (1) because of the small period of impact compared to case (1).

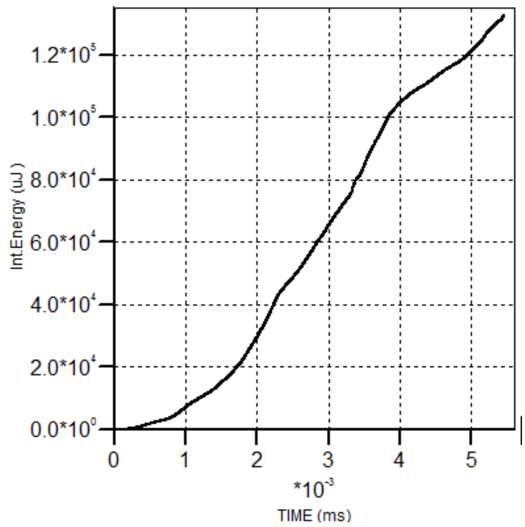

Figure (29): The change in internal energy with time for
Carbon/Epoxy plate 8mm thick impacted by 9mm bullet.

Figure (30) shows the change in the residual velocity with thickness for the Carbon/Epoxy plates in both experimental and numerical solution. The residual velocity curve are decreasing with the increase in the plate thickness to reach zero at the 5 mm thickness, that is mean with increasing plate thickness the absorbing energy increase and at 5 mm thick all the bullet energy is absorbed by the composite plate. Both experimental and numerical result shows good agreement in result.

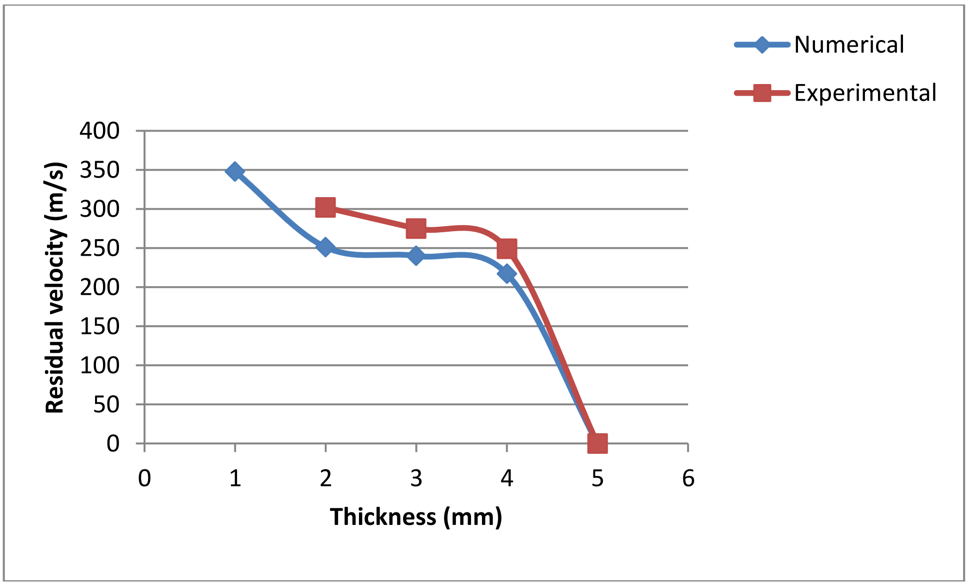

Figure (30): The change in the residual velocity with thickness for the
Carbon/Epoxy plates in both analytical and numerical solution.

Figure (31) shows comparison between the ballistic limit for the Carbon/Epoxy plate 5 mm thickness. The experimental work ballistic limit of 371 m/s for the 5 mm plate thickness and that is agreed with the numerical results.

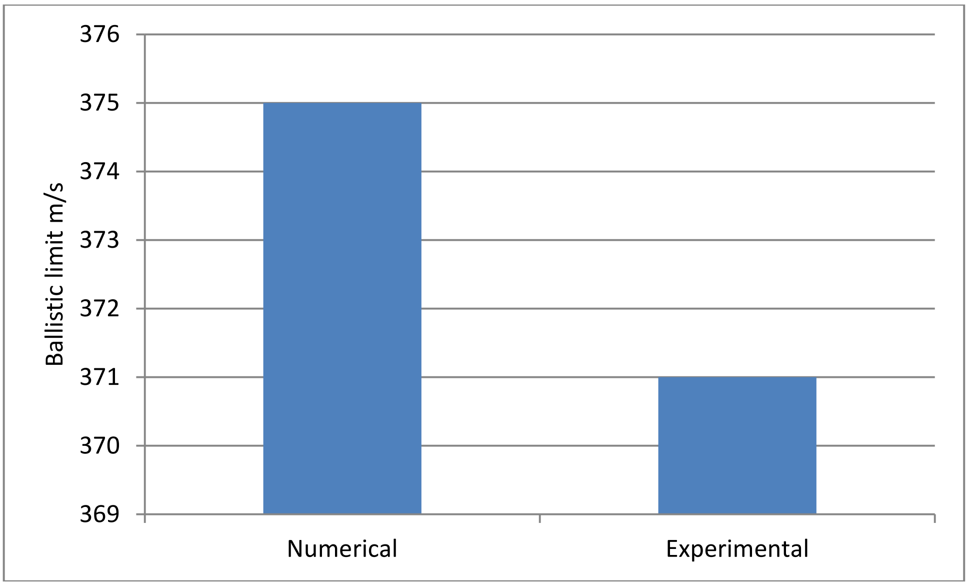

Figure (31): Comparison in the ballistic limit between the experimental work and the numerical solution for the Carbon/Epoxy plate 5mm thick.

. Conclusions:-

1. The absorbed impact energy is increasing with the increase in the plate thickness.
2. In all cases for the bullet velocity which are above the ballistic limit the damaged area are decreasing with the increase of the bullet velocity.
3. In all cases for the bullet velocity which are below the ballistic limit the damaged area are increasing with the increase of the bullet velocity.
4. In all cases the damage was more towered the exit side of the laminates than the entry surface.

Nomenclature

Symbol	Description	Units
A_c	Composite area	m^2
A_f	Fibers area	m^2
A_m	Matrix area	m^2
E_c	Composite modulus of elasticity	Pa
E_f	Fibers modulus of elasticity	Pa
E_m	Matrix modulus of elasticity	Pa
P_c	Composite load	N
p_f	Fibers load	N
P_m	Matrix load	N
V_c	Composite volume	m^3
V_f	Fibers volume	m^3
V_m	Matrix volume	m^3
γ	Shear strain	%
ε	Strain	%
ν	Poisson's ratio	---
σ	Stress	Pa
τ	Shear stress	Pa

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