

MODELLING OF COMPOSITE FROM 3-D CARBON FIBRE AND PARTICULATES REINFORCED ULTRA-HIGH DENSITY POLYETHYLENE FOR HUMAN HARD BODY ARMOUR PROTECTION

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ABSTRACT

Human hard body armour protection is a very important device in the hands of military and para-military in Nigeria. The problem of insecurity in almost all parts of the country has led to the loss of lives and properties. This research work is based on developing hybrid fibre/particulates reinforced ultra-high-density Polyethylene composite for human hard body armour applications. The development of Human Hard Body Armour protection involves a hybrid composite from the 6cm of (3-D) woven mat Carbon Fibre and particulates: 0.075 μ m Metal Chips (Mild Steel), 0.075 μ m of Aluminium Silicate (Glass), 0.040 μ m Alumina (Ceramic) are for the reinforcements while the smelted ultra-high-density Polyethylene was the matrix. The percentage by weight of Polyethylene (matrix) was varied from 44wt% to 76wt% for optimization. The sample specimen of composites were produced for Mechanical property tests; Tensile Strength of (10x15x100)mm³, Impact Strength of (10x10x100)mm³, Flexural Strength of (30x30x100)mm³, and Hardness Strength of (30x30)mm². The experimental results showed that the highest Tensile Strength of 113MPa, Impact Strength of 2.855J, Flexural Strength of 122.517MPa and Hardness Strength of 67Hv were obtained. The optimal values of the composites were modelled using Solid Works and Simulated in ANSYS to ascertain the effectiveness of the hard body armour. It was observed that the designed and simulated Human Hard Body Armour stopped the projectile from passing through with good effect of blunt trauma effect. Further research work should centered on other locally and easily available materials with high mechanical properties for the production of human hard body armour to minimize high cost of importation of the device from foreign countries of the world.

Keywords: Composites, Solid-Works, ANSYS, Body Armour, Blunt Trauma

1 INTRODUCTION

The purpose of armor systems is to prevent the entry of bullets into the protected area. The armor to be used should be durable and easy to produce, use, and repair. The traditional method of armoring is the use of thick steel plates. However, multilayer armor was developed in decades and improved penetration resistance/weight ratio relative to steel. In multilayered armors, the outer ceramic layer deflects the bullets, the artificial fibers hold the bullet particles, and the metal part stops the bullets. This kind of armor systems significantly has less weight than one-layer solid steel armors providing equivalent protection. Enhancing the ballistic resistance of armors is by using composite materials that are generally accepted practice in armor design. In the past few decades, laminate armors have been investigated to achieve good durability and lightweight. Kevlar and steel are commonly used materials in ballistic armor industry especially in structural armor types. Armor design is typically performed in two stages especially for those that contain multiple stacks for

maximum efficacy. First steps of this stage are the armor design and selection of appropriate materials for the application and the threat under consideration. Second stage includes simulation and testing the structure which define the ballistic limits of the materials being used in designing the armor and total efficiency of the design [1]. According to EN 1063 Ballistic Standards, there are different types of projectiles and testing conditions of the ballistic test. Tests are classified into levels listed from BR1 to BR7 based on the geometry, the tip shape, the shooting distance, the mass, the speed, and the material of the projectile. There are two major applications of ballistic armors, the body armor and the structure armors. In the battlefield, humans are usually encountered BR2 level of threat, while vehicles and buildings are encountered a higher level of threat BR7. Material type, geometry, application, and working conditions are the key parameters of the armor design. In the simulation process, the modeling conditions of both target and projectile are playing an important role in the results. Meshing tool, mechanical properties, physical properties of the materials and material modeling characterizing like the type of elasticity and failure conditions are the most important modeling conditions in ballistic armor simulation process. Commercial software tools like Solid Works, CATIA V5, and ANSYS design modeler are commonly used to model the geometry of both armor and projectile. While tools like ABAQUS, Ansys with LS-DYNA, and AUTODYN 3D are used for material and test modeling [1]. [2] carried out an Optimization Approach to the Computer Simulation of Composite. A procedure for the optimal modal design of a beam made of a composite material. The two components considered for the composite are a light concrete as the matrix and a polyester fiber as the filler. The fibers inside of the matrix tend to aggregate and to take this into account in the modeling, a subroutine that generates random finite elements corresponding to the fiber clusters was constructed. Three-dimensional simulation using a volumetric model allows obtaining the solutions by means of a coupled modal analysis-optimization procedure, by employing the ANSYS software. The weight of the beam is considered as the objective function. Restrictions are imposed on the first resonant frequency as well as on the design parameters: percentage of fiber polyester, density of the components, and thickness of the beam. The results provide the optimum set of solutions in terms of the parameters that minimize the weight of the beam, while maintaining the first frequency within as specified range of values. [3] carried out a simulation of the mechanical behavior of a carbon nanotubes-reinforced polymeric composite, based on Flory's statistical segment approach. The material is modeled at the micro and nano levels. Interactions between molecules are Morse-like potentials, as well as Van der Waals forces. Traditional simulations involve Molecular Dynamics by solving Newton's equations of motion, instead, a finite element approach was applied, involving nonlinear elements to take into account the potential interactions. Amorphous polymer chains are represented by statistical segments, in which several repeating units of a chain are treated as single and independent components. This model allows the simulation at a large scale as compared to those using the unit-atom model or those performed at the atomistic level. [4] carried out a research on polymer concretes improved by fibre reinforcement using gamma irradiation. The well-known key problem with concrete is that its compressive strength and the compression modulus are insufficient for a variety of applications. The polymer concrete (PC) consists of an unsaturated polyester resin as the polymeric matrix, silica sand as the inorganic aggregate, plus a tactic polypropylene (PP) fibers. A further property improvement was achieved by gamma irradiation which applied two methods. The first method consists in irradiation of PP fibers first and then adding them to the PC. The second route consists in irradiation of PC after inclusion of PP fibers. Both routes were applied the radiation at dosages ranging from 5 to 150 kGy. In the second route irradiation of silica sand results in larger contact areas of surfaces with PP fibers and with the polyester resin using scanning electron microscopy (SEM). The second route provides compressive properties which are better by a factor of two three (depending on the irradiation dose) than the first one. [5] Investigated on direct numerical simulation of composite structures. Full microscopic models of composite structures have rarely been dealt with, mainly because of their difficulties arising in the actual computation of the finite element model with immense degree of freedoms. To overcome the difficulties and analyze full microscopic models of composite structures, an efficient parallel multi frontal solver, which can utilize distributed computing resources unlimitedly, was developed and applied to the Direct Numerical Simulation (DNS) of composite structures. DNS, virtual experiments were carried out, where material constants are directly obtained through DNS. Microscopic model with defects were also analyzed and compared with a perfect model to validate the potential of the DNS in dealing with irregularity of microscopic

models of composite structures coming from imperfection. [6] Carried out an accurate stress analysis of composite and sandwich narrow beams using two –point boundary value problem. A simple, semi-analytical methodology defining a two-point boundary value problem (BVP) governed by a set of linear first-order ordinary differential equations (ODEs) with mixed primary variables whose number equals the order of partial differential equations (PDEs) for narrow layered beams. These primary quantities consist of displacements (u, w) and the corresponding transverse stresses (τ_{xz}, σ_z). Continuity of transverse stresses and displacements through the thickness of a laminated beam is enforced naturally in the formulation. The accuracy and the effectiveness of the proposed methodology were addressed by comparing numerical results from the formulation with available closed-form analytical and finite element (FE) solutions.

2 METHODOLOGY

The material used include carbon fibre, metal Chips (Mild Steel), aluminium Silicate (Al_2SiO_5), ceramic- Alumina (Al_2O_3), and ultra-High Density Polyethylene. The percentage weight of aluminium silicate, alumina, metal chips (mild steel), polyethylene and carbon fibre each are measured with a digital weighing balance.

The required pellets of polyethylene were smelted and the quantities of these particulates were added to the TwoRoll Mill and rolled for ten (10) minutes for proper mixing of the particulates. The composites were layed into the mould and were placed in a compressive machine at a holding temperature of 120°C for 15 minutes. The laminates produced are cooled in the air for about 30 minutes before the mechanical test was carried out. Sample specimen preparation for bending strength of (30 x 30 x 100) mm³, tensile strength of (100 x 15 x 10) mm³, impact strength of (100 x 10 x 10) mm³ and hardness strength of (30 x 30) mm² were carried out.

The tensile test was carried out using Universal Electronic Testing Machine, WDW-100KN 190536. The test samples were placed and gripped in between the jaws of the machine. The load was gradually applied through a hydraulic press until deformation occurred and the result was displayed digitally [7] Ultimate tensile strength stresses were calculated using equations 1 and 2.

$$\sigma = \frac{P}{A} \quad (1)$$

$$A = \frac{\pi d^2}{4} \quad (2)$$

Where P is the maximum applied load; A is the cross-sectional area of the machine sample; d is the diameter of the machined samples.

The impact test was carried out on the Charpy impact testing Machine in accordance to HD96QD (15J and 25J). The machine consists of tops between which the test sample is inserted. With the specimen positioned in the vice, a blow was stroked by two released pendulums in opposite directions from their calibrated standard height to fracture off the specimen. The energy retained was determined by the height rise of the pendulum as indicated by the dial gauge. The difference between the energy input and energy retained gave the energy absorbed [8].

The hardness values of the hybrid fibre composites were determined in accordance with the ASTM E140 standard using the Vickers Hardness testing machine present in the shell office, department of Mechanical Engineering A.B.U., Zaria. The machine consists of a digital display reading HV and HB, 0.42cm steel ball indenter with a load of 0.3kgf. The specimens prepared to a good finish of perfectly horizontal surface were indented. The depth of indentation indicated the hardness of the laminates [9].

The machine used for the flexural test is a universal tester of model Nr. 261. It has a hydraulic press that actuates the pressure of the machine to grip the load and the result of the force is displayed digitally on the machine of the composite materials. The Universal Material Testing Machine is situated in Mechanical Engineering Department, ABU Zaria [10]. Table 1 shows the percentage by weight of the composites of metal chips, aluminum silicate, alumina, ultra-high density polyethylene and 3-D woven mat of carbon fibre. Table 1 shows the percentage (%) by weight of the composites of

metal chips, aluminum silicate, alumina, ultra-high density polyethylene and 3-D woven mat of carbon fibre

Table 1. Percentage (%) by weight of the composites of metal chips, aluminum silicate, alumina, ultra-high density polyethylene and 3-D woven mat of carbon fibre

S/No.	Processing factors	Factors designation	Level 1 Wt%	Level 2 Wt%	Level 3 Wt%	Level 4 Wt%	Level 5 Wt%
1	3-D Woven Carbon Fibre	A	10	15	20	25	30
2	Metal Chips -Mild Steel	B	6	7	8	9	10
3	Aluminum Silicate (Glass)	C	5	6	7	8	9
4	Alumina (Ceramic)	D	3	4	5	6	7

3 RESULTS AND DISCUSSION

3.1 Modelling and Simulation of the composite in ANSYS

The results of the impact, compressive, tensile, hardness and the physical properties such as thermal analysis, density and grain particle sizes of the alumina, aluminum silicate, metal chips (mild steel) and carbon fibre were inputted into the Solid Works for modelling. The composite were simulated in ANSYS to know their behavior when projectile is subjected to the hard body armour protection.

3.1.2 Modelling and Simulation of the composite in ANSYS of 76wt% polyethylene(matrix)

Figure1 shows that the projectile did not pass through the human hard armour protection therefore, the armour is a ballistic device.

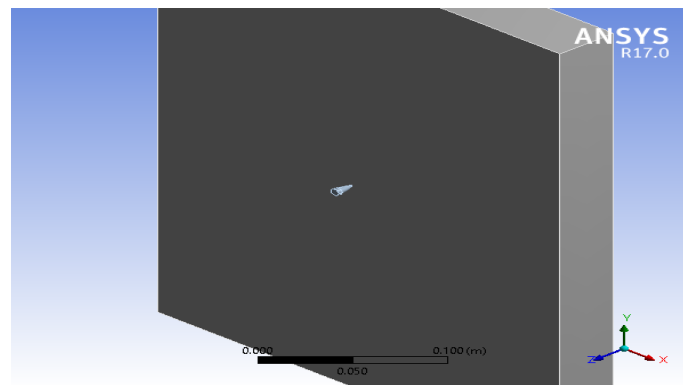


Figure 1. Modelling of projectile Impact on the Hard Body Armour of 76% Resin in Composite

Figure 2 shows the representation in Ansys of the 3D mesh of the bullet.

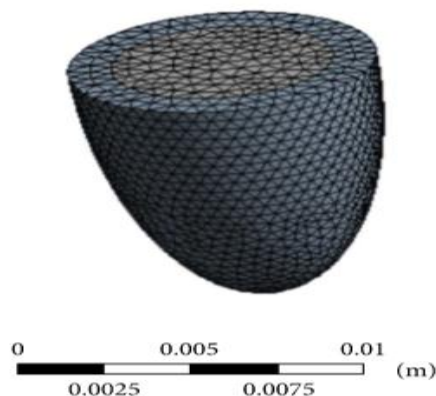


Figure 2. The representation in Ansys of the 3D mesh of the bullet

Figure 3 shows the representation in ANSYS of the projectile geometry.

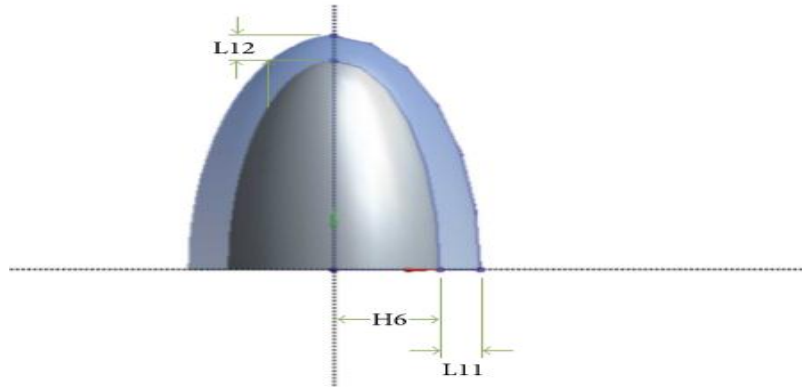


Figure 3. The representation in ANSYS of the projectile geometry

Figure 4 shows that the projectile did not pass through the human hard armour protection, therefore it is a ballistic device. The strain energy of the projectile is 0.14 while as the strain energy of the human hard body armour has the maximum of 0.211. The armour has higher strain energy than the projectile.

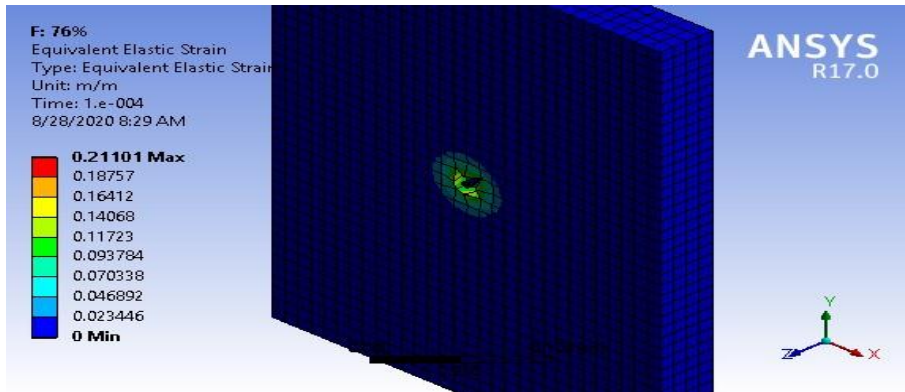


Figure 4. ANSYS Simulation of Projectile Impact on Hard Body Armour for 76% Resin in Composite

Figure 5 shows the explicit dynamics for energy/cycles of projectile impact for 76% resin in the composite.

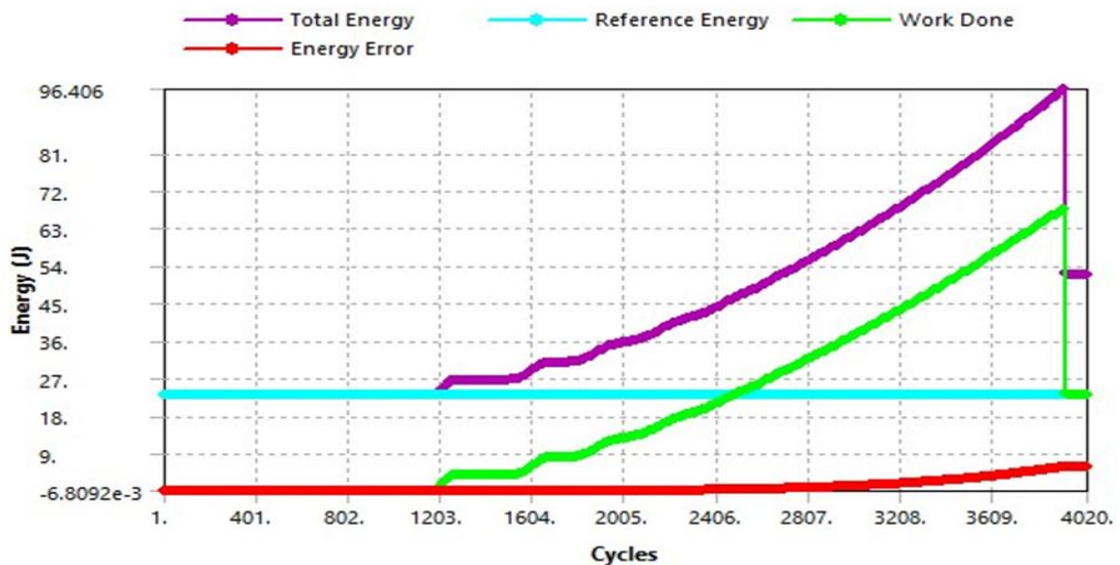


Figure 5. Explicit dynamics for energy/cycles of projectile impact for 76% resin in the composite

Figure 6 shows explicit dynamics for the equivalent elastic stress for 76% resin in composite in Composite. The composite of 76wt%, the impact of the projectile from explicit dynamics for the equivalent elastic stress per second shows that ultimate stress is 9.750×10^9 Pa and it takes 2.0×10^{-5} second. The time taken for the impact energy of the projectile to come to rest was 3.5×10^{-5} seconds. From the explicit dynamics for energy/cycles, the total energy was 96.406J/4017cycles of hard human body armour and the maximum work done was 67.5J. From Figure 6, the smooth graph curve, indicates that the human hard body armour has good control for blunt trauma on the wearer because vibration of projectile impact moves slowly. The composites have high impact energy and had the ability of slowing down the projectile to zero level without passing through the armour. Comparing this result with the [19], who carried out modeling and analysis of hybrid composite joint using FEM in ANSYS validated the result.

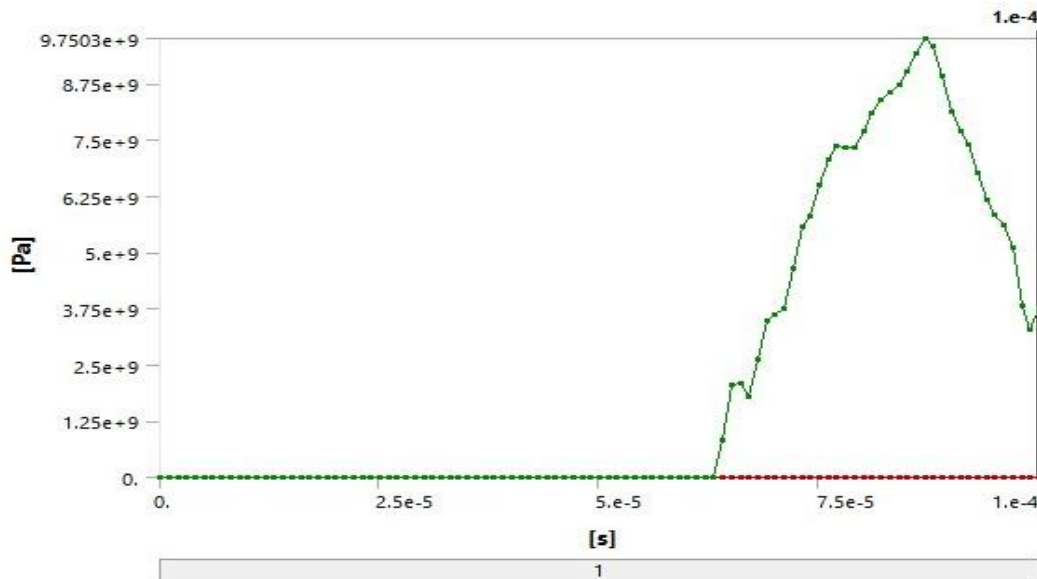


Figure 6. Explicit dynamics for the equivalent elastic stress for 76% resin in composite in Composite

3.1.3 Modelling and Simulation of the composite in ANSYS of 68wt% polyethylene(matrix)

Figure 7 shows that the projectile did not pass through the human hard armour protection since the values of the strain energy for the armour is higher than the projectile. The strain energy of the projectile is 0.17503 while the strain energy of the armour has 0.22504.

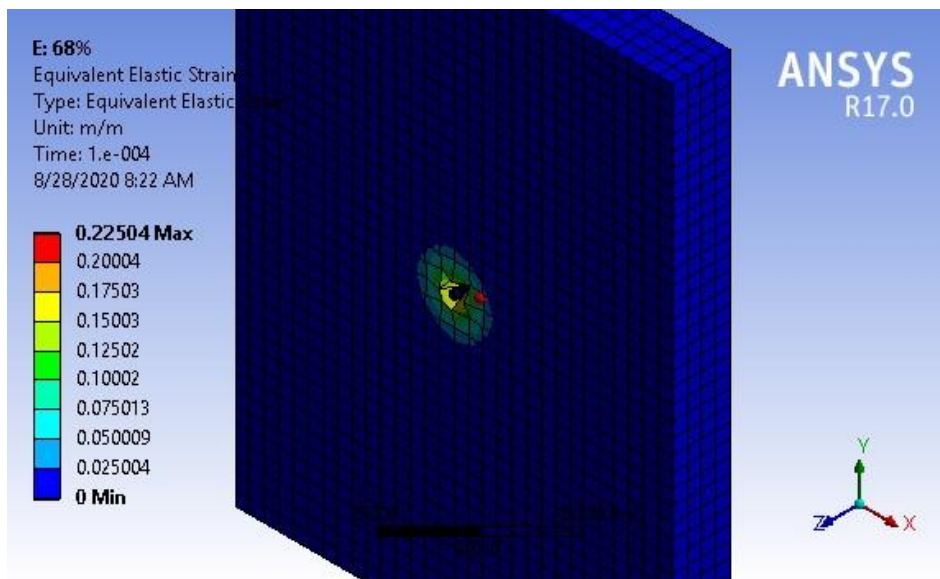


Figure 7. Ansys Simulation of Projectile Impact on Hard Body Armour for 76% Resin in Composite

Figure 8 shows the explicit dynamics for energy/cycles of projectile impact for 68% resin in the composite.

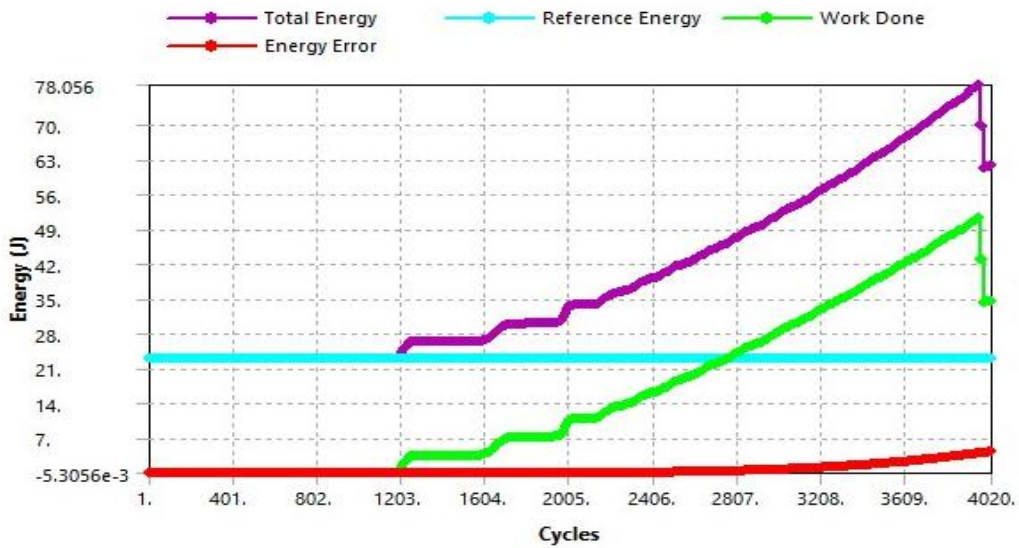


Figure 8. Explicit dynamics for energy/cycles of projectile impact for 68% resin in the composite

Figure 9 shows the explicit dynamics for the equivalent elastic stress for 68% resin in composite. The composite of 68%, the impact of the projectile from explicit dynamic for the equivalent elastic stress per second shows that ultimate stress was 1.03334×10^9 Pa and it takes 0.5×10^{-5} second. The time taken for the impact energy of the projectile to come to rest was 5.5×10^{-5} seconds. The explicit dynamics for energy/cycles, the total energy was 78.056J / 2777cycles of the projectile on human hard body armour and the maximum work done was 53J. From Figure 9, the graph shows a sharp curve which means that the composite is very good for human hard body armour, and it has a moderate vibration and therefore, the blunt trauma to the wearer will cause little or no effect to internal organs of the wearer. The hard body armour resisted the projectile from passing through, it was known as ballistic material. Comparing this result with the [19], who carried out modeling and analysis of hybrid composite joint using FEM in ANSYS validated the result.

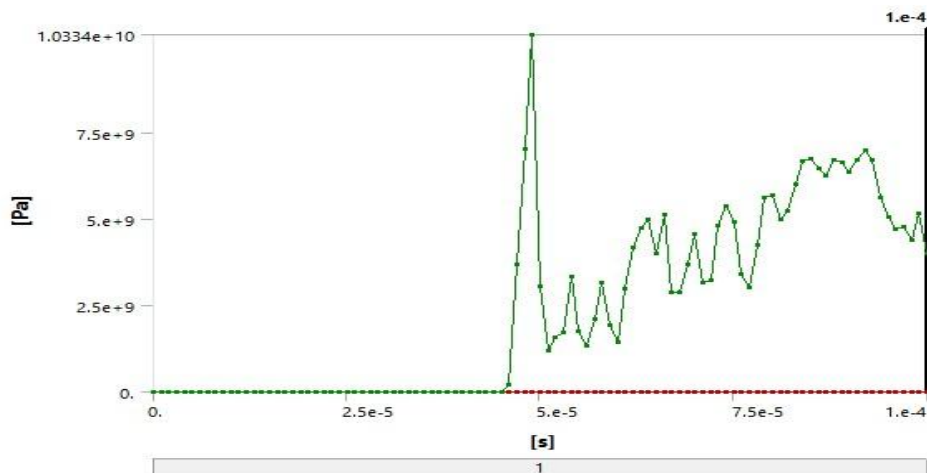


Figure 9. Explicit dynamics for the equivalent elastic stress for 68% resin in composite

3.1.4 Modelling and Simulation of the composite in ANSYS of 60wt% polyethylene(matrix)

Figure 10 shows that the projectile did not pass through the human hard armour protection. The strain energy of the armour is 0.23392 while the strain energy of the projectile is 0.15595 therefore, the armour is a ballistic device.

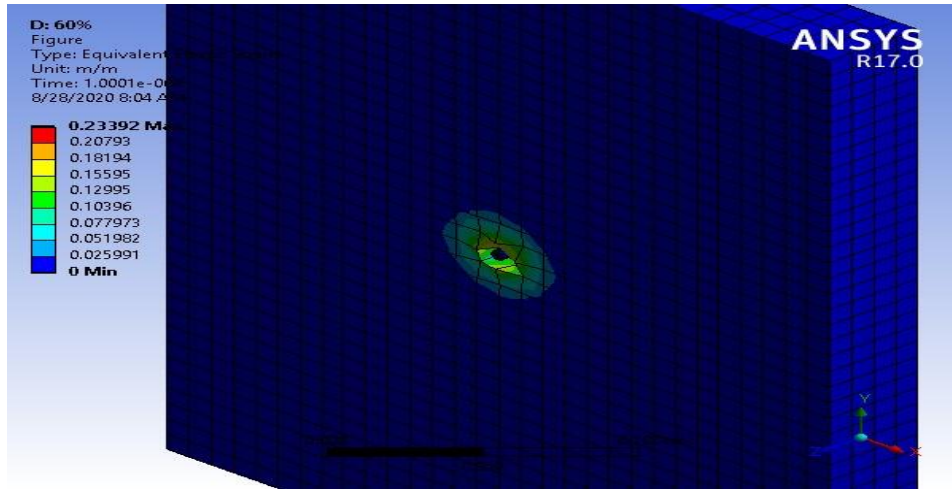


Figure 10. ANSYS Simulation of Projectile Impact on Hard Body Armour for 76% Resin in Composite

Figure 11 shows the explicit dynamics for energy/cycles of projectile impact for 60% resin in the composite.

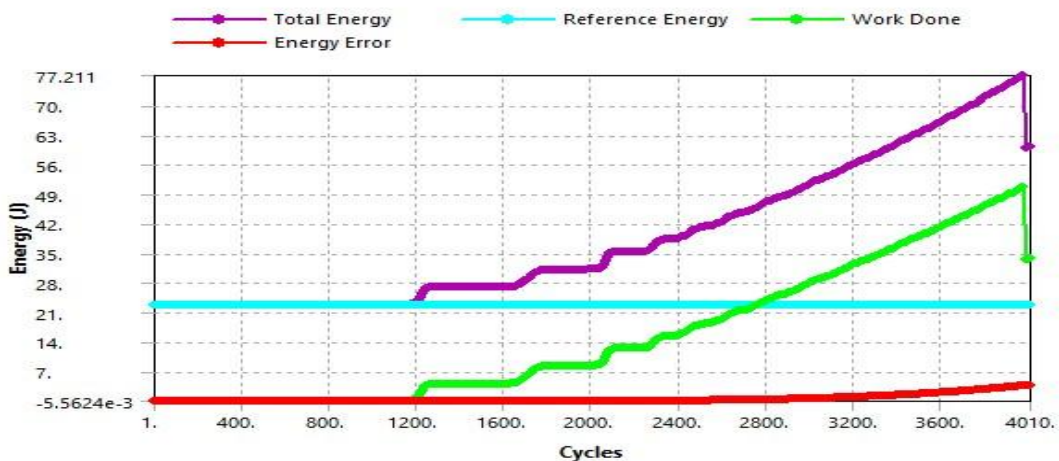


Figure 11. Explicit dynamics for energy/cycles of projectile impact for 60% resin in the composite

Figure 12 shows the explicit dynamics for the equivalent elastic stress for 60% Resin in Composite. The composite of 60wt%, the impact of the projectile from explicit dynamic for the equivalent elastic stress per second shows that ultimate stress was $9.6622e^9$ Pa which takes $0.4e^{-5}$ second. The time taken for the impact energy of the projectile to come to rest was $5e^{-5}$ seconds. The explicit dynamics for energy/cycles, the total energy was 77.211J / 2800cycles of the projectile on human hard armour and the maximum work done was 52J. From the Figure 12, the sharp curve of the graph shows that the composite was very good for hard body armour although, the composite of 68wt% has higher impact energy than the composite of 60wt%, the vibration on the human hard body armour for composite of 60wt% was higher than that of 68wt%. The hard body armour protection does not allow the projectile to pass through but the blunt trauma was high which may not be good enough for the wearer. Comparing this result with the [19], who carried out modeling and analysis of hybrid composite joint using FEM in ANSYS validated the result.

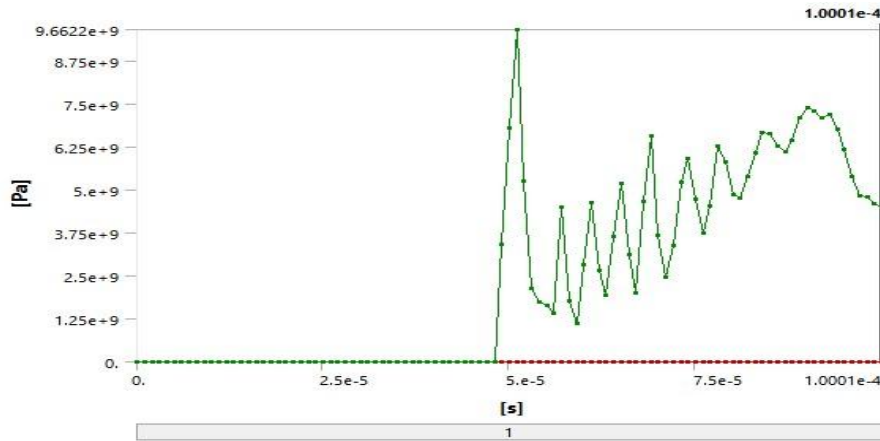


Figure 12. Explicit dynamics for the equivalent elastic stress for 60% Resin in Composite

3.1.5 Modelling and Simulation of the composite in ANSYS of 52wt% polyethylene(matrix)

Figure 13 shows that the projectile did not pass through the human hard body armour protection since the strain energy of the armour is higher than the projectile. The strain energy of the projectile is 0.16454 while the strain energy for the armour is 0.24681 therefore it is a ballistic device.

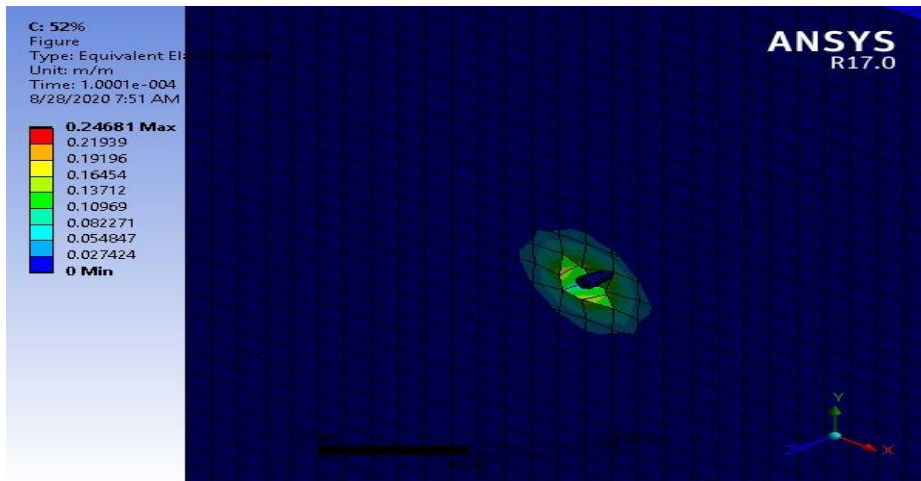


Figure 13. ANSYS Simulation of Projectile Impact on Hard Body Armour for 76% Resin in Composite

Figure 14 shows the explicit dynamics for energy/cycles of projectile impact for 52% resin in the composite.

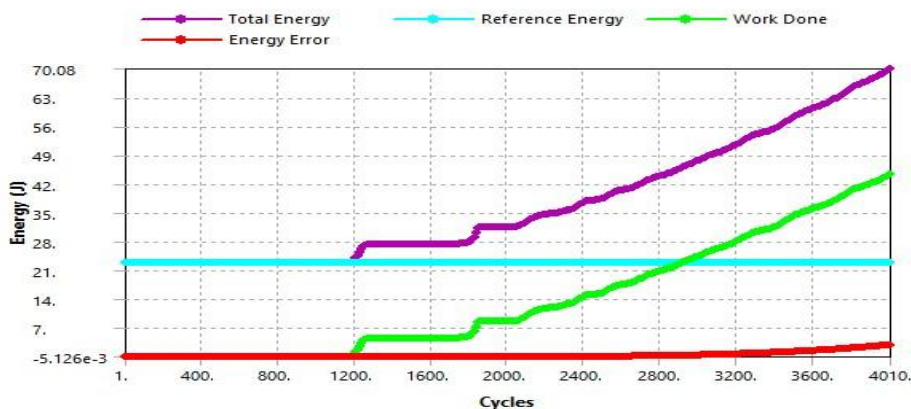


Figure 14. Explicit dynamics for energy/cycles of projectile impact for 52% resin in the composite

Figure 15 shows the graph of the explicit dynamics for the equivalent elastic stress for 52% resin in composite. The composite of 52wt%, the impact of the projectile from explicit dynamic for the equivalent elastic stress per second shows that ultimate stress was 8.1873×10^9 Pa which takes 0.7×10^{-5} second. The time taken for the impact energy of the projectile to come to rest was 5.7×10^{-5} seconds. The explicit dynamics for energy/cycles, the total energy was 70.08J / 2810cycles of the projectile on human hard body armour and the maximum work done was 44J. From Figure 15, the sharp curves of the graph indicates that the composite was good for hard body armour but the repetition of the curves after the impact of the projectile indicates high energy of vibration level. Therefore, this composite it has highest blunt trauma on the wearer even though it slows down the projectile. Comparing this result with the [19], who carried out modeling and analysis of hybrid composite joint using FEM in ANSYS validated the result.

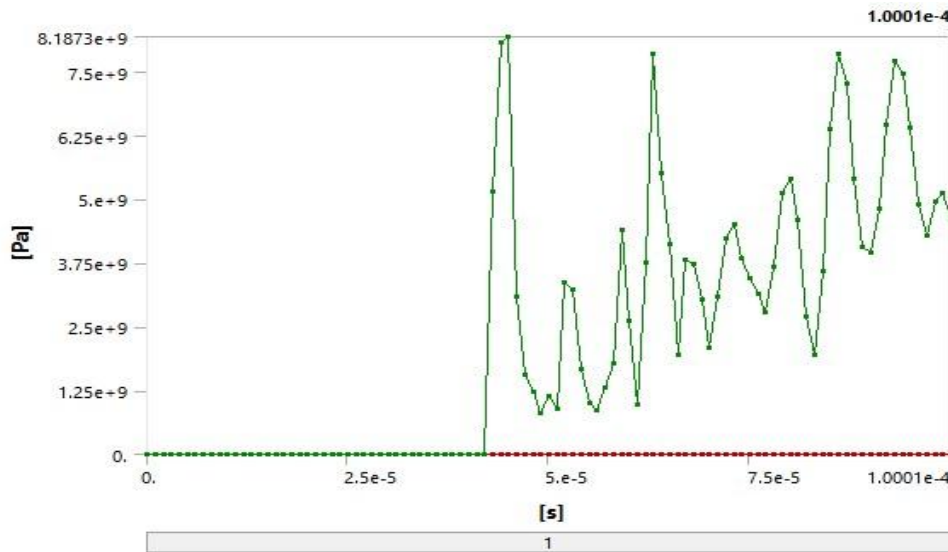


Figure 15. Graph of the Explicit dynamics for the equivalent elastic stress for 52% resin in composite

3.1.6 Modelling and Simulation of the composite in ANSYS of 44wt% polyethylene(matrix)

Figure 16 shows that the projectile did not pass through the human hard armour protection, since the armour has higher strain energy of 0.24681 while the projectile has the strain energy of 0.16454 therefore it is a ballistic device.

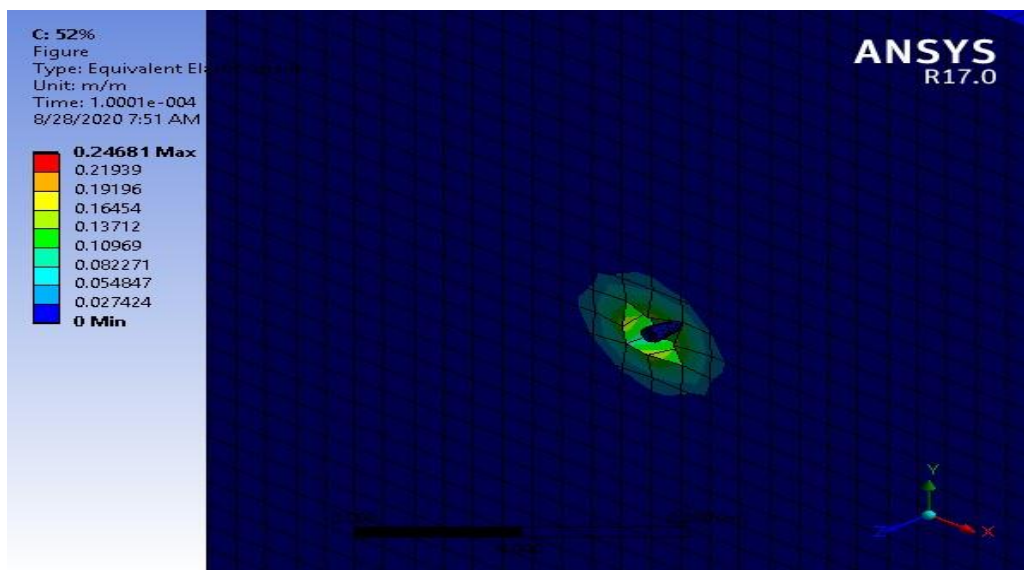


Figure 16. ANSYS Simulation of Projectile Impact on Hard Body Armour for 76% Resin in Composite

Figure 17 shows the explicit dynamics for the equivalent elastic strain for 44% resin in composite.

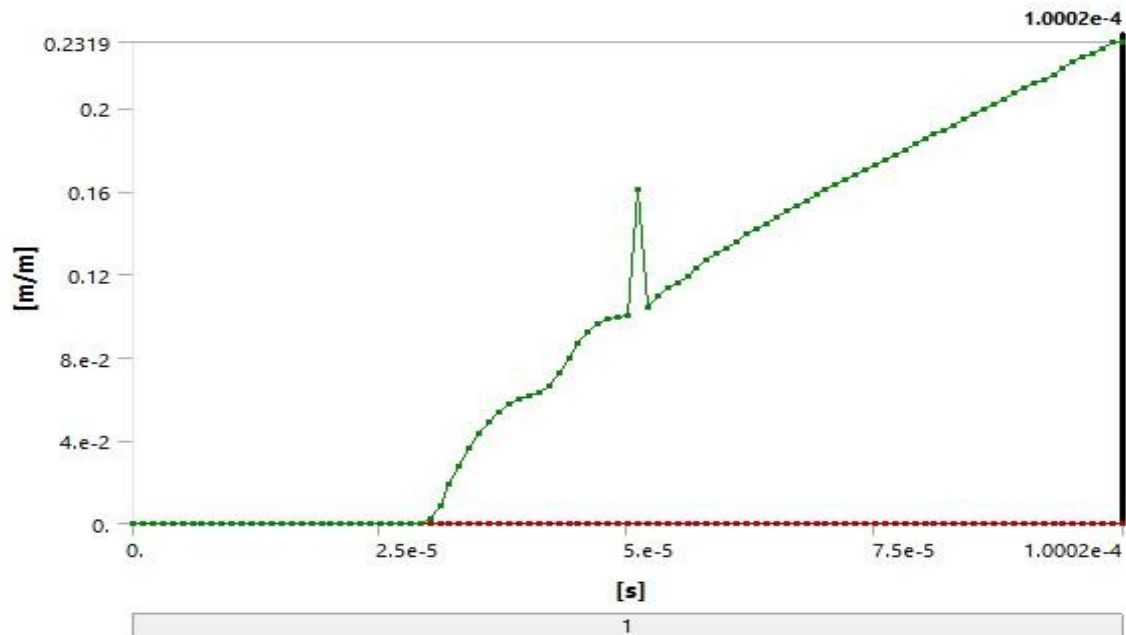


Figure 17. Explicit dynamics for the equivalent elastic strain for 44% resin in composite

Figure 18 shows the graph of the Explicit dynamics for the equivalent elastic stress for 44% resin in composite. The composite of 44wt%, the impact of the projectile from explicit dynamic for the equivalent elastic stress per second shows that ultimate stress was 1.5409×10^{10} Pa and it takes 0.5×10^{-5} second. The time taken for the impact energy of the projectile to come to rest was 5.3×10^{-5} seconds. The explicit dynamics, the total energy was 9.750×10^{-5} J / 4017 cycles of the projectile on hard human armour and the maximum work done is 59J for composite of 44wt%. From Figure 18, the sharp graph curve indicates that the composite was very good for human hard body armour. It has the highest impact strength and also better control of vibration energy level of the projectile impact therefore, it has less blunt trauma to the wearer than the composite of 68wt%. Comparing this result with the [19], who carried out modeling and analysis of hybrid composite joint using FEM in ANSYS validated the result.

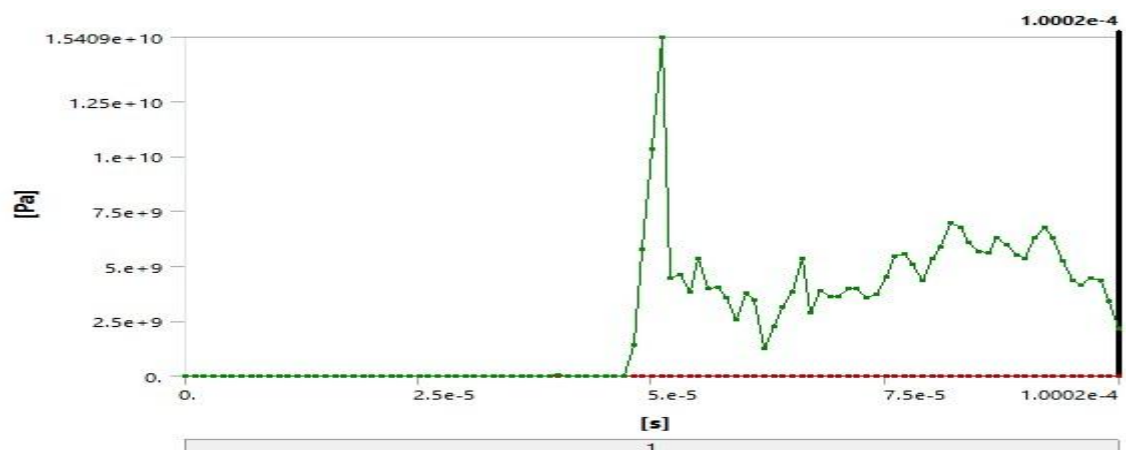


Figure 18. Graph of the Explicit dynamics for the equivalent elastic stress for 44% resin in composite

Table 2 shows the summary of the ANSYS Simulation for different percentage of resin in Composite.

Table 2. Summary of the ANSYS Simulation for different percentage of resin in Composite

S/N	Composition of materials wt(%)	Ultimate stress(Pa)	Time(s) to reach σ_{ult}	Time(s) to Slowdown bullet	Total energy (J)	Work done (J)	Vibration energy (Pa)
1	76	9.750e ⁹	2.0e ⁻⁵	3.5e ⁻⁵	96.406	67.5	6.75e ⁹
2	68	10.334e ⁹	0.5e ⁻⁵	5.5e ⁻⁵	78.056	53.0	6.90e ⁹
3	60	9.6622e ⁹	0.4e ⁻⁵	5.0e ⁻⁵	77.211	52.0	7.50e ⁹
4	52	8.1873e ⁹	0.7e ⁻⁵	5.7e ⁻⁵	70.08	44.0	7.80e ⁹
5	44	15.409e ⁹	0.5e ⁻⁵	5.3e ⁻⁵	77.731	52.8	6.80e ⁹

4 CONCLUSIONS

All these percentages by weight of the resin (76wt%, 68wt%, 60wt%, 52wt% and 44wt%) of composites slow down the impact energy to zero level. The composite of 44wt% resin has the highest impact energy and lowest vibration energy level. It has better blunt trauma effect therefore, it is recommended the best among the five percentages by weight of resin in composites for the human hard body armour protection. The composite of 52wt% resin has the highest vibration energy level, therefore, it has highest negative effect on the wearer after the impact of the projectile.

REFERENCES

1. Caldwell, J.N., Engelen, L. and Van der, H.C. (2011). The interaction of body armour, low-intensity exercise and hot humid conditions on physiological strain and cognitive function. *Military Medicine*, vol. 176, pp. 488-493.
2. James, H.R., Witold, B., Gonzalo, M.B. and Victor, M.C. (2015). Optimization approach to the computer simulation of composite materials. *Com Journal of Reinforced Plastic and Composite*, vol. 28, pp. 91-99.
3. Jaime, H., Witold, B., Ricardo, S. and Victor, M.C. (2015). 3-D Molecular dynamics/finite element simulation of carbon Nanotubes-reinforced polymer composites. *Journal of Computational and Theoretical Nanoscience*, vol. 19, no. 3, pp. 851-856.
4. Gonzaba, C.A., Boris, A.Z. and Nicholas, A.M. (2009). Oxidative stress and gamma radiation on polymer composite. *Applied Polymer Science*, vol. 108, issue 1, pp. 152-161.
5. Ana, L.R., Jaime, H., Augustine, D.L. and Victor, M.C. (2013). Fracture of femur simulation and photoelasticity analysis. *Digest Journal of nanomaterials and Biomedical Engineering*, vol. 8, no. 1, pp. 177-185.
6. Tarun, K., Sandeep, S.P. and Yogesh, M.D. (2007). An accurate stress analysis of composite and sandwich narrow beams. *International Journal for Computational Methods in Engineering Science and Mechanics*, vol. 8, issue 3, pp. 165-177.
7. Asim, S. (2019). Investigation into fatigue strength of natural/synthetic fibre-based composite materials. Mechanical and physical testing of Biocomposites, fibre-Reinforced composite and hybrid composite. *Woodhead publishing*, pp. 215-239.
8. Gabriel, O.G., Frederico, M.M. and Carolina, G.D. (2015). Charpy impact test of epoxy composites reinforced with giant bamboo fibres. *Material Research*, vol. 2, issue 18, pp. 178-184.
9. Venkata, R.G., Venkata, N.S. and Shobha, R.T. (2009). A study on hardness and flexural properties of kapot/sisal composites. *Journal for Reinforced Plastics and Composites*, vol. 28, pp. 2035-2044.

10. Satish, K. and Helminiak, T.E. (2011). Compressive strength of higher performance fibres material science and engineering of rigid-rod polymers. *Cambridge University Press*, vol. 134, pp. 134-363.
11. Jaime, H., Ana, L.R. and Victor, M.C. (2009). Modal behavior of bones during fracture. *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 13, no. 1, pp. 91-95.
12. Yang, C., Lionel, G., Camille, C., Michel, B., Cedric, S. and Andrew, K. (2019) Analysis of the damage initiation in a SIC/SIC composite tube from a direct comparison between large-scale numerical simulation and synchrotron X-ray micro-computed tomography. *International Journal of Solids and Structures*, vol. 161, pp. 111-126. <https://org/10.1016/j.isolstr.2018.11.009>.
13. Laing, R., Gore, S. and Wilson, C. (2010). Standard test methods adapted to better simulate fabrics in use. *Textile Research Journal*, vol. 82, pp. 157-1163.
14. Wambua, P., Vangrimde, B. and Lomov, S. (2007). The response of natural fibre composites to ballistic impact by fragment simulating projectiles. *Composite Structure*, vol. 77, pp. 232-240.
15. Nolan, G., Lawes, S. and Hainsworth, S. (2012). A study considering the force required for broken glass bottles to penetrate a skin simulant. *International Journal Legal Medicine*, vol. 126, pp. 19-25.
16. Song, J., Ortiz, C. and Boyce, M.C. (2011). Threat protection mechanics of an armoured. *Fish Journal Mechanical Behaviour Biomed*, vol. 4, issue 5, pp. 699-712.
17. Xu, T. and Farris, R.J. (2007). Comparative studies of ultra-high molecular weight polyethylene fibre reinforced composites. *Polymer Engineering Science*, vol. 5, pp. 1544-1553.
18. Venkateswarlu, S. and Rajasekhar, K. (2022). Modelling and analysis of hybrid composite joint using fem in ANSYS. *Journal of Mechanical and Civil Engineering*, vol. 6, issue 6, pp. 1-6.
19. Aswani, K.B., Lakshmi, V. and Suhail, A. (2015). The effect of hybridization on the ballistic impact behavior of hybrid composite armours. *Composites part B: Engineering*, vol. 76, pp. 300-319.