EUROPEAN JOURNAL OF MATERIALS SCIENCE AND ENGINEERING
Volume 8, Issue 3, 2023: 183-191 | www.ejmse.ro | ISSN: 2537-4338

DOI: 10.36868/ejmse.2023.08.03.183

INVESTIGATION OF INFLUENCE OF LAYUP CONFIGURATION ON BALLISTIC RESISTANCE OF GLASS FIBRE REINFORCED POLYMER (GFRP) USING FINITE ELEMENT ANALYSIS

Ndubuisi Isaac MBADA[1,2*], Malik ABDULWAHAB[1], Tajudeen MOJISOLA[1,3], Solomon Sudi DANIEL[1], Kolawole MAKONJUOLA[2]

[1]Air Force Institute of Technology, Kaduna, Nigeria
[2]Nigerian Institute of Transport Technology (NITT), Zaria, Nigeria
[3]Centre for NanoEngineering and Tribocorrosion, School of Mining,
Metallurgy and Chemical Engineering, University of Johannesburg, South Africa.

Abstract

This study is aimed primarily to investigate the influence of layup configuration on ballistic resistance of glass fibre reinforced polymer (GFRP) using finite element analysis (FEA). Although, numerical simulation has been used to improve on the ballistic resistance of composite materials for combat helmet applications. However, not many FEA works have considered linear static analysis of different layup configurations of GFRP composites ballistic resistance for combat helmet. Four different layup configurations Θ_1, Θ_2, Θ_3 *and* Θ_4 *of Glass Fibre Reinforced Plastic laminate for combat helmet were investigated in this study. The FEA result showed that all the tested configurations based on NIJ-0106.01 standard using 9 mm, 8g Full Metal Jacket (FMJ) bullet at a velocity of 358 m/s ±15 were well within the failure surface of the failure criterion. The ply failure indices of 0.1520, 0.1510,0.1480 and 0.137 for* Θ_1, Θ_2, Θ_3 *and* Θ_4 *respectively were quite within the failure envelope. Hence, they are failure safe most especially within the test region. In addition, numerical simulation showed that* Θ_3 *has better ballistic resistance among the lot.*

Keywords: *Ballistic resistance, Brain Traumatic injury (BTI), Combat helmet, FEA, GFRP, Layup configuration.*

Introduction

With recent advances in materials synthesis, composite materials of fibre reinforced polymer based are being looked into as key materials in the production of amour wares and ballistic protective gadgets [1]. Combat helmet, an amour ware is one of the body armours worn for safety and personal protection by military and para-military personnel in battle field [2]. The helmet serves to protect against ballistic assaults and other traumatic injuries or death which may arise from high velocity projectiles [3]. Modern combat helmets are designed to protect against shrapnel, shockwaves and blunt impact and penetration. Combat helmets are worn on the head, which is a sensitive part of the body, and as such can be vulnerable to assaults from enemy attack [1,4]. Aside mortality, loss of memory or other permanent impairments could be forestalled or prevented by the use of adequately designed ballistic resistant combat helmet [3].

Combat helmets are designed to offer some measures of protection to the armoured personnel in the face of heavy fire and assault from the enemy, hence they are graded according to the protection level they offer [5]. In addition, combat helmets help in the protection against

---

*Corresponding author: izerk09@yahoo.com

brain traumatic injuries occasioned by the use of improvised explosive devices and other types of assaulted weapons [6].

The impact of the ballistic attacks on the combat helmets depends on the velocity of projectile, stand-off distance, the weight of the bullets, impact angle among many other parameters [7]. Bullets used in assault weapons come in different sizes and dimension with classified ballistic limits. Some types of bullets used include 9 mm Full Metal Jacket (FMJ), 1.1g FSP, 223 FMJ [8]. Some combat helmets are primarily designed to handle light civil unrest like rioters and protesters who may be armed with small-hand propelled projectiles, Molotov, clubs, petrol bomb and so on. On the other hand, a soldier may be faced with enemy's fires from heavy artillery barrages, mortals, shells, long-range heavy weapons and even a land mine [9].

Research has shown that different types of materials have been used for the production of combat helmets [10], and these materials are dated in antiquity [1,11]. Historically, the use of combat helmet predates the Bronze Age era circa 300 BCE [12]. Materials such as leather, later the use of metals such as Brass and Bronze were developed as part of body armour. Some of these materials were also limited due to the fact that the nature of weapon for which they were deployed against were not totally based on high velocity projectiles [3]. Until recent years, polymer-based fibre reinforced composites were not so much in use as combat helmet [13]. The development of combat helmets has now evolved over the years, chronologically, the MI helmets made with hardened steel were deployed by the USA military during the II World War [14]. In the 60's following after the II World War, Personnel Armour System Ground Troop (PASGT) helmets made of Kevlar 29 fabrics were introduced with good toughness, impact strength and thermal resistance by the US Army. This was followed by Advanced Combat Helmet (ACH) based on Kevlar 129, which was an improvement on the properties of PASGT [13,14].

However, the use of fibre reinforced polymer composites has recently been attracted to the military hardware developers [8]. This increased attraction might not be unconnected to the appealing properties of composites such as light weight, improved impact strength, good thermal resistance, high toughness and lower cost [2, 15,16]. Some of the polymeric matrices and fibres used include: phenol, nylon, aramid, e-glass fibre, carbon fibre, polypropylene, UHMWPE [13]. Besides these properties, fibre reinforced polymer composites, have gained increased acceptability as anti-ballistic materials for combat helmets; while other factors also play large role in designing of combat helmets. A good military gear must be able to offer comfort to the personnel, hence combat helmet must be designed to meet the ergonomic peculiarities of the military [17].

Several works have been done on the use of fibre reinforced polymer composites for combat helmet applications [8, 16,18]. Nasser *et al.,* 2020 [19] studied the ballistic resistance of ZnO functionalized glass fibre reinforced polymer matrix composites for combat applications. The glass fibre reinforced composites resulted in 96% increase in Interfacial shear strength. Several studies have detailed the use of aramid fibre in combat helmet application, and most of the standard combat helmets deployed by the military are based on the use of these fibres, for instance ACH and the PASGT [13,16]. Notably, most works on the design and performance evaluation of combat helmet ballistic resistance properties rely on numerical simulation based on finite element analysis [5 - 8,14 - 18].

Palta *et al.,* (2017) [14] conducted numerical and experimental analysis of advanced combat helmet (ACH) to determine its ballistic performance. The model was validated using NIJ and V50 military test standards; the comparison of simulation result to experimental data showed that the developed ACH model was capable of predicting ACH responses under ballistic impacts of 9 mm. Rajput *et al.,* (2017) [18] studied the ballistic resistance through numerical simulation of PASGT body armour helmet. The simulations were based on fragment simulating projectile and 9 mm full jacket metal bullet impact on PASGT and the effectiveness of the Kevlar as anti-ballistic material was affirmed. Li *et al.,* (2015) [5] studied the back face deformation behaviour of ACH combat helmet using FE modelling. The investigation showed a correlation of the ballistic performance of four different sizes as linear.

In this study, combat helmet model of Glass Fibre Reinforced Plastic (GFRP) composites subjected to Finite Element Modelling and Finite Element Analysis (FEA) based on linear static analysis were developed and investigated using the constitutive properties of (GFRP) composites. Particularly, the influence of stacking sequence and layup configuration on the ballistic resistance of GFRP combat helmets were further investigated.

Material and Methods

Numerical simulation approach based on finite element analysis was used to estimate the impact behaviour of Glass Fibre Reinforced Plastic base on linear static analysis. In order to investigate the suitability of the GFRP combat helmet model subjected to FEM and FEA analysis, the following assumptions were made:

Assumptions and Procedure

While we are trying to solve the problem of elastic deformation of a combat helmet subjected to high velocity impact, the kinetic energy generated from the ballistic impact is used in determining the impact load while using the principles of energy conservation in our assumption. The solution of the problem is a conservative approach to numerical simulation of deformation regime, which is observed with problems involving high velocity impact and the associated work of strain. Based on the foregoing, the following assumptions are made:

i. The finite element analysis solution type does not consider the material failure of the combat helmet in the non-linear regime.

ii. The present analysis does not consider the dynamic degree of freedom in building the numerical simulation of the problem. Hence the mass and the damping energies of the material are not built into the analysis.

iii. Dynamic loads are not considered for the numerical simulation of the combat helmet, in a similar vein the time varying responses were not also considered for this analysis.

iv. The material stiffness, for instance, the elastic resistance due to strain energy is the basic consideration for the numerical simulation.

v. The loading type is considered as static loading, as opposed to transient loading.

Based on the above, the strain energy, strain, ply stress, and displacement are among the parameters that would be evaluated. Linear static analysis solution sequence and solution 101 would be performed in this study. The statement required is: SOL 101. Mode description l, for instance, the geometry of the combat helmet model was created in the NX CAD environment and stored as part of the files used for the finite element modelling, analysis and simulation. Fig. 1 showed the modelled combat helmet.

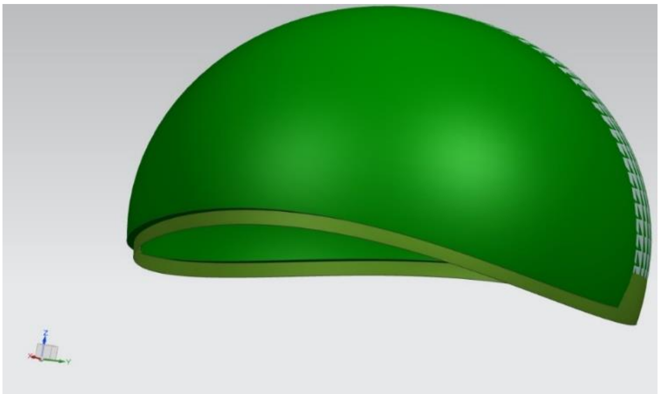

Fig. 1. Model of GFRP composites combat helmet

The model for the combat helmet is defined as a thin 2-D shell element, with PCOMP element used to define the physical and material properties of the GFRP combat helmet ballistic resistance behaviour. The shell element was draped as a laminate structure with properties defined in the laminate modeler. The meshing of the 2-D combat helmet shell was performed with a quadrilateral element CQUAD4, with a small percentage of CTRIA3 elements of a 5 mm mesh size. Fig. 2 showed a wireframe meshed model of the GFRP combat helmet.

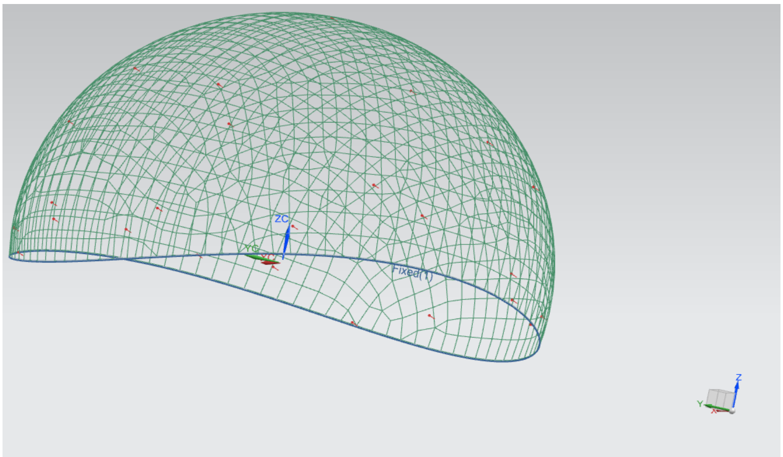

Fig. 2. Meshed Model of GFRP Combat Helmet

PCOMP element was used to define the material properties for the shell elements. The GFRP composite combat helmet shell model was defined as an orthotropic material, given by equation 1 for the 2-D stress state of the combat helmet. Here the stress in the Z-axis is zero. Hence, the following relationship holds:

$\sigma_3 = \tau_{23} = \tau_{31} = 0$ and the constitutive relation is expressed in terms of the principal material directions as:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{\mathrm{E}_1} & -\frac{\nu_{21}}{\mathrm{E}_2} & 0 \\ -\frac{\nu_{12}}{\mathrm{E}_1} & \frac{1}{\mathrm{E}_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \tag{1}$$

where: $\sigma_1, \sigma_2 =$ Normal stresses; $\tau_{12} =$ Shear stress; $\varepsilon_1, \varepsilon_2 =$ Normal strain; γ_{12} = Shear strain; $\mathrm{E}_1, \mathrm{E}_2 =$ Young moduli; $\nu_{12}, \nu_{21} =$ Poisson's ratios; G_{12} = Shear modulus.

The defined material properties were then assigned to the combat helmet with the type selected as laminate. The laminate layup was built, assigned and subsequently to the combat helmet model using a ply-based modelling approach. Plies were created in the 'Laminate Modeler' with thickness and ply orientation angle assigned. The composite material, which is a glass fibre reinforced plastic composites was assigned to each of the ply. In total, 14 plies of symmetric layup were created with four different layup configurations as follows:

Θ_1 = $(45/\text{-}45/0/0/0/45/\text{-}45)_s$ layup.
Θ_2 = $(45/0/\text{-}45/0/\text{-}45/0/45)_s$ layup.
Θ_3 = $(0/\text{-}45/45/0/45/\text{-}45/0)_s$ layup.
Θ_4 = $(0/90/0/\text{-}45/45/90/0)_s$ layup.

After defining the layup input arrangement, the model of the combat helmet is selected, and the draping operation is performed on the uniform layup of the model to complete the draping simulation. The constraint is applied to the helmet around the edge with fixed constraint which constrained the element in all the six degrees of freedom (DOF). It is essential to constrain the model in the six DOF in order to prevent rigid body motion, which can make the global stiffness matrix singular. The load is applied as impact load on the combat helmet by selecting the face of the helmet with an appropriate magnitude calculated from the kinetic energy associated with firing a bullet from a standard military ballistic weapon.

Thickness of the combat helmet was 8 mm. While relating the kinetic energy to the strain energy, the impact energy from a high velocity projectile is stored in a deformable material as elastic strain energy. Based on the foregoing, the impact test was based on USA NIJ-0106.01 standard using 9 mm, 8g Full Metal Jacket (FMJ) bullet at a velocity of 358m/s±15 ((Palta *et al.*, 2017)).

The kinetic energy of the bullet is given by the equation:

$$\mathrm{E} = \frac{1}{2} m v^2 \tag{2}$$

where: m is mass, v is velocity of the bullet and E is the kinetic energy.

The strain energy is expressed by the formula:

$$u = \frac{1}{2} F \delta \tag{3}$$

where u is the strain energy; F is the Force and δ is the strain. By equating the kinetic energy to the strain energy, the impacting force could be established. For this analysis, compressive strain value of $\delta = 0.021$ was used, thus getting a force $F = 53000N$.

However, based on Eq. 1, the material properties defined for the GFRP composites is as given in Table 1.

Table 1. Material Property of GFRP [20]

S/No	Property	Value	Unit
1	E_1	35.5	GPa
2	E_2	8	GPa
3	G_{12}	4.1	GPa
4	v_{12}	0.25	-
5	ρ	1900	Kg/m^3
6	XT$_1$	0.03	-
7	XC$_1$	0.021	-

Result and Discussion

From the FEA simulation of the GFRP combat helmet, the ballistic resistance of the combat helmet was analyzed for four different layup configurations as Θ_1, Θ_2, Θ_3 and Θ_4. The mesh model of the 2-D shell element has 1591 CQUAD4 elements and 89 CTRIA3 elements. While a load of 53000N was applied on the combat helmet model, the constraint was observed to be fixed in all the degrees of freedom. It was observed as shown in Figures 3 - 5 that the critical region with highest likelihood of deformation can be inferred by observation from the result probes.

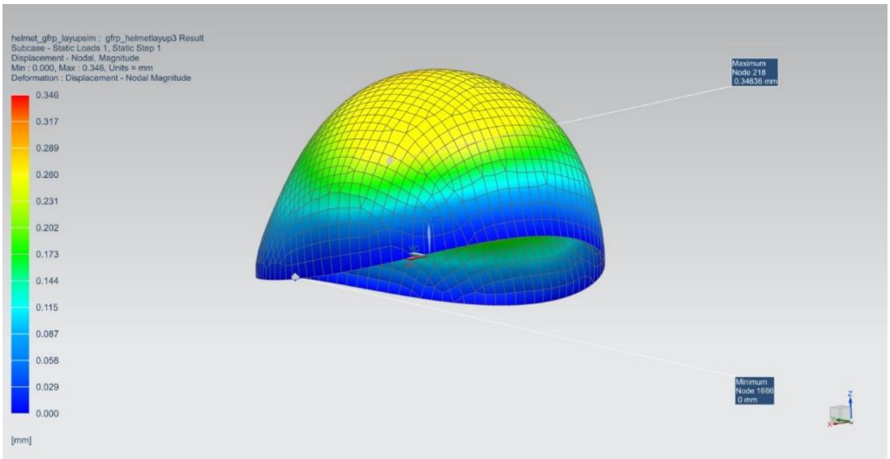

Fig. 3. Displacement Nodal Magnitude for Configuration Θ_3

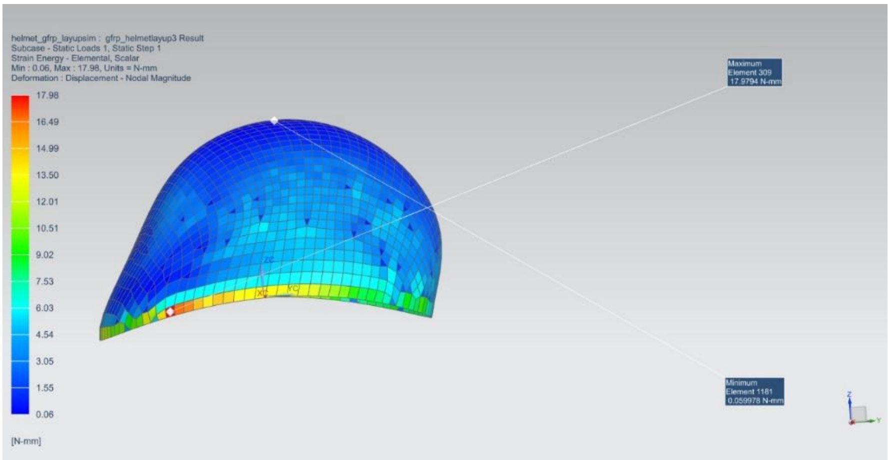

Fig. 4. Strain Energy-Elemental Scalar for Configuration Θ_3

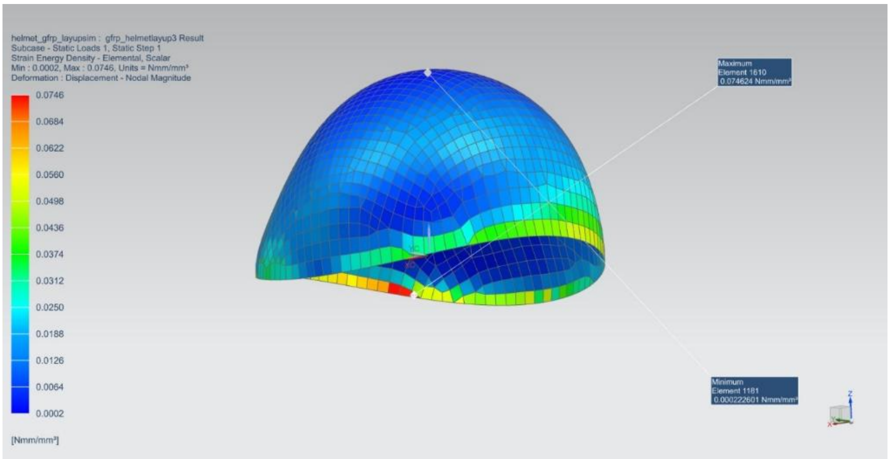

Fig. 5. Strain Energy Density-Elemental Scalar for Configuration Θ_3

From the finite element analysis simulation, it was observed that the layup configuration of the GFRP composites laminate affects the ballistic resistance of the material. The variation in the simulated results of the different layup configuration of the structural properties attest to that. Table 2 showed the variation in the structural properties of the GFRP as a result of the layup configuration of the helmets.

Table 2. Simulated Mechanical Properties of GFRP Combat Helmet based on different Layup Configurations

Structural Property	**Layup Configuration**			
	Θ_1	Θ_2	Θ_3	Θ_4
Displacement	0.345	0.344	0.346	0.319
Strain Energy (N.mm)	17.78	17.59	17.98	17.11
Strain Energy Density (N.mm/ mm^3)	0.0738	0.074	0.0746	0.0632
Ply Failure Index	0.152	0.151	0.148	0.137
Ply Stress (MPa)	138.51	138.98	129.98	115.39
Ply Strain (mm/mm)	0.0028	0.0028	0.0028	0.0027

From the Table 2, we observed that the simulated structural properties of the combat helmets vary as a result of the layup configurations, given that the FEA for the different layup configurations were based on the same finite element method (FEM), materials properties, boundary conditions and load types. Also inferred from the table, it was observed that the ply strains were the same for Θ_1, Θ_2 and Θ_3. However, layup configuration for Θ_4 slightly varies from the others by -3.57 %, indicating that the laminate layup exhibits lower strain than others. If it is assumed that layup configuration $\boldsymbol{\Theta_1}$ is taken to be benchmarked against other layup configurations, then by comparing the results of other layup configurations with that of the layup configuration $\boldsymbol{\Theta_1}$, then it will be easy to estimate the percentage increase or decrease in the simulated properties of the combat helmets. Table 3 showed the percentage change in properties.

Table 3. Percentage Change in Simulated Properties of GFRP Combat Helmet

FEM	**%Layup Configuration**		
Structural Property	$(\Theta_2 - \Theta_1)/\Theta_1 * 100$	$(\Theta_3 - \Theta_1)/\Theta_1 * 100$	$(\Theta_4 - \Theta_1)/\Theta_1 * 100$
Displacement	-0.28986	0.289855	-7.53623
Strain Energy	-1.06862	1.124859	-3.76828
Strain Energy Density	0.271003	1.084011	-14.3631
Ply Failure Index	-0.65789	-2.63158	-9.86842
Ply Stress	0.339326	-6.1584	-16.6919
Ply Strain	0	0	-3.57143

From the displacement results as shown in Table 3, layup configurations Θ_2 and Θ_4 decreased by 0.0.2899 and -7.5362 %, respectively. However, configuration Θ_3 increased by 0.2896 %. For the strain energy, configurations Θ_2 and Θ_4 decreased by -1.0686 and -3.7683 %, respectively, while layup configuration Θ_3 had an incremental strain energy of 1.1249 %. Similarly, the strain energy density of the whole layup configurations had similar trend just as the strain energy with layup configuration Θ_3, which had an increment of 1.0840 %. The trend is equally predictable for other properties such as ply failure index and ply stress. From the simulated results of the combat helmet model, the significance of some of the observed parameters from the results can be related to ballistic resistance properties. The strain energy observed indicated the amount of elastic work done due to ballistic impact on the helmets. This also signals the elastic energy absorbed by the GFRP combat helmet within the elastic region. The strain energy density is indicative of the area under the stress-strain curve towards the deformation, which is the strain energy per unit volume. From the strain energy density results, it could be inferred that the deformation experienced by the GFRP laminate combat helmet is within the elastic envelope, that is the modulus of resilience of the GFRP would not be exceeded as a result of the ballistic impacted indicated by the kinetic energy of the FMJ bullet at 358m/s±15. For the finite element analysis of the GFRP laminate shell modelled combat helmet with a PCOMP material property, the failure criterion adopted was maximum strain energy. The failure index is indicative of the failure criterion used. From the observed values of the ply failure indices, all the simulated values were less than 1; and these values are phenomenological in the sense that it shows that the observed values are within the failure surface. Thus, based on the kinetic energy of the impact of the FMJ Bullet, there wouldn't be no indication of failure of the GFRP laminate combat helmet based on NIJ-0106.01 test standard. Hence, from the simulated results of the combat helmet, it could be observed that the layup configuration Θ_3 = (0/-45/45/0/45/-45/0)$_s$ symmetric layup had better ballistic resistance properties than other configurations.

Conclusion

The finite element analysis (FEA) simulation of the GFRP laminate shell combat helmet ballistic resistance properties using FMJ bullet at 373 m/s was successfully modelled. The simulation result was significantly able to support the investigated hypothesis of the effect of fibre orientation and layup configuration on mechanical properties of GFRP laminate composites. The variation in the strain energy, strain energy density, ply stress, ply failure index and ply strain is highly likely due to the variation in the internal material texture of the simulated combat helmet. The configuration Θ_3 = (0/-45/45/0/45/-45/0)$_s$ was observed to exhibit the best ballistic resistance properties within the test regime compared to other layup configurations examined. It was equally observed that, Θ_4 = (0/90/0/-45/45/90/0)$_s$ layup exhibited the least properties, and this may not be unconnected with the fact that the 90° transverse direction of fibre orientation within the laminate could have resulted in lowering the strength of the modelled helmet [21]. The GFRP laminate combat helmet simulation model highly suggests that the inherent material properties of the GFRP is quite capable of shaping the ballistic resistance of the combat helmet based on NIJ-0106.01 standard. The finite element analysis (FEA) of the GFRP laminate composite combat helmet model reveals the fact that blunt injury and other traumatic projectile related injuries could be resisted based on NIJ-0106.01 test standard. Finally, this numerical simulation was able to elucidate the effect of layup configurations on the ballistic resistance of the GFRP combat helmet without the use of capitally intensive experimental set-up.

Acknowledgments

The lead author would like to appreciate the Nigerian Institute of Transport Technology (NITT), Zaria, for its support in the course of this investigation. All the authors are equally grateful to the Air Force Institute of Technology, Kaduna for providing an enabling environment for the conduct of the study.

References

[1] M. Modlinger, *Protecting the Body in War and Combat,* **Verlag der Osterreichischen Akademie der Wissenchaften, 380(6),** 2017, pp. 1.

[2] I. G. Crouch, *Body Armour-New Materials, New Systems,* **Defence Technology, 15(3),** 2019, pp. 241-253.

[3] J. Y. Sone, D. Kondziolka, J. H. Huang, U. Samadani, *Helmet Efficacy Against Concussion and Traumatic Brain Injury: A Review,* **Journal of Neurosurgery, 126(3)**, 2017, pp. 768-781.

[4] J. Breeze, E. A. Lewis, D. J. Carr, *Ballistic Threats and Body Armour Design,* **In: Military Injury Biomechanics. London: CRC Press,** 2017, pp. 5-18.

[5] Y. Q. Li, X. G. Li, X. L. Gao, *Modelling of Advanced Combat Helmet Under Ballistic Impact,* **Journal of Advanced Mechanics, 82(11),** 2015, pp. 1-9.

[6] D. Wallace, S. Rayner, *Combat Helmet and Blast Traumatic Brain Injury,* **Journal of Military and Veterans Health, 20(1)**, 2012, pp. 10-17.

[7] T. H. Johnson, L. Freeman, J. Hester, J. L Bell, *A Comparison of Ballistic Resistance Testing Techniques in the Department of Defense,* **IEEE Access, 2**, 2014, pp. 1442-1455.

[8] M. Rodriguez-Millan, T. Ito, J.A. Loya, A. Olmedo, M.H. Miguez, *Development of Numerical Model for Ballistic Resistance Evaluation of Combat Helmet and Experimental Validation,* **Materials and Design, 110**, 2016, pp. 391-403.

[9] A. Bhatnagar, D. Lang, *Military and Law Enforcement Application of Lightweight Ballistic Materials,* **Lightweight Ballistic Composites**, 2006, pp. 364-397.

[10] M. Z. Asyraf, M.J. Suriani, C.M. Ruzaidi, A. Khalina, R.A. Ilyas, M. R.M. Asyraf, A. Syamsir, A. Azmi, A. Mohammed, *Development of Natural Fibre-Reinforced Polymer Composites Ballistic Helmet using Concurrent Engineering Approach*, **Sustainability, 14**, 2022, pp. 1-20.

[11] E. P. Gellert, R. L. Woodward, *A Study of the Effect of Target Thickness on the Ballistic Performance of Glass-Fibre-Reinforced Plastic Composites,* **International Journal of Impact Engineering, 24(5),** 2000, pp. 445-456.

[12] R. Hixenbaugh, A. Valdman, *Ancient Greek Helmets,* **New York: Ancient Art Ltd**, 2019.

[13] Y. Li, H. Fan, X. L. Gao, *Ballistic Helmets: Recent Advances in Materials, Protection Mechanisms, Performance, and Head Injury Mitigation,* **Composites Part B: Engineering, 238**, 2022.

[14] E. Palta, H. Fang, D. C. Weggel, *Finite Element Analysis of Advanced Combat Helmet under Various Ballistic Impacts,* **International Journal of Impact Engineering,112**, 2018, pp. 125-143.

[15] S. D. Salman, Z. Leman, M. T. Sultan, M. R. Ishak, F. Cardona, *Effect of Kenaf Fibre on Trauma Pentration Depth and Ballistic Impact Resistance for Laminated Composites,* **Textile Research Journal, 87(17),** 2017, pp. 2051-2065.

[16] C. Stephen, S. Kannan, *Design and Finite Element Study of Kevlar Based Combat Helmet for Protection Against High Velocity Impacts,* **Materials today: Proceedings, 56(6)**, 2022, pp. 3636-3641.

[17] S. G. Kulkarni, et al., *Ballistic Helmets- Their Design, Materials, and Performance Against Traumatic Brain Injury,* **Composites Structures, 101**, 2013, pp. 313-331.

[18] M. S. Rajput, M. K. Bhuarya, A. Gupta, *Finite Element Simulation of Impact on PASGT Army Helmet,* **Procedia Engineering, 173**, 2017, pp. 251-256.

[19] J. Nasser, K. Steinke, H. Sodano, *ZNO nanostructured Interphase for Multifunctional and Lightweight Glass Fibre Reinforced Composite Materials Under Various Loading Conditions,* **ACS Applied Nano Materials, 3(2)**, 2020, pp. 1363-1372.

[20] R. Kussmaul, Static *and Buckling Analysis of Fibre Reinforced Composites in Siemens NX 10,* **Zurich: Eidgenössische Technische Hochschule**, 2016.

[21] M. Cordin, T. Bechtold, T. Pham, *Effect of Fibre Orientation on the Mechanical Properties of Polypropylene-Lyocell Composites,* **Cellulose, 25**, 2018, pp. 7197-7210.

Received: February 19, 2023
Accepted: March 28, 2023