

Finite Element Analysis of Pilot's Helmet Design Using Composite Materials for Military Aircraft

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ABSTRACT: The objective of this research was to design pilot helmets and to perform analysis of designed ballistic helmet against impact strength of bullet in Solidworks and Laminator software. The material used for construction of the helmet is fiber reinforced polymer matrix composite in which polymer matrix is made of nylon, a thermoset resin, and the fibers are aramid, an aromatic polyimide resin developed by E.I. duPont de Nemours and Company and sold under the trademarks "Kevlar®" and "Nomex®". The design of the helmet is done by deciding the stacking sequence of various laminae which are oriented with main material directions at different angles to the global laminate axes in order to produce a structural element in the form of a shell. The simulation of the helmet in Solidworks and Laminator is done with an 8-g AK 47 bullet, hitting it with a velocity of 710 m/s. The model is validated against published data and a good correlation is observed. The result of this project is that a 1.30 kg helmet with shell thickness of 7 mm is obtained, which is economical, light weight and is able to give high-performance protection against ballistic shrapnel and bullets.

KEYWORDS: Finite element analysis, Pilot helmets, Thermoplastic aramid, Composite materials.

INTRODUCTION

The sizing, fit, and comfort have been the most frequent concern of the aviators in each of the different types of aircraft squadrons. Pilot helmet has been used as protective equipment in order to shield human head against serious injuries from shrapnel and bullets. Most modern ballistic helmets are made from a plurality of plies of ballistic material which are laid up in a mold and shaped to the configuration of the helmet. Pilot helmet made of composite materials has become a better equipment compared to traditional steel helmet in terms of the reduction in weight and the improvement in ballistic resistance. Therefore, finite element analysis can be used as a method to characterize the response of composite pilot helmet and to obtain valuable information on parameters affecting impact phenomena (Othman 2009). The first dimension of the helmet is decided according to the average size of human head (Figure 1).

In general, there are two ballistic test standards that are used to determine the quality of protection of the helmet: (1) NIJ-STD-0106.01 Type II and (2) MIL-H-44099A. Nevertheless, different helmet manufacturers may have different ballistic test methods.

Helmet improvement around the head and over the eyes during air combat maneuvers (ACM) or sharp turns in flight involves positive "G" forces in excess of 2 "G". This is attributable to the poor profile of the helmet and its misplaced center of gravity (CG).

The main focus of this research is to study the response of pilot helmet made of composite materials when impacted

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at high velocity for different sequences of lamina or plies by using finite element analysis. The objectives of this research are:

- To design a pilot helmet that provides high performance protection against ballistic shrapnel and bullets.
- To design a light-weight and economical pilot helmet.
- To analyze deformation as well as stress distribution of the helmet when struck by a bullet at a velocity of 710 m/s.
- To evaluate the failure mechanism occurred on pilot helmet after the impact.

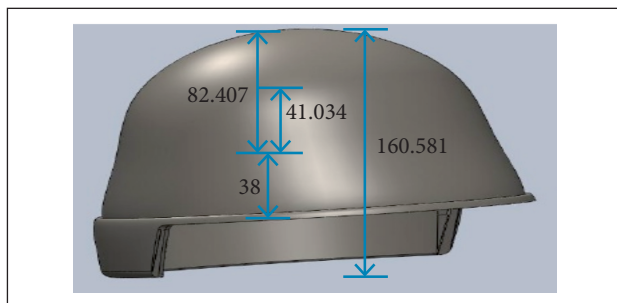


Figure 1. Front view showing dimensions of the helmet.

HELMET DESIGN AND MATERIAL CONSIDERATIONS

Helmet materials and designs have evolved primarily in light of prevailing threats and the invention of new and improved

ballistic materials. Figure 2 is a basic summary of U.S. helmet designs and materials since World War I (WWI). For example, the helmet design in WWI was significantly different than in World War II (WWII). WWI was characterized by an unprecedented amount of trench warfare, and the hot and sharp debris falling from relatively high angles were typical. This gave rise to the fairly wide “brim” that gave the WWI helmet its distinctive look.

The combined shells provided higher protection levels over a greater coverage area than the previous M1917 copy of the British Mk I “Brodie” helmet of WWI. The one-size M1 helmet weighed 1.55 kg, had 0.12 m² of surface coverage, and protected against the 0.45 caliber round at 244 m/s with a 50% ballistic limit of 396 m/s against the standard North Atlantic Treaty Organization (NATO) 1.1-gram fragment simulator. Thermoplastic aramid matrix systems, one of the most common materials used, have excellent, mass-efficient ballistic properties. However, the thermoplastic matrix is typically 30 to 60% less rigid than even the toughened thermoset (e.g. phenolic) matrix. This has significant implications for the overall static structural stability and resilience of the thermoplastic aramid shell, as well as the dynamic deflections associated with a ballistic event. To illustrate this phenomenon, consider Fig. 3. A Phantom v.7 high-speed digital camera was used to capture the effects of a simulated ballistic fragment impact on the back side of a flat thermoplastic aramid panel.

This panel had an areal density that was nearly 50% of that recommended for producing a helmet shell. As can be seen in

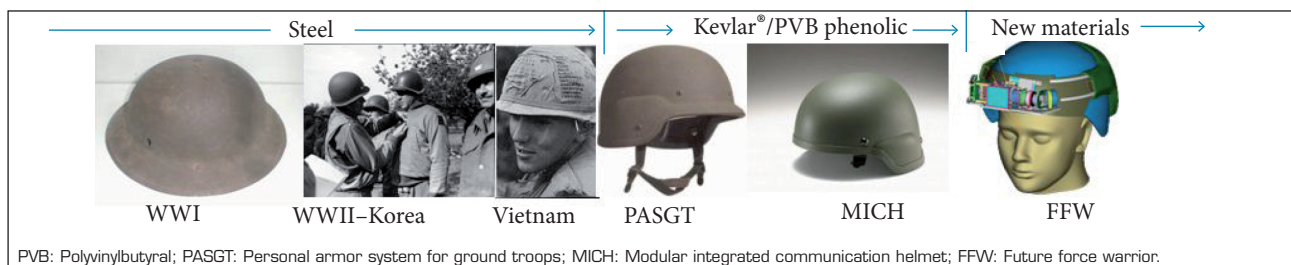


Figure 2. Historical perspective of U.S. Army helmet design and materials (Walsh et al. 2005).

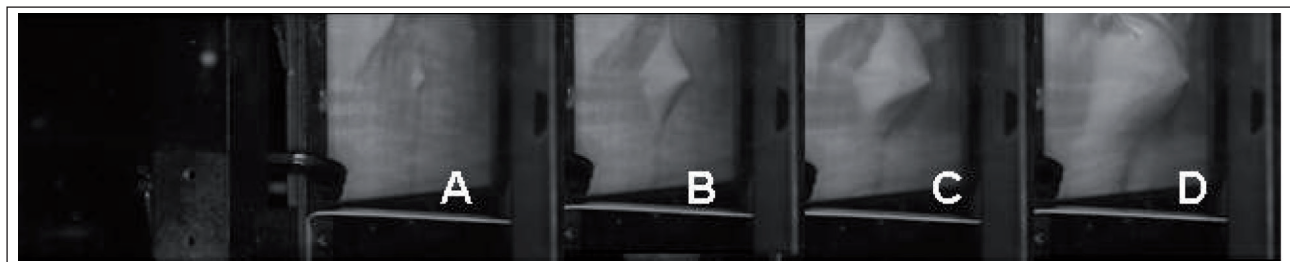


Figure 3. Still photographs from high-speed digital imaging of thermoplastic aramid panel (Walsh et al. 2005).

the sequence of images, the fragment is effectively contained and stopped but not before it induced significant deformation to the overall panel.

A thermoplastic Kevlar® shell at this low areal density may be well-suited for certain applications, but given that the deformation is well over 1 in, it could cause severe skull fracture (and possibly death).

The primary goal of the helmet shell is to protect the pilot from a variety of threats. First, the requirement is to limit the perforation by fragments or bullets through the helmet. Even if the fragment is stopped, the deflection of the shell can engage the skull and cause injury. The current PASGT uses an effective air gap of approximately 13 mm between the inner shell wall and the soldier's head to accommodate any deflection during projectile arrest.

Transient deformation is a direct result of the kinetic energy being dissipated within the ballistic material. Fabrics, although extremely ballistically resilient at real densities around 0.975 g per cm², tend to deform significantly. The fragment or bullet could conceivably be arrested by the fabric, but the resulting deformation could still result in a fatal injury by adversely engaging the skull. By contrast, thermoset composites, such as polyvinylbutyral (PVB) phenolic aramid systems, reduce the transient deformation, even though their ballistic performance may be less than that of a pure fabric system. Thermoplastic composite materials offer a compromise of fabric and thermoset composite performance. That is, the thermoplastic tends to deform but not as much as pure fabric, and it tends to have better ballistic resistance than a thermoset-based composite material (Campbell and Cramer 2008).

Practical durability is a necessary trait for any article used in combat. Helmets must also pass static structural tests as well. "Ear-to-ear" loads of 2,000 to 3,500 kPa must be withstood by the helmet for several cycles without any permanent deformation in its structure. Thermoset composites tend to do well, given the higher matrix modulus (as compared to a thermoplastic matrix).

Fully realizing the material and performance benefits of thermoplastic aramids and hybridized solutions will require the rethinking of the manufacturing processes currently in use by most of the U.S. helmet manufacturers. Current processes are configured for mass production of thermoset-based, monolithic Kevlar® helmets. These manufacturing systems typically use expensive, matched steel tools to consolidate the materials. Cold helmet pre-forms are placed in a hot mold and held under pressure until fully cured. Figure 4 is a conceptual schema of such a process.

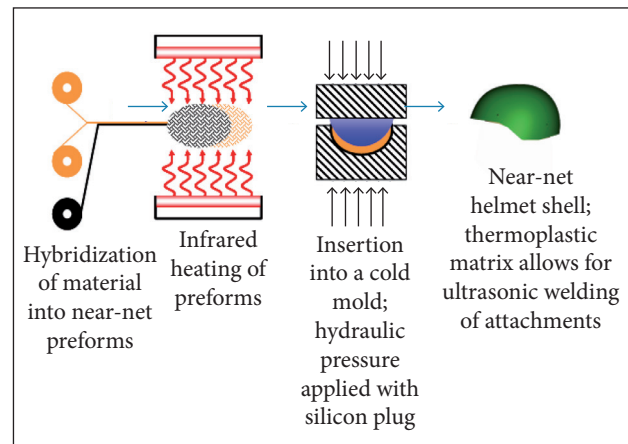


Figure 4. Conceptual schema of the production process of thermoset-based, monolithic Kevlar® helmets (Walsh et al. 2005).

The composite consists of two or more constituents. One is called matrix and the other, reinforcement. The main functions of matrix are:

- It binds the fibers (reinforcement) together and transfers the load to fibers. It provides rigidity and shape to the structure.
- It isolates the fibers so that an individual fiber can act separately. This helps to stop propagation of cracks.
- It provides good surface finish quality and protection to reinforcement fibers against chemical attack and mechanical damage (wear).
- Failure mode of composite is strongly affected by the type of matrix material, and performance characteristics, such as ductility, impact strength etc., are also influenced.

Reinforcement is an important constituent of composite materials. Fiber reinforcement is a thin rod-like structure (Fig. 5). The main functions of fiber reinforcement are:

- It carries the load. In structural composites, 70 to 90% of the load is carried by fiber reinforcements.
- It provides stiffness, strength and thermal stability to the composite.
- It provides electrical conductivity or insulation, depending on the fiber used in the composite.

The general properties of composite materials are light weight, low thermal expansion, high stiffness, high strength and high fatigue resistance.

The matrix in a reinforced plastic may be either thermoset or thermoplastic. In the early days nearly all the thermoset moulding materials were composites in that they contained fillers such as wood flour, mica, cellulose etc. to increase

their strength. However, these were not generally regarded as reinforced materials in the sense that they did not contain fibers. Nowadays the major thermoset resins, used in conjunction with glass fiber reinforcement, are unsaturated polyester resins and, to a lesser extent, epoxy resins (Piggott 1980). The most important advantages which these materials can offer are: (i) they do not liberate volatiles during cross-linking and (ii) they can be moulded using low pressures at room temperature.

A wide variety of thermoplastics have been used as the base for reinforced plastics. These include polypropylene, nylon, styrene-based materials, thermoplastic polyesters, acetyl, polycarbonate, polysulfone etc. The choice of a reinforced thermoplastic depends on a wide range of factors which include the nature of the application, the service environment and costs. In many cases conventional thermoplastic processing techniques can be used to produce moulded articles.

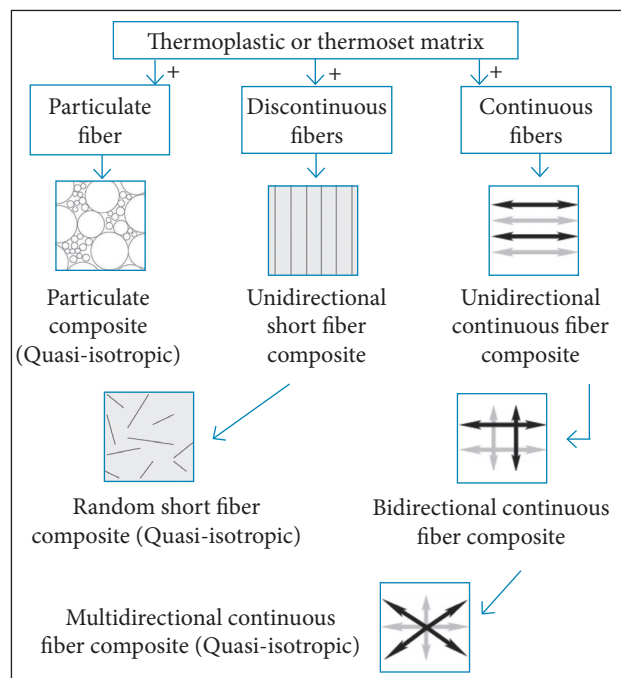


Figure 5. Types of reinforcement.

DESIGN CALCULATIONS AND ANALYSIS

The following assumptions have been taken while designing and analyzing this project:

- It is assumed that the velocity at which the bullet hits the helmet surface is the same as the muzzle velocity.

- It is assumed that the impact time of the bullet on the helmet is 1.5 ms, i.e. the bullet comes to rest 1.5 ms after hitting the surface of the helmet.
- The impact of the bullet on the helmet is assumed to be uniaxial (along x -axis).
- For applying the boundary conditions of the helmet during analysis, the bottom part of the helmet is fixed.
- The shape of the bullet is not taken into account while calculating the force of the bullet on the helmet.

The dimensions of the helmet are: width — 180.00 mm, height — 160.58 mm and length — 180.00 mm (Fig. 6).

The composite material chosen is Kevlar® 149/epoxy (fiber/matrix) whose material properties are mentioned in Table 1. Various laminae are prepared out of this composite material,

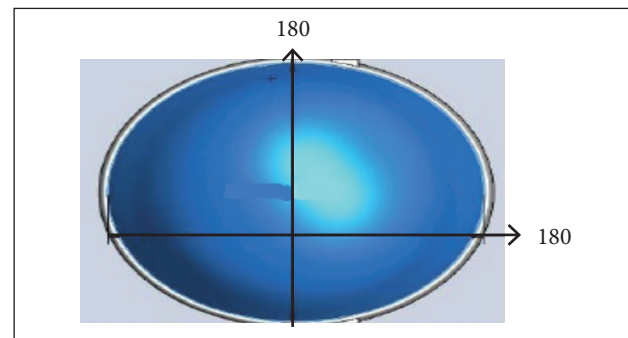


Figure 6. Top view showing the dimensions of the helmet.

Table 1. Properties of Kevlar® 149/epoxy.

| Property | Value | Units | Value type |
|-------------------------------|-----------|--------------------|------------|
| Elastic modulus | 1.26e+007 | Psi | Constant |
| Elastic modulus | 8e+005 | Psi | Constant |
| Poisson's ratio | 0.34 | NA | Constant |
| Shear modulus | 3.1e+005 | Psi | Constant |
| Mass density | 0.05299 | lb/in ³ | Constant |
| Tensile strength | 1.85e+005 | Psi | Constant |
| Compressive strength | 49,000 | Psi | Constant |
| Yield strength | 1.8e+005 | Psi | Constant |
| Thermal expansion coefficient | 1.1e-006 | F | Constant |
| Thermal expansion coefficient | 3.3e-005 | F | Constant |
| Tensile strength | 4,200 | Psi | Constant |
| Compressive strength | 22,900 | Psi | Constant |
| Shear strength | 7,100 | Psi | Constant |

and the stacking of various laminae is done, which is oriented with principal material directions at different angles to the global laminate axes producing a structural element in the form of a shell. The strength of this shell is analyzed when a bullet, at a certain velocity, hits it (Silva *et al.* 2005).

The specification of the bullet is as follows: AK 47; caliber: 7.62; mass: 8 g; muzzle velocity: 710 m/s. The force exerted on the helmet is: $m \times a = 8 \times 10^{-3} \times (710/0.0015) = 3,786.667$ N. The force with which the bullet hits the helmet is approximately taken as 4,000 N along the x -axis.

Here a software called Laminator is used, which takes the abovementioned material properties, load applied (4,000 N) and different angles of each lamina as the input. It calculates the $[A]$, $[B]$ and $[D]$ matrices and the inverse of these matrices, as well as laminate stiffness properties. Each stacking sequence has 24 laminae. The material of each ply is the same and their thickness is taken as 0.21 mm. This process is repeated for several combinations.

STACKING SEQUENCE 1

After applying the load and defining the boundary conditions to the helmet with the given stacking sequence, a simulation was made to run. The following plots in the form of results were obtained and studied to find the optimum configuration.

Stacking sequence 1: [(45)4, (0)4, (90)4] s with each lamina thickness of 0.21 mm. $[A]$, $[B]$ and $[D]$ matrices are:

$$[A] = \begin{bmatrix} 2.910e+007 & 6.300e+006 & 4.993e+006 \\ 6.300e+006 & 2.910e+007 & 4.993e+006 \\ 4.993e+006 & 4.993e+006 & 6.481e+006 \end{bmatrix}$$

$$[B] = \begin{bmatrix} -4.889e-009 & -2.328e-010 & -2.328e-010 \\ -2.328e-010 & -9.546e-009 & -4.657e-010 \\ -2.328e-010 & -4.657e-010 & -6.985e-010 \end{bmatrix}$$

$$[D] = \begin{bmatrix} 6.412e+007 & 2.490e+007 & 2.231e+007 \\ 2.490e+007 & 3.594e+007 & 2.231e+007 \\ 2.231e+007 & 2.231e+007 & 2.529e+007 \end{bmatrix}$$

The inverse of these matrices is:

$$[A]^{-1} = \begin{bmatrix} 3.998e-008 & -3.884e-009 & -2.780e-008 \\ -3.884e-009 & 3.998e-008 & -2.780e-008 \\ -2.780e-008 & -2.780e-008 & 1.971e-007 \end{bmatrix}$$

$$[B]^{-1} = \begin{bmatrix} 4.872e-024 & -3.116e-024 & -2.562e-024 \\ -3.423e-024 & 2.372e-023 & -1.668e-023 \\ -1.750e-024 & -1.825e-023 & 2.165e-023 \end{bmatrix}$$

$$[D]^{-1} = \begin{bmatrix} 2.339e-008 & -7.510e-009 & -1.401e-008 \\ -7.510e-009 & 6.394e-008 & -4.979e-008 \\ -1.401e-008 & -4.979e-008 & 9.583e-008 \end{bmatrix}$$

The laminate stiffness properties are:

Ex: 4.963e+006

Ey: 4.963e+006

Gxy: 1.006e+006

Vxy: 0.097

We have similar stacking sequence for 2, 3, 4, 5, and 6. After applying the load and defining the boundary conditions to the helmet with the given stacking sequence, a simulation was made to run. The following plots in the form of results were obtained and studied to find the optimum configuration.

Firstly, taking the dimensions for the ballistic helmet, three circular sketches were made. By using those circular sketches as a guiding profile and carefully adjusting various parameters, a shell was formed with the help of surface loft feature (Fig. 7a).

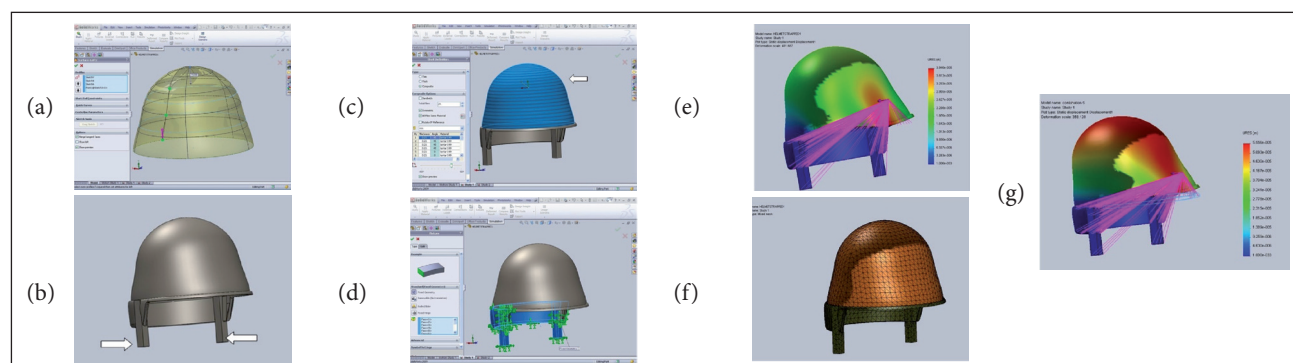


Figure 7. Helmet configuration. (a) Shell forming; (b) Helmet with the support structure; (c) Defining composite layers; (d) Fixed support at the bottom; (e) Application of force; (f) Meshing; (g) Displacement distribution.

For analysis purposes, a support structure was designed to provide the fixture support at the sides of pilot helmet (Fig. 7b). This support works similarly to the straps provided for the support of the helmet in real time.

Linear elastic orthotropic material Kevlar® 149 is defined for all the layers (Fig. 7c). The bottom part of the helmet along with the designed vertical fixtures are fixed and used as boundary conditions for analysis purposes (Fig. 7d). Now, after defining the boundary conditions, the calculated force is applied (Fig. 7e) at the target point taken (where the bullet will hit the helmet). A fine high-quality mesh (with approximate element size equal to 7.9 mm) is generated having parabolic triangular elements with 10,354 nodes and total number of elements equal to 5,058 (Fig. 7f). Results in the form of stress distribution, strain distribution, displacement distribution and factor of safety distribution are obtained and analyzed (Fig. 7g).

ANALYSIS RESULTS

Displacements are measured in meters from the position where the bullet hits the helmet surface before any deformation occurs (Fig. 8a).

Distributions of von Mises stresses are shown in the stress plot obtained after running the simulation (in N/m^2). In this case, a material is said to start yielding when its von Mises stress reaches a critical value known as yield strength. The von Mises stress is used to predict yielding of materials under any loading condition from results of simple uniaxial tensile tests (Fig. 8b).

The plot in Fig. 8c shows the distribution of strain in the top part of pilot helmet when the bullet hits the surface. The plot in Fig. 8d shows the factor of safety at every node. Factor of safety (FoS) is a term describing the structural capacity of a system beyond the applied or actual loads. Tsai-Hill failure criterion

is used to evaluate the FoS at the top part of pilot helmet (composite shell). This criterion considers the distortion energy portion of the total strain energy that is stored due to loading. The reaction forces are shown in Table 2. It has proposed that

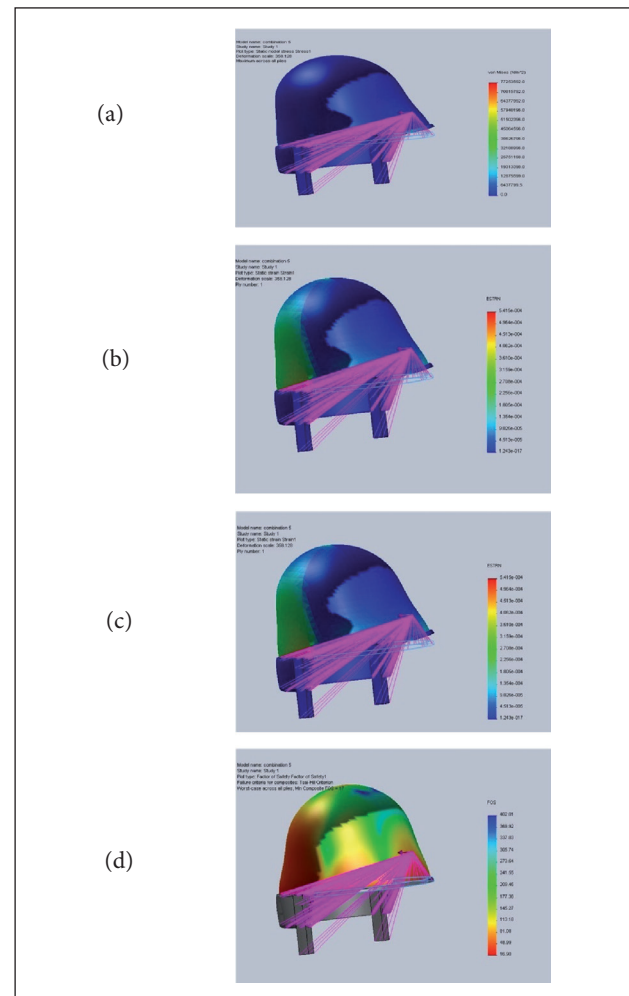


Figure 8. Analysis results. (a) Displacement plot for [(90)4, (0)4, (90)4] s; (b) Stress plot for [(90)4, (0)4, (90)4] s; (c) Strain plot for [(90)4, (0)4, (90)4] s; (d) Factor of safety plot for [(90)4, (0)4, (90)4] s.

Table 2. Reaction forces.

| Selection set | Unit | Sum of X | Sum of Y | Sum of Z | Resultant |
|---------------|------|-----------|-------------|-------------|-----------|
| Entire body | N | -2,403.53 | 0.100185 | -0.00871483 | 2,403.53 |
| Entire body | N | -2,403.56 | -0.0747453 | -0.00140771 | 2,403.56 |
| Entire body | N | -2,403.56 | -0.0443136 | -0.00578333 | 2,403.56 |
| Entire body | N | -2,403.49 | 0.140461 | 0.0142988 | 2,403.49 |
| Entire body | N | -2,403.57 | -0.00499602 | 0.000274185 | 2,403.57 |
| Entire body | N | -2,403.53 | 0.0195969 | -0.00771621 | 2,403.53 |

Table 3. Configuration by analysing the results of both Laminator and Solidworks simulations.

| Serial number | Sequence | Ex | Ey | Gxy | Vxy | FoS |
|---------------|--|------------|------------|------------|-------|-----|
| 1 | [(45)4, (0)4, (90)4] s | 4.963e+006 | 4.963e+006 | 1.006e+006 | 0.097 | 21 |
| 2 | [(0)4, (90)2, (0)2, (45)2, (0)2] s | 8.857e+006 | 2.959e+006 | 7.074e+005 | 0.152 | 14 |
| 3 | [(90)2, (0)2, (45)2, (0)2, (90)2, (0)2] s | 6.903e+006 | 4.934e+006 | 7.263e+005 | 0.092 | 17 |
| 4 | [(90)2, (0)2, (45)2, (0)2, (90)2, (0)2] s | 4.821e+006 | 1.033e+006 | 8.338e+005 | 0.454 | 6.8 |
| 5 | [(90)4, (0)4, (90)4] s | 4.760e+006 | 8.715e+006 | 3.100e+005 | 0.031 | 17 |
| 6 | [(0)2, (45)2, (90)2, (0)2, (45)2, (90)2] s | 4.963e+006 | 4.963e+006 | 0.097 | 0.097 | 20 |

there should be four helmets to suit flight requirements. After the careful study and comparison of different composite layer combinations in Solidworks and Laminator, the most optimum configuration is shown by stacking sequence 1 — [(45)4, (0)4, (90)4] s, as can be seen in Table 3.

CONCLUSIONS

It has been concluded that the pilot helmet with 24 layers (each layer with 0.21 mm) with total thickness equal

to 5.04 mm provides the optimum configuration with the best combination of laminate stiffness properties and FoS (Chawla 1998) under the specified testing conditions (8 g bullet travelling with 710 m/s velocity). The weight of the helmet shell comes out to be 300 g but, in order to give stability and comfort, certain features like foam padding, straps etc. are provided, which increases the weight of the helmet to approximately 1 kg.

The stacking sequence 1 [(45)4, (0)4, (90)4] s, is found as the optimum configuration by analysing the results of both Laminator and Solidworks simulation.

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