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Design, simulation, and experimental analysis of a full-face motorbike helmet using composite material

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Abstract

Motorbike riders are highly exposed to severe accidents, and it is possible that the standard plastic helmets currently used in markets might not offer the required protection to them in these circumstances. To overcome this problem, this paper intends to design, simulate, fabricate, and conduct standard tests of a motorbike helmet made of composite materials to target producing a high ratio of strength-to-weight and an IS 4151 compliance helmet. The methodology starts with the selection of E-glass fibers and polyester resin. The CAD modeling of the helmet of standard size 580 mm was performed in SolidWorks, and computational analysis was performed in ANSYS to assess the structural performance in real-world scenarios. Also, an analytical comparison of the composite helmet with traditional ABS (Acrylonitrile Butadiene Styrene) helmets was conducted. The helmet was fabricated through the hand layup method and cured at normal atmospheric conditions. The manufactured helmet underwent the IS standard tests of rigidity, impact absorption, and resistance to penetration, and met all the required performance standards. Comparison of simulation results with the physical testing proved the validity of the design. On the whole, the project managed to create a motorbike helmet, which had a high level of structural strength and safety to be used in real-life situations.

1. Introduction

According to the recently published Nepal Demographic and Health Survey (NDHS) 2022, motorcycle passengers are the most likely to die in road accidents. The 2022 census indicates that around 68% of people killed in road accidents are motorcyclists, translating to 2,760 fatalities annually. In the past 12 months, individuals injured in road accidents experienced various injuries: 36% had cuts or open wounds, 28% had broken bones, 23% had internal injuries, and 13% sustained head injuries [1]. Given the high fatality rate of head injuries in recent accidents, there is a need for helmets with better materials. Composite materials, with their high strength-to-weight ratio, exceptional impact resistance, and adaptability, provide a promising alternative to prevalent plastics. Modern helmets utilize composite materials where reinforcements like glass fiber and carbon fiber are combined with resins such as epoxy and polyester.

Fiberglass is available in two main types: E-glass and S-glass. E-glass is widely used due to its cost-effectiveness, while S-glass offers higher strength and modulus but comes at a higher price. Carbon fibers are known for their exceptional specific stiffness and strength, making them superior to glass fibers and comparable or even better than high-grade steel. Epoxy resins are the most commonly used matrix polymers in aircraft composites due to their excellent mechanical properties and handling characteristics [2]. Among the many types of polyester resin, ortho resin is widely used because of its low cost and versatility [3]. Composite materials offer key advantages, including improved impact resistance, reduced weight, enhanced durability, and customizable properties [2].

Advanced computational modeling and simulation techniques are used to design and simulate the most effective helmet. Finite element analysis (FEA) facilitates the evaluation of structural integrity, impact response, aerodynamics, and thermal management, leading to more robust and efficient helmet designs [4]. By analyzing stress concentrations, strain distribution, and

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potential failure points, designers can identify areas where the helmet might crack or break. This allows them to strengthen these areas or explore alternative materials for better impact absorption and energy distribution [5]. Common fabrication methods include Hand Lay-Up (HLU) and Vacuum Assisted Resin Transfer Molding (VARTM). HLU is one of the simplest and oldest techniques for fabricating fiber-reinforced polymer (FRP) composites, whereas VARTM is favored for its ability to produce high-quality composite parts [2].

Composite specimen development and testing are critical for the validation of the performance of the material. Composite specimens are tested under standardized protocols such as ASTM D3039/D3039M, which provides a comprehensive approach to determining the in-plane tensile properties of polymer matrix composite materials reinforced with high-modulus fibers. Mechanical properties such as ultimate tensile strength, modulus of elasticity in tension, Poisson's ratio, and transition strain may be obtained [6]. Regulatory compliance ensures user safety, with standards like IS 4151, which define performance requirements for several tests, including impact absorption (flat and hemispherical anvil methods), resistance to penetration, and rigidity tests. Passing criteria are based on strict thresholds for acceleration, penetration depth, and deformation recovery [7].

Several studies have explored the application of composite materials in helmet shells to enhance protective performance. Tinard et al. (2011) examined the structural characterization and description of composite outer shells in motorcycle helmets. The experiment formulated a fine numerical model of the knowledge of stiffness as well as deformation behavior and damage evolution under impact loading. Characterization of the composite laminates in terms of material was implemented to produce precise input in the simulations, and proven analytical models were suggested that would forecast shell behavior in regulatory test situations [8]. Murali and Nagarani (2013) developed and made a construction helmet with hybrid composite materials with a focus on reduction in weight and mechanical resistance. The experiment adopted experimental fabrication and mechanical testing and showed that the hybrid fiber reinforcement had the potential to enhance load-bearing capacity when compared with the traditional thermoplastic helmets [9]. Bajpai et al. (2018) made an industrial safety helmet based on a glass/jute/epoxy composite system and tested the performance of the helmets. Sustainable material incorporation into the work included the use of natural fibers reinforced by synthetic materials, and mechanical analyses revealed enhanced strength properties and the admissible deformability, which proved the appropriateness of the material in protective headgear [10]. The study by Raji et al. (2021) was dedicated to the production and mechanical determinations of a composite bike safety helmet of hybrid type. Several composite layups were made and evaluated on the basis of rigidity, impact strength, and durability. The research noted that hybrid reinforcement also helped to enhance failure resistance and energy absorption capacity, and thus the use of multi-fiber composite systems in helmet shells [11].

Murali et al. (2014) prepared industrial safety helmets with hybrid composite laminates and tested their performance as compared to the conventional helmets. The study has revealed that significant changes in structural integrity, stiffness, and mechanical loading resistance have been achieved, which supports the possibility of using hybrid composites in protecting equipment in industry [12]. Bhudolia et al. (2021) investigated innovative fully thermoplastic and hybrid composite bicycle helmet shells with an accent on high impact energy absorption. The work by experimental impact testing and failure analysis revealed that thermoplastic composites have enhanced toughness and progressive damage behavior, which leads to enhanced rider protection over conventional thermoset-based shells [13]. Gohel et al. (2021) created a bicycle helmet shell in the form of an acrylic thermoplastic composite and performed a full impact characterization. The authors of the study have indicated that because energy dissipation and controlled crack growth were better, they were able to achieve better safety performance and proved the benefits of thermoplastic matrices with regard to the design of protective headgear [14]. Obst et al. (2023) provided an overview of the manufacturing, testing, and evaluation of motorcycle helmets and their association with the outcome of the injury in real-world crashes. The review has synthesized the evidence on the choice of materials, the structure of the helmet, and the procedure of the regulatory tests, and the authors have stressed how the design of a helmet has direct effects on the severity of injury and the possibility of survival of a motorcyclist [15]. Hitchen and Kemp conducted a thorough investigation of stacking sequences with plies oriented at 0°, 45°, -45°, and 90°. The key finding was that the damage initiation energy increased when the ±45° plies were added to the surface layers, and the number of interfaces in the lamina [16].

Although much research has been conducted on composite helmet material, none of the studies incorporate the entire process of product development in motorcycle helmets, such as the selection of materials, structural design, numerical simulation, fabrication, specimen development, and testing. Moreover, there is a lack of literature on the direct comparison of conventional ABS helmets with composite helmets and the relationship and confirmation of simulation and experimental testing findings. This paper fills this gap by presenting a holistic concept of evaluating composite helmet shells in terms of optimizing the design of the shells and design validation.

2. Research methodology

For this research, a quantitative research approach was adopted as it involved designing, analyzing, and fabricating a motorbike helmet from composite materials. The research was based on quantitative data, engineering simulations, and material testing to examine the strength, impact resistance, and performance of the helmet. This is described by the flow chart in Figure 1.

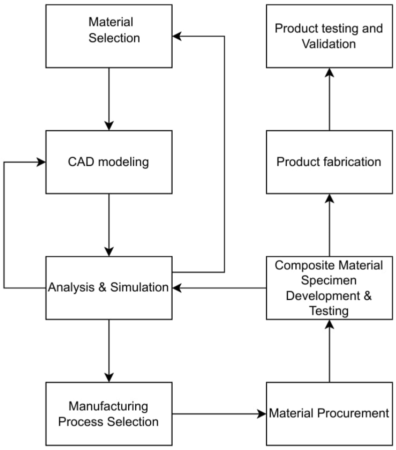

Figure 1: Research methodology

2.1. Material selection

When selecting fiber material and resin for a specific composite application, several factors must be thoroughly considered. The material selection process was carried out based on factors like performance, weight, cost, availability, and handling. Following a detailed analysis, E-glass fiber was selected as the reinforcement material. Polyester resin was chosen as the matrix material because of its lower cost and ease of handling compared to alternatives.

2.2. CAD modelling

The conceptual design phase involved gathering reference data from existing market-prevalent helmets. This provided a foundation to understand the design trends, safety standards, and material usage in helmet manufacturing. Once the conceptual design was established, SOLIDWORKS was used to create a CAD model of the helmet. During the initial design of the helmet, a surface feature with a lofted and boundary surface was used. Different design iterations were performed to address any identified weaknesses or areas for improvement. Once the final design was optimized through simulation iterations, a detailed CAD model was created in SOLIDWORKS, as shown in Figure 2. This stage included finalizing all dimensions, adding precise features, and ensuring manufacturability. The detailed model serves as the basis for both production and further testing in real-world scenarios.

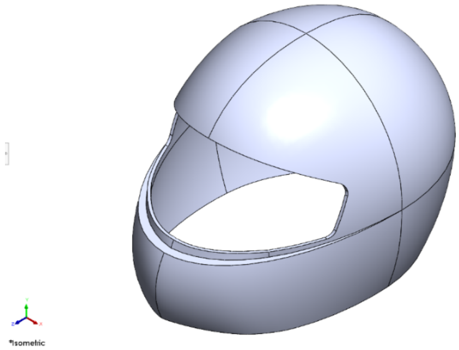

Figure 2: Final detail design

2.3. Analysis and simulation

After developing the initial CAD model, it was exported to ANSYS. The preprocessing, which includes geometry cleanup, meshing, and boundary condition setup, was performed. As for the analysis, the criteria set by ISI for the standard test were simulated using ANSYS.

1. **Preprocessing**

   - **Definition of geometry:** The 2D model was either created or imported, incorporating layered composite structures.
   - **Material assignment:** Composite material properties were assigned to each layer, including fiber orientation, matrix properties, and thickness. The layers of glass fiber and polyester resin were combined to form the composite material. ANSYS Composite Pre-Post (ACP) was utilized to establish a composite environment for further analysis. Market-available helmet materials were also tested for comparison.
   - **Meshing:** A fine mesh suitable for layered composites was generated, ensuring proper representation of each layer. For the complex shape of the motorbike helmet, a high-quality fine mesh with the following characteristics was produced for analysis, as rep-

resented in Figure 3.

  - Mesh size: 2.5 mm
  - Mesh type: Mixed (Tetrahedral and Hexahedral)
  - Element order: Linear (First-order element)
  - Elements: 30,799 and nodes: 37,800

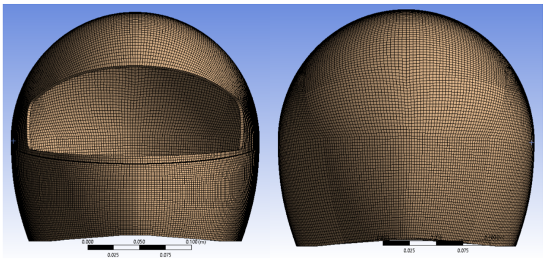

Figure 3: Front and rear view of mesh generated

- **Boundary conditions and loads** There are three tests involved in validating if the helmet satisfies the ISI standards using FEA analysis. Each test, however, has certain test points on which it would be performed and analyzed to spot any unwanted or unexpected behavior of the helmet after testing.
  - **Impact absorption test:** For the impact absorption test, flat and hemisphere anvil tests were performed with the impact velocities of 7m/s and 6m/s, respectively.
  - **Penetration test:** The conical hammer of specified shape, hardness value, and weight falls from a 1 m height onto the helmet. During the test, the helmet, fixed at its neck opening, is supported at the base to evaluate the resistance to penetration.
  - Rigidity Test: The helmet, mounted sideways in the transverse direction at two denoted points, is subjected to a compression test, starting at 30 N and increasing to 630 N, with the force increasing every minute and then reducing back to 30N.
- **Composite setup (ACP):** Using the inbuilt ANSYS Composite Pre-Post (ACP), different layers of fabric and resin were modeled in various orientations as per the analysis. For achieving high impact resistance, the fiber orientations of [0/90], [±45], and [90/0] were used[16]. The polar chart shown in Figure 4 illustrates the anisotropic (directional) elastic properties of the composite stackup, showing E1, E2, and G12 variations with orientation.

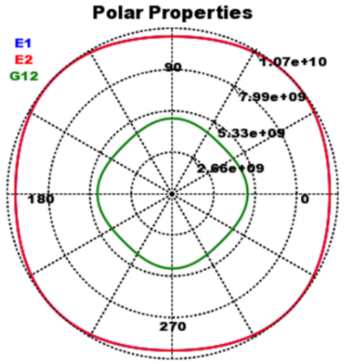

Figure 4: Polar chart of composite stackup

2. **Solving**

   In the solving stage of the FEA process, the preprocessed model was subjected to computational simulation based on the defined physics, boundary conditions, and material properties. In this research, the helmet model was analyzed through static structural analysis and explicit dynamic analysis using ANSYS.

3. **Post-processing**

   Post-processing was carried out to extract numerical and graphical results from the computed solution to evaluate the performance of the composite helmet under setup conditions. The obtained numerical and graphical results were compared against ISI standard limits to assess whether the helmet met safety requirements. Static, dynamic analysis results, and energy balance validation in explicit dynamic analysis were verified to ensure result accuracy.

4. **Failure criteria** The Tsai-Wu Failure Criterion is highly effective for composite helmet design due to its detailed consideration of stress interactions. Along with that, the Tsai-Wu Criterion's ability to handle multi-axial stress states makes it the best choice for critical applications like helmet safety.

   The Tsai-Wu failure criterion is expressed as:

$$F_1\sigma_1+F_2\sigma_2+F_{11}\sigma_1^2+F_{22}\sigma_2^2+2F_{12}\sigma_1\sigma_2+F_{66}\tau_{12}^2 \leq FI \tag{1}$$

Table 1: Properties of glass fiber and resin

Property	**E-Class Glass Fiber**	**Unit**	**Resin Polyester**	**Unit**
Density	2343	kg m^{-3}	1300	kg m^{-3}
Mass-Matrix Damping Multiplier (α)	0.02	—	—	—
K-Matrix Damping Multiplier (β)	0.0005	—	—	—
Young's Modulus (X-direction)	2.0×10^{10}	Pa	3.0×10^{9}	Pa
Young's Modulus (Y-direction)	2.0×10^{10}	Pa	—	—
Young's Modulus (Z-direction)	1.2×10^{10}	Pa	—	—
Poisson's Ratio (XY)	0.20	—	0.316	—
Poisson's Ratio (YZ)	0.30	—	—	—
Poisson's Ratio (XZ)	0.30	—	—	—
Shear Modulus (XY)	1.0×10^{9}	Pa	1.1398×10^{9}	Pa
Shear Modulus (YZ)	7.0×10^{9}	Pa	—	—
Shear Modulus (XZ)	7.0×10^{9}	Pa	—	—
Bulk Modulus	—	—	2.7174×10^{9}	Pa
Tensile Ultimate Strength	—	—	6.5×10^{10}	Pa

$$FOS = \frac{1}{FI} \tag{2}$$

Where:

- σ_1, σ_2 : Normal stresses in the longitudinal and transverse directions.
- τ_{12} : Shear stress.
- $F_1, F_2, F_{11}, F_{22}, F_{12}, F_{66}$: Material-specific coefficients derived from strength properties.
- FI : Failure Indication
- FOS : Factor of Safety

The coefficients are computed as:

$$F_1 = \frac{1}{\sigma_{1t}} - \frac{1}{\sigma_{1c}}, \quad F_2 = \frac{1}{\sigma_{2t}} - \frac{1}{\sigma_{2c}} \tag{3}$$

$$F_{11} = \frac{1}{\sigma_{1t}\,\sigma_{1c}}, \quad F_{22} = \frac{1}{\sigma_{2t}\,\sigma_{2c}} \tag{4}$$

$$F_{66} = \frac{1}{\tau_{12}^2}, \quad F_{12} = 0 \tag{5}$$

Where:

- σ_{1t}, σ_{1c} : Longitudinal tensile and compressive strengths.
- σ_{2t}, σ_{2c} : Transverse tensile and compressive strengths.
- τ_{12} : Shear strength.

2.4. Manufacturing process selection

The manufacturing process selection was performed based on parameters such as availability, part configuration, tooling, cost, and quality. After thorough analysis, the hand lay-up method was selected over resin transfer molding (RTM). The decision was influenced by the widespread availability of materials and tools for the hand lay-up method, as well as its lower cost and ease of implementation. The hand lay-up process was thus deemed appropriate for achieving the desired balance between cost-effectiveness and production feasibility.

2.5. Composite material specimen development and testing

Three specimens each of 30X290X2.5 mm were developed, which were then tested using a Universal Testing Machine (1000 kN capacity) at Thapathali Campus. The specification of specimen and UTM testing was based on ASTM D3039/D3039M.

2.6. Product fabrication

Following the specimen development and testing, actual helmets were made in two steps. During mold preparation, an old helmet was modified with PVA putty to achieve the desired design, then coated with a release agent. It was divided into two parts using cardboard and glue, with Waxpol and clay beads applied to ensure separation and proper alignment during mold preparation. A gel coat mixture was applied and partially cured before layering chopped strand E-glass fibers with resin solution. After curing in normal atmospheric conditions for a day, the first mold half was removed, and the same process was repeated for the second half. Both halves were then ready for use in helmet fabrication.

The helmet construction followed the mold preparation steps. Two molds were clamped, coated with Waxpol, and filled with PVA putty and chalk powder at the edges. A gel coat mixture was applied for a smooth finish and binding. Pre-cut woven roving bi-directional E-glass fibers of 600 GSM with a thickness of 0.7 mm were placed, with three layers applied at 0°, 45°, and 90°, each saturated with resin to remove air pockets. After curing in normal atmospheric conditions for 2 days, the helmet was removed from the molds. The overall thickness of the helmet shell thus fabricated was observed to be 2.5 mm.

2.7. Product testing

The three major tests, including impact absorption, rigidity, and resistance to penetration test were done in the fabricated helmet. These tests were performed as per all the specifications and guidelines described by IS 4151:2015.

3. Result and discussion

3.1. Composite material specimen testing

From UTM testing, the respective load and displacement were recorded to determine the modulus of elasticity along with the ultimate strength of the material. From Figure 5, the modulus of elasticity and ultimate strength, on average, from three specimens were calculated as 9.320GPa and 129.33 MPa, respectively. Comparing the modulus of elasticity with the polar chart of Figure 5 of the composite material, which computed the modulus of elasticity as 10.7GPa, a deviation of 14.8% was observed.

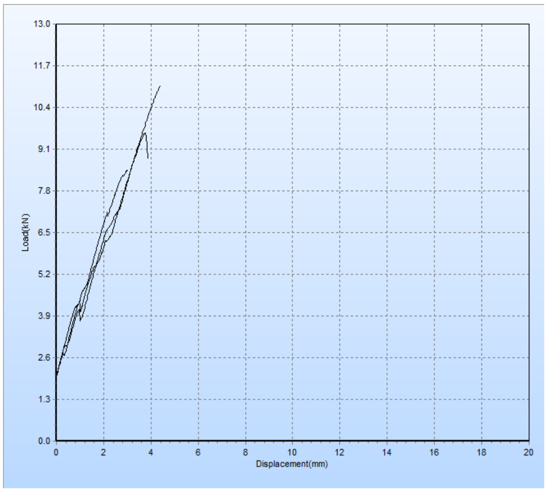

Figure 5: Load v/s Displacement graph of all specimen combined

3.2. Analysis and simulation

1. **Impact absorption test**

    - **Flat anvil test**

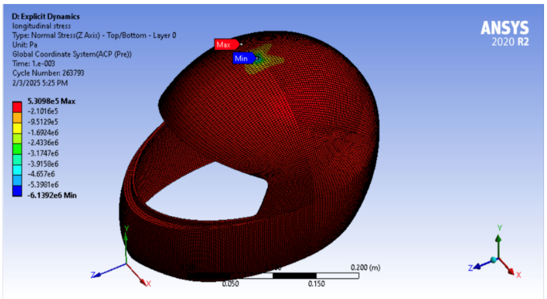

Figure 6: Longitudinal stress for flat anvil test

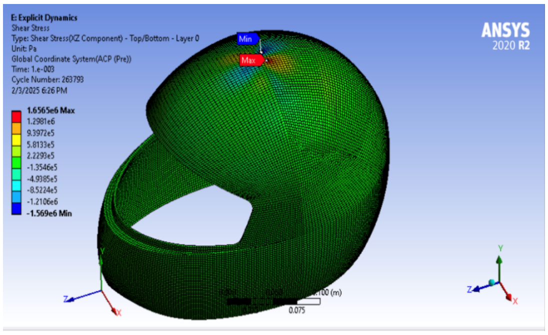

Figure 7: Shear stress for flat anvil test

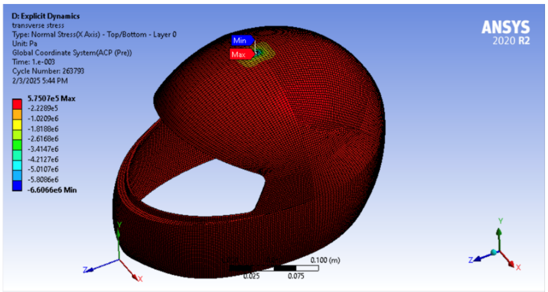

Figure 8: Transverse stress for flat anvil test

    - **Hemispherical anvil test**

    The failure of material during impact absorption testing is further calculated using the Tsai-Wu criteria. The simulated results, as shown in Figure 6, 7, 8, 9, 10, and 11 (Longitudinal, transverse & shear), are evaluated during failure analysis later on.

2. **Resistance to penetration test**

    According to the standard followed, the minimum deformation should not exceed 5mm. As per our

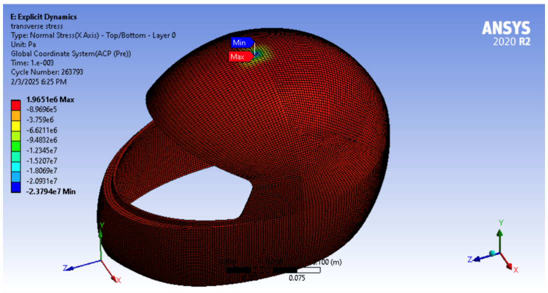

Figure 9: Transverse stress for hemispherical anvil test

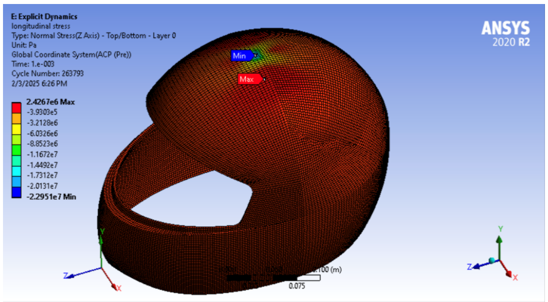

Figure 10: Longitudinal stress for hemispherical anvil test

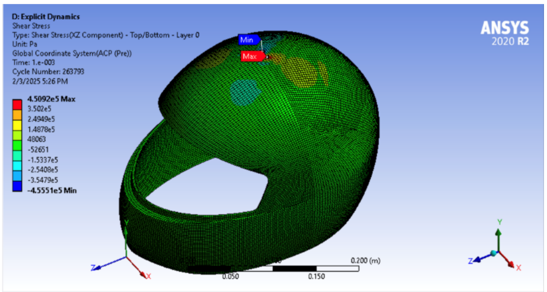

Figure 11: Shear stress for hemispherical anvil test

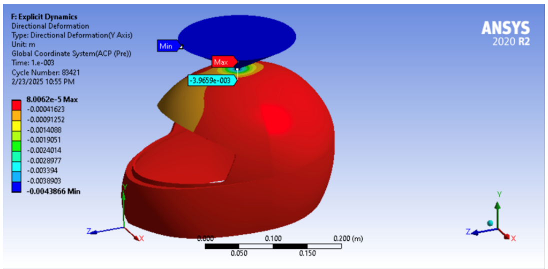

Figure 12: Directional deformation for penetration test

simulation result from Figure 12, the penetration test deformation was found to be less than 5mm.

3. **Rigidity test**

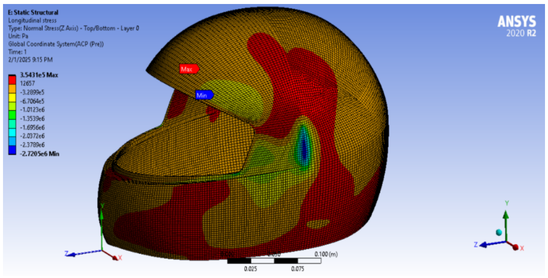

Figure 13: Longitudinal stress in transverse direction of rigidity test

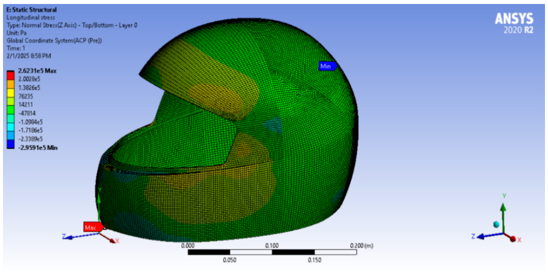

Figure 14: Longitudinal stress in longitudinal direction for rigidity test

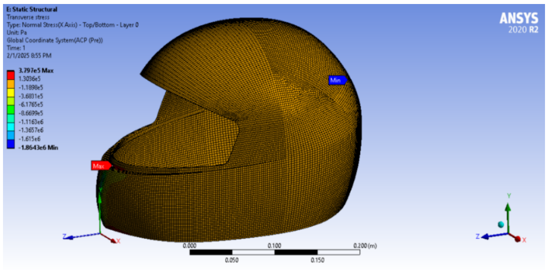

Figure 15: Transverse stress in longitudinal direction for rigidity test

The failure of material during rigidity testing is further calculated using the Tsai-Wu criteria. The simulated results, as shown in Figures 13, 14, 15, 16, 17, and 18 (Longitudinal, transverse & shear), are evaluated during failure analysis later on.

4. **Calculations of factor of safety using Tsai-Wu criteria**

Based on the Tsai-Wu criteria, and using the formula [17], the factor of safety for longitudinal compression and transverse compression in the rigidity test is found to be 6.29 and 6.14, respectively. Similarly, in the impact absorption test factor of safety is observed as 7.5 for the flat anvil and 4.55 for the hemispherical anvil.

5. **Comparison of the energy absorption of the composite material with the ABS (market-**

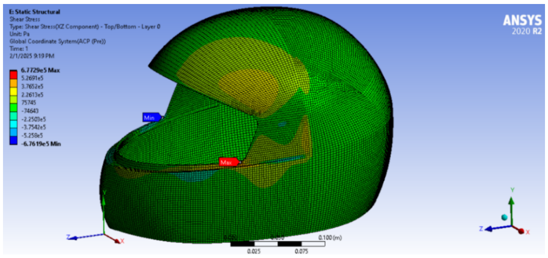

Figure 16: Shear stress in longitudinal direction for rigidity test

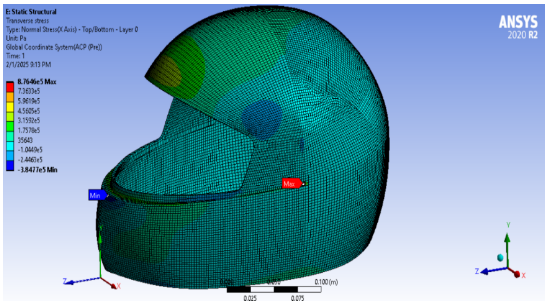

Figure 17: Transverse stress in transverse direction for rigidity test

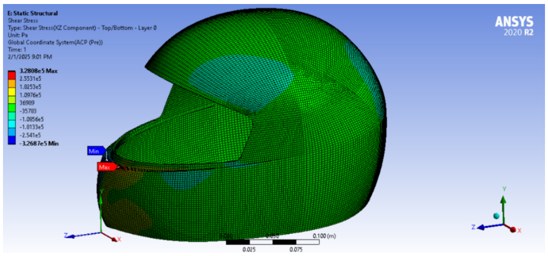

Figure 18: Shear stress in transverse direction for rigidity test

prevalent) material

The intrinsic damage mechanisms found in fiber-reinforced composites are responsible for the composite helmet's better energy absorption, as shown in Figure 19, when compared to the ABS helmet, as illustrated in Figure 20. The composite helmet distributes impact energy through a variety of mechanisms, including matrix cracking, fiber–matrix debonding, interlaminar shear, and progressive fiber failure, in contrast to ABS, which mainly absorbs impact energy by plastic deformation and localized cracking. Lower peak accelerations are the outcome of these systems, which allow for progressive energy dissipation over a longer period of time. Furthermore, the multi-directional laminate structure [0/90], [±45] reduces stress concentration at the point of contact by promoting more uniform stress redistribution upon impact. Studies on composite helmets and protective gear have frequently documented similar behavior, with fiber-reinforced laminates showing better impact energy management than thermoplastic shells. From a safety perspective, this improved energy absorption directly contributes to reduced head injury risk by limiting transmitted acceleration to the wearer.

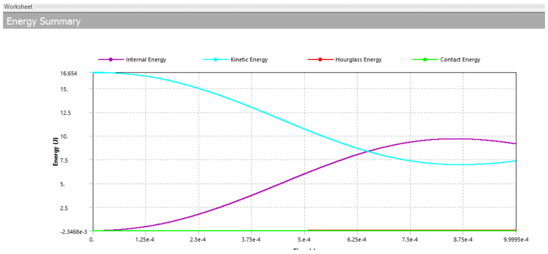

Figure 19: Energy summary for composite helmet

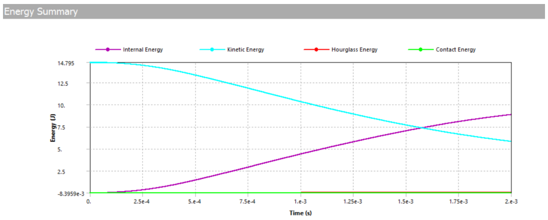

Figure 20: Energy summary for ABS helmet

3.3. Product fabrication

The product fabrication was completed using the prepared molds. E-glass fibers and polyester resin were layered and infused carefully. After curing, the helmets were removed from the molds, trimmed, and finished to achieve a strong and smooth-designed helmet.

The fiber-to-resin ratio was determined as:

Weight of fibers= 175g

Weight of resin= 505g

Hence, fiber-to-resin ratio by weight= 1:2.88

The fiber-to-resin ratio of 1:2.88 resulted from the hand lay-up fabrication process. The comparatively higher resin content was intentionally adopted to simplify fabrication and to minimize void formation, ensuring that the product remained functionally safe even though this ratio might not be optimal for structural applications.

3.4. Product testing and validation

1. **Impact absorption test**

Table 2: Evaluation of passing criteria

	Flat anvil	**Hemispherical anvil**	**Passing Criteria**
Time $> 150g$	0 ms	1.7 ms	$<$ 5 ms
Peak acceleration	146.1 g	245 g	$<$ 300 g

Table 3: Displacement data under varying load in the rigidity test

Load (N)	30	130	230	330	430	530	630	30
Displacement (mm)	1.3	4.3	6.5	8.1	9.9	11.6	13.4	3.9

- **Flat anvil test**

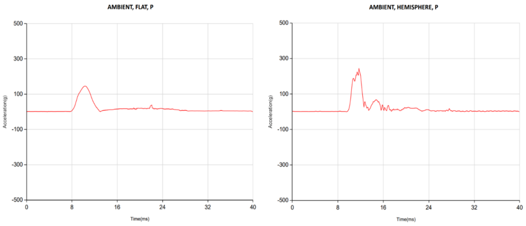

Figure 21: Acceleration graph of impact absorption test for flat and hemispherical anvil

Table 2, shows that the helmet has cleared the passing criteria for both tests as per IS 4151.

2. **Resistance to penetration test**

Initial setup datum = 31.37mm

Penetration after striking the hammer = 28.23mm

Net penetration = (31.37 – 28.23) mm = 3.14mm

This is less than 5mm penetration as defined by IS 4151 as the passing criteria. Hence, the helmet has passed the resistance to penetration test.

High energy absorption in these cases is associated with a progressive damage mechanism of the composite helmet shell, with matrix cracking, fiber breakage, and interlaminar delamination sequentially taking place during impact. These mechanisms absorb a considerable fraction of the kinetic energy and eliminate a sudden catastrophic failure, thereby making the impact load transmitted through the headform considerably less [18].

3. **Rigidity test**

The recorded displacement data for different consecutive loadings were obtained as:

Evaluation of passing criteria:

- Difference in deformation at 630N load and initial 30N load = (13.4 – 1.3) mm = 12.1mm < (40mm as per IS 4151)
- Difference in deformation at initial and final 30N load = (3.9 – 1.3) mm = 2.6mm < (15mm as per IS 4151)

This shows that the helmet has cleared the passing criteria as defined by IS 4151.

3.5. Comparison of physical testing and analysis data

1. **Resistance to penetration test**

Comparison of the result data from the simulation and experimental testing is shown in Table 4.

Table 4: Comparison of Physical Test and Analysis Data of Resistance to Penetration Test

Penetration (mm)		**Error %**
Physical Test	**Analysis Data**	
3.14	3.9659	20.825

2. **Rigidity test**

Comparison of the rigidity test of simulation with experimental test data is provided in Table 5.

The following may be the probable cause of these error percentages:

- Uneven resin-to-fiber ratio because of limitations in keeping the composition the same throughout the hand layup process.
- The existence of air pockets and voids created during the layup causes weakened composite areas and stress concentration.
- Layer misalignment decreases the directional strength of the helmet.

Table 5: Comparison of physical test and analysis data of the rigidity test

Load (N)	**Displacement (mm)**		**Error %**	**Average Error %**
	Physical Test Data	**Analysis Data**		
30	1.3	0.7431	42.8385	12.0889
130	4.3	4.2403	1.38837	
230	6.5	7.5021	15.4169	
330	8.1	7.7824	3.92099	
430	9.9	10.141	2.43434	
530	11.6	12.499	7.75	
630	13.4	14.857	10.8731	

- 2D representation in FEA restricts proper modeling of through-thickness behavior.
- Inaccuracy of contact modeling between the striker and the helmet in the FEA impact simulation.
- Functionally simplified FEA boundary conditions that are not a realistic representation of the human head constraint.

4. Conclusion

This paper successfully designed, fabricated, and tested a motorbike helmet using composite materials, meeting ISI 4151 safety standards. E-glass fiber and polyester resin were chosen, and the helmet was made using hand layup with a fiber-to-resin ratio of 1:2.88. Impact testing showed 146.1g for the flat anvil and 245g for the hemispherical anvil, which were less than 300g ISI. Penetration was limited to 3.14 mm, which was lower than 5mm, and rigidity tests showed deformation within reasonable ranges, 12.1mm at 630N load. A comparative study showed a smoother dissipation of energy in the composite helmet as compared to the conventional ABS helmets. These results prove that the composite helmet increases the safety of the riders. The paper has associated finite element analysis and full-scale experimental testing, with the focus on the effect of imperfections caused by fabrication on mechanical response. The originality of the study is in the validation of a locally produced composite helmet through the use of available materials and the simplified processing without compromising regulatory safety standards. The study is, however, limited by the hand-layup fabrication methodology, which resulted in a resin-rich laminate and which also led to discrepancies between numerical and experimental results. The cost constraints of materials, the lack of access to the advanced fibers and resins, the lack of access to the controlled curing facilities, and the partial testing because of the resource limitations further affected the quality of the material achievable and the range of certification. Also, long-term performance at environmental exposure and performance at higher impact energies were not tested.

Future work could employ vacuum-assisted fabrication techniques to achieve a more balanced fiber volume fraction, thereby improving stiffness, reducing weight, and minimizing numerical–experimental deviations. Further studies should also focus on durability assessment, expanded impact testing, and optimization of material systems to balance cost, manufacturability, and safety performance.

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