

Design and Analysis of Carbon Fiber 300–Kevlar Hybrid Composite Bumper for Enhanced Impact Resistance in Automobiles

S. Soundararajan^{1,*}, R. Venkatachalam², M. Anil Kumar³, V. Kondusamy⁴, S. Gokul⁵, S. Rajkumar⁶

^{1,2,5}Department of Automobile Engineering, K.S.R. College of Engineering, Tiruchengode, Namakkal, Tamil Nadu, India.

³Department of Mechanical Engineering, Sagi Rama Krishnam Raju Engineering College, Bhimavaram, Andhra Pradesh, India.

⁴Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore, Tamil Nadu, India.

⁶Department of Mechanical Engineering, Institute of Technology, Hawassa University, Hawassa, Sidama Region, Ethiopia.
soundararajans2024@hotmail.com¹, rvengiitmt@gmail.com², anilkumar.mudunuri@gmail.com³, vkondusamy@gmail.com⁴, gokul19ae017@gmail.com⁵, ccetraj@gmail.com⁶

Abstract: The extremely important design challenge is the vehicle's safety. Both active and passive approaches help to provide the vehicle's safety. One of the passive ways to guard the passengers is a bumper. By properly constructing the bumper, which prevents unexpected collisions, one can significantly enhance the vehicle's safety. Most research on polymer composite bumpers has concentrated on single-fibre reinforcement; hybrid composites have proven to offer higher performance than single reinforcement. Because hybrid composites have the in-built qualities of both fibres, the final composite's strength increases. This work uses Kevlar fibre in addition to carbon fibre to build a bumper. Using finite element analysis, the model was subjected to crashworthiness testing. The model was first created with 3D modelling tools and then exported to FEA analysis. Structural integrity, impact energy absorption, and deformation all show that the CF 300-Kevlar composite bumper beats traditional single-fibre composite bumpers. Simulations of finite element analysis (FEA) confirmed the experimental results and demonstrated that hybrid reinforcement significantly enhances crash performance. Among other benefits over conventional metal and single-fibre composite bumpers, the CF 300-Kevlar hybrid composite bumper is lightweight, durable, and environmentally friendly.

Keywords: Carbon Fibre; Flexural Strength; Impact Strength; Elastic Stress; Elastic Strain; Hybrid Composites; Impact Energy; Energy Absorption; Structural Integrity; Vehicle's Safety; FEA Analysis.

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1. Introduction

Bumpers form the first line of protection in vehicle collisions, and they are vital for passenger safety. These energy-absorbing systems are meant to minimise damage and lower the forces that impact travellers in low-speed collisions. Contemporary

*Corresponding author.

automotive bumpers are composed of multiple parts that work together for optimal protection. While the underlying bumper beam is usually composed of steel, aluminium, or reinforced plastic, which provides structural strength, the outward bumper cover offers the apparent surface. Usually composed of foam or honeycomb materials that collapse during impact to dissipate energy to the energy absorber. Reducing repair costs in minor incidents, safeguarding vital vehicle systems such as lights and cooling components, and most crucially, minimising the acceleration forces reaching the passenger compartment are the main safety features. Current rules allow up to 5 mph for vehicles with merely cosmetic damage and require bumpers to resist hits at speeds up to 2.5 mph without damaging safety systems. With softer materials and a particular geometry designed to reduce damage severity in pedestrian crashes, advanced bumper designs today often include pedestrian protection elements [17].

Certain luxury cars even feature active systems that can change or lengthen bumper components upon sensor detection of an impending collision. Bumpers must be correctly aligned and maintained for optimal performance. Their capacity to efficiently absorb energy may be compromised even with a small injury. Typical inspections should look for cracks, loose mounting points, or compression of energy-absorbing material [18]. The passenger survival rates of modern cars have been significantly improved by a comprehensive protective network created through the combination of bumpers with various safety technologies, including crumple zones, airbags, and electronic stability control. Constant innovation in the automotive sector is driven by the worldwide demand for safer, fuel-efficient, and environmentally friendly vehicles. Governments tightening pollution rules and consumers seeking safer, more efficient transportation create increasing pressure on manufacturers to enhance vehicle design without sacrificing performance [19]. In this regard, lowering the general weight of cars while preserving or improving their structural strength, crashworthiness, and occupant protection presents a significant challenge. The vehicle bumper, a structural component designed to absorb energy during crashes and protect the car and its occupants, is one of the primary elements that contribute to stability. Due to their inherent strength and durability, metals such as steel and aluminium have long been used in the construction of automobile bumpers.

Although these materials have great impact resistance, they significantly contribute to determining the vehicle's total weight. In the era of environmentally sensitive transportation, this extra weight results in higher fuel consumption and increased carbon emissions, presenting a significant problem. To replace conventional metal bumpers, the automotive sector has been increasingly looking to lightweight substitutes, especially polymer composites. High strength-to-weight ratios, excellent energy absorption capacity, and corrosion resistance—characteristics that define polymer composite materials—are well known. Their special fit for usage in car bumpers stems from these qualities. Most recent studies and commercial uses, however, have concentrated on composites reinforced with a single type of fibre, usually glass or carbon. Although these single-fibre reinforced composites have many advantages, they may not offer the optimal balance of stiffness, strength, toughness, and impact resistance required for critical structural components, such as bumpers. Comprising two or more kinds of reinforcing fibres, hybrid fibre-reinforced composites, which help to circumvent these restrictions, are becoming increasingly popular as potential vehicle materials. These components utilise the unique properties of each fibre to enhance the composite's overall mechanical performance. Combining the superior impact resistance and toughness of Kevlar (an aramid fibre) with the stiffness and high tensile strength of carbon fibre, for example, produces a composite that surpasses its single-fibre equivalents in terms of crashworthiness, durability, and weight economy [21].

2. Literature Review

Many studies on the structural, material, and design elements of vehicle bumpers have been conducted recently to enhance their performance during collisions. These researchers highlight the need for appropriate material choice, structural optimisation, and sophisticated simulation methods in reaching safer and smaller bumper designs. Kumar and Rao [1] emphasised the importance of selecting suitable materials and structural shapes to enhance impact resistance without compromising other vehicle safety systems in their analysis of automotive bumper structures. Their research pointed out that the geometry of the bumper and its material composition play a crucial role in determining how energy is distributed and absorbed during a collision.

Khore et al. [2] expanded on this understanding by focusing on a specific safety device known as the Rear Under Run Protection Device (RUPD). They utilised advanced simulation software such as LS-DYNA, HyperMesh, and Pro-E to model and analyse the crash behaviour of the RUPD. Their findings highlighted how structural reinforcements and material optimisation can significantly improve energy absorption, thereby enhancing passenger safety during rear-end collisions. In another study, Bibin and Manogar [3] evaluated the impact performance of Glass Fibre Reinforced Plastic (GFRP) bumpers. They adopted a non-isotropic laminate approach and used ANSYS Workbench 13.0 for simulations, comparing traditional GFRP structures to hybrid laminates that included both glass fibre and aluminium. Their results revealed that combining different materials in a laminated structure can significantly improve impact resistance and overall mechanical behaviour.

Calienciug and Radu [4] also explored novel composite bumper designs using CREO for CAD modelling and Abaqus for finite element analysis. Their study analysed the response of different materials under varying impact conditions, emphasising how

hybrid materials can better adapt to multiple crash scenarios. Rao and Saikumar [5] conducted detailed simulations of bumper beams under offset impact loading conditions using ANSYS-LS DYNA. They validated a modelling process that could simulate forming processes and accurately represent the curvature and behaviour of bumper beams. Their study provided valuable insights into how bumper materials respond under real-world offset collisions, a critical consideration in modern vehicle safety standards. Similarly, Hosseinzadeh et al. [6] examined commercial bumper beams made from Glass Mat Thermoplastic (GMT), simulating crash conditions using LS-DYNA ANSYS 5.7. They adhered to the European ECE United Nations crash test standards and compared the GMT bumpers to conventional steel and aluminium bumpers. Their findings recommended Sheet Moulding Compound (SMC) bumpers as a high-strength alternative, reinforcing the viability of composite materials as a replacement for metals.

Du [7] reported that by enhancing the bumper beam-forming technique, the weight of carbon fibre composite beams was reduced by 45% compared to traditional steel beams. However, the maximum load capacity dropped to 14.9 kN. In the study conducted by Cheon and Choi [8], composite bumper beams underwent both collision cushioning tests and static bending evaluations. The findings indicated that, while maintaining equivalent bending strength, composite materials achieved a weight reduction of approximately 30%. Evans [9] assessed the performance characteristics of composite bumper beams produced through various moulding techniques by conducting impact tests at a collision speed of 16 km/h over a temperature range of -30°C to 60°C .

Davoodi et al. [10] conducted simulations of low-velocity impacts on natural fibre composite bumper beams using the Abaqus software. They developed an evaluation framework based on six criteria—deflection, strain energy, weight, cost, manufacturability, and rib feasibility—and subsequently identified a suitable double-hat profile (DHP) material configuration for use in compact vehicle bumper beams. Mohammadi et al. [11] studied high-strength glass fibres that were used as reinforcement in polymer composites to develop a lightweight and high-performance car bumper beam. The methodology involved selecting appropriate composite materials, designing the bumper structure, and evaluating mechanical properties through simulations and experimental tests. Manufacturing techniques such as compression moulding were utilised to fabricate the bumper beams. The findings revealed that glass fibre-reinforced composites (GRP) offered superior impact resistance and weight reduction compared to conventional steel bumpers. This demonstrates GRP's potential for enhancing fuel efficiency and structural performance in automotive applications.

Nachippan et al. [12] conducted a static analysis of automobile bumpers using finite element analysis (FEA), based on the geometric parameters of a four-wheeler bumper. The investigation evaluated deformation, von Mises stress, and strain for both glass fibre-reinforced composites and hybrid composites made of glass fibre and treated hemp fibre in an epoxy matrix. The materials were modelled and simulated using FEA software to compare their structural responses under static loading. The findings indicated that the hybrid composite with S-glass fibre and treated hemp fibre exhibited the least deformation [20].

This suggests its superior suitability for use in automotive bumper applications due to improved strength and reduced weight. Bennbaia et al. [13] designed and experimentally analysed a 3D-printed composite–plastic hybrid bumper beam with a collapsible spiral structure for energy absorption. Low-impact tests were conducted to examine failure mechanisms and energy absorption across different spiral diameters ranging from 0.5 cm to 2.5 cm. Three 3D-printed structures were tested: plain thermoplastic, thermoplastic reinforced with Kevlar fibres, and thermoplastic filled with foam. The thermoplastic foam composite with nine spirals and a diameter of 0.97 cm exhibited the highest energy absorption and progressive, controlled failure. The findings suggest its strong potential for use in impact-absorbing automotive applications. Ham et al. [14] proposed a piecewise-integrated composite bumper beam for passenger vehicles, designed using machine learning models aligned with the crash test protocols of the Insurance Institute for Highway Safety. Finite element (FE) models were developed, and reference elements were used to gather training data, enabling the machine learning model to predict loading types across individual elements. Both 2D and 3D implementations were employed to optimise stacking sequences within the bumper structure.

The results showed that the ML-designed composite bumper beam significantly improved bending strength and reduced the risk of structural failure compared to conventional designs. The 3D model outperformed the 2D version, especially at corners and junctions, due to more accurate contextual loading-type predictions. Selwyn [15] addresses the shortcomings of conventional automobile bumpers by developing a composite alternative using layers of Aramid fibre arranged at different interior angles to enhance mechanical properties. The composites were fabricated using the hand layup method, followed by mechanical testing and morphological analysis to assess structural integrity. The results showed that the composite achieved a high tensile strength of 147 MPa and a flexural strength of 86.8 MPa. These findings confirm the superior performance and suitability of Aramid fibre composites as a replacement material for automotive bumper applications. Chandrasekaran et al. [16] studied the design of a lightweight yet high-performance automotive bumper using a Basalt fabric composite as an alternative to conventional steel. Finite element analysis using ANSYS R15.0 was employed to evaluate and optimise the bumper's performance. The results showed that the Basalt composite bumper is 49% lighter and 56% more cost-effective than the steel counterpart. Additionally, it demonstrated a 47.6% higher impact strength and a 32.5% greater factor of safety. Despite

showing 51% more deformation (32 mm vs. 15.7 mm), the composite still met structural requirements, proving its suitability for automotive applications.

3. Methodology

From the initial design to the final evaluation of structural performance using Finite Element Analysis (FEA), the method chosen in this work for designing and analysing the hybrid Carbon F300-Kevlar composite bumper employs a systematic and structured workflow. Conceptual design, CAD modelling, finite element meshing, material property assignment, application of boundary conditions and loading, simulation, and results evaluation form consecutive phases in the process. Using cutting-edge technical tools like Creo for 3D modelling and ANSYS Workbench for simulation, every action has been completed precisely. The first and most important phase of the approach is the conceptualising of the bumper beam design. This work chooses a hybrid composite material consisting of Kevlar and Carbon F300. This hybridisation aims to maximise the high impact resistance and ductility of Kevlar fibres as well as the tensile and flexural qualities of carbon fibres. The main reasons composites are used instead of more traditional materials like steel or aluminium are to lower weight and increase crash energy absorption without sacrificing structural integrity. The design considerations include geometric parameters such as bumper length, width, curvature, and mounting locations. The proposed design also takes into account ergonomic and safety standards as outlined by automotive regulations (Figure 1).

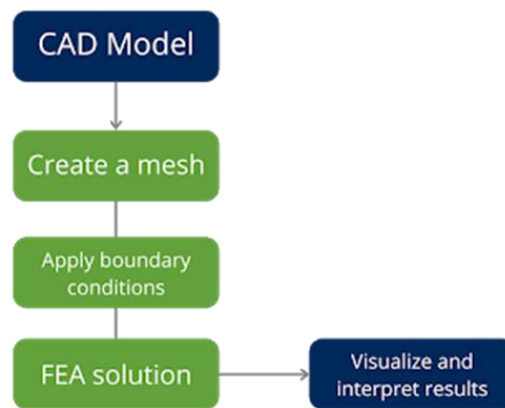
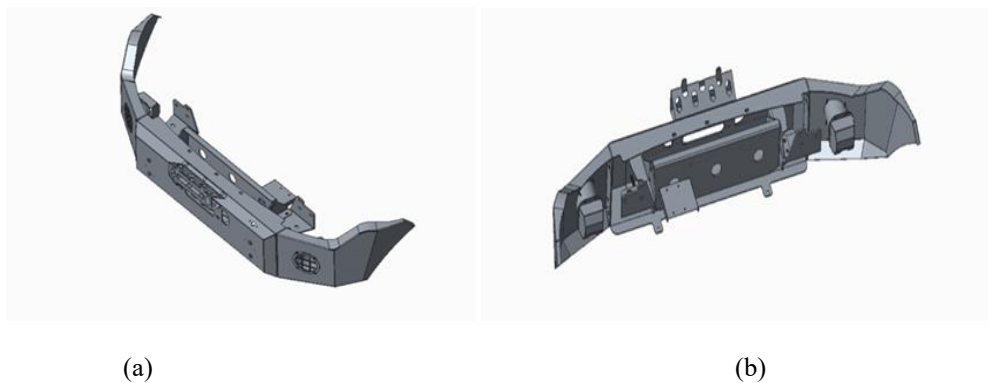


Figure 1: Flow chart of methodology

3.1. Modelling of Bumper

Once the design is finalised, the next step involves creating a detailed 3D CAD model of the bumper beam using Creo Parametric, a powerful CAD software widely used in the industry for modelling mechanical components. The bumper beam model is developed to resemble an actual automotive bumper, complete with features such as curvature for aerodynamic considerations and mounting points for attachment to the vehicle chassis. Special attention is given to maintain accuracy in dimensional tolerances, as the CAD model serves as the basis for finite element analysis. During this phase, various iterations of the design may be created to compare alternative geometries or to ensure compatibility with existing vehicle systems (Figure 2).



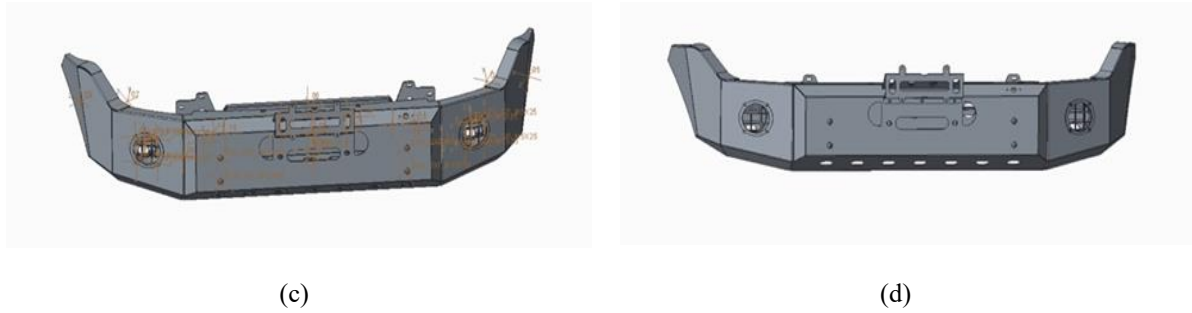


Figure 2: Modelled bumper at different views

3.2. Analysis

After completing the 3D modelling, the CAD file is exported in a suitable format (usually in STEP or IGES) and imported into ANSYS Workbench, a widely used platform for performing finite element simulations. This stage marks the transition from design to analysis, where virtual testing is used to evaluate how the bumper behaves under various loading conditions, especially during impact scenarios. In the ANSYS environment, the geometry is first checked for integrity. Small gaps, overlaps, or surface irregularities in the imported CAD model are cleaned up to ensure successful meshing and simulation. This preprocessing is essential for achieving reliable results in the later stages of analysis. Meshing is a critical step in the finite element analysis process. In this phase, the bumper model is discretised into small elements, usually tetrahedral or hexahedral in shape, which allows the software to perform numerical calculations over the geometry. The mesh density is determined by the complexity of the geometry and the desired level of accuracy. A finer mesh is applied to regions that are expected to experience higher stress gradients, such as mounting points or regions near curves and edges. A convergence study is also conducted to ensure that the simulation results are not highly sensitive to mesh size and refinement. Meshing ensures that the load and stress distribution throughout the bumper is captured effectively and that deformation, strain, and failure predictions are reliable.

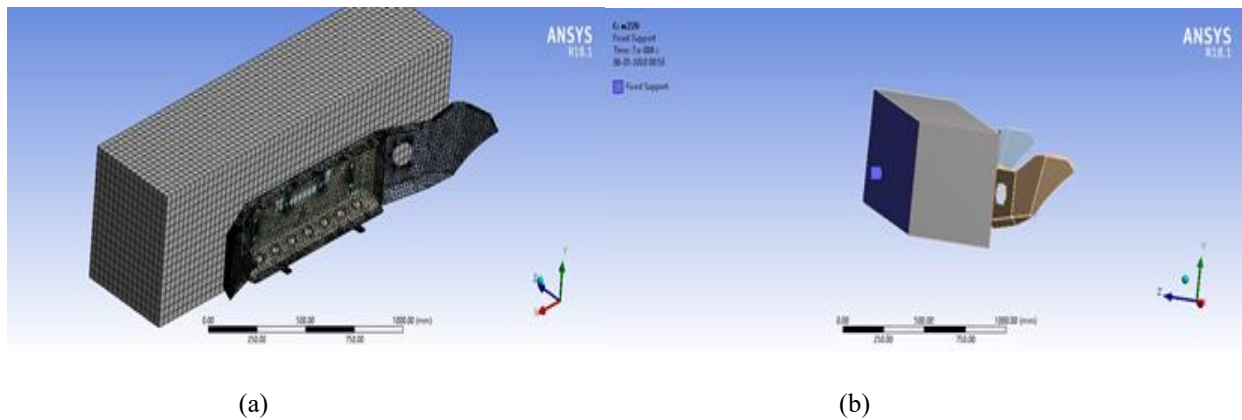


Figure 3: (a) Meshed model and (b) boundary condition applied on the model

The success of any simulation greatly depends on the accuracy of the assigned material properties. The hybrid Carbon F300-Kevlar composite is modelled using orthotropic material properties, as composites exhibit different properties in different directions (longitudinal, transverse, and through-thickness). The material data include: elastic modulus in longitudinal and transverse directions, Shear modulus, Poisson's ratios, Tensile and compressive strengths, and Density. If a layered composite model is used, the lamina stacking sequence is also defined, such as $[0/90/\pm 45]$ orientations for each ply. These parameters are crucial for accurate simulation, particularly in predicting the behaviour under multi-directional loads. Once meshing and material properties are in place, boundary conditions and external loads are applied. The boundary conditions simulate real-world constraints. In this case, fixed supports are applied to the mounting ends of the bumper beam, replicating the manner in which the bumper is attached to the vehicle chassis. The loading conditions are selected to simulate collision scenarios. A static force or distributed load is applied to the front surface of the bumper to mimic the forces experienced during a low-velocity collision. In more advanced simulations, impact loading can be conducted using transient dynamic analysis; however, for this methodology, a linear static analysis is considered adequate. With the model fully defined, the simulation is run in ANSYS Workbench.

The solver processes the input data and computes the responses, including total deformation, Von Mises stress, Equivalent strain, and Factor of safety. These results provide insight into how the hybrid bumper will behave under collision loading. Regions with excessive stress or strain concentrations are identified as critical areas, and further design modifications may be considered. The post-processing stage involves analysing the simulation outputs in detail. Deformation contours reveal how much and where the bumper flexes. The Von Mises stress plots help in identifying zones that are at risk of yielding or failure. The factor of safety (FOS) is calculated by comparing the maximum induced stress to the allowable stress of the composite material (Figure 3).

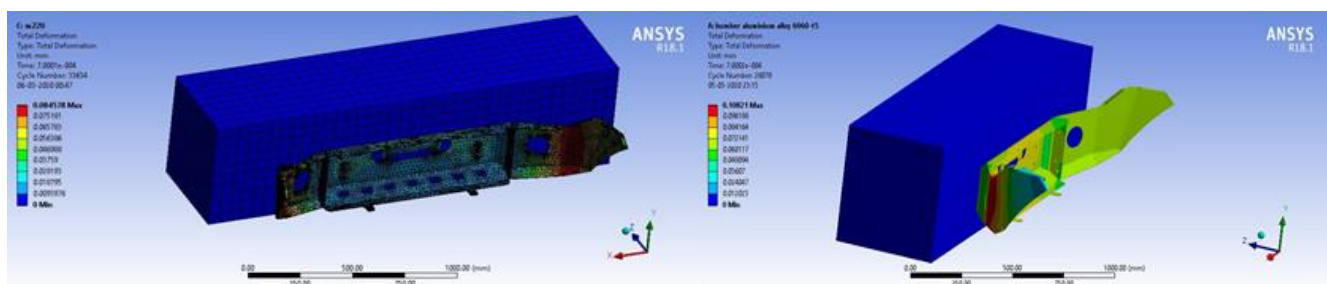
4. Results and Discussion

In this study, bumpers fabricated from three different materials—M220 steel, Aluminium Alloy 6060-T5, and a Hybrid Carbon F300-Kevlar Composite—were analysed and compared to identify the most suitable material for automotive bumper applications. The primary objective was to evaluate and compare the mechanical performance of each material under impact conditions that mimic real-world collision scenarios. This comparative structural analysis was essential for understanding how each material behaves under stress and deformation, ensuring that the selected bumper material offers both safety and weight optimisation for modern vehicles. The evaluation was conducted using Finite Element Analysis (FEA) tools to simulate impact forces and assess key parameters, including total deformation, equivalent strain, and equivalent elastic (Von Mises) stress. These parameters indicate how much a bumper will deform under load, the strain it will undergo before failure, and the stress it can withstand during a collision. M220 steel, being a high-strength material, exhibits high resistance to deformation but comes with a significant weight penalty, which can negatively impact vehicle fuel efficiency. Aluminium Alloy 6060-T5, known for its lightweight properties and good corrosion resistance, exhibited moderate deformation under impact, but had comparatively lower strength than steel. On the other hand, the Hybrid Carbon F300-Kevlar Composite demonstrated a balanced performance offering high impact resistance, excellent energy absorption, and significant weight reduction.

4.1. Total Deformation

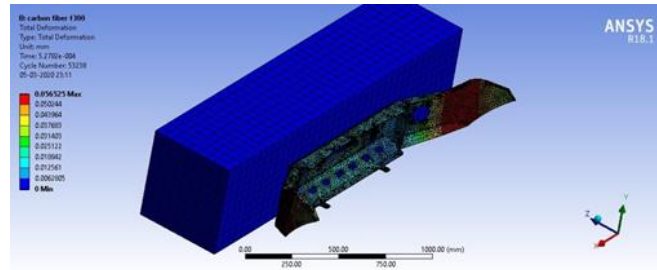
Deformation in the context of materials refers to the change in form or displacement caused by an external force or impact. It is a fundamental indication of the mechanical behaviour of a material under dynamic load circumstances. Lower deformation in the context of impact resistance indicates greater rigidity and structural integrity, thereby rendering the material more suitable for applications requiring stability and load-bearing capability. The overall deformation findings of three different materials — Aluminium Alloy 6060-T5, M220, and a hybrid carbon F300-Kevlar Composite — are shown in Figure 4 under abrupt impact. Among these, the Hybrid Carbon F300-Kevlar Composite exhibits the lowest overall deformation, thereby demonstrating its superior mechanical stress resistance. The combined action of the component materials in this hybrid composite helps it: Kevlar adds great impact resistance and toughness, while carbon fibres provide great stiffness and strength. The hybrid composite may therefore more efficiently absorb and disperse the impact energy, hence reducing deformation.

Under such impact conditions, M220, an engineering-grade material, shows moderate deformation. Its performance falls between those of the aluminium alloy and the hybrid composite. M220 deforms more than the hybrid composite, suggesting somewhat reduced structural performance in high-impact situations, even if it provides stronger resistance than ordinary metals. Aluminium Alloy 6060-T5, on the other hand, among the three materials examined, shows the most deformation. Although aluminium alloys have good mechanical qualities and are lightweight, they often distort more under impact than fibre-reinforced composites. This significant deformation implies that the alloy may not be suitable for applications requiring low deflection and high impact resistance. Under sudden load, the deformation analysis reveals that the Hybrid Carbon F300-Kevlar Composite is the most robust and stable material; therefore, it is well-suited for use in the aerospace, automotive, and defence sectors, where a strength-to-weight ratio and impact resistance are of great importance.



(a) M220

(b) Aluminium Alloy 6060-t5



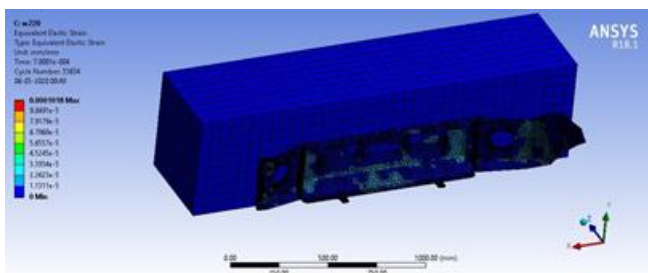
(c) CF 300-Kevlar hybrid composite

Figure 4: Total deformation

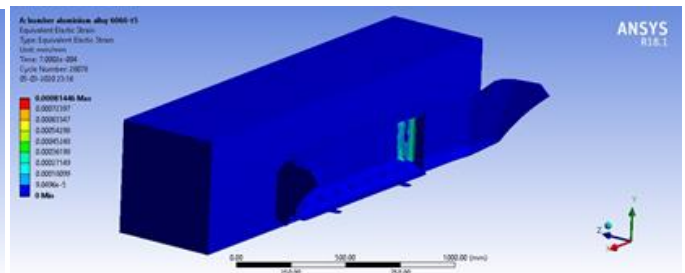
4.2. Equivalent Elastic Strain

Considering deformation in all directions, equivalent elastic strain is the total or effective strain a material experiences when under external forces. When assessing how much a substance stretches or compresses under pressure while staying within its elastic limit — the range within which it returns to its original form once the pressure is removed —it serves as a vital gauge. In impact scenarios, such as those involving car bumpers, where multi-directional forces are applied simultaneously during crashes, this parameter is crucial. Three materials utilised in bumper design —Hybrid Carbon F300-Kevlar Composite, Aluminium Alloy 6060-T5, and M220 —exhibit equivalent elastic strain distributions, as shown in Figure 5. Among the three, the Figure clearly illustrates how low the equivalent elastic strain of the hybrid composite is. This decreased strain suggests that the hybrid composite deforms less elastically under load, therefore showing improved stiffness and resistance to deformation. The great mechanical synergy between Kevlar reinforcement and carbon fibres explains such performance. Kevlar improves toughness and energy absorption, while carbon fibres provide great tensile strength and rigidity.

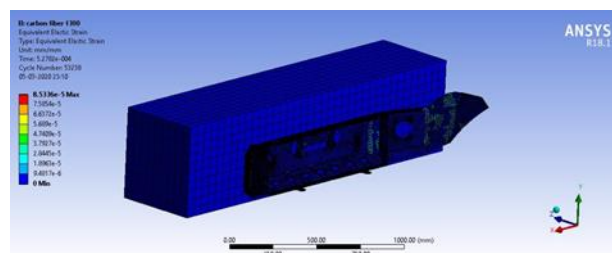
By comparison, Aluminium Alloy 6060-T5 has the largest comparable elastic strain. This suggests lesser rigidity and structural integrity compared to composite materials, as the aluminium bumper exhibits higher elastic deformation under the same loading conditions. In between, M220, a polymer-based material with modest mechanical qualities, provides higher performance than aluminium but does not exactly match the hybrid composite. The low elastic strain of the hybrid composite indicates its ability to withstand significant loads without appreciable deformation. In automobile uses, where the bumper must absorb energy during contact without sending too strong a force to the structure or occupants, this quality is crucial. Thus, under rigorous operating conditions, the hybrid composite guarantees not only safety but also durability and long-term performance.



(a) M220



(b) Aluminium Alloy 6060-t5



(c) CF 300-Kevlar hybrid composite

Figure 5: Equivalent elastic strain

4.3. Equivalent Elastic Stress

A fundamental indication used in structural analysis to determine how a material distributes internal stress under external loads is the equivalent elastic stress, also known as von Mises stress. It enables one to evaluate whether a material is likely to yield or fail under complicated loading situations by representing the cumulative effect of stresses in all directions. This characteristic is especially significant in automotive components such as bumpers, which must withstand unexpected impacts and adequately disperse the ensuing stresses to prevent structural damage.

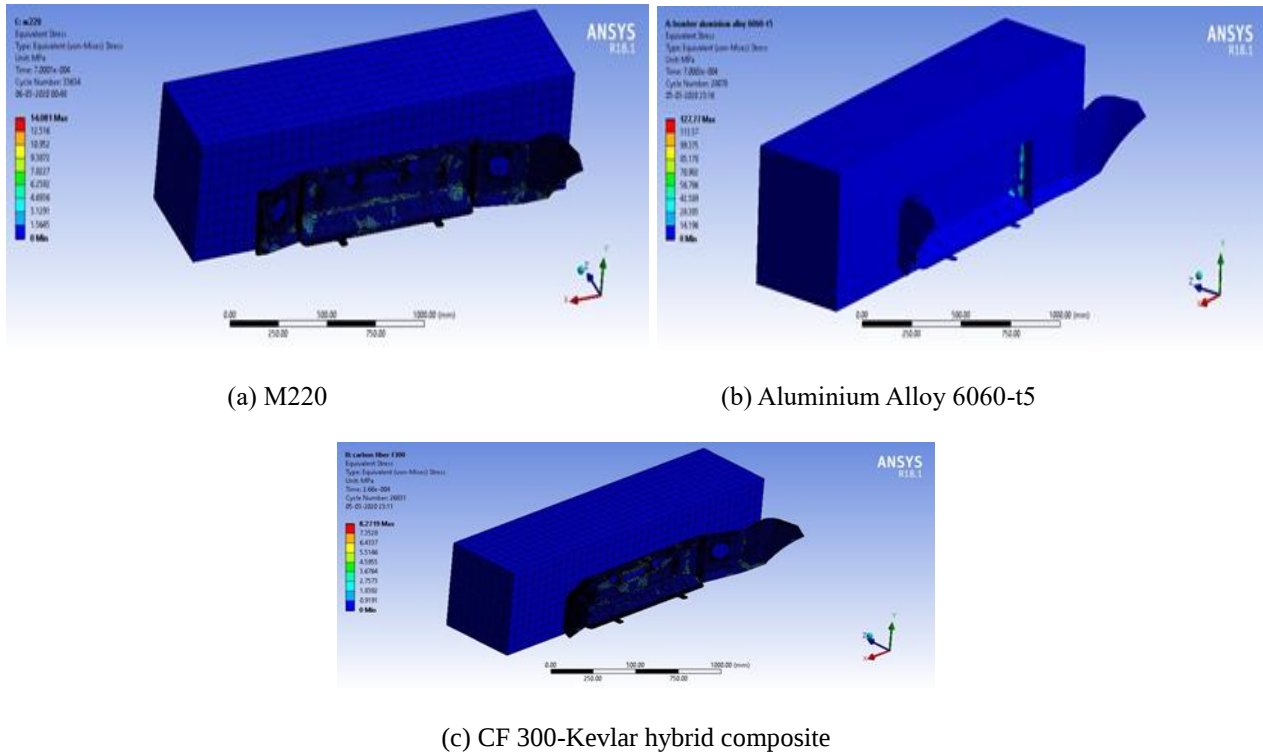


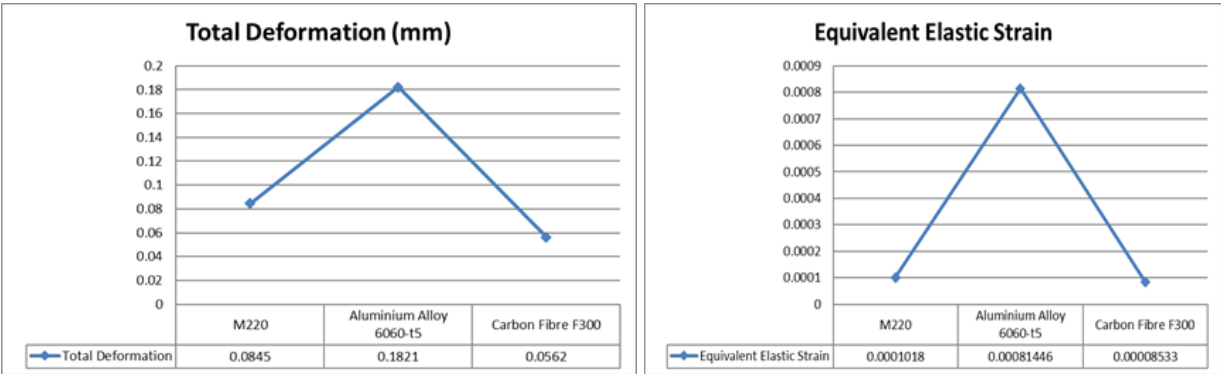
Figure 6: Equivalent elastic stress

The corresponding elastic stress distribution for three-material bumpers, Hybrid Carbon F300-Kevlar Composite, Aluminium Alloy 6060-T5, and M220, is shown in Figure 6. Under impact load, among them, the bumper made from the hybrid composite shows the lowest equivalent elastic stress. This suggests that the hybrid material effectively controls and disperses the applied forces, therefore lowering the stress concentration in any one part of the construction. The complementary characteristics of the hybrid composite's constituent carbon fibres offer great tensile strength and stiffness, while Kevlar improves toughness and impact absorption capacity, helping to explain its outstanding performance. By contrast, Aluminium Alloy 6060-T5 and M220 bumpers show much higher equivalent elastic stress levels. Though it is lightweight and has good strength, aluminium lacks the natural damping and load distribution properties of fibre-reinforced composites. M220 indicates a possible vulnerability to deformation or failure under sudden load, even if it is better than aluminium in some aspects. It shows higher stress concentrations than the hybrid composite. The results of the stress distribution graphs highlight the benefit of using hybrid carbon F300-Kevlar Composites in applications likely to cause impact. Their ability to maintain lower stress levels under heavy loads results in superior longevity, increased safety, and improved crashworthiness qualities, which are absolutely vital for critical vehicle components such as bumpers (Table 1).

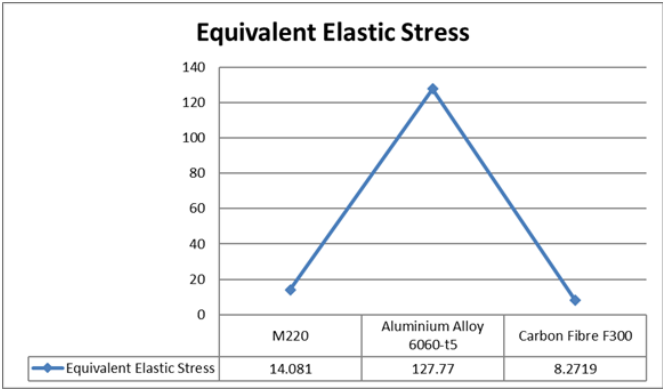
Table 1: Analysis result for crash worthiness

No.	Material	Total Deformation	Equivalent Elastic Strain	Equivalent Elastic Stress
1	M220	0.0845	1.1018e-4	14.081
2	Aluminium Alloy 6060-t5	0.1821	8.1446e-4	127.77
3	CF 300-Kevlar hybrid composite	0.0562	8.5336e-5	8.2719

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(a) Total Deformation (b) Equivalent Elastic Strain



(c) Equivalent Elastic Stress

Figure 7: Comparative chart of structural analysis of bumpers made up of different materials

5. Conclusion

The successful conclusion of modelling and analysis of the Carbon Fibre F300-Kevlar hybrid composite bumper for automotive uses shows its performance under impact situations. The simulation results clearly demonstrate that the hybrid composite outperforms conventional materials, including M220 and Aluminium Alloy 6060-T5. Under abrupt loads, the hybrid composite exhibits significantly reduced total deformation, equivalent elastic strain, and equivalent elastic stress. These results highlight the exceptional mechanical properties of the material, including high stiffness, strength, and energy absorption capacity. The combination of Kevlar, known for its toughness and impact resistance, and carbon fibres, which provide rigidity, enhances its performance. Consequently, the suggested bumper design ensures improved crashworthiness, making it particularly suitable for vehicles where structural integrity and occupant safety are of paramount importance. For contemporary car crash protection systems, this hybrid composite bumper presents a convincing, lightweight, and robust alternative.

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