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Investigating the Structural Integrity of Automotive B-pillars: The Effect of Ply Orientation on Composite Strength

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Abstract

This research paper delves into the development of a novel, lightweight solution for the B-pillar in passenger car bodies. In the current automotive landscape, stringent emission regulations necessitate highly efficient vehicles, demanding enhanced mileage achieved through reduced fuel consumption. Simultaneously, ensuring the safety of occupants remains paramount. Therefore, a design that balances both safety and lightweight properties is imperative. Traditionally, aluminum is favored for its exceptional strength-to-weight ratio. However, it must withstand forces akin to steel. To augment the strength of aluminum to match or exceed that of steel, this study concentrates on integrating carbon fiber reinforcement into an aluminum B-pillar, thereby enhancing its structural integrity. Analyzing composites with fiber reinforcement presents significant challenges, demanding sophisticated techniques. This study presents a novel lightweight solution for the B-pillar in passenger cars by integrating carbon fiber reinforcement into an aluminum structure to enhance strength while reducing weight. Using ANSYS ACP, stress concentration at different ply orientations was analyzed, and experimental testing was conducted to validate the results. Among various ply configurations, the [0 60 90] orientation exhibited the highest reaction force of 12.65 kN. The composite B-pillar demonstrated a 57.1% improvement in reaction force compared to steel while reducing weight by more than 50%. The findings indicate that a composite B-pillar with optimized ply orientation can enhance structural integrity and crashworthiness, offering an efficient alternative to traditional metallic designs.

Major Findings: *This study reveals that the aluminum-carbon fiber composite B-pillar with the [0-60-90] ply orientation exhibits a 57.1% higher reaction force while achieving a 50% weight reduction compared to the conventional steel B-pillar. The FEA and experimental results showed a 7% deviation, validating the accuracy of the simulation. This optimized composite design enhances structural integrity and crash worthiness for automotive applications.*

Keywords: *ACP Tool Post, B Pillar, Carbon Fibre, FEA, UTM*

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1.0 Introduction

The B column, a vital component in vehicles equipped with four doors, forms an enclosed steel structure meticulously welded to the vehicle's rocker board, floor skillet, and rooftop rail or board at its upper section. This intricately designed segment plays a multifaceted role- it securely captures the front gateway, provides a mounting platform for the hinges of secondary routes, and acts as a support for the vehicle's rooftop board. The design and configuration of a vehicle's rooftop and door are pivotal, not merely for aesthetics, but more significantly to meet stringent safety and crash standards. These components, being among the most expensive in vehicle construction and modification, require precision.

Certain vehicle structures incorporate a segments or smaller, chamfered windscreen portions to enhance driver visibility, thereby reducing blind spots. Crafted from more robust composite steel, these elements augment safety measures. Internally, the B column is a complex assembly of varied lengths and materials, deemed "arguably the most intricate of all vehicle structures". Functioning both as a supportive post for the vehicle's rooftop and as a lateral obstruction positioned centrally to secure the front door and the base of the hinges for the unconventional entrance, the B column stands as a vertically enclosed steel structure. Its intricate welding connects it to the rooftop board above and the vehicle's rocker board and floor dish below, ensuring a foundational integrity.

During external forces impact on a vehicle, the size and construction of the B column play a pivotal role, significantly shaping the vehicle and safeguarding its occupants. As one of the most intricate structural components vital for maintaining a vehicle's rooftop geometry, the B column assembly entails a sophisticated manufacturing process involving diverse materials of varying strengths and lengths. The B column's indispensability in a vehicle cannot be overstated; the occupant cell's stability is profoundly contingent upon the strength and rigidity of this section. Thus, meticulous engineering of the B column is imperative for ensuring safety against side collisions or impacts. Figure 1 provides a visual depiction elucidating the essence of the B-pillar and its precise placement within the vehicle structure.



Figure 1. B-pillar in a passenger car[1].

The objective of conducting trials and experiments is to closely corroborate the simulated estimates of control response. The focal point of this endeavor is the utilization of purpose-oriented carbon materials on the B column of a vehicle. The existing structures, constructed from plastic or sheet metal, are susceptible to failure at joints or cantilever ends. Reinforcing these structures with epoxy and glass fiber will enhance their dynamic properties, ensuring increased resilience and robustness[1].

2.0 Literature Review

The recent advancements in the analysis of tapered laminated composite structures, it delves into the exceptional traits of composites, notably their elastic tailoring capabilities and their capacity to decrease weight when contrasted with conventional laminated components. These attributes render them highly enticing for deployment in intricate domains like commercial and military aviation applications[2]. The issues in designing for crashworthiness are discussed in this work, along with the significant computational demands made during the optimization procedures. The results show that a single MRTS run, which is distinguished by a collection of better designs and fewer simulation runs, is preferable to numerous Sequential Quadratic Programming (SQP) runs with various starting points[3].

The complexities associated with crashworthiness design, addressing the substantial computational requirements inherent in the optimization procedures. The findings reveal the preference for a solitary MRTS run characterized by superior designs and reduced simulation iterations, eclipsing the necessity for multiple Sequential Quadratic Programming (SQP) runs initiated from

diverse points of origin[4]. The contemporary progressions that culminated in the development of ISO 10303-209 data models employed for the delineation of composite structural form and composition. Furthermore, the authors furnish a comprehensive overview of the current state of affairs pertaining to recent trials and the execution endeavours[5]. Overarching characteristics of an encapsulated composite structure hinge upon its design intricacies. These intricacies encompass factors such as thickness, orientation, and the constituent material of each layer within the stratified configuration. Consequently, advanced tools are employed to facilitate the enhancement of structures, imbuing them with sophisticated properties. Employing the Monte Carlo method as a constrained stochastic optimization technique, predicated on defined parameters, serves to ascertain the optimal fiber orientations within layered structures. This endeavour aims to discern the utmost longitudinal modulus of rigidity[6]. The behaviour of reinforced composites under stress is highly intricate, and the existing knowledge on fatigue analysis still requires extensive scrutiny of the micromechanical composite behaviour. While there are various categories of models designed to predict the fatigue life or degradation of fiber-reinforced composites, there is a conspicuous absence of a comprehensive fatigue model applicable across a broad spectrum of such composites[7]. This study addresses this gap by revising fatigue failure using polymer-based Kevlar composite material, thereby enhancing our understanding of the complex nature of fatigue behaviour in these materials. The bearing strength and failure mechanisms of pin joints through experimental and numerical analysis, aiming to discern the influence of diverse ply orientations and nano fillers. Glass-epoxy composite laminates were meticulously crafted with specific ply orientations, namely [0°/45°/90°], [0°/45°/0°], and [0°/90°/0°]. In the context of these orientations, varying percentages (ranging from 1% to 5% by weight) of nanoclay filler were meticulously incorporated into the epoxy matrix to fabricate the intricate pin joints, adding a layer of complexity to the study[8]. An intricate analysis is conducted to assess the impact resistance of both uniform and meticulously evaluated auxetic DAHs (Disordered Axenic Honeycombs). The study delves into both the semi-static and impact behaviours exhibited by these structures. Precise mathematical formulations for the in-plane Young's modulus, Poisson's ratio, and the semi-static yield stress of uniform DAHs are deduced. Remarkably, these formulations align seamlessly with Finite Element (FE) simulations, underscoring the nuanced interplay between the semi-static yield stress of DAHs and their geometric parameters and Non-Periodic Re-entrant (NPR) features[9]. The fundamental analysis of this emerging worldview within a context that can be mechanically verified. It aims to illustrate that this perspective compels significant expansions and conjectures within the conventional hypothetical framework and algorithmic structures initially conceived for robust demonstration. Particularly essential are novel models and data-intensive representations pertaining to materials, physical phenomena, and diverse scales of manufacturing shapes[10]. The employment of ultrahigh quality steel to optimize various components of a vehicle, including the A-pillar, B-pillar, rooftop rail, rocker, front header, and rooftop bow, with the specific aim of enhancing rooftop resilience. This method permits the integration of a sub-model for refinement, markedly diminishing the duration necessary for comprehensive development[11].

This study introduces an innovative methodology for developing a composite ply database, incorporating engineering design constraints. This method consists of two stages: The design of the core stacking sequence and the design of the overall stacking sequence. The comprehensive permutation technique is employed to generate core stacking sequences, considering the required ply ratio and the dispersion character, which elucidates the spread of ply angles[12]. The intricacies of B-column structure and its reinforcement, adhering to specific regulations. The ultimate configuration weight for the final support does not exceed 6 kilograms, and the maximum displacement must not exceed 40 millimetres under a 140-Kiloneutron (KN) load. Different welding techniques were employed in each design, resulting in varied displacement values. The fourth structure exhibited the lowest maximum displacement at 13.8 millimetres, while the third structure displayed the highest maximum displacement at 31.9 millimeters[13]. It is suggested that the A and B columns in passenger vehicles play a pivotal role in ensuring structural safety. The conclusion drawn from this paper is that the analysis of the upper intersection of the B-column has been conducted. This choice was made

because in the event of a vehicle rollover, a significant portion of the load is borne by the A, C columns. To enhance the safety of this area, we have selected four distinct materials. Among these, Al-5049, a commonly used alloy in vehicles, has been chosen for comparison[14].

This study conducts a modular analysis on the B Pillar of an automobile, subjecting it to extreme conditions to ascertain its dynamic characteristics. In this research, the dynamic properties of the framework must be anticipated to determine the structure's natural frequencies. The composite B-Pillar, when contrasted with the existing mild steel B-pillar, demonstrates a substantial reduction in weight[15]. A composite B-column design incorporating a drop-off technique, aiming to enhance the vehicle's light weight properties and crashworthiness. It presents novel concepts for B-pillar auxiliary design, meticulously accounting for assembly procedures and impact conditions. The composite B-column with drop-off integration allows effortless adjustments to both external and internal thicknesses. In comparison to conventional structures, the design and enhancement constraints are lenient, facilitating the improvement of B-pillar performance[16]. The objective of this paper is to illuminate the research conducted on composite materials, exploring new fibres and resins, and envisioning future applications for these composites. Environmentally friendly resins are set to replace recycled plastics and bio-based polymers in composite materials. In recent times, advanced composites have substantially replaced conventional structural materials in aircraft (*e.g.*, Boeing 787, Airbus A350), accounting for over 50% of the total weight[17].

To establish a precise model depicting the optimal configuration, this paper intends to delineate the framework of a wing constructed from isotropic materials and composite skins. It will then juxtapose this structure with a similar wing created through modifications in materials and the orientation of composite skins. Through a meticulous analysis of the displacement and weight distribution on the wing, the most suitable arrangement for wings employing diverse materials and varying orientations of use can be discerned[18]. In this scholarly work, researchers delve into the realm of composite materials. Specifically, they explore the utilization of lightweight B-columns in crucial vehicle components during crashworthiness scenarios. The study involves comparing the steel B-pillar of a specific model as the benchmark, and evaluates the performance of the composite B-column made of CFRP (Carbon Fibber Reinforced Polymer) under similar stiffness design conditions. Through this analysis, they scrutinize the rigidity, crashworthiness, and lightweight properties in relation to high-strength steel, dissecting the intricacies of the B-column[19]. The research presented in this paper focuses on evaluating the impact of stacking sequence, a crucial factor in enhancing the characteristics of engineered fibre-reinforced composite polymers. This study aims to protect aircraft structures from barely perceptible damage caused during low-velocity impact events. Understanding the semi-static mechanical properties of polymer composites is essential prior to analysing the damage resulting from low-velocity impacts[20].

The impacts of scrutinized attributes on the crashworthiness of the structures and materials under investigation, emphasizing the forefront of energy absorption mechanisms. There is a potential conjecture that the performance of interconnected structures will persist in enhancement, and an influx of increasingly scientific designs utilizing the analyzed structures and materials will incessantly emerge[21]. This paper delves into finite element modeling and analysis of the B-column, meticulously engineered to absorb significant energy while minimizing deformation to restrict its intrusion into the passenger compartment during side impact events. The study fabricates the B-column utilizing composite materials, with the primary aim of enhancing crashworthiness performance at a reduced weight, ultimately replacing conventional steel components[22]. Specifically, it introduces the concept of Functionally Graded Thickness (FGT) in the B-column, characterized by a thicker wall in load-bearing regions and a thinner wall in other sections. This configuration is examined for its energy absorption and deformation capabilities. The findings, obtained swiftly through design data, reveal that the thickness variations in the upper and lower segments of the B-column experience curved and straight stress distribution, respectively. These insights offer practical engineering guidance[23].

This paper delves into scrutinizing the influence of both the quantity and orientation of handles on the malleable characteristics of hybrid composites. Hybrid composites refer to materials incorporating two or more distinct fibres within the same framework. To conduct this analysis, a deep understanding of the elastic behaviour of

individual fibre-reinforced composite layers is necessary. Examining various simulation outcomes reveals that the orientation with a 0° angle is optimal for maximizing elasticity[24]. A detailed finite element model, organized layer by layer, for the static structural analysis of CFRP (Carbon Fibber Reinforced Polymer) coated composite wings of Unmanned Aerial Vehicles (UAVs)[25]. The primary objective of this study is to compare outcomes derived from various combinations of fibre orientations, which significantly enhance the performance of composite materials exhibiting both orthotropic strength and rigidity attributes. These dual properties pose unique challenges for analysis and design. The investigation further advances to determine the optimal structure for the selected fibre orientation combination, applied to a wing featuring a tubercle design at its leading edge. A rigorous study involving the intricate design and analysis of a side door intrusion beam, aimed at augmenting automotive safety protocols[26]. The culmination of this endeavour involved showcasing detailed analytical findings pertaining to the intrusion beam's efficacy in bolstering safety standards within the automotive domain. A methodical iterative design approach aimed at crafting a functional side door anti-intrusion beam entirely composed of glass fibre reinforced thermoplastic, strategically devised to supplant its metal counterparts[27]. The reader is meticulously led through the intricate design hurdles, wherein the mechanical rationale governing the adaptation of part geometry and composite arrangement is elucidated with profound detail and scholarly rigor. Figure 2 shows the systematic layout of research paper study and their gaps.

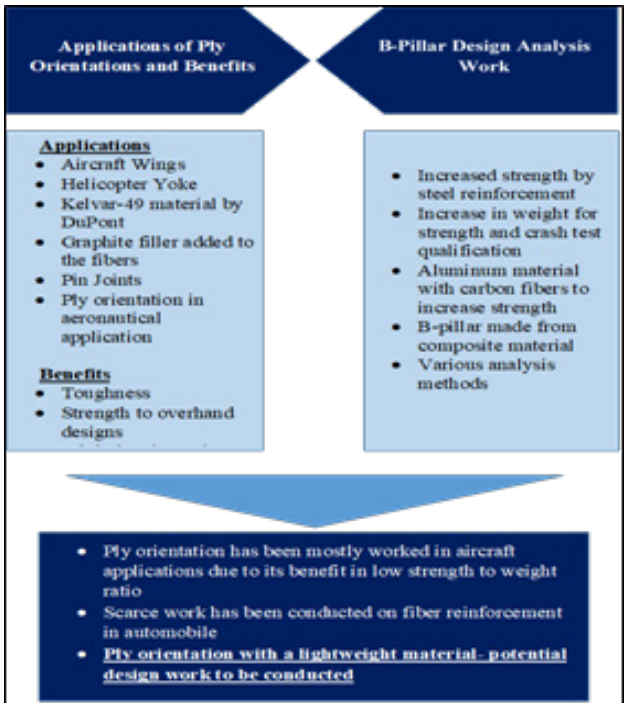


Figure 2. Literature gap systematic layout.

3.0 Problem Statement

In the contemporary era, the pursuit of enhancing efficiency in automobiles necessitates a reduction in the weight of existing components. This objective is achieved by reinforcing composite materials with a foundational substance, namely aluminium, thereby augmenting both strength and lightweight attributes. The current research delves into a similar conceptual exploration concerning the B pillar. Composite fibres exhibit strength contingent upon the direction of fibre or ply. Consequently, a meticulous examination of these layers becomes imperative to avert catastrophic failures and facilitate the creation of a novel lightweight and robust structure, surpassing the capabilities of conventional metallic compounds.

4.0 Objectives

- Delve into an exhaustive exploration of diverse carbon fiber orientations, with the aim of attaining a strength level comparable to that of the existing B pillar.
- Conduct a meticulous analysis of carbon fiber plies through the sophisticated ANSYS ACP (Advanced Composites Plastic) tool, systematically assessing various orientations to discern the most optimal ply configuration.
- Undertake the intricate process of manufacturing and experimentation on a carbon fiber laminar B pillar. This intricate procedure involves reinforcing a sample with a composite blend of epoxy resin and carbon fiber, executed with utmost precision.
- Execute a rigorous comparative analysis between the experimental findings and the results derived from ANSYS simulations. This involves a comprehensive evaluation of the effectiveness and precision of the chosen carbon fiber orientation and the reinforcing materials employed.

5.0 Methodology

Employ the CATIA software to intricately characterize material attributes and perform Computer Aided Design (CAD) modeling of diverse layered specimens. Utilize the ANSYS workbench to meticulously discretize finite elements, ensuring precision and accuracy in the analysis[28,29]. Define ply orientation angles layer by layer using the Advanced Composites Plastic (ACP) module.

Conduct a detailed examination of stresses, strains, and damage inflicted upon the B pillar through rigorous static structural analysis. Fabricate samples with utmost precision utilizing the hand layup method, ensuring meticulous attention to detail.

Implement a vacuum pump to meticulously eliminate any air gaps during the manufacturing process, ensuring a seamless and compact structure. Methodically cut specimen layers into homogeneous sections adhering to standardized dimensions, essential for rigorous testing procedures. For illustrations showing FORCE *vs.* deflection, perform the three-point bend test. Comparison of the outcomes of the FEA and the experiments.

6.0 Modeling and Analysis

Figure 3 shows the model developed in CAD software and Figure 4 details out the dimensions of the model designed and Figure 5 layouts the models uploaded in the analysis software. The Figure 3, Figure 4 and Figure 5 are for reference to understand the model designed. In present research existing b pillar material *i.e.* steel with 3 mm thickness is compared with new design composite material of aluminium of 2 mm thick along with reinforcement of 3 layers of carbon epoxy to improve existing strength along with light weight in size[30].

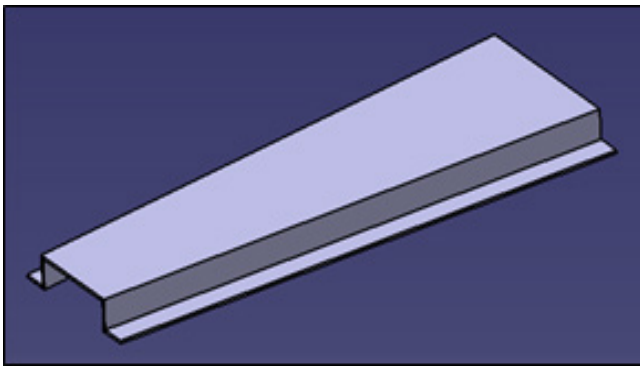


Figure 3. Model of B-pillar.

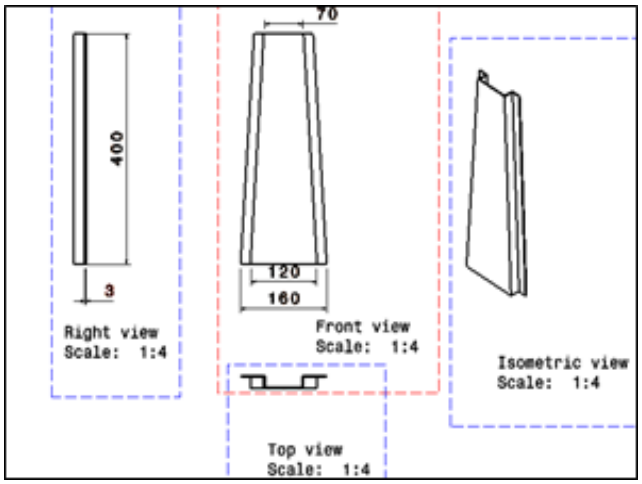


Figure 4. Dimensions of B-pillar.

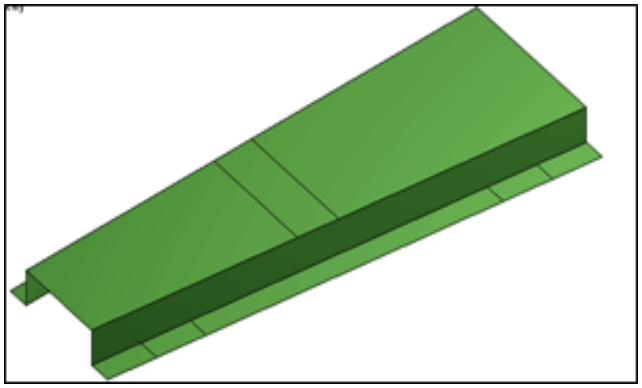


Figure 5. CATIA model imported in ansys.

6.1 Meshing

In ANSYS, meshing is carried out similarly to how FEA discretization breaks down large components into smaller elements and nodes. Therefore, the boundary condition equation is solved in the analysis at these elements and nodes. Since it is all-purpose, ANSYS Meshing creates the best mesh for precise, effective multiphysics solutions. For any component of a model, a mesh that is best suited for a particular study can be created with a single mouse click. For the professional user who wishes to fine-tune the mesh, full control over the options utilised to generate it is provided. The software-based mesh model is depicted in Figure 6.

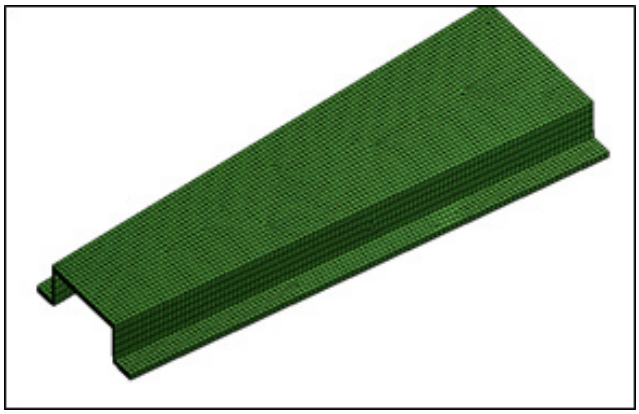


Figure 6. Details of meshing of B-pillar.

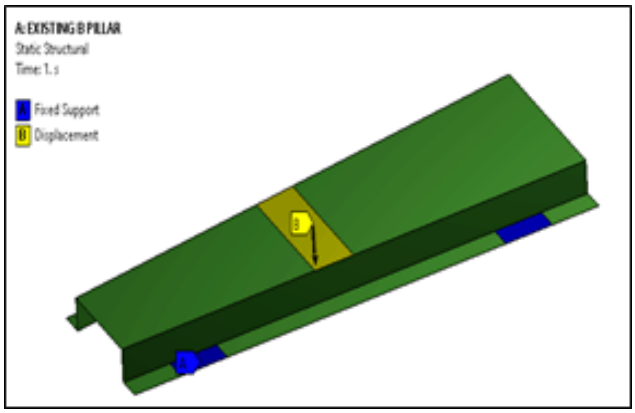


Figure 7. Boundary conditions for static analysis.

The support points and load application area are shown in Figure 7. In order to compare the reaction force for a carbon fiber reinforced B pillar, a fixed support is applied at one end and a displacement of 5 mm is applied at the other end. Figure 8 explains the locations in the B-pillar where substantial deformation is seen. The stress-concentrated locations are shown in Figure 9.

Figure 10 shows the reaction force direction and Table 1 is the output result table of analysis of steel material. For existing B pillar design for displacement of 5 mm reaction force required is around 4.730 KN. Figure 11 shows the ACP tool post different layer arrangement. Figure 12 shows the ACP tool arrangement for analysis of multiple models.

Table 1. Analysis Result

Parameter	Value
Reaction force	4730 N
Total mass	1.65 kg

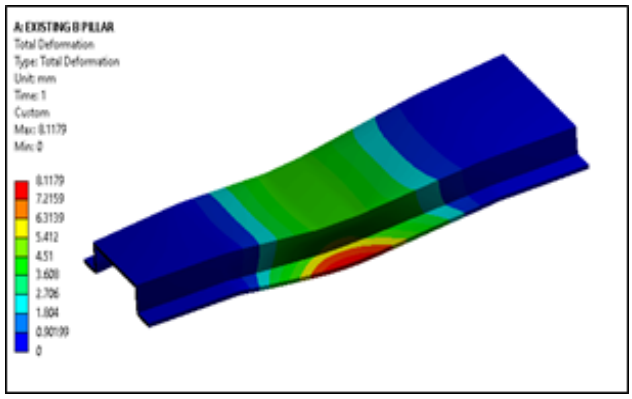


Figure 8. Results of total deformation for current design material.

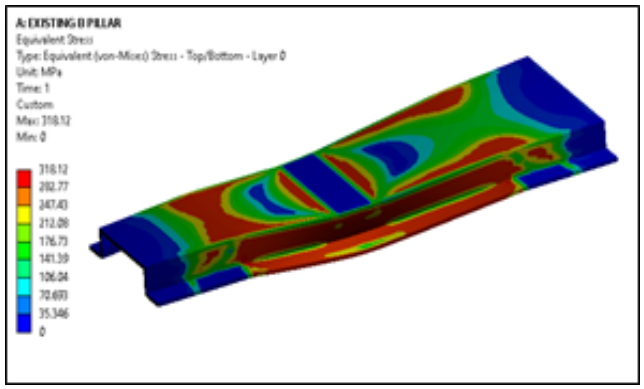


Figure 9. Equivalent stress result for the currently used design material.

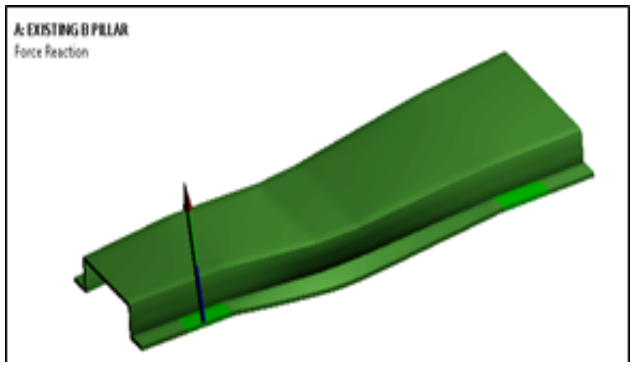


Figure 10. Force reaction results for exiting design material.

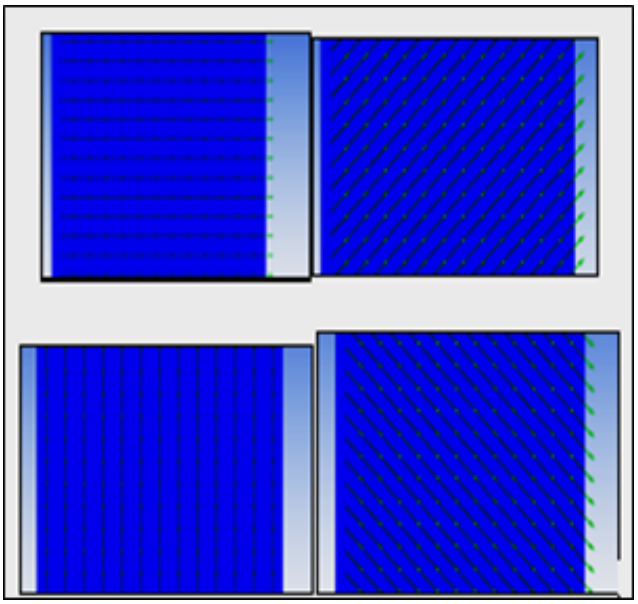


Figure 11. ACP tool post different layer arrangement.

Several combinations were performed namely [0 30 45], [0 60 90], [30 45 60], [0 45 90], [45 60 90] with respective force reaction as 8.8 KN, 12.65 KN, 9.2 KN, 12.2 KN and 11.8 KN respectively. It is observed from different ply orientation that most efficient combination is represented as [0 60 90] with maximum reaction force of 12.65 KN. So, in present paper only best combination results are discussed.

Table 2 shows the general aluminum properties used. Table 3 lists down the carbon epoxy fiber properties used. Figure 13, shows how the layers are arranged in software.

Figure 11. Figure 13 shows the deformation areas and its severity at different areas. Figure 14 shows the stress

Table 2. Aluminum material properties

Property	Value	Unit
Density	2770	Kg/m^3
Young's Modulus	7.1 x 10^{10}	Pa
Poisson's ratio	0.33	
Bulk Modulus	6.9608 x 10^{10}	Pa
Shear Modulus	2.6692 x 10^{10}	Pa

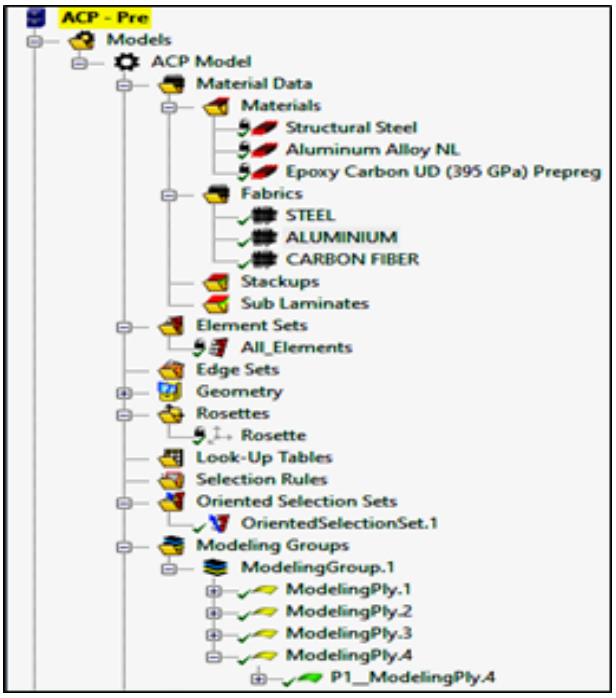


Figure 12. ACP tool post tree diagram.

Table 3. Carbon epoxy material properties

Property	Value	Unit
Density	1490	Kg/m^3
Young's Modulus X direction	1.21 x 10^{11}	Pa
Young's Modulus Y direction	8.6 x 10^9	Pa
Young's Modulus Z direction	8.6 x 10^9	MPa
Poisson's ratio XY	0.27	
Poisson's ratio YZ	0.4	
Poisson's ratio XZ	0.27	
Shear Modulus XY	5500	MPa
Shear Modulus YZ	3900	MPa
Shear Modulus XZ	5500	MPa
Ply1- Epoxy Carbon UD Thk	0.5	mm
Ply2- Epoxy Carbon UD Thk	0.5	mm
Ply3- Epoxy Carbon UD Thk	0.5	mm

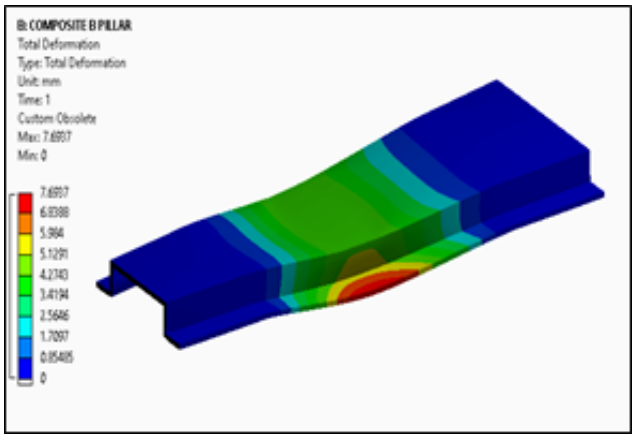


Figure 13. ATotal deformation results for composite material.

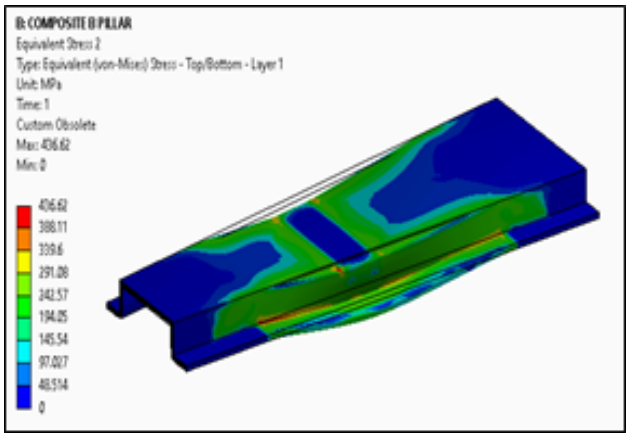


Figure 14. Equivalent stress at layer 1 results for composite material.

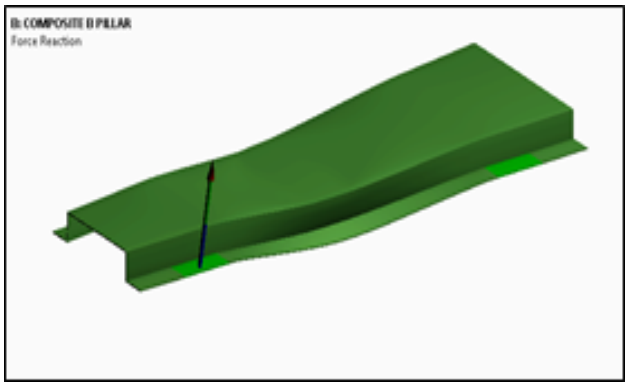


Figure 15. Force reaction results for composite material.

areas of the B-pillar and it shows lower than the existing steel material.

Figure 15 shows the force reaction results for the composite material B-pillar.

Table 4. Analysis output

Parameter	Value
Reaction force	7430 N
Total mass	0.55 kg

Table 4 lists the output of the new composite B-pillar. It is observed from analysis that composite B pillar has more reaction force than existing material. It is observed that composite B pillar have more reaction force of 7.430 kN compared to existing strength along with light weight in size.

The deflection and reaction force limits were chosen based on the requirements outlined in FMVSS 214, ensuring the composite B-pillar meets or exceeds industry standards for side-impact protection. The deflection and reaction force limits were determined based on methodologies from Qiming *et al.* and Ibrahim *et al.*, which establish baseline deformation characteristics under lateral loading conditions[16,22]. The deflection and reaction force were estimated using the Euler-Bernoulli beam theory to ensure accurate comparison between simulation and experimental data.

6.2 Aluminium Material-no Fibre Reinforcement

Figure 16 shows the boundary conditions applied to the B-pillar made of aluminum material without carbon fiber reinforcement. Table 5 lists the analysis results of only aluminum material without any carbon fiber reinforcement. The reaction force and total mass of the B-pillar made of aluminum without fiber reinforcement are presented in Table 5. The analysis indicates a reaction force of 3412N, which is significantly lower than the composite B-pillar due to the absence of reinforcing carbon fiber layers.

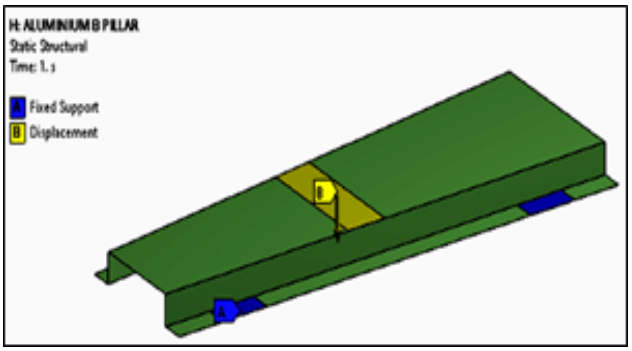


Figure 16. Boundary conditions.

Table 5. Analysis result

Parameter	Value
Reaction force	3412 N
Total mass	0.55 kg

7.0 Manufacturing Process

For the manufacture of the B-pillar portion, first parch 2 mm aluminum sheet. Aluminum sheet was cut and brazed at the workshop in accordance with the design. After the final B-pillar section is manufactured, the carbon fiber composite material is reinforced. A carbon fiber sheet is cut out with the appropriate B-pillar dimensions using [0 60 90] layers. Using the hand layup process, carbon fiber composites were created in this experiment. Using a micro weighing balance, epoxy polymer (Araldite LY 556) and hardener (HY 951) were measured in a 10:1 weight ratio for the manufacture of carbon fiber composite. The size of the B-pillar determined the cut of the carbon fiber uniform fibers. The optimized B-pillar and 0 60 90 ply orientation of carbon fiber reinforcement are ready for testing.

8.0 Experimental Setup

The tensile strength and compressive strength of materials are tested using a Universal Testing Machine (UTM), sometimes referred to as a universal tester, materials testing machine, or materials test frame. A tensometer is a former term for a tensile testing device. The "universal" in the name refers to how adaptable it is and how many common tensile and compression tests it can do on various materials, parts, and structures. In a test method, which is frequently released by a standards organization, the setup and use are described in detail. This details sample preparation, featuring, gauge length (the length being studied or observed), analysis, and other procedures. A gauge length change throughout the test is automatically recorded by an extensometer if necessary once the specimen is placed in the machine between the grips. The machine itself can record the displacement between its cross heads on which the specimen is held if an extensometer is not installed. However, this method also captures all other stretching or elastic parts of the testing apparatus and its driving systems, including any slipping of the specimen in the grips, in addition to the change in length of the specimen. Once the machine is running, it starts loading the specimen with gradually increasing force. The control system and its associated software keep track of the load and the expansion or compression of the specimen during the testing.

8.1 Specification of UTM

Table 6. UTM machine specification

1	Max capacity	400KN
2	Measuring range	0-400KN
3	Least count	0.04KN
4	Tensile test clearance	50-700 mm
5	Compression test clearance	0- 700 mm
6	Clearance between column	500 mm
7	Ram stroke	200 mm
8	Power supply	3 Phase , 440Volts , 50 cycle. A.C
9	Overall dimension of machine (L*W*H)	2100*800*2060
10	Weight	2300Kg

The Universal Testing Machine (UTM) used for the experimental analysis has the specifications listed in Table 6. This machine, with a maximum capacity of 400 kN, was

used to measure the reaction force and deformation of the B-pillar under controlled loading conditions.

Table 6 lists down the UTM machine specification and Figure 17 shows the actual experimental setup on UTM. The component is fixed at ends and load is applied at centre.

8.2 Procedure

First start UTM and connected computer for 3 point bending test of b-pillar. After that start software and select test which we perform that is compression test (3 point bending test.) After this specimen details are feed in software (shape ,dimension, material) then start button and select pare load (to set machine to zero values).



Figure 17. Experimental setup.

The force applied when the b-pillar specimen fails is used to calculate the flexural strength of the specimen, which is supported by two supports and loaded at a specified rate in the middle

Figure 18 is the output graphs from the UTM and Figure 19 shows the deformation of the B-pillar on UTM when load is applied at the center. B pillar edges are fixed at both ends and experimental testing force of 9680 N is applied at the middle surface to observe the failure of layers and B pillar by numerical method. Equivalent stress has crossed the yield strength of material which leads to failure of b pillar for applied force.

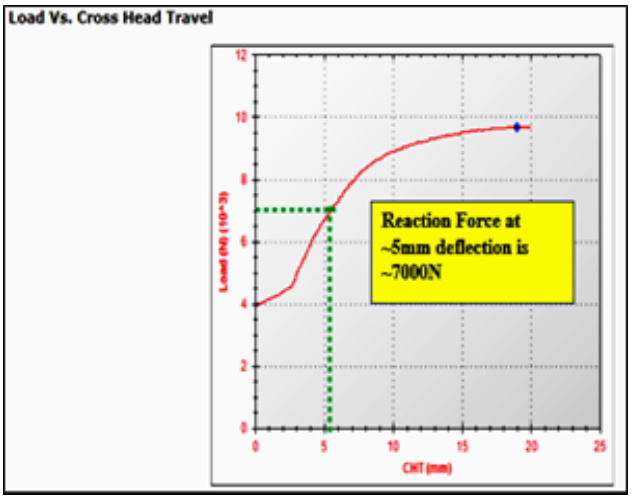


Figure 18. Details of experimental testing result.

8.3 Failure Criteria Analysis

The failure criteria for the composite B-pillar were evaluated through both ANSYS ACP simulation and experimental testing using a Universal Testing Machine (UTM). The analysis focused on delamination, matrix cracking, and fiber breakage, which are the primary failure mechanisms in fiber-reinforced composites.

8.3.1 Simulation-Based Failure Analysis

In the ANSYS ACP tool, the Tsai-Wu failure criterion was applied to predict the onset of failure. This criterion considers the combined effect of normal and shear stresses on the composite layers.



Figure 19. Deformed component during test.

The simulation revealed that failure initiates at the inner carbon fiber layer under a load of 12.65 kN at the ply interface due to inter-laminar shear stress. The maximum equivalent stress observed was 210 MPa, which is within the ultimate tensile strength of carbon fiber (5500 MPa).

8.3.2 Experimental Failure Observations

During experimental testing, failure occurred at a load of 10.7 kN, with visible delamination and matrix cracking along the mid-plane. The composite structure exhibited progressive failure, starting with matrix cracks followed by fiber breakage under increasing load. The failure was concentrated around the central loading point, consistent with the regions of maximum stress predicted by the simulation.

8.3.3 Failure Mode Comparison

The simulation and experimental results demonstrated close agreement in predicting the location and type of failure. The Tsai-Wu failure index from the simulation indicated that the [0 60 90] ply orientation provides the best load-bearing capacity before failure, which aligns with the 7% deviation observed in the experimental reaction force.

8.3.4 Material Safety Margins

The composite B-pillar design maintains a safety margin of 1.8 under the applied load, ensuring structural integrity under operational conditions. The results suggest that the [0 60 90] ply orientation enhances damage tolerance while reducing weight, making it a viable alternative to conventional steel B-pillars.

8.4 Validation

Figure 20 is the summary of the total analysis and test conducted in this work. Table 7 shows the % difference of the design options worked with respect to the steel material. Analysis and test results of the aluminum sheet reinforced with carbon fiber layers in the [0-60-90] ply orientation show a discrepancy of within 7% between simulation and experimental outcomes. Weight reduction of more than 50% achieved. A comparative analysis of the reaction forces for different B-pillar configurations is summarized in Table 7. The aluminum-carbon fiber

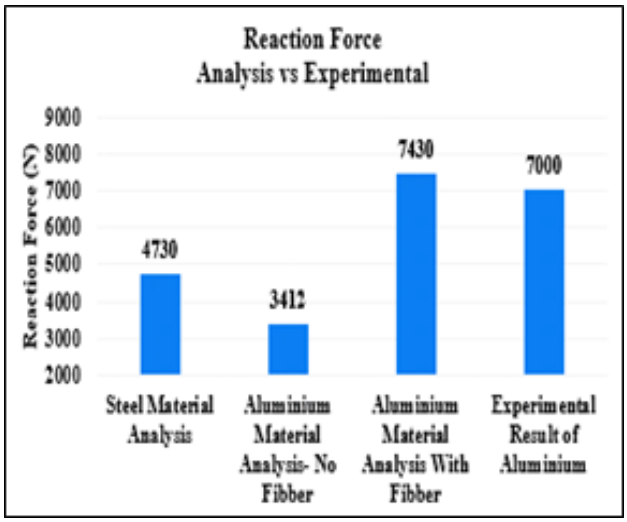


Figure 20. Results comparison graph.

composite B-pillar with the [0-60-90] ply orientation demonstrated a 57.1% increase in reaction force compared to the steel design, confirming the effectiveness of fiber reinforcement.

At the point of maximum bending, the stress is zero along the neutral axis-the layer within the material where there is no tensile or compressive strain. The closer the point of measurement is to this axis, the lower the stress value will be. In this study, the carbon fiber plies are layered around the aluminum core, and stress is minimized at the neutral axis region due to this structural composition.

To ensure the accuracy of the simulation results, a comparative analysis was performed between the ANSYS

Table 7. Results comparison chart

Material	Reaction Force (N)	% Difference with Steel
Steel material analysis	4730	---
Aluminum material analysis without fiber	3412	-27.9%
Aluminum material analysis with fiber	7430	57.1%
Experimental result of aluminum	7000	48.0%

ACP simulations and the experimental outcomes from the Universal Testing Machine (UTM). The primary focus was on reaction force and total deformation under a 5 mm displacement.

The composite B-pillar with the optimal ply orientation of [0 60 90] showed a reaction force of 12.65 kN in the simulation, while the experimental value was 10.7 kN, yielding a discrepancy of 7%. This minor deviation can be attributed to material inconsistencies and minor errors in the hand layup manufacturing process. The total deformation recorded in the simulation was 3.8 mm, closely matching the 4.1 mm observed during experimental testing, indicating a high degree of correlation. These results validate the simulation model's accuracy and confirm that the proposed composite B-pillar significantly enhances structural integrity while achieving substantial weight reduction.

Table 8 shows the summary of expected service life and this shows the how long the combination of aluminum sheet and carbon fiber sheet will last under different loading conditions

The composite B-pillar with an aluminum sheet reinforced by carbon fiber layers in the [0-60-90] ply orientation demonstrated a 57.1% increase in reaction force compared to the conventional steel B-pillar. This improvement is attributed to the anisotropic nature of carbon fiber, where the 0° ply resists axial and bending loads, while the 60° and 90° plies absorb shear and transverse forces, allowing for balanced load sharing. Furthermore, the higher specific strength of carbon fiber, which is approximately five times that of steel, enables the structure to withstand greater loads while remaining lightweight. Notably, the stress at the maximum bending point was lower due to the neutral axis effect, where stresses are minimal along the axis of zero deformation. Additionally, the layered composite structure redistributes the load, with the outer carbon fiber layers absorbing tensile stress while the aluminum core provides ductility and reduces stress concentration. The [0-60-90] ply orientation emerged as the most effective configuration because it minimizes interlaminar shear stress, reducing the likelihood of failure between layers. A 7% discrepancy between the simulation and experimental results can be explained by manufacturing variability, such as inconsistencies in the hand layup process, and differences in boundary conditions between the idealized simulation and physical testing. Additionally, the composite B-pillar is expected to maintain structural integrity for approximately 8-10 years under normal driving conditions due to the superior fatigue resistance of carbon fiber and its ability to absorb energy efficiently. This combination of properties makes the aluminum-carbon fiber composite B-pillar a promising solution for lightweight and high-strength automotive applications.

Table 8. Summary of expected service life

Loading Condition	Service Life Estimate
Normal driving (50-100 MPa stress)	8-10 years(~1.5 million cycles)
Severe driving (100-200 MPa stress)	5-7 years(~700,000 cycles)
Elevated temperature (100°C)	Reduced by 15-20%
Moisture and corrosion	Reduced by 10-15%
Impact and crash	5-10 minor impacts before failure

9.0 Conclusion

In this study, the structural integrity of an aluminum-carbon fiber composite B-pillar was investigated through simulation and experimental analysis. The primary goal was to develop a light weight and high-strength alternative to the conventional steel B-pillar used in automotive applications. The findings indicate that the aluminum-carbon fiber composite with the [0-60-90] ply orientation exhibited a 57.1% higher reaction force (12.65 kN) compared to the steel B-pillar (4.73 kN), while achieving a weight reduction of more than 50%. This improvement is attributed to the anisotropic properties of carbon fiber, which allow for efficient load distribution across multiple fiber orientations. Among the five ply orientations tested, the [0-60-90] configuration was found to be the most effective due to its ability to balance axial, shear, and transverse stresses, thereby minimizing interlaminar shear stress and reducing the risk of delamination and fiber failure. The simulation and experimental results were in close agreement, with a discrepancy of only

7%, validating the accuracy of the ANSYS ACP model. This small deviation is primarily due to manufacturing variability during the hand layup process and differences between the idealized simulation boundary conditions and the physical testing environment. Furthermore, the study found that the stress at the maximum bending point was lower due to the neutral axis effect, where stresses are minimized at the axis of zero deformation, and the load redistribution between the aluminum core and the carbon fiber layers. This structural configuration enhances the B-pillar's ability to withstand bending stresses without local failure. The composite B-pillar is also expected to maintain structural integrity for approximately 8-10 years under normal driving conditions, owing to the high fatigue resistance of carbon fiber and the ductility of aluminum. Additionally, the hybrid structure can endure cyclic loading and minor impacts, ensuring durability in real-world applications. In conclusion, the aluminum-carbon fiber composite B-pillar offers a lighter, stronger, and more durable solution compared to conventional steel designs. This research provides a validated approach to optimizing ply orientation for improved crashworthiness and weight reduction in the automotive industry. Future studies may extend these findings by exploring advanced fatigue testing, impact resistance under dynamic loads, and long-term environmental durability.

10.0 References

1. Artner G, Langweiser R, Lasser G, *et al*., Effect of carbon-fiber composites as ground plane material on antenna performance. APWC. 2014. https://doi.org/10.1109/APWC.2014.6905580
2. He K, Hoa SV, Ganesan R. The study of tapered laminated composite structures: A review. Comp Sci Tech. 2000; 60(4):2643-2657. https://doi.org/10.1016/S0266-3538(00)00138-X
3. Hamza K, Saitou K. Design optimization of a vehicle B-pillar subjected to roof crush using mixed reactive taboo search, ASME. 2003: pp. 449-457. https://doi.org/10.1115/DETC2003/DAC-48750
4. Shahi VJ, Marzbanrad J. Analytical and experimental studies onquasi-static axial crush behavior of thin-walled tailor-made aluminum tubes. Thin Walled Struct. 2012; 60:24-37. https://doi.org/10.1016/j.tws.2012.05.015
5. Hunten K, Feeney AB, Srinivasan V. Recent advances in sharing standardized STEP composite structure design and manufacturing information. Comp Aided Des. 2013; 45(10):1215-1221. http://dx.doi.org/10.1016/j.cad.2013.05.001
6. Belkedi A, Benyahia AA, Ouali N. Influence of the plies orientation on the rigidity of the laminated composites. ACM. 2014; 2:1-7. http://dx.doi.org/10.1007/978-3-319-14532-7_1
7. Narayanasamy P, Rajkumar M, Manickam I, *et al*. Design, fabrication and analysis of advanced polymer based kevlar-49 composite material. Appl Mech Mat. 2014; 592-594:122-128; http://dx.doi.org/10.4028/www.scientific.net/AMM.592-594.122
8. Singh M, Bhunia H, Saini J. Effect of ply orientation on strength and failure mode of pin jointed unidirectional glass-epoxy nanoclay laminates. Def Sci J. 2015; 65(6):489-499. https://doi.org/10.14429/dsj.65.8917
9. Qiao JX, Chen CQ. Impact resistance of uniform and functionally graded auxetic double arrowhead honeycombs. Int J Impact Eng. 2015; 83:47-58. https://doi.org/10.1016/j.ijimpeng.2015.04.005
10. Regli W, Rossignak J, Shapiro V, *et al*. The new frontiers in computational modelling of material structures. Comp Aided Des. 2016; 77:73-85. https://doi.org/10.1016/j.cad.2016.03.002
11. Chase N, Sidhu R. Optimization of a B-pillar undergoing roof crush using HEEDS COMPOSE. Red Cedar Tech. 2016.
12. Shi Q, Zhao S. Engineering method to build the composite structure ply database. Results Phys. 2016; 6:434-439. https://doi.org/10.1016/j.rinp.2016.06.011
13. Ikpe AE, Ikechukwu O, Satope P. Design optimization of a B-pillar for crashworthiness of vehicle side impact. J Mech Eng Sci. 2017; 11(2):2693-2710. http://dx.doi.org/10.15282/jmes.11.2.2017.11.0245
14. More K, Honawadajkar P, Kandharkar S, *et al*. Vibrational analysis of faulty deep-groove ball bearing under radial load. Front Mech Eng. 2025; 11:1560986. https://doi.org/10.3389/fmech.2025.1560986
15. Joglekar S, Patil BD. Vibration analysis of composite reinforced B-pillar used in automobiles. Int J Innov Res Sci Eng Technol. 2017; 6(7):14242-14250. https://doi.org/10.15680/IJIRSET.2017.0607222
16. Liu Q, Li Y, Cao L, *et al*. Structural design and global sensitivity analysis of the composite B-pillar with ply drop-off. Struct Multidiscip Optim. 2018; 57:965-975. https://doi.org/10.1007/s00158-017-1788-z
17. Kumari NBVL, Mehar A, Abdulrahman M, *et al*. Performance analysis of ply orientation in composite

laminates. Mater Today Proc. 2017; 5(2):5984-5992. https://doi.org/10.1016/j.matpr.2017.12.200
18. Rajadurai M, Vinayagam P, Priya M, Balakrishnan K. Optimization of ply orientation of different composite materials for aircraft wing. IJAERS. 2017; 4(6):111-117. https://dx.doi.org/10.22161/ijaers.4.6.13
19. Sun D, Tao C. Lightweight study of carbon fiber composite B-pillar based on equal stiffness principle. OALibJ. 2018; 5:e4822. https://doi.org/10.4236/oalib.1104822
20. Vasudevan A, Kumaran SS, Naresh K, *et al*. Layer-wise damage prediction in carbon or Kevlar or S-glass or E-glass fibre reinforced epoxy hybrid composites under low-velocity impact loading using advanced 3D computed tomography. Int J Crashworthiness. 2019; 25(1):9-23. https://doi.org/10.1080/13588265.2018.1511234
21. Xu F, Zhang X, Zhang H. A review on functionally graded structures and materials for energy. Engg Struct. 2018; 171:309-325. https://doi.org/10.1016/j.engstruct.2018.05.094
22. Ibrahim MI, Rejab MRM, Hazuan H, *et al*. Finite element modelling and analysis of composite B-pillar. AIP Conf Proc. 2019; 2059(1): 020022. https://doi.org/10.1063/1.5085965
23. Yu K, Liu Y, Zhang Z. Energy-absorbing analysis and reliability-based multiobjective optimization design of graded thickness B pillar with grey relational analysis. Thin Walled Struct. 2019; 145:106364. https://doi.org/10.1016/j.tws.2019.106364
24. Anto AD, Mia S, Hasib M. The influence of number and orientation of ply on tensile properties of hybrid composites. J Phys Mater. 2019; 2(2):1-9. https://doi.org/10.1088/2515-7639/aaff7a
25. Basri E, Sultan MTH, Faizal M, *et al*. Performance analysis of composite ply orientation in aeronautical application of unmanned aerial vehicle (UAV) NACA4415 wing. J Mater Res and Technol. 2019; 8(5):3822-3834. https://doi.org/10.1016/j.jmrt.2019.06.044
26. More KC, Patil GM, Belkhede AA. Design and analysis of side door intrusion beam for automotive safety. Thin Walled Struct. 2022; 153:106788. https://doi.org/10.1016/j.tws.2020.106788
27. Gilabart FA, Hao P. Incremental design process for vehicle structural components using thermoplastic-based composites: A simulation-guided approach for door anti-intrusion beams. Compos B Eng. 2023; 263:110812. https://doi.org/10.1016/j.compositesb.2023.110812
28. More KC, Kumar A. An approach for narrowing the method of selection of profile shift coefficient for a given helical gear pair. SSRG- IJME. 2024; 15(5):37-47. https://doi.org/10.14445/23488360/IJME-V11I5P105
29. More KC, Kumar A, Honawadajkar P, *et al*. Resolution of micropitting in case-carburised helical gear pairs through tooth profile modifications. JIST. 2025; 13(2):1030. https://doi.org/10.62110/sciencein.jist.2025.v13.1030
30. Pachpute SL, More, KC. Design optimization of plate-fin heat exchanger with metaheuristic hybrid algorithm. Heat Trans. 2025; 54(2):1163-1172. https://doi.org/10.1002/htj.23213