

Comparative Crashworthiness Assessment of Advanced Materials for Automotive Front Bumper Systems Using Finite Element Analysis

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ABSTRACT:

Automotive bumper systems play an important role in absorbing and dissipating impact energy and limiting the transmission of crash loads to the vehicle structure. This study evaluated the crashworthiness and energy absorption characteristics of Glass Mat Thermoplastics (GMT), Carbon Fibre Reinforced Polymer (CFRP) and Expanded Polypropylene (EPP) using finite element analysis. A three-dimensional bumper model was developed and analyzed in ANSYS Workbench Explicit Dynamics under identical frontal impact conditions. A 1500 kg impactor was assigned an initial velocity of 56 km/h (15.56 m/s), corresponding to an initial kinetic energy of approximately 181.6 kJ. The bumper models were constrained at their mounting locations and subjected to surface-to-surface contact with a rigid impactor. A mesh convergence study was conducted, and a final element size of 5 mm was adopted after the monitored response varied by less than 5% with further refinement. The principal performance indicators were total deformation, equivalent (von Mises) stress, and internal energy. In this study, the reported energy absorption represents the internal energy output calculated by the ANSYS Explicit Dynamics solver and is therefore interpreted as the numerically predicted energy absorbed by each bumper model under the specified impact conditions. CFRP produced a maximum deformation of 31.75 mm and an internal energy output of 148.27 kJ, while GMT produced 52.40 mm and 62.15 kJ, respectively. EPP produced the largest deformation of 84.85 mm and an internal energy output of 96.38 kJ. The corresponding maximum equivalent stresses were 428.57 MPa for CFRP, 392.14 MPa for GMT and 215.83 MPa for EPP. These numerical results provide a consistent basis for comparison of the crash response of the three materials under the same impact loading and show clear differences in deformation, stress, and internal energy response. The findings indicate that material properties strongly influence bumper crash behaviour and that different materials may provide different structural and energy absorbing functions in automotive bumper systems. Experimental validation is required to verify the numerical predictions and establish the applicability of the simulated results under physical crash conditions. Further work may also consider optimization of material distribution, bumper geometry, impact conditions and environmental effects.

KEYWORDS:

Automotive bumper, Crashworthiness, Energy absorption, Explicit Dynamics, Finite element analysis.

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I. INTRODUCTION

Road traffic crashes remain an important public-safety concern, and automotive bumper systems contribute to the management of impact loads during vehicle collisions. A bumper is designed to absorb and dissipate impact energy, control structural deformation and reduce the transmission of crash loads to other vehicle components. Conventional bumper systems have traditionally incorporated metallic structural members, including steel and aluminium, together with polymer-based fascia components. However, the continuing demand for lightweight vehicles has increased interest in advanced materials that can provide favourable combinations of specific strength, stiffness, deformation capacity and energy absorption.

Advanced materials, including fibre-reinforced polymers, cellular polymers, sandwich structures, metallic foams and functionally graded materials, have been investigated for automotive crash applications because they can dissipate impact energy through different material and structural mechanisms. Fibre-reinforced composites may dissipate energy through fibre fracture, matrix cracking, delamination and progressive crushing, whereas cellular polymers such as expanded polypropylene can absorb energy through controlled cell collapse and compressive deformation. These mechanisms provide opportunities for reducing structural mass while maintaining required crashworthiness performance.

Previous studies have demonstrated that material selection significantly affects bumper impact response. However, comparisons among different material classes are often conducted using different bumper geometries, impact velocities, masses, boundary conditions, contact definitions and numerical modelling approaches. Such differences can make it difficult to distinguish whether variations in reported crash performance arise from the material itself or from differences in the simulation setup. In addition, studies focusing on individual materials generally provide detailed information about their respective deformation and energy-absorption mechanisms but do not necessarily provide a direct comparison between composite, thermoplastic and cellular polymer materials under a common set of impact conditions. These limitations indicate the need for a controlled numerical comparison in which the principal geometric, loading, contact and boundary-condition parameters are maintained consistently.

Accordingly, the present study contributes a comparative finite element assessment of Glass Mat Thermoplastic (GMT), Carbon Fibre Reinforced Polymer (CFRP), and Expanded Polypropylene (EPP) using a common three-dimensional automotive front-bumper model and identical frontal impact conditions. The comparison is based on total deformation, equivalent (von Mises) stress, and internal energy obtained from the ANSYS Explicit Dynamics solver. By maintaining the same impact mass, impact velocity, bumper geometry, mounting constraints, contact formulation and general numerical procedure, the study provides a consistent basis for examining differences in the simulated crash response of the three materials. The numerical results are intended to support material selection for bumper crash-energy management, while experimental testing remains necessary to validate the finite element predictions.

II. MATERIAL AND METHODS

Finite Element Model Development

Finite Element Analysis (FEA) was selected as the numerical approach because the impact problem involves transient loading, large deformation, nonlinear contact, and material-dependent structural response. A three-dimensional bumper assembly consisting of the bumper structure and associated impact-facing geometry was developed using computer-aided design and imported into ANSYS Workbench. The analysis was performed using the Explicit Dynamics module. The same bumper geometry and loading arrangement were maintained for GMT, CFRP and EPP to permit direct comparison. This modelling approach was selected to provide a consistent numerical framework in which the effect of material selection could be compared under identical geometric, loading and boundary conditions. For CFRP, an equivalent homogeneous isotropic representation was adopted to maintain consistency with the comparative finite element formulation. As a result, the model does not explicitly account for fibre orientation, orthotropic laminate behaviour, or local variations in directional stiffness. Similarly, detailed damage mechanisms such as matrix cracking, fibre fracture, delamination, progressive crushing and material degradation were not explicitly represented. These assumptions simplify the model and are appropriate for the comparative numerical assessment undertaken, but they limit its ability to predict detailed composite failure behaviour under an actual crash event.

Material Definition

The three investigated materials were Glass Mat Thermoplastics (GMT), Carbon Fibre Reinforced Polymer (CFRP), and Expanded Polypropylene (EPP). The numerical model used equivalent homogeneous material properties based primarily on density, Young's modulus, and Poisson's ratio. CFRP was represented using an equivalent isotropic formulation; consequently, orthotropic laminate behaviour, fibre orientation, matrix cracking, fibre fracture and delamination were not explicitly modelled. Equivalent von Mises stress was therefore treated as a comparative structural-response indicator rather than a composite failure criterion. The material models also did not explicitly incorporate material-specific failure strain limits or progressive damage evolution. Consequently, failure initiation and post-failure behaviour, including fracture, crushing, cracking, delamination and stiffness degradation were not explicitly captured. In addition, strain-rate-dependent material behaviour was not explicitly considered, although the materials can exhibit different mechanical responses under high-rate impact loading. Therefore, the predicted stress, deformation and internal-energy responses should be interpreted as comparative numerical results under the specified modelling assumptions rather than as a complete representation of material failure behaviour under actual crash conditions.

Table I: Materials properties

Material	Density (kg/m ³)	Young's modulus (GPa)	Poisson's ratio
GMT	2000	12	0.30
CFRP	1600	150	0.27
EPP	2000	0.15	0.30

Impact and Boundary Conditions

A rigid steel impactor representing an effective 1500 kg passenger vehicle mass was assigned an initial longitudinal velocity of 56 km/h (15.56 m/s). The corresponding initial kinetic energy was approximately 181.6 kJ. The bumper was constrained at its mounting locations to represent attachment to the vehicle chassis, while the remaining surfaces were allowed to deform during impact. Surface-to-surface contact was defined between the impactor and bumper using the Penalty Contact algorithm, with a friction coefficient of 0.20. Contact separation after impact was permitted. These loading and boundary conditions represent a controlled comparative crashworthiness assessment, with the same impact conditions applied consistently to each bumper material to enable direct comparison of their deformation and energy absorption responses.

Meshing and Numerical Solution

The bumper geometry was discretized using tetrahedral finite elements suitable for the complex three-dimensional geometry and nonlinear impact response. A mesh convergence study was performed using progressively refined meshes. The monitored deformation and stress response approached convergence with refinement, and a final element size of 5 mm was adopted because further refinement resulted in less than 5% change in the monitored response. The final mesh contained 148,972 elements and 196,845 nodes. The transient analysis was conducted for 0.020 s using automatic time stepping with the stable time increment determined internally by the Explicit Dynamics solver. Numerical stability was assessed using the energy histories, with hourglass energy maintained below 5% of total internal energy.

Crashworthiness Performance Indicators

The bumper materials were compared using three principal indicators: total deformation, equivalent (von Mises) stress, and internal energy absorption. Total deformation was used to describe the magnitude of structural displacement during impact. Equivalent stress was used to compare the internal stress response under the common loading condition. Internal energy recorded by the explicit solver was used as the principal measure of energy absorbed through structural deformation and material response.

III. RESULTS AND DISCUSSION

Comparative Simulation Results

Table II: Material results

Material	Maximum deformation (mm)	Maximum von Mises stress (MPa)	Energy absorption (kJ)
GMT	52.40	392.14	62.15
CFRP	31.75	428.57	148.27
EPP	84.85	215.83	96.38

The simulation results show clear differences in the structural response of the three bumper materials. CFRP produced the smallest total deformation, whereas EPP produced the largest deformation. GMT exhibited an intermediate deformation response. The results indicate that the stiffness of the material strongly influenced the extent to which the bumper displaced during impact.

Deformation Response

CFRP recorded a maximum deformation of 31.75 mm. Its comparatively high Young's modulus enabled the bumper structure to resist deformation under the imposed impact load. GMT recorded 52.40 mm, representing an intermediate deformation response. EPP recorded 84.85 mm, reflecting the highly compressible cellular structure of the polymer foam. The large deformation of EPP is associated with progressive cellular compression and energy dissipation through deformation. Within the modelled configuration, the EPP response supports its use as an energy-absorbing insert rather than as the principal load-bearing bumper member.

Stress Response

The maximum equivalent stresses were 428.57 MPa for CFRP, 392.14 MPa for GMT, and 215.83 MPa for EPP. The relatively high CFRP stress is consistent with its high stiffness and ability to carry larger internal loads while undergoing limited deformation. GMT exhibited an intermediate stress level, while EPP produced the lowest equivalent stress because a greater portion of the impact response was accommodated through

cellular deformation. These stress levels should be considered together with the deformation and energy absorption responses: CFRP recorded the lowest total deformation of 31.75 mm and the highest internal energy absorption of 148.27 kJ, indicating a relatively stiff response with substantial load-carrying and energy-absorption capability. GMT showed a higher deformation of 52.40 mm and an intermediate stress level, reflecting greater structural deformation during impact. EPP exhibited the lowest equivalent stress and absorbed 96.38 kJ, with its deformation response primarily associated with cellular compression and energy dissipation. Thus, the differences in stress, deformation, and energy absorption reflect the different mechanisms by which the three materials accommodate the applied impact loading. In terms of failure behaviour, the present simulations provide stress and deformation responses rather than direct predictions of material fracture or damage initiation. Because CFRP was modelled as an equivalent homogeneous isotropic material, the stress values should not be interpreted as predictions of fibre fracture, matrix cracking or delamination.

Energy Absorption

The initial impact kinetic energy was approximately 181.6 kJ. CFRP absorbed 148.27 kJ, corresponding to the largest internal energy absorption among the three materials. EPP absorbed 96.38 kJ, while GMT absorbed 62.15 kJ. The remaining energy in the impact event was associated with other numerical and physical energy components, including residual kinetic energy and contact interactions. The relatively high CFRP energy absorption is associated in the dissertation discussion with the high strength and stiffness of the carbon-fibre composite and its ability to redistribute load through the structure. EPP dissipated energy mainly through progressive crushing of its cellular structure, while GMT exhibited a lower energy absorption response under the same simulated conditions.

Comparative Engineering Interpretation

The results demonstrate that bumper material selection affects the balance among stiffness, deformation, energy absorption, weight, manufacturability, and cost. CFRP combined high energy absorption with low deformation and relatively low density, whereas GMT provided an intermediate structural response together with manufacturing and cost advantages identified in the dissertation. EPP combined low structural stiffness with substantial energy absorption and large deformation, supporting its application as an auxiliary energy-absorbing component. Therefore, the appropriate material arrangement depends on the intended structural role and the required balance between crash response and practical manufacturing considerations.

IV. MODEL VALIDATION AND BENCHMARK

The finite element results were compared with benchmark ranges compiled in the dissertation from published crashworthiness literature. All three materials produced deformation, stress, and energy absorption values within the corresponding benchmark ranges used for the study. This comparison provides numerical consistency with the reported literature, although it does not replace physical experimental validation of the complete bumper system.

Table III: Materials Parameters

Material	Parameter	Simulation value	Literature source	Benchmark range	Percentage difference (%)
GMT	Deformation	52.40 mm	Wang and Li (2022)	45-80 mm	94.5%
GMT	Stress	392.14 MPa	Hu et al. (2023)	350-500 MPa	97.2%
GMT	Energy absorption	62.15 kJ	Wang and Li (2022)	50-90 kJ	91.1%
CFRP	Deformation	31.75 mm	Hu et al. (2023)	25-60 mm	74.8%
CFRP	Stress	428.57 MPa	Hosseinzadeh et al. (2025)	380-520 MPa	92.5%
CFRP	Energy absorption	148.27 kJ	Shenoy et al. (2024)	120-180 kJ	83.6%
EPP	Deformation	84.85 mm	Halder et al. (2026)	70-110 mm	79.9%
EPP	Stress	215.83 MPa	Kim et al. (2025)	150-300 MPa	88.5%
EPP	Energy absorption	96.38 kJ	Mallela and Sharma (2023)	70-120 kJ	84.7%

V. CONCLUSION

This study evaluated the crashworthiness response of automotive frontal bumper systems made from GMT, CFRP and EPP under identical frontal impact conditions using ANSYS Explicit Dynamics. The comparison considered total deformation, equivalent von Mises stress, and internal energy absorption. CFRP recorded 31.75 mm maximum deformation and 148.27 kJ energy absorption, GMT recorded 52.40 mm and 62.15 kJ, and EPP recorded 84.85 mm and 96.38 kJ, respectively. The maximum equivalent stresses were 428.57 MPa, 392.14 MPa, and 215.83 MPa for CFRP, GMT, and EPP. The results show that the mechanical

properties and structural characteristics of the materials substantially influence bumper impact response under the investigated simulation conditions. The numerical results also fell within the benchmark ranges used for the study, supporting the consistency of the FE model with the selected literature data. These findings are limited to the specified bumper geometry, material models, impact mass and velocity, boundary conditions, contact assumptions and numerical modelling conditions investigated in this study and should not be interpreted as general predictions of full-vehicle crash performance or physical failure behaviour.

VI. RECOMMENDATIONS

The findings support consideration of advanced composite and polymeric materials in lightweight bumper development where the required structural and crashworthiness requirements can be achieved. Bumper designs should promote progressive deformation and efficient energy absorption while limiting excessive load transmission to the vehicle structure. Future studies should investigate hybrid bumper configurations combining CFRP, GMT, EPP or other advanced materials; different impact velocities, oblique impacts, and off-center collisions; and the effects of temperature, moisture, ageing, and ultraviolet exposure. Experimental crash testing should also be conducted to validate the numerical predictions. In addition, topology optimization, response-surface methods, genetic algorithms or related optimization approaches can be applied to determine suitable material distributions and geometric parameters for reducing mass while maintaining controlled deformation and energy absorption. Manufacturing cost, recyclability and environmental implications should also be evaluated.

VII. CONTRIBUTION OF THE STUDY

The study contributes a comparative finite element assessment of GMT, CFRP, and EPP under identical frontal impact conditions. It provides quantitative evidence on deformation, equivalent stress, and energy absorption and demonstrates how these indicators can be used to assess material behaviour in automotive bumper applications. The study also provides a numerical basis for considering material-specific structural roles and for guiding future experimental and optimization studies of lightweight bumper systems.

Declarations

Funding: No specific external funding was reported for this study.

Conflict of interest: The author declares no competing interests.

Ethics approval: Not applicable.

About the Author

Salum Rindini is a Master of Engineering student in Mechanical Engineering with Transportation Machinery at the National Institute of Transport (NIT), Tanzania. His research focuses on finite element simulation and crashworthiness assessment of advanced materials for automotive bumper systems.

Data Availability Statement

The numerical results and material-model information reported in this article are derived from the finite element simulation study. Additional non-confidential simulation information may be made available by the author upon reasonable request, subject to applicable institutional requirements.

Author Contributions

Salum Rindini: conceptualization, methodology, finite element modelling, simulation, data analysis, interpretation of results and manuscript preparation.

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