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Finite Element Analysis and Structural Performance of Composite Vehicle Bumpers

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Abstract:

- ***Background:***

The increasing demand for lightweight, durable, and impact-resistant automotive components has accelerated the adoption of composite materials in vehicle structural applications. Conventional metallic bumpers provide adequate strength but contribute significantly to vehicle weight, which adversely affects fuel efficiency and environmental sustainability. Fibre-reinforced polymer composites, particularly carbon fibre composites, offer a promising alternative because of their high strength-to-weight ratio, corrosion resistance and superior energy absorption characteristics. Finite Element Analysis (FEA) has become an essential tool for evaluating the structural performance of composite bumper systems under different loading conditions enabling engineers to optimize designs while reducing the need for costly experimental testing. Assessing the mechanical behaviour of composite bumper structures is therefore essential for improving vehicle safety, structural reliability and material efficiency.

- ***Method:***

A curved bumper beam was modelled in Abaqus/CAE (Computer Aided Engineering) using isotropic steel and an orthotropic, 13-ply carbon epoxy laminate. A uniform static pressure of 334135Pa was applied to the effective beam surface with constrained support regions. Mesh sensitivity was examined, and the third composite ply was evaluated at 20%, 40%, 60%, 80% and 100% of its original thickness. Stress and displacement were extracted along the beam.

- ***Results:***

The baseline steel and composite models produced peak stresses of 186MPa and 155MPa, respectively, and maximum displacements of 1.14mm and 1.94mm. The composite therefore showed 16.7% lower peak stress but 70.2% greater displacement. At 20% retained thickness in the third ply, peak stress increased to 541MPa and displacement to 7.58mm, approximately 3.49 and 3.91 times the intact composite values. Increasing retained thickness reduced both responses.

- ***Conclusion:***

The composite beam combined lower baseline peak stress with greater baseline displacement, while severe local thickness loss substantially increased both response measures. Laminate thickness and manufacturing tolerances must therefore be assessed together. These static results support comparative design screening, but do not establish impact energy absorption, failure initiation or regulatory crashworthiness.

Keywords: *Finite Element Analysis; Carbon Epoxy; Composite Vehicle Bumpers; Ply Thickness; Manufacturing Imperfections; Structural Performance*

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I. INTRODUCTION

Vehicle bumper beams distribute frontal loads and help limit damage to adjacent components. Composite alternatives to metallic beams are attractive because material selection and laminate architecture can be adjusted to meet structural and mass requirements [1]. Research on hybrid kenaf/glass epoxy bumper materials illustrates the importance of assessing mechanical properties for a specific bumper application rather than assuming that all composites provide equivalent performance [2].

According to [3], replacing steel with carbon epoxy changes more than density Steel can be represented by an isotropic elastic model whereas a fibre composite requires direction - dependent stiffness and an explicit definition of ply

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thickness and orientation. A design with reduced mass may still exhibit greater deflection under the same load [4]. Stress, displacement, material failure and energy absorption must consequently be treated as distinct performance measures [5].

Manufacturing quality introduces additional uncertainty. Material selection, component design and manufacturing route are interdependent, as discussed by [6]. Defects can alter the response of the finished component even when the nominal geometry and elastic constants appear suitable [7]. Studies of void geometry and manufacturing - induced defects show why defect characteristics matter to composite properties and damage development [8].

Furthermore, in recent years, the automotive industry has faced unprecedented pressure to minimize environmental impact driven by strict global regulations targeting carbon emissions and fuel efficiency [9]. Consequently, vehicle lightweighting has emerged as a primary engineering objective since every 10% reduction in vehicle weight translates to an approximate 6% to 8% improvement in fuel economy as a result, traditional heavy metals are systematically being phased out [10].

In automotive industry, International road traffic safety data and analysis (IRTAD) in 2017 report indicated that over 1.3 million people are dying every year worldwide with over 50m remaining injured due to accidents. It further reveals that in 2000, United States alone spent $59.9bn in accident compensations and United Kingdom $10bn. The UK expenditure of 70% was used on low-speed accident which would otherwise be controlled or minimized by use of composite material front bumper systems which would save more lives and reduce on expenditure.

Although existing literature has examined composite materials for automotive bumper applications, the combined consideration of baseline steel–composite structural comparisons and the sensitivity of a selected composite ply to progressive thickness reduction warrants further investigation. In particular, it is important to distinguish between lower calculated stress and greater structural stiffness, since a material configuration exhibiting lower peak stress may simultaneously experience greater displacement under identical loading conditions. Similarly, understanding the consequences of local ply thickness reduction can provide useful information for preliminary structural design and manufacturing quality assessment.

This study therefore investigates the structural performance of a curved automotive bumper beam manufactured from conventional steel and a 13-ply carbon epoxy composite laminate using Abaqus finite element modelling. The analysis compares maximum stress and displacement under a uniform static pressure and subsequently examines the influence of progressive thickness reduction in the third composite ply. Five retained-thickness conditions, corresponding to 20%, 40%, 60%, 80% and 100% of the original ply thickness, are considered.

II. METHODOLOGY

➢ *Research Design and Numerical Modelling Approach*

The study employed a deterministic numerical simulation approach using the finite element method to evaluate the structural performance of steel and carbon epoxy composite automotive bumper beams project [11]. Finite element modelling was performed using Abaqus/CAE, a computer-aided engineering software package capable of analysing structural responses under specified material properties, loading conditions and boundary constraints [12].

Two baseline bumper configurations were considered: an isotropic steel bumper beam and an orthotropic carbon epoxy composite bumper beam. The steel configuration served as the reference model for evaluating the structural response of the composite alternative. Subsequently, a parametric thickness-sensitivity analysis was undertaken on the composite configuration to investigate the influence of localized laminate thickness reduction.

The analysis focused on maximum stress and displacement under a prescribed uniform static pressure. The modelling approach was intended to support comparative structural assessment rather than to simulate dynamic vehicle collisions or predict impact-induced material.

Table 1 Geometry and Analysis Parameters

Parameter	Reported Specification
Overall beam length	1.155 m
Effective beam length	0.924 m
Overall breadth	0.179 m
Effective breadth	0.095 m
Radius of curvature	1.49 m
Steel thickness	2 mm
Composite ply count	13
Nominal ply thickness in layup description	0.25 mm
Applied uniform pressure	334135 Pa
Selected global mesh size	0.01 m
Analysis type	Static
Section integration	Simpson rule with 3 integration points

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➢ *Geometrical Modelling of the Bumper Beam*

The bumper beam geometry was developed in Abaqus/CAE as a three-dimensional deformable swept-shell structure with a curved profile. The beam had an overall length of 1.155m, an effective loading length of 0.924m, and a radius of curvature of 1.49m. The overall breadth and effective breadth were 0.179m and 0.095m, respectively.

The steel bumper was assigned a nominal thickness of 2 mm, while the composite configuration consisted of 13 individual plies, each having a nominal thickness of 0.25 mm in the laminate definition.

Geometrical partitions were introduced to distinguish the constrained support regions from the effective loading region. Crash boxes were excluded from the numerical model to isolate the structural response of the bumper beam without additional deformation or energy absorption from supporting crash-management components.

Steel was modelled as isotropic, with a Young's modulus of 210GPa, Poisson's ratio of 0.30 and density of 7800kg/m^3. Carbon epoxy was described using nine orthotropic engineering constants and a density of 1600 kg/m^3.

Table 2 Elastic Material Inputs

Property	Steel	Carbon Epoxy
E or E11 in GPa	210	138
E22 in GPa	Not applicable	9.5
E33 in GPa	Not applicable	9.5
Poisson ratio or nu12	0.30	0.28
nu13	Not applicable	0.28
nu23	Not applicable	0.40
G12 in GPa	Derived from isotropic inputs	5.2
G13 in GPa	Derived from isotropic inputs	5.2
G23 in GPa	Derived from isotropic inputs	1.45
Density in kg/m3	7800	1600

The 13-ply laminate orientation sequence was [45°/90°/45°/0°/45°/90°/45°/0°/−45°/90°/45°/0°/45°]. The material orientations were defined within the composite section utilizing Simpson integration with three integration points per ply.

A uniform static pressure of 334,135 Pa was applied to the effective bumper surface, with constrained support regions. A selected global mesh size of 0.01 m was used, and mesh sensitivity was examined. To investigate the influence of manufacturing-related thickness variations, the third composite ply was evaluated at 20%, 40%, 60%, 80%, and 100% of its original thickness, while the remaining plies retained their nominal dimensions.

Maximum stress and displacement were extracted from the finite element simulations and compared between the steel and composite bumper configurations. The influence of third-ply thickness reduction was assessed by calculating stress and displacement ratios relative to the intact composite laminate. Percentage changes were used to quantify structural response differences across the five thickness conditions. The analysis was limited to static structural behaviour and did not include dynamic impact or material failure simulations.

III. RESULTS

➢ *Structural Performance of Steel and Composite Bumpers*

Finite element analysis revealed differences in the structural responses of steel and carbon epoxy bumper beams under identical static loading conditions. As presented in the Table 3 below, the composite bumper exhibited a maximum stress of 155MPa compared with 186MPa for steel, representing a 16.7% reduction. However, the composite recorded a maximum displacement of 1.94mm compared with 1.14mm for steel, indicating a 70.2% increase in deformation.

Table 3 Baseline Structural Response

Response Measure	Steel	Carbon Epoxy
Peak stress in MPa	186	155
Maximum displacement in mm	1.14	1.94

➢ *Influence of Composite Ply Thickness Reduction*

Reducing the thickness of the third composite ply increased both maximum stress and displacement. At 20% retained thickness, maximum stress reached 541MPa and displacement increased to 7.58mm, corresponding to approximately 3.49 and 3.91 times the intact composite values, respectively as presented below in Table 4. Both responses decreased progressively as the retained ply thickness increased.

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Table 4 Reported Maxima for Third Ply Thickness Cases

Retained Ply Thickness	Peak Stress MPa	Displacement mm	Stress Ratio	Displacement Ratio
20%	541	7.58	3.49	3.91
40%	449	4.80	2.90	2.47
60%	377	3.90	2.43	2.01
80%	339	3.55	2.19	1.83
100%	155	1.94	1.00	1.00

The findings demonstrate that localized ply thickness reduction substantially influences the static structural response of composite bumper beams, highlighting the importance of laminate thickness control during manufacturing.

IV. CONCLUSION

The study demonstrated that carbon epoxy composite bumper beams exhibited 16.7% lower maximum stress than steel but 70.2% greater displacement under identical static loading conditions. Reducing the third composite ply thickness to 20% increased maximum stress from 155MPa to 541MPa and displacement from 1.94mm to 7.58mm. These findings indicate that localized thickness reduction substantially affects structural response, supporting the importance of manufacturing quality and defect control emphasized by Talreja [13].

Furthermore, the findings highlight the influence of laminate thickness on structural performance and emphasize the importance of manufacturing precision in composite bumper design. This suggests that although the composite configuration experienced lower peak stress, it demonstrated greater deformation, highlighting the importance of considering both stress and stiffness in bumper design. This observation is consistent with the importance of material properties and laminate configurations discussed by [14].

The study recommends careful optimization of laminate configurations and further investigation under dynamic impact conditions to establish crashworthiness and energy absorption performance.

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