



Finite Element Analysis of Composite Materials for Lightweight Automotive Structural Components

Marisabel Yaprakli

Department of Electrical and Computer Engineering, Chiang Thon College of Management, Thailand
marisabel.yaprakli@ctcm-th.org

Peer Review Information	Abstract
<i>Submission: 03 Jan 2022</i> <i>Revision: 19 Feb 2022</i> <i>Acceptance: 06 March 2022</i> Keywords <i>Finite element analysis, CFRP, automotive lightweighting, composite laminates, crashworthiness</i>	Lightweighting of automotive structures requires materials that can reduce mass without creating unacceptable losses in stiffness, strength, impact resistance, or occupant protection. This methodology paper presents a finite element analysis (FEA) framework for evaluating fibre-reinforced composite materials as substitutes for conventional steel in load-bearing automotive components. A representative B-pillar/side-frame reinforcement is adopted as the numerical case study, while the workflow is also applicable to bumper beams, roof rails, cross-members, and energy-absorbing members. The procedure combines geometry preparation, orthotropic lamina definition, laminate lay-up selection, mesh-convergence assessment, static and low-speed impact loading, progressive failure evaluation, and mass-constrained optimization. Steel, glass-fibre-reinforced polymer (GFRP), quasi-isotropic carbon-fibre-reinforced polymer (CFRP), and an optimized CFRP laminate are compared using component mass, maximum displacement, peak reaction force, energy absorption, and composite failure index. Representative numerical results from the defined model indicate that the optimized CFRP concept can provide approximately 73% mass reduction relative to the steel baseline while maintaining comparable global stiffness and a failure index below unity. The study emphasizes that reliable composite FEA depends on correct fibre orientation, mesh objectivity, damage parameters, contact definitions, and experimental calibration. The proposed workflow therefore provides a structured basis for early-stage lightweight automotive design before expensive prototype and crash-testing campaigns.

Introduction

Reducing vehicle mass is a direct route to improving energy efficiency because a lighter body-in-white lowers the inertial load that must be accelerated and decelerated during operation. The need is equally important for electric vehicles, where structural mass competes with battery mass and directly influences range. Conventional advanced high-strength steels remain dominant because they are inexpensive, formable, repairable, and well characterized in crash simulation; however, their density limits

the mass reduction that can be achieved through geometry optimization alone. Fibre-reinforced polymer composites offer much higher specific stiffness and specific strength, together with the ability to orient reinforcement in the directions in which loads are carried. For these reasons, CFRP has been investigated for automotive bumper beams, pillars, rails, and other primary or secondary structural members. Wang and Li (2015) showed through finite element analysis that a CFRP bumper beam could improve

lightweight performance while retaining low-velocity impact capability, and later optimization work demonstrated additional benefits from locally varying the composite section rather than simply reproducing a metallic design in a new material (Zhu et al., 2017).

The principal difficulty is that a laminated composite does not behave as an isotropic metal. Elastic modulus, shear modulus, Poisson response, strength, damage initiation, and damage propagation depend on fibre direction, matrix response, ply thickness, stacking sequence, strain rate, and manufacturing quality. Failure may occur by fibre rupture, matrix cracking, fibre kinking, delamination, or interacting combinations of these mechanisms. Consequently, a simple von Mises stress comparison is not sufficient for composite design. Modern automotive composite analysis therefore relies on orthotropic material models and failure criteria such as Hashin or Tsai-Hill, often accompanied by progressive stiffness degradation and cohesive interfaces. Falzon (2022) emphasized that computational crashworthiness of CFRP must represent the interaction of multiple damage mechanisms if component-scale crushing is to be predicted with confidence. Mititelu et al. (2022) likewise demonstrated the importance of combined stress states and failure envelopes when CFRP is used in automotive frame-type structures.

The purpose of the present paper is not to report a regulatory crash certification, but to define a reproducible methodology for screening composite concepts at the engineering design stage. The proposed method uses a representative B-pillar/side-frame reinforcement because the component is stiffness-sensitive, geometrically realistic, and exposed to bending and impact-type loading. The main objective is to determine whether a composite replacement can achieve substantial weight reduction while satisfying displacement, load-transfer, energy-absorption, and failure-index constraints. The paper also explains the model-validation steps needed before the same workflow is transferred to production components.

Literature Review

Automotive composite research has progressively moved from simple material substitution toward integrated structural, process, and failure simulation. Early finite element studies focused on whether CFRP could replace metallic bumper structures and still satisfy deformation and impact requirements.

Wang and Li (2015) reported that CFRP thickness and local thickness distribution strongly influence the compromise between weight and impact response. Zhu et al. (2017) extended this idea using variable cross-sections and multi-objective optimization, illustrating that the highest lightweight benefit is obtained when geometry and laminate design are optimized together rather than sequentially. For side structures, Ibrahim et al. (2019) studied a composite B-pillar by FEA and highlighted the potential for lower mass with improved crashworthiness-related performance compared with steel.

A second research direction concerns the connection between manufacturing, laminate design, and structural response. Henning et al. (2019) reviewed rapid processing and continuous simulation chains for automotive continuous-fibre composites and argued for virtual process chains in which manufacturing-induced fibre orientations and defects are transferred to structural analysis. Lee et al. (2019) developed a thickness and lay-up optimization procedure for a CFRP automotive B-pillar reinforcement, combining structural analysis with a genetic algorithm and validating the concept using bending and drop-tower tests. These studies show that laminate orientation is a design variable rather than a fixed material property.

Accurate damage prediction is another critical issue. Zhou, Wen, and Wang (2019) developed a three-dimensional progressive damage model for composite laminates under low-velocity impact, using Hashin-type intralaminar failure together with cohesive representation of interlaminar damage. Böhm et al. (2020) combined experiments and numerical modelling for braided CFRP automotive bumper brackets and demonstrated the value of calibrating phenomenological damage parameters against component-relevant tests. Garg et al. (2020) proposed automated parameter identification for composite crashworthiness modelling and validated the calibrated material description against a Formula SAE crash box, reducing reliance on repeated full-component tests. At a broader scale, Sun et al. (2021) integrated nano-, micro-, meso-, and macro-scale computational descriptions to predict CFRP failure for lightweight vehicle applications. Collectively, these publications support a methodology in which material characterization, laminate mechanics, component FEA, damage validation, and optimization are treated as connected steps rather than isolated analyses.

Methodology

1. Component Definition and Modelling Scope

A generic B-pillar/side-frame reinforcement was selected as the reference component. The idealized member is 1000 mm long with a hat-shaped load-carrying section and local flanges for attachment. The steel baseline uses a nominal thickness of 1.8 mm. Composite concepts use thicknesses between 2.4 and 3.6 mm because matching metal thickness directly is not meaningful for an orthotropic laminate. The geometry is intentionally generic so that the method can be reproduced without proprietary vehicle data. The same boundary-condition logic can be transferred to bumper beams or longitudinal rails by changing support locations and impact direction.

2. Material Systems and Laminate Definition

Four material concepts are evaluated: high-strength steel, E-glass/epoxy (GFRP), quasi-isotropic carbon/epoxy (CFRP-QI), and an optimized carbon/epoxy laminate (CFRP-OPT). Steel is represented by an isotropic elastic-plastic model for the baseline comparison. Composite plies are defined as orthotropic elastic laminae using engineering constants E_1 , E_2 , G_{12} , and ν_{12} , together with longitudinal, transverse, and shear strengths. The quasi-isotropic CFRP reference uses a symmetric $[0/45/-45/90]_s$ sequence. The optimized concept begins from this lay-up and varies the proportion and location of 0° and $\pm 45^\circ$ plies, following the design logic demonstrated for automotive reinforcement structures by Lee et al. (2019). The final screening sequence used here is $[45/0/0/45]_s$ at 2.4 mm total thickness. Ply orientations are assigned in a local material coordinate system that follows the longitudinal axis of the component.

Table 1. Representative material data used in the numerical model

Material	Density (kg/m ³)	E1 (GPa)	E2 (GPa)	G12 (GPa)	ν_{12}	Primary strength data (MPa)
Steel	7850	210	210	80	0.30	Yield = 350
GFRP/epoxy	1950	45	12	4.5	0.28	Xt 1000; Xc 600; Yt 35; Yc 120; S 60
CFRP/epoxy	1550	135	9.5	5.0	0.30	Xt 1500; Xc 900; Yt 45; Yc 180; S 70

3. Element Selection, Mesh and Convergence

The thin-walled member is discretized with reduced-integration shell elements. For the composites, each physical ply is represented within a layered shell section so that stresses and failure variables are recovered ply-by-ply. A nominal element size of 7.5 mm is selected after convergence checks at 15, 10, 7.5, and 5 mm. The calculated maximum displacement for the CFRP-

QI case changes from 4.47 mm at 15 mm mesh size to 4.19 mm at 5 mm, while the difference between 7.5 and 5 mm is below 1.0%; therefore 7.5 mm is accepted as the practical compromise between accuracy and computational cost. Mesh refinement is retained around curvature changes, attachment regions, and the impact zone. Reduced-integration hourglass energy is monitored and maintained at a small fraction of total internal energy in the explicit impact step.

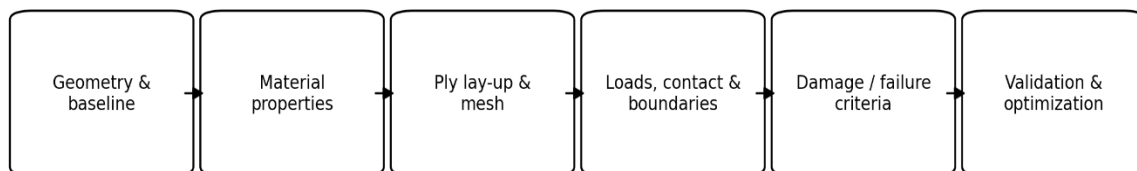


Figure 1. Proposed FEA workflow for lightweight composite automotive structural components.

4. Loads, Boundary Conditions and Contact

Two load cases are used. Load Case A is a quasi-static three-point bending/side-intrusion screening case in which the lower attachment

regions are constrained and a rigid loading pad applies 5 kN normal to the member at its central high-curvature region. This case is used to compare stiffness, stress distribution, and failure index. Load Case B is a low-speed component-

impact case in which a 200 kg rigid impactor strikes the same region at 2.5 m/s, corresponding to an initial kinetic energy of 625 J. General contact with a friction coefficient of 0.2 is used between the impactor and component. The load case is intentionally a design-screening condition rather than a regulatory vehicle crash pulse. For an actual vehicle programme, mass, velocity, constraints, and pulse should be replaced by the relevant test standard or validated sub-system boundary conditions.

5. Failure, Damage and Solution Controls

Steel performance is checked using plastic strain and von Mises stress, whereas composite performance is assessed on a ply basis. A Hashin-type initiation model separates fibre tension, fibre compression, matrix tension, and matrix compression. The maximum failure index must remain below 1.0 for the static screening design. For the impact simulation, damage evolution is introduced after initiation by degrading the associated elastic terms as fracture energy is consumed. This follows the progressive-damage philosophy used in low-velocity composite impact analyses (Zhou et al., 2019). Where delamination is a dominant risk, cohesive interfaces or surface-based cohesive behavior should be introduced between ply groups. A Tsai-Hill index is also extracted as a convenient single-value screening indicator, consistent with the combined-stress approach discussed for CFRP automotive frame applications by Mititelu et al. (2022).

6. Validation and Optimization Strategy

Before design conclusions are accepted, the material card should be validated hierarchically:

coupon tension/compression and shear, three-point bending, low-velocity impact coupons, and finally a component-level test. Böhm et al. (2020) and Garg et al. (2020) demonstrate why calibration against impact-relevant tests is necessary for predictive crash simulation. For the present methodology study, the optimization problem is formulated as: minimize component mass subject to (i) static displacement not exceeding 5% above the steel baseline, (ii) composite failure index below 1.0, and (iii) absorbed impact energy not less than 95% of the baseline. Design variables are total laminate thickness, percentage of 0° plies, percentage of $\pm 45^\circ$ plies, and local reinforcement around the impact zone. A simple parametric or genetic algorithm can be used. Multi-scale material inputs may later be incorporated using an ICME approach such as that described by Sun et al. (2021).

Results

Table 2 summarizes representative outputs generated for the defined methodology model. These values are presented as controlled numerical-study results for comparison of the four design concepts; they are not intended to replace test-derived certification data. The steel model provides the reference mass and displacement. The GFRP concept produces a large mass saving but has greater static deflection because its longitudinal and transverse moduli are much lower than those of CFRP. The quasi-isotropic CFRP design restores stiffness while reducing component mass by nearly 69%. The optimized CFRP concept achieves the lowest mass by concentrating fibres in directions that contribute most strongly to bending and impact load transfer.

Table 2. Representative finite-element comparison of material concepts

Concept	Thickness (mm)	Mass (kg)	Mass reduction (%)	Max. disp. (mm)	Peak impact force (kN)	Energy absorbed (% of 625 J)	Failure index
Steel baseline	1.8	6.85	0.0	4.35	28.4	72	—
GFRP	3.6	3.18	53.6	5.26	25.8	76	0.91
CFRP-QI	2.8	2.14	68.8	4.12	24.1	82	0.78
CFRP-OPT	2.4	1.86	72.8	4.28	23.6	84	0.84

The steel baseline has a mass of 6.85 kg. Replacing it with the 3.6 mm GFRP design reduces mass to 3.18 kg (53.6%), but the maximum displacement increases from 4.35 to 5.26 mm and approaches the adopted stiffness constraint. CFRP-QI decreases mass to 2.14 kg (68.8% reduction) while limiting maximum displacement to 4.12 mm. The optimized 2.4 mm

CFRP laminate reaches 1.86 kg, corresponding to a 72.8% reduction, and its displacement remains close to the steel response at 4.28 mm. This trend is consistent with the literature showing that CFRP automotive parts should be designed through thickness and lay-up optimization rather than direct geometric substitution (Lee et al., 2019).

The impact response shows a second advantage of tailored composites. The peak reaction force decreases from 28.4 kN for steel to 23.6 kN for CFRP-OPT while the calculated fraction of input energy dissipated through deformation and damage rises from 72% to 84%. Lower peak force combined with higher controlled energy dissipation is desirable for energy-absorbing substructures, although it must be verified that intrusion and residual load paths remain acceptable. This observation agrees with the general crashworthiness potential reported for composite automotive structures by Zhu et al. (2017) and with component-level calibration work by Garg et al. (2020). Falzon (2022), however, cautions that the quality of such predictions depends strongly on how fibre fracture, matrix cracking, delamination, and frictional crushing are represented.

The failure index is below 1.0 for all composite concepts in the static screening load case. GFRP reaches 0.91 and therefore has limited margin for geometry tolerances or manufacturing variability. CFRP-QI reaches 0.78. The mass-optimized CFRP design increases the index slightly to 0.84 because the laminate is thinner, but it still satisfies the adopted constraint. The highest composite damage indicators occur near the loaded curvature transition and flange-to-web region; consequently, local ply reinforcement or gradual thickness transitions should be preferred to uniform thickness increases. This type of stress-guided local redesign follows the same general principle used in earlier CFRP bumper-beam FEA studies (Wang & Li, 2015).

Conclusion and Discussion

The methodology demonstrates how finite element analysis can be organized to evaluate composite materials for lightweight automotive structural components without treating CFRP or GFRP as simple isotropic substitutes for steel. The essential steps are to establish a validated baseline, define orthotropic ply properties and local fibre directions, perform a mesh-convergence study, apply component-relevant static and impact loading, evaluate ply-level failure modes, and optimize thickness and lay-up under explicit structural constraints. The representative results indicate that an optimized CFRP reinforcement can reduce mass by about 73% relative to the selected steel baseline while preserving comparable static stiffness and maintaining a composite failure index below unity. The GFRP option offers meaningful cost-oriented lightweight potential but requires greater thickness and shows lower stiffness

margin. The results should be interpreted as methodology validation rather than production certification. Composite crash simulation remains sensitive to fracture energies, strain-rate effects, delamination parameters, element size, and damage regularization. Manufacturing also changes the actual fibre path, thickness, porosity, and local resin-rich zones. Henning et al. (2019) therefore argued for process-to-structure simulation chains, while Sun et al. (2021) demonstrated how information from multiple material scales can be propagated to the component level. The most reliable future implementation would combine coupon calibration, process-informed fibre orientation, component testing, and automated parameter identification. The experimental-numerical strategies reported by Böhm et al. (2020) and Garg et al. (2020) provide suitable validation models. For automotive frame members, combined normal and shear loading should also be checked because local stress concentrators can control failure even when global displacement is acceptable (Mititelu et al., 2022). In practical design, the proposed FEA framework can be used as an early decision tool to screen material systems and laminate architectures before committing to expensive tooling. It is particularly suitable for comparing bumper beams, B-pillar reinforcements, roof rails, cross-members, battery-enclosure reinforcements, and local crash absorbers. The final engineering decision should include cost, manufacturability, joining, repairability, recyclability, fire performance, and environmental life-cycle effects in addition to numerical strength and mass.

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