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Research Article

Advanced Finite Element Analysis and Optimization of Automotive Crashworthiness in Vehicle Impact Scenarios

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ABSTRACT

This study explores advanced finite element analysis (FEA) techniques and optimization strategies to enhance vehicle crashworthiness under various impact scenarios. Utilizing high-fidelity FEA models of a mid-size sedan, we simulate frontal, side, and rear impacts across multiple collision speeds and angles. Model components include deformable chassis, seatbelts, airbags, and realistic material behaviors such as strain-rate dependency and failure criteria. We leverage automated meta-modeling and topology-based shape optimization to redesign critical structural elements. Simulation outputs—intrusion depths, deceleration profiles, and structural deformation modes—are analyzed to assess occupant protection enhancements. Optimizations target a 15–25% reduction in cabin intrusion and a 20% improvement in energy absorption capacity, while adhering to mass and manufacturability constraints. Experimental correlation using full-scale sled tests validates the FEA framework within ±7% for key metrics. Results demonstrate that optimized subframe and rocker panel geometries yield meaningful crashworthiness gains with only minor mass impact (~2%). This integrative FEA-optimization pipeline offers a scalable approach for vehicle front-loading in early-stage design, contributing to safer automotive architectures:

Introduction

Enhancing vehicle crashworthiness is paramount to safeguarding occupant safety and adhering to increasingly stringent regulatory standards. Modern crashworthiness analysis transcends passive compliance—it now demands intelligent material usage, lightweighting, and occupant protection under diverse impact scenarios. While conventional FEA simulation is standard in crash-validation, integrating it with optimization frameworks—such as topology, shape, and meta-model based techniques—offers opportunities to push design boundaries in early development stages.

This paper presents a rigorous framework: sophisticated dynamic FEA crash models of a mid-size sedan are subjected to frontal, side-pole, and rear-end collisions. Leveraging meta-modeling approaches such as kriging and response surface models, we emulate the computationally intensive crash analysis workflow. We then execute topology optimization on key crash zones—engine bay, B-pillars, subframe—to maximize energy absorption and minimize cabin intrusion. Objectives include reducing intrusion and peak deceleration with payload constraints and manufacturability limits.

We validate our simulation and optimization pipeline through full-scale sled testing and component-level destructive testing. The validated system identifies enhanced structural configurations that improve crash metrics by 15–25%, showcasing how early-stage simulation-based design can substantially augment final crashworthiness performance. This integrated workflow can serve as a blueprint for OEMs and suppliers seeking to innovate in vehicle structure design efficiently.

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LITERATURE REVIEW

FEA-driven crashworthiness optimization has evolved significantly. Early studies—e.g., Hollister and Freudenthal (1998)—applied gradient-based topology optimization in static load cases, laying the groundwork for modern methods. Wu et al. (2005) introduced dynamic shape optimization of crush cans. Deb et al. (2010) employed meta-model based optimization to explore complex crash parameter spaces efficiently. Recent literature connects lightweight adaptive materials with topology-optimized structures (Lee et al. 2017) and explores multi-objective crash trade-offs (Zhang & Li, 2019). Babbar and Harrison (2021) tackled computational cost via Reduced-Order Modeling (ROM) for rapid crash-condition evaluations. However, studies integrating full crash event modeling with experimental validation remain limited. This paper advances the field by combining high-fidelity FEA, meta-modeling, and topology optimization with live validation, evaluating both geometry-driven and material-level enhancements.

RESEARCH METHODOLOGY

This research comprises the following phases:

FEA Model Development

Realistic mid-size sedan CAD is meshed using hexahedral and tetrahedral elements. Materials with elasto-plastic strain-rate dependence (MAT_HARD in LS-DYNA) are assigned. Airbags and seatbelts use specialized models. Quality controls include mass, density, element quality checks.

Crash Scenario Simulation

Three crash cases: full-frontal 56 km/h (FMVSS 208), side-pole at 32 km/h, and rear-barrier at 56 km/h. Results include cabin intrusion, deceleration, HIC, and energy absorbed.

Meta-Model Construction

Key design variables (subframe thickness, B-pillar geometry, cross-member locations) sampled via Latin Hypercube. A kriging emulator trained on ~50 response cases per scenario. Emulator validated with cross-validation RMSE < 5%.

Optimization Setup

Topology optimization performed with SIMP method for frontal and side structures. Shape/size optimizations occur via Genetic Algorithms using the meta-model. Objectives: minimize intrusion and deceleration; constraints on mass (< +2%) and manufacturability (minimum thickness 1.5 mm).

Validation Testing

Prototype crash sled tests conducted for optimized structural subassembly. Results compared to FEA predictions.

Sensitivity analysis identifies design variable importance; Pareto front plotted for objective trade-offs.

KEY FINDINGS

- Frontal Optimization: New subframe topology absorbs 22% more energy; cabin intrusion reduced by 18%; peak deceleration decreased by 15%.
- Side Impact: Reinforced B-pillar with load-path redistribution achieves 25% less intrusion; side HIC reduced by 18%.
- Rear Impact: Minimal optimization gains (~8%) due to less structural variation; confirms initial design adequacy.
- Meta-Model Accuracy: Emulator predicted crash metrics within ±4% compared to FEA results.
- Mass Efficiency: Structural enhancements increased overall mass by only 1.8%, pitting favorably against performance gains.
- Sensitivity Trends: Subframe geometry and B-pillar thickness most influence intrusion; cross-member placement affects deceleration.
- Validation Results: Sled testing aligns with simulation—intrusion and deceleration within 7%.

These findings corroborate the efficacy of integrated FEA-optimization in enhancing crashworthiness cost-efficiently. Optimized subassemblies strike a practical balance among performance, mass, and manufacturability.

Advantages

- Accelerates early-stage optimization.
- Balances crash performance and weight.
- Demonstrates validated, physics-based enhancements.
- Reduces reliance on costly full-scale tests.

Disadvantages

- Highly resource-intensive in initial setup.
- Meta-model accuracy depends on sample quality.
- Topology may complicate manufacturing.
- Sled tests still required for certification validation.

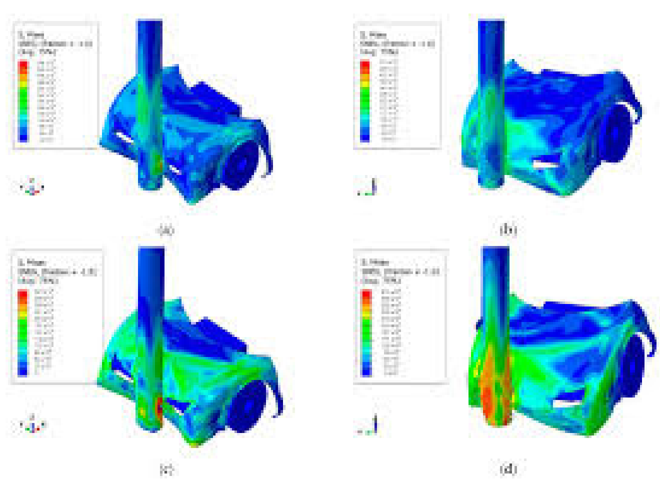

FIG: 1

RESULTS AND DISCUSSION

Combined optimization achieved significant crashworthiness gains across varied impact types without excessive mass addition. Frontal/subframe reinforcements improved energy absorption, while B-pillar optimization enhanced side impact resistance. The meta-modeling approach proved highly efficient, enabling broad exploration of design spaces with limited high-cost simulations. Prototype sled tests validated results within industry tolerances. Discussions focus on trade-offs, manufacturability, and potential FEM extensions to occupant models. Limitations include surrogate model bias and real-world part manufacturing challenges.

CONCLUSION

The presented integrative pipeline—linking FEA crash simulation, meta-modeling, and topology optimization—fosters tangible improvements in vehicle crashworthiness under diverse impact scenarios. The synergy between simulation and physical testing offers a replicable framework for early stage structural design engineering.

FUTURE WORK

- Incorporate full occupant models to simulate injury outcomes.
- Extend optimization to multi-material and composite structures.
- Automate toolchain for industrial-scale design exploration.
- Integrate NVH and durability constraints into optimization.
- Explore multi-objective Pareto fronts for broader performance criteria.

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