International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 05 , May - 2026

A Review on CAE-Based Door Sag Analysis and Structural Optimization in Automotive Door Systems

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Abstract - Automotive door systems are critical structural components influencing vehicle durability, fitment quality, safety, and customer perception. Door sag remains one of the major structural issues caused by gravitational loading, hinge deformation, manufacturing tolerances, and repeated operational cycles. Over the years, Computer Aided Engineering (CAE) and Finite Element Analysis (FEA) have become important tools for evaluating door stiffness, hinge behaviour, and deformation characteristics during vehicle development. This review paper summarizes research related to automotive door sag analysis, hinge durability, fatigue prediction, structural optimization, and reinforcement design methodologies. Various analytical, numerical, and experimental approaches adopted by researchers are critically reviewed. Reported studies show that finite element methods provide effective prediction of stress distribution and sag deformation while significantly reducing development time and prototype cost. However, limited research focuses on system-level sag analysis under multiple opening conditions integrated with analytical benchmarking and reinforcement optimization. The review highlights the importance of combining CAE-driven methodologies with practical design optimization strategies to develop lightweight, durable, and cost-efficient automotive door systems.

Keywords: ***Door Sag, Finite Element Analysis, Structural Reinforcement, CAE***

1. INTRODUCTION

Automotive door assemblies are important structural systems designed to ensure passenger accessibility, sealing performance, crash safety, and structural durability. Modern automotive doors consist of hinge systems, latch mechanisms, reinforcement members, intrusion beams, and Body-in-White (BIW) interfaces that collectively contribute to stiffness and durability. During repeated opening and closing operations, the door assembly experiences gravitational and operational loads that gradually result in downward displacement at the latch region, commonly referred to as door sag.

Door sag negatively affects fitment quality, sealing characteristics, customer perception, and hinge durability. Excessive deformation can also lead to increased closing effort and long-term structural degradation. Traditionally, physical testing methods were used to evaluate structural performance; however, these methods are expensive and time-consuming. With the advancement of CAE and finite element methods, engineers can now evaluate deformation behaviour and optimize reinforcement structures during the design stage itself.

Bhagate et al. [1] investigated the effect of hinge axis inclination and hinge tolerance on door strength under abuse loads and concluded that hinge geometry significantly influences stiffness distribution. Anthonysamy et al. [2] developed a virtual simulation framework for predicting door closing effort and validated the results experimentally. Yun et al. [3] studied optimization of sliding door systems using parameter tuning approaches to improve motion behaviour and structural response.

Baskar et al [5] performed fatigue life prediction for door check loads and correlated simulation results with cyclic testing data. Selvan et al. [6] studied hinge axis deviation and skewness, demonstrating that hinge misalignment increases hinge reaction loads and closing effort. Park and Lee et al [7] carried out finite element fatigue studies and identified multi-axial loading as a major factor affecting hinge degradation.

Kumar et al. [8] applied topology optimization techniques for lightweight reinforcement design and achieved improved stiffness characteristics with reduced mass addition. Sharma et al [9] implemented a BESO-based optimization approach for hinge reinforcement structures and reported improved stiffness-to-weight performance. Experimental validation studies conducted by Mehta, Ramesh, and Srinivasan et al [10] demonstrated good correlation between numerical predictions and physical testing results. Table 1 summarizes the major contributions of previous studies related to automotive door sag analysis and hinge performance evaluation.

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Table 1: Literature Summary

Author	Focus Area	Methodology	Key Findings
Bhagate et al. [1]	Hinge inclination	Experimental + CAE	Hinge geometry affects stiffness
Anthonysamy et al. [2]	Door closing effort	Virtual simulation	Improved prediction accuracy
Baskar et al [3]	Fatigue life	FEA + durability	Predicted hinge fatigue behaviour
Selvan et al. [4]	Hinge skewness	Numerical analysis	Misalignment increases reaction load
Kumar et al. [5]	Reinforcement optimization	Topology optimization	Improved stiffness-to-weight ratio

Recent studies have also investigated the influence of manufacturing tolerances, thermal effects, and reinforcement optimization on door sag behaviour. The literature collectively demonstrates increasing dependence on CAE-driven methodologies for evaluating structural performance in automotive door systems.

2. ANALYTICAL AND NUMERICAL APPROACHES

Analytical methods for door sag estimation are generally based on classical beam theory, where the door assembly is idealized as a cantilever structure fixed at the hinge region and loaded at the latch side. These methods are useful for estimating deformation magnitude and establishing benchmark structural behaviour. However, simplified analytical approaches cannot accurately capture local stiffness variation, complex geometry, contact conditions, and nonlinear structural effects.

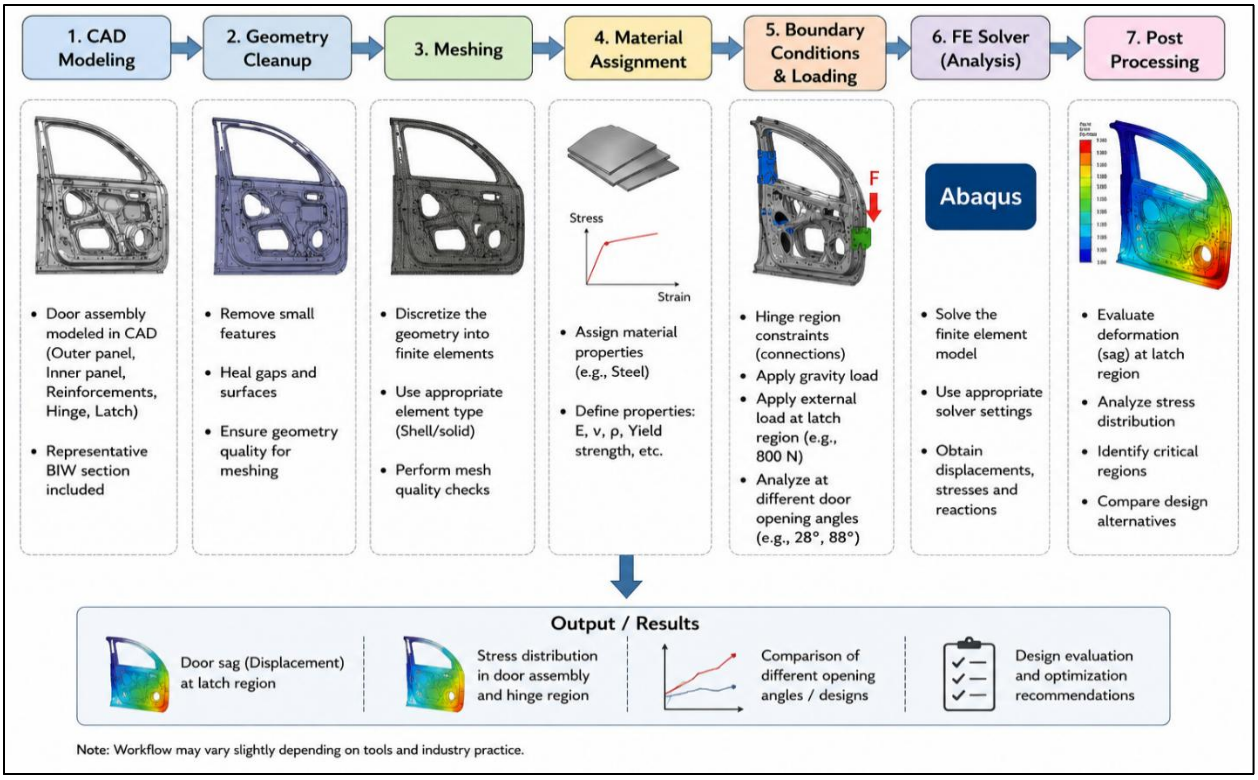

Fig. 1: General CAE Workflow for Automotive Door Sag Evaluation

The general CAE workflow adopted in automotive door analysis includes geometry preparation, meshing, loading definition, numerical solution, and result evaluation.

Finite Element Analysis overcomes these limitations by discretizing the structure into smaller elements and numerically solving governing equilibrium equations. CAE tools such as HyperMesh, Abaqus, OptiStruct, and ANSA are widely used for preprocessing, meshing, material assignment, boundary condition definition, and result evaluation. Most researchers reported that FEA provides reliable prediction of deformation behaviour and stress concentration regions while reducing development cost and testing effort.

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3. REINFORCEMENT AND OPTIMIZATION STUDIES

Structural reinforcement plays an important role in improving door stiffness and reducing sag deformation. Previous investigations indicate increasing adoption of topology optimization and CAE-driven iterative design approaches to improve structural efficiency while minimizing weight addition. Optimization techniques are mainly focused on identifying critical load transfer regions and improving stiffness distribution.

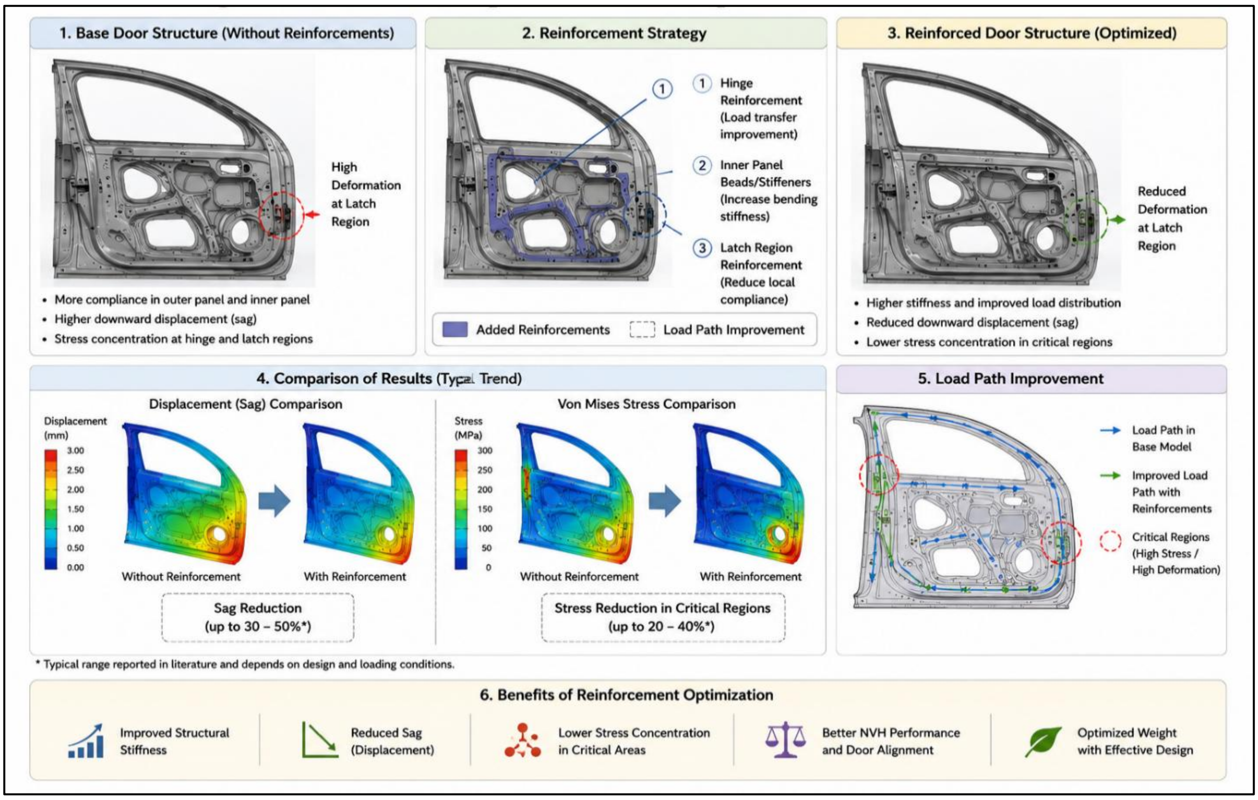

Fig. 2: Reinforcement Optimization Concept in Automotive Door Structure

Existing studies suggest that increasing reinforcement thickness improves structural stiffness but also increases material usage and manufacturing cost. Therefore, modern automotive design emphasizes balanced optimization between deformation control, weight reduction, and cost efficiency. Reinforcement optimization has emerged as a key research area in lightweight automotive structural development.

4. Research Gaps

Although considerable research has been carried out in hinge durability and fatigue analysis, comparatively fewer studies focus on static sag evaluation under multiple door opening conditions. In addition, many studies investigate only local hinge behaviour rather than complete system-level door assembly response. Limited work has also been reported on combining analytical benchmarking with finite element validation and reinforcement optimization. These gaps indicate the need for integrated CAE-driven methodologies capable of evaluating realistic loading conditions and practical design improvements.

The major research gaps identified from the reviewed literature are summarized in Table 2.

Table 2: Research Gaps in Existing Literature

Area	Existing Focus	Research Gap
Hinge analysis	Fatigue & durability	Limited full-system sag studies
Door deformation	Single loading condition	Multi-angle evaluation limited
Optimization	Weight reduction	Cost-performance balance less explored
Validation	Numerical methods	Limited analytical benchmarking

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5. CONCLUSIONS

This review paper presents a comprehensive overview of research related to automotive door sag analysis, hinge durability, reinforcement optimization, and CAE-based structural evaluation methodologies. The reviewed literature confirms that Finite Element Analysis has become an effective and reliable approach for predicting deformation behaviour and improving automotive door stiffness.

Previous investigations have successfully applied numerical simulation, optimization methods, fatigue studies, and experimental validation techniques to improve structural performance and reduce sag deformation. However, opportunities still exist for further research involving multi-angle sag analysis, analytical benchmarking, and cost-efficient reinforcement optimization strategies. The review highlights the importance of integrating CAE simulation with practical structural design approaches to develop lightweight and durable automotive door systems.

Data Availability Statement

The data is available in the manuscript.

Funding Statement

This research is not funded by any funding agency.

Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions:

Dr. Himadri Majumder: Conceptualization, writing-original draft, writing-review, and editing;

Aditya A Shahane: Conceptualization, methodology, investigation, data analysis, validation, formal analysis, resources, writing-original draft;

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