Structural Analysis and Development of a Moderate-Duty Heavy Vehicle Chassis

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***Abstract*—This paper presents an integrated finite element analysis (FEA) study of ladder-type chassis frames for both on-highway commercial and off-highway military vehicle applications. A comprehensive simulation framework incorporating static structural, modal (free vibration), and harmonic response analyses is developed to evaluate structural performance under realistic operating conditions. For the off-highway (military-type) chassis, global stiffness characteristics, load transfer mechanisms, and structural integrity are assessed under full payload and gravitational loading. For the on-highway commercial chassis, resonance behaviour, vibration amplification, and fatigue life are investigated as root causes of real-world field failures near the leaf-spring mounting regions. Material comparison between conventional Structural Steel and high-strength A710 Steel shows that A710 Steel delivers approximately 20% lower deformation and stress, shifts natural frequencies away from the engine operating range, reduces harmonic deformation amplitude by up to 80%, and improves fatigue life by 94-177% at critical locations. Analytical validation using Dunkerley's and Rayleigh's methods confirms model accuracy within 3%. The study establishes that a combined static-modal-harmonic FEA framework is essential for reliable chassis durability assessment.**

***Index Terms*—A710 Steel, Chassis, Fatigue Life, Finite Element Analysis (FEA), Harmonic Response, Ladder Frame, Modal Analysis, Resonance, Static Structural Analysis, Structural Steel.**

I. INTRODUCTION

A. Background

Ladder-type chassis frames form the primary load-bearing structure for a wide range of automotive platforms, including both on-highway commercial vehicles and off-highway or military applications. Their high load-carrying capacity, modularity, and structural robustness make them a preferred architecture across diverse vehicle segments.

In modern automotive development, manufacturers increasingly adopt common platforms to support multiple vehicle variants. While such platform consolidation improves manufacturing efficiency and reduces cost, it introduces significant engineering challenges including distinct ride, handling, and regulatory compliance requirements per region. Design deficiencies can propagate across multiple models, increasing the risk of large-scale recalls.

These challenges are further intensified in off-highway and military applications, where operating conditions are considerably more severe. Such vehicles are routinely subjected to large payload variations, severe terrain-induced excitations, asymmetric wheel loading due to uneven ground conditions, and stringent durability requirements. Under these conditions, the structural stiffness of the chassis plays a critical role in governing vehicle performance.

B. Motivation

Field observations in commercial vehicle applications indicate that structural failures often occur despite stresses being within allowable limits under static loading. Such failures are frequently associated with resonance phenomena, vibration amplification, and fatigue damage under cyclic loading. This highlights the necessity of incorporating modal and harmonic response analyses in addition to conventional static evaluations.

C. Objectives

The objectives of this study are as follows:

1. To develop a computationally efficient and structurally representative finite element model of a ladder-type chassis
2. To evaluate the global stiffness characteristics through modal analysis
3. To assess the structural response under worst-case static loading conditions
4. To investigate dynamic behavior, including resonance and vibration response
5. To compare the performance of Structural Steel and A710 Steel in terms of durability and fatigue resistance
6. To interpret the results in a physically meaningful and engineering-relevant manner

D. Scope and Limitations

The present analysis focuses on global structural and dynamic behavior. The following aspects are excluded from scope:

- Local bolt preload effects
- Detailed weld-level fatigue behavior
- Compliance of rubber bushings and joints
- Tire-road contact interactions

II. LITERATURE REVIEW

Marco C. and Andrea B. [1] presented a comprehensive methodology for automotive chassis weight reduction using topology, topometry, and size optimization integrated with FEM analyses, demonstrating substantial weight reduction while maintaining structural integrity. Patil and Kachave [3] conducted FEM-based stress analysis of a truck chassis showing that modification of cross-member positioning and thickness significantly reduces stress concentrations. Roslan Abd-Rahman et al. [4] identified critical stress regions near bolt openings, emphasizing fatigue failure risks.

Dynamic behavior plays a crucial role in ride comfort and durability. Kallappa et al. [6] demonstrated that increasing rib and channel thickness reduces vibration levels, while Christian and Stephan [7] used vibration transfer path analysis to identify dominant low-frequency excitation paths. Torsional rigidity has been identified as a key parameter influencing vehicle handling and dynamic stability [13]. Investigations on Formula Student vehicles show that while higher torsional stiffness improves structural performance, an optimal balance between stiffness and weight is essential [14].

Material selection plays a critical role in chassis durability. Comparative studies on ASTM A710 steel and aluminum alloys have demonstrated that appropriate material selection significantly enhances strength, reduces deformation, and improves fatigue resistance [17]. Modal analysis has been widely used to evaluate natural frequencies and mode shapes, enabling identification of resonance conditions [22]. Recent work also emphasizes integrating structural, dynamic, and fatigue analyses into a unified framework for improved prediction of real-world failure mechanisms [24, 25].

Research Gap

Despite significant advancements in chassis design, most studies focus on individual aspects such as static strength, material optimization, or vibration behavior. There remains a lack of integrated multi-physics approaches that simultaneously consider structural response, dynamic loading, and fatigue life under realistic operating conditions. The present study addresses this gap through a unified FEA framework encompassing static, modal, harmonic, and fatigue analyses for two distinct chassis application domains.

III. PROBLEM DEFINITION AND METHODOLOGY

Field observations have indicated repeated failures of ladder-type chassis frames near the rear leaf-spring mounting region despite stresses remaining within allowable static limits. The root cause has been identified as resonance, where engine excitation frequencies coincide with natural frequencies of the chassis under full-load operating conditions. To address both on-highway and off-highway scenarios, two independent chassis models are considered:

- An on-highway commercial ladder chassis model, focused on vibration, resonance, and fatigue behavior
- An off-highway (military-type) chassis model, focused on global structural response and load transfer under extreme conditions

A. On-Highway Commercial Chassis

Payload: 12.5 tonnes (122.625 kN). Side member: I-section (250 × 150 × 12.5 mm). Material 1: Structural

Steel (E = 200 GPa, σy = 250 MPa). Material 2: A710 Steel (E = 205 GPa, σy = 415 MPa). Analyses performed: static structural, modal (free vibration), harmonic response (0-100 Hz), fatigue life evaluation, and analytical validation.

B. Off-Highway (Military-Type) Chassis

The off-highway model includes the chassis frame along with suspension components (axles, leaf springs, brackets). Analyses performed: static structural analysis under payload and gravity loading, and modal analysis to evaluate global dynamic behavior. Emphasis is on global stiffness characteristics, load transfer through suspension components, and structural robustness under asymmetric and terrain-induced loading.

IV. GEOMETRY MODELING

A. Off-Highway Chassis CAD Preparation

The original CAD assembly contained numerous manufacturing and cosmetic features not relevant to global structural behavior. Geometry simplification preserved primary load paths, removed features with negligible stiffness contribution (small brackets, fillets, holes), and maintained correct relative positioning of major components.

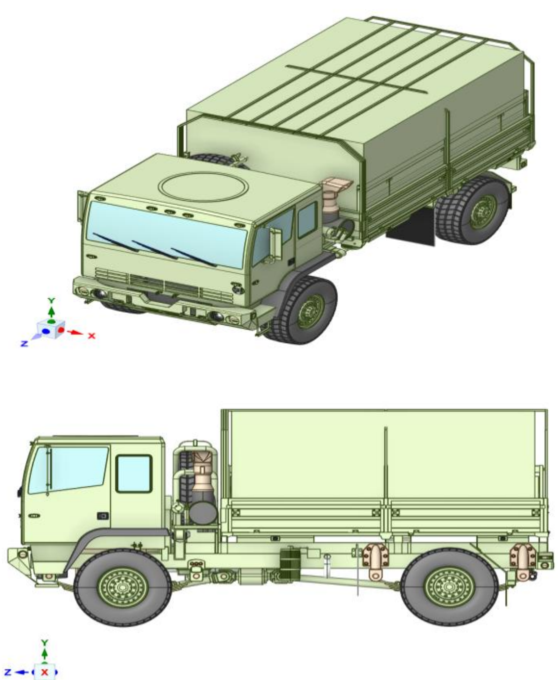

Fig. 1. Original CAD assembly of off-highway (military-type) chassis

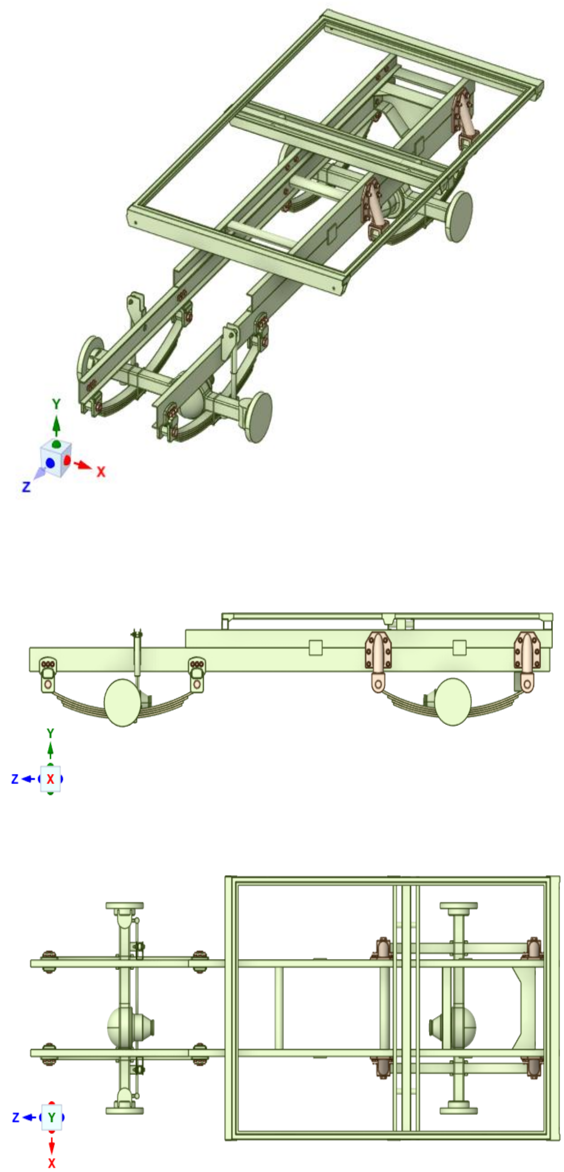

Fig. 2. Simplified analysis-ready geometry of off-highway chassis showing major structural components

B. On-Highway Chassis CAD Preparation

The commercial ladder chassis geometry was simplified for system-level FEA by retaining primary structural members (longitudinal rails, cross-members) responsible for global stiffness, removing small fillets, holes, brackets with negligible influence on overall structural response, and preserving correct geometric proportions and spatial relationships.

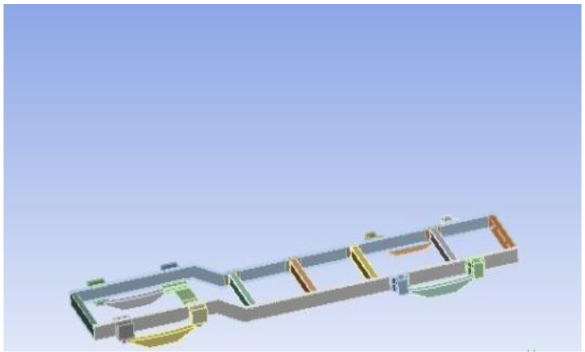

Fig. 3. Commercial on-highway ladder chassis CAD model

C. Simplifications and Justifications

Simplification	Engineering Justification
Removal of small brackets	Negligible global stiffness contribution
No tire modeling	Boundary conditions represent tire effects
No powertrain modeled	Mass represented as equivalent distributed mass
Uniform thickness assumptions	Acceptable for global response evaluation

V. FINITE ELEMENT MODEL

A. Material Properties

All components are assigned structural steel properties for global analysis: Density: 7800 kg/m³; Young's modulus: 210 GPa; Poisson's ratio: 0.3. Since modal behavior is stiffness-dominated and relative stiffness distribution is more important than exact yield strength, a homogeneous material model is appropriate for this stage.

B. Element Selection and Mesh Strategy

3D solid elements were chosen to capture bending, shear, and torsion accurately and enable stress visualization under static loading. Hexahedral elements were used wherever geometry permitted. Critical chassis members were meshed with three elements through thickness to ensure bending stiffness accuracy and avoidance of shear locking. Mesh statistics: Nodes ≈ 630,000; Elements ≈ 830,000.

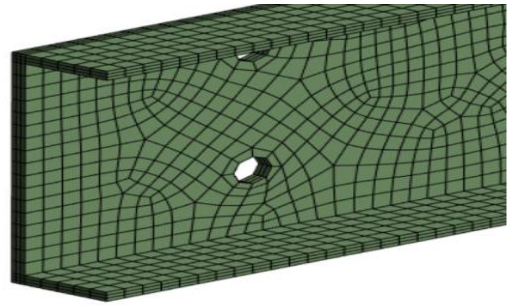

Fig. 4. Through-thickness meshing of chassis rail cross-section

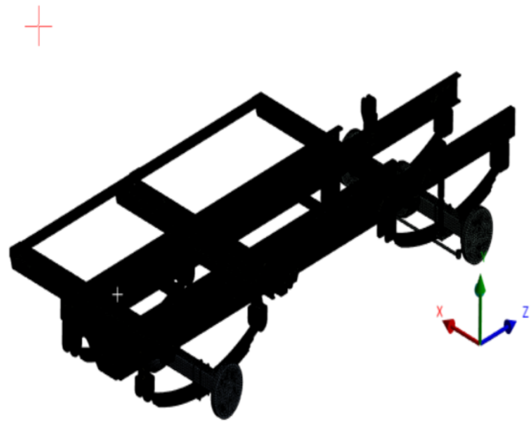

Fig. 5. Complete FE mesh of the chassis assembly

C. Contact Modeling

All contacts were defined as Bonded with program-controlled formulation (MPC where applicable). Bonded contacts ensure stable convergence, clear force transmission paths, and avoidance of artificial compliance. This approach is appropriate for global stiffness studies where relative slip between components is secondary to load transfer continuity.

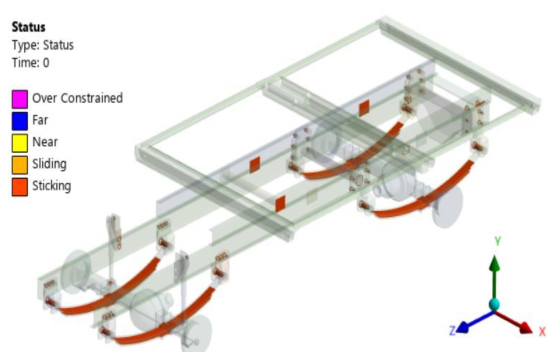

Fig. 6. Contact region definitions in the FE model

VI. BOUNDARY CONDITIONS AND LOADING

A. Off-Highway Chassis - Modal Analysis BCs

Modal boundary conditions were applied using remote displacement constraints at four wheel-mount locations. Vertical displacement was constrained at all wheels. Lateral displacement was constrained at one front wheel and longitudinal displacement at the opposite front wheel to eliminate rigid-body motion without artificially increasing structural stiffness. All rotational DOFs were left unconstrained, allowing natural global bending and torsional modes to develop.

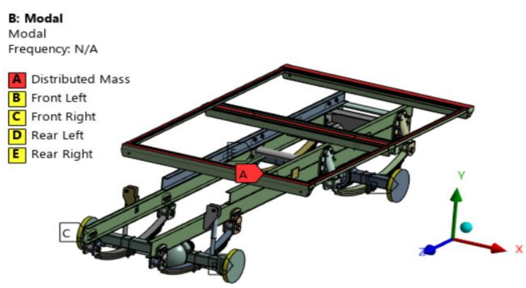

Fig. 7. Modal analysis boundary condition setup - off-highway chassis

Location	Geometry	X (mm)	Y (mm)	Z (mm)	Rotations	Engineering Role
Front Left	2 axle-end faces	Free	0	0	Free	Vertical and longitudinal restraint
Front Right	2 axle-end faces	0	0	Free	Free	Prevents lateral drift at front axle
Rear Left	2 axle-end faces	Free	0	Free	Free	Vertical support only
Rear Right	2 axle-end faces	Free	0	Free	Free	Vertical support only

B. Off-Highway Chassis - Loading Conditions

A distributed mass of 2500 kg was applied to the upper chassis frame members to represent vehicle payload. Standard Earth gravity (9806.6 mm/s², negative Y-axis) was applied in static structural analysis. Gravity was not applied in modal analysis, which was conducted as an un-prestressed modal analysis.

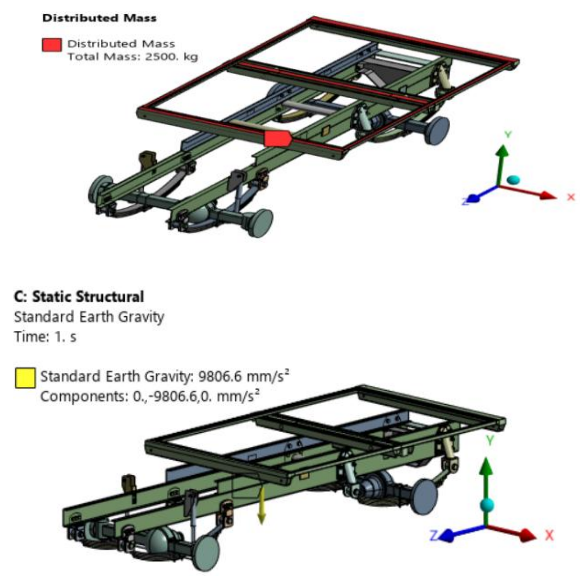

Fig. 8. Distributed payload mass scoping on off-highway chassis upper frame

C. On-Highway Chassis - Loading and BCs

A concentrated force of 1.2258×10^5 N (negative Y-axis) is applied at the loading region, representing the combined payload and structural weight. Fixed supports are applied at the leaf spring mounting regions, restricting all translational DOFs (UX, UY, UZ), representing the physical constraints imposed by the suspension system.

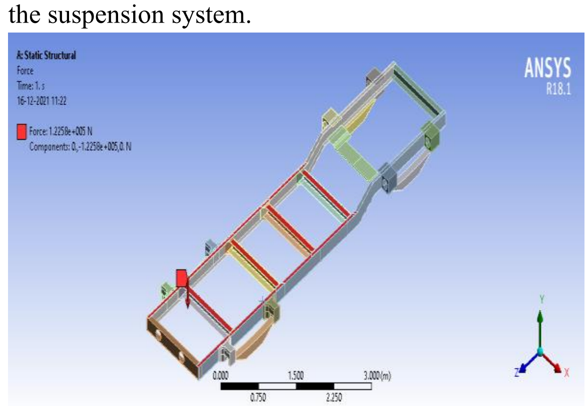

Fig. 9. Applied loading on on-highway commercial chassis model

VII. RESULTS — OFF-HIGHWAY (MILITARY-TYPE) CHASSIS

A. Modal Analysis — Natural Frequencies and Mode Shapes

The first ten natural modes were extracted up to ~18 Hz. Modes below ~10 Hz are global chassis-dominated modes, while modes above ~10 Hz progressively shift towards localized suspension and axle behavior. The modal characteristics align well with expected vehicle chassis dynamics under lightly constrained conditions.

Mode 1 — Near Rigid Body Rotation (0 Hz): Represents near rigid-body motion with the front-left support acting as anchor point. This mode confirms that the constraint strategy avoids over-stiffening and is excluded from structural interpretation.

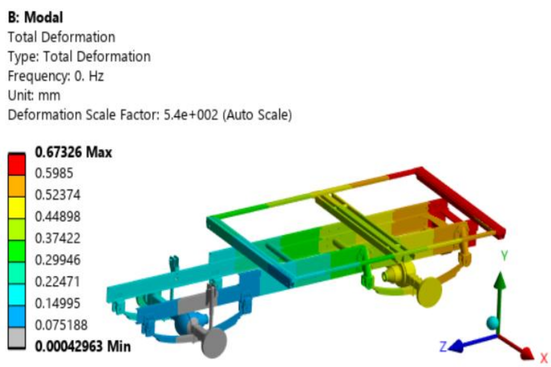

Fig. 10. Mode 1 - Near Rigid Body Rotation (0 Hz)

Mode 2 — Global Lateral Bending (3.05 Hz): Both longitudinal rails move in phase in the lateral direction. Right-side axles show larger displacement, indicating asymmetric stiffness distribution. Critical for side-load inputs, road camber effects, and lateral excitation during cornering.

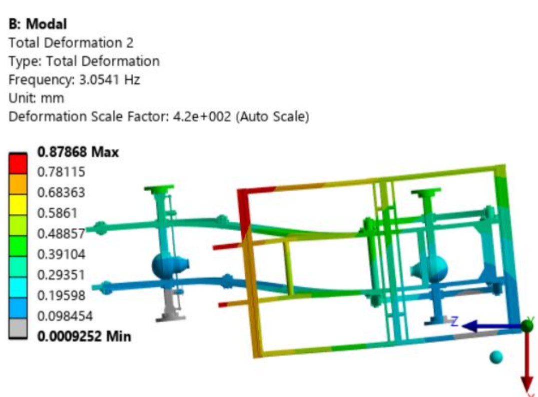

Fig. 11. Mode 2 - Global Lateral Bending (3.05 Hz)

Mode 3 — Global Axial (Longitudinal) Mode with Coupled Vertical Motion (5.15 Hz): Dominant longitudinal motion with the rear half of the chassis moving forward and backward relative to the front-left axle. Governs braking/acceleration-induced vibration response and drivetrain-induced longitudinal excitations.

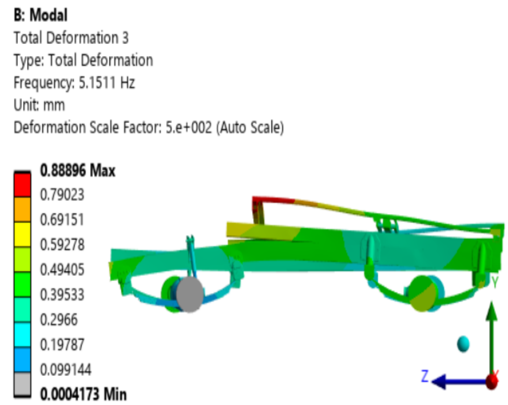

Fig. 12. Mode 3 - Global Axial Mode with Coupled Vertical Motion (5.15 Hz)

Mode 4 — Global Vertical Bending (6.70 Hz): Clear vertical bending (sagging/hogging) behavior with the central region exhibiting maximum vertical displacement. Front and rear axles act as approximate nodal points. This is a primary ride-related mode, strongly influencing comfort and vertical load transfer.

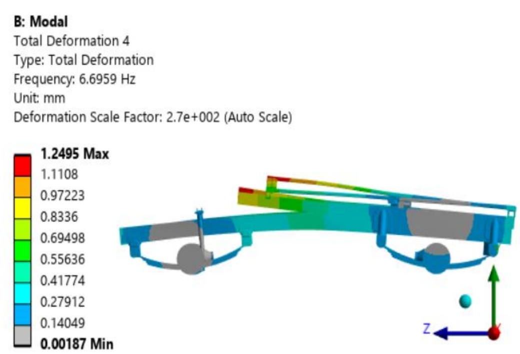

Fig. 13. Mode 4 - Global Vertical Bending Mode (6.70 Hz)

Mode 5 — Coupled Vertical Bending with Anti-Symmetric Rail Motion (7.73 Hz): Left and right chassis rails move out of phase, representing a coupled bending-torsion mode. This mode is sensitive to uneven road inputs such as one-wheel bump events.

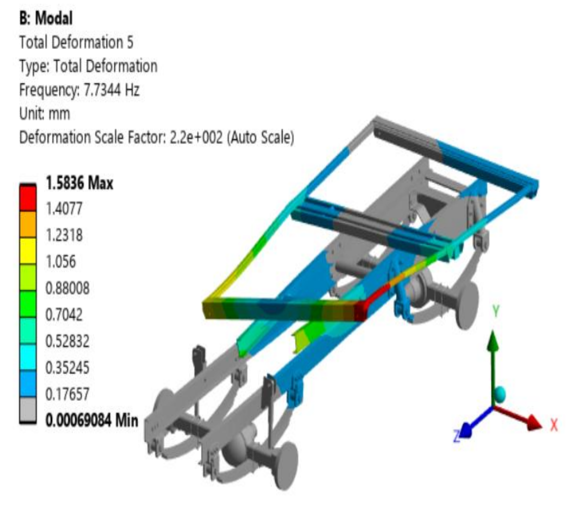

Fig. 14. Mode 5 - Coupled Vertical Bending with Anti-Symmetric Rail Motion (7.73 Hz)

Mode 6 — Rear-Dominant Coupled Vertical-Torsional Mode (10.15 Hz): Similar to Mode 5 but with dominant deformation at the rear section. Rear leaf springs and axle show significant deformation, indicating strong chassis-suspension interaction. Important for rear axle hop and durability assessment of rear suspension mounts.

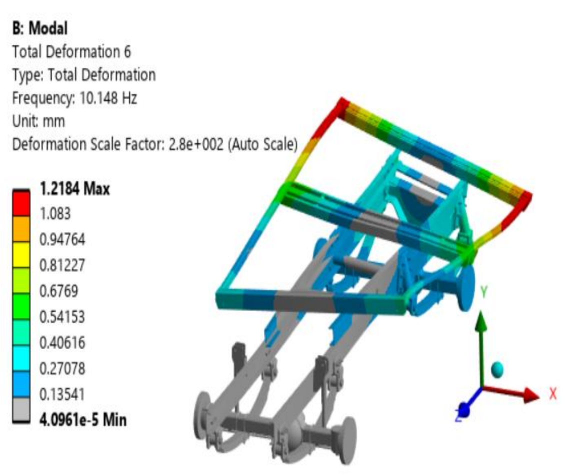

Fig. 15. Mode 6 - Rear-Dominant Coupled Vertical-Torsional Mode (10.15 Hz)

Mode 7 — Rear-Dominant Lateral Bending (12.18 Hz): Both rails move laterally in phase with the rear half being more active and the front half behaving comparatively rigid. Relevant for rear lateral stability under asymmetric loading conditions.

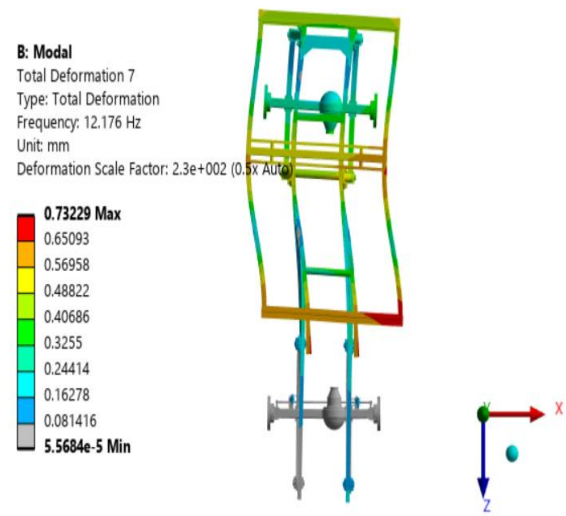

Fig. 16. Mode 7 - Rear-Dominant Lateral Bending (12.18 Hz)

Mode 8 — Rear Vertical Bending with Active Suspension Participation (12.83 Hz): Predominantly vertical bending of the rear half with suspension components actively participating. Front section remains relatively rigid. This mode directly affects ride comfort and suspension tuning at higher speeds.

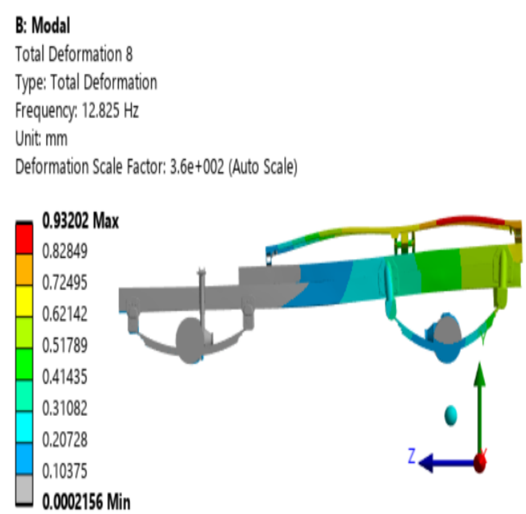

Fig. 17. Mode 8 - Rear Vertical Bending with Suspension Participation (12.83 Hz)

Mode 9 — Rear-Dominant Torsional Mode (15.68 Hz): Clear torsional twisting of the chassis with the rear half being more flexible. Critical for chassis torsional stiffness evaluation, especially for uneven terrain and diagonal wheel inputs.

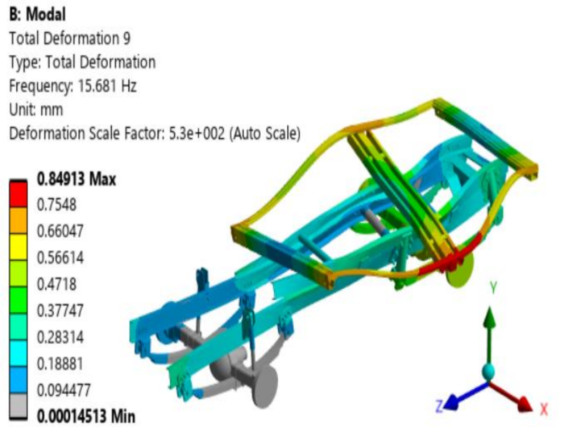

Fig. 18. Mode 9 - Rear-Dominant Torsional Mode (15.68 Hz)

Mode 10 — Local Rear Axle and Leaf Spring Mode (17.57 Hz): Highly localized mode dominated by the rear axle and leaf spring assembly with minimal global chassis involvement. Important for NVH refinement and local fatigue analysis of rear suspension components.

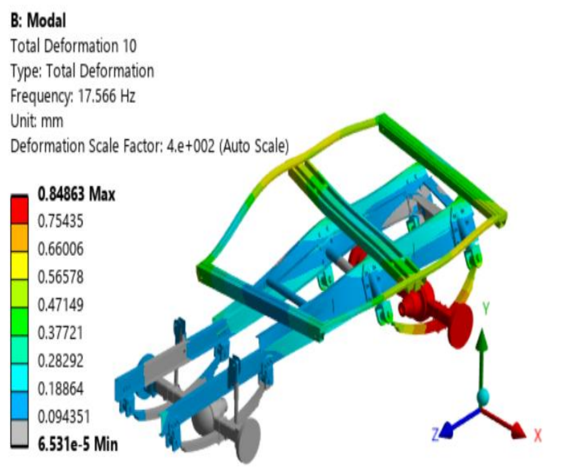

Fig. 19. Mode 10 - Local Rear Axle and Leaf Spring Mode (17.57 Hz)

B. Static Structural Results — Off-Highway Chassis

The static structural analysis evaluated deformation and stress response under gravity and distributed payload loading. Maximum deformation occurs in the mid-span region of the chassis, between the front and rear suspension mounting points. Front and rear axle regions exhibit comparatively lower deformation, acting as effective support locations. Longitudinal rails show smooth deformation gradients, indicating proper load distribution.

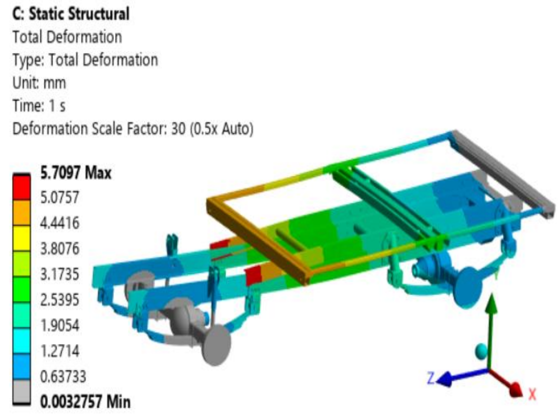

Fig. 20. Total deformation contour — off-highway chassis under payload and gravity loading

The equivalent von Mises stress distribution shows a predominantly uniform stress state across main chassis members. Peak stresses are observed near bolt locations, contact interfaces, and mounting brackets — these are characteristic stress singularities caused by idealized boundary conditions. The majority of the chassis structure experiences stress levels below 250 MPa, confirming it remains well within the elastic regime.

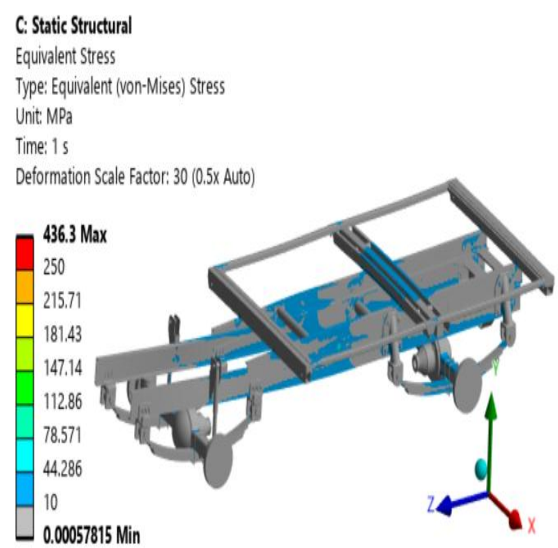

Fig. 21. Equivalent (von Mises) stress distribution — off-highway chassis

VIII. RESULTS — ON-HIGHWAY COMMERCIAL CHASSIS

A. Static Structural Analysis

Table I presents the key static structural results comparing Structural Steel and A710 Steel:

TABLE I. STATIC STRUCTURAL RESULTS COMPARISON

Parameter	Structural Steel	A710 Steel	% Improvement
Max. Total Deformation (mm)	2.4468	1.964	20% lower
Max. von Mises Stress (MPa)	404.05	322.4	20% lower
Max. Principal Stress (MPa)	394.59	322.4	18% lower
Max. Equivalent Strain	2.10×10^{-3}	1.69×10^{-3}	19% lower

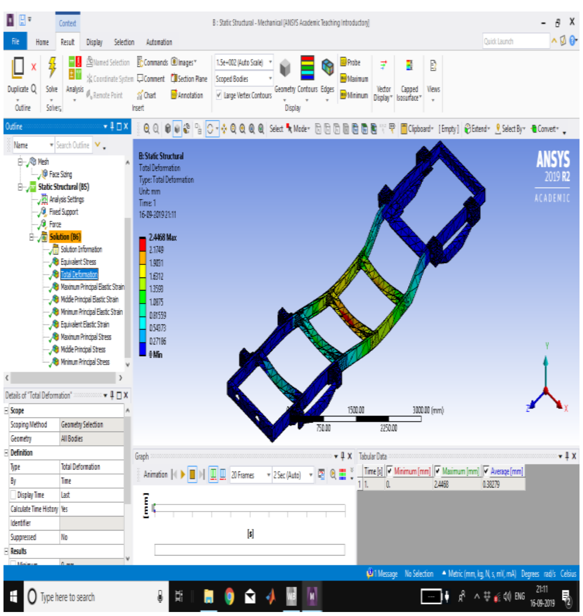

Fig. 22. Total Deformation — Structural Steel

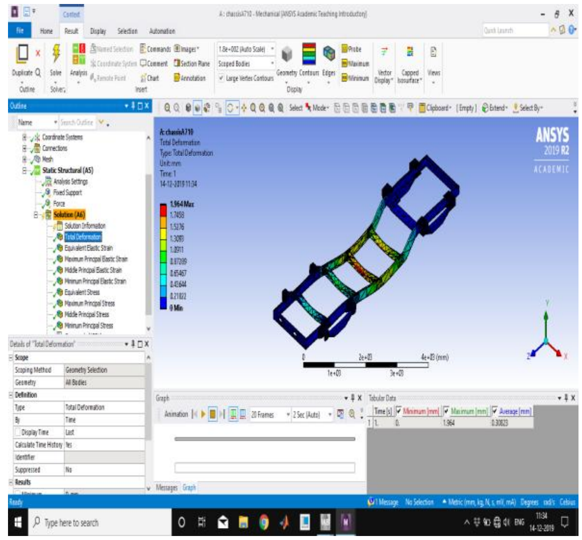

Fig. 23. Total Deformation — A710 Steel

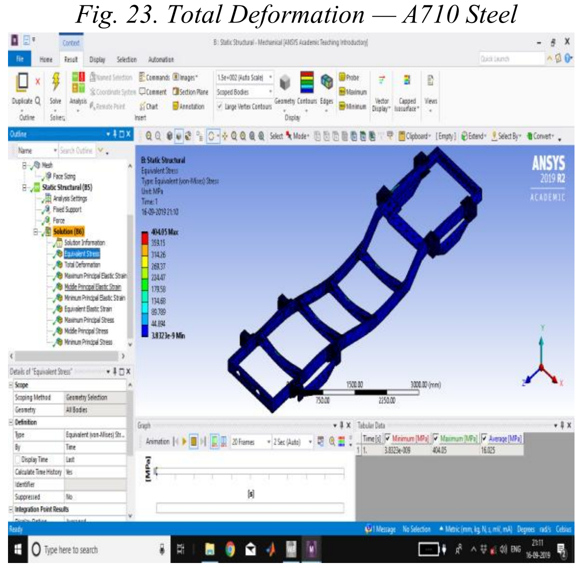

Fig. 24. Equivalent Stress Distribution — Structural Steel

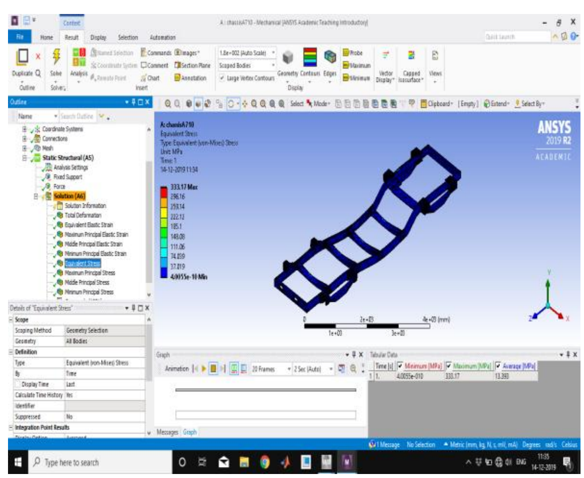

Fig. 25. Equivalent Stress Distribution — A710 Steel

B. Modal Analysis Results — On-Highway Chassis

TABLE II. MODAL ANALYSIS RESULTS (FIRST THREE MODES)

Mode	Struct. Steel (Hz)	Engine (rpm)	A710 Steel (Hz)	Engine (rpm)	Mode Shape
1	33.801	≈ 2028	34.191	≈ 2052	First Vertical Bending
2	35.796	≈ 2148	36.188	≈ 2171	Lateral Bending + Rung Lifting
3	66.35	≈ 3981	51.76	≈ 3106	Torsion + Second-Order Bending

A710 Steel shows slightly higher natural frequencies, shifting resonance away from the typical heavy-vehicle operating range (< 2200 rpm).

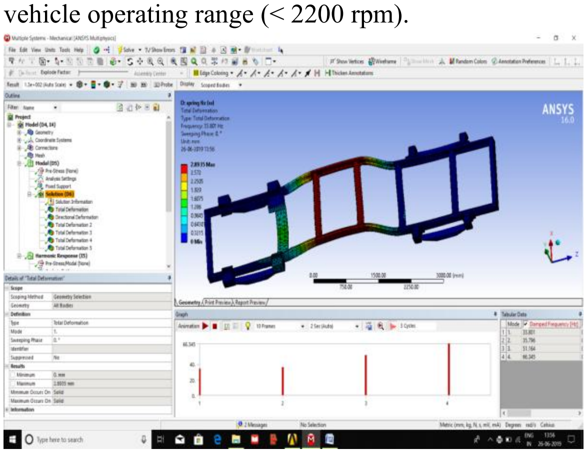

Fig. 26. Mode 1 — First Vertical Bending under applied force (Structural Steel)

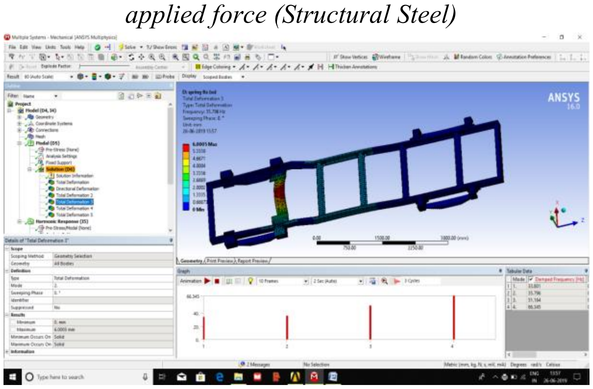

Fig. 27. Mode 2 — Lateral Bending under applied force (Structural Steel)

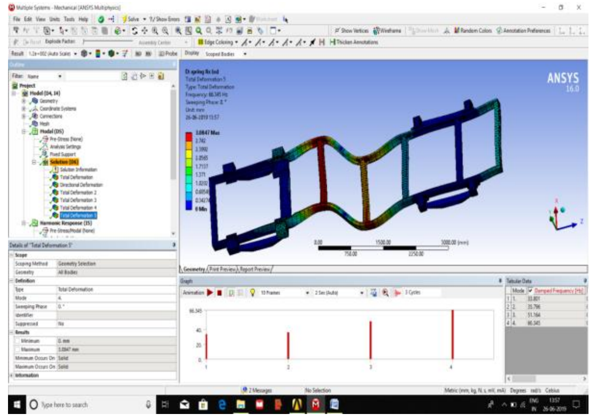

Fig. 28. Mode 3 — Torsional Mode under applied force (Structural Steel)

C. Analytical Validation

TABLE III. ANALYTICAL VALIDATION OF FUNDAMENTAL NATURAL FREQUENCY

Method	Struct. Steel (Hz)	A710 Steel (Hz)	ANSYS Modal (Hz)	% Error
Dunkerley's	33.41	34.02	33.80 / 34.19	< 2%
Rayleigh's	34.18	34.79	33.80 / 34.19	< 3%

Excellent agreement (< 3% error) between hand calculations and FEA confirms the validity of the finite element model.

D. Harmonic Response Analysis

TABLE IV. HARMONIC RESPONSE RESULTS AT 50.5 Hz EXCITATION

Parameter	Structural Steel	A710 Steel
Max. Normal Stress (MPa)	155.66	156.93 (similar peak, lower elsewhere)
Max. Directional Deformation (mm)	2.92	0.575 (80% lower)

A710 Steel exhibits dramatically lower vibration amplitude at resonance, making it significantly safer under cyclic road inputs.

E. Fatigue Life and Safety Factor

TABLE V. FATIGUE LIFE AND SAFETY FACTOR AT CRITICAL LEAF-SPRING MOUNTING ZONE

Parameter	Structural Steel	A710 Steel	Improvement
Min. Fatigue Life (cycles)	7,160	19,871	+177%
Min. Safety Factor (ANSYS Fatigue)	0.453	0.505	+11%
Safety Factor (Soderberg criterion)	0.341	0.566	+66%

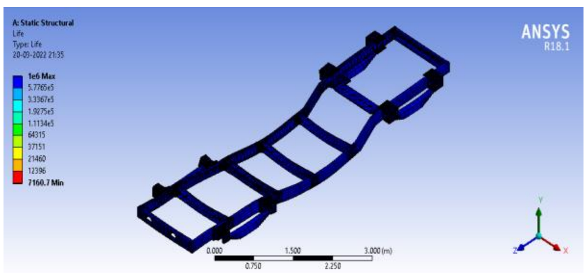

Fig. 29. Fatigue Life (Number of Cycles) — Structural Steel

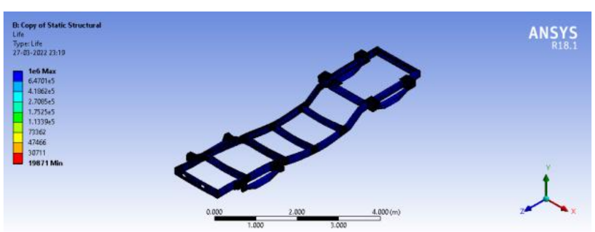

Fig. 30. Fatigue Life (Number of Cycles) — A710 Steel

IX. CONCLUSIONS

A comprehensive finite element investigation was carried out on two distinct ladder-type chassis configurations representing off-highway (military-type) and on-highway (commercial vehicle) applications. The study incorporated static structural, modal, and harmonic response simulations, along with material comparison and fatigue assessment.

For the off-highway chassis, the modal analysis identified fundamental deformation modes including lateral bending, vertical bending, axial motion, and torsional behavior within the low-frequency range (0-18 Hz). Static structural analysis confirmed global deformation dominated by vertical bending, consistent with expected ladder-frame behavior. The chassis demonstrates adequate stiffness, realistic load transfer characteristics, and stable dynamic behavior.

For the on-highway commercial chassis, field failures are primarily driven by resonance phenomena. The first natural frequency (~33-36 Hz) coincides with typical engine excitation frequencies, leading to vibration amplification and fatigue failure at leaf-spring mounting regions. This confirms that static analysis alone is insufficient for chassis durability evaluation.

Material comparison demonstrates that A710 Steel is superior to conventional Structural Steel: (1) 20% reduction in maximum deformation and stress; (2) Higher natural frequencies shifting resonance away from the operating range; (3) 80% reduction in vibration amplitude under harmonic excitation; (4) 94-177% improvement in fatigue life at critical locations; (5) 66% improvement in Soderberg safety factor.

A710 Steel is recommended as a direct material replacement for conventional structural steel in commercial chassis applications, offering immediate improvements in durability, vibration response, and fatigue life without requiring geometric modifications.

A combined static-modal-harmonic FEA framework is essential for reliable chassis design and durability assessment.

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