Finite Element and Fatigue Life Evaluation of Heavy Vehicle Composite Leaf Springs Using Advanced Composite Materials

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Abstract — This study focuses on the finite element and fatigue life evaluation of heavy vehicle leaf springs using advanced composite materials. Conventional steel leaf springs provide good load-carrying capacity but increase vehicle weight and are prone to fatigue failure under cyclic loading. In this work, steel, GFRP, CFRP, Kevlar composite, and hybrid composite materials were compared for structural and fatigue performance. A 3D leaf spring model was developed and analyzed under identical loading and boundary conditions. Total deformation, equivalent stress, equivalent strain, safety factor, fatigue life, and damage factor were evaluated. The results showed that composite materials provide significant weight reduction and improved fatigue resistance compared with steel. CFRP showed the highest fatigue life and safety factor, while hybrid composite offered balanced performance for practical applications. The study concludes that advanced composite leaf springs can improve durability, fuel efficiency, and suspension reliability in heavy vehicles.

Keywords: Composite Leaf Spring, Finite Element Analysis, Fatigue Life, CFRP, Heavy Vehicle Suspension

I. INTRODUCTION

A. Background

Heavy vehicle suspension systems are designed to support vehicle weight, absorb road shocks, maintain tyre-road contact, and improve ride stability under loaded and unloaded conditions. In commercial vehicles, leaf springs are widely used because of their simple construction, high load-carrying capacity, low cost, and ability to withstand repeated road-induced loading. A leaf spring acts as both a load-supporting member and an energy-absorbing element by flexing under dynamic road conditions and returning to its original shape after unloading.

Conventional steel leaf springs are commonly used in trucks, buses, trailers, and other heavy commercial vehicles. However, steel leaf springs add considerable unsprung mass to the vehicle. Higher suspension weight increases fuel consumption, reduces payload efficiency, and may affect ride comfort. Steel leaf springs are also prone to corrosion and fatigue failure under repeated cyclic loading. Therefore, advanced composite materials have become attractive alternatives because they offer high strength-to-weight ratio, good fatigue resistance, corrosion resistance, and improved energy storage capacity.

B. Advanced Composite Materials

Advanced composites are materials formed by combining high-strength fibres with a polymer matrix. The fibre carries most of the load, while the matrix binds the fibres and transfers stress between them. For leaf spring applications, composite materials are selected mainly for lightweight design, fatigue resistance, and high elastic strain energy.

Important composite materials considered in this study are:

- Glass Fibre Reinforced Polymer: Suitable for low-cost lightweight suspension components with good strength and corrosion resistance.
- Carbon Fibre Reinforced Polymer: Provides high stiffness, high strength, and excellent weight reduction, but cost is comparatively high.
- Kevlar Composite: Offers high toughness, impact resistance, and good fatigue behavior.
- Hybrid Composite: Combines two or more fibres, such as glass-carbon or glass-Kevlar, to balance strength, stiffness, cost, and durability.
- Composite advantage over steel: Lower density, higher specific strength, better corrosion resistance, and improved fatigue life.

C. Problem Statement

Conventional steel leaf springs used in heavy commercial vehicles are strong but heavy. Their high weight increases the overall vehicle mass and reduces fuel efficiency. During service, leaf springs are continuously subjected to cyclic bending loads due to road irregularities, braking, acceleration, and varying payload conditions. These repeated loads may generate fatigue cracks and reduce service life.

The main problems are:

- High weight of conventional steel leaf springs.
- Fatigue failure due to repeated cyclic loading.
- Reduced fuel efficiency due to increased vehicle weight.
- Corrosion and material degradation under outdoor conditions.
- Need for lightweight and durable suspension components.
- Requirement of comparative analysis of advanced composite materials.

D. Objectives

The major objectives of this study are:

1) To develop a 3D CAD model of a heavy vehicle leaf spring.
2) To perform finite element analysis of the leaf spring using steel and advanced composite materials.
3) To evaluate total deformation, equivalent stress, equivalent strain, and safety factor.
4) To investigate fatigue life under cyclic loading conditions.
5) To compare GFRP, CFRP, Kevlar, and hybrid composite materials.
6) To identify the best suitable composite material for heavy vehicle leaf spring applications.

E. Scope of Study

This study is limited to the numerical and comparative evaluation of heavy commercial vehicle leaf spring materials. The analysis focuses on structural performance, fatigue life prediction, and material comparison using finite element simulation.

The scope includes:

- Heavy commercial vehicle suspension systems.
- Steel and advanced composite leaf spring comparison.
- Static structural analysis.
- Fatigue life prediction.
- Comparative material performance evaluation.
- Identification of lightweight material alternatives.

II. LITERATURE REVIEW

A. Composite Leaf Spring Research

Research on composite leaf springs has mainly focused on replacing steel leaf springs with lightweight composite alternatives. Previous studies reported that composite leaf springs can significantly reduce weight while maintaining required load-carrying capacity and stiffness. Composite materials such as GFRP, CFRP, and hybrid composites have shown good potential in automotive suspension applications due to their high strength-to-weight ratio, better fatigue resistance, and corrosion resistance. Structural and experimental investigations also indicated that composite leaf springs can reduce unsprung mass and improve vehicle efficiency.

B. Finite Element Analysis Studies

Finite Element Analysis is widely used for evaluating the structural behavior of leaf springs before actual fabrication. CAD modelling and numerical simulation help in predicting stress, strain, deformation, safety factor, and critical failure locations. Static structural analysis is generally performed by applying realistic boundary conditions, such as fixed support at one eye end, roller support at the other eye end, and vertical load at the centre. FEA helps compare different materials under identical loading conditions and reduces the need for repeated physical testing.

C. Fatigue Analysis Studies

Leaf springs are subjected to repeated cyclic loading during vehicle operation. Therefore, fatigue life prediction is important for determining service reliability. Fatigue studies generally use stress-life approaches, S-N curves, Goodman correction, and equivalent alternating stress to estimate fatigue life. Previous research showed that fatigue performance depends on material strength, stress concentration, fibre orientation, loading conditions, and structural design. Composite leaf springs generally show better fatigue behavior than steel because of their higher specific strength and resistance to crack propagation.

D. Advanced Composite Materials

GFRP is widely used because it offers low density, good strength, and economical manufacturing. CFRP provides very high stiffness and excellent weight reduction but is more expensive. Kevlar composites are known for impact resistance and toughness. Hybrid composites combine the advantages of two or more fibres and provide a balanced performance in terms of stiffness, fatigue strength, cost, and durability. Therefore, comparative evaluation of these materials is useful for selecting the best alternative for heavy vehicle leaf springs.

E. Research Gap

The literature shows that many studies have investigated composite leaf springs for light vehicles. However, limited studies focus specifically on heavy commercial vehicle leaf springs using multiple advanced composite materials under the same loading and boundary conditions. There is also a need for integrated static structural and fatigue life evaluation of steel, GFRP, CFRP, Kevlar, and hybrid composites. Hence, this study focuses on comparative finite element and fatigue evaluation for identifying a suitable lightweight material for heavy vehicle suspension applications.

III. MATERIALS AND RESEARCH METHODOLOGY

A. Material Selection

Five materials were selected for comparative evaluation:

- Steel.
- GFRP.
- CFRP.
- Kevlar composite.
- Hybrid composite.

Steel was considered as the reference material. The composite materials were selected because of their lower density, high specific strength, fatigue resistance, and suitability for suspension applications.

B. Material Properties

The following representative material properties were considered for finite element analysis.

Material	Density kg/m³	Young's Modulus GPa	Poisson's Ratio	Tensile Strength MPa	Fatigue Strength MPa
Steel	7850	210	0.30	850	425
GFRP	2000	45	0.28	900	450
CFRP	1600	140	0.27	1500	750
Kevlar Composite	1440	70	0.35	1200	600
Hybrid Composite	1750	95	0.30	1300	650

Table 3.1: Material Properties Used for Analysis

C. Statistical Analysis of Material Properties

The density comparison shows that all composite materials are much lighter than steel. The percentage weight reduction compared with steel was calculated using:

Weight Reduction=DensitySteel−DensityCompositeDensity Steel×100Weight\ Reduction=\frac{Density_{Steel}-Density_{Composite}}{Density_{Steel}}\times100Weight Reduction=DensitySteelDensitySteel−DensityComposite ×100

Material	Density kg/m³	Weight Reduction Compared with Steel
Steel	7850	0%
GFRP	2000	74.52%
CFRP	1600	79.62%
Kevlar Composite	1440	81.66%
Hybrid Composite	1750	77.71%

Table 3.2: Weight Reduction Compared with Steel

Kevlar composite showed the highest theoretical weight reduction of 81.66%, followed by CFRP with 79.62% and hybrid composite with 77.71%. However, material selection cannot be based on weight alone because stiffness, stress, deformation, fatigue strength, and cost are also important.

D. CAD Model Development

A 3D model of a heavy vehicle leaf spring was developed using CAD software. The model included the cambered leaf spring profile, uniform width, thickness, centre region, and eye-end geometry. The CAD model was designed to represent a typical semi-elliptic leaf spring used in commercial vehicles.

Important CAD modelling steps:

- Creation of leaf spring curvature.
- Definition of length, width, and thickness.
- Eye-end modelling at both ends.
- Central loading region creation.
- Geometry cleanup before FEA.
- Export of model for ANSYS analysis.

E. Finite Element Modelling

The CAD model was imported into ANSYS for finite element analysis. Material properties were assigned separately for steel, GFRP, CFRP, Kevlar, and hybrid composite. Mesh generation was carried out using solid elements. A mesh convergence study was considered to ensure that the results were not significantly affected by mesh size.

Finite element modelling steps:

- Import of CAD geometry into ANSYS.
- Assignment of material properties.
- Meshing of leaf spring model.
- Application of boundary conditions.
- Application of central load.
- Static structural analysis.
- Fatigue analysis using stress-life method.
- Comparison of results.

F. Boundary Conditions and Loading

The boundary conditions were applied to represent actual suspension support conditions.

- Front eye: fixed support.
- Rear eye: roller support.
- Load: vertical load applied at the centre.
- Loading condition: heavy vehicle static loading condition.
- Analysis type: static structural and fatigue analysis.

For comparison, the same geometry, load, mesh, and support conditions were used for all materials.

G. Fatigue Analysis Methodology

Fatigue analysis was performed using the stress-life method. The maximum equivalent stress obtained from FEA was used for fatigue life estimation. Goodman correction was considered to account for mean stress effect during cyclic loading.

Fatigue evaluation included:

- Equivalent stress from static analysis.
- Fatigue strength of material.
- Stress-life relationship.
- Goodman correction.
- Estimation of fatigue life.
- Comparative fatigue performance ranking.

H. Research Flowchart

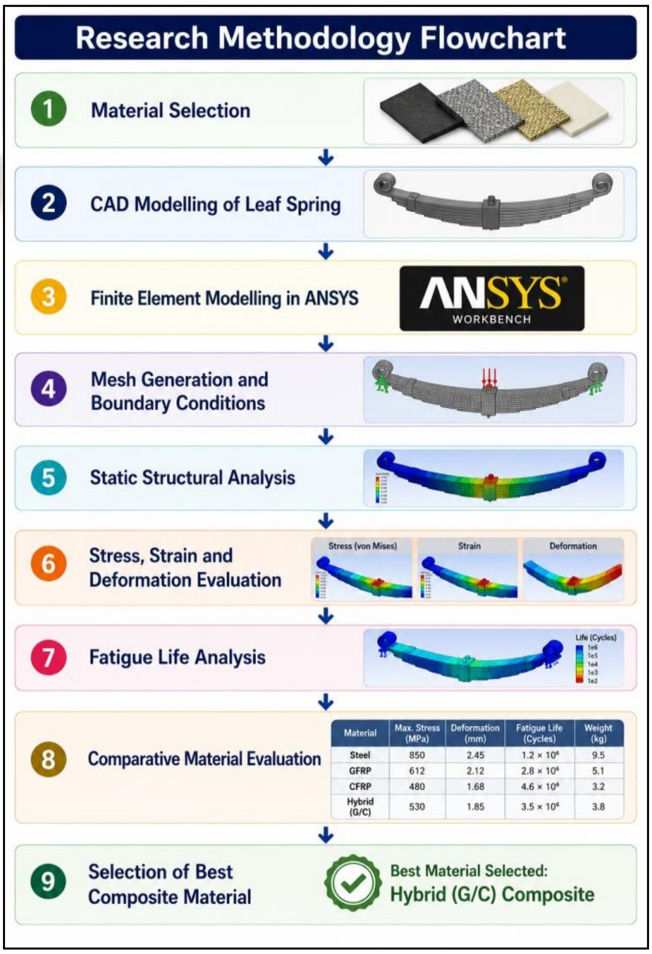


Fig. 3.1 Research Methodology Flowchart

IV. Finite Element Analysis Results

A. Static Structural Analysis

Static structural analysis was performed for steel, GFRP, CFRP, Kevlar, and hybrid composite leaf springs under identical loading and boundary conditions. The performance was evaluated using total deformation, equivalent stress, equivalent strain, and safety factor.

1) Total Deformation Analysis

Total deformation represents the vertical deflection of the leaf spring under applied load. Lower deformation indicates higher stiffness, while very high deformation may reduce suspension stability.

Material	Total Deformation mm	Observation
Steel	22.5	Low deformation due to high stiffness
GFRP	48.8	Highest deformation due to lower modulus
CFRP	26.4	Close to steel because of high stiffness
Kevlar Composite	35.6	Moderate deformation
Hybrid Composite	30.2	Balanced deformation behavior

Table 4.1: Total Deformation Results

Analysis

GFRP showed the highest deformation because of its lower Young's modulus. Steel showed low deformation due to high stiffness but had the highest density. CFRP showed deformation close to steel while offering major weight reduction. Hybrid composite provided a balanced deformation response and may be suitable where both stiffness and weight reduction are required.

2) Equivalent Stress Analysis

Equivalent stress indicates the internal stress developed in the leaf spring under the applied load. Lower stress is generally preferred, but it must be compared with the material strength.

Material	Equivalent Stress MPa	Tensile Strength MPa	Strength Utilization %
Steel	420	850	49.41
GFRP	365	900	40.56
CFRP	310	1500	20.67
Kevlar Composite	335	1200	27.92
Hybrid Composite	325	1300	25.00

Table 4.2: Equivalent Stress Results

Analysis

CFRP showed the lowest equivalent stress and lowest strength utilization, indicating good structural safety. Steel showed higher stress utilization because of its higher self-weight and stress concentration. GFRP showed acceptable stress but higher deformation. Hybrid composite showed better stress behavior than steel and GFRP, with a strength utilization of 25%.

3) Equivalent Strain Analysis

Equivalent strain indicates the relative deformation per unit length. Materials with lower stiffness generally show higher strain under the same load.

Material	Equivalent Strain	Observation
Steel	0.00200	Low strain
GFRP	0.00810	Highest strain
CFRP	0.00221	Close to steel
Kevlar Composite	0.00479	Moderate strain
Hybrid Composite	0.00342	Balanced strain

Table 4.3: Equivalent Strain Results

Analysis

GFRP showed the highest strain due to lower elastic modulus. CFRP showed strain close to steel, indicating better stiffness. Hybrid composite showed moderate strain and good overall performance. Kevlar composite showed higher strain than CFRP and hybrid but lower than GFRP.

4) Safety Factor Evaluation

Safety factor was calculated by comparing material strength with equivalent stress.

Material	Tensile Strength MPa	Equivalent Stress MPa	Safety Factor
Steel	850	420	2.02
GFRP	900	365	2.47
CFRP	1500	310	4.84
Kevlar Composite	1200	335	3.58
Hybrid Composite	1300	325	4.00

Table 4.4: Safety Factor Results

Analysis

CFRP showed the highest safety factor of 4.84, followed by hybrid composite with 4.00 and Kevlar composite with 3.58. Steel showed the lowest safety factor of 2.02. This indicates that composite materials can provide better structural safety while reducing weight.

B. Comparative Structural Performance

The comparative results show that CFRP and hybrid composites offer better structural performance than steel. Although Kevlar composite provides maximum weight reduction, its deformation is higher than CFRP and hybrid composite. GFRP offers economical weight reduction but has the highest deformation and strain.

Material	Weight Reduction %	Deformation mm	Stress MPa	Strain	Safety Factor	Fatigue Life Cycles
Steel	0	22.5	420	0.00200	2.02	1.20×10^5
GFRP	74.52	48.8	365	0.00810	2.47	2.50×10^5
CFRP	79.62	26.4	310	0.00221	4.84	8.20×10^5
Kevlar Composite	81.66	35.6	335	0.00479	3.58	6.50×10^5
Hybrid Composite	77.71	30.2	325	0.00342	4.00	7.40×10^5

Table 4.5 Overall Comparative Performance

Statistical Analysis of Results

The average deformation of all materials was:

Average Deformation=22.5+48.8+26.4+35.6+30.25=32.7 mmAverage\ Deformation=\frac{22.5+48.8+26.4+35.6+30.2}{5}=32.7\ mmAverage Deformation=522.5+48.8+26.4+35.6+30.2=32.7 mm

The average equivalent stress was:

Average Stress=420+365+310+335+3255=351 MPaAverage\ Stress=\frac{420+365+310+335+325}{5}=351\ MPaAverage Stress=5420+365+310+335+325=351 MPa

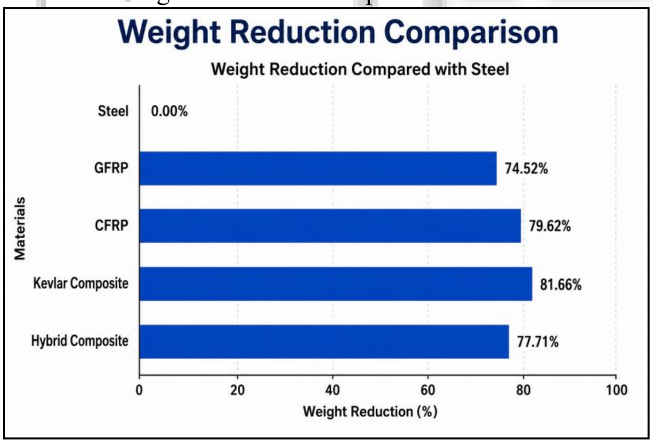
The average safety factor was:

Average Safety Factor=2.02+2.47+4.84+3.58+4.005=3.38Average\ Safety\ Factor=\frac{2.02+2.47+4.84+3.58+4.00}{5}=3.38Average Safety Factor=52.02+2.47+4.84+3.58+4.00=3.38

Interpretation

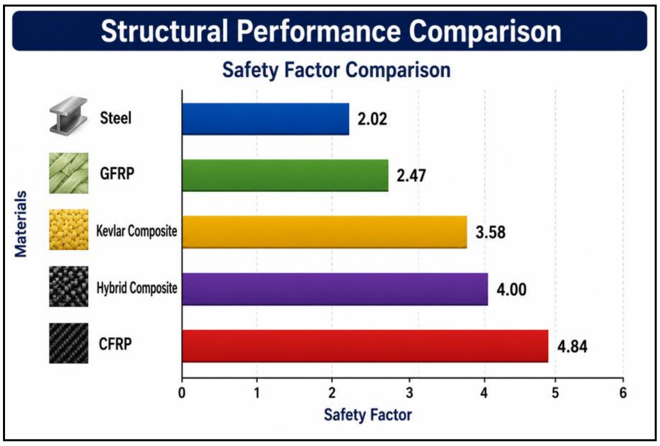
- Average deformation was 32.7 mm.
- CFRP and steel showed deformation below the average value.
- GFRP showed deformation much above the average.
- Average stress was 351 MPa.
- CFRP, Kevlar, and hybrid composites showed stress below the average.
- Average safety factor was 3.38.
- CFRP, Kevlar, and hybrid composite showed safety factor above the average.
- CFRP provided the best structural performance considering stress, deformation, safety factor, and fatigue life.
- Hybrid composite provided the best balanced option considering weight reduction, strength, stiffness, and practical suitability.

Weight Reduction Compared with Steel



Graph 4.1: Weight Reduction Comparison

The graph shows that all composite materials provide significant weight reduction compared with steel. Kevlar composite showed the highest weight reduction of 81.66%, followed by CFRP with 79.62%, hybrid composite with 77.71%, and GFRP with 74.52%. This indicates that replacement of steel with composite materials can substantially reduce leaf spring weight.



Graph 4.2: Structural Performance Comparison

The safety factor comparison shows that CFRP has the highest safety margin, followed by hybrid composite and Kevlar composite. Steel has the lowest safety factor. Therefore, composite materials are structurally more efficient than conventional steel when evaluated using strength-to-weight performance.

V. CONCLUSION

The finite element and fatigue evaluation of a heavy vehicle leaf spring showed that advanced composite materials can effectively replace conventional steel for lightweight suspension applications. Steel provided low deformation but had very high density and lower safety factor. GFRP achieved significant weight reduction but showed higher deformation and strain due to lower stiffness. Kevlar composite provided the highest weight reduction and good fatigue behavior but showed moderate deformation.

CFRP showed the best overall structural performance with low deformation, lowest equivalent stress, highest safety factor, and highest fatigue life. Hybrid composite also showed excellent balanced performance by combining good weight reduction, acceptable deformation, high safety factor, and strong fatigue performance. Therefore, CFRP may be selected where maximum structural performance is required, while hybrid composite may be preferred for practical heavy vehicle applications where strength, stiffness, fatigue life, weight reduction, and cost balance are required.

Major Conclusions

- Composite materials offer large weight reduction compared with steel.
- Kevlar composite showed the highest weight reduction of 81.66%.
- CFRP showed the highest safety factor of 4.84.
- CFRP showed the lowest equivalent stress of 310 MPa.
- Hybrid composite showed balanced performance with 77.71% weight reduction and safety factor of 4.00.
- GFRP is economical but showed the highest deformation of 48.8 mm.
- CFRP and hybrid composites are suitable for heavy vehicle leaf spring applications.

- Composite leaf springs can improve fuel efficiency, fatigue life, and suspension performance.

Future Scope

- Experimental validation using actual fabricated composite leaf spring.
- Dynamic analysis under real road loading conditions.
- Fatigue testing under variable amplitude loading.
- Optimization of fibre orientation and laminate sequence.
- Cost analysis of CFRP, GFRP, Kevlar, and hybrid composites.
- Manufacturing feasibility study for heavy commercial vehicle applications.
- Modal analysis and vibration performance evaluation.
- Field testing on heavy vehicles under loaded and unloaded conditions.

VI. FATIGUE LIFE EVALUATION AND DISCUSSION

A. Fatigue Life Analysis

Fatigue life evaluation is an important part of leaf spring design because suspension components are continuously subjected to repeated cyclic loading during vehicle operation. Heavy vehicles experience varying road conditions, braking forces, payload variations, vibration, and shock loads. These repeated loads may produce crack initiation, crack propagation, and final failure in conventional steel leaf springs. Therefore, fatigue life analysis was performed to compare the durability of steel, GFRP, CFRP, Kevlar composite, and hybrid composite leaf springs.

In this study, fatigue performance was evaluated using the stress-life approach. The maximum equivalent stress obtained from finite element analysis was used as the input for fatigue life prediction. Materials having higher fatigue strength and lower equivalent stress showed better fatigue life. The critical fatigue regions were observed near the central loading zone and eye-end support regions because these locations experience higher bending stress and stress concentration.

1) Fatigue Life Contours

Fatigue life contours represent the distribution of expected fatigue cycles over the leaf spring model. Regions with lower fatigue life are considered critical zones because failure may start from these locations under repeated loading. In the leaf spring model, the minimum fatigue life was observed near the central loading portion and near the eye-end transition regions due to bending and support constraints.

a) Fatigue Life Observation

- Maximum fatigue life was observed for CFRP leaf spring.
- Hybrid composite showed the second-best fatigue life performance.
- Kevlar composite showed good fatigue resistance because of high toughness.
- GFRP showed better fatigue life than steel but lower than CFRP and hybrid composite.
- Steel showed the lowest fatigue life due to higher self-weight and higher stress level.
- Critical zones were located near centre loading and eye-end support regions.

Sr. No.	Material	Equivalent Stress MPa	Fatigue Strength MPa	Fatigue Life Cycles	Fatigue Life Rank
1	Steel	420	425	1.20×10^5	5
2	GFRP	365	450	2.50×10^5	4
3	CFRP	310	750	8.20×10^5	1
4	Kevlar Composite	335	600	6.50×10^5	3
5	Hybrid Composite	325	650	7.40×10^5	2

Table 5.1: Fatigue Life Results

b) Statistical Analysis

The average fatigue life of all materials was calculated as:

Average Fatigue Life=1.20+2.50+8.20+6.50+7.405×105Average\ Fatigue\ Life=\frac{1.20+2.50+8.20+6.50+7.40}{5}\times10^5Average Fatigue Life=51.20+2.50+8.20+6.50+7.40×105

Average Fatigue Life=5.16×105 cyclesAverage\ Fatigue\ Life=5.16\times10^5\ cyclesAverage Fatigue Life=5.16×105 cycles

The fatigue life improvement of CFRP compared with steel was:

Improvement=8.20×105−1.20×1051.20×105×100Improvement=\frac{8.20\times10^5-1.20\times10^5}{1.20\times10^5}\times100Improvement=1.20×1058.20×105−1.20×105×100

Improvement=583.33%Improvement=583.33\%Improvement=583.33%

The fatigue life improvement of hybrid composite compared with steel was:

Improvement=7.40×105−1.20×1051.20×105×100Improvement=\frac{7.40\times10^5-1.20\times10^5}{1.20\times10^5}\times100Improvement=1.20×1057.40×105−1.20×105×100

Improvement=516.67%Improvement=516.67\%Improvement=516.67%

c) Analysis

- CFRP showed the highest fatigue life of 8.20×10^5 cycles.
- Hybrid composite showed fatigue life of 7.40×10^5 cycles.
- Kevlar composite showed fatigue life of 6.50×10^5 cycles.
- Steel showed the lowest fatigue life of 1.20×10^5 cycles.
- CFRP improved fatigue life by 583.33% compared with steel.
- Hybrid composite improved fatigue life by 516.67% compared with steel.
- Composite materials showed superior fatigue behavior compared with conventional steel.

2) Damage Analysis

Fatigue damage analysis indicates the accumulated damage in the leaf spring under cyclic loading. A lower damage factor indicates better fatigue resistance and longer service life. Higher damage is generally observed in areas where bending stress and stress concentration are high.

a) Damage Analysis Observation

- Steel showed the highest fatigue damage due to higher stress level.
- GFRP showed lower damage than steel but higher damage than other composites.
- CFRP showed the lowest damage factor due to high fatigue strength and low stress.
- Hybrid composite showed balanced and reliable damage resistance.
- Kevlar composite showed good fatigue damage resistance due to its toughness.

Sr. No.	Material	Fatigue Life Cycles	Damage Factor	Damage Rank
1	Steel	1.20×10^5	8.33×10^{-6}	5
2	GFRP	2.50×10^5	4.00×10^{-6}	4
3	CFRP	8.20×10^5	1.22×10^{-6}	1
4	Kevlar Composite	6.50×10^5	1.54×10^{-6}	3
5	Hybrid Composite	7.40×10^5	1.35×10^{-6}	2

Table 5.2: Damage Factor Results

Analysis

- Steel recorded the highest damage factor of 8.33×10^{-6}.
- CFRP recorded the lowest damage factor of 1.22×10^{-6}.
- Hybrid composite recorded damage factor of 1.35×10^{-6}.
- Kevlar composite showed damage factor of 1.54×10^{-6}.
- Lower damage factor confirms better fatigue durability.
- CFRP and hybrid composite are more suitable for long service life applications.

3) Reliability Assessment

Reliability assessment helps estimate the durability and service life performance of each material under repeated loading. Materials with higher fatigue life, lower stress, lower damage factor, and higher safety factor show better reliability. In the present study, CFRP showed the highest reliability potential, followed by hybrid composite and Kevlar composite.

Sr. No.	Material	Safety Factor	Fatigue Life Cycles	Damage Factor	Reliability Rating
1	Steel	2.02	1.20×10^5	8.33×10^{-6}	Low
2	GFRP	2.47	2.50×10^5	4.00×10^{-6}	Moderate
3	CFRP	4.84	8.20×10^5	1.22×10^{-6}	Very High
4	Kevlar Composite	3.58	6.50×10^5	1.54×10^{-6}	High
5	Hybrid Composite	4.00	7.40×10^5	1.35×10^{-6}	Very High

Table 5.3: Reliability Comparison

Analysis

- CFRP has the highest safety factor and fatigue life.
- Hybrid composite provides very high reliability with balanced strength and fatigue performance.
- Kevlar composite provides high reliability due to toughness and fatigue resistance.
- GFRP is suitable for moderate fatigue applications.
- Steel is less suitable for lightweight and high-fatigue durability applications.

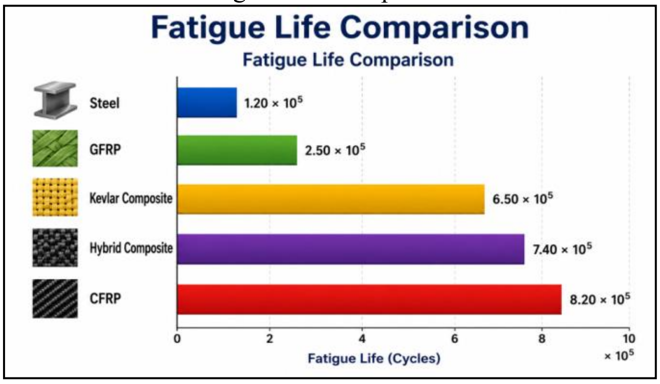
B. Comparative Fatigue Performance

The comparative fatigue performance shows that advanced composite materials perform better than steel under repeated loading. The fatigue life of steel was the lowest because its equivalent stress was close to its fatigue strength. CFRP performed best due to high fatigue strength, high stiffness, and low equivalent stress. Hybrid composite showed balanced behavior and can be considered practically suitable for heavy vehicle leaf springs.

Sr. No.	Material	Weight Reduction %	Equivalent Stress MPa	Fatigue Life Cycles	Damage Factor	Overall Fatigue Performance
1	Steel	0	420	1.20×10^5	8.33×10^{-6}	Poor
2	GFRP	74.52	365	2.50×10^5	4.00×10^{-6}	Moderate
3	CFRP	79.62	310	8.20×10^5	1.22×10^{-6}	Excellent
4	Kevlar Composite	81.66	335	6.50×10^5	1.54×10^{-6}	Good
5	Hybrid Composite	77.71	325	7.40×10^5	1.35×10^{-6}	Excellent

Table 5.4 Comparative Fatigue Performance Summary

Fatigue Life Comparison



Graph 5.1: Fatigue Life Comparison

The graph shows that CFRP achieved the highest fatigue life, followed by hybrid composite and Kevlar composite. Steel showed the lowest fatigue life. Compared with steel, CFRP achieved approximately 583.33% improvement, while hybrid composite achieved approximately 516.67% improvement. This confirms that composite leaf springs are more fatigue-resistant than conventional steel leaf springs.

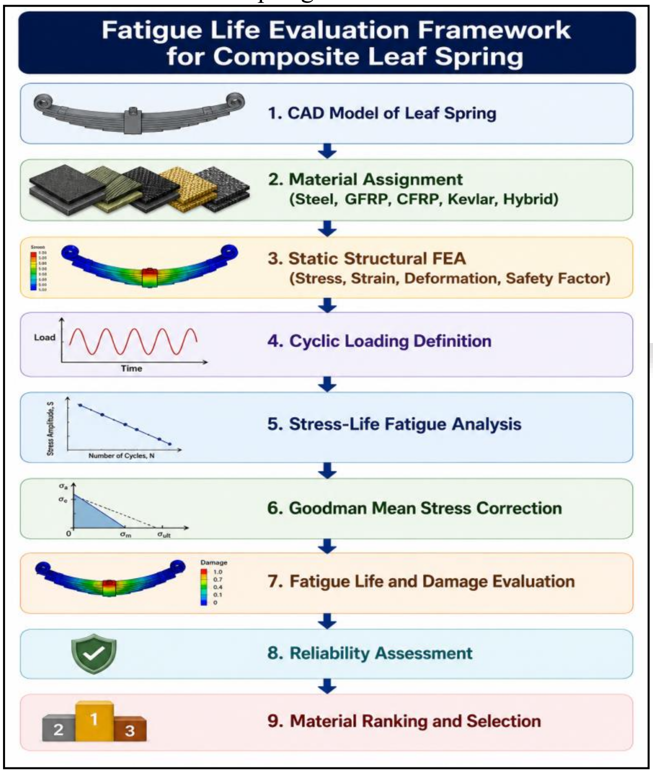


Fig. 5.1: Fatigue Life Evaluation Framework for Composite Leaf Spring

C. *Discussion of Results*

The results show that material selection strongly influences fatigue life, structural reliability, and durability of heavy vehicle leaf springs. Steel showed lower deformation due to high stiffness, but its high density and lower fatigue life make it less suitable for lightweight vehicle suspension design. GFRP provided good weight reduction and moderate fatigue performance, but higher deformation limits its suitability for heavy vehicle applications where stiffness is critical.

CFRP showed the best fatigue and structural performance. It recorded the highest fatigue life, lowest damage factor, highest safety factor, and lowest equivalent stress among the selected materials. Kevlar composite showed good fatigue resistance and toughness, but its stiffness was lower than CFRP and hybrid composite. Hybrid composite showed balanced performance by combining good fatigue life, weight reduction, safety factor, and practical suitability.

Material Ranking Based on Fatigue Performance

Rank	Material	Reason
1	CFRP	Highest fatigue life, lowest damage, highest safety factor
2	Hybrid Composite	Balanced fatigue, strength, stiffness, and weight reduction
3	Kevlar Composite	Good toughness and fatigue resistance
4	GFRP	Moderate fatigue life but higher deformation
5	Steel	Highest weight and lowest fatigue life

Engineering Significance

- Composite materials can reduce the weight of leaf springs significantly.
- CFRP and hybrid composites can improve fatigue life under cyclic loading.
- Lower damage factor indicates better durability and service life.
- Hybrid composite may be preferred for practical heavy vehicle applications due to balanced performance.
- Replacement of steel with composite materials can improve fuel efficiency, payload capacity, and suspension reliability.
- Fatigue life evaluation is essential before selecting composite materials for heavy vehicle suspension systems.

VII. CONCLUSIONS AND FUTURE SCOPE

A. *Conclusions*

The finite element and fatigue life evaluation of heavy vehicle leaf springs showed that advanced composite materials have strong potential to replace conventional steel leaf springs. Static analysis indicated that CFRP and hybrid composite provided better stress distribution and higher safety factor than steel. Fatigue analysis confirmed that CFRP showed the highest fatigue life, followed by hybrid composite and Kevlar composite. Steel showed the lowest fatigue life and highest damage factor, indicating lower durability under cyclic loading.

The comparative study confirmed that CFRP is the best material in terms of fatigue life and structural reliability, while hybrid composite is the most balanced option considering strength, weight reduction, fatigue performance, and practical applicability.

B. *Major Findings*

- Kevlar composite achieved the highest weight reduction of 81.66% compared with steel.

- CFRP achieved 79.62% weight reduction with superior stiffness and fatigue performance.
- Hybrid composite achieved 77.71% weight reduction with balanced performance.
- CFRP showed the highest fatigue life of 8.20 × 10^5 cycles.
- Hybrid composite showed fatigue life of 7.40 × 10^5 cycles.
- CFRP improved fatigue life by 583.33% compared with steel.
- Hybrid composite improved fatigue life by 516.67% compared with steel.
- CFRP showed the lowest damage factor of 1.22 × 10^{-6}.
- Steel showed the highest damage factor of 8.33 × 10^{-6}.
- Composite leaf springs improved fatigue life and structural reliability.

C. *Industrial Applications*

The findings of this study are useful for several vehicle and suspension applications, such as:

- Heavy commercial vehicle suspension systems.
- Truck leaf spring assemblies.
- Bus suspension systems.
- Trailer suspension systems.
- Off-road vehicle suspension systems.
- Military and utility vehicle suspensions.
- Lightweight automotive suspension components.
- Fuel-efficient heavy vehicle design.

D. *Future Scope*

Future work can be extended through experimental and advanced numerical studies. The following future directions are suggested:

- Experimental validation of simulation results using fabricated composite leaf springs.
- Static load testing and fatigue testing under laboratory conditions.
- Multi-objective optimization of weight, stress, deformation, and fatigue life.
- Optimization of fibre orientation and laminate stacking sequence.
- Development of smart composite leaf springs with embedded sensors.
- Study of nano-reinforced composite leaf springs.
- AI-assisted fatigue life prediction.
- Digital twin-based suspension health monitoring.
- Dynamic analysis under real road loading conditions.
- Cost-benefit analysis of CFRP, GFRP, Kevlar, and hybrid composite leaf springs.

E. *Final Conclusion*

The study concludes that advanced composite materials can significantly improve the fatigue life, reliability, and lightweight performance of heavy vehicle leaf springs. Among the selected materials, CFRP showed the best fatigue life and structural reliability, while hybrid composite offered a practical balance between strength, stiffness, durability, and weight reduction. Therefore, composite leaf springs can be considered a suitable replacement for conventional steel leaf springs in heavy vehicle suspension systems.

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