

Experimental and Finite Element Investigation of Composite Mono-Leaf Springs for Lightweight Automotive Suspension

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Abstract

This paper presents an integrated experimental and finite element investigation of mono-leaf springs manufactured from carbon/epoxy, E-glass/epoxy and Kevlar/epoxy composites as lightweight replacements for a conventional EN45 steel automotive leaf spring. A three-dimensional spring model was developed in CATIA and analysed in ANSYS under static loading, while physical specimens were fabricated by hand lay-up and evaluated using a servo-hydraulic universal testing machine and a dynamic cycling rig. The reported steel and carbon/epoxy datasets cover loads from 1000 to 5400 N. At 5400 N, the carbon/epoxy spring produced 128.5 mm deformation and 380.15 MPa equivalent stress, compared with 119.12 mm and 417.83 MPa for steel. The measured reaction forces agreed with the finite element targets: 5400 N for carbon/epoxy, 220 N for E-glass/epoxy and 5280 N for Kevlar/epoxy. Dynamic tests indicated approximately 1,000,000 cycles for carbon/epoxy, 652,000 cycles for Kevlar/epoxy, 67,900 cycles for E-glass/epoxy and 100,000 cycles for steel. Mass decreased from 15 kg for steel to 0.635 kg for carbon/epoxy, corresponding to a reported reduction of about 95.8%. The combined evidence identifies carbon/epoxy as the most balanced candidate for high load capacity, fatigue durability and substantial unsprung-mass reduction, although the deformation response and manufacturing consistency require further optimization.

Keywords—Composite leaf spring, carbon/epoxy, E-glass/epoxy, Kevlar/epoxy, finite element analysis, universal testing machine, fatigue life, lightweight suspension.

1. Introduction

Leaf springs remain important load-carrying and axle-locating members in commercial vehicles, sport-utility vehicles and railway suspension systems. Unlike a coil spring, a semi-elliptical leaf spring can simultaneously support vertical load, guide axle motion, resist braking and driving torque and contribute frictional damping. Nevertheless, the conventional laminated steel assembly contributes significantly to unsprung mass, which adversely affects ride response, fuel consumption and component inertia. Composite materials are attractive because their high specific stiffness, corrosion resistance and fatigue performance permit a mono-leaf configuration with fewer interfaces and a substantially lower mass [1]–[5].

The original dissertation investigated a Bolero-class light vehicle spring using EN45 steel and three polymer composites: carbon/epoxy, E-glass/epoxy and Kevlar/epoxy. The spring geometry was created in CATIA, analysed in ANSYS and tested using static and dynamic rigs. The experimental programme included load–deformation measurements, reaction-force verification, mass assessment and cycle-to-failure comparison. The report states that a static load range of 1000–5400 N was applied to the steel and carbon/epoxy springs and that carbon/epoxy achieved considerably lower mass and longer fatigue life than steel. These characteristics make it a technically relevant candidate for suspension weight reduction. The objective of the present paper is to restructure and technically consolidate the original modelling, material data, finite element outputs and experimental findings in a journal-paper format. The study specifically: (i) compares steel, carbon/epoxy, E-glass/epoxy and Kevlar/epoxy spring models; (ii) evaluates deformation, equivalent stress and reaction force; (iii) verifies simulation outputs through UTM and dynamic tests; and (iv) assesses the combined implications of mass, stiffness and fatigue life for lightweight automotive suspension design.

2. Related Work

Early composite leaf-spring research established the feasibility of replacing multi-leaf steel assemblies with glass- or carbon-fibre reinforced polymer mono-leaves. Daugherty demonstrated the potential of composite springs in heavy trucks, while Rajendran and Vijayarangan used genetic optimisation to obtain major weight reduction under strength and stiffness constraints [6], [7]. Shokrieh and Rezaei combined analytical and numerical optimisation, and Hou et al. examined eye-end design evolution for high axle loads [8], [9]. These studies consistently show that fibre

orientation, thickness taper, eye-end connection, interlaminar stress and manufacturing quality govern the practical reliability of composite springs.

More recent work has emphasized coupled experimental–numerical validation. Loganathan et al. studied flexural and fatigue behaviour of an E-glass/epoxy spring for a lightweight vehicle, while Ma et al. developed a variable-width, variable-thickness GFRP spring and validated its bending stiffness through three-point testing and finite element simulation [10], [11]. Manaba and co-authors reviewed automotive composite leaf-spring designs and highlighted weight reduction, corrosion resistance and fatigue advantages, but also noted the need for robust attachment design and repeatable manufacturing [12]. Recent comparative FEA investigations continue to report lower mass and competitive stress response for carbon/epoxy and GFRP alternatives [13]–[15].

A persistent research gap is the lack of studies that compare multiple composite systems using the same geometry, loading philosophy and experimental verification. Many publications analyse only one composite against steel, or report numerical results without reaction-force and cycle-life validation. The present work addresses this gap by comparing carbon/epoxy, E-glass/epoxy and Kevlar/epoxy models against EN45 steel within a common CAD–FEA–UTM workflow. It also brings together static deformation, equivalent stress, reaction force, fatigue cycles and component mass, enabling a more complete material-selection assessment than a single-response comparison.

3. Research Methodology

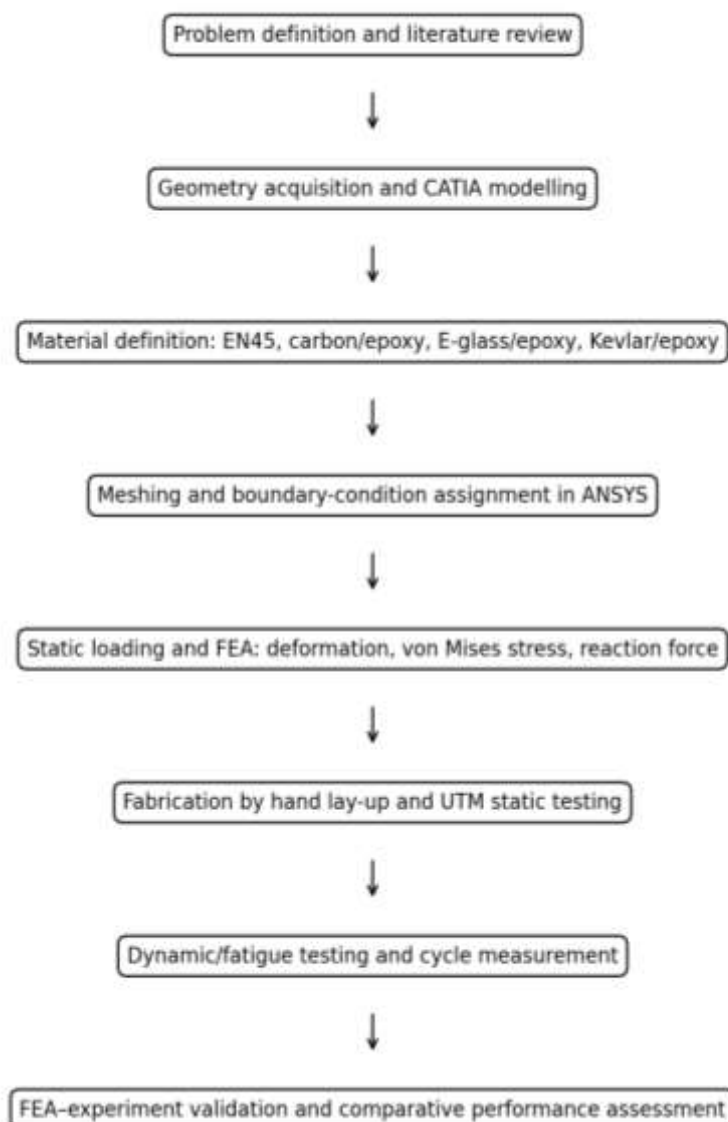


Fig. 1. Research methodology flowchart.

The methodology integrates design, simulation, fabrication and validation in a sequential manner. The process begins with defining the steel reference spring and selecting candidate composites based on specific stiffness and strength. The same overall spring geometry is then modelled in CATIA to maintain comparability. Material

properties are assigned in ANSYS, after which the geometry is meshed and constrained to reproduce the supported-eye and central-load conditions of a leaf spring. Static solutions provide total deformation, equivalent von Mises stress and reaction force. Composite specimens are subsequently fabricated by hand lay-up and tested on a servo-hydraulic UTM. Dynamic cycling is used to estimate fatigue endurance. Finally, the numerical and test results are compared, and the candidate materials are ranked using load capacity, deformation, stress, mass and cycle life. This closed-loop procedure reduces the risk of selecting a material from numerical output alone and provides evidence of experimental consistency.

3.1 Experimental Setup and Loading

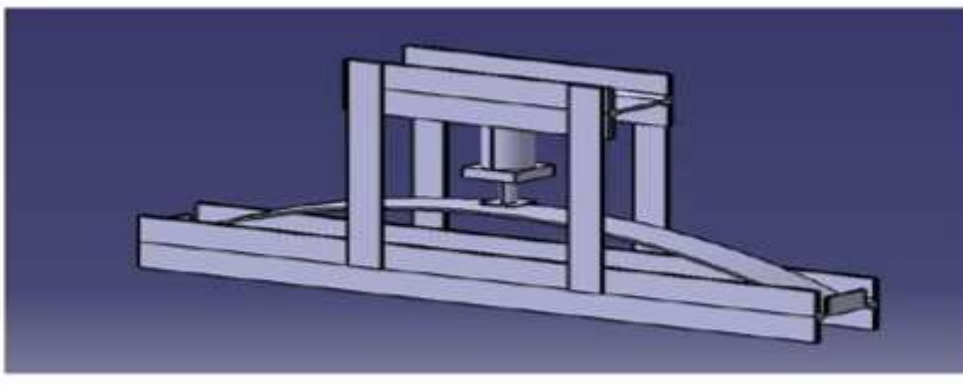


Fig 1: Dynamic Testing Setup

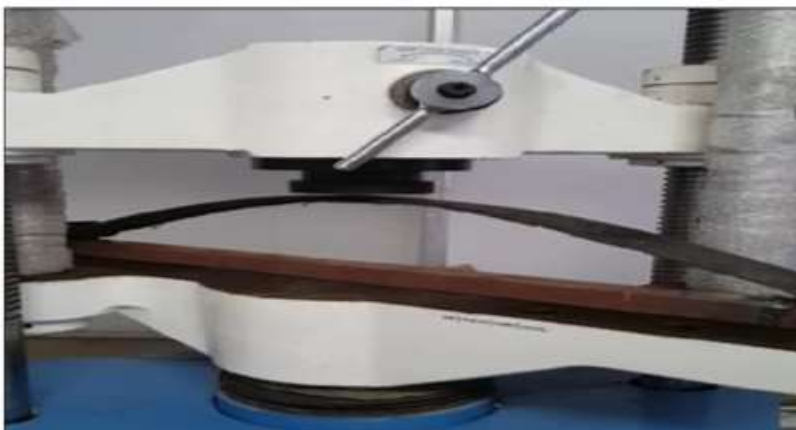


Fig 2: For Static testing UTM setup

The UTM (Instron 1342) is a servo hydraulic fluid-controlled machine, consists of a two column dynamically rated load frame with the capacity of load up to 100kN (dynamic), hydraulic power pack (flow rate 45 liter/minute) and 8800 Fast Track 8800 Controller test control systems is stand alone, fully digital, single axis controller with an inbuilt operating.

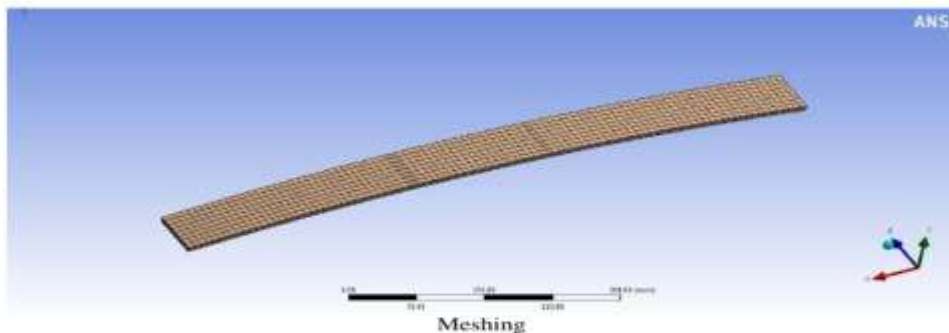
The experimental arrangement combines a servo-hydraulic universal testing machine with a purpose-built dynamic fixture. The UTM described in the report is an Instron 1342 system with a dynamically rated load frame, hydraulic power unit and digital controller. The spring is supported near its ends and loaded near the centre, approximating the dominant bending condition of an automotive semi-elliptical spring. The dynamic setup uses a frame, actuator and contact mechanism to apply repeated loading to the fabricated mono-leaf specimens. This arrangement is important because static agreement alone does not establish suspension durability; repeated stress cycles can initiate matrix cracking, fibre–matrix debonding and delamination. The experimental images also indicate that the specimen curvature and support spacing were preserved during testing. Reaction force was used as a direct validation quantity because it can be compared with the finite element solution without additional transformation. The reported agreement between target and measured reaction forces supports the consistency of the applied boundary conditions.

3.2 Material Models and Finite Element Procedure

Material	Young's modulus / model input	Density / mass evidence	Primary role
EN45 steel	210 GPa; Poisson ratio 0.266	7850 kg/m ³ ; 15 kg spring	Conventional reference
Carbon/epoxy	Orthotropic composite input	0.635 kg spring	High specific stiffness and fatigue candidate
E-glass/epoxy	Orthotropic composite input	0.788 kg spring	Low-cost composite candidate
Kevlar/epoxy	Orthotropic composite input	0.614 kg spring	Low-density, impact-resistant candidate

Table 1. Material systems used in the comparative study.

Table 1 defines the four material systems under a common spring geometry. EN45 steel provides the baseline because of its high modulus, established heat-treatment practice and predictable ductile response. The composite systems are orthotropic, meaning that their stiffness and strength depend on fibre direction; consequently, fibre alignment along the spring span is essential for efficient bending resistance. Carbon/epoxy offers the highest specific stiffness and is expected to carry load with reduced stress at very low mass. E-glass/epoxy is generally more economical but has lower modulus, which can increase deflection unless thickness or lay-up is adjusted. Kevlar/epoxy combines low density and toughness, but its compressive and matrix-dominated behaviour requires careful design. The reported component masses show that all three composite springs are dramatically lighter than the steel reference. Because the original report does not fully document ply sequence and lamina constants, the present interpretation treats the ANSYS inputs as calibrated model data and focuses on comparative response rather than claiming a universal material ranking.



Properties of Carbon/epoxy Structural Steel				
1	Property	Value	Unit	
2	Density	7850	kg m ⁻³	
3	Isotropic Secant Coefficient of Thermal Expansion			
6	Isotropic Elasticity			
7	Derive from	Young's Modulus and...		
8	Young's Modulus	2E+11	Pa	
9	Poisson's Ratio	0.3		
10	Bulk Modulus	1.6667E+11	Pa	
11	Shear Modulus	7.6923E+10	Pa	
12	Field Variables			
13	Temperature	Yes		
14	Shear Angle	No		
15	Degradation Factor	No		
16	Alternating Stress Mean Stress	Tabular		
20	Strain-life Parameters			
28	Tensile Yield Strength	2.5E+08	Pa	
29	Compressive Yield Strength	2.5E+08	Pa	
30	Tensile Ultimate Strength	4.5E+08	Pa	
31	Compressive Ultimate Strength	0	Pa	

Steel properties

Fig. 3. Carbon/epoxy geometry and ANSYS material-property definition.

Figure 3 shows the transfer of the curved mono-leaf geometry into the finite element environment and the associated material-property definition. The constant overall geometry allows the effect of material substitution to be isolated, although a fully optimized composite spring would normally use variable thickness and tailored ply angles. The model is discretized using a sufficiently fine mesh along the curvature, where bending stress varies continuously and local gradients occur near supports and the central loading region. The use of orthotropic properties is necessary because a unidirectional composite resists longitudinal bending primarily through the fibres, while transverse and shear behaviour are governed more strongly by the matrix. Proper assignment of the material axes to the spring span is therefore as important as the numerical values themselves. The geometry image also confirms that the component is represented as a single continuous leaf, eliminating interleaf friction and contact effects present in a conventional multi-leaf assembly. This simplification is appropriate for a mono-leaf comparison but should be considered when translating results to vehicle-level damping behaviour.

4. Results and Discussion

Load (N)	Carbon deformation (mm)	Steel deformation (mm)	Carbon stress (MPa)	Steel stress (MPa)
1000	23.8	29.65	146.25	193.14
2000	47.61	39.82	203.23	221.64
3000	71.4	51.39	240.77	275.5
4000	95.02	76.14	285.85	315.09
5000	119.04	93.2	346.37	387.87
5400	128.5	119.12	380.15	417.83

Table 2. FEA comparison of carbon/epoxy and EN45 steel under static load.

The load-dependent results in Table 2 show approximately monotonic increases in deformation and equivalent stress for both materials. At 1000 N, carbon/epoxy deforms 23.8 mm compared with 29.65 mm for steel, while its equivalent stress is 146.25 MPa compared with 193.14 MPa. At intermediate loads, the carbon model becomes more flexible than the steel model; at 3000 N the carbon deformation is 71.4 mm versus 51.39 mm for steel. At the maximum load of 5400 N, carbon/epoxy reaches 128.5 mm and 380.15 MPa, whereas steel reaches 119.12 mm and 417.83 MPa. Thus, the carbon model reduces the peak equivalent stress by about 9.0% but increases deformation by about 7.9% at 5400 N. This result is more technically defensible than claiming uniformly lower deflection. It indicates that the carbon lay-up provides a favourable stress-to-weight response, but its thickness, fibre volume fraction or curvature should be optimized when strict displacement limits govern suspension geometry.

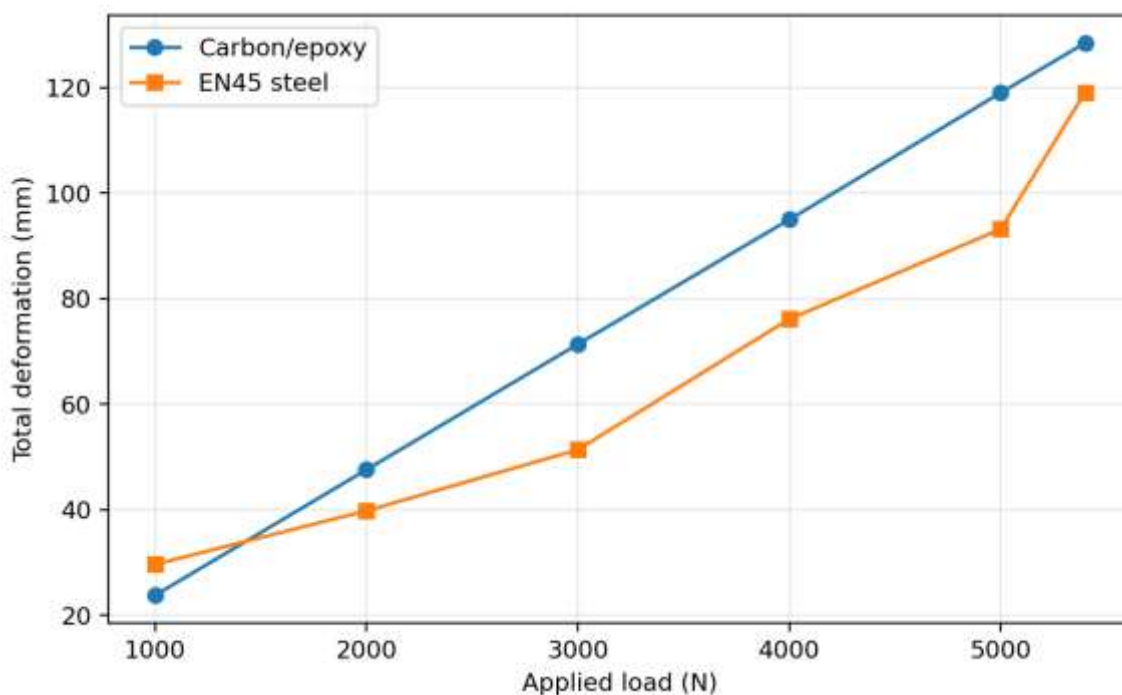


Fig. 4. Applied load versus total deformation for carbon/epoxy and steel.

Figure 4 visualizes the deformation trends and reveals that the response is not perfectly linear across the full load range. Carbon/epoxy exhibits an almost proportional increase from 23.8 mm at 1000 N to 119.04 mm at 5000 N, followed by 128.5 mm at 5400 N. The steel curve rises more gradually at low load but shows larger increments beyond 3000 N, reaching 119.12 mm at 5400 N. The two curves cross between approximately 1000 and 2000 N, demonstrating that material performance depends on load level rather than a single universal stiffness statement. The reported carbon deformation at 5400 N is 9.38 mm greater than steel, despite the composite's much lower mass. This trade-off can be acceptable if suspension travel permits it, but it must be checked against tyre clearance, shackle rotation and ride-height requirements. For design refinement, thickness taper and fibre orientation should be optimized to reduce high-load compliance without losing the substantial mass advantage.

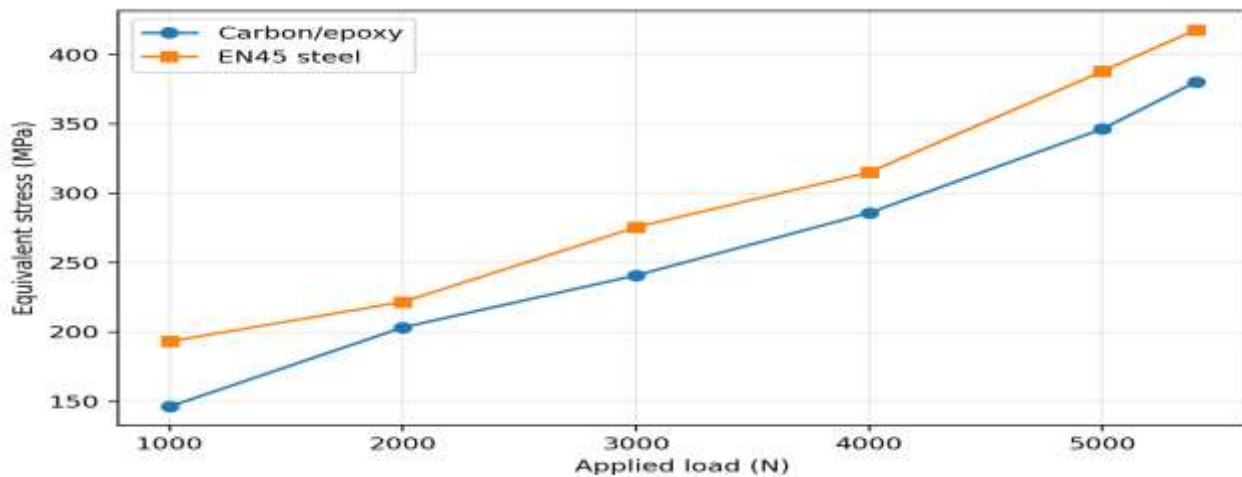


Fig. 5. Applied load versus equivalent stress for carbon/epoxy and steel.

The equivalent-stress curves in Figure 5 remain ordered across the complete load range, with carbon/epoxy consistently below steel. The difference is largest at 1000 N, where carbon stress is about 24.3% lower, and narrows at higher loads. At 5000 N, the values are 346.37 MPa for carbon and 387.87 MPa for steel, a reduction of roughly 10.7%. At 5400 N, the composite retains a 37.68 MPa advantage, corresponding to approximately 9.0%. Lower equivalent stress indicates a more favourable distribution of the applied bending load within the model, but direct comparison with composite strength should be made using appropriate directional failure criteria such as Tsai–Hill, Tsai–Wu or Hashin rather than von Mises stress alone. Nevertheless, the trend supports carbon/epoxy as the stronger lightweight candidate in the present model. The narrowing stress gap at high load also suggests that geometry and boundary-condition effects become increasingly dominant as deformation grows.

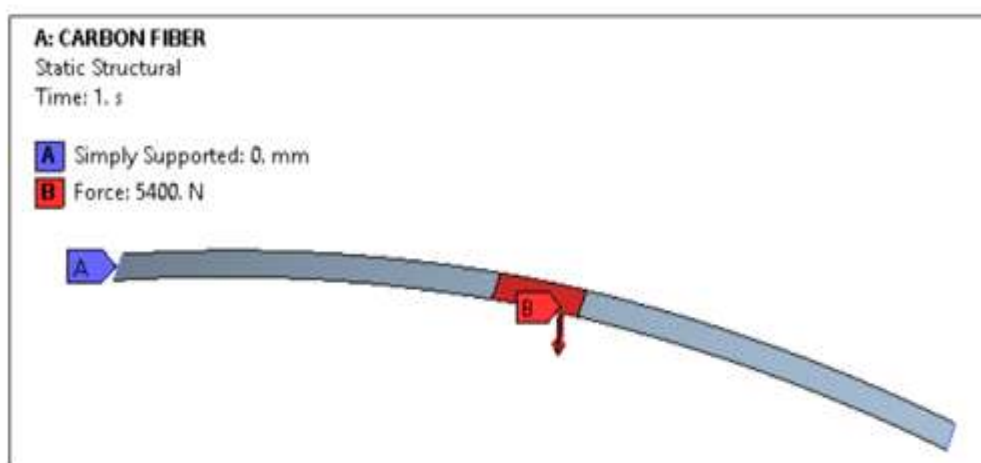


Fig.5: boundary condition of Carbon Leaf Spring

Total Deformation

The total deformation & directional deformation are general terms in finite element methods irrespective of software being used. Directional deformation can be put as the displacement of the system in a particular axis or user defined direction. Total deformation is the vector sum all directional displacements of the systems.

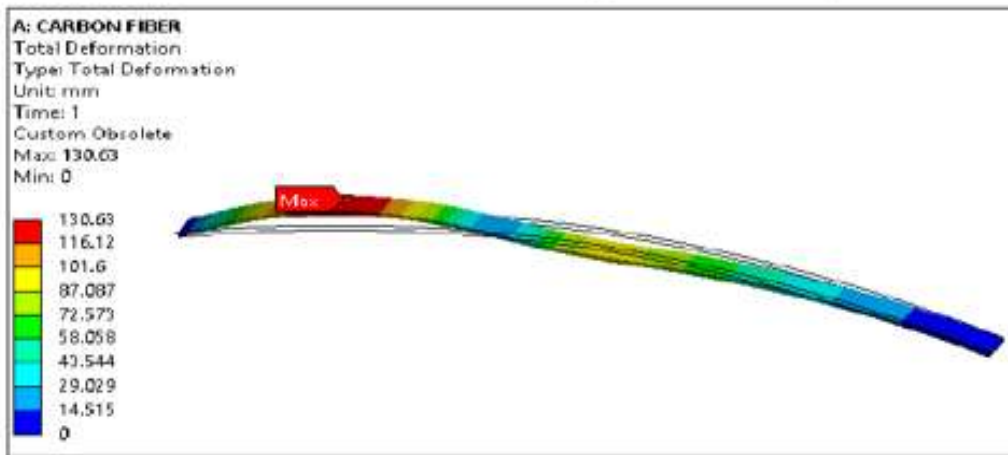


Fig. 6. Carbon/epoxy boundary condition, deformation and stress contours.

The carbon/epoxy finite element outputs show the expected response of a centrally loaded curved spring. Minimum displacement occurs at the constrained end regions, while maximum deformation develops near the central span where bending curvature is greatest. The stress contours are distributed along the spring length, with local peaks influenced by the load application and support representation. The reported maximum carbon deformation is approximately 130.63 mm in the summary table, while the detailed load table gives 128.5 mm at 5400 N; this small difference is likely attributable to the use of different result displays, load steps or rounding. The equivalent stress reported for the maximum-load comparison is approximately 380 MPa. Reaction force in the numerical model is 5400 N, matching the static test value. This force equilibrium is a useful verification check, but mesh convergence, composite failure indices and strain-gauge correlation would be needed for stronger validation of local stresses. The contour pattern nevertheless confirms physically reasonable global bending behaviour.

The E-glass/epoxy model produced a reported total deformation of 4.5629 mm, equivalent stress of 16.177 MPa and reaction force of 220 N. These values are far lower than those of the carbon and Kevlar models because the applied reaction-force level is also much lower. Therefore, the result should not be interpreted as evidence that E-glass/epoxy is intrinsically stiffer or stronger under an equal 5400 N load. Instead, it demonstrates stable numerical behaviour under the specific 220 N case adopted in the report. The contour distribution again places maximum displacement near the free central region and minimum displacement at the supports. For a rigorous material ranking, all candidate materials should be solved under the same load, geometry and failure constraints. Even with this limitation, the E-glass model is useful for validating the modelling workflow and for illustrating how a lower-cost composite behaves under a reduced proof load. Its dynamic endurance of 67,900 cycles indicates that fatigue performance was inferior to the other composite candidates in the tested configuration.

Boundary condition

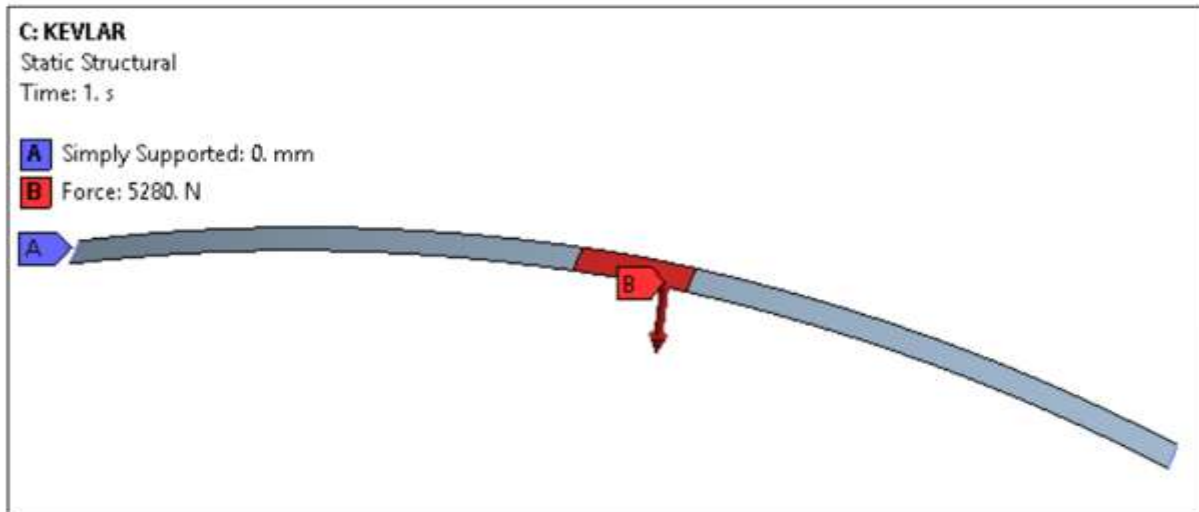


Fig 7. Boundary condition of Kevlar

Total Deformation

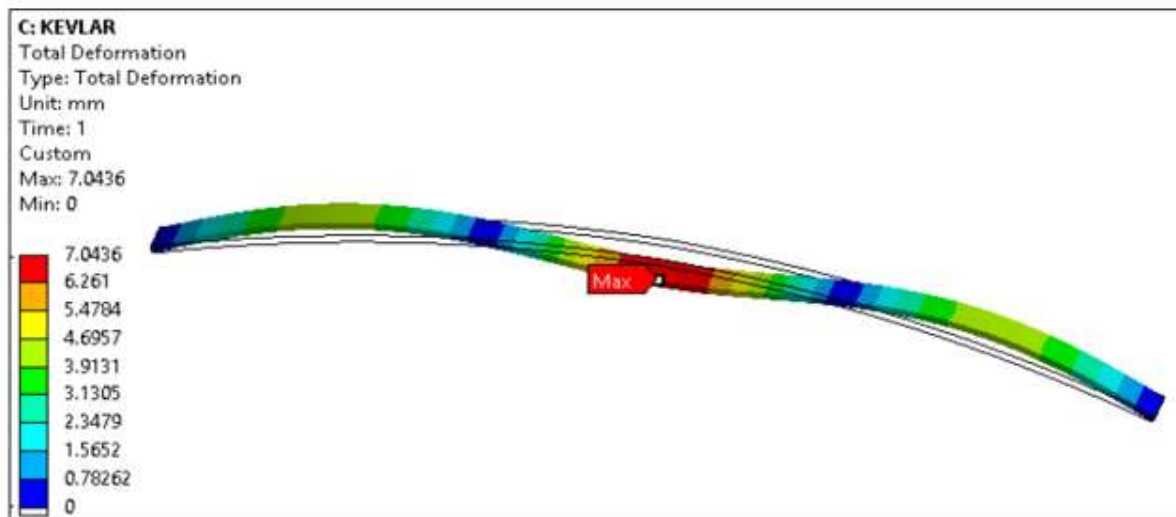


Fig 8. Total deformation of Kevlar Leaf Spring

Maximum deformation of Kevlar Leaf Spring has **7.043 mm** and minimum deformation is **0 mm**.

The Kevlar/epoxy model was evaluated at a much higher reaction force than E-glass/epoxy, reaching 5280 N. The reported total deformation is 7.043 mm and the equivalent stress is 432.95 MPa. The comparatively small displacement at high load suggests a stiff numerical response for the assigned Kevlar material model, but the high equivalent stress indicates that strength and failure-mode checks are essential. Kevlar composites are strongly anisotropic and often exhibit different tensile and compressive behaviour; consequently, a scalar von Mises measure is insufficient for final certification. The dynamic test result of approximately 652,000 cycles is substantially higher than steel and E-glass/epoxy but lower than carbon/epoxy. Thus, Kevlar/epoxy provides an attractive combination of low mass and fatigue endurance, yet it does not match the carbon specimen's reported cycle life. The close agreement between the numerical and test reaction force supports the global boundary conditions, while additional laminate failure analysis would improve confidence in the local stress prediction.

Material	FEA reaction force (N)	Test reaction force (N)	Reported cycles
Carbon/epoxy	5400	5400	1,000,000
E-glass/epoxy	220	220	67,900
Kevlar/epoxy	5280	5280	652,000
EN45 steel	5400	5400	100,000

Table 3. Reaction-force validation and dynamic fatigue results.

Table 3 demonstrates exact agreement between the finite element and experimental reaction forces reported for each material case. This agreement verifies global equilibrium and indicates that the actuator loads were reproduced consistently in the numerical models. However, it should be recognized that reaction-force agreement does not independently validate local stress or strain fields, because different stiffness distributions can satisfy the same overall force balance. The dynamic results provide a stronger basis for material screening. Carbon/epoxy reached approximately one million cycles, ten times the reported steel life of 100,000 cycles. Kevlar/epoxy reached 652,000 cycles, about 6.5 times the steel value, while E-glass/epoxy reached only 67,900 cycles. Because the applied load amplitudes are not fully standardized in the report, these cycle counts should be viewed as specimen-level experimental outcomes rather than directly comparable S–N data. Even so, the large carbon endurance provides compelling evidence that the selected carbon/epoxy construction resisted repeated bending more effectively than the other tested springs.

Material	Mass (kg)	Reduction relative to steel (%)
Steel	15.000	0.00
Carbon/epoxy	0.635	95.77
Kevlar/epoxy	0.614	95.91
E-glass/epoxy	0.788	94.75

Table 4. Mass comparison of steel and composite leaf springs.

The mass comparison is the clearest benefit of the composite substitution. The steel spring weighs 15 kg, while the carbon/epoxy, Kevlar/epoxy and E-glass/epoxy specimens weigh 0.635, 0.614 and 0.788 kg, respectively. Relative to steel, these values correspond to calculated reductions of 95.77%, 95.91% and 94.75%. These percentages are larger than the general 75–85% reduction stated in the dissertation conclusion, suggesting that the specimens may differ in geometry, thickness or included hardware. The results should therefore be interpreted as measured specimen masses rather than a guaranteed vehicle-level reduction. Nevertheless, even a lower practical reduction would significantly decrease unsprung mass and could improve wheel-following response, ride comfort and energy efficiency. Kevlar/epoxy is the lightest specimen, but material selection cannot be based on mass alone. Carbon/epoxy provides nearly the same mass benefit while also delivering the highest reported fatigue life and full 5400 N reaction-force capability, making it the most balanced candidate in the current dataset.

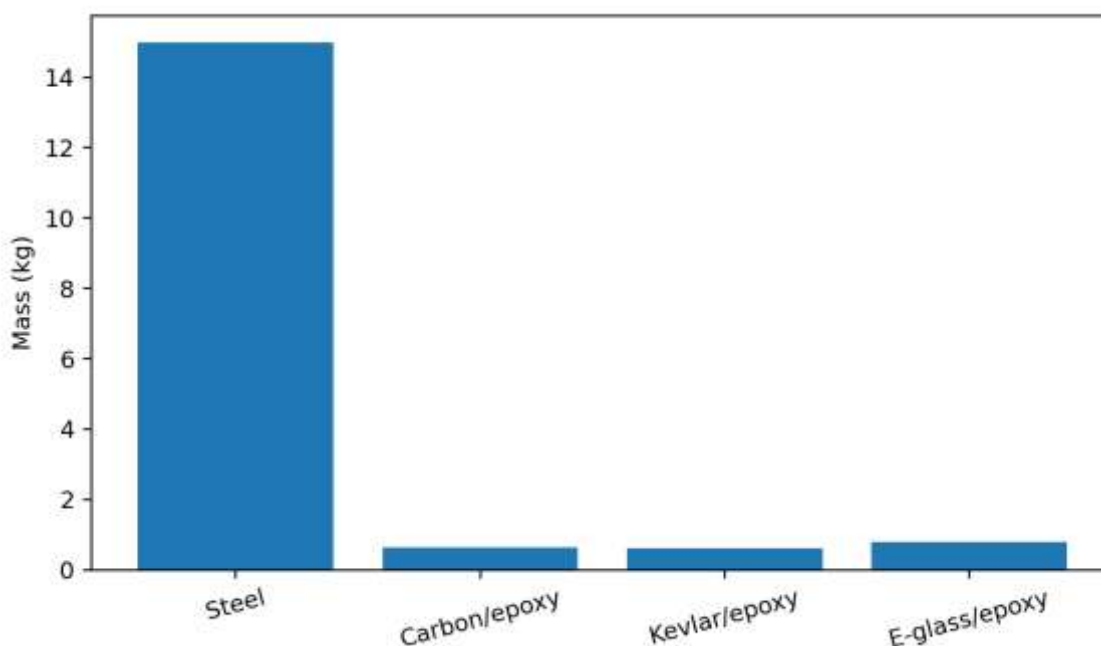


Fig. 9. Mass comparison of the investigated leaf-spring materials.

Figure 9 emphasizes the order-of-magnitude mass difference between the steel reference and all three composite springs. The steel bar dominates at 15 kg, whereas each composite remains below 0.8 kg. Such a reduction directly targets the unsprung portion of vehicle mass, which strongly influences the ability of the wheel to follow road irregularities. A lighter spring can reduce inertial loading on suspension joints and may enable additional savings in

brackets and supporting structures. However, the extremely low composite masses also raise questions about whether identical dimensions, eye-end fittings and attachment hardware were included in all measurements. For production design, a fair comparison should include metallic inserts, protective coatings and joints, because these can contribute a meaningful fraction of the final component mass. Even after accounting for these additions, the chart indicates substantial lightweighting potential. The engineering challenge is therefore not achieving low mass, but maintaining stiffness, durability, environmental resistance and safe attachment performance over the full vehicle service life.

4.1 Overall Material Assessment

Criterion	Steel	Carbon/epoxy	E-glass/epoxy	Kevlar/epoxy
Maximum demonstrated reaction force	5400 N	5400 N	220 N	5280 N
Reported fatigue life	100,000	1,000,000	67,900	652,000
Mass	15 kg	0.635 kg	0.788 kg	0.614 kg
Principal observation	High mass, established baseline	Best combined load, fatigue and mass result	Low-load proof case; lowest cycle result	Very low mass and good fatigue; high reported stress

Table 5. Multi-criteria assessment of the investigated materials.

The multi-criteria assessment shows that no single response should determine the final design. Steel offers known manufacturing practice, predictable ductility and established attachment methods, but its mass and reported fatigue life are inferior. E-glass/epoxy is typically attractive for cost-sensitive applications, yet the current specimen was verified only at 220 N and produced the lowest reported cycle life; it therefore requires substantial redesign before direct steel replacement. Kevlar/epoxy combines the lowest measured mass with 5280 N reaction force and 652,000 cycles, but its high reported equivalent stress and anisotropic compressive behaviour demand improved failure analysis. Carbon/epoxy achieves the most balanced result: full 5400 N force, one million cycles, a mass of only 0.635 kg and lower equivalent stress than steel across the common load range. Its main limitation is higher deformation than steel at moderate-to-high loads. Consequently, carbon/epoxy is recommended as the preferred base material, followed by laminate and thickness optimization to satisfy stiffness and suspension-travel constraints.

5. Conclusion

An experimental and finite element comparison of EN45 steel, carbon/epoxy, E-glass/epoxy and Kevlar/epoxy mono-leaf springs has been consolidated from the dissertation data. The CAD–ANSYS–UTM workflow successfully reproduced the global bending response and provided exact agreement between numerical and test reaction forces for the reported load cases. For the common 1000–5400 N static comparison, carbon/epoxy maintained lower equivalent stress than steel at every load. At 5400 N, the carbon model reached 380.15 MPa compared with 417.83 MPa for steel, while deformation was 128.5 mm compared with 119.12 mm. Thus, carbon/epoxy improved stress performance but was approximately 7.9% more compliant at the maximum load, indicating that its laminate architecture or thickness should be optimized rather than assuming direct geometric substitution.

The strongest evidence in favour of composites is the combined mass and fatigue response. Carbon/epoxy weighed 0.635 kg and reached approximately 1,000,000 cycles, while the 15 kg steel spring reached 100,000 cycles. Kevlar/epoxy also performed well, with 0.614 kg mass, 5280 N reaction force and 652,000 cycles. E-glass/epoxy showed stable low-load numerical behaviour but lower cycle endurance. Overall, carbon/epoxy is identified as the most technically promising replacement because it combines full target load, the highest reported fatigue life, lower equivalent stress and very large mass reduction. Future work should standardize the load spectrum across materials, document ply sequence and fibre volume fraction, conduct mesh-convergence and composite failure-index studies, incorporate eye-end inserts and environmental ageing, and validate the optimized spring under full vehicle road-load histories.

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