

# Failure Mode Analysis of Composite Leaf Springs Under Dynamic Loading Conditions

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**Abstract**---This research delineates the typical configuration of the longitudinal Composite Leaf Springs (CLS) and the stress experienced by its various components. When analyzed with force evaluation, many failure modes may manifest in the central and terminal sections of the CLS. Attention must be directed towards the stress accumulation in the clamping region near the center of the leaf spring, resulting from U-bolt pre-tightening. At the terminus of the CLS, sufficient lengths between bolt holes and edges must be maintained, and consideration should be given to the concentrated stress induced by the bolt. In the spring layout, the static rigidity of the CLS may be suitably augmented to guarantee that the suspension has enough offset frequencies. Simultaneously, it is essential to consider the resin's glass transition temperature (T<sub>g</sub>), which is recommended to exceed 80 °C.

**Keywords**--- Failure Mode Analysis, Leaf Springs, Dynamic Loading, Composite.

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## I. Introduction

The leaf spring (LS) (Malleh et al., 2021) is the predominant elastic component in car suspension systems. Steel leaf springs (SLS) (GS et al., 2024) are utilized in the market. SLS has straightforward construction and dependable functionality, facilitating ease of fabrication. SLS possesses the drawbacks of substantial construction, elevated rigidity, and inadequate comfort. Conventional LS can no longer satisfy industrial requirements. The reduction of a car's weight is of paramount importance to its performance. To enhance the efficiency of LS, decrease their weight, and increase comfort, scientists have extensively investigated the materials and structures of LS.

They have created Composite Leaf Springs (CLS) (Jolaiy et al., 2023) using plastic instead of steel. CLSs weigh only 30-40% of the standard SLS of the same kind. CLS retains the benefits of the straightforward design and dependable functionality of SLS. It has substantial elastic strain, elevated specific strain energy, extended fatigue life, and commendable safety in fracture performance. CLSs are not found in huge quantities and have not been implemented. Compared to conventional metal substances, composite materials offer advantages such as high strength, substantial specific modulus, reduced weight, immunity to corrosion, superior shock absorption, exceptional resilience to impacts, extended service life, effective noise cancellation, and outstanding design flexibility.

## II. Background

### *CLS Configuration*

There are two categories of CLSs: transversal CLSs and transverse CLSs (Bellini-Pereira et al., 2021). The transversal CLS is often mounted in vehicles equipped with autonomous suspension systems. The two extremities of the Spring Body (SB) (Nathoo et al., 2022) convey weights via the lap connection. The operational state of the spring is satisfactory, so there is no need for a specialized joint design. The longitudinal CLS is often mounted on vehicles using a non-independent suspension system. The service conditions are rather severe, necessitating the construction of a joint with reliable operation.

The primary considerations for SB design are material usage, fiber volume, and manufacturing. Upon completion of the structural design, a mathematical model for the CLS must be developed using the principles of material physics (Irshad et al., 2025). The geometric specifications of the SB will be established based on the

installation conditions and the intended stiffness of the CLS. In optimizing structures, the finite element approach will be used to examine and assess the solution to the design. A test will ascertain whether the structure's durability satisfies the standards.

### ***Mechanical Evaluation***

Tensile examinations were performed with a 100 kN tensile test equipment. During examination, a biaxial clover strain gauge was used on the tensile samples to quantify the axial and transverse stresses (Moncy et al., 2021). Three trials were conducted for each instance. Displacements and weights were routinely documented using an electronic program. The acquired data was employed in the finite element modeling of CLS made of leaves for modal modeling with the ANSYS software.

### ***Dynamic Evaluation***

Experimental modal analysis was conducted to ascertain various CLSs' inherent frequency ranges, mode forms, and damping ratios. An impact test was conducted to evaluate the impulse excitation caused by CLSs. A device (1) was created for CLSs (2) to oscillate freely from both ends upon stimulation. The CLSs were excited using an impact hammer with a force sensor. A speedometer (5) was affixed to the CLS to quantify the reaction acceleration at a designated location. The roving sledgehammer technique is used to gather modal information. A 32-channel gathering system autonomously captures the impact information as an input signal and the reaction speed as the resultant signal, obtained from the contact sledgehammer and the speedometer. The collected acceleration against time data was transformed into an amplitude versus frequency plot with post-processing modal technology to determine the Frequency Reaction Functions (FRF), the proportion of the resultant response compared with the input stimulation reaction (Allemand et al., 2022).

## **III. Analysis of Failure in CLSs: Condition Assessment**

Presently, most CLSs are substitutes for SLS, and their operational circumstances are fundamentally identical to those of metal springs. Given the operational temperature, mechanical characteristics, composition, methodology, minimal toxicity, low irritability, and cost-effectiveness, the glass fiber utilized in the CLS is often E fiber; the resin selection is commonly epoxy or polyurethane. Given the properties of the composite material, the intersection and link between the SB and the support require inspection.

### ***Assessment of Rigidity***

The rigidity of the LS directly influences the vehicle's handling and comfort, the LS' principal efficiency metric. The various configurations, kinds, and operational metrics of the suspension mechanism in each vehicle subsystem will influence the vehicle's overall efficiency. The damping and elasticity elements in the suspension's structure exert the most significant impact. Theoretical study and empirical evidence demonstrate that the regularity of the suspension mechanism is a primary factor influencing vehicle ride ease, which is dictated by suspension rigidity.

### ***Stress Examination***

Vertical, sideways, and longitudinal stresses on the automotive chassis influence the transverse CLS. The force has varying effects on each segment of the LS. The pre-tightening of the bolts primarily influences the clamping areas of U-bolts. The assembly consists of the U-bolt, SB, cover plate, upper plate, and lower plate. The SB comprises material composites, whilst the other components are metallic. Various U-bolts are chosen based on distinct vehicle workloads. Bolts of varying grades and sizes exhibit distinct torque values.

### ***Failure mode and impact analysis***

Typically, the bench testing (sometimes referred to as the standard test), the system bench examination, and the road testing are necessary to ascertain the viability of LS. The bench testing is a three-point bending assessment of the uniaxial LS to evaluate its stiffness and fatigue endurance. The framework of the bench testing is a biaxial or triaxial linkage assessment designed to examine the performance of multi-axial LS. The primary objective of the road test is to assess the efficiency of the LS under diverse, harsh driving conditions. Analysis of stresses on a CLS categorizes failure into two kinds according to the failure item: failure of the spring mechanism and failure of the metal attached to the spring mechanism. Based on the failure locations in the springs, the failures are evident in the following areas: the U-bolt clamping region in the center of the spring, the friction zone involving the LS and the vehicle assistance, and the junction between these components.

## IV. Results

The existence, position, and severity of cracks in CLSs are assessed as follows.

### Existence of Fracture

The modal normal frequency is the appropriate metric to verify the existence of cracks on a global scale. Measurements of the frequency ranges of a fractured spring with those of healthy springs for lower modes are conducted. The average frequency is diminished in the presence of a broken spring.

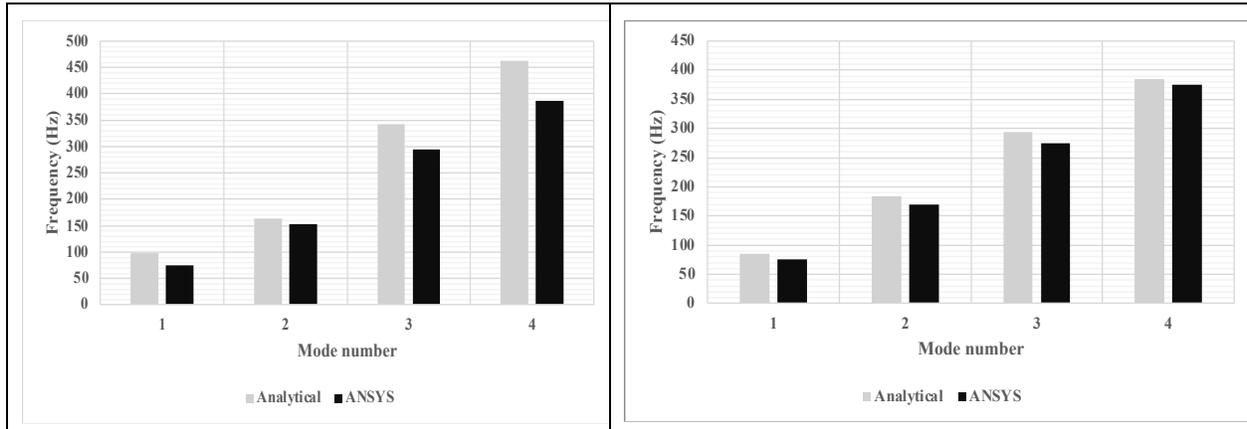


Figure 1: Healthy Leaf and Composite Leaf Analysis of Frequencies

Figure 1 illustrates the frequency fluctuation corresponding to the mode number for healthy and fractured LS, as determined by mathematical, ANSYS, and empirical models. It demonstrates the frequency variation between both springs, as quantitative data from ANSYS shows.

### Crack Placement

Modal elasticity variation and modal curved differences are employed to identify the location of the deliberately induced fracture on the mono-CLS using modal approaches. The alteration in modal elasticity was seen to be greatest in the beam segments ranging from 0.3 to 0.4 m, as illustrated in Fig. 2. The highest modal curving variation was detected in the beam sections around 0.35 and 0.40 m.

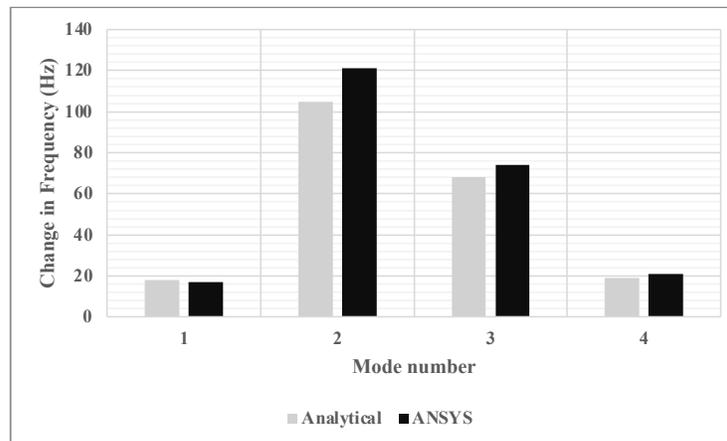


Figure 2: Change in Frequency Analysis

### Crack Intensity

The severity of a fracture is measured using modal characteristics, including modal mobility and modal curves. The fracture severity for modal elasticity is recorded at 16.49%, as seen in Fig. 3. The degree of severity of the fracture for modal bending is 266.07% for the first mode and 45.15% for the second mode, correspondingly.

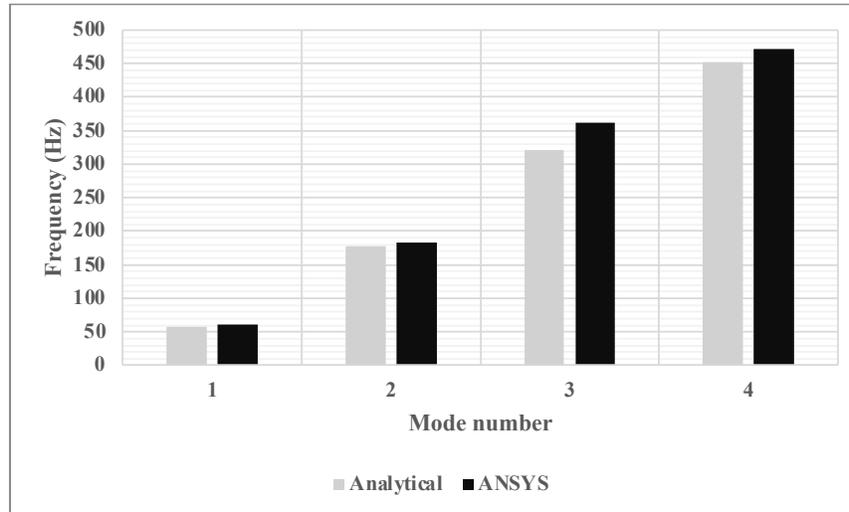


Figure 3: Crack Severity Analysis

## V. Conclusion

The CLS has lower dynamic stiffness than the benchmark SLS due to the dampening properties of its construction. To guarantee that the vehicle's offset frequencies align with the distinctive, it is advisable for the stiffness of the CLS to exceed the goal value by 10-20%. U-bolt clamping increases stress at the contact between the LS and the metal plates. In real scenarios, high stress concentrations may lead to the SB and cover plate deterioration. A layer of soft substances should be inserted between the top plate and the SB to mitigate concentrated stress, safeguarding the SB, upper, and lower plates. Adequate hole margins must be included in the design of the spring ends. A poor ratio of the spring's hole-end length to the hole's width will result in shearing and tensile failure of the spring. The resin's glass transition temperature ( $T_g$ ) must be considered when selecting the material. The  $T_g$  point is recommended to exceed 80 °C. Additional research is required about the significant lateral movement of the CLS.

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