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Prediction of Fatigue Life of Coil Springs and Lower Suspension Arms Based on Strain-Life Approach

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ABSTRACT
This study predicts the fatigue life of helical coil springs and lower suspension arms in automotive suspension systems using the strain-life approach. The strain-life method, which incorporates local plastic strain effects, is particularly suitable for components experiencing variable amplitude loading under road-induced vibrations. Finite element analysis (FEA) was employed to determine critical strain locations and magnitudes under typical loading conditions. Fatigue life was estimated using the Coffin-Manson relation, with mean stress corrections via the Morrow and Smith-Watson-Topper (SWT) models. Results indicate that coil springs exhibit fatigue lives ranging from 10^5 to 10^6 cycles under rural road excitations, while lower suspension arms show shorter lives at high-stress regions due to multiaxial loading. The findings highlight the importance of material selection and geometry optimization for improved durability in automotive applications.

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1. Introduction

Automotive suspension components, including helical coil springs and lower suspension arms (often referred to as lower control arms), operate under repeated loading generated by road surface irregularities, which progressively induces fatigue-related damage. Such fatigue-driven degradation remains a dominant cause of structural failure in suspension systems and directly affects vehicle safety and maintenance demands. Conventional stress–life (S–N) methods are widely applied in high-cycle fatigue analysis; however, their accuracy decreases when cyclic plastic deformation becomes significant, as commonly observed in suspension parts subjected to variable road loading. To address this limitation, strain–life formulations relate fatigue damage to local strain amplitudes and provide a more suitable framework for conditions involving combined elastic–plastic behavior. The Coffin–Manson relation has been extensively adopted to describe strain-based fatigue response, while mean stress effects are typically incorporated through correction models to reflect realistic service conditions. Prior investigations have demonstrated the applicability of strain–life approaches to lower suspension arms using numerical strain histories and experimental validation (Rahman *et al* ., 2009; Omiya *et al* ., 2023). Parallel studies on coil springs have examined fatigue reliability under road-induced vibrations, highlighting the influence of loading randomness, material properties, and road profiles on durability predictions (Kong *et al* ., 2019; Abdullah *et al* ., 2018; Salman *et al* ., 2019; Tausif *et al* ., 2017). More recent work has further refined fatigue modeling by incorporating advanced signal processing and road excitation characterization to improve life estimation accuracy for suspension springs (Lemu *et al* ., 2023; Kihong *et al* ., 2020). Building upon these studies, the present work evaluates coil springs and lower suspension arms within a unified analytical framework, employing finite element analysis to estimate local strain responses and predict fatigue life for a representative passenger vehicle suspension system.

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2. Methods

2.1 Material Properties and Geometry

The coil spring was modeled using SAE 5160 carbon steel with an elastic modulus $E = 210\ GPa$ and a yield strength $\sigma_y = 1100\ MPa$. Fatigue parameters were taken from standard strain–life data and defined using a fatigue strength coefficient σ'_f fatigue strength exponent b, a fatigue ductility coefficient $\varepsilon'_f = 0.45$ and a fatigue ductility exponent c = -0.6. The lower suspension arm was assumed to be manufactured from AISI 1513 steel, with fatigue parameters adjusted to account for multiaxial stress effects expected near joint and bushing regions. Geometric definitions followed standard automotive designs, consisting of a helical coil spring with a wire diameter of 15 mm, a mean coil diameter of 120 mm, and eight active coils, while the lower suspension arm was represented as a forged component incorporating ball joint and bushing connections.

2.2 Finite Element Analysis

Static and dynamic finite element analyses were conducted using commercial FEA software to obtain local strain responses governing fatigue damage. The primary output used in subsequent fatigue calculations was the total strain amplitude $\Delta\varepsilon/2$ at critical locations. Applied loads included vertical forces associated with vehicle weight, reaching up to 5 kN per wheel, combined with lateral forces generated during cornering. Road-induced excitations were modeled as random loading histories based on power spectral density (PSD) profiles representative of rural and highway road conditions. Critical fatigue locations were identified from the numerical results, corresponding to the inner surfaces of the coil spring and the bushing mounting regions of the lower suspension arm, where peak values of $\Delta\varepsilon/2$, mean stress σ_m, and maximum stress σ_{max} were observed.

2.3 Fatigue Life Prediction

Fatigue life was expressed consistently in terms of the number of cycles to failure N_f, as reported in the Results section. The strain–life relationship was defined using the Coffin–Manson equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

Where $\Delta\varepsilon/2$ is the total strain amplitude obtained from FEA, σ'_f is the fatigue strength coefficient, b is the fatigue strength exponent, ε'_f is the fatigue ductility coefficient, c is the fatigue ductility exponent, and N_f denotes the number of cycles to failure. Mean stress effects were incorporated using the Morrow formulation, written as:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f - \sigma_m}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

Where σ_m represents the mean normal stress calculated at the same critical location used for strain extraction. For loading cases involving combined or multiaxial stress states, the Smith–Watson–Topper (SWT) parameter was applied and expressed as:

$$\sigma_{\max}\frac{\Delta\varepsilon}{2} = \sigma_f'^2(2N_f)^{2b}$$

Where σ_{max} is the maximum normal stress within a loading cycle. The same definitions of $^{\Delta\varepsilon}/_{2}\,, \sigma_m, and\ \sigma_{max}$ were maintained in the Results section to ensure direct comparison of predicted fatigue lives. For variable amplitude loading, cumulative damage was evaluated using the Palmgren–Miner rule:

$$D = \sum_i \frac{n_i}{N_{f,i}}$$

Where n_i denotes the number of applied cycles at a given strain level and $N_{f,i}$ is the fatigue life predicted for that level using the strain–life relations. Fatigue failure was assumed to occur when the accumulated damage parameter reached *D* = 1.

3. Results

Finite element analysis identified localized strain responses that govern fatigue behavior in both suspension components. Under rural road excitation, the total strain amplitude $^{\Delta\varepsilon}/_{2}$ at critical regions of the coil spring ranged from 0.002 to 0.005, with peak values observed at the inner surfaces of the coils. In the lower suspension arm, higher strain amplitudes were obtained, ranging from 0.003 to 0.007, primarily concentrated at the bushing mounting regions where load transfer and geometric discontinuities coincide. Using the extracted strain amplitudes as input to the strain–life formulations, fatigue life was quantified in terms of the number of cycles to failure N_f. For the coil spring operating under rural road conditions, the Coffin–Manson relation predicted a fatigue life of $N_f = 4.2\ x\ 10^5$ cycles. Incorporation of mean stress effects through the Morrow correction reduced the predicted life to $N_f = 3.8\ x\ 10^5$ cycles, while application of the Smith–Watson–Topper (SWT) parameter yielded the most conservative estimate of $N_f = 3.5\ x\ 10^5$ cycles. These differences reflect the increasing influence of tensile mean stress and maximum stress on fatigue damage at the critical spring locations. For the lower suspension arm, strain–life analysis predicted a fatigue life of approximately $N_f = 1.8\ x\ 10^5$ cycles under rural road excitation, with fatigue damage concentrated at the bushing interface. This region consistently exhibited the highest values of $^{\Delta\varepsilon}/_{2}\,, \sigma_m, and\ \sigma_{max}$, indicating a strong correlation between local stress–strain response and fatigue life reduction. When highway road profiles were applied, reduced strain amplitudes led to a marked increase in predicted fatigue life for both components. Across all strain–life models, the estimated values of N_f increased by a factor of approximately two to three compared with rural road conditions, confirming the sensitivity of fatigue life to loading severity and road-induced excitation characteristics.

4. Discussion

The results demonstrate that fatigue behavior in automotive suspension components is strongly governed by localized strain response rather than nominal stress levels, supporting the use of a strain–life framework for life estimation under road-induced loading. The higher strain amplitudes observed in the lower suspension arm compared with the coil spring explain the shorter predicted fatigue life, particularly at the bushing interface where load transfer and geometric discontinuities coexist. Such locations promote non-uniform stress–strain fields, which accelerate fatigue damage accumulation even when global loading remains within elastic limits. This behavior is consistent with reported failure patterns in service, where suspension arms often exhibit cracking near joints and mounting regions. Differences in predicted fatigue life among the applied strain–life models further illustrate the influence of mean and maximum stress on durability assessment. The Coffin–Manson relation, which neglects mean stress effects, produced the highest life estimates for the coil spring, while the Morrow correction reduced the predicted life by explicitly accounting for tensile mean stress. The Smith–Watson–Topper formulation yielded the lowest values of NfN_fNf, reflecting its sensitivity to peak stress levels that arise during combined loading. For suspension components subjected to variable road excitation and intermittent tensile loading, such conservatism is appropriate when evaluating durability margins, particularly for safety-critical parts. The contrast between rural and highway road conditions highlights the strong dependence of fatigue life on excitation severity. Reduced strain amplitudes under highway profiles resulted in a two- to three-fold increase in predicted life for both components across all models. This trend confirms that road roughness directly influences fatigue damage rates and reinforces the need to evaluate suspension durability under representative operating environments rather than idealized loading scenarios. Although the present analysis provides consistent life predictions and clear trends, several simplifying assumptions warrant consideration. The fatigue assessment relied primarily on strain histories extracted from finite element simulations, and material behavior was represented using parameters obtained from standard strain–life data. Variations in surface condition, residual stress, and manufacturing-induced defects were not explicitly included and may affect fatigue performance in practical applications. In addition, multiaxial effects were addressed through correction models rather than fully multiaxial fatigue criteria, which may further refine life predictions for complex loading paths. Overall, the findings confirm that strain-based fatigue analysis offers a suitable framework for comparing the durability of suspension components under realistic road loading. The observed differences between coil springs and lower suspension arms underscore the importance of local geometry and loading mode in fatigue behavior, while the variation among fatigue models emphasizes the need for careful model selection when evaluating safety margins in suspension design.

5. Conclusions

This study evaluated the fatigue life of a helical coil spring and a lower suspension arm under road-induced loading using a strain–life framework supported by finite element analysis. The results show that fatigue behavior in both components is controlled by localized strain response rather than nominal loading, with higher strain amplitudes leading to shorter predicted life. Under rural road conditions, the coil spring exhibited fatigue lives on the order of 10^5 cycles, while the lower suspension arm showed lower durability, with damage concentrated at the bushing interface where combined loading effects are most pronounced. Comparison among strain–life models indicates that fatigue life predictions are sensitive to the treatment of mean and maximum stress. The Coffin–Manson relation produced the highest life estimates, whereas the inclusion of mean stress through the Morrow correction and the Smith–Watson–Topper formulation progressively reduced predicted life, with the latter providing the most conservative results. Reduced loading severity under highway road profiles resulted in a two- to three-fold increase in predicted fatigue life for both components, confirming the strong influence of road excitation characteristics on durability. Overall, the findings support the use of strain-based fatigue analysis for suspension components operating under variable road loading and highlight the need to account for local geometry and loading mode when assessing durability. While the present results provide a consistent comparison between coil springs and lower suspension arms, further refinement through detailed multiaxial fatigue criteria and consideration of manufacturing-related effects would improve life estimation accuracy for practical design applications.

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