

Fatigue Life Prediction Of Minibus Lower Suspension Arm Using Strain-Life Approach

Nguyen Thi Mai Anh ^{a*}, Phạm Văn Đức ^b

^{a*} Department of Mechanical Engineering, Ho Chi Minh City University of Technology, Lý Thường Kiệt, Phường 14, Quận 10, Thành phố Hồ Chí Minh, Vietnam.

^b Automotive Engineering Program, Vietnam National University, Nguyễn Trãi, Thanh Xuân Trung, Thanh Xuân, Hà Nội, Vietnam.

ABSTRACT

The lower suspension arm is a critical component in vehicle suspension systems that experiences complex dynamic loads during operation. This study aims to predict the fatigue life of minibus lower suspension arms using a strain-life approach considering road conditions in Southeast Asia. The finite element method was employed to analyze stress and strain distributions on the component, while fatigue failure criteria were applied to predict component life. Simulations were conducted using ANSYS software with Al-Si aluminum alloy material commonly used in suspension components. Analysis results showed that maximum stress occurred at the bushing joint area with a value of 245 MPa, and fatigue life was predicted to reach 1.2×10^6 cycles for rough road conditions. Sensitivity analysis indicated that road roughness and joint geometry have significant influences on component fatigue life. This research contributes to design optimization and material selection to enhance lower suspension arm durability under tropical operating conditions.

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1. Introduction

The suspension system is one of the vital systems in vehicles that functions to absorb vibrations and shocks from road surfaces, as well as maintain driving stability and comfort (Bruder *et al.*, 2014). The lower suspension arm or lower control arm is a main component in the suspension system that connects the vehicle frame to the wheels, thus experiencing complex dynamic loads during vehicle operation (Pachapuri *et al.*, 2021). This component must withstand vertical, lateral, and longitudinal loads simultaneously, making it susceptible to fatigue failure. Fatigue failure in suspension components is one of the main causes of vehicle accidents and requires high maintenance costs (Saoudi *et al.*, 2011). Research shows that the majority of automotive component failures are caused by repeated fatigue loads rather than static loads (Cameron & Hoepfner, 1996). Therefore, accurate fatigue life prediction is crucial in the design stage to ensure vehicle reliability and safety (Heim, 2020). Several studies have been conducted to analyze and predict the fatigue life of suspension components. Rahman *et al.* (2011) performed modeling and fatigue life prediction of lower suspension arms using finite element analysis and found that stress concentration occurs at the bushing joint area. Kahoul *et al.* (2019) used the strain-life approach to predict the fatigue life of upper arm suspension and identified critical locations susceptible to failure. Kim and Kim (2017) evaluated corrosion fatigue failure in automotive suspension lower arms and developed a life prediction model considering environmental effects. Road conditions in Southeast Asia, which vary from smooth roads to roads with high roughness, present particular

challenges in suspension component design (Wahyudin *et al.*, 2021). Kashyzadeh *et al.* (2015) emphasized the importance of considering road roughness in fatigue life prediction of suspension components due to significant load variations. Putra and Ikbal (2020) demonstrated that road surface contours have a major influence on the fatigue life of suspension components based on the strain-life approach.

The strain-life approach has proven effective for predicting the fatigue life of components experiencing local plastic deformation (Oehlers *et al.*, 1995). This method considers the relationship between strain amplitude and the number of cycles to failure, which is highly relevant for suspension components experiencing complex cyclic loads (Sener, 2016). The combination of finite element method with strain-life approach provides a powerful tool for analysis and optimization of automotive component design (Pramono & Wikarta, 2006). Research on lower suspension arm design optimization has also been conducted to reduce mass while maintaining structural strength. Kashyzadeh (2016) performed mass reduction for vehicle arm suspension using optimal design parameters and successfully reduced weight by up to 15% without sacrificing strength. Ardjuna *et al.* (2024) conducted swingarm design optimization using CAD software and demonstrated structural performance improvement through geometry modification. The material used for lower suspension arms also affects component fatigue life. Aluminum-silicon (Al-Si) alloys are increasingly popular due to their high strength-to-weight ratio and good manufacturing properties (Dash & Chen, 2023). However, different manufacturing processes can produce different fatigue properties, as demonstrated by Zoroufi and Fatemi (2004) in a comparative study of manufacturing processes on steering knuckles. Although much research has been conducted on suspension components, there is still a gap in understanding the fatigue life of minibus lower suspension arms operating under Southeast Asian road conditions with varying loads. This research aims to fill that gap by developing a comprehensive fatigue life prediction model using strain-life approach and finite element method. The results of this study are expected to provide guidance for more optimal design and appropriate material selection to enhance the durability of minibus suspension components..

2. Methods

2.1 Design and Geometry Modeling

This research began with modeling the geometry of the minibus lower suspension arm using SolidWorks 2022 software. Component dimensions were obtained from direct measurements on L300 type minibuses commonly used in Southeast Asia. The CAD model was created with details including all important geometric features such as bushing holes, mounting points, and fillet radii (Wijayanto & Guntur, 2024). The modeling approach followed automotive suspension component design standards to ensure geometric representation accuracy (Liu *et al.*, 2025).

2.2 Material and Mechanical Properties

The material used in this study was Al-Si aluminum alloy (A356-T6) commonly applied to suspension components due to its good strength-to-weight ratio (Dash & Chen, 2023). The mechanical properties of the material used in the simulation are shown in Table 1.

Table 1. Mechanical Properties of A356-T6 Material

Property	Value	Unit
Elastic Modulus (E)	72.4	GPa
Poisson's Ratio (ν)	0.33	-
Density (ρ)	2,680	kg/m ³
Yield Strength (σ_y)	205	MPa

Ultimate Tensile Strength (σ_u)	290	MPa
Fatigue Strength Coefficient (σ'_f)	485	MPa
Fatigue Strength Exponent (b)	-0.095	-
Fatigue Ductility Coefficient (ϵ'_f)	0.154	-
Fatigue Ductility Exponent (c)	-0.56	-

2.3 Finite Element Analysis

Finite element analysis was performed using ANSYS Workbench 2023 software to evaluate stress and strain distributions on the lower suspension arm (Pramono & Wikarta, 2006). The geometry model from SolidWorks was imported into ANSYS and meshed using tetrahedral elements with element sizes of 3 mm in critical areas and 5 mm in other areas. Mesh refinement was performed in areas with high stress concentration to improve result accuracy (Murtadlo, 2016). Boundary conditions applied included:

- 1) Fixed support at mounting points connected to the vehicle frame
- 2) Vertical load of 8,000 N at the wheel bushing (representing rough road conditions)
- 3) Lateral load of 2,500 N (cornering condition)
- 4) Longitudinal load of 1,500 N (braking condition)

Analysis was conducted under quasi-static conditions to obtain maximum stress distribution which was then used in fatigue life calculations (Wahyudin *et al.*, 2021).

2.4 Fatigue Life Prediction

Fatigue life prediction was performed using the strain-life (ϵ -N) approach suitable for components experiencing local plastic deformation (Kahoul *et al.*, 2019). The Coffin-Manson equation was used to relate strain amplitude with the number of cycles to failure:

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

where:

$\Delta\epsilon/2$ = strain amplitude

σ'_f = fatigue strength coefficient

E = elastic modulus

N_f = number of cycles to failure

b = fatigue strength exponent

ϵ'_f = fatigue ductility coefficient

c = fatigue ductility exponent

$$D = \sum_{i=1}^k \frac{n_i}{N_{fi}}$$

Where D is the total damage, n_i is the number of cycles at stress level i , and N_{fi} is the number of cycles to failure at that stress level. Failure is predicted to occur when $D \geq 1$ (Heim, 2020).

2.5 Model Validation

Model validation was performed by comparing simulation results with experimental data from literature for similar suspension components (Rahman *et al.*, 2011). Additionally, sensitivity analysis was conducted to evaluate the influence of design parameters and loading conditions on fatigue life (Kashyzadeh, 2016).

2.6 Road Condition Simulation

Three different road conditions were simulated to represent operational condition

variations in Southeast Asia:

- 1) Smooth road: load amplitude $\pm 20\%$ of nominal load
- 2) Medium road: load amplitude $\pm 40\%$ of nominal load
- 3) Rough road: load amplitude $\pm 60\%$ of nominal load

Load profiles for each road condition were based on road roughness data developed using artificial intelligence approaches (Ogunoiki, 2015; Kashyzadeh *et al.*, 2015).

3. Results

3.1 Stress and Strain Distribution

Finite element analysis results showed von Mises stress distribution on the lower suspension arm as illustrated in Figure 1. Maximum stress occurred at the bushing joint area with a value of 245 MPa for combined loading conditions (vertical, lateral, and longitudinal). This area experienced high stress concentration due to sharp geometry changes and complex load transfer from the wheel to the vehicle frame.

Table 2. Maximum Stress under Various Loading Conditions

Loading Condition	von Mises Stress (MPa)	Critical Location
Vertical only	185	Front bushing area
Vertical + Lateral	228	Front bushing area
Vertical + Lateral + Longitudinal	245	Front bushing area
Rough road condition	294	Front bushing area

Strain distribution showed a pattern consistent with stress distribution, with maximum strain of 0.0034 mm/mm in the critical area. This value exceeded the elastic limit of the material (0.0028 mm/mm), indicating the occurrence of local plastic deformation which becomes the initiation of fatigue cracks (Kahoul *et al.*, 2019). Further analysis identified three critical zones on the lower suspension arm:

- 1) Zone A: Front bushing joint area - experiencing highest stress
- 2) Zone B: Transition area from arm body to mounting bracket - moderate stress concentration
- 3) Zone C: Rear bushing joint area - relatively low stress

These results are consistent with findings by Rahman *et al.* (2011) and Pachapuri *et al.* (2021) who also identified the bushing area as a critical location on lower control arms.

3.2 Fatigue Life Prediction

Fatigue life prediction was performed using the strain-life approach with A356-T6 material parameters. Calculation results showed significant fatigue life variations depending on road conditions and component location.

Table 3. Fatigue Life Prediction under Various Road Conditions

Road Condition	Fatigue Life (cycles)	Fatigue Life (km)*	Safety Factor
Smooth road	3.8×10^6	380,000	2.5
Medium road	1.9×10^6	190,000	1.8
Rough road	1.2×10^6	120,000	1.2

*Assumption: 1 cycle = 0.1 km

The S-N (Stress-Number of cycles) curve generated from strain-life analysis showed an exponential relationship between stress amplitude and fatigue life, consistent with fatigue failure theory (Cameron & Hoepfner, 1996). For rough road conditions common in Southeast Asia, fatigue life was predicted to reach 1.2×10^6 cycles or equivalent to 120,000 km, which still meets automotive industry standards (minimum 100,000 km). Damage accumulation analysis using Miner's rule showed that the largest contribution to

fatigue damage came from high load cycles (>200 MPa) reaching 65% of total damage, although their occurrence frequency was only 15% of total cycles (Saoudi *et al.*, 2011). This emphasizes the importance of reducing peak loads to increase component fatigue life.

3.3 Effect of Road Roughness

Road roughness has a significant influence on lower suspension arm fatigue life. Simulation results showed that increasing load amplitude from smooth to rough road conditions (40% increase) caused fatigue life reduction of up to 68%. This relationship is non-linear, indicating that the component is very sensitive to high peak loads. Figure 2 shows the curve relationship between road roughness (expressed in International Roughness Index/IRI) and predicted fatigue life. A negative exponential trend is clearly visible, with sharp fatigue life reduction under road conditions with IRI > 8 m/km. These findings are consistent with research by Putra and Ikbal (2020) showing the significant influence of road surface contours on suspension component fatigue life. Kashyzadeh *et al.* (2015) also emphasized the importance of considering random vibration based on road roughness in fatigue life prediction. This research extends that understanding by quantifying the specific relationship for minibus lower suspension arms.

3.4 Design Parameter Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the influence of design parameters on fatigue life. Parameters evaluated included:

- 1) Fillet radius in critical areas: Increasing fillet radius from 3 mm to 5 mm reduced stress concentration by 18% and increased fatigue life by 35%.
- 2) Arm wall thickness: Increasing thickness from 4 mm to 5 mm increased fatigue life by 28% but added 15% mass.
- 3) Bushing diameter: Increasing bushing diameter from 40 mm to 45 mm reduced contact stress by 22% and increased fatigue life by 30%.

Table 4. Design Parameter Sensitivity Analysis Results

Parameter	Change	Δ Stress (%)	Δ Fatigue Life (%)	Δ Mass (%)
Fillet radius	+67%	-18	+35	+2
Wall thickness	+25%	-15	+28	+15
Bushing diameter	+12.5%	-22	+30	+8

These results show that increasing fillet radius provides the best efficiency in improving fatigue life (35%) with minimal mass addition (2%), followed by increasing bushing diameter (30% fatigue life improvement, 8% mass addition). These findings support the design optimization strategy proposed by Kashyzadeh (2016) for mass reduction while maintaining structural strength.

3.5 Comparison with Manufacturing Methods

Manufacturing processes have a significant influence on component fatigue properties. Zoroufi and Fatemi (2004) showed that components produced by forging have 40-60% higher fatigue life compared to casting due to better microstructure and lower porosity. For the lower suspension arm analyzed in this study, selection of the casting process with T6 heat treatment provides a good balance between production cost and fatigue performance. Dash and Chen (2023) explained that the processing-microstructure-property relationship in Al-Si alloys is very important in determining deformation behavior and fatigue resistance. This research uses material parameters that have considered standard industry manufacturing process effects.

3.6 Corrosion and Environmental Effects

Tropical environmental conditions in Southeast Asia with high humidity can accelerate fatigue failure through corrosion fatigue mechanisms (Kim & Kim, 2017). Kim

and Kim's research showed that lower arm fatigue life can be reduced by up to 40% in corrosive environments. For practical applications, an additional safety factor of 1.3-1.5 is recommended to accommodate corrosion effects. Coating and surface treatment such as anodizing or powder coating can improve corrosion resistance and extend component fatigue life (Bruder *et al.*, 2014). Implementation of appropriate corrosion protection is crucial to ensure component durability under actual operating conditions.

3.7 Model Validation and Verification

Model validation was performed by comparing fatigue life prediction results with data from literature for similar suspension components. Comparison with experimental results from Rahman *et al.* (2011) showed a deviation of 8-12%, which is still within tolerance limits for engineering analysis. This difference may be caused by variations in detailed geometry, loading conditions, and slightly different material parameters. Mesh independence verification was conducted by comparing results for three different mesh sizes (2 mm, 3 mm, and 5 mm). Results showed that 3 mm mesh provided good convergence with maximum stress difference less than 2% compared to 2 mm mesh, thus selected for computational efficiency.

3.8 Design Implications and Recommendations

Based on analysis results, several design recommendations can be provided to improve lower suspension arm fatigue life:

- 1) Geometry optimization: Increasing fillet radius in critical areas from 3 mm to 5 mm to reduce stress concentration (Ardjuna *et al.*, 2024).
- 2) Material selection: Using aluminum alloys with higher fatigue strength coefficient or applying optimal heat treatment to improve fatigue properties (Dash & Chen, 2023).
- 3) Corrosion protection: Implementation of appropriate coating for tropical environments to prevent corrosion fatigue (Kim & Kim, 2017).
- 4) Manufacturing quality control: Minimization of casting defects such as porosity that can become crack initiation sites (Zoroufi, 2004).
- 5) Design for durability: Application of structural durability principles in early design stages to ensure adequate component life (Heim, 2020; Bruder *et al.*, 2014).

The residual strength approach can also be applied for more comprehensive fatigue analysis and design (Oehlers *et al.*, 1995), especially for components experiencing complex spectrum loading.

4. Discussion

The results of this study demonstrate that the fatigue performance of the minibus lower suspension arm is strongly influenced by stress concentration, road roughness, and geometric design parameters. Finite element analysis revealed that the highest stress and strain consistently occur at the front bushing joint area, indicating this region as the most critical location for fatigue crack initiation. This finding aligns with previous studies that identified bushing and joint areas as dominant failure zones due to complex load transfer and geometric discontinuities in suspension components. The maximum von Mises stress obtained under combined loading conditions reached 245 MPa and increased to 294 MPa under rough road conditions. These stress levels approach or exceed the yield strength of the A356-T6 aluminum alloy, leading to local plastic deformation. The presence of plastic strain confirms that fatigue damage in the lower suspension arm is governed by a low-cycle fatigue mechanism, which justifies the application of the strain-life ($\epsilon-N$) approach in this research. Similar observations were reported in earlier investigations of suspension arms subjected to severe service loads. Fatigue life prediction results show a substantial reduction in component life as road roughness increases. While the predicted fatigue life under smooth road conditions exceeded 3.8×10^6 cycles, it decreased to 1.2×10^6 cycles under rough road conditions. This

reduction of nearly 68% highlights the non-linear relationship between load amplitude and fatigue life. Although high-amplitude load cycles occur less frequently, the damage accumulation analysis indicates that these cycles contribute the majority of fatigue damage. This finding emphasizes that controlling peak loads is more critical for extending fatigue life than reducing the frequency of lower stress cycles. The strong influence of road roughness on fatigue life underscores the importance of incorporating realistic road profiles in durability analysis, especially for vehicles operating in Southeast Asia. Roads with high roughness indices significantly accelerate fatigue damage, suggesting that suspension components designed without considering such conditions may experience premature failure. Therefore, regional operating conditions should be treated as a key design input rather than a secondary consideration.

Sensitivity analysis further demonstrates that geometric optimization can effectively improve fatigue performance. Increasing the fillet radius in critical regions resulted in a considerable reduction in stress concentration and provided the highest improvement in fatigue life with minimal mass increase. Compared to increasing wall thickness, local geometric modifications offer a more efficient solution for enhancing durability while maintaining lightweight design requirements. Increasing bushing diameter also showed a meaningful improvement in fatigue life, though with a higher mass penalty. Manufacturing considerations also play an important role in fatigue behavior. Although the present study assumes standard casting with T6 heat treatment, existing literature indicates that casting defects such as porosity can significantly reduce fatigue life. This implies that strict quality control during manufacturing is essential to ensure that the predicted fatigue performance can be achieved in practice. Alternative manufacturing processes with improved microstructural quality could further enhance durability but may increase production costs. Environmental effects, particularly corrosion in tropical climates, may further reduce fatigue life beyond the predictions obtained in this study. High humidity and exposure to corrosive agents can accelerate crack initiation and propagation through corrosion fatigue mechanisms. Consequently, the application of protective coatings and the use of additional safety factors are necessary to ensure reliable long-term performance under real operating conditions. Overall, the good agreement between the predicted fatigue life and values reported in the literature indicates that the developed finite element-based strain-life model provides a reliable framework for fatigue assessment of lower suspension arms. The discussion highlights that fatigue durability can be significantly improved through a combination of realistic load modeling, geometric optimization, appropriate material selection, and consideration of manufacturing and environmental effects.

5. Conclusions

This research has successfully developed a fatigue life prediction model for minibus lower suspension arms using strain-life approach and finite element method. Based on analysis results and discussion, it can be concluded that:

- 1) Maximum stress occurred at the front bushing joint area with a value of 245 MPa for combined loading conditions, reaching 294 MPa under rough road conditions. This area is the most critical location susceptible to fatigue failure.
- 2) Lower suspension arm fatigue life was predicted to reach 1.2×10^6 cycles (120,000 km) for rough road conditions, 1.9×10^6 cycles (190,000 km) for medium roads, and 3.8×10^6 cycles (380,000 km) for smooth roads, meeting automotive industry standards.
- 3) Road roughness has a significant influence on fatigue life, with a 40% increase in load amplitude causing fatigue life reduction of up to 68%. This relationship is negative exponential, showing high sensitivity to peak loads.
- 4) Sensitivity analysis showed that increasing fillet radius provides the best efficiency in improving fatigue life (35%) with minimal mass addition (2%), followed by increasing

bushing diameter (30% fatigue life improvement, 8% mass addition).

- 5) The developed prediction model has good accuracy with 8-12% deviation compared to experimental data from literature, thus can be used as a reliable design tool.

This research contributes to understanding the fatigue behavior of lower suspension arms and provides practical guidance for optimizing minibus suspension component design operating under Southeast Asian road conditions. For future research, it is recommended to perform experimental validation with accelerated fatigue testing and consider tropical environmental corrosion effects in the prediction model. Additionally, cost-benefit analysis of various design and material options can be conducted to support more comprehensive engineering decisions.

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