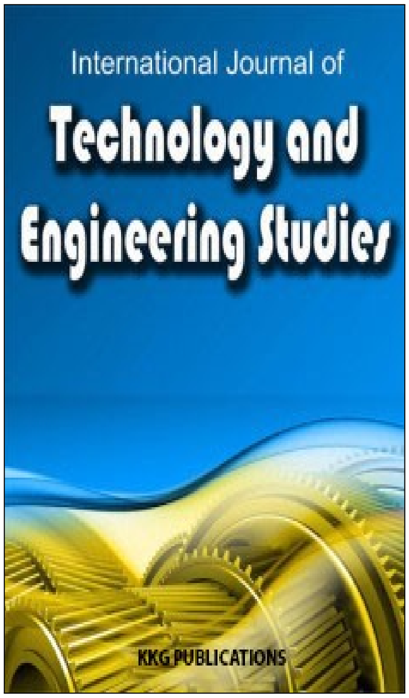


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**IJTES**

# FATIGUE DAMAGE SIMULATION OF AUTOMOBILE STEERING KNUCKLE SUBJECTED TO VARIABLE AMPLITUDE LOADING

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**Abstract.** This study aims to present a fatigue damage simulation of an automobile steering knuckle of a 1300 cc national automobile using finite element analysis. In this study, the steering knuckle is modeled using computer-aided design software, in which the dimensions are assigned according to 3D scanning files. The critical area on the steering knuckle is determined using commercial finite element software. The strain gauge is then mounted on the steering knuckle and connected to a data acquisition system to capture the actual fatigue strain signal while driving on a residential road. The fatigue strain signal is then used as the VAL in the fatigue damage simulation of the automobile steering knuckle. Forged steel, cast aluminum, and cast iron are used and analyzed in the simulation. Results indicate that the different types of material used significantly influenced the fatigue damage of the automobile steering knuckle. Based on these findings, future study can optimize steering knuckle material and correlate the strain signal behavior with fatigue damages.

## INTRODUCTION

Fatigue failure is caused by cyclic loading that occurs below the ultimate strength of a material. Structural or engineering components are exposed to fatigue failure when the number of cycles of applied stress results in the progressive degradation of material properties, which causes eventual failure [1]. Fatigue failure is a major failure mechanism that occurs in the structure and engineering components. Fatigue failure has accounted for approximately 90% of total mechanical failures [2], [3], [4], [5].

In industrial activities, the failure assessment of a mechanical component is an important design stage. The failure of a mechanical component experiencing VAL condition is a complex phenomenon and is difficult to assess, particularly because of load interactions [6]. Most of the material fatigue characterization is conventionally observed under constant sinusoidal loading [7], [8]. Nonetheless, persuasive theories suggest that VAL stress cycle could be more damaging than the same stress cycle under constant amplitude loading [9]. Thus, recognizing the failure mechanism associated with VAL and the critical area of steering knuckle is critical.

Steering knuckle is an important part of the automobile system; it links parts of the steering system and the suspension system. A steering knuckle component is demanded to support the load and torque induced by bumping, braking and accelerating, and the force exerted by the road condition while maneuvering the automobile [10]. Being subjected to multiple dynamics from strut and wheel during operating condition may lead to fatigue failure of the steering knuckle. The steering knuckle substance is subjected to time-varying loads along its service life. Furthermore, it has a direct influence on the performance, durability, and steering ability of vehicles.

A recognizable progression exists in the implementation of optimum materials and components in the automobile industry. Automobile designers have a broad range of materials and processes to choose from [11]. The steering knuckle is normally made of cast iron. However, as automobile industry leans on innovative process technologies and new design methodologies, implementing light alloy applications in the automobile compartment is still analyzed [12].

Moreover, shape optimization is used in reducing the weight of steering knuckles. Tagade et al. [12] studied the weight reduction of a steering knuckle made from cast iron and aluminum alloy 2011-T3. Similarly, Sharma et al. [13] optimized the weight reduction of a steering knuckle made from aluminum alloy 2011-T3 using model and static analysis. Meanwhile, [11], [14], [15], [16] compared the fatigue performance of different steering knuckles using finite element analysis.

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However, these previous studies did not implement random VAL according to actual road profiles in their experiments. Thus, this study aims to discuss the fatigue damage of different types of material of automobile steering knuckles subjected to VAL. In this study, the critical area of a steering knuckle is determined using finite element analysis. The actual fatigue strain signal is then obtained from the steering knuckle using a strain gauge and data acquisition system. This fatigue load history is used as the input loading calculation for fatigue damage on the steering knuckle. The fatigue damage of automobile steering knuckle is expected to be subjected to VAL, which can be predicted using finite element analysis.

## MATERIAL AND METHODS

The fatigue failures of structural components are normally subjected to cyclic loadings although the maximum value of the cyclic load is inferior to the static strength of a material. The fatigue damage $D$ for one cycle can be calculated as follows:

$$D = \frac{1}{N_f} \quad (1)$$

For loadings comprised of a large number of cycles, failure only occurs when the number of cycle-applied load $n1$ is equal to the number of cycles to failure $N1$ from the endurance curve. Among the fatigue damage accumulation rules, the linear damage accumulation rule, known as the Palmgren-Miner rule, is most commonly used [1], [17]. The fatigue damage accumulation under VAL can be calculated using the following rule

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \quad (2)$$

Where $D$ is the fatigue damage of the material, $ni$ is the number of applied loading cycles corresponding to the $i$-th load level, and $Ni$ is the number of cycles to fail at the $i$-th load level from constant amplitude experiments.

The overall experimental process flow is presented in Figure 1. Cast iron ASTM A536, forged steel grade 11V37, and aluminum alloy 2011-T3 are the materials used in this study. The selection of ASTM A536 is based on an actual material that is used for the automobile steering knuckle of a 1300 cc national car, as shown in Figure 2. Part of the steering knuckle is saw using a bent saw equipped with a coolant. Subsequently, this part is polished using sandpaper to obtain a good surface finish for Scanning Electron Microscopy (SEM) analysis. The composition of this material is determined using SEM, and its chemical composition is shown in Table 1.

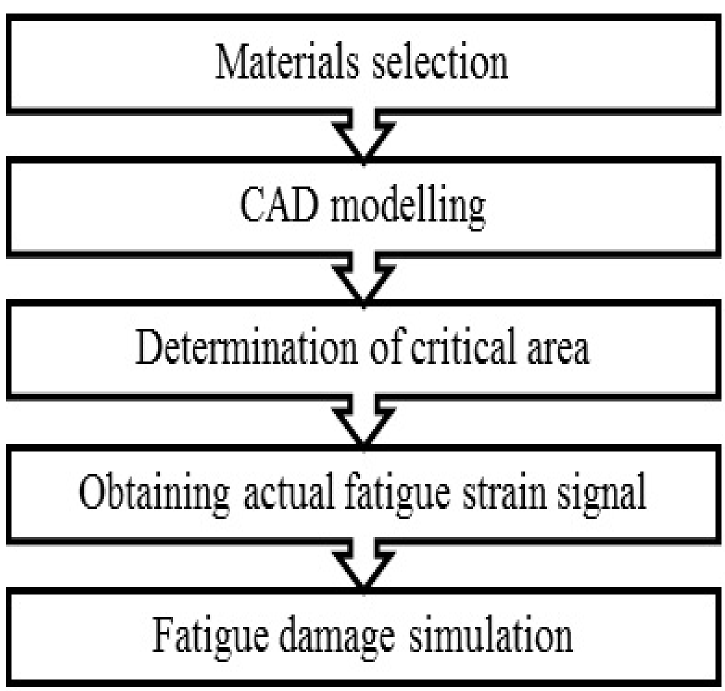


Fig. 1. Overall process flow

Fig. 2. Automobile steering knuckle of 1300 cc national automobile

TABLE 1
CHEMICAL COMPOSITION OF THE STEERING KNUCKLE

| Element | C | Cr | Cu | S | Ni | P | Si | Fe |
|---|---|---|---|---|---|---|---|---|
| Weight (%) | 3.80 | 0.07 | 0.035 | 0.02 | 0.04 | 0.045 | 2.40 | 93.59 |

Meanwhile, material-forged steel grade 11V37 and aluminum alloy 2011-T3 are commonly used for automobile steering knuckles. Forged steel SAE grade 11V37 is widely used in four cylinder sedans [15]. Aluminum alloy is widely used in the automobile industry due to its light weight, low density, and yield strength compatibility [17]. Thus, this material helps in reducing $CO_2$ emission and fuel consumption and has been making its way into steering knuckle manufacturing [12]. Table 2 presents the mechanical properties of the materials used in this study.

TABLE 2
MECHANICAL PROPERTIES OF THE MATERIALS

| Name | Forged Steel SAE Grade 11V37 [14], [15] | Cast Iron ASTM A536 [14], [15] | Aluminum Alloy 2011-T3 [12], [13] |
|---|---|---|---|
| Yield Strength | 556 MPa | 300 MPa | 280 MPa |
| Ultimate Tensile Strength | UTS 821 MPa | 471 MPa | 310 MPa |
| Elastic Modulus E | 201.5 GPa | 193 GPa | 71 GPa |

Static finite element analysis employs computational-aided design on the steering knuckle. A 3D scanner is used to produce a precise geometry on the steering knuckle.

Strut mount, steering arm, and the lower ball joint of the steering knuckle are subjected to force magnitudes of 5000 N, 2500 N, and 4500 N, respectively [10], as shown in Figure 3. The steering knuckle is constrained at the hub; the brake clamp of the steering knuckle is also a constraint. As the car is driven at a constant speed, the brake force is assumed to be zero.


Fig. 3. Finite element model of the steering knuckle

A set of VAL data is obtained using a strain gauge fixed on the steering knuckle of the 1300 cc automobile. The strain gauge of the 2.0-mm gauge length with a resistance of 120 Ω is fixed on the bracket based on ASTM E1237. The position of the strain gauge is located at the most critical area on the steering knuckle [19] and is connected to a data acquisition system. The fatigue strain signal is captured while traveling on a residential road at a speed of 15 km/h, as shown in Figure 4. The velocity is the approximate speed for most of the cars on a residential road and is most stable for capturing strain data signals [1], [20].


Fig. 4. Capturing the fatigue strain signal process: (a) Strain gauge mounted on the steering knuckle, (b) Data acquisition system, (c) Condition of the road surface

The geometry model, materials, and loading histories are mapped together and analyzed using DesignLife® software to predict the fatigue damage on the steering knuckle of the automobile. Model analysis of the three materials used in the steering knuckle is tested with 1 min of strain signal input. The material mapping is set to forged steel SAE grade 11V37, aluminum alloy 2011-T3, and cast iron ASTM A536. The analysis in this study implements Morrow's mean stress correction in confronting residual stress, which could affect the rate of the fatigue damage results. Figure 5 shows the interface of the fatigue damage analysis.

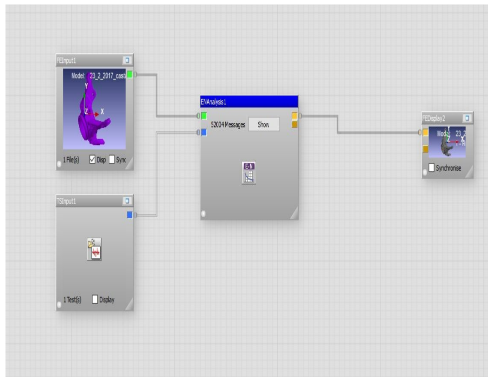

Fig. 5. Fatigue damage simulation process

## RESULTS AND DISCUSSION

Figure 6 shows the stress distribution on the steering knuckle from the finite element analysis. Results indicate that the maximum stress occurs at the point under the strut mount with a magnitude of 297.03 MPa. Therefore, this area is identified as a critical area for the steering knuckle where fatigue failure may occur. The strut mount is essentially connected with the shock absorber, which supports the majority of the car weight. Furthermore, the induced force also comes from the VAL generated from the uneven surface of the road condition. The location of this critical area is in good agreement with the study conducted by Zoroufi and Fatemi [11], [14], [15], who discovered that the critical area of cast iron steering knuckle is at the neck of the strut mount. The maximum Von Mises stress location is further used in implanting the strain gauge to record a fatigue strain signal history.

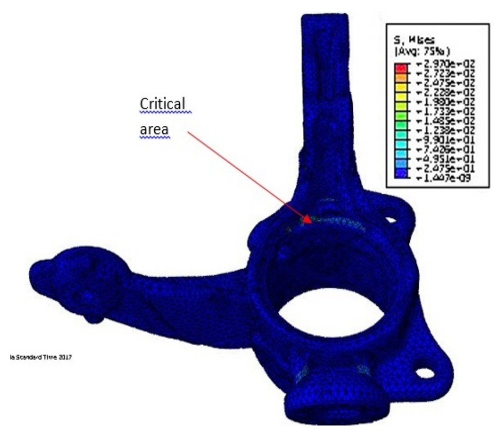


Fig. 6. Stress distribution of cast iron ASTM A536

The behavior of the captured fatigue strain signal is shown in Figure 7. The strain signal history recorded from data acquisition at a 500-Hz frequency at 60 s generates 30000 data points. The strain signal fluctuates with a maximum range of 316 $\mu\varepsilon$. The strain signal produces a maximum value of -112 $\mu\varepsilon$, a minimum value of -143 $\mu\varepsilon$, an average value of -123 $\mu\varepsilon$, and a standard deviation value of 3.7087 $\times 10^{-3}$ $\mu\varepsilon$. Two points on the strain signal shows a high strain range due to the presence of road bumper along the residential road. This high strain range indicates that the steering knuckle experienced a significant displacement when the automobile is driven on the road bumper. The magnitude of displacement or elongation is at a specified and localized area on the steering knuckle, which is measured by the strain gauge in the form of time series history [17].

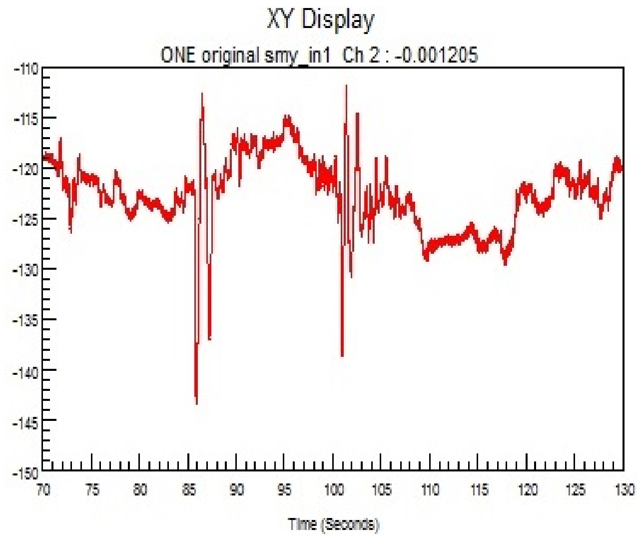


Fig. 7. Captured fatigue strain signal history

Fatigue failure occurs and the material weakens due to repeated load application. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. In this case, fatigue damage may initiate at the critical area on the steering knuckle before propagating enough failures. Figures 8, 9, and 10 show the results of fatigue damage simulation for different types of steering knuckle materials that are subjected to VAL. All three steering knuckles show the same location of fatigue damage, which is located at the neck of the strut mount.

The simulation reveals that aluminum alloy 2011-T3 has the highest fatigue damage with $1.41\times10^{-5}$, followed by cast iron ASTM A536 with fatigue damage of $8.98\times10^{-6}$, which is lesser by $5.12\times10^{-6}$ compared to aluminum alloy 2011-T3. Meanwhile, forged steel SAE grade 11V37 has the lowest fatigue damage with $5.27\times10^{-7}$, which is approximately 24 times smaller than the fatigue damage of aluminum alloy 2011-T3 and approximately 15 times smaller than cast iron ASTM A536. The comparison of fatigue damage results indicates that forged steel SAE grade 11V37 is superior to aluminum alloy 2011-T3 and cast iron ASTM A536.

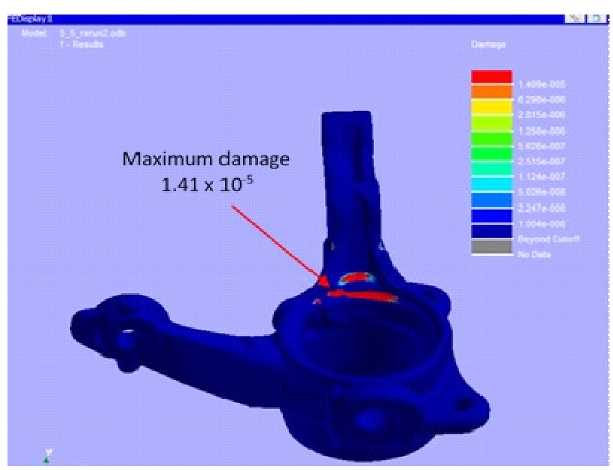


Fig. 8. Fatigue damage of aluminum alloy 2011-T3

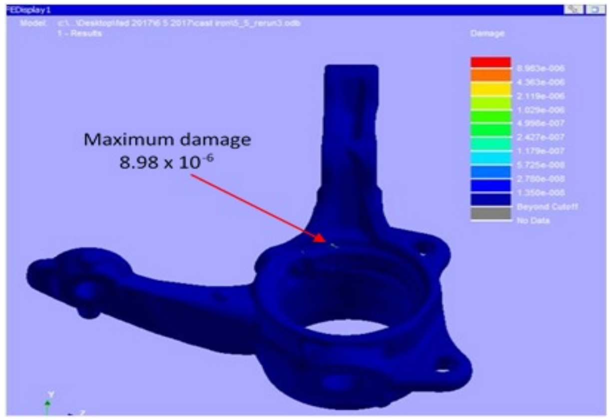


Fig. 9. Fatigue damage of cast iron ASTM A536

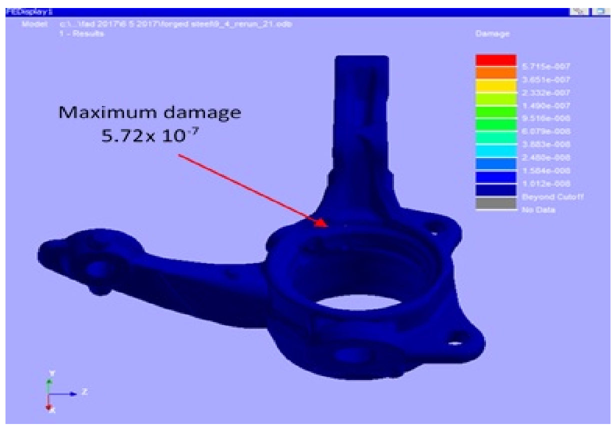


Fig. 10. Fatigue damage of forged steel SAE Grade 11V37

## CONCLUSION AND RECOMMENDATIONS

In this study, actual fatigue strain signal is captured from the steering knuckle of a 1300 cc national automobile while traveling on a residential road surface. This VAL is then used as input loading for fatigue analysis. The analysis indicates that the most critical area on the steering knuckle is located at the neck of the strut mount and is considered as the potential area for a crack-initiated damage. The fatigue damage analysis for the three types of common materials used for a steering knuckle reveals that aluminum alloy 2011-T3 has the highest fatigue damage, followed by cast iron ASTM A536 and forged steel SAE 11V37. Based on these findings, future study can be done in optimization of steering knuckle material and to correlate the strain signal behavior with fatigue damages.

### Declaration of Conflicting Interests

There are no conflicts of interest.

### Acknowledgment

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