

# Fatigue Life Prediction of an Automobile Cradle Mount

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## ABSTRACT

Elastomers have large reversible elastic deformation, good damping and high energy absorption capabilities. Due to these characteristics along with low cost of manufacturing, elastomeric components are widely used in many industries and applications, including in automobiles. These components are typically subjected to complex multiaxial and variable amplitude cyclic loads during their service life. Therefore, fatigue failure and life prediction are important issues in the design and analyses of these components. Availability of an effective CAE technique to evaluate fatigue damage and to predict fatigue life under complex loading conditions is a valuable tool for such analysis. This paper discusses a general CAE analytical technique for durability analysis and life prediction of elastomeric components. The methodology is then illustrated and verified by using experimental fatigue test results from an automobile cradle mount. The developed methodology involves constitutive behavior and fatigue behavior of the material, finite element analysis of the component, and fatigue damage quantification for life predictions. The commonly used Rainflow cycle counting method and Miner linear cumulative damage rule for metals are also evaluated for their application to variable amplitude loading of elastomeric components. The experiments included axial as well as combined in-phase and out-of-phase axial-torsion constant amplitude and variable amplitude tests. Comparisons of the predictions with experimental results show that the developed methodology correctly predicts the failure location. It also provides reasonably accurate estimates of the fatigue initiation life.

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## INTRODUCTION

Elastomeric components have a wide usage in many applications especially at automotive industry and their field of application has broadened in recent years. Car tires, bumper components, engine mounts and cradle mounts are some of the examples. Rubber mounts are typically used as vibration isolators in vehicles. Their function is damping high-amplitude and low frequency road induced vibrations in cradle mounts and low-amplitude high frequency engine induced vibrations in engine mounts. Most of these components typically operate under repeated loads over a period of time which makes them prone to fatigue failure. Therefore, it is necessary to deal with durability and fatigue failure aspects of elastomeric components and fatigue life evaluation is an important consideration in their design to assure their safety and reliability.

Several inputs are necessary for fatigue life prediction of elastomeric components. These are relevant material

properties, loading history and the component geometry. For fatigue analysis, first stress and/or strain history at critical location(s) of the component could be obtained via finite element analysis. Then, using the obtained history, a proper fatigue damage quantification parameter and a cumulative damage rule are needed to predict the fatigue life.

The elastomer's material behavior is complex due to high deformability, quasi incompressibility, stress softening, and time-dependent effects. Therefore, a reliable analysis must include these characteristics. Also, properties of rubber can change drastically depending on material composition, manufacturing conditions, loading condition and environmental conditions. Mars and Fatemi discussed the aforementioned effects in detail in [1].

Mars and Fatemi [2] performed a literature survey on different approaches of fatigue analysis for rubber. They classified fatigue failure process into two distinct phases, crack initiation phase in which crack nucleates in part of the material that was initially crack free, and crack growth phase

in which the initiated cracks grow to failure or rupture. They mentioned that maximum principal strain and strain energy density are two broadly used fatigue damage quantification parameters for the crack initiation stage.

Li et al. [3] performed fatigue life prediction of a rubber mount by using the maximum principal strain at the critical region obtained from FEA as a fatigue damage parameter. To verify their analysis, they conducted constant amplitude load-controlled fatigue experiments in directions perpendicular to the mount axial direction. Their results showed good agreement with the predicted fatigue lives.

Kim et al. [4] used the maximum Green-Lagrange strain and the maximum energy density as fatigue damage parameters for life predictions in another study on an engine rubber mount. They obtained material fatigue-life equations from fatigue experiments of dumbbell-shaped specimens. Then by utilizing FEA, a load versus Green-Lagrange strain relation was determined. They concluded that the Green-Lagrange strain is a better fatigue damage parameter than the strain energy density for component life predictions based on their load-controlled constant amplitude fatigue tests of rubber engine mount.

Woo et al. [5] studied the fatigue life of natural rubber components and used the Green-Lagrange strain at a critical location for damage evaluation. To validate their analysis, displacement-controlled fatigue tests with different values of mean displacement and amplitude were conducted. Their experimental results showed reasonable results compared to the predictions.

Luo and Wu [6] conducted fatigue failure analyses of rubber springs, which are widely used as anti-vibration components. Their study showed the capability of nonlinear quasi-static FE simulation for modeling geometric and material nonlinearities of elastomeric components in product design and failure analysis. They analyzed fatigue life of anti-vibration rubber springs used in a rail vehicle suspension system [7,8,9]. Mooney-Rivlin hyper-elastic material model and FEA were used in their study to obtain the stress contour. By using the S-N curve obtained from uniaxial loading, they performed fatigue life predictions and proposed a three-dimensional effective stress criterion describing an ellipsoidal failure envelope for fatigue failure based on principal stress values. They conducted fatigue tests on two types of rubber springs in the longitudinal direction under uniaxial loading and their experimental results indicated good agreement with the predictions for both crack initiation location and direction [9].

Zhao et al. [10] studied a rubber mount using a FEA method. They found that the main reason for fatigue cracking was the stress concentration at the interfaces between the rubber and metal layers. This was also observed in their constant amplitude mount fatigue testing. They then modified the geometry of the mount and changed the shape of the inner bushing by dig grooving in the rubber layers which resulted in a reduction of maximum equivalent strain due to lower stress concentration and, therefore, improved fatigue life.

Kim et al. [11] performed a study on fatigue life prediction of automotive rubber components under variable amplitude loading. They conducted fatigue testing in displacement control and used the maximum Green-Lagrange strain as a damage parameter for analysis. The SAE transmission load history [12] was used in their study. The relationship between displacement and fatigue life was generated by fatigue testing of dumbbell specimens in displacement control. By utilizing the Odgen strain energy density function and FEA, they related the maximum Green-Lagrange strain at the critical component location to displacement, and subsequently to fatigue life. The complex load history was simplified by using the racetrack cycle counting method. Their results which were obtained based on Miner's linear damage rule indicated fairly good agreement, with a factor of two correlation between the predicted and the experimental fatigue lives.

Andre et al. [13] conducted torsion experiments on rubber specimens with an axisymmetrical notched geometry. They concluded that the maximum principal Cauchy stress is related to multiaxial fatigue damage mechanisms and proposed that this parameter could be used as a fatigue damage quantification parameter. They also observed that the crack orientation was perpendicular to the maximum principal stress direction.

A crack initiation approach which is used in this current study is normally related to the macroscopic continuum mechanics quantities such as stress or strain. The maximum principal Green-Lagrange strain, the maximum principal Cauchy stress, and the strain energy density (SED) are some examples of the parameters which are typically used for this approach. Critical plane approaches such as the cracking energy density (CED) or the approaches based on configurational mechanics such as Eshelby stress tensor [such as in 15] are more complex and recent approaches which are appropriate to deal with multiaxial fatigue analysis of elastomers. However, the maximum principal Green-Lagrange strain criterion introduced by Cadwell et al. [13] still remains one of the most widely used criteria. The commonly used parameter of strain energy density (SED) has some drawbacks including inability to differentiate between simple tension and compression, therefore, inability to account for crack closure. SED criterion cannot account for the fact that all of the stored energy in the material would not release due to crack growth [16].

Mars and Fatemi [17] showed that scalar equivalence criteria were not capable of predicting the fatigue initiation life in natural rubber and suggested using the cracking energy density (CED) which is the portion of the strain energy density that is available to cause crack growth on a particular plane. The application of this method needs knowledge of the constitutive behavior of the material. In another study Harbour et al. [18] used the maximum normal strain to find the critical plane and then the cracking energy density on that plane as a damage quantification parameter to determine fatigue life. Their results showed similar fatigue life

predictions compared to cracking energy density. Because of the fact that maximum normal strain is independent of constitutive behavior, the critical plane can be identified easier than when using the CED.

The main objectives of this study was using CAE durability analytical techniques for predicting crack initiation life of an automotive cradle mount and validate the results under different constant and variable amplitude uniaxial and multiaxial loadings. The capabilities of the rainflow cycle counting procedure and Miner's linear damage rule are also evaluated with component testing. A filled natural rubber material with 21% carbon black and 9.5% plasticizer was used in manufacturing of the cradle mount used.

In this paper, the cradle mount and FE modeling aspects are first presented. Then the experimental work conducted on the component is discussed. Finally, life predictions based on the developed methodology involving cycle counting, cumulative damage, and damage parameter is presented in terms of correlations between the predicted and the experimental results. This methodology relates the fatigue properties obtained from material specimens under constant amplitude fatigue tests to service loading conditions. An optimum method for crack initiation life prediction is also described.

## CRADLE MOUNT FINITE ELEMENT MODELING

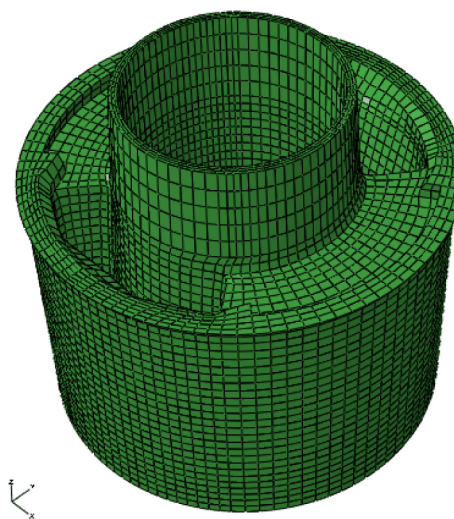
The rubber component evaluated was a cradle mount in a vehicle. Component geometry is shown in [Figure 1\(a\)](#). The nonlinear FE program ABAQUS was used to simulate the nonlinear and large deformation behavior of the mount made of hyper-elastic rubber material. The FE mesh is shown in [Figure 1\(b\)](#) with a relatively fine mesh of about 30,000 elements to adequately model the geometry. Three-dimensional eight node brick (hexahedral) elements with an approximate size of  $1\text{ mm} \times 2\text{ mm} \times 2\text{ mm}$  were used in this model. Fully hybrid formulation elements with full integration [19] were used for large deformations due to lower distortion [20]. The output stress was from the integration point of the element, therefore, an averaged quantity in the element.

The Marlow strain energy density form was used to characterize deformation of incompressible isotropic elastomers in the software. In order to simulate a load cycle efficiently for fatigue loading, the “amplitude” tool of the FE software was used. Stable deformation curve for the material used in manufacturing the cradle mount was obtained by incremental step tests conducted on a simple tension specimen geometry. Significant softening was observed during initial straining cycles due to Mullin's effect. However, this behavior was stabilized after about 20 cycles. The stable loops at different strain levels are shown in [Figure 2](#) [21]. These tests were conducted at frequencies between 0.03 and 0.1 Hz, depending on the applied stress range. Primary hyper-elastic curve is constructed by fitting peak

strain and peak stress points of the different stabilized hysteresis loops [22], as shown in [Figure 2](#). Cyclic stable deformation curve was applied as an input to the model, therefore initial softening was inherently considered.



(a)



(b)

**Figure 1. (a) Vehicle cradle mount used and, (b) FE model mesh.**

To model the hyper-elastic behavior of the rubber as a highly non-linear elastic material with incompressibility, strain energy potential is typically used. Strain energy potential defines the strain energy stored at a point as a function of the strain at that point assuming the material is isotropic and homogeneous. In the case of Marlow form which was used in this study, strain energy potential is