Useful Life time Evaluation and Prediction for Automotive Rubber Mount

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Abstract. Fatigue lifetime prediction and evaluation are the key technologies to assure the safety and reliability of automotive rubber components. The objective of this study is to develop the durability analysis process for vulcanized rubber components, which is applicable to predict fatigue lifetime at initial product design step. Fatigue lifetime prediction methodology of vulcanized natural rubber was proposed by incorporating the finite element analysis and fatigue damage parameter of maximum Green-Lagrange strains appearing at the critical location determined from fatigue test. In order to develop an appropriate fatigue damage parameter of the rubber material, a series of displacement controlled fatigue tests was conducted using 3-dimensional dumbbell specimens with different levels of mean displacement. It was shown that the maximum Green-Lagrange strain was a proper damage parameter, taking the mean displacement effects into account. Nonlinear finite element analyses of rubber mount and 3-dimensional dumbbell specimens were performed based on a hyper-elastic material model determined from the uniaxial tension, equi-biaxial tension and pure shear test. Fatigue lifetime prediction of rubber mount was made by incorporating the maximum Green-Lagrange strain values, which was evaluated from the finite element analysis and fatigue tests, respectively. Predicted fatigue lives of the rubber component showed a fairly good agreement with the experimental fatigue lives. Fatigue analysis procedure employed in this study could be used approximately for the fatigue design.

Introduction

Rubber's ability to withstand very large strains without permanent deformation or fracture makes it ideal for many applications. Applications include vibration isolators, seals, structural bearing, to name a few[1]. These applications impose large static and time-varying strains over a long time. Long-time durability is therefore a critical issue. While many factors contribute to long-time durability, mechanical fatigue, the nucleation and growth of cracks in the rubber, is often the primary consideration[2,3]. To address the issue effectively and economically, engineers need to model and design for mechanical fatigue early in the product development process. Most of rubber components are subjected to static and dynamic loadings in service[4]. To prevent failures during operation is one of the critical issues in rubber component design[5,6]. Therefore, fatigue analysis and lifetime evaluation are very important in design procedure to assure the safety and reliability of mechanical rubber component. In order to get the excellent result of fatigue lifetime and have the short time test cycles, we expected the development of new method of fatigue test. As result, we have studied to obtain the new fatigue test, which is able to expect the fatigue lifetime for rubber component, by using of correlations with actual vehicle parts by conventional fatigue test, at the stage of material development test.

This paper show the fatigue test by newly designed test piece, which is supposed to simulate actual parts strain by finite element analysis method, and also show the relationship between test piece fatigue life and actual parts. Fatigue lifetime evaluation of rubber components has hitherto relied mainly on a real load test, road simulator test or bench fatigue test. Although above methods have advantages in accuracy of fatigue life, but cannot be used before the first prototype is made and the fatigue test should be always conducted whenever material or geometry changes are made[7]. In order to predict the fatigue life of the rubber components at the design stage, a simple procedure of life prediction is suggested in Fig. 1. Fatigue lifetime prediction methodology of vulcanized natural rubber was proposed by incorporating the finite element analysis and fatigue damage parameter determined from fatigue test. In this paper, rubber mount for automobile, which is damaged by repeated loading during operation, is selected for a typical application of fatigue life prediction methodology developed in the research. Uniaxial tension, equi-biaxial tension and pure shear test were conducted to determine the nonlinear material constants of the rubber components[8]. The maximum Green-Lagrange strain of 3-dimensional dumbbell specimens and rubber mount were obtained from the nonlinear finite element analysis using the hyper-elastic material model determined from the material tests. Fatigue tests of 3-dimensional dumbbell specimens with various mean strains were performed, and a fatigue life curve equation represented by the maximum Green-Lagrange strain was obtained. Fatigue lifetime prediction of rubber mount was made by incorporating the maximum Green-Lagrange strain values, which was evaluated from the finite element analysis and fatigue tests, respectively. Predicted fatigue lives of the rubber component showed a fairly good agreement with the experimental fatigue lives. Therefore, fatigue lifetime estimation procedure employed in this study could be used approximately for the fatigue design of the rubber components at the early design stage.

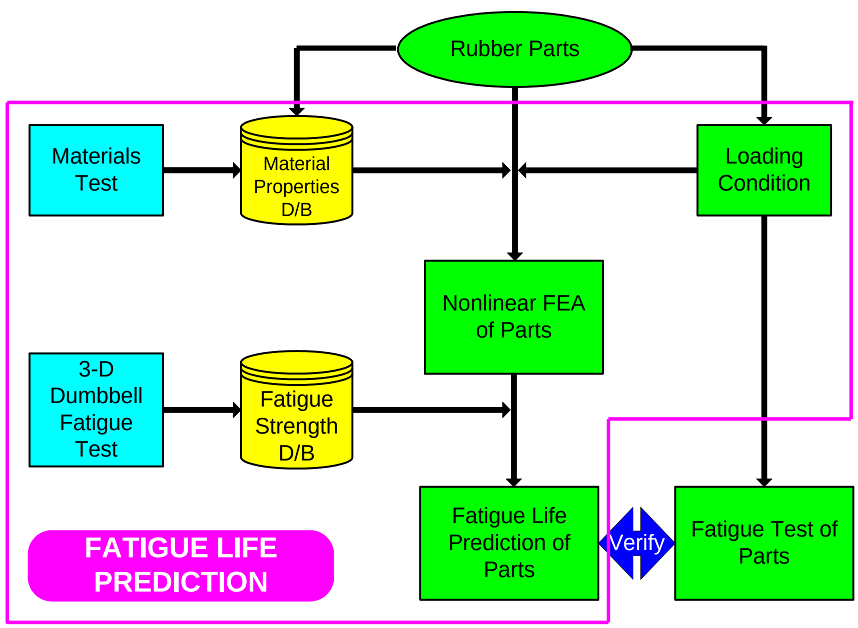


Fig.1. Procedure to fatigue life prediction system

Experiment

The rubber material property, which is essential in finite element analysis, is expressed with the coefficient values of strain energy function and these values are determined by fitting stress-strain data obtained from the material tests under various load conditions into the stress-strain curve induced from strain energy function. And it is determined to minimize the differences between the test values and calculated values. Therefore, we analyzed the property of the material and determined the nonlinear material coefficient, which is necessary in finite element analysis, by conducting uniaxial, equi-biaxial tension and pure shear test. Mechanical test was loaded by a universal testing machine at a speed of 100mm/min, and the deflection was measured using a laser extensometer in Fig. 2. Ten loading and unloading cycles were applied for each strain level, and strain levels were progressively increased to the maximum value. According to Fig. 3, the stress-strain curves during the second repetition showed a greater decline than in the first repetition. The stress-strain curve gradually decreased as the number of repetitions increased, and ultimately stabilized to a fixed stress-strain value, which is known as Mullin's effect[9]. In order to predict the behavior of the rubber components using the finite element analysis, the rubber material constants must be determined from the stabilized cyclic stress-strain curve. The stress-strain curve varies significantly depending on the cyclic strain levels. A 5^{th} loading cycle was selected as the stabilized stress-strain relationship in this study. But this stabilized relation should be shifted to pass through the origin of the curve, to satisfy the hyper-elastic nature of rubber. Fig. 4 shows the stress-strain relation of rubber material for various mechanical tests. The shift of curve meant that the gage length and initial cross sectional area were changed as shown in Eq. (1).

$$\varepsilon = \frac{\varepsilon' - \varepsilon_p}{1+\varepsilon_p} \qquad \sigma = \sigma'(1+\varepsilon_p) \tag{1}$$

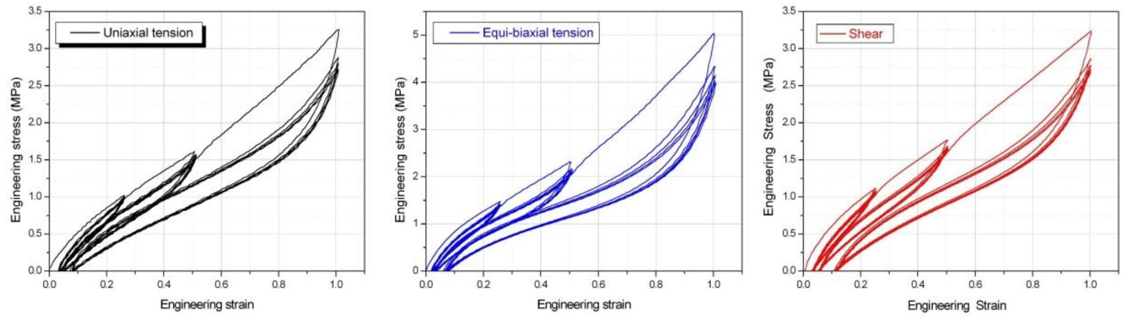
We performed the curve fitting with uniaxial tension, equi-biaxial tension and pure shear test data. Mooney-Rivlin 2-terms and Ogden 3-terms fits that uses progressively more information as the basis for the curve fitting. Table 1 contains the values of rubber material coefficient calculated in each case.

Table 1. Mooney-Rivlin and Ogden function of rubber material

Strain	Mooney-Rivlin 2-terms			Ogden 3-terms						
	C_{10}	C_{01}	GM	μ_1	α_1	μ_2	α_2	μ_3	α_3	GO
25%	0.889	0	1.779	1.1e-4	2.291	0.968	3.710	4.5e-4	3.081	1.796
50%	0.772	0	1.543	2.0e-5	1.030	2.140	1.3e-6	1.182	2.602	1.532
100%	0.723	0.009	1.463	0.028	4.391	5.813	0.031	0.953	2.593	1.390

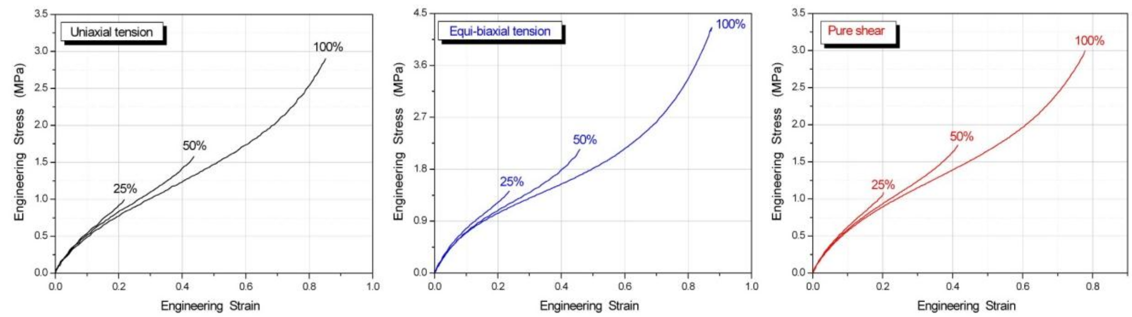
(a) Uniaxial tension test (b) Equi-biaxial tension test (c) Pure shear test

Fig.2. Mechanical test of rubber material



(a) Uniaxial tension (b) Equi-biaxial tension (c) Pure shear

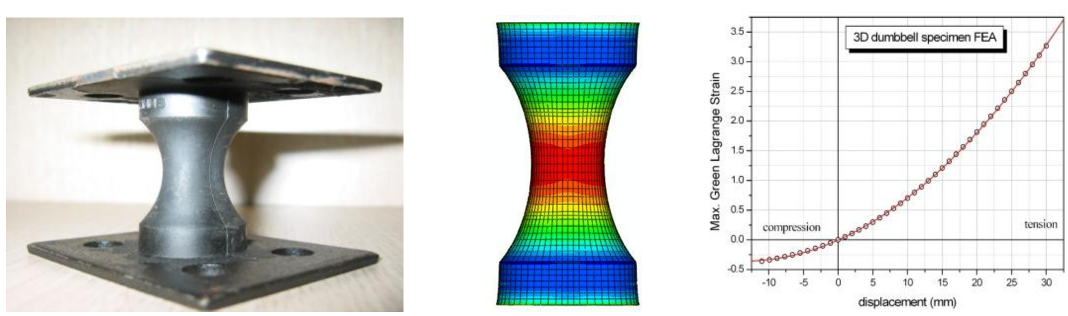
Fig.3. Stress-strain curve at various loading and strain range



(a) Uniaxial tension (b) Equi-biaxial tension (c) Pure shear

Fig.4. Stabilized stress-strain curve and shift curve to zero

The fatigue test piece has the basic shape of the 3-dimensional dumbbell specimen with a metal fitting cure bonded to each end. The geometry of the central part of the cylinder was designed to meet the following criteria in relation to fatigue test data for rubber components and strain distribution profile. It should have a smooth strain distribution and the position at which maximum tensile strain develops should be the same for any deformation. The 3-dimensional dumbbell specimen has an elliptical cross-section and parting lines are located on the minor axis of specimen to avoid undesirable failure at the surface discontinuities. The basic geometry of the test piece for materials fatigue testing is shown in Fig. 5(a). The following finite element analysed strain in terms of maximum tensile and compression strain using finite element analysis software to select the geometry of the curvature and central portion of the test piece. Strain was calculated using the Green-Lagrange strain. Fig. 5(b) and (c) shows the strain distribution according to FEM analysis from 3-dimensional dumbbell specimen in compression and tension[10]. Maximum Green-Lagrange strain was found to develop at a constant position in the surface at the centre of the rubber part of the test piece in both compression and tension.

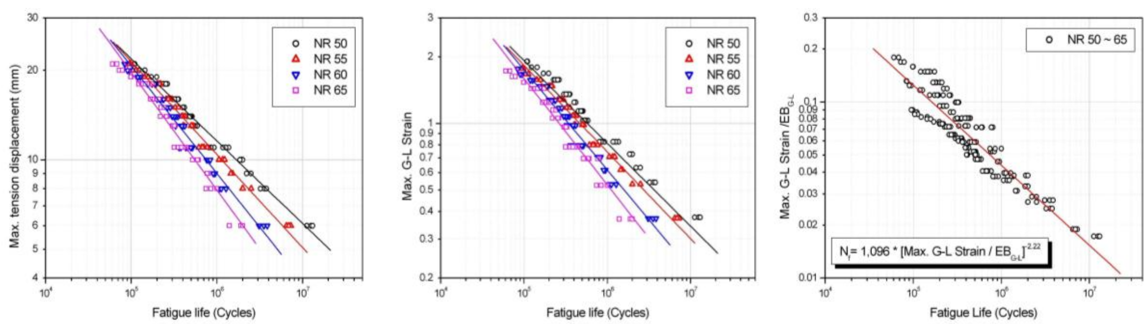


(a) Fatigue test specimen (b) FEM model (c) Displacement-strain curve

Fig.5. Three dimensional fatigue test specimen

In order to evaluate a fatigue damage parameter of the natural rubber material and to determine the experimental fatigue life, fatigue tests of 3-dimensional dumbbell specimens were performed using the fatigue testing system. The material used in this study is a carbon-filled vulcanized natural rubber, which have the hardness of the International Rubber Hardness Degree 50, 55, 60, 65(NR50, NR55, NR60, NR65). Fatigue tests were conducted in an ambient temperature under the stroke-controlled condition with a sine waveform of 5 Hz and the mean displacement is 0, 3, 5, 8, 10mm at the displacement range is -11~21mm. The fatigue failure was defined as a number of cycles at which the maximum load dropped by 20 percent. As increasing the cycles in initial phase, the maximum load decreased little by little. When the crack grew over the critical size, the maximum load decreased suddenly and the final failure reached. Fig. 6(a) shows the relationship between the maximum tension displacement and fatigue life of 3-dimensional dumbbell specimen. The fatigue life decreased as the maximum tension displacement increases. It is possible to express the fatigue life with the maximum tension displacement fairly good. Relationship between the applied displacement and corresponding Green-Lagrange strain of 3-dimensional dumbbell specimen are obtained from the finite element analysis and shown in Fig. 5(c). Fatigue lives of the 3-dimensional dumbbell specimen represented by the maximum Green-Lagrange strain parameter ($\varepsilon_{\text{G-L}}$) are shown in Fig. 6(b). By using the fatigue test and finite element analysis, the normalized maximum strain defined as dividing by elongation at break (ε_{EB}) for the maximum Green- Lagrange strain ($\varepsilon_{\text{G-L}}$) for each hardness. Fig. 6(c) shows relation of normalized maximum strain and fatigue life. It was observed that the maximum G-L strain was a good parameter to account for the hardness, mean displacement, amplitude effects. Fatigue lives of the 3-dimensional dumbbell specimen represented by the maximum G-L strain and elongation at break are shown in Eq. (2). The fatigue lives effectively represented by a single function using the maximum G-L strain and elongation at break for each natural rubber materials.

$$N_f = 1{,}096 \cdot [\varepsilon_{G-L} / \varepsilon_{EB}]^{-2.22} \tag{2}$$

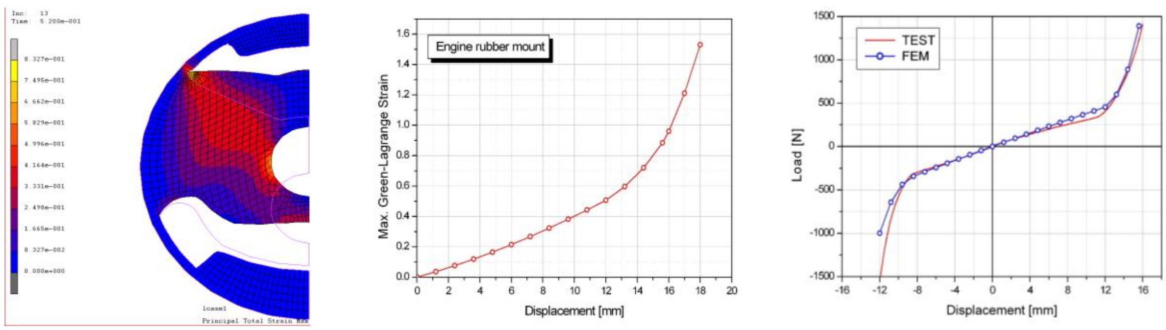


(a) Maximum displacement (b) Maximum G-L strain (c) Life prediction curve

Fig.6. Maximum displacement and G-L strain versus cycles to failure

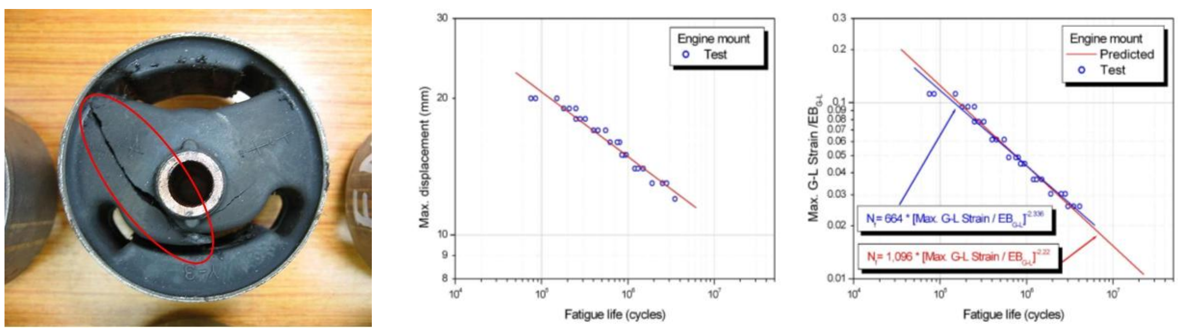
Fatigue Lifetime Prediction and Evaluation

The methodology was applied to the fatigue lifetime estimation of the rubber mount. Finite element analysis was performed to investigate the deformation behavior of rubber component. Material constants representing the Ogden strain energy potential of order 3 was used for defining a constitutive relation of the natural rubber. Fig. 7 shows the Green-Lagrange strain distribution of rubber mount under a tensile displacement. The maximum Green-Lagrange strain at the critical location was used for evaluating the fatigue damage parameter of rubber mount. Static and fatigue test were performed using a servo-hydraulic fatigue testing system. Load-displacement curve is very similar to correlation between test and FEM. Maximum Green-Lagrange strain occurred at the location as indicated in Fig. 8, and fatigue cracking at the critical location was observed during the fatigue test of rubber mount. Correlation between the fatigue test life and predicted life of rubber mount using the normalized maximum strain is shown in Fig. 8(c). The predicted fatigue lives of the rubber engine mount agreed fairly well with the experimental fatigue lives.



(a) Finite element analysis (b) G-L strain versus displacement (c) Test and FEM

Fig.7. Green-Lagrange strain distributions of engine rubber mount



(a) Fatigue failure (b) Displacement-fatigue life (c) Predicted and test lifetime

Fig.8. Fatigue lifetime evaluation of engine rubber mount

Conclusion

In this paper, to develop the durability analysis process for vulcanized rubber components, which is applicable to predict fatigue life at initial product design step, methodology to extract the material properties for finite element analysis input data from limited minimum test results was proposed. Also, in order to investigate the applicability of commonly used fatigue damage parameters, fatigue tests and corresponding finite element analyses were carried out and optimum fatigue damage parameter was selected. Fatigue lifetime prediction methodology of the rubber components was proposed by incorporating the finite element analysis and fatigue damage parameter. The fatigue life of rubber material was effectively represented by the maximum Green-Lagrange strain. Predicted fatigue lives of the rubber component were in fairly good agreements with the experimental lives. Therefore, fatigue life estimation procedure employed in this study could be used approximately for the fatigue design of rubber components at the early design stage.

Acknowledgements
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