Durability Analysis Process for Vulcanized Rubber Component

C. S. Woo[1*], H. Y. Park[1], W. D. Kim[1], S. I. Moon[2]

[1]*Korea Institute of Machinery and Materials, 104 Sinseong-ro, Yuseong-gu, Daejeon, 305-343, Korea*
[2]*Korea Atomic Energy Research Institute, 1045 Daedeok-ro, Yuseong-gu, Daejeon, 305-353, Korea*
**cswoo@kimm.re.kr*

Keywords: Rubber component, FEM, Fatigue damage parameter, Fatigue life prediction.

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. In order to develop an appropriate fatigue damage parameter of the rubber material, a series of displacement controlled fatigue tests was conducted using three dimensional dumbbell specimens with different levels of mean displacement. Fatigue analysis procedure employed in this study could be used approximately for the fatigue design.

1 Introduction

Rubber component have been widely used in automotive industry as anti-vibration component for many years. These subjected to fluctuating loads, often fail due to the nucleation and growth of defects or cracks. To prevent such failures, it is necessary to understand the fatigue failure mechanism for rubber materials and evaluate the fatigue life for rubber components. For these reasons, not only the rubber component manufacturers but also their customers like automotive makers perform a series of strict fatigue test on the components such as component fatigue tests and driving fatigue tests. Currently, designers rely on their own trial-error based experiences for the fatigue design. Thus, those designs depending on only experience may result in disqualification from the fatigue test during final product evaluation. Those fatigue failures of any new designs are prohibitive for automotive manufacturers. In order to avoid this problem, many researchers [1,2,3] are focusing on evaluation of fatigue life using CAE techniques that could supplement drawbacks of evaluation through tests and could significantly reduce the time for fatigue-proof design. However, there are some following problems. First, the rubber materials show particular mechanical properties according to compounding ingredients and manufacturing conditions [4,5]. Therefore, in order to evaluate the fatigue life of designed rubber components, the material properties of the components should be obtained. It is practically impossible to measure the material properties for the whole component. Second, some parameters like stress, strain, SED (Strain Energy Density) and so on are generally used to estimate fatigue life of rubber components [6] but the question remains how we should use these parameters to estimate component life and what the limitation of the parameters is. The objective of this paper is to develop the durability analysis process for vulcanized rubber components, which is applicable to predict fatigue life at initial product design step. Fig. 1 is a schematic diagram showing the fatigue life evaluation procedure. The fatigue damage parameters such as principle strain, SED and so on, which are calculated by FEA (Finite Element Analysis), and the fatigue properties of the material are used in order to estimate the fatigue life of rubber components. For this, in this paper, the methodology to extract the material properties for finite element analysis input data from limited minimum test results was proposed. Then, fatigue tests and corresponding finite element analyses were carried out so as to investigate the applicability of commonly used fatigue damage parameters, and optimum fatigue damage parameter was selected. Also, the fatigue analysis for automotive rubber components was performed.

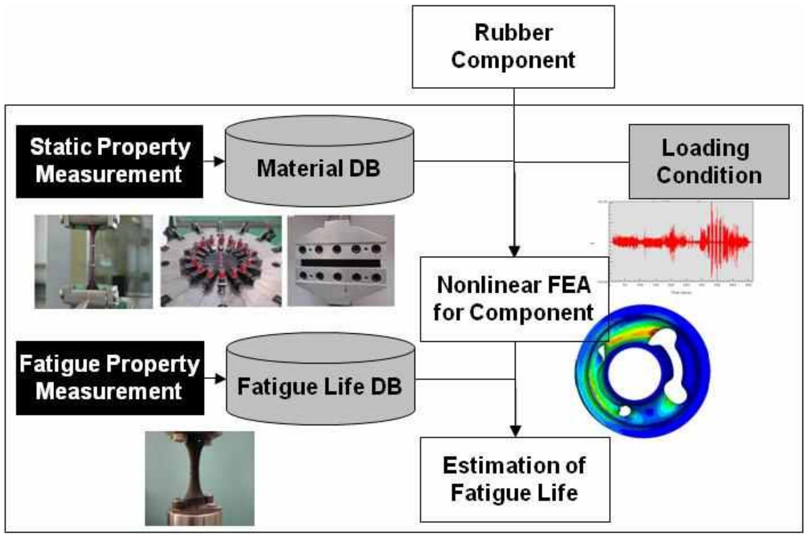


Figure 1. Fatigue lifetime prediction procedure.

2 Measurement of material property and fatigue test of component

2.1 Non-linear material constants for hyper-elastic material

The material of the rubber component is taken to be an incompressible rubberlike material modeled as a hyper-elastic material. The constitutive behavior of a hyper-elastic material is defined as a total stress–total strain relationship. Hyper-elastic materials are described in terms of a strain energy potential, which defines the strain energy stored in the material per unit of reference volume as a function of the strain at that point in the material. The strain energy functions have been represented either in term of the strain invariants that are functions of the stretch ratios, or directly in terms of the principal stretch. Successful modeling and design of rubber components relies on both the selection of an appropriate strain energy function and an accurate determination of material coefficient in the function. Material coefficient in the strain energy functions can be determined from the curve fitting of experimental stress-strain data. There are several different types of experiments, including simple tension, equi-biaxial tension and pure shear test. In general, a combination of simple tension, equi-biaxial tension and pure shear tests are used to determine the material coefficient. The classical Mooney-Rivlin and Ogden model are an example of a hyper-elastic model that is implemented in finite element analysis [7,8]. In order to explain the deformation of the rubber materials, it is assumed that the material has elastic behavior and is isotropic. Then, strain energy function (W) can be written as Eq. (1), with strain invariant function $(I_1,\ I_2,\ I_3)$ and principal stretch function $(\lambda_1, \lambda_2, \lambda_3)$.

$$W = W(I_1,\ I_2,\ I_3),\quad W = W(\lambda_1,\lambda_2,\lambda_3) \tag{1}$$

When the material is isotropic, I_1, I_2, I_3 can be expressed as follows;

$$\begin{aligned} I_1 &= \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \\ I_2 &= \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \\ I_3 &= \lambda_1^2\lambda_2^2\lambda_3^2 \end{aligned} \tag{2}$$

Most rubber materials are incompressible and its bulk modulus is much greater than its shear modulus. Thus, it is widely accepted to presume the materials to be incompressible when they are under less restriction. When the materials are incompressible in Eq. (2), $\lambda_1, \lambda_2, \lambda_3$ = 1 and $I_3 = 1$. Since, Eq.(1) can be rewritten as follows,

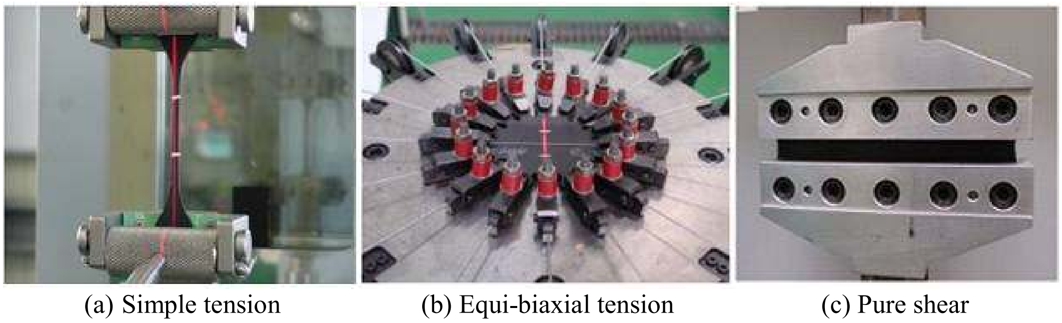
$$W = W(I_1,\ I_2) \tag{3}$$

Strain energy function, which is widely used to analyze deformation of incompressible materials, can be described with Mooney-Rivlin's function and Ogden's function.

Mooney-Rivlin's function: $W = \sum_{n=1}^{N} C_{ij}(I_1 - 3)^i (I_2 - 3)^j$ (4)

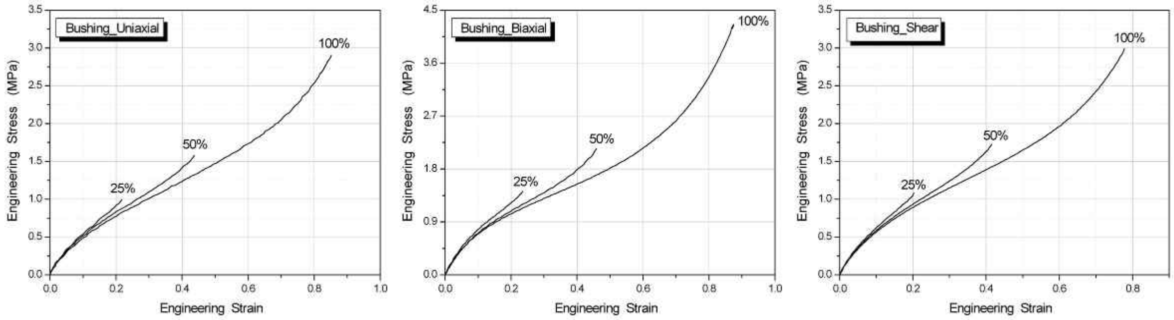
Ogden's function: $W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n}(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3)$ (5)

Here, I_1 and I_2 are first and second strain invariant, respectively, and C_{ij}, μ_n, α_n are the material constants determined from the stress-strain relationship between simple tension test, equi-biaxial tension test and pure shear test results. Three basic tests for strain states, simple tension, equi-biaxial tension and pure shear test, were carried out and the strain levels were progressively increased up to the maximum value, 1.0. For the mechanical tests, UTM (Universal Test Machine) was used at a speed of 100mm/min, and deflection was measured using a laser extensometer in Fig. 2. Fig. 3 is the stress-strain curves for each stress state and equi-biaxial tension, pure shear and simple tension arrange in order of stiffness magnitude. The non-linear material constants were determined through curve fitting for these stress-strain curves and Table 1 shows the non-linear material constant of Mooney-Rivlin function for suspension bush.



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

Figure 2. Nonlinear material constant test.



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

Figure 3. Stress-strain curve.

Strain Range	C_{10}	C_{01}	$2(C_{10}+C_{01})$
25%	0.901	0	1.802
50%	0.781	0	1.562
100%	0.727	0.001	1.468

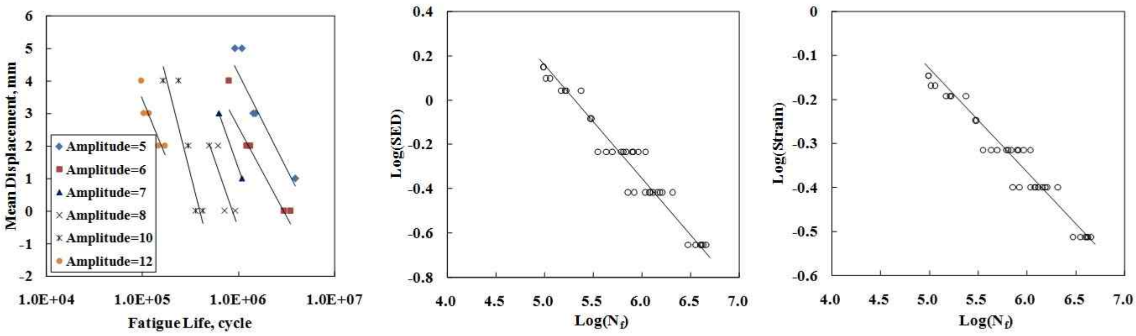
Table 1. Non-linear material constant of Mooney-Rivlin function for suspension bush.

2.2 Fatigue property of rubber material

The fatigue test piece has the basic shape of the three 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. The test piece should be capable of compression and tensile deformation without developing slackness under cyclic deformation. It should have a smooth strain distribution and the position at which maximum tensile strain develops should be the same for any deformation. The three 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. 4(a). In order to determine a fatigue damage parameter of the rubber material and fatigue life, fatigue tests using three dumbbell specimens were conducted. Fatigue tests were carried out in ambient temperature under the displacement controlled condition with a sine waveform of 3 Hz. The mean displacement varies from 0 mm to 5 mm and the amplitude displacement ranges from 3 mm to 12 mm. With increase of cycles in fatigue test, the maximum load decreased little by little. When the crack grew over the critical size, the maximum load suddenly decreased, and the specimen was finally fractured. In this paper, it was assumed that fatigue failure occurs when the maximum load drops up to 20 % level of initial maximum load. Fig. 5(a) shows the relationship between the mean displacement and the fatigue life for three dimensional dumbbell specimens. The fatigue life was reduced as the mean displacement and amplitude displacement increase. To determine the relationship between fatigue damage parameters and the fatigue life, the deformation behavior of the dumbbell specimen was estimated by using 3D finite element analysis and ABAQUS Ver. 8.0 package was used for the finite element analysis. Fig. 4(b) shows a finite element mesh of the 3D dumbbell specimen. A eighth of the specimen was modeled by considering the symmetry condition and the mesh was constructed with using 8-node linear brick, hybrid elements. It was assumed that fatigue life was determined by the maximum value of fatigue damage parameters. [3] From a series of finite element analysis results and test results, the relationship between the fatigue life and the typical fatigue damage parameter, principle stain and SED, was obtained and presented in Fig. 5(b) and (c).

(a) Three dimensional dumbbel specimen (b) Finite element model

Figure 4. Fatigue specimen.



(a) Displacement-fatigue life (b) 1st Principle strain (c) Strain energy density

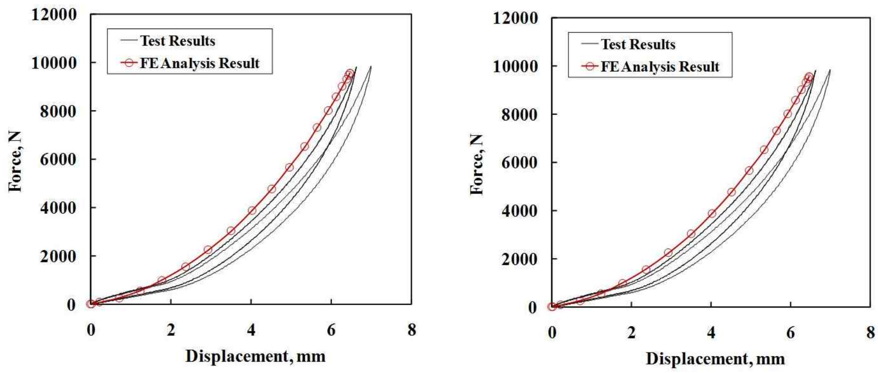
Figure 5. Damage parameter and fatigue life curves.

2.3 Characteristic and Durability tests for rubber component

To verify the validity of finite element analyses and durability analyses, static stiffness and fatigue life was measured by using a suspension bush for vehicle. Fig. 6 shows the suspension bush being used in the tests. The static stiffness was measured in three directions, void direction (P-direction) and bridge direction (Q-direction) and the durability test was performed under the condition presented in Table 2. The finite element analyses for the suspension bush were performed by using the non-linear material constants. The deformation behavior of the suspension bush was estimated by using finite element analysis and ABAQUS Ver. 8.0 explicit code was used for the analysis. Fig. 6(b) shows the finite element mesh for the suspension bush and was constructed with 10-node quadratic tetrahedron elements (C3D10M). It was assumed that the initial ratio of bulk elastic modulus to shear elastic modulus, K_0/μ_0, was 100. Fig. 7 depicts the load-displacement curves for the suspension bush. The estimated results showed a good agreement with experimental results within maximum difference of 15%.

(a) Loading condition (b) Finite element model (c) Tested specimen

Figure 6. Suspension bush specimen.



(a) P-direction (b) Q-direction

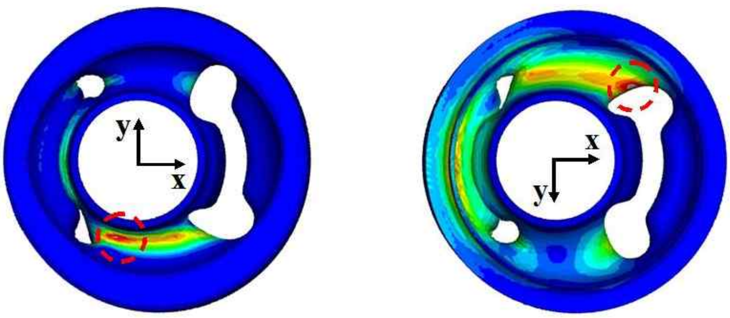
Figure 7. Load-displacement curves for the suspension bush.

Direction	Load	Frequency (Hz)
Radial *P*	*P*±5.5*P*	3.3
Torsion *θ*	*T*±1.2*T*°	3.3

Table 2. Loading condition for fatigue test

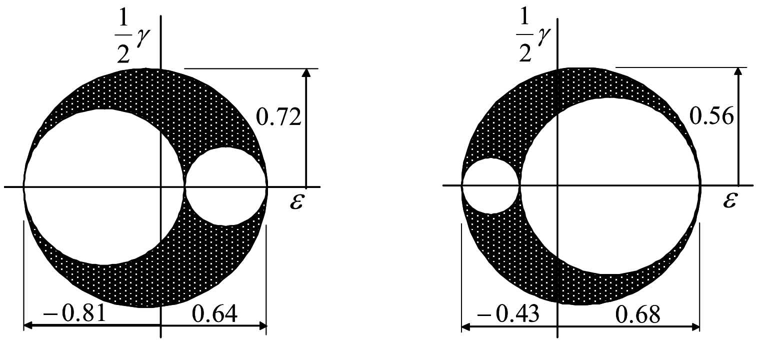
2.4 Determination of fatigue damage parameter

For fatigue life evaluation it is commonly considered not only crack nucleation but also crack growth. However, in the case of rubber component in vehicles, crack initiation is defined as failure because the mechanical characteristic of rubber can be changed, and the estimation for crack nucleation was focused in this study. The two widely used fatigue damage parameters for crack nucleation prediction in rubber components are maximum principle strain (or stretch) and SED. Stress has rarely been used as a fatigue damage parameter in rubber components [9]. The contour plots of strain energy density and first principle strain at maximum load were shown in Fig. 8. In this figure, we can see that the maximum points of the damage parameters are different each other. The maximum point of SED was identical to crack nucleation point observing from the fatigue life tests for the suspension bush. Consequently, it is thought that SED as fatigue damage parameter can be used for predicting the crack nucleation point. Fig. 9 shows the Mohr's circles for strain at the maximum points of SED and first principle strain, respectively. In this figure, it is known that the maximum shear strain appears at the maximum SED point but different from the maximum principle strain point. Hence, it was thought that to only use the first principle strain is not proper to estimate the failure of rubber components in case shear deformation dominantly influence the failure of rubber components.



(a) Strain energy density (b) 1st principle strain

Figure 8. Contour plots of strain energy density and principle strain.



(a) Maximum strain energy density point (b) Maximum principle strain point

Figure 9. Mohr's circle for strain.

2.5 Fatigue life prediction for rubber component

The fatigue life was calculated by using SED and first principle strain obtained from finite element analyses. The fatigue properties measured by using 3-D dumbbell specimens were used, and the relationship between fatigue life and fatigue damage parameters, SED and maximum principle parameter, was presented as follows.

$$N_f = 190{,}546(SED)^{-2.063} \quad (6)$$

$$N_f = 21{,}314(Strain)^{-4.521} \quad (7)$$

The fatigue life calculated by using SED and first principle strain was overestimated, and the fatigue life normalized with fatigue test results was 0.33 and 0.52, respectively. As stated above it is thought that these overestimated results are caused by shear deformation. SED is as a scalar quantity so that it does not predict crack nucleation appears in a specific orientation. Also, equi-biaxial tension fatigue life was longer than simple tension fatigue life by a factor of approximately 4, when compared based on equal strain energy density [8]. Therefore, it is not appropriate to evaluate the fatigue life of rubber components by using SED. Also, in case normal deformation is dominant in failure mode, the fatigue life can be estimated by using maximum principle strain as fatigue damage parameter [3, 5]. Thus, for the purpose of more accurate fatigue life, it is thought that both normal strain and shear strain should be considered, and fatigue properties for shear deformation are needed.

3 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 life prediction methodology of the rubber components was proposed by incorporating the finite element analysis and fatigue damage parameter. In case strain energy density was used as fatigue damage parameter, the crack initiation point was accurately predicted. In order to estimate more accurate fatigue life, both normal strain and shear strain should be considered, and fatigue properties for shear deformation are needed.

References

[1] Woo, C. S., Kim, W. D. and Kwon, J. D. "A Study on the Fatigue Life Prediction and Evaluation of Rubber Components for Automobile Vehicle," *Transaction of KSME*, **13**, No. 6, pp. 56~62 (2005)

[2] Kim, C. H., Kim, K. J., Jeong, H. T., Kim, C. W., Sohn, I. S. And Kim, J. B., "Prediction of Durability, Static and Dynamic Properties on Rubber," *Transaction of KSME*, **14**, No. 6, pp. 17~23 (2006).

[3] Woo, C. S., Kim, W. D. and Kwon, J. D., "A Study on the Material Properties and Fatigue Life Prediction of Natural Rubber Component," *Material Science and Engineering*, pp. 367~381 (2008).

[4] Kim, J. H., Jeong, H. Y., "A Study on the material properties and fatigue life of natural rubber with different carbon blacks," *Internal Journal of Fatigue*, **27**, pp. 263~272 (2005).

[5] Roberts, B. J. and Benzies, J. B., "The Relationship between Uniaxial and quibiaxial Fatigue in Gum and Carbon black filled Vulcanizates," *Proceedings of Rubbercon*, **2.1**, pp. 2.1~2.13 (1997).

[6] Mars, W. V., Fatemi, A., "A Literature Survey on Fatigue Analysis Approaches for Rubber," *International Journal of Fatigue*, **24**, pp. 949~961 (2002).

[7] GM, "Standard Test Methods for Vulcanized Rubber and TPE for Use in finite Element Analysis Modeling."

[8] Agyris, J.H, Dunne, P.C., Angelpoulos, T and Bichat, B., "Large Nature Strains and Some special difficulties due to Nonlinearity and Incompressibility in Finite Elements," *Comp. Meths in Appl. Eng*., **4**, pp. 219-278 (1974).

[9] Andre, N., Cailletaud, G. and Piques, R., "Haigh Diagram for Fatigue Crack Initiation Prediction of Natural Rubber Components," *Kautschuk Und Gummi dunstoffe*, **52**, pp. 120~123 (1999).