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Fatigue Life Prediction of Automotive Rubber Component Subjected to a Variable Amplitude Loading

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가변진폭하중에서의 자동차 고무 부품의 피로 수명 예측

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ABSTRACT : Fatigue life prediction methodology of the rubber component made of vulcanized natural rubber under variable amplitude loadings was studied. The displacement-controlled fatigue tests were conducted at different levels and the maximum Green-Lagrange strain was selected as damage parameters. A fatigue life curve of the rubber represented by the maximum Green-Lagrange strain was determined from the nonlinear finite element analysis. The transmission load history of SAE as variable amplitude loading was used to perform the fatigue life prediction. And then a signal processing of variable loading by racetrack and simplified rainflow cycle counting methods were performed. The modified miner's rule as cumulative damage summation was used. Finally, when the gate value is 30%, the predicted fatigue life of the rubber component agreed well with the experimental fatigue lives with a factor of two.

요 약 : 가변진폭 하중에서 고무부품의 피로수명 예측방법에 대하여 연구하였다. 서로 다른 변위에서 변위제어 피로시험을 수행하였으며 피로손상변수로 최대 Green-Lagrange 변형률을 선정하였다. Green-Lagrange 변형률에 의한 고무의 피로수명 곡선은 3차원 덤벨시편의 비선형 유한요소법을 이용하여 결정하였다. 피로수명 예측을 위하여 가변진폭 하중이력으로 SAE의 하중이력을 이용하였다. 레이스트랙법과 단순화된 레인플로집계법을 이용하여 하중이력신호를 축약하였다. 누적손상피로를 계산하는 방법으로 수정Miner 법칙을 이용하였으며, 최종적으로 하중이력신호에서 최대 진폭의 30% 이하를 노이즈로 간주하여 예측하였을 경우의 피로수명은 실제 가변진폭 하중 하에서의 피로시험결과와 비교적 잘 일치하였다.

Keywords : vulcanized natural rubber, 3D dumbbell specimen, fatigue life, variable amplitude history, cycle counting

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Ⅰ. Introduction

Rubber components are extensively used in many applications because of their large reversible elastic deformation, excellent damping and energy absorption characteristics.[1] Typical applications include engine mounts and tires for automobiles, and vibration isolators for household electric appliances and rubber bearings for bridges, etc. Most of these rubber components are subjected to static and dynamic loadings in service. To prevent failures during operation, fatigue prediction is one of the critical issues in rubber component design. Therefore, fatigue analysis and strength evaluation are very important in design procedure to assure the safety and reliability of mechanical rubber components.[2,3]

Fatigue strength evaluation of rubber components for automotive applications has relied mainly on a real load test, road simulation test or bench fatigue test. Although these methods have advantages in accurate fatigue life estimation, they cannot be used before the prototype is made and the fatigue test should be always conducted whenever material or geometry changes are made. Also, it needs that the fatigue test is performed under real load history to evaluate the fatigue life of the rubber component, but it cost too much.

Therefore, the fatigue life estimation using a fatigue life curve and a fatigue damage parameter which can be determined from specimen tests and component analysis, respectively, is needed for the fatigue design of the rubber components.[2,4,5,6]

In this study, we predict the fatigue life of a rubber component subjected to a variable loading, and then compare prediction result with the experimental result. The procedures are as follows.

The fatigue test of 3D dumbbell rubber specimens subjected to constant displacement amplitude is conducted in section 2. And then the relationship between displacement and Green-Lagrange strain is investigated from finite element analysis of 3D dumbbell specimen in section 3. In section 4, the process of reducing a variable load history into a number of constant amplitude events, cycle counting, was involved. Finally, the fatigue life was predicted using the damage rule.

Ⅱ. Experimental

1. Material and specimen

The natural rubber compound was prepared using NR (SMR CV60), carbon black (N762 and N550), cure activators (ZnO and stearic acid) and curative (sulfur) for this study. The total filler content was 60 phr and the filler compositions were N762/N550 = 20/40 phr. The formulation is given in Table 1.

The elastomer was molded into 3D dumbbell shaped solid cured as shown in Figure 1. The 3D dumbbell specimen has an elliptical cross section and parting lines are located on the minor axis of the specimen to avoid undesirable failure at the surface discontinuities.[6]

That is used for the fatigue damage evaluation of the natural rubber and prediction of fatigue life.

Table 1. Formulation of Compound

Ingredients	Content (phr)
NR (SMR CV60)	100.0
SRF (N762)	20.0
FEF (N550)	40.0
Stearic acid	1.0
ZnO	5.0
Sulfur	1.8

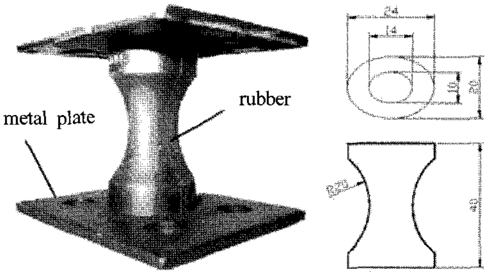


Figure 1. The 3D dumbbell specimen

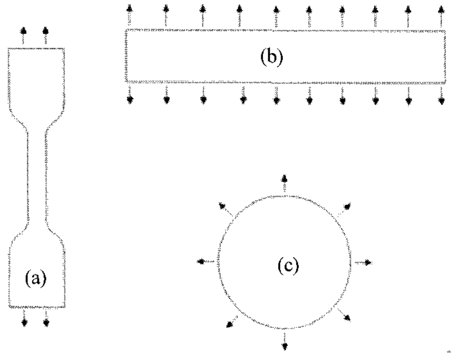


Figure 2. Simple tension(a), planar tension(b) and equi-biaxial tension(c) test results.

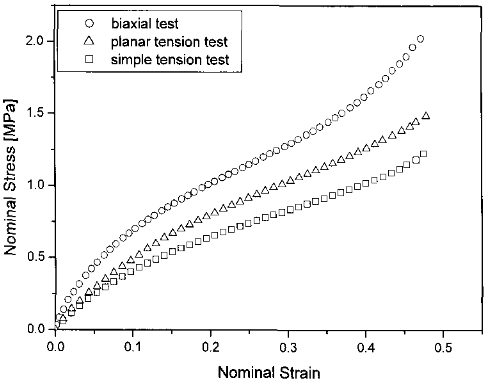


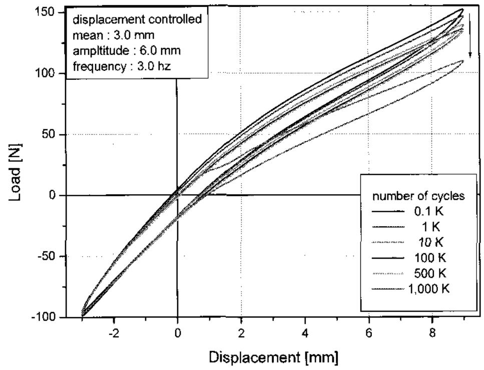
Figure 3. Simple tension, planar tension and equi-biaxial tension test results.

2. Static stress-strain relationship

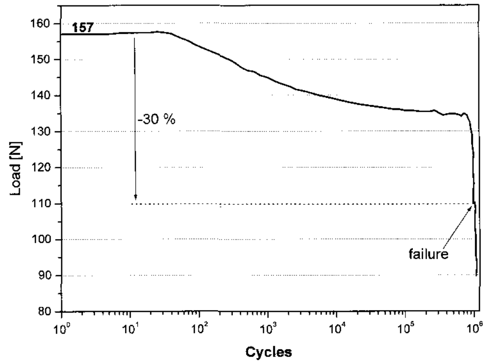
Three basic tests for strain states, namely, simple tension, planar tension and equi-biaxial tension tests were performed to characterize the material properties for finite element analysis in section 3. The schematic of basic tests was shown in Figure 2. From this, Figure 3 shows the stress-strain relations of the simple tension, planar tension and equi-biaxial test, respectively.

3. Fatigue tests of 3D dumbbell specimen

The uniaxial fatigue tests were performed on 3D dumbbell specimens to evaluate a fatigue damage parameter of the vulcanized natural rubber material.



(a) Load-displacement curves after 100, 1000, 10000, 100000, 500000, 1000000 cycles, respectively.



(b) Load-cycles relationship.

Figure 4. Stress softening response in the displacement controlled fatigue test with 3D dumbbell specimens.

Fatigue tests were conducted in an ambient temperature of 25℃ using a servo-hydraulic fatigue testing system. The controlled displacement is a sine waveform, frequency of 3~5 Hz, depending on the magnitude of maximum displacement from 6 to 18 mm, respectively. Load responses of each test specimen corresponding to applied displacement were periodically recorded as shown in Figure 4.

A continuous decrease of load in tensile direction was observed during the initial stage of the fatigue test of the 3D dumbbell specimen. This phenomenon can be expected from Mullins effect, which is a significant decrease in stiffness due to the stress softening of the rubber material during the first few cycles

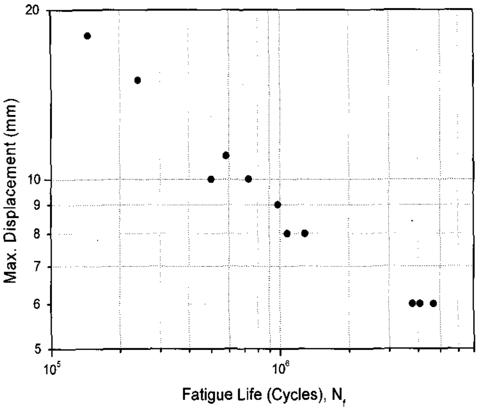


Figure 5. Scatter obtained from uniaxial displacement controlled fatigue test of 3D dumbbell specimens.

of repetitive loading.[7] The load-displacement response was stabilized after about 100. The crack initiation appears in the middle of the sample. The crack propagation of the 3D dumbbell specimen under the displacement-controlled condition would cause a decrease in tensile modulus cycles as shown in (a), (b) of Figure 4. Therefore, a fatigue life is defined as a number of cycles at which the tensile modulus of the 3D dumbbell specimen dropped by 30 % in this study.

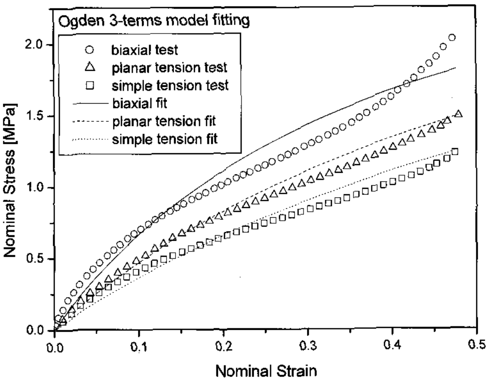
The relationships between the maximum displacement and fatigue life are shown in Figure 5, As shown, the fatigue life decreases with increased the maximum displacement.

Ⅲ. Finite element analysis

1. Material characterization

Rubber is a hyperelastic material, showing highly nonlinear elastic isotropic behavior with incompressibility. A relationship between stress and strain in the hyperelastic material, generally characterized by strain energy functions, is essential for the finite element analysis of the rubber components.

Material parameters in Ogden strain energy potential of order N = 3 represented in Eq. (1) can be determined from the experimental stress strain data.[8]



	1	2	3
μ_i [MPa]	0.0	0.56	0.84
α_i	1.22	1.85	1.88

Figure 6. Ogden function fitting result using simple tension, planar tension and equi-biaxial tension test data.

$$W=\sum_{i=1}^{N}\frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i}+\lambda_2^{\alpha_i}+\lambda_3^{\alpha_i}-3) \tag{1}$$

where, μ_i, α_i are material parameters in Ogden model and λ_i are the principal stretch ratio. The material coefficients are obtained by curve fitting of uniaxial tension, pure shear and equi-biaxial tension test data as shown Figure 6.

2. FEA of 3D dumbbell specimen

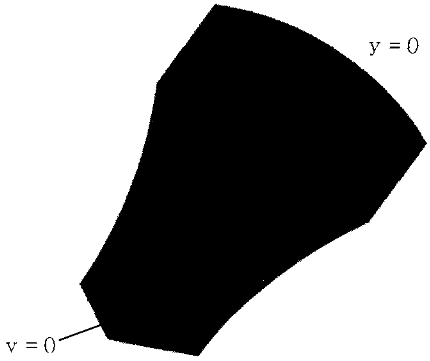
The deformation behaviors of the 3D dumbbell specimen were investigated by finite element analysis using the finite element software MARC. One eighth of the 3D dumbbell specimen was modeled due to the geometric symmetry and totals of 2,562 nodes and 1,520 elements were used for modeling. The 3D dumbbell specimen was modeled with tetrahedron element as shown in Figure 7(a).

For materials like rubber which experiences a large deformation, the Green-Lagrange strain, $\varepsilon_{G\text{-}L}$, has been used as a strain measure, represented by the stretch ratio.[9]

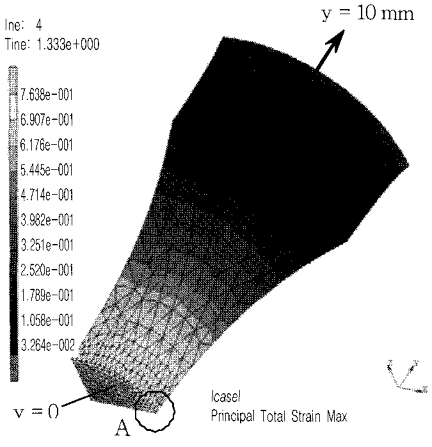
$$\varepsilon_{G-L} = \frac{1}{2}(\lambda^2 - 1) \tag{2}$$

The Green-Lagrange strain was found at the surface of the major axis in the 3D dumbbell specimen. The Green-Lagrange strain at the critical location determined from the finite element analysis as shown Figure 6(b). The maximum Green-Lagrange strain was presented at the location A.

The relation between the applied displacements and the corresponding Green-Lagrange strains for the 3D dumbbell specimen was obtained from the finite element analysis shown in Figure 7(b). This displacement versus Green-Lagrange strain curves of the specimen would be used for generating a fatigue life equation of the natural rubber expressed by the maximum Green-Lagrange strain as damage.



(a) 0 mm (initial condition)



(b) 10 mm tension

Figure 7. The Green-Lagrange strain distribution in the one eighth of the 3D dumbbell specimen model subjected to a tensile displacement of 10mm from finite element analysis.

3. Fatigue damage rule

Fatigue process begins with the accumulation of damage at a localized region due to alternating loads, leading to crack initiation, propagation and final failure.

In this study, the fatigue damage of a natural rubber was evaluated from the 3D dumbbell specimen. The damage parameter of maximum Green-Lagrange strain is considered to predict the life of natural rubber, and they can be written in the following form.

$$\psi = \kappa \cdot N_f^{\beta} \tag{3}$$

In Eq. (3), ψ denotes the damage parameter, and κ and β are coefficient and exponent of the damage equation, respectively.

The relation between the maximum displacement and fatigue cycles were converted the relation between the maximum Green-Lagrange strain and fatigue cycles for 3D dumbbell specimen using the equations presented in Figure 8.

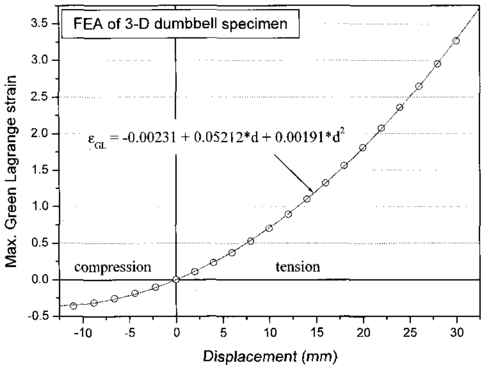


Figure 8. Displacement amplitudes versus Green-Lagrange strain of 3D dumbbell specimens.

Figure 9 present the fatigue lives of the 3D dumbbell specimen represented by the maximum Green-

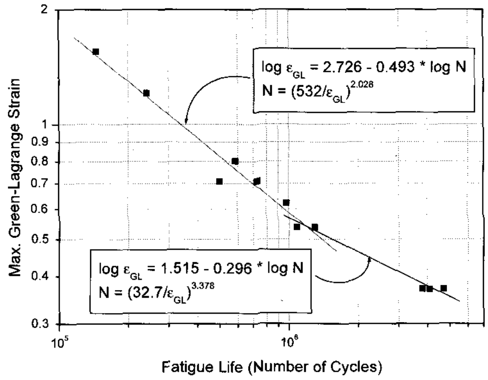


Figure 9. The maximum Green-Lagrange strain versus fatigue lives of the 3D dumbbell specimens.

Lagrange strain parameter, $\varepsilon_{G\text{-}L,\max}$. It can be seen from Figure 8 that the fatigue lives can be effectively represented by a following single functions using the maximum Green-Lagrange strain.

In this study, we selected the two fatigue life curves to reduce the error from the test results in long time range, over 2E+6 cycles.

$$N_f = (532/\varepsilon_{G\text{-}L,\max})^{2.028} \quad \text{in } \varepsilon_{G\text{-}L,\max} > 0.5 \tag{4}$$

$$N_f = (32.7/\varepsilon_{G\text{-}L,\max})^{3.378} \quad \text{in } \varepsilon_{G\text{-}L,\max} < 0.5 \tag{5}$$

The coefficients and exponents of the Eq. (4) and (5) of natural rubber were determined by the log-log linear regression analysis from Figure 9. Fatigue life also has been represented by the strain energy density as a damage parameter. But, it was excluded from this study. The equations are used in fatigue life prediction. Damage model was considered as the modified Miner's rule.[10]

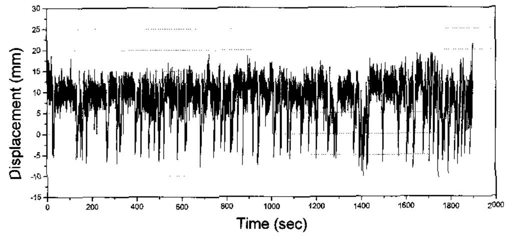
Ⅳ. Result and discussion

1. Variable amplitude loading

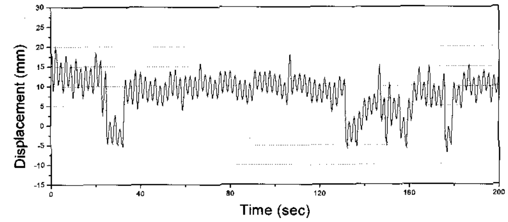
The major problems encountered when analyzing a component for fatigue is that the actual service load history may be unknown. In most situations a representative service history, or loading block, is obtained from field tests.

Life is then predicted in terms of a number of these block, where a block may represented a particular loading event. In this study, we selected the transmission load history offered at SAE(The Society of Automotive Engineers) to predict the fatigue life subjected to variable amplitude histories.[10] The transmission history contains large changes in the mean load value. The number of segment of the load history is 1708, the maximum value is 999 and the minimum value is - 495 in load. But, in this study, we converted the amplitude in SAE transmission load history into the displacement amplitude considering a buckling of 3D dumbbell specimen as shown in Figure 10.

To predict the life of a component subjected to a variable amplitude loading, it is necessary to reduce the complex history into a number of events that can be compared to the available constant amplitude test data.[10] In this study, we used the racetrack method that is one of the rainflow cycle counting to reduce the complex history.[10] The racetrack method is useful to reduce the load history data be



(a)



(b)

Figure 10. The displacement history transformed from the SAE load history considered buckling : (a) Full history (one block), (b) Initial segment of history.

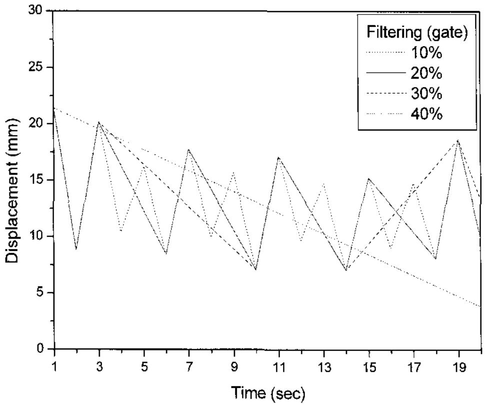


Figure 11. Some segment of the displacement history reduced by the racetrack method from Figure 10.

Table 2. The number of reversals reduced.

Gate value (%)	No. of segments (block)	Ratio (%)
0	1,708	-
10	1,708	100.0
20	750	43.9
30	262	15.3
40	132	7.8

cause it removes the small amplitude affected on fatigue life little. Therefore, we can reduce the time of fatigue test. Figure 11 shows some result of using this procedure from the displacement history given in Figure 10.

We regarded the histories under 10%, denotes gate value of the amplitude between the maximum peak and the minimum valley as noise data and filtered. This case agreed with the initial history. However, about gate value of 20, 30 and 40%, it is reduced in 43.9, 15.3 and 7.8% as shown Table 2, respectively. And then, the fatigue life can be predicted using the number of range-mean-cycle from the simplified rainflow counting results.

2. Fatigue life prediction

Figure 12 shows the cumulative fatigue damage and fatigue life to the gate value that is acquired by the modified Miner's rule[10] from Eq. (4), (5) in case that the maximum displacement is 21.41 mm. A correlation between experimental fatigue life and predicted fatigue life of the 3D dumbbell specimen to the gate value is shown in Figure 13. Predicted fatigue lives in the gate value of 30, 40% were in good agreement with the experimental lives within a factor of 2. Also, the error between predicted value and experimental value increases as the gate value decreases.

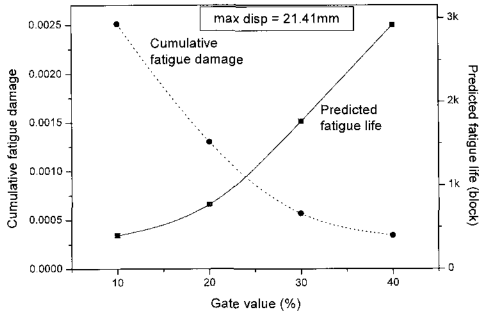


Figure 12. The cumulative fatigue damage and predicted fatigue life to different gate values.

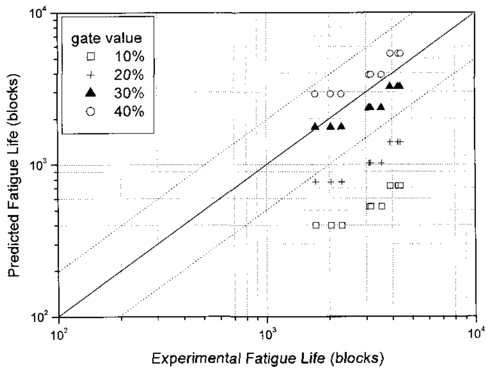


Figure 13. A correlation between experimental and predicted fatigue lives to the gate value of the 3D dumbbell specimens.

V. Conclusion

Fatigue life prediction methodology of the vulcanized rubber component subjected to variable amplitude load was proposed. Nonlinear finite element analysis of the 3D dumbbell specimen was performed using a constitutive relation defined by the

Ogden strain energy function. The relationship between the displacement and the Green-Lagrange strain of the 3D dumbbell specimen was obtained from the finite element analysis.

In order to determine the fatigue damage parameter of the natural rubber material, fatigue tests using the 3D dumbbell specimens with various displacement amplitudes were conducted. The fatigue damage of the natural rubber was effectively represented by the maximum Green-Lagrange strain.

A signal processing of loading waveform by racetrack method and the simplified rainflow cycle counting were performed. Also, the modified miner's rule as damage models was considered. When the gate value is 40%, predicted fatigue lives of the rubber component agreed fairly well with the experimental fatigue lives within a factor of two. Therefore, fatigue life estimation procedure employed in this study can be used appropriately for the fatigue design of the rubber components under variable amplitude loading at the early design stage.

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