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Useful Lifetime Prediction of Chevron Rubber Spring for Railway Vehicle

Chang Su Woo, Hyun Sung Park

Abstract**—**Useful lifetime evaluation of chevron rubber spring was very important in design procedure to assure the safety and reliability. It is, therefore, necessary to establish a suitable criterion for the replacement period of chevron rubber spring. In this study, we performed characteristic analysis and useful lifetime prediction of chevron rubber spring. Rubber material coefficient was obtained by curve fittings of uniaxial tension equibiaxial tension and pure shear test. Computer simulation was executed to predict and evaluate the load capacity and stiffness for chevron rubber spring. In order to useful lifetime prediction of rubber material, we carried out the compression set with heat aging test in an oven at the temperature ranging from 50°C to 100°C during a period 180 days. By using the Arrhenius plot, several useful lifetime prediction equations for rubber material was proposed.

Keywords**—**Chevron rubber spring, material coefficient, finite element analysis, useful lifetime prediction.

I. INTRODUCTION

RUBBER is one of the most versatile materials widely used in innumerable applications in our day to day life. Perhaps, it would be difficult to quantity the number of applications rubber is used for products which fulfill important functions in almost all areas ranging from simple household, commercial and automotive products to more complex uses in the aviation and space industries. The interest of the useful lifetime evaluation for rubber component was increasing according to the extension of warranty period [1], [2]. A design of rubber component against failure is one of the critical issues to prevent the failures during the operation. Therefore, lifetime prediction and evaluation are technological requirements to assure the safety and reliability of mechanical rubber components [3], [4]. In this paper, evaluation of characteristics and useful lifetime prediction of the chevron rubber spring as shown Fig. 1 was investigated. Chevron rubber spring is used in primary suspension system for railway vehicle. Recent advance in finite element method technology has resulted in industrial application of simulation tools in the design of rubber components. The computer simulation was executed to predict and evaluate the load capacity and stiffness for chevron rubber spring. When rubber is used for a long period of time, it usually becomes hardened and losses its damping capacity. This aging process results mainly from heat due to hysteric loss and is affects not only the material properties but also the useful lifetime of rubber components. In order to investigate the heat-ageing effects on the material properties, the stress-strain curves were obtained from the material tests. Also, the accelerated heat aging tests were carried out to predict the useful lifetime of rubber material. By using the rubber material test several useful life prediction equations for rubber component was proposed.

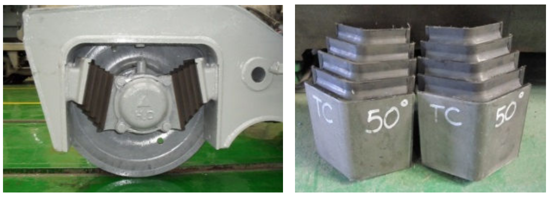

Fig. 1 Chevron rubber spring for railway vehicle

II. EXPERIMENT

A. Material Test

The material of rubber component for chevron rubber spring was carbon-filled vulcanized natural rubber, which have the hardness of IRHD 60. 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 test 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 tension, equibiaxial tension and pure shear test [5].

Fig. 2 (a) shows the uniaxial tension test by using non contacting strain measurement (laser extensometer). In uniaxial compression test, it is very difficult to obtain the pure compressed stress-strain relationship because of the frictions on the grip and the contact plane of rubber test specimen. Also, there is some bubbling phenomenon in the middle part of test sample due to this friction. Therefore, it is hard to say that the property values of materials obtained from uniaxial compression test are accurate. Thus, [6] suggested equibiaxial tension tests, in which the pure strain values can be obtained, are more preferred in order to resolve such issues in uniaxial compression test. For equibiaxial tension tests, we prepared round shaped test specimen shown in Fig. 2 (b). The pure shear test imposes plane strain conditions on the test specimen by preventing the edges of the specimen from contracting.

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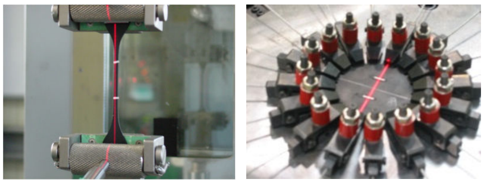
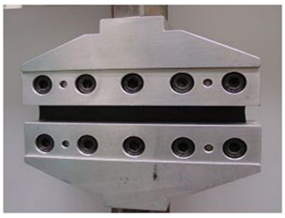
This is achieved through the use of test specimens with high aspect ratios. In current work, 100 mm wide specimen was clamped with a grip separation of 10 mm using the wide grips shown in Fig. 2 (c).

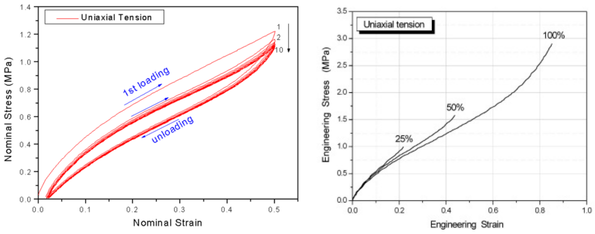


(a) Uniaxial tension test (b) Equibiaxial tension test

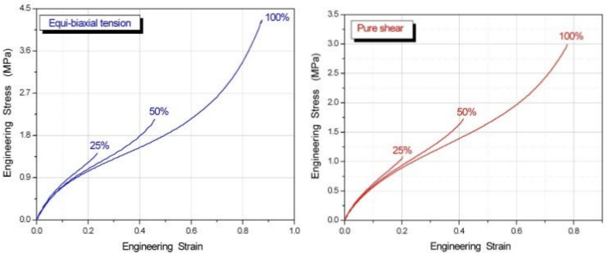


(c) Pure shear test

Fig. 2 Rubber material test



(a) Mullins effect (b) Uniaxial tension



(c) Equibiaxial tension (d) Pure shear

Fig. 3 Stress-strain curve at various strain range

Fig. 3 shows the stress-strain curves obtained from the mechanical test with 25%, 50% and 100% of the strain range for natural rubber. Figs. 3 (a) and (b) show the raw data of the uniaxial tension test. Ten loadings and un-loadings were applied for each stain level, and strain levels were progressively increased to the maximum value. The stress-strain relationship of the rubber changed drastically during the first several cycles and stabilized after 3 to 10 times cycle, which is known as Mullin's effect [7]. The effect of pre-stressing is due to the physical breakdown or the reformation of the rubber network structures. Therefore, 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 10^{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. Figs. 3 (c) and (d) show the stress-strain relation of rubber material for various mechanical tests.

In order to define the hyper-elastic material behavior, mechanical test data are required for the accurate calculation of material parameters in the strain energy potential. Material parameters in Ogden strain energy potential of order N=3 represented in (1) can be determined from the experimental stress-strain data [8].

$$W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n}(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3) \qquad (1)$$

where, μ_i, α_i are material parameters and λ_i is the principal stretch ratio. The stretch ratio is defined as the ratio of the extended length of a specimen L, to the un-extended length L_o. In this study, the material coefficient was obtained by curve fittings of uniaxial tension, equibiaxial tension and pure shear test data. We performed the curve fitting with physical test data. Ogden 3-terms fits that uses progressively more information as the basis for the curve fitting. Table I contains the values of rubber material coefficient calculated in each case.

TABLE I
RUBBER MATERIAL COEFFICIENT

Strain	Ogden 3-terms						
	μ_1	α_1	μ_2	α_2	μ_3	α_3	G
25%	1.9e-5	0.519	0.467	3.3e-7	0.896	2.942	1.318
50%	0.662	2.6e-6	0.933	2.429	7.9e-6	0.412	1.133
100%	0.263	0.002	0.911	2.241	4.451	2.7e-5	1.021

B. Finite Element Analysis

Chevron rubber spring provide three modes of flexibility for axle-box primary suspension. The springs are fitted at an angle to the vertical axis, loading the rubber layers in shear and compression. The values quoted for lateral and longitudinal stiffness may vary with vertical deflection. Finite element analysis was performed to investigate the deformation and strain distribution behavior of rubber component by using rubber material coefficient. Finite element model is shown in Fig. 4. Four rubber layers and five layers of steel interleaves were modeled using Full-Hermann formulation 82 elements. The number of total elements is 8,114 and the total nodes are 10,682. The load cases can be classified into two types. The first type is a design case (tare=4,000kg), the second type is the design case plus passenger weight (crush=7,500kg). Finite element analysis was executed to evaluate the behavior of deformation and strain distribute by using the commercial finite element code.

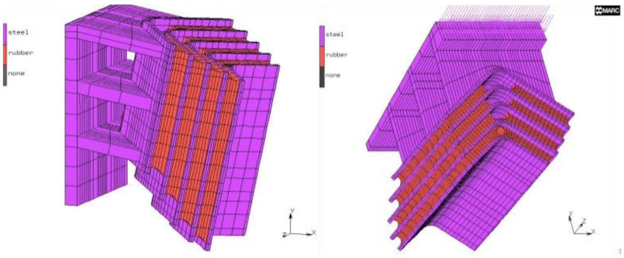
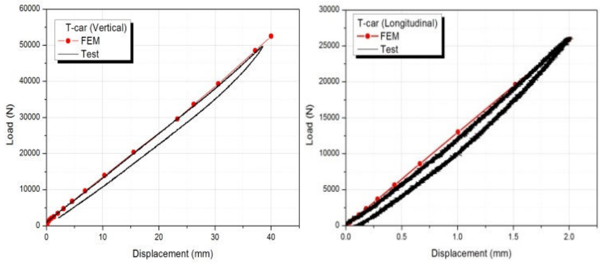


Fig. 4 Finite element model of chevron rubber spring

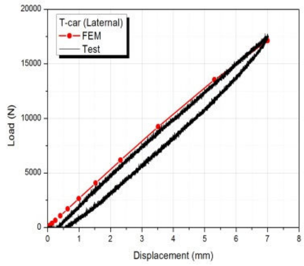
The spring constants were made between the simulation and test in order to verify the finite element model, as shown in Table II and Fig. 5. There is a good agreement between the calculation and test. A typical stress and strain distribution of chevron rubber spring is shown in Fig. 6.

TABLE II
SPRING CONSTANT OF CHEVRON RUBBER SPRING

Direction	Condition	Spec. (KN/mm)	FEM	Test
Vertical	Tare	2.0	1.97	1.99
	Crush	2.2	2.14	2.18
Longitudinal	Tare	21.5	19.6	21.3
	Crush	24.8	23.0	24.5
Lateral	Tare	9.9	11.2	10.0
	Crush	10.8	12.6	11.1

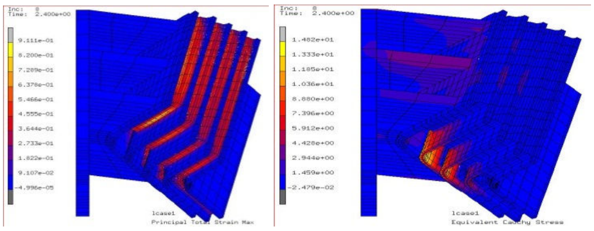


(a) Vertical direction (b) Longitudinal direction

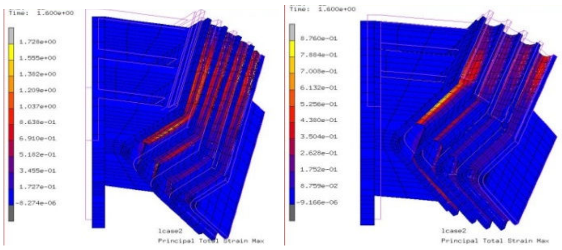


(c) Lateral direction

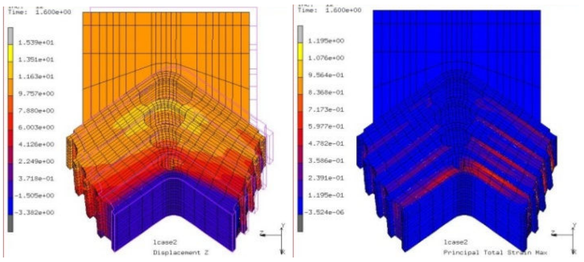
Fig. 5 Load-displacement curve of chevron rubber spring



(a) Strain at vertical load (b) Stress at vertical load



(c) Strain at longitudinal load (d) Stress at longitudinal load



(e) Strain at lateral load (f) Stress at lateral load

Fig. 6 Strain and stress distribution of chevron rubber spring

III. LIFETIME PREDICTION OF CHEVRON RUBBER SPRING

A. Arrhenius Model

It is difficult to estimate the useful lifetime of rubber products because its processing environment and condition are complicated and there are a variety of use and combination conditions and degradation factors such as temperature, humidity, ozone, light, mechanical and electric stress. In this study, the Arrhenius model was selected to estimate the useful lifetime of rubber material with data obtained by acceleration heat aging test, in which we adapted the an acceleration method where the rubber is thermally aged. In the Arrhenius model, the useful lifetime is determined by the time when specific change from the initial state of a property occurs over temperature, and the useful lifetime is represented by the master curve and the relation of time and temperature. Through this relationship the lifetime of rubber can be estimated at a particular temperature. The lifetime by natural aging at room temperature can be estimated using data obtained in acceleration tests [9]. Assuming that the value of a property of rubber is P in the aging reaction, the Arrhenius Equation can be represented as in (2):

$$-\frac{dP}{dt} = kP,\ \ln[\frac{P}{P_0}] = -kt \tag{2}$$

where, P : the value of a property of rubber, P_0 : the value of the property before aging, t : time, and k : reaction rate.

In (2), the reaction rate k is a constant that represents the going reaction of the value of the property. In 1889, S. Arrhenius obtained the Empirical Equation as in (3):

$$k = A\cdot e^{-E/RT},\ \ln k(t) = -\frac{E}{RT} + C \tag{3}$$

where, A and C: constant, E: activity energy(J/mol K), R: constant of gas (8.314 J/mol K), and T : absolute temperature.

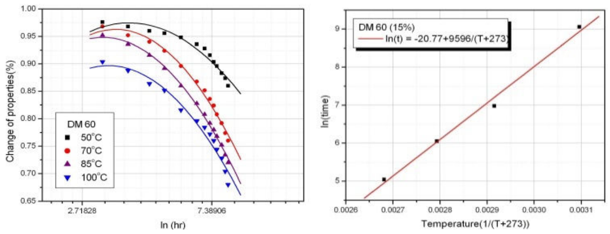
In (2), the lifetime (t) can be derived from (4). If lifetime is plugged in for time when there is the value of the aged property (P).

$$t = -\ln(P/P_0)/k \tag{4}$$

In (4), the lifetime (t) can be transformed to temperature because the lifetime can be related with temperature in the reaction rate relation (3). That is, the lifetime t_1 at temperature T_1 is equal to the lifetime t_2 at temperature T_2 for the value of the property (P). This can be represented by (5):

$$\ln[\frac{t_1}{t_2}] = \frac{E}{R}[\frac{1}{T_1} - \frac{1}{T_2}] \tag{5}$$

Long term changes at low temperature are the same with short term changes at high temperature. Changes at room temperature for several years, therefore, can be estimated under accelerated aging conditions at high temperature.



(a) Change of property (b) Arrhenius plot

Fig. 7 Arrhenius plot of material for chevron rubber spring

B. Useful Lifetime Prediction

In order to useful lifetime prediction of chevron rubber spring, we carried out the compression set with heat aging test in an oven at the temperature ranging from 50°C to 100°C during a period 180 days. Oven aging was carried out in air-circulating ovens (stable and accurate to ~ ±1°C) equipped with thermocouples connected to continuous strip chart recorders. The compression set was determined according to ISO 815. To carry out this test a simple compressive force is applied to rubber mount, usually to a fixed degree of strain. Not surprisingly, in all cases compression set increased with time of exposure and with increasing temperature. Compression set results presented graphically in Fig. 7 (a). Figures illustrate how the rate of change with time will vary for materials and temperatures. By using the compression set test and Arrhenius methodology, useful lifetime to threshold value (15%) was plotted against reciprocal of absolute temperature as shown in Fig. 7 (b). By using the Arrhenius plot, several useful lifetime prediction equations for rubber material was proposed as shown in (6). Useful lifetime of rubber material for chevron rubber spring was predicted about 10 years at 15% decrease in properties.

$$\ln(t) = -20.77 + \frac{9596}{(T+273)} \tag{6}$$

where, t is time, T is the temperature.

IV. CONCLUSION

Useful lifetime prediction and evaluation are the key technologies to assure the safety and reliability of rubber components. In this paper, prediction of characteristics and useful lifetime of chevron rubber spring were experimentally investigated. Rubber material coefficient was obtained by curve fittings of uniaxial tension, equibiaxial tension and pure shear test. Computer simulation was executed to predict and evaluate the load capacity and stiffness for chevron rubber spring. Relationships between the applied load and displacement are obtained from the finite element analysis. Results of the finite element analysis are a good agreement with the experimental data. By using the accelerated heat-aging test, several useful lifetime prediction equations for rubber material was proposed. Useful lifetime of rubber material was predicted about 10 years at 15% decrease in property.

ACKNOWLEDGMENT

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Chang Su Woo graduated in mechanics at the Seoul National University and went on to do a PhD. He was recruited in 1989 by the Korea Institute of Machinery and Materials (KIMM) to work on fatigue analysis of mechanical component, but later turned to research on design and analysis of rubber engineering components, working with colleagues both on choice of characteristics to meet the give function and on design methodology for meeting those characteristics. Particular areas are stress-strain and failure properties, and the use of simulation software such as finite element analysis (FEA) to predict the related component characteristics such as load-deflection behavior and lifetime. He has published approximately 50 papers relating to research on rubber engineering components and their applications, such as automotive mounts and bushings, suspension of railway vehicles, shock & vibration isolators, marine fenders and structure energy dissipation systems.