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Evaluation of Characteristics and Useful Life of Rubber Spring for Railway Vehicle

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Abstract

Rubber components are widely used in many application such as vibration isolators, damping, ride quality. Rubber spring is used in primary suspension system for railway vehicle. Characteristics and useful life prediction of rubber spring was very important in design procedure to assure the safety and reliability. Non-linear properties of rubber material which are described as strain energy function are important parameter to design and evaluate of rubber spring. These are determined by physical tests which are uniaxial tension, equi-biaxial tension and pure shear test. The computer simulation was executed to predict and evaluate the load capacity and stiffness for rubber spring. In order to investigate the useful life, the acceleration test were carried out. Acceleration test results changes as the threshold are used for assessment of the useful life and time to threshold value were plotted against reciprocal of absolute temperature to give the Arrhenius plot. By using the acceleration test, several useful life prediction for rubber spring were proposed.

Keywords : *Rubber spring, Finite element analysis, Acceleration test, Useful life prediction*

1. Introduction

Rubber springs are important components in railway vehicles. They can be used for both primary or secondary suspension systems. Rubber springs have function which reduce vibration and noise, support load carried in operation of rail vehicle. The useful life prediction was increasing according to the extension of warranty period of the railway vehicle components. Therefore, characteristic and lifetime evaluation are very important in design procedure to assure the safety and reliability of mechanical rubber component.

Recent advance in finite element method technology has resulted in industrial application of simulation tools in the design of rubber components. In this study, The computer simulation was executed to predict and evaluate the load capacity and stiffness for rubber spring. Also, in order to investigate the useful life, the acceleration test were carried out. Acceleration test results changes as the threshold are used for assessment of the useful life and time to threshold value were plotted against reciprocal of absolute temperature to give the Arrhenius plot. By using the acceleration test, several useful life prediction for rubber spring were proposed.

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2. Finite Element Analysis

2.1 Strain energy function

The special material modeling for the analysis of rubber components by nonlinear finite element analysis is required. The material modeling of hyperelastic properties of rubber is characterized by the strain energy functions. These functions imply the assumption that rubber material is isotropic and elastic. The strain energy functions have been represented either in terms 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 bases on the select of an appropriate strain energy function, and accurate determination of material constants in the function. Material constants in the strain energy functions are able to be determined via the curve fitting of experimental stress-strain data.

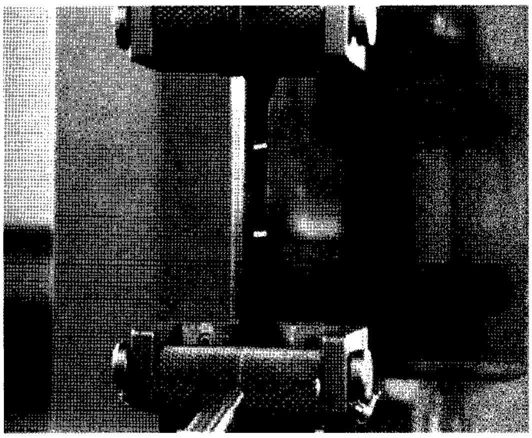
Strain energy potential can be expressed as the following polynomial series :

$$U = \sum_{i+j=1}^{N} C_{ij}(I_1-3)^i(I_2-3)^j + \sum_{i=1}^{N} \frac{1}{D_i}(I_{el}-1)^{2i} \qquad (1)$$

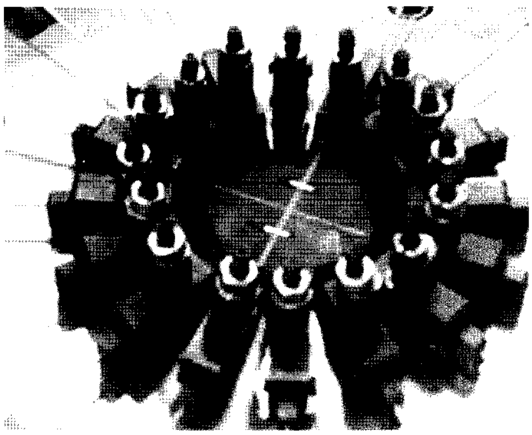
where C_{ij} and D_i are temperature dependent material parameters, J_{el} is the elastic volume strain, I_1 and I_2 are strain invariants. If $N=1$, the polynomial formulation represents the Mooney-Rivlin hyperelasticity model. The energy potential is as follows :

$$U = C_{10}(I_1-3) + C_{01}(I_2-3) + \frac{1}{D_1}(I_{el}-1)^2 \qquad (2)$$

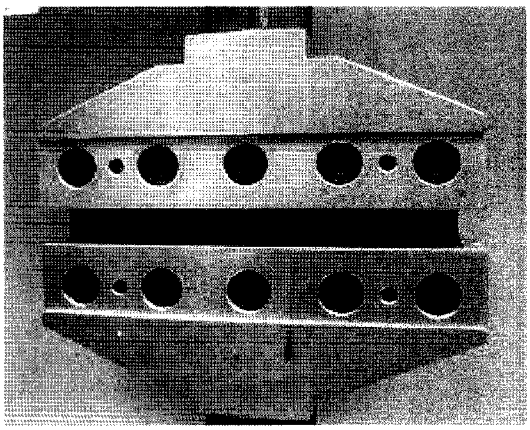
The Mooney-Rivlin form was used to model the rubber spring components. The material constants in equation (2) were determined form experiments.



(a) simple tension



(b) equi-biaxial tension



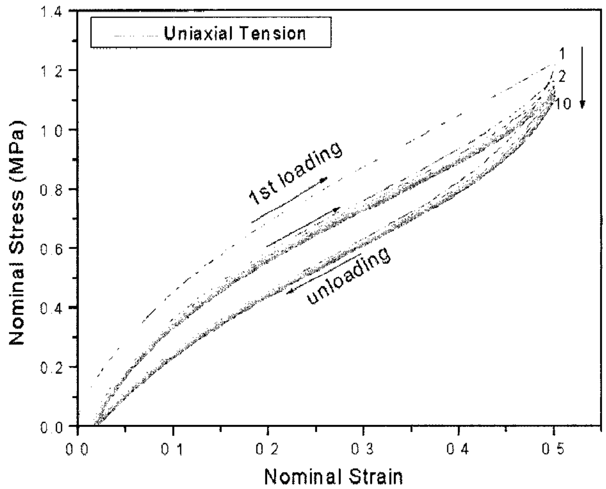
(c) pure shear

Fig. 1. Physical Tests of Rubber Material

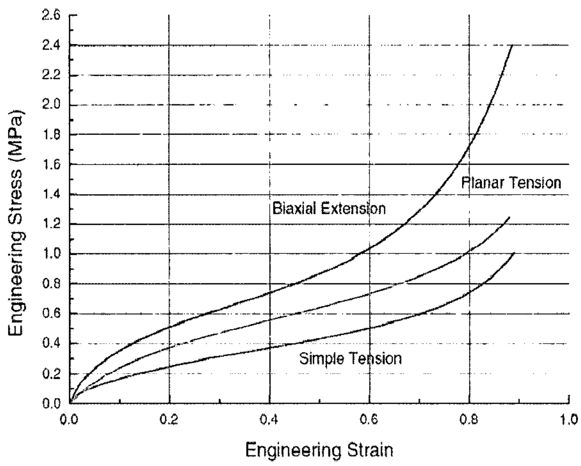
2.2 Physical test of rubber material

There are several different types of experiments, including simple tension, simple compression, equi-biaxial tension, pure shear tests. In general, a combination of simple tension, equi-biaxial, and pure shear tests are used to determine the material constants. Physical test was loaded by a UTM at a speed of 100 mm/min, and the deflection was measured using a laser extensometer in Fig. 1.

The material used in this study is a carbon-filled vulca-



(a) mullin's effect



(b) stress-strain curve

Fig. 2. Mechanical Properties of Rubber Material

Table 1. Non-linear Properties of Rubber Material (Mooney-Rivlin)

Mat.	Strain	C_{10}	C_{01}	G
NR60	25%	0.868	0	1.736
	50%	0.743	0	1.486
	100%	0.615	0.0523	1.334

nized natural rubber, which have the hardness of the International Rubber Hardness Degree 60. Fig. 2(a) and (b) shows the raw data of the simple 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 5 cycles, which is known as Mullin's effect. 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. Fig. 2(b) shows the stress-strain relation of rubber material for various physical tests. The table 1 was summarized the material constant calculated in each case.

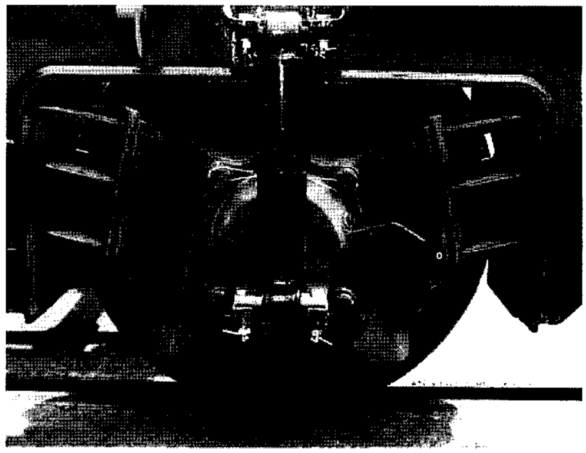
2.3 Finite element analysis of rubber spring

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.

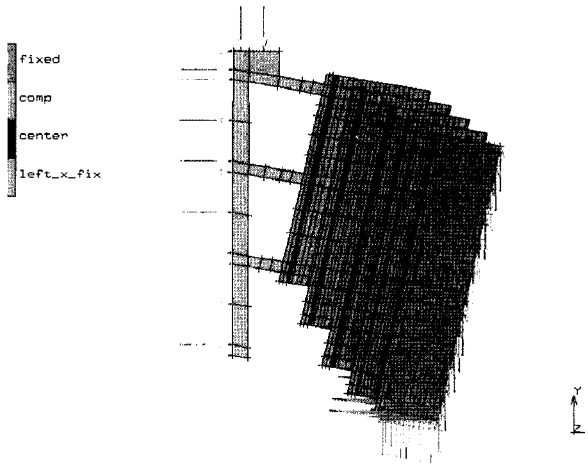
Finite element model is shown in Fig. 3. Four rubber layers and five layers of steel interleaves were modelled using Full-Hermann formulation 82 element. The number of total elements is 8,114 and the total nodes is 10,682. The boundary conditions are listed in table 2. The load cases can be classified into two types. The first type is a design case (tare=4,000 kg), the second type is the design case plus passenger weight (crush=7,500 kg). Finite element analysis was executed to evaluate the behavior of

Table 2. Boundary Conditions for Chevron Rubber Spring

Direction	Vertical	Longitudinal	Lateral
Displacement	x and z : fixed	z : fixed	x : fixed
Loading	y-direction	y and x	y and z



(a) chevron rubber spring



(b) finite element model

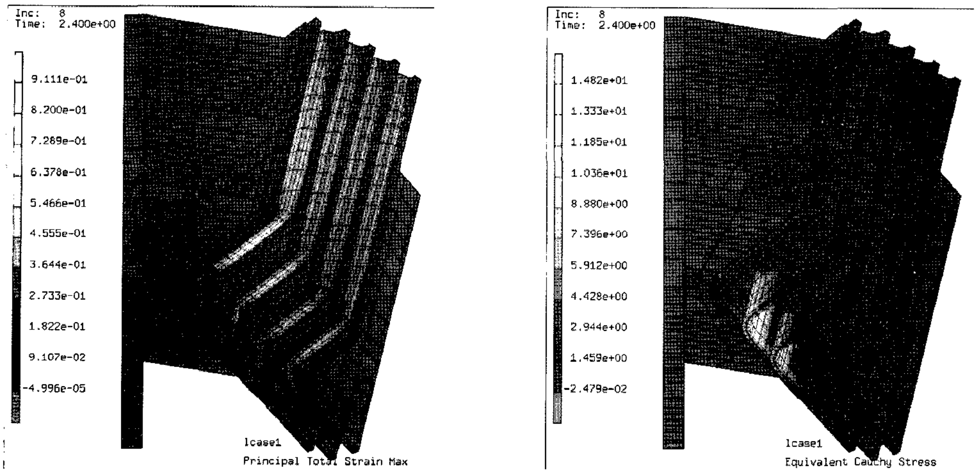
Fig. 3. Finite Element Model of Rubber Spring

Table 3. Stiffness of Chevron 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

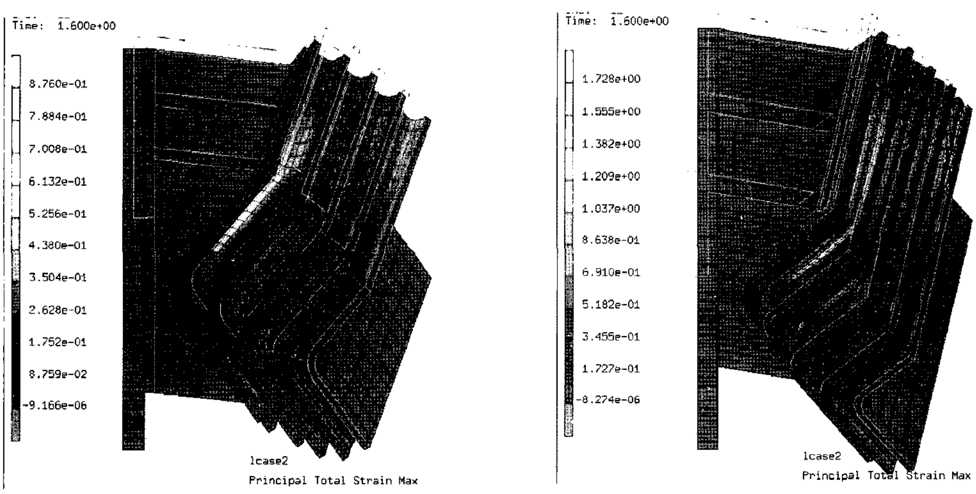
deformation and strain distribute by using the commercial finite element code.

A stiffness was made between the simulation and teg test in order to verify the FE model, as shown in table 3. The deflection range compared is up to 40 mm which is equivalent to laden load. There is a good agreement between the calculation and test. A typical deformed shape and strain and stress distribution of the the rubber spring is



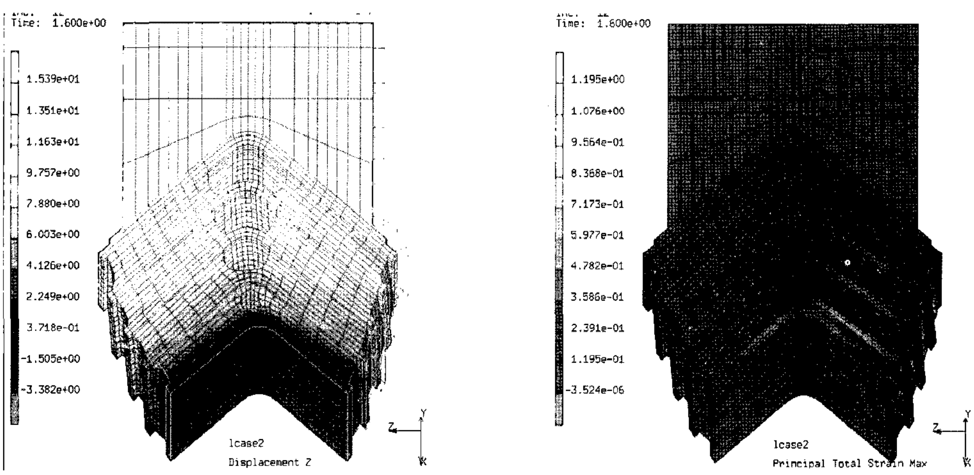
(a) principal strain (b) equivalent cauchy stress

Fig. 4. Strain and Stress Distribution on Vertical Load



(a) tension (b) compression

Fig. 5. Distribution of Strain for Longitudinal Analysis



(a) displacement (b) maximum principal strain

Fig. 6. Displacement and Strain for Lateral Analysis

shown in Figs. 4~6, which is the same as that observed from the test. Therefore the stress and strain profile derived from the model can be used to analyse the stress and strain distribution of the rubber spring.

3. Lifetime Prediction of Rubber Material

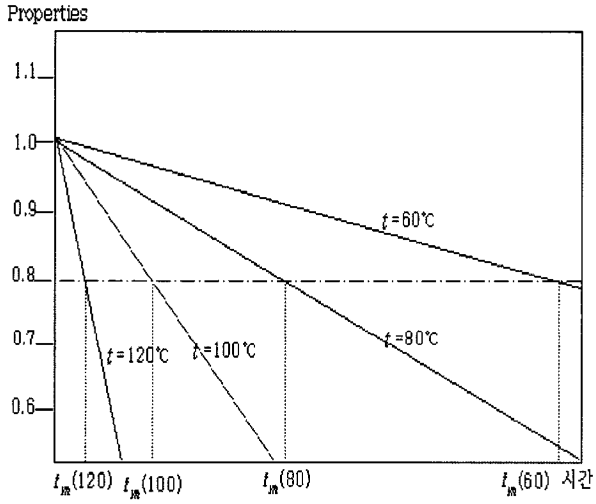
3.1 Arrhenius model

The reaction rate of a chemical reaction normally increases with increasing temperature. By exposing test pieces to a series of elevated temperatures and measuring property change, the relation between the reaction rate of degradation mechanisms and temperature can, in principle, be deduced. Estimates can then be made by extrapolation of the degree of degradation after a given time at a given temperature (Brown 1996). The Arrhenius relation is the best known and most widely used of the two applications to the permanent effects of temperature. The relation rate and temperature relationship can often be represented by the Arrhenius equation.

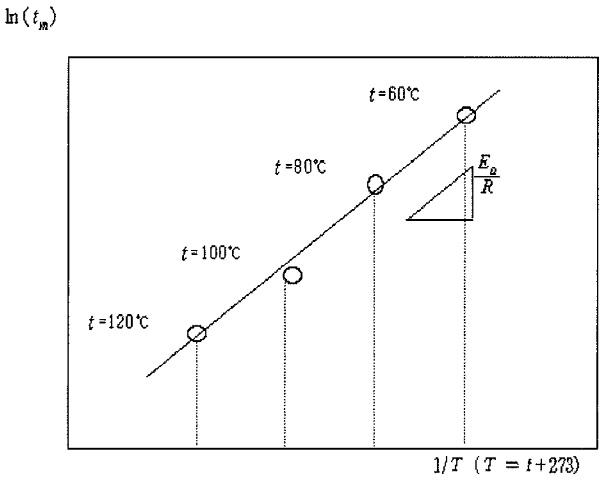
$$K(T) = A \bullet e^{\frac{-E}{RT}} \tag{3}$$

where, $K(T)$ is the reaction rate, A is constants, E is the activation energy, R is the gas constant, T is the absolute temperature.

The reaction rate at any temperature is obtained from the change in the selected property with exposure time at that temperature. Although the Arrhenius relation is generally the first choice to apply to the effect of temperature, no general rule can be given for the measure of the reaction rate to be used with it. In the example shown in Fig. 7(a) the property parameter has been plotted against time at four temperatures, and the reaction rate taken as the time for the property to reach a given threshold value or end of life criterion. The log of the chosen measure of reaction rate is plotted against the reciprocal of absolute temperature, which should result in straight line as illustrated in the Arrhenius plot in Fig. 7(b).



(a) change of property



(b) Arrhenius plot

Fig. 7. Arrhenius Model for Lifetime Prediction

3.2 Lifetime prediction

In order to lifetime prediction of rubber material, we carried out the compression set with heat-aged in an oven at the temperature ranging from 50°C to 100°C for a period ranging from 1 day to 180 days.

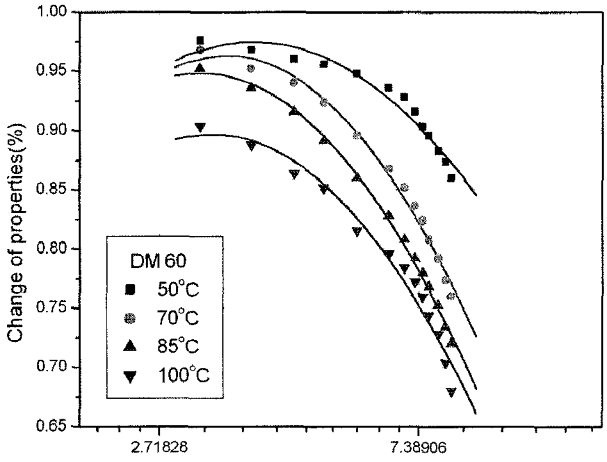
The compression set was determined according to ISO 815. To carry out this test a simple compressive force is applied to rubber mount, usually to a fixed degree of strain. Not surprisingly, in all cases compression set increased with time of exposure and with increasing temperature. Compression set results presented graphically in Fig. 8(a).

Figures illustrate how the rate of change with time will vary for different materials and temperatures. Compression set results changes as the threshold are used for assessment of the useful life and time to threshold value (10%, 15%) were plotted against reciprocal of absolute temperature to give the Arrhenius plot. By using the compression set test, several useful life prediction equations for rubber material were proposed as shown in equation (4) and (5).

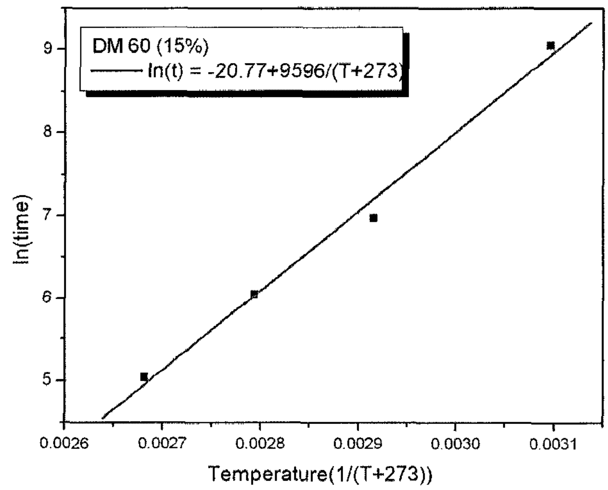
$$\text{In}(t) = -22.08 + \frac{9564}{(T+273)} \tag{4}$$

$$\text{In}(t) = -20.77 + \frac{9596}{(T+273)} \tag{5}$$

Figure 8(b) and table 4 was shown on the useful lifetime of rubber material using the rubber spring for railway vehicle. According to Arrhenius equation, useful



(a) change of property



(b) Arrhenius plot

Fig. 8. Arrhenius Plot of Rubber Material

Table 4. Useful Life Prediction of Rubber Material

Mat.	Change of properties (%)	Useful life (25°C)		
		hr	days	years
NR60	10	22,247	927	2.5
	15	920,419	3,835	10.5

lifetime of rubber material was about 10 years at 25°C temperature. Useful life estimation procedure employed in this study could be used approximately for the design of the rubber components at the early design stage.

4. Conclusion

The useful life prediction was increasing according to the extension of warranty period of the railway vehicle components. Therefore, characteristic and lifetime evaluation are very important in design procedure to assure the safety and reliability of mechanical rubber component.

In this study, the computer simulation was executed to predict and evaluate the load capacity and stiffness for rubber spring. Also, in order to investigate the useful life, the acceleration test were carried out.

Nonlinear finite element analysis of rubber spring was performed based on the hyperelastic material model determined from the simple tension, equi-biaxial tension and pure shear test. A stiffness is a good agreement between the calculation and test.

By using the compression set test, several useful life prediction equations for rubber material were proposed. According to Arrhenius equation, useful lifetime of rubber material was about 10 years at 25°C temperature. Useful life estimation procedure employed in this study could be used approximately for the design of the rubber components at the early design stage.

Acknowledgement

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