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Viscous characteristics of ETFE film sheet under temperature change

TATSUYA YOSHINO* AND SHIRO KATO†

* Taiyokogyo Corporation
3-20, Syodai-Tajika, Hirakata-shi, Osaka, 573-1132, Japan
e-mail: yt003051@mb.taiyokogyo.co.jp, web page: http://www.taiyokogyo.co.jp/

†Toyohashi University of Technology
1-1 Hibarigaoka, Tempaku-cho, Toyohashi-shi, Aichi, 441-8580, Japan
Email: kato-shiro@tg.commufa.jp

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1 INTRODUCTION

Because ETFE film is a high polymer material its visco-elastic characteristics are observed by the researchers. Besides, the linear expansion coefficient of the ETFE is 10 times greater compared to steel products or the like. For that reason, due to change in temperature, there are cases where expansion and contraction are regarded as an issue. Therefore, in order to design and construct ETFE film membrane structures, research focused on its visco-elastic characteristics has been done.

For research focused on viscosity of ETFE film, in addition to that carried out by the authors, there is research by Moriyama and Kawabata[1,2], by Jeong and Kawabata[3], by Wu[4], by Galliot and Luchsinger[5] and by Li and Wu[6] and so on. These studies take into account either the viscosity, the change in temperature or introducing the constitutive equation of FEM. There is no research that takes into account all of them.

The authors[7], under the condition of fixed temperature, (1) based on MSAJ Standards[8, 9], carried out biaxial tension tests and shearing tests of ETFE Film. (2) With respect to 5 types of stress ratio, biaxial tensile test was conducted, and the relationship between equivalent stress and equivalent plastic strain was identified. From the results, regardless of stress ratio, the curves of equivalent stress and equivalent plastic strain were consistent. (3) It was confirmed that the yield stress as well as stress after break down and the strain relationship can be expressed by the proposed elastic-plastic constitutive equation. (4) Performing pressurization test on membrane of a square plan showed that it can be sufficiently expressed by the proposed elastic-plastic constitutive equation.

Moreover, in reference[10], the proposed incremental nonlinear viscoelasticity constitutive equation regarding the uniaxial tension field is extended to biaxial tension field in reference[11, 12] and the validation is performed. This constitutive equation is formulated in the incremental form on the assumption of integration with FEM. Also, elapsed time, stress change and temperature difference can be taken into account. However, regarding the temperature, 1) the effect of temperature difference on the viscosity component can be taken into account using Time-temperature superposition principle but, 2) expansion and contraction due to temperature change cannot be taken into account.

Upon this, in this paper, the incremental form of the nonlinear viscoelasticity constitutive equation of the biaxial tension field - mentioned in the previous paper - is extended into a constitutive equation that takes into account the expansion and contraction due to temperature change. Confirming that this constitutive equation is capable of taking into account elapsed time, stress change and temperature change.

Specifically:

1) Extend the incremental constitutive equation for the biaxial tension field proposed in the previous paper into an equation where expansion and contraction due to temperature change are added.

2) Perform uniaxial creep test accompanied with temperature change and show the results. From these results, focusing on expansion and contraction due to temperature change, compute various constants necessary for the constitutive equation.

3) Use the proposed constitutive law and computed constants to perform simulation of uniaxial creep test accompanied with temperature change.

2. FORMULATION OF INCREMENTAL CONSTITUTIVE EQUATIONS FOR ETFE FILM

2.1. Incremental constitutive equations are extended to be used in biaxial stress

The generalized Voight model in figure 2.1.1 is used for incremental constitutive equations. In order to understand biaxial stress condition, variables related to Maxwell elements and Voigt elegments are divided into deviatoric components and volumetric components. Divided variables are shown in Table 2.1.1.

2.1.1. Incremental stresses

Consider the stress and temperature at a time of the j-th step, where $\sigma(t_j)$ denotes the stress and T_j denotes the temperature at the time t_j. After a time increment Δt, the stress and temperature will change by incremental step $\Delta\sigma$ and ΔT respectively as follows.

$$t_{j+1} = t_j + \Delta t \tag{2.1.1}$$

$$\sigma(t_{j+1}) = \sigma(t_j) + \Delta\sigma \tag{2.1.2}$$

As shown in Figure 2.1.2, assuming that during the time interval Δt, stress changes linearly from $\sigma(t_j)$ to $\sigma(t_{j+1})$ which makes it possible to be expressed by the following formula.

$$\frac{\Delta\sigma}{\Delta t} = \frac{\sigma(t_{j+1}) - \sigma(t_j)}{t_{j+1} - t_j} = \text{const.} \tag{2.1.3}$$

$$\sigma(\tau) = \sigma(t_j) + \frac{\Delta\sigma}{\Delta t}(\tau - t_j) \tag{2.1.4}$$

Similarly for temperature change ΔT,

$$T(\tau) = T(t_j) + \frac{\Delta T}{\Delta t}(\tau - t_j) \tag{2.1.5}$$

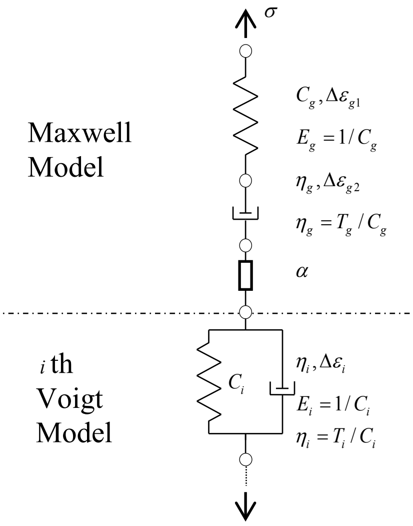

Figure 2.1.1 : generalized Voigt model

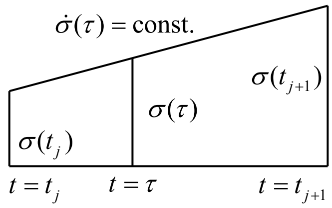

Figure 2.1.2 : Linear variation of stress during a time increment Δt step

Table 2.1.1 :Variables of the constitutive equations of biaxial tension

Item	Variable
For Maxwell model	Suffix g
For Voigt model	Suffix i
Time increment	Δt
Temperature increment	ΔT
stress increment	$\Delta\sigma', \Delta\sigma_m$
Viscoelastic strain increment	$\Delta\varepsilon^{el}$
Incremental strain for Maxwell element	$\Delta\varepsilon_{g1}', \Delta\varepsilon_{g1m}, \Delta\varepsilon_{g2}', \Delta\varepsilon_{g2m}$
Incremental strain for voigt element i	$\Delta\varepsilon_{i}', \Delta\varepsilon_{im}$
Compliance of elastic spring element	C_{Gg} , C_{Kg} , C_{Gi} , C_{Ki}
Viscosity	η_{Gg} , η_{Kg} , η_{Gi} , η_{Ki}
Relaxation and retardation time	$T_g = T_{Gg} = T_{Kg}, T_i = T_{Gi} = T_{Ki}$
Coefficient of linear expansion	$\alpha(T)$

2.1.2. Incremental visco-elastic strains for each element

Consider the evaluation of deviatoric (') and volumetric (m) components of the viscoelastic strain increment $\Delta\varepsilon^{el}$ for the Voigt model shown in Figure 2.1.1. The expansion and contraction component accompanying the temperature change is only considered for Maxwell elements.

A) Maxwell elements

The incremental strain of Maxwell elements is divided into deviatoric (') and volumetric (m) components. The incremental strain during time interval t_j, t_{j+1} will be calculated by integration. The resultant equations are shown below;

$$\Delta\varepsilon^{el}{}_{g1}{}' = C_{Gg}\cdot\Delta\sigma', \quad \Delta\varepsilon^{el}{}_{g1m} = C_{Kg}\cdot\Delta\sigma_m \tag{2.1.6}$$

$$\Delta\varepsilon^{el}{}_{g2}{}' = \frac{1}{\eta_{Gg}}\Delta t\left(\sigma'(t_j)+\frac{1}{2}\Delta\sigma'\right), \quad \Delta\varepsilon^{el}{}_{g2m} = \frac{1}{\eta_{Kg}}\Delta t\left(\sigma_m(t_j)+\frac{1}{2}\Delta\sigma_m\right) \tag{2.1.7}$$

In the next equation, the incremental heat strain $\Delta\varepsilon^{\theta}$ accompany incremental temperature ΔT is put in equation form by using coefficient of linear expansion $\alpha(T)$. Coefficient of linear expansion $\alpha(T)$ is a function in temperature *T*.

$$\Delta\varepsilon^{\theta} = \alpha(T)\Delta T \tag{2.1.8}$$

B) Voigt elements

Similarly, considering the deviatoric (') and volumetric (m) strain components for the Voigt model, the equations will be as follows;

$$\begin{aligned}\Delta\varepsilon^{el}{}_i{}' &= \left(C_{Gi}\sigma'(t_j)-\varepsilon^{el}{}_i{}'(t_j)\right)\left(1-e^{-\Delta t/T_i}\right)+C_{Gi}\cdot\Delta\sigma'\left(1-\frac{T_i}{\Delta t}\left(1-e^{-\Delta t/T_i}\right)\right)\\ \Delta\varepsilon^{el}{}_{im} &= \left(C_{Ki}\sigma_m(t_j)-\varepsilon^{el}{}_{im}(t_j)\right)\left(1-e^{-\Delta t/T_i}\right)+C_{Ki}\cdot\Delta\sigma_m\left(1-\frac{T_i}{\Delta t}\left(1-e^{-\Delta t/T_i}\right)\right)\end{aligned} \tag{2.1.9}$$

2.1.3. Incremental constitutive equations for linear viscoelasticity

From Eqs. (2.4.6) - (2.4.9), the incremental stresses are obtained as follows;

$$\Delta\sigma = \Delta\sigma' + \Delta\sigma_m = \frac{2\Delta\varepsilon'}{\bar{C}_G(t)} + \frac{3\Delta\varepsilon_m}{\bar{C}_K(t)} - \frac{\Delta\varepsilon_{\alpha}{}'}{\bar{C}_G(t)} - \frac{\Delta\varepsilon_{\alpha m}}{\bar{C}_K(t)} - \frac{\Delta\varepsilon^{\theta}}{\bar{C}_K(t)} \tag{2.1.10}$$

where

$$\begin{aligned}\Delta\varepsilon' &= \frac{1}{2}\left(C_G+\frac{\Delta t}{2\eta_G}\right)\Delta\sigma' + \sum_i\frac{C_{Gi}}{2}\left\{1-\left[1-\exp\left(-\frac{\Delta t}{T_{Gi}}\right)\right]\frac{T_{Gi}}{\Delta t}\right\}\Delta\sigma'\\ &+\frac{\Delta t}{2\eta_G}\sigma'(t)+\sum_i\frac{C_{Gi}}{2}\left[1-\exp\left(-\frac{\Delta t}{T_{Gi}}\right)\right]\sigma'(t)-\sum_i\left[1-\exp\left(-\frac{\Delta t}{T_{Gi}}\right)\right]\varepsilon_i'(t)\\ \Delta\varepsilon_a{}' &= \frac{\Delta t}{\eta_G}\sigma'(t)+\sum_i C_{Gi}\left[1-\exp\left(-\frac{\Delta t}{T_{Gi}}\right)\right]\sigma'(t)-2\sum_i\left[1-\exp\left(-\frac{\Delta t}{T_{Gi}}\right)\right]\varepsilon_i'(t)\end{aligned} \tag{2.1.11}$$

$$\Delta\varepsilon_m = \frac{1}{2}\left(C_K + \frac{\Delta t}{3\eta_K}\right)\Delta\sigma_m + \sum_i \frac{C_{Ki}}{3}\left\{1 - \left[1 - \exp\left(-\frac{\Delta t}{T_{Ki}}\right)\right]\frac{T_{Ki}}{\Delta t}\right\}\Delta\sigma_m$$

$$+\frac{\Delta t}{3\eta_K}\sigma_m(t) + \sum_i \frac{C_{Ki}}{3}\left[1-\exp\left(-\frac{\Delta t}{T_{Ki}}\right)\right]\sigma_m(t) - \sum_i\left[1-\exp\left(-\frac{\Delta t}{T_{Ki}}\right)\right]\varepsilon_{mi}(t) \tag{2.1.12}$$

$$\Delta\varepsilon_{am} = \frac{\Delta t}{\eta_K}\sigma_m(t) + \sum_i C_{Ki}\left[1-\exp\left(-\frac{\Delta t}{T_{Ki}}\right)\right]\sigma_m(t) - 3\sum_i\left[1-\exp\left(-\frac{\Delta t}{T_{Ki}}\right)\right]\varepsilon_{mi}(t)$$

$$\overline{C}_G(t) = C_{Gg} + \frac{\Delta t}{2\eta_G} + \sum_i C_{Gi}\left\{1-\left[1-\exp\left(-\frac{\Delta t}{T_{Gi}}\right)\right]\frac{T_{Gi}}{\Delta t}\right\}$$

$$\overline{C}_K(t) = C_{Kg} + \frac{\Delta t}{2\eta_K} + \sum_i C_{Ki}\left\{1-\left[1-\exp\left(-\frac{\Delta t}{T_{Ki}}\right)\right]\frac{T_{Ki}}{\Delta t}\right\} \tag{2.1.13}$$

2.2. Incremental constitutive equations for nonlinear viscoelasticity under uniaxial tension

Depending on strain level of ETFE Film, the creep strain shows nonlinearity. Accordingly, the relation between linear strain vector, $\{\varepsilon^{el}\}$ and nonlinear strain vector, $\{\varepsilon^{nl}\}$ is expressed in the following equations with nonlinear viscoelastic coefficient, $\beta(\overline{\sigma})$. Provided that the expansion and contraction part accompanying temperature change is excluded.

$$\{\varepsilon^{nl}\} = \beta(\overline{\sigma})\cdot\left\langle\{\varepsilon^{el}\} - \{\varepsilon^{\theta}\}\right\rangle + \{\varepsilon^{\theta}\} \tag{2.2.1}$$

where

$$\overline{\sigma} = \left(\sigma_x{}^2 - \sigma_x\sigma_y + \sigma_y{}^2 + 3\tau_{xy}{}^2\right)^{1/2} \tag{2.2.2}$$

Put equation of the nonlinear viscoelastic coefficient $\beta(\overline{\sigma})$ in the following form where the coefficients B_2, B_1, B_0 are calculated separately.

$$\beta(\overline{\sigma}_i) = B_2\overline{\sigma}_i{}^2 + B_1\overline{\sigma}_i + B_0 \tag{2.2.3}$$

Here, regarding each strain vector during time interval t_j, t_{j+1}, the equation will be as follows;

$$\{\varepsilon^{nl}{}_j\} = \beta(\overline{\sigma}_j).\langle\{\varepsilon^{el}{}_j\} - \{\varepsilon^{\theta}{}_j\}\rangle + \{\varepsilon^{\theta}{}_j\} \tag{2.2.4}$$

$$\{\varepsilon^{nl}{}_{j+1}\} = \beta(\overline{\sigma}_{j+1}).\langle\{\varepsilon^{el}{}_{j+1}\} - \{\varepsilon^{\theta}{}_{j+1}\}\rangle + \{\varepsilon^{\theta}{}_{j+1}\} \tag{2.2.5}$$

Subtract equation (2.2.5) from equation (2.2.4) to get the following equation of the nonlinear viscoelastic strain increment vector $\{\Delta\varepsilon^{nl}{}_{j+1}\}$;

$$\begin{aligned}\{\Delta\varepsilon^{nl}{}_{j+1}\} &= \{\varepsilon^{nl}{}_{j+1}\} - \{\varepsilon^{nl}{}_j\} \\ &= \left[\beta(\overline{\sigma}_{j+1}) - \beta(\overline{\sigma}_j)\right]\left[\{\varepsilon^{el}{}_j\} - \{\varepsilon^{\theta}{}_j\}\right] + \beta(\overline{\sigma}_{j+1})\left[\{\Delta\varepsilon^{el}{}_{j+1}\} - \{\Delta\varepsilon^{\theta}{}_{j+1}\}\right] + \{\Delta\varepsilon^{\theta}{}_{j+1}\}\end{aligned} \tag{2.2.6}$$

From the above, we can obtain the nonlinear viscoelastic strain increment vector $\{\Delta\varepsilon^{nl}{}_{j+1}\}$ by using the nonlinear viscoelastic coefficient $\beta(\sigma)$.

2.3. Time-temperature superposition principle

Consider the creep compliance C at two temperatures T and T_0. The principle of time-temperature superposition states that the change in temperature from T and T_0 is equivalent to multiplying the time scale by a constant factor a_T which is only a function of the two temperatures T and T_0. In other words,

$$\log(a_{T_0}(T)) = \log(t/t') \tag{2.3.1}$$

where t and t' denote the original and shifted times, respectively. The shift factor, a_T, is also expressed as follows with the activation energy ΔH,

$$\log_{10} a_T(T) = \frac{1}{2.303}\frac{\Delta H}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right) \tag{2.3.2}$$

where $R = 8.314\times10^{-3}\,kJ/(mol\cdot K)$ is applied.

3. Evaluation of constants used in the incremental model constitutive equations

3.1. Creep compliance of ETFE

In our previous paper, in order for the mathematical expresion to be compatible with the experimental results by Moriyama and Kawabata, a type of generalized Voigt model is proposed assuming several constants.

In this paper, in order to express in more details the high temperature characteristics, a minimum retardation time is assumed to be 4.90E-07 *sec*, then the constants are evaluated again. The results are shown in Table 3.1.1 and using C_g=4.14E-04.

The deviatoric and volumetric components for compliance of elastic spring element are expressed as follows.

$$\begin{aligned} C_{Gg} &= 2(1+\nu_c)C_G, \quad C_{Gi} = 2(1+\nu_c)C_i \\ C_{Kg} &= (1-2\nu_c)C_G, \quad C_{Ki} = (1-2\nu_c)C_i \end{aligned} \tag{3.1.1}$$

where, ν_c is creep Poisson's ratio.

Table 3.1.1 : Retardation time T_i and compliance C_i

i	T_i	C_i	i	T_i	C_i	i	T_i	C_i
1	9.13E+13	9.12E-04	10	9.35E+06	1.72E-05	19	9.57E-01	1.25E-05
2	3.65E+12	2.37E-04	11	1.87E+06	2.69E-04	20	1.91E-01	6.04E-05
3	7.30E+11	6.65E-04	12	3.74E+05	4.70E-05	21	7.66E-03	1.66E-05
4	1.46E+11	2.65E-04	13	7.48E+04	1.98E-04	22	1.53E-03	8.20E-07
5	2.92E+10	1.07E-03	14	1.50E+04	2.22E-05	23	3.06E-04	1.48E-04
6	5.84E+09	1.54E-04	15	2.99E+03	1.35E-04	24	1.23E-05	1.92E-05
7	1.17E+09	7.95E-04	16	5.98E+02	3.49E-05	25	2.45E-06	5.54E-05
8	2.34E+08	1.21E-04	17	1.20E+02	1.28E-04	26	4.90E-07	7.44E-06
9	4.67E+07	4.61E-04	18	4.79E+00	6.30E-05			

3.2. Activation energy ΔH

In this paper, similarly as in previous paper, the data of Moriyama and Kawabata[1,2] is used. Moriyama and Kawabata[1,2] evaluated and presented the activation energy, ΔH , of ETFE. The results are shown in Table 3.2.1 and Figure 3.2.1. These values are to be utilized later in the present analysis.

Table 3.2.1 : Activation energy[1,2]

temperature T	activation energy ΔH
$T <$ 40°C	113.707
40°C $< T <$ 90°C	342.261
90°C $< T$	447.237

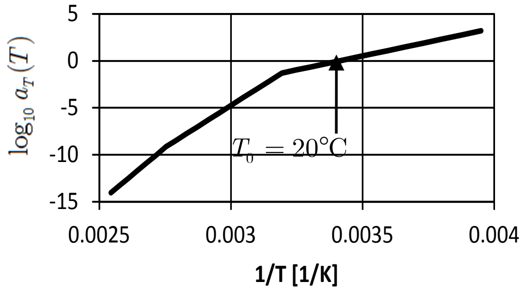

Figure 3.2.1 : Relationship between inverse of temperature T and shift factor represented in $\log_{10} a_T(T)$ with reference temperature T_0 of 20°C

3.3 Coefficient of linear expansion $\alpha(T)$

Coefficient of linear expansion $\alpha(T)$ is obtained through tests based on JIS K 7197-1991[13]. It's Testing method for linear thermal expansion coefficientof plastics by thermomechanical analysis. Rise Film temperature from room temperature to 423K then cool down to -223K. After that, Coefficient of linear expansion is obtained by rising it again to 423K. The results are shown in figure 3.3.1. The next approximate equation is obtained from these results.

$$\alpha(T) = -2.057\times10^{-8}T^4 + 3.289\times10^{-5}T^4 - 1.847\times10^{-2}T^2 + 4.443T - 379.6 \tag{3.3.1}$$

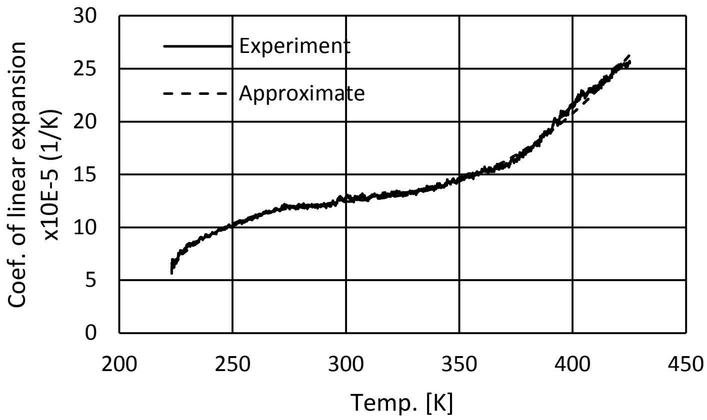

Figure 3.3.1 : Coefficient of linear expansion $\alpha(T)$

4. UNIAXIAL CREEP TEST OF ETFE FILM

4.1. Uniaxial creep test of fixed temperature

Uniaxial tensile testing machine is used to carry out uniaxial creep test with fixed temperature. Shape of test specimen is shown in figure 4.1.1. Test conditions are shown in table 4.1.1. Results of the creep test are shown in table 4.1.2. When considering the temperature strain, it is necessary to pay attention to not only the temperature strain of the specimen but also to the temperature strain of the jig.

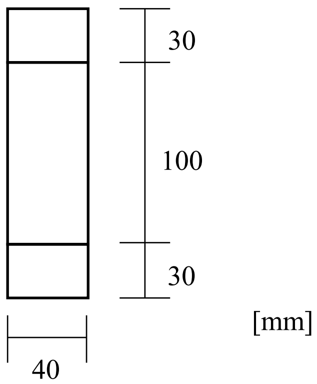

Figure 4.1.1 : Shape of test specimen for uniaxial creep test

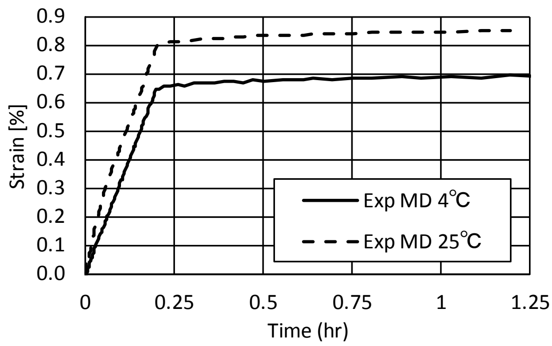

Figure 4.1.2 : Strain – Time relationship

Table 4.1.1 : Uniaxial tensile test conditions

Film thickness	$250\mu m$
Direction	MD
Width of test specimen	40mm
Distance between chucks	100mm
Max stress	6.1MPa
Loading rate	0.5MPa/min
Present temperature	Fixed temperature 4 and 25 °C

4.2. Uniaxial creep test of 30°C temperature change

Uniaxial tensile testing machine is used to carry out uniaxial creep test accompanied with change in temperature. Conditions of temperature change are shown in table 4.2.1. Shape of test specimen is shown in figure 4.1.1.

Preset temperature is shown in table 4.2.1 and temperature setting values during test is shown in figure 4.2.1. Test results are shown in figures 4.2.2 and 4.2.3.

Table 4.2.1 : Setting of temperature change

Initial temperature 30°C, loading time and 1 hour soaking 30°C - 0°C, 6 cycles Temperature rate is $30°C/hr$ for cycling time

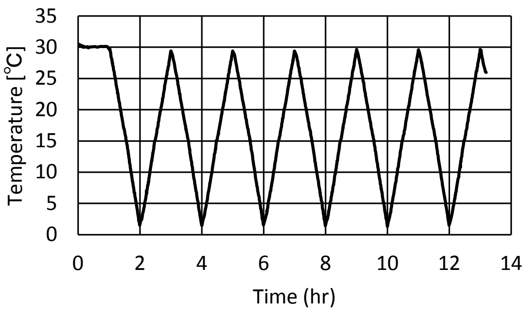

Figure 4.2.1 : Temperature of creep test

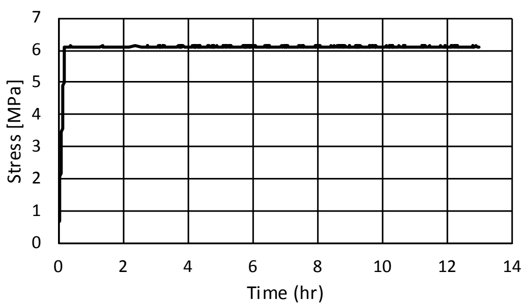

Figure 4.2.2 : Stress-Time relationship

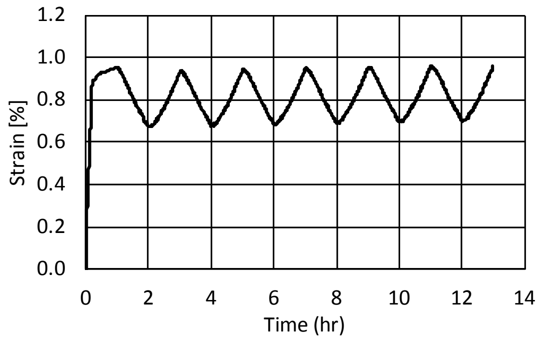

Figure 4.2.3 : Strain-Time relationship

4.3. Uniaxial creep test of $10°C$ temperature change

Uniaxial tensile testing machine is used to carry out uniaxial creep test accompanied with change in temperature. Conditions of temperature change are shown in table 4.3.1. Shape of test specimen is shown in figure 4.1.1.

Preset temperature is shown in table 4.3.1 and temperature setting values during test is shown in figure 4.3.1. Test results are shown in figures 4.3.2 and 4.3.3.

Table 4.2.1 : Setting of temperature change

Initial temperature $30°C$, loading time and 3 hour soaking $30-0°C$, $20-10°C$, $10-0°C$, 5 cycles each Temperature rate is $10°C/15\,\mathrm{min}$ for cycling time

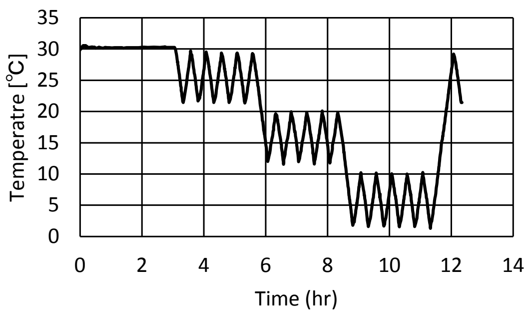

Figure 4.3.1 : Temperature of creep test

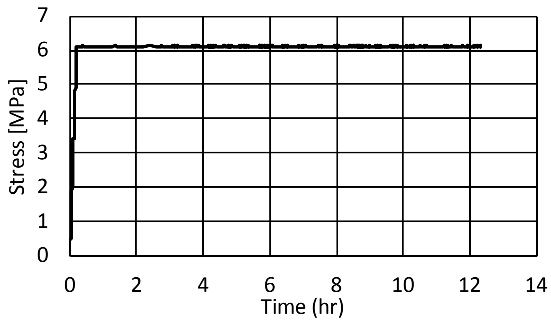

Figure 4.3.2 : Stress - Time relationship

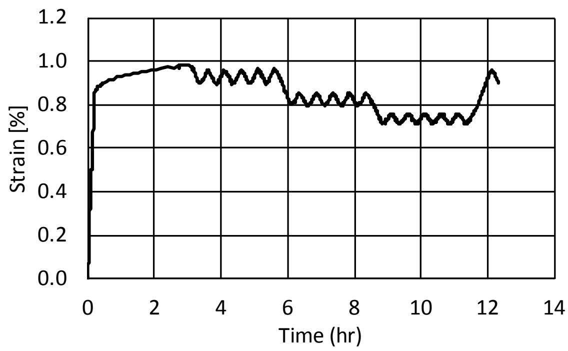

Figure 4.3.3 : Strain - Time relationship

5. SIMULATION OF EXPERIMENTAL TEST

Using the proposed constitutive equation, simulation of uniaxial creep test carried out in section 4 is performed. The values of the coefficients mentioned in section 3 are used. Simulation results are shown in figures 5.1~5.3. Creep strain in both of them can be confirmed to be sufficiently estimated.

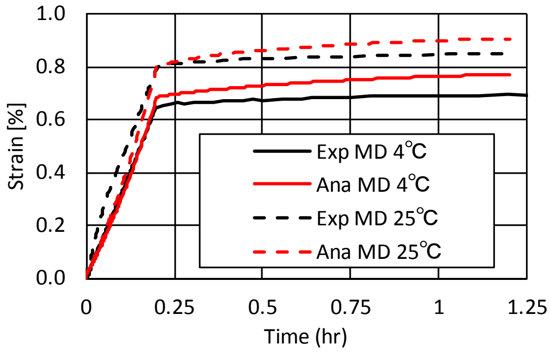

Figure 5.1 : Strain - Time relationship
(fixed temperature)

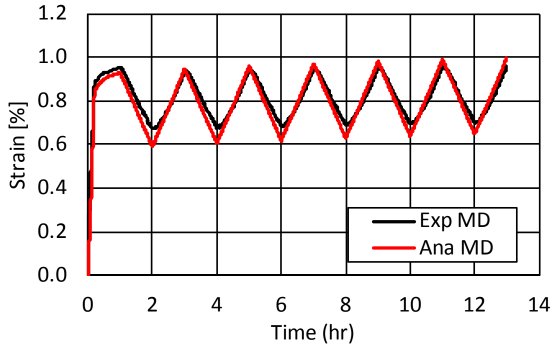

Figure 5.2 : Strain - Time relationship (30°C change)

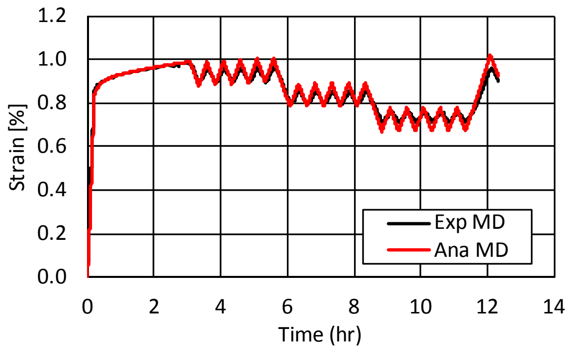

Figure 5.3 : Strain - Time relationship (10°C chage)

6. CONCLUSION

In this paper, the incremental nonlinear viscoelasticity constitutive equation for biaxial tension field was extended to consider the expansion part due to temperature change. Through thermomechanical analysis, the characteristic of expansion due to temperature change is obtained as the coefficient of linear expansion.

As well, performing uniaxial creep test under fixed temperature and under temperature change, uniaxial creep characteristics depended on temperature was confirmed.

Again, using the proposed constitutive equation, simulation of uniaxial creep test that depended on temperature was carried out. Simulation results showed that creep characteristics can be expressed by the proposed equation.

From the above, it was confirmed that elapsed time, stress change and temperature change can be taken into account using the constitutive law. In order to make comparison with the test results of limited conditions, it is necessary to carry out additional comparative studies. For example, biaxial creep accompanied with temperature change in random stress ratio and so on.

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