Characterization of Nonlinear Viscoelastic Behavior Using a Dynamic Mechanical Approach

Thomas W. Strganac,* Alan Letton,† Debbie Flowers Payne,‡ and Bruce A. Biskup§
Texas A&M University, College Station, Texas 77843

The authors present a method to characterize nonlinear viscoelastic behavior using measurements from dynamic (oscillatory) mechanical tests. Frequency-derived measurements are transformed into time-domain properties providing the capability to predict long-term material performance without a lengthy experimentation program. Results are presented for thin-film high-performance polymer materials used in the fabrication of high-altitude scientific balloons. Predictions based on a linear test and analysis approach are shown to deteriorate for moderate to high stress levels expected for long-duration balloon systems. Tests verify that nonlinear viscoelastic response is induced by large stresses. Thus, an approach is developed in which the stress-dependent behavior is examined in a manner analogous to modeling temperature-dependent behavior with time-temperature correspondence and superposition principles. The development leads to time-stress correspondence and superposition of measurements obtained through dynamic mechanical tests. Predictions of material behavior using measurements based on linear and nonlinear approaches are compared with experimental results obtained from traditional creep tests. Excellent agreement is shown for the nonlinear model.

Nomenclature

a_T	= temperature-dependent shift factor
a_ε	= strain-dependent shift factor
a_σ	= stress-dependent shift factor
D	= creep compliance
D_0	= initial component of D
E	= relaxation modulus
E^*	= dynamic (or complex) modulus
E'	= storage modulus
E''	= loss modulus
E_∞	= final component of E
g_0, g_1, g_2	= material parameters, Eq. (5)
h_∞, h_1, h_2	= material parameters, Eq. (8)
T	= temperature
t	= time
ΔD	= transient component of D
ΔE	= transient component of E
$\Delta \varepsilon$	= magnitude of oscillatory strain
$\Delta \sigma$	= magnitude of oscillatory stress
δ	= damping
ε	= strain
ε_t	= creep component of strain
ρ	= reduced time (strain dependent)
ρ'	= reduced time (strain dependent)
σ	= stress
σ_0	= stress due to preload
τ	= relaxation time, dummy variable for time
Ψ	= reduced time (stress dependent)
Ψ'	= reduced time (stress dependent)
ω	= frequency

Introduction

THE authors present a method to describe the nonlinear viscoelastic behavior of materials used in the fabrication of high-

*Associate Professor, Department of Aerospace Engineering. Associate Fellow AIAA.
†Associate Professor, Department of Mechanical Engineering.
‡Graduate Research Assistant, Department of Aerospace Engineering.
§Graduate Research Assistant, Department of Aerospace Engineering. Member AIAA.

altitude scientific balloons. The primary objectives of this research include the experimental measurement of nonlinear viscoelastic properties using dynamic (oscillatory) mechanical methods and the development of nonlinear constitutive laws which employ these measurements. Three primary issues are examined: 1) the superposition of material properties measured at different conditions, such that measurements at one condition (for example, temperature or load) are equivalent to measurements at another condition but on a compressed or expanded time scale; 2) the transformation of measurements obtained in the frequency domain into material properties in the time domain, thus characterization is performed on a much shorter time scale; and 3) the nonlinear characterization of material behavior examined in a manner analogous to modeling temperature-dependent behavior using time-temperature correspondence and linear superposition principles.

Many investigators characterize thin-film materials using linear viscoelastic techniques. Wilbeck[1] has developed a constitutive relationship for thin polyethylene films such as those used in high-altitude scientific balloons. Wilbeck predicts the state of stress in the film given strain and temperature histories; however, he shows that the properties of these materials exhibit nonlinear behavior due to the dependence of the behavior on the load history. In several studies, the efforts of Schapery[2-5] form the basis for the characterization of nonlinear behavior of viscoelastic materials. Smart and Williams[6] compare Schapery's theory to the modified superposition principle (MSP) in which the creep behavior is separated into time-dependent and stress-dependent components. Predictions using the MSP are poor; however, Schapery's theory is shown to accurately model the constitutive behavior. In another investigation, Dillard et al.[7] compares Schapery's theory to several nonlinear viscoelastic models, including the MSP. Dillard's findings also suggest that Schapery's theory produces the most accurate results. Additionally, Dillard shows that Schapery's theory is appropriate for complex load histories.

A comparison of experimental results and predictions using Schapery's theory is presented by Crook.[8] Crook's research utilizes the experimental results from traditional creep tests as parameters for Schapery's theory. Crook accurately predicts the strain response of polycarbonate materials to a three-step stress input. In another study, Popelar et al.[9] analyzes a comprehensive set of experimental data obtained from stress relaxation and constant strain-rate tests. Again, the relaxation data are utilized to develop the nonlinear constitutive model, and the nonlinear response is accurately characterized by Schapery's theory.

These earlier studies have shown that Schapery's theory is the most general and the most adaptable of the examined techniques.

Herein, we describe a technique to predict nonlinear viscoelastic response based on Schapery's theory but extended to incorporate results derived from dynamic oscillatory tests. Strganac et al.[10,11] and Letton et al.[12] examine materials retrieved from NASA's Long Duration Exposure Facility (LDEF). The linear viscoelastic characteristics of these materials are determined using dynamic mechanical methods. These studies confirm that, although the linear approach provides an accurate approximation for small strains or loads, predictions based on a linear test and analysis approach deteriorate for moderate to high stress levels. Tests verify that nonlinear viscoelastic response is induced by large stresses, and this nonlinear behavior is not appropriately treated in dynamic mechanical testing methodologies. Yet, dynamic mechanical testing is important as transformation of measurements obtained in the frequency domain into properties in the time domain provides viscoelastic characterization on a much shorter time scale. Payne et al.[13] describes the initial efforts, leading to the study presented herein, to examine nonlinear behavior of materials using superposition of measurements obtained from dynamic mechanical methods.

Theoretical Approach

The constitutive properties of viscoelastic materials are dependent on the rate at which the load or deformation occurs. Additionally, nonlinear viscoelastic behavior exists if the material properties are dependent on the magnitude of stress or strain as well as the rate at which the load or deformation occurs. The theory developed by Schapery allows the material properties to be expressed in terms of either stress- or strain-dependent behavior. This theory is a modification of the single integral solution for linear viscoelasticity at a constant temperature.

For linear theory, the stress and strain are related by the Boltzmann superposition integral

$$\varepsilon(t) = \int_0^t D(t - \tau)\frac{\partial\sigma}{\partial\tau}\, d\tau \qquad (1)$$

where $D(t)$ is the compliance. A similar relation defines stress in terms of strain but is not presented for brevity. By assuming a form of the compliance, such that $D(t) = D_0 + \Delta D(t)$, Eq. (1) may be expressed as

$$\varepsilon(t) = D_0\sigma(t) + \int_0^t \Delta D(t - \tau)\frac{\partial\sigma}{\partial\tau}\, d\tau \qquad (2)$$

Time–Temperature Correspondence

Time–temperature correspondence principles[14] are typically employed to characterize the viscoelastic behavior of materials. The strength of the method is the superposition of data measured on different time scales; properties measured at one temperature are equivalent to those at a second temperature on a compressed or expanded time scale. Furthermore, transformations between measurements in the frequency domain and response in the time domain exist allowing for measurement of properties in the frequency domain and prediction of properties in the time domain. Thus, the properties measured at one temperature and frequency correspond to the properties at another temperature and frequency through a temperature-dependent shift factor

$$E^{\ddagger}(\omega, T_1) = E^{\ddagger}(\omega a_T, T_2) \qquad (3)$$

where $E^{\ddagger}$ represents either the dynamic modulus or a component of the dynamic modulus for the material. This approach is similar to time-temperature correspondence principles in the time domain.

This shift factor is a measure of the temperature dependence of the relaxation process[12] for the material and is determined by the superposition of measurements at two distinct temperatures. The effect of a change in temperature is equivalent to measurements on a different frequency scale. This strategy allows the superposition of measurements taken over a range of temperatures at a specific frequency interval. A master curve of the dynamic modulus as a function of frequency is formed for a reference temperature.

Frequency–Time Transformation

Traditional creep measurements require significant test time to adequately characterize the material response for a large time interval. However, the transformation of the modulus measured in the frequency domain to the modulus in the time domain provides rapid characterization and, consequently, long experimentation is eliminated. A numerical transformation from the frequency domain to the time domain is described by Ninomiya and Ferry[14] for determining the relaxation modulus

$$E(t) = E'(\omega) - 0.40E''(0.4\,\omega) + 0.014E''(10\,\omega)_{t=1/\omega} \qquad (4)$$

where t is the relaxation time.

Time–Stress Superposition

We extend the approach of time–temperature superposition to time-stress superposition based on the work of Schapery. Schapery modifies the constitutive equation to describe nonlinear viscoelastic responses by introducing a reduced time variable which is dependent on the magnitude of the stress. If stress is the independent state variable, Schapery suggests the constitutive behavior may be described by

$$\varepsilon(t) = g_0 D_0\sigma(t) + g_1\int_0^t \Delta D(\Psi - \Psi')\frac{\partial g_2\sigma}{\partial\tau}\, d\tau \qquad (5)$$

where g_0, g_1, and g_2 are stress-dependent material properties, and Ψ and Ψ' are reduced time variables defined by

$$\Psi = \Psi(t) = \int_0^t \frac{dt}{a_\sigma} \qquad (6)$$

$$\Psi' = \Psi'(\tau) = \int_0^\tau \frac{dt}{a_\sigma} \qquad (7)$$

In a similar manner, if strain is the independent state variable, the constitutive equations are

$$\sigma(t) = h_\infty E_\infty\varepsilon(t) + h_1\int_0^t \Delta E(\rho - \rho')\frac{\partial h_2\varepsilon}{\partial\tau}\, d\tau \qquad (8)$$

where h_∞, h_1, and h_2 are strain-dependent material properties, and ρ and ρ' are reduced time variables defined by

$$\rho = \rho(t) = \int_0^t \frac{dt}{a_\varepsilon} \qquad (9)$$

$$\rho' = \rho'(\tau) = \int_0^\tau \frac{dt}{a_\varepsilon} \qquad (10)$$

The parameters g_0, g_1, g_2, h_∞, h_1, and h_2 are unique for each material. The values of these parameters are determined experimentally if traditional creep tests are used; but, with our approach, these parameters are integrated within the experimental measurements. The creep compliance (or relaxation modulus) developed from the experimental measurements will contain the effects of these parameters.

Time–Stress Correspondence

As will be fully described in the subsequent section, the dynamic modulus is measured as a function of preload and frequency, and these measurements are used to describe nonlinear behavior resulting from the preload. Using a method analogous to time–temperature correspondence based on temperature-dependent shift factors, time-stress correspondence[13] is employed to identify stress-dependent shift factors. Thus, the properties measured at one preload and frequency correspond to the properties at another preload and frequency

$$E^{\ddagger}(\omega, \sigma_0) = E^{\ddagger}(\omega a_\sigma, \sigma_0) \qquad (11)$$

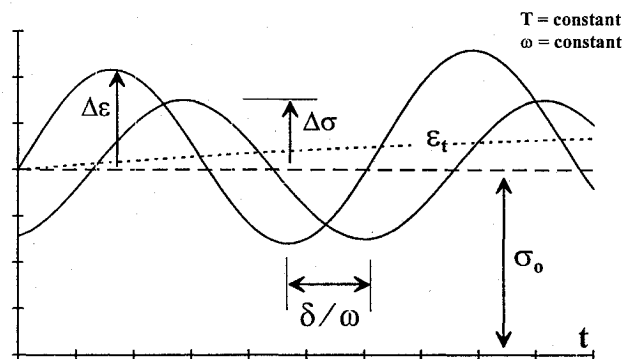where $E^{\ddagger}$ represents either the dynamic modulus or a component of the dynamic modulus for the material, and σ_0 is the preload.

Fig. 1 Force $\Delta\sigma$ and damping δ is measured from an oscillatory deformation $\Delta\varepsilon$ input, constant preload σ_0 is applied.

Fig. 2 Measurements of the dynamic modulus are dependent on the magnitude of the oscillatory deformation $\Delta\varepsilon$ and preload σ_0.

Experimental Approach

Dynamic oscillatory tests[10] are used to measure the viscoelastic response. Experimental measurements are conducted with the Rheometrics Solids Analyzer II. Measurements are obtained through a sweep of frequencies ($0.1 \le \omega \le 100$ rad/s) at a constant temperature and preload. Depending on the nature of the analysis, either the temperature or preload is changed, and new measurements are obtained through a sweep of frequencies. Temperatures range from $-150°C$ ($-238°F$) to the melt temperatures. Preloads may approach the yield of the material. This test strategy is illustrated in Fig. 1. Two parameters are measured directly: the force due to an oscillatory deformation input and the phase lag between input and output. Material damping is measured as the phase lag δ between the measured force (stress) response output

$$\sigma(t) = \sigma_0 + \Delta\sigma e^{i(\omega t + \delta)} \qquad (12)$$

and the oscillatory deformation (strain) input

$$\varepsilon(t) = \varepsilon_t + \Delta\varepsilon e^{i\omega t} \qquad (13)$$

In Eqs. (12) and (13), σ_0 is the stress resulting from the preload which is held constant during the experiment, $\Delta\sigma$ is the measured stress response, and ε_t is the strain (creep) which occurs during the dynamic oscillatory test.

Typically, dynamic oscillatory tests are used to measure the linear viscoelastic properties of the test specimen. A dynamic modulus E^* is derived from these measurements as

$$E^*(\omega, T) = \frac{\Delta\sigma e^{i(\omega t + \delta)}}{\Delta\varepsilon e^{i\omega t}} = |E|e^{i\delta} = |E|\cos\delta + i|E|\sin\delta \qquad (14)$$

where $|E|\cos\delta$ is defined as the storage modulus E' and $|E|\sin\delta$ is defined as the loss modulus E'' (Refs. 14 and 15).

However, in our studies, two sources of nonlinear behavior are identified with the dynamic oscillatory tests.[10,13] The first source is associated with the magnitude of the oscillatory strain $\Delta\varepsilon$. The second source is associated with the magnitude of the preload σ_0. Thus, the development of the dynamic modulus will be modified

$$E^*(\omega, T, \sigma_0) \sim \frac{\sigma_0 + \Delta\sigma e^{i(\omega t + \delta)}}{\varepsilon_t + \Delta\varepsilon e^{i\omega t}} \qquad (15)$$

A preload is used to maintain a tensile load on the specimen throughout the test; however, our results indicate a strong dependence of the measured response due to this preload. Typical measurements of the dynamic modulus are illustrated in Fig. 2. In our measurements of the linear viscoelastic behavior for the material we require that the measured properties are independent of the magnitude of both the oscillatory strain and the preload. In our measurements of the nonlinear viscoelastic behavior for the material we require that the measurements are dependent of only the magnitude of the preload. Thus, in either case, the magnitude of the oscillatory strain is selected such that measurements of the dynamic modulus are independent of the magnitude of oscillatory strain. Nonlinearities are due only to preload.
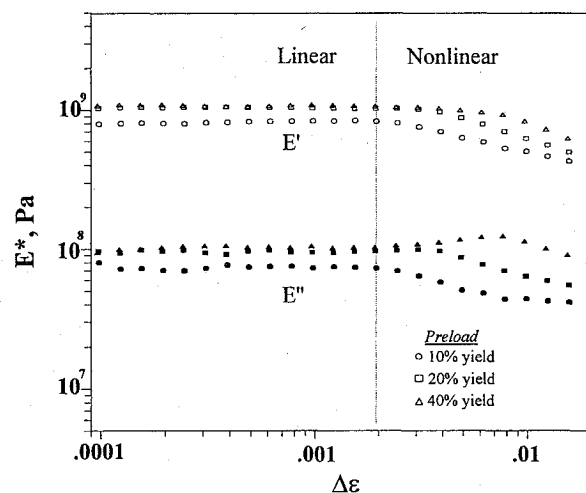
In the linear analysis we measure the dynamic modulus at different temperatures.[12] In the nonlinear analysis we measure the dynamic modulus at different preloads (stresses).[13] In both the linear analysis and nonlinear analysis the process of forming the master curve is identical. The experimental data consist of a collection of measurements obtained for the full range of test frequencies at a constant temperature (or preload for the nonlinear tests). This data establishes a family of curves relating the dynamic modulus to frequency. This family of temperature-dependent (or stress-dependent) curves are used to form a master curve which provides the dynamic modulus over a larger range of frequencies for a reference temperature (or reference preload). The temperature-dependent (or stress-dependent) shift factors are produced as a result of shifting and superposing the measured data.[12] The properties measured at one temperature (or preload) and frequency correspond to the properties at another temperature (or preload) and frequency through the shift factor. The effect of a change in temperature (or preload) is equivalent to measurements on a different frequency scale. We note that the master curve provides the dynamic modulus over a larger range of time when the results are appropriately transformed from the frequency domain to the time domain.

Results

Description of Test Specimens

We examine results for two thin-film polyethylenes—Stratofilm® and Astrofilm—which are used in the fabrication of high-altitude scientific balloons. Stratofilm® (SF-372) is a linear low-density polyethylene manufactured by Winzen International, Inc. Astrofilm (AF-E2) is a low-density polyethylene manufactured by Raven Industries. These films are produced through a blown-film extrusion process which induces a directionality in the properties of the material. Thus, tests are conducted in the machine direction and the transverse direction; tests are not conducted through the thickness. The nominal length of each test specimen is 2.54 cm (1.0 in.), the nominal width is 0.635 cm (0.25 in.), and the nominal film thickness is 0.0203 mm (0.0008 in.).

Linear Analysis with Temperature Effects

Linear viscoelastic characteristics are measured for SF-372 and AF-E2 at temperatures ranging from $-150°C$ ($-238°F$) to the melt temperature of the specimen. For the linear analysis, the dynamic modulus is dependent on the frequency and temperature. Although a preload is used to maintain a tensile load on the specimen, in our measurements of the linear behavior we require that the measurements are independent of the preload.

The dynamic modulus for SF-372 is presented in Fig. 3 for a reference temperature of 20°C (68°F) and the associated temperature-dependent shift factors are presented in Fig. 4. The dynamic modulus for AF-E2 is presented in Fig. 5 for a reference temperature of 20°C (68°F) and the associated temperature-dependent shift factors are
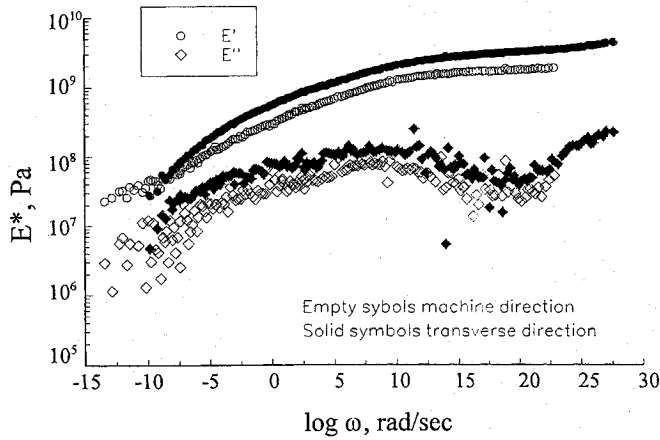
Fig. 3 Master curve for SF-372, derived from temperature–frequency measurements of the dynamic modulus with T_{ref} = 20°C (68°F).

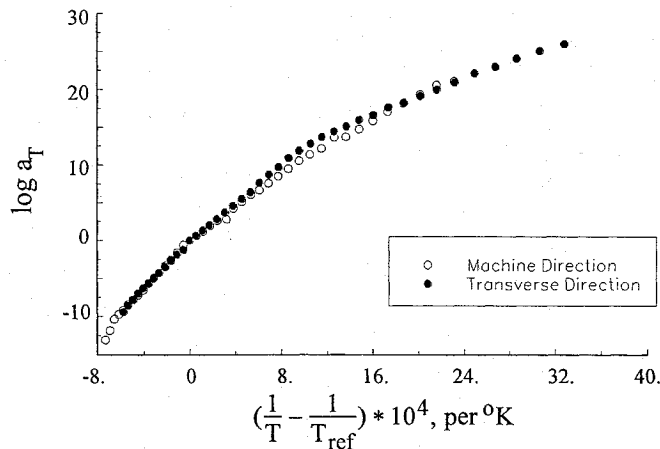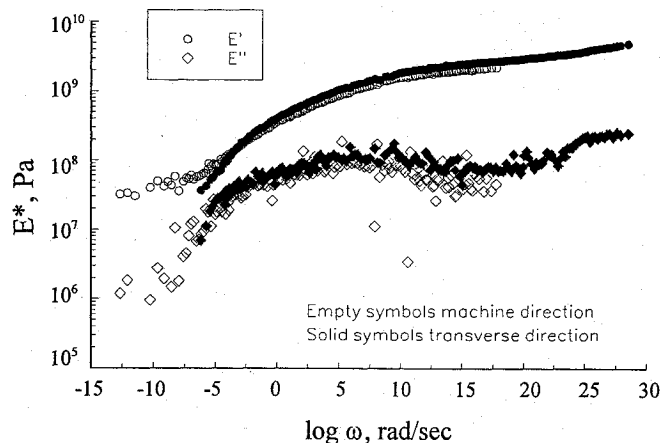Fig. 6 Temperature-dependent shift factors for AF-E2, T_{ref} = 20°C (68°F).
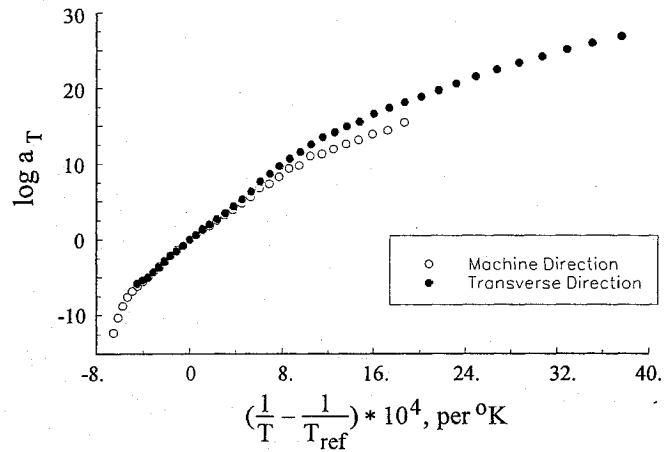

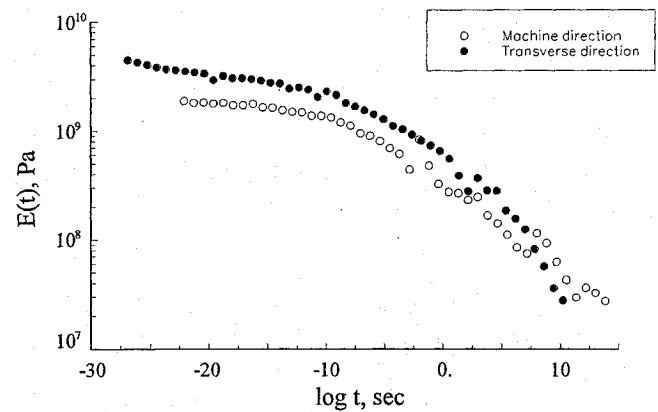Fig. 4 Temperature-dependent shift factors for SF-372, T_{ref} = 20°C (68°F).

Fig. 7 Relaxation modulus for SF-372, derived from measurements of the dynamic modulus (refer to Fig. 3), T_{ref} = 20°C (68°F).
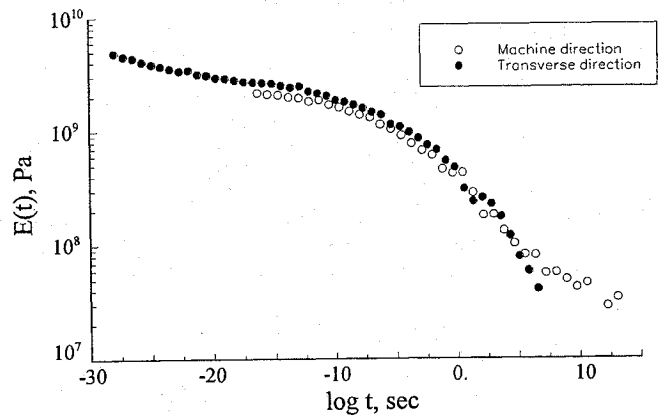

Fig. 5 Master curve for AF-E2, derived from temperature–frequency measurements of the dynamic modulus with T_{ref} = 20°C (68°F).

Fig. 8 Relaxation modulus for AF-E2, derived from measurements of the dynamic modulus (refer to Fig. 5), T_{ref} = 20°C (68°F).

presented in Fig. 6. Although the viscoelastic properties for both materials are measured under identical conditions (frequency and temperature range), the results presented in Figs. 3–6 suggest otherwise. Two reasons for this aberration exist: first, the measured data does not behave in a linear manner (thus, the data cannot be superposed) at the extremely low temperatures (which relates to behavior at high frequency or short time scales); and, second, the melt temperature is not uniform for all specimens.

The relaxation modulus for SF-372 is presented in Fig. 7. The relaxation modulus for AF-E2 is presented in Fig. 8. The measured values of the dynamic modulus and the method of Ninomiya and

Ferry[14] are used to derive the relaxation modulus. Since measurements of the dynamic modulus are used in the derivation, differences in the range of time for the presented data exist for the same reasons as described in the preceding paragraph.

Creep response is predicted using the creep compliance derived from the dynamic oscillatory measurements. These predictions are compared with the creep response measured in traditional creep tests. Figure 9 provides a comparison of predictions and measurements for SF-372. Figure 10 provides a comparison of predictions and measurements for AF-E2. Predictions for two preloads are shown in each figure. As expected due to the nonlinear effects induced by the large stresses due to preload, the predictions clearly deteriorate for both SF-372 and AF-E2 as the preload increases. Consequently, stress-dependent contributions must be included in
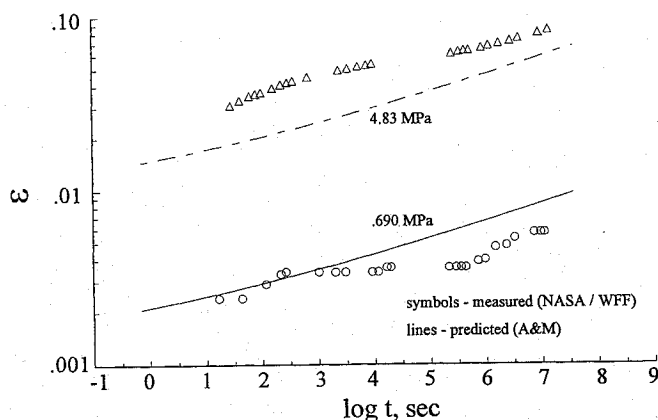
Fig. 9 Creep predicted using the compliance derived from measurements of the dynamic modulus, comparison with traditional creep measurements for SF-372, machine direction (data courtesy of NASA Goddard Space Flight Center/Wallops Flight Facility).
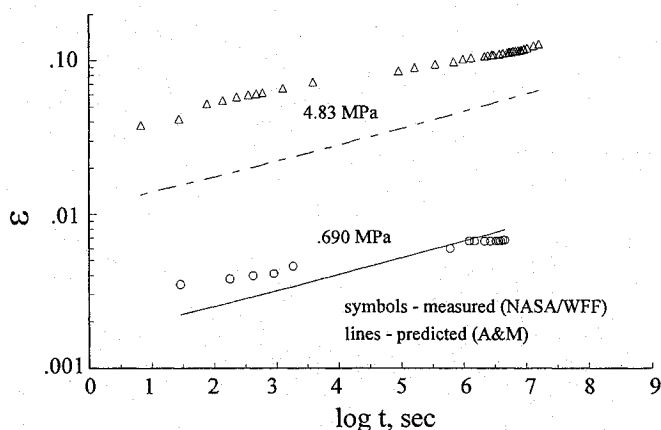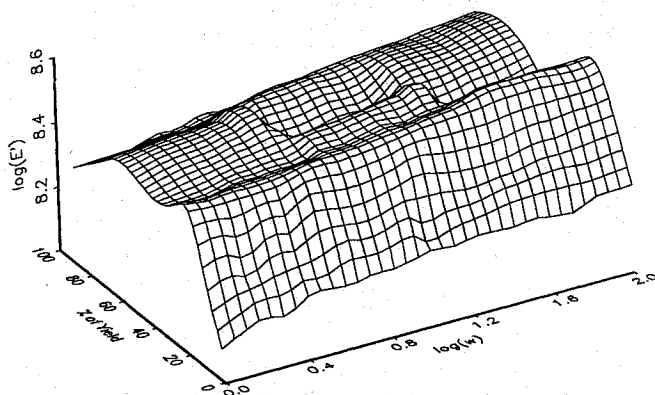

Fig. 10 Creep predicted using the compliance derived from measurements of the dynamic modulus, comparison with traditional creep measurements for AF-E2, machine direction (data courtesy of NASA Goddard Space Flight Center/Wallops Flight Facility).

Fig. 11 Viscoelastic properties measured at several preloads and frequencies, storage modulus E' is shown as a function of preload (measured as percent yield) and frequency, $T_{ref} = 20°C$ (68°F).

the characterization of viscoelastic properties for materials exposed to higher stresses.

Nonlinear Analysis with Preload Effects

The yield stress for these materials is highly dependent on the temperature.[13] The yield stress for these materials is approximately 40 MPa (5800 Ψ) at $T = -100°C$ ($-148°F$) and 9 MPa (1300 Ψ) at $T = 23°C$ (73.4°F) (data courtesy of Winzen International, Inc., these measurements are determined from a 0.2% strain offset on the stress-strain curve). Thus, a preload which is 25% of the yield stress at $T = -100°C$ ($-148°F$) exceeds the yield stress at room
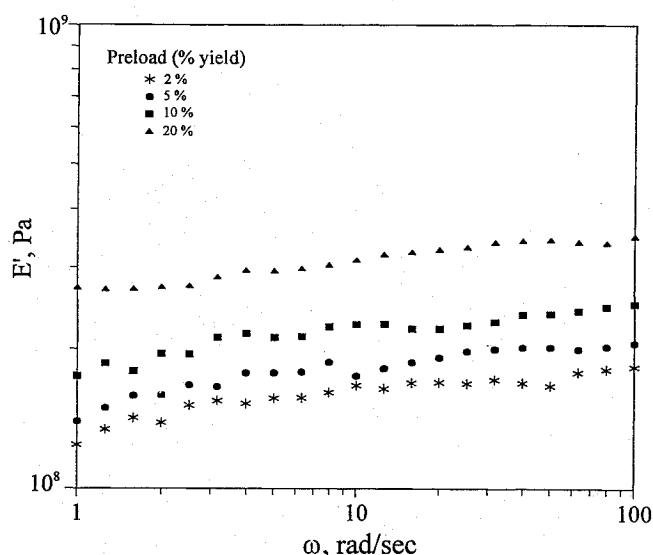
Fig. 12 Stress-dependent measurements obtained for preloads below 30% yield.
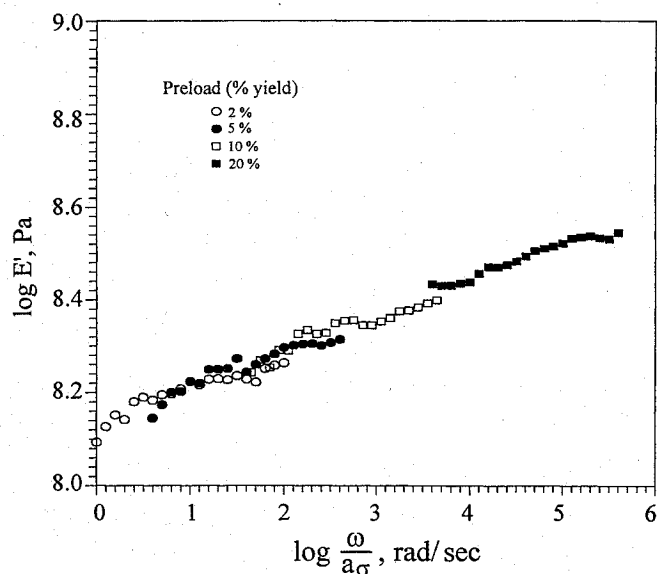
Fig. 13 Master curve of the dynamic modulus derived from time-stress superposition, storage modulus shown for a reference preload of 2% yield.

temperature. We introduce a convention in which we refer to the preload as a percentage of the yield stress; and, therefore, tests performed at different temperatures will be compared with preloads at identical percents of yield stress. Stress-dependent shift factors are also developed using this convention.

A limiting stress is noted in Fig. 11, where the storage modulus is presented as a function of preload and frequency for a temperature of 20°C (68°F). At a preload of approximately 35% yield stress, a drop in E' is observed. This material stiffening is not yet fully understood; consequently, the preload is limited to 30% of the yield stress to avoid complications associated with this region.

Nonlinear viscoelastic characteristics are measured for SF-372 for preloads ranging from 2% to 20% of the yield stress. For the nonlinear analysis, the dynamic modulus is dependent on preload, as well as the frequency and temperature. In these measurements of nonlinear viscoelastic behavior we require that the measurements are dependent on the magnitude of the preload, and measurements are performed at a constant temperature of 23°C (73.4°F).

The results of a series of oscillatory tests performed at several preloads below 30% of the yield stress are shown in Fig. 12. The effect of the stress level on the response of the material is evident. On the basis of superposition, the data presented in Fig. 12 are shifted to obtain the master curve shown in Fig. 13. These results
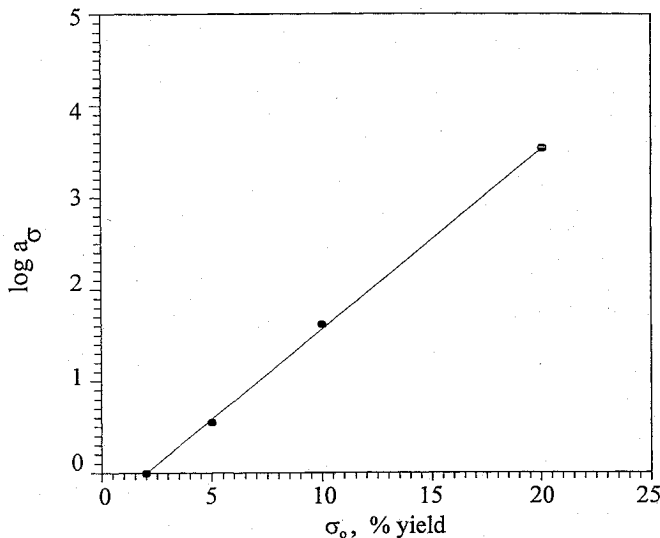
Fig. 14 Stress-dependent shift factors provide correspondence between different stress levels.
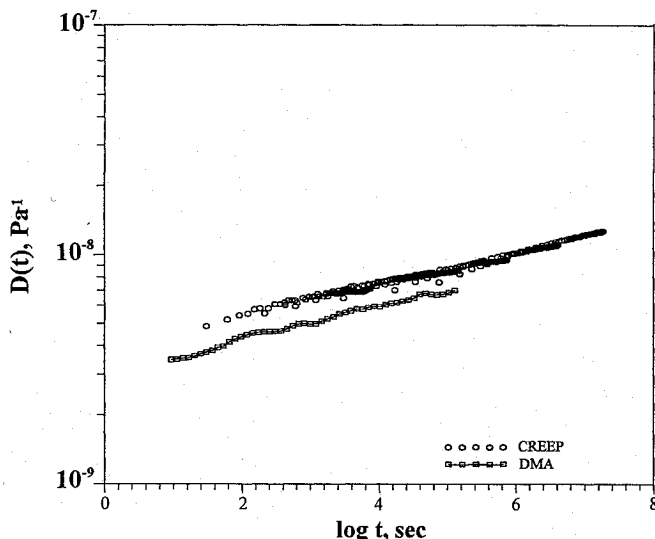

Fig. 15 Creep compliance derived from dynamic (oscillatory) mechanical measurements, comparison to creep compliance data obtained from traditional creep measurements (courtesy of Winzen International, Inc.).

are referenced to a preload level of 2% yield stress. The corresponding stress-dependent shift factors are shown in Fig. 14. The linear behavior of the results in Figs. 13 and 14 establishes confidence in the test and analysis procedure.

Measurements obtained from dynamic oscillatory tests are compared to measurements obtained from traditional creep tests. A comparison of the creep compliance is presented in Fig. 15. The reference stress (preload) is 20% of the yield stress at room temperature. For the dynamic oscillatory tests, the creep compliance is derived from the stress relaxation modulus found using measurements of the dynamic modulus and the transformation of Ninomiya and Ferry. For the comparison data, the creep compliance is derived from traditional creep measurements provided by Winzen International, Inc. The creep compliance is fit to a function of the form $D(t) = D_0 + \Delta D(t)$, and this function is used to predict creep response. On initial observation, differences between the creep compliance may be deemed unacceptable; however, the materials are extremely thin ($\sim$0.0203 mm). The profile thicknesses of these materials have significant variation, and accurate thickness measurements are difficult to consistently obtain. The difference between the two sets of data is easily attributed to very small differences in the measured thickness of the test specimen and very small differences in the stress-dependent shift factors.
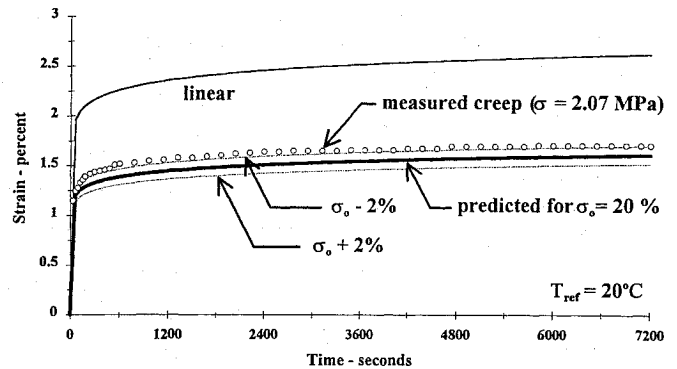
Fig. 16 Creep predicted using the stress-dependent measurements; comparison with traditional creep measurements (courtesy of Winzen International, Inc.).

The results from the dynamic oscillatory tests accurately predict the trends of the measured data (Fig. 16); however, the predictions are slightly underestimated. The difference between the two sets of data reflects the difference in the creep compliance data. The predictions are sensitive to the stress-dependent shift factors.

Conclusions

Dynamic (oscillatory) mechanical tests are used as a basis to characterize the linear (temperature-dependent) and nonlinear (stress-dependent) viscoelastic behavior of materials. Nonlinear stress-dependent behavior may be characterized using correspondence and superposition principles. Thin polyethylene films used in the manufacture of high-altitude scientific balloons are examined. Dynamic oscillatory test measurements produce predictions consistent with the results of traditional creep tests. In addition, the effective transformation of measurements obtained in the frequency domain to response in the time domain allows for the characterization of balloon materials without an extended test program. Results show that the response of the materials examined is best characterized by nonlinear viscoelastic methods.

Acknowledgments

References

[1]Wilbeck, J. S., "Nonlinear Viscoelastic Characterization of Thin Polyethylene Film," NASA CR-156876, Feb. 1981.

[2]Schapery, R. A., "A Theory of Nonlinear Thermoviscoelasticity Based on Irreversible Thermodynamics," Proceedings of the 5th U.S. National Congress of Applied Mechanics, edited by L. E. Goodman, June 1966.

[3]Schapery, R. A., "On the Characterization of Nonlinear Viscoelastic Materials," Polymer Engineering and Science, Vol. 9, 1969, p. 295.

[4]Schapery, R. A., "On a Thermodynamic Constitutive Theory and its Application to Various Nonlinear Materials," Proceedings of the International Union of Theoretical and Applied Mechanics Symposium on Thermoinelasticity, Springer-Verlag, 1969.

[5]Schapery, R. A., "Irreversible Thermodynamics and Variational Principles with Applications to Viscoelasticity," Ph.D. Dissertation, California Inst. of Technology, Pasadena, CA, Aug. 1962.

[6]Smart, J., and Williams, J. G., "A Comparison of Single-Integral Nonlinear Viscoelasticity Theories,"Journal of the Mechanics and Physics of Solids, Vol. 20, 1972, p. 313.

[7]Dillard, D. A., Straight, M. R., and Brinson, H. F., "The Nonlinear Viscoelastic Characterization of Graphite/Epoxy Composites," Polymer Engineering and Science, Vol. 27, 1987, p. 116.

[8]Crook, R. A., "Application of a Nonlinear Viscoelastic Model to the Design of Polymeric Structures," Ph.D. Dissertation, Texas A&M Univ., College Station, TX, Aug. 1991.

[9]Popelar, C. F., Popelar, C. H., and Kenner, V. H., "Viscoelastic Material Characterization and Modeling for Polyethylene," Polymer Engineering and Science, Vol. 30, 1990, p. 577.

[10]Strganac, T. W., Letton, A., Farrow, D. A., Rock, N. I., and Williams, K. D., "The Investigation of Balloon Materials Exposed to the Low Earth Orbit Environment," AIAA Paper 91-3657, Oct. 1991.

[11]Strganac, T. W., Letton, A., Rock, N. I., Williams, K. D., and Farrow, D. A., "Characterization of Polymer Films Retrieved from Long Duration Exposure Facility," *Journal of Spacecraft and Rockets* (to be published).

[12]Letton, A., Farrow, D. A., and Strganac, T. W., "Viscoelastic Characterization of Thin-Film Polymers Exposed to Low-Earth Orbit," *Proceedings of Long Duration Exposure Facility—69 Months in Space, Second Post-Retrieval Symposium*, NASA CP-3194, Pt. 3, San Diego, CA, June 1992, pp. 849–866.

[13]Payne, D., Biskup, B., Letton, A., and Strganac, T. W., "On Nonlinear

Viscoelastic Analysis of Thin Film Materials using a Dynamic Mechanical Approach," *Proceedings of the 34th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, (La Jolla, CA), AIAA, Washington, DC, 1993, pp. 2364–2370 (AIAA Paper 93-1578).

[14]Ferry, J. D., *Viscoelastic Properties of Polymers*, third ed., Wiley, New York, 1980.

[15]Findley, W. N., Lai, J. S., and Onaran, K., *Creep and Relaxation of Nonlinear Viscoelastic Materials*, edited by H. A. Lauwerier and W. T. Koiter, North Holland, New York, 1976.