Constitutive Models for 3M Pressure Sensitive Adhesives

Small Strain Model

Introduction

Pressure-sensitive adhesives (PSAs) are used in many bonding applications and can provide both good adhesion and damping performance. These materials are generally soft, and their mechanical response exhibits both rate and temperature-dependency. In order to accurately model the response of a PSA using the Finite Element Method (FEM), an appropriate constitutive model must be selected, and the parameters associated with this constitutive model must be derived using experimental measurements. To help our customers be successful in their product development and modeling efforts, 3M has established standardized procedures for characterizing PSAs, fitting constitutive model parameters, and subsequently exporting material models for use in commercial finite element codes. This document describes the testing and parameter fitting methods used to define a small strain viscoelasticity model. Considerations associated with the usage of these material models are also covered.

Topics covered include:

- Nomenclature
- Characterization methods
- Constitutive equations
- Parameter fitting
- Software support
- Modeling considerations
- References
- Trademarks
- Disclaimer

Nomenclature

Term	Definition
Material data card (MDC) files	Text-based files containing the definition of a material model, including the associated parameters. These files typically use a code-specific format or an XML file format.
Pressure sensitive adhesive (PSA)	A sticky, viscoelastic material used to bond two substrates
Linear Elasticity	The term used to describe materials in which the elastic (i.e., recoverable) stress is proportional to strain. This assumption is typically only valid under small strains.
Viscoelasticity	The term used to describe materials that exhibit both viscous and elastic responses under deformation. Viscoelastic materials exhibit a time and rate-dependent response, including an increase in effective modulus as a function of strain rate, and a decrease in stress (i.e., stress relaxation) under a constant strain.
Linear viscoelasticity	The term used to describe viscoelastic materials which obey the time-temperature superposition principle.
Small strain viscoelasticity	A constitutive model based on the combination of linear elasticity and linear viscoelasticity.
Time-temperature superposition (TTS)	A principle of linear viscoelasticity in which the moduli measured at low frequencies can be treated as equivalent to the moduli measured at high temperatures. Conversely, moduli measured at high frequencies can be equated to moduli measured at low temperatures. This equivalency allows the derivation of a *master curve* from DMA tests performed over a limited range of frequencies and temperatures. The correlation between time and temperature is often defined by the Williams-Landau-Ferry (WLF) equation.
Dynamic mechanical thermal analysis (DMTA)	An analysis technique often used to measure the moduli of viscoelastic materials. A sinusoidal strain is applied to a sample, and the phase-shifted sinusoidal stress response gives a complex modulus at a given oscillation frequency and temperature (see test method description below). Used to

	define the *master curve* associated with a material.
Master curve	A reference curve which defines modulus as a function of frequency at a reference temperature. The modulus vs. frequency curves at other temperatures can be derived by shifting the reference curve along the frequency axis using a shift factor (e.g., the WLF equation).
Elastic modulus	For a linear elastic material, the ratio of normal stress to normal strain.
Shear modulus	For a linear elastic material, the ratio of shear stress to shear strain.
Poisson's ratio	For a linear elastic material, the negative of the ratio of lateral strain to axial strain (and a measure of the compressibility of a material). For PSAs the Poisson's ratio is typically around 0.49.
Prony series	Linear viscoelasticity is most commonly defined using the *Generalized Maxwell* model. The Maxwell model can be represented by a parallel series of elements, each consisting of a viscous damper connected in series with an elastic spring. Each element is represented by a normalized modulus g_i and a relaxation time τ_i. The Prony series is the set of these terms. Note that separate Prony series can be defined for the deviatoric and volumetric response of a material.

Characterization methods

The material model is built from a calibration data set obtained through dynamic mechanical/thermal analysis (DMTA). In the DMTA test, the material is subjected to small oscillatory shear strains at frequencies between 0.01 and 100 Hz while stepping through a range of temperatures. Due to the time-temperature superposition (TTS) principle, an equivalency can be made between temperature and frequency shifts. This equivalency is defined in terms of a *shift factor* which enables the translation of the modulus vs. frequency curves along the frequency axis as a function of the difference between the experimental temperature value and a reference temperature. In this way, a *master curve* can be constructed which defines the modulus vs. frequency curve at a single reference temperature over a much larger frequency range (~10^{-5}-10^{10} Hz) than can be achieved using standard DMTA equipment. DMTA testing standards are well defined (Macosko 1994) as are the procedures used to derive shift factor parameters and master curves (Ferry 1980).

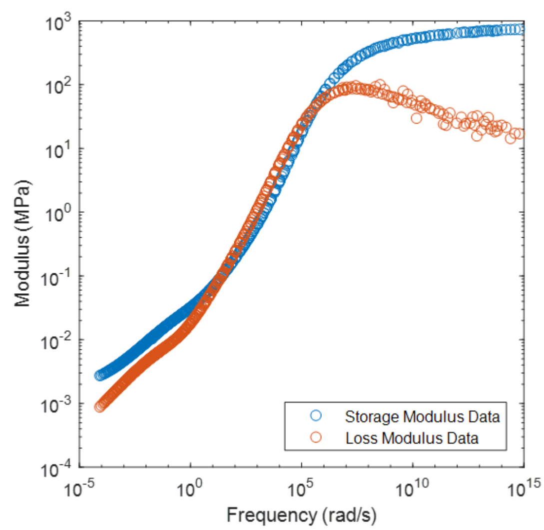

Figure 1. Example Master Curve

In a typical 3M DMTA test, the PSA is laminated to create a thin (e. g., 1 mm thick) sheet, cut to a diameter of 8 mm, and fixtured between parallel plates in the instrument. A moderate normal force of ~50 g is applied to the sample to ensure constant contact between the adhesive and the plates. The application of a normal force rather than a specified gap ensures that normal forces do not become excessively large at elevated temperatures due to thermal expansion. Frequency sweeps with logarithmically sampled frequencies are performed at 5° C isothermal steps over a temperature range relevant to the material. The raw data obtained from this test, including frequency, temperature, and complex modulus, is subsequently transformed into a master curve (Figure 1).

The master curve dataset consists of the storage and loss moduli as a function of frequency at the reference temperature. The storage G' and loss G'' moduli are components of the complex modulus G^*:

$$G^* = G' + jG'' \tag{1}$$

These moduli can be related to the complex stress and strain histories through the relationships:

$$G' = \frac{\sigma_o}{\varepsilon_o} \cos\delta \tag{2}$$

$$G'' = \frac{\sigma_o}{\varepsilon_o} \sin\delta \tag{3}$$

Where σ_o and ε_o are the stress and strain amplitudes, respectively, and δ is the phase shift between the stress and strain values.

The storage and loss modulus values can be used directly within a frequency-domain analysis. However, for a time-domain analysis the master curve must be used to create a Prony series using the procedure described in the parameter fitting section.

The WLF equation is frequently used to approximate the shift factors used in construction of the master curve:

$$-log(A_T) = h(T) = \frac{C_1(T-T_R)}{C_2+(T-T_R)} \tag{4}$$

where A_T is the frequency shift factor, T_R is the reference temperature, and C_1 and C_2 are fitting parameters.

Constitutive equations

For a small strain viscoelastic model, the relaxation modulus $G(\tau)$ can be defined as:

$$G(\tau) = G_o\left[1 - \sum_{i=1}^{N} g_i\left(1 - e^{-\tau/\tau_i}\right)\right] \tag{5}$$

where G_o is the *instantaneous modulus*, N defines the number of terms in the Prony series, and $g_i \equiv G_i/G_o$ and τ_i are, respectively, the normalized modulus and relaxation times associated with each Prony series term. Note that the instantaneous modulus represents the material response that would be observed at very high frequencies or strain rates. The *long-term modulus* G_∞ (which defines the material response that would be observed at very low frequencies or strain rates) is defined as:

$$G_\infty = G_o\left(1 - \sum_{i=1}^{N} g_i\right) \tag{6}$$

The deviatoric engineering stress tensor **S** can be related to the engineering strain tensor **e** through the equation:

$$\mathbf{S} = 2G_o\left(\mathbf{e} - \sum_{i=1}^{N} g_i \mathbf{e}_\mathrm{i}\right) \tag{7}$$

where $\mathbf{e}_i$ is the viscous strain tensor associated with the Prony series term i. These viscous strains are updated at each time increment using the relationship:

$$\mathbf{e}_i^{n+1} = \mathbf{e}_i^{n} + \frac{\tau_i}{\Delta\tau}\left(\frac{\Delta\tau}{\tau_i} + e^{-\tau/\tau_i} - 1\right)\Delta\mathbf{e} + \left(1 - e^{-\tau/\tau_i}\right)(\mathrm{e}^n - \mathbf{e}_i^n) \tag{8}$$

In this equation, $\Delta\tau$ is the *reduced time increment*:

$$\Delta\tau = \frac{A_T^{-1}(T^{n+1}) - A_T^{-1}(T^n)}{h(T^{n+1}) - h(T^n)}\Delta t \tag{9}$$

where T^n and T^{n+1} are the temperatures as the beginning and end of the time increment, respectively, and Δt is the actual time increment.

Parameter fitting

The time-domain Prony series is derived from the frequency-domain storage G' and loss G'' moduli by first using Fourier transforms to convert the Prony series to the frequency domain (Abaqus 2019):

$$G'(\omega) = G_o\left[1 - \sum_{i=1}^{N} g_i\right] + G_o \sum_{i=1}^{N} \frac{g_i \tau_i^2 \omega^2}{1+\tau_i^2 \omega^2} \tag{10}$$

$$G''(\omega) = G_o \sum_{i=1}^{N} \frac{g_i \tau_i \omega}{1+\tau_i^2 \omega^2} \tag{11}$$

A nonlinear least-squares regression can be used to obtain the Prony series terms by minimizing the error function χ^2:

$$\chi^2 = \sum_{i=1}^{M}\left[(\ln(G_s) - \ln(G_s^t))_i^2 + (\ln(G_l) - \ln(G_l^t))_i^2\right] \tag{12}$$

where M is the number of data points in the master curve, and G_s^t and G_l^t are, respectively, the measured storage and loss moduli. Note that the instantaneous modulus G_o is also derived as part of the fitting process.

In practice, the number of Prony series terms N and the relaxation times τ_i are often selected so that the frequency content of the master curve is well represented, and only the optimal values of the normalized moduli g_i are obtained through the parameter fitting process. Alternatively, optimization methods can be used to derive both the normalized moduli and relaxation times, or to minimize the number of Prony series terms.

The Poisson's ratio ν can be obtained from uniaxial compression or tension tests, but, for PSAs, is typically assumed to be 0.45. The initial bulk modulus K_o, if required by the finite element program, is calculated using the equation:

$$K_o = \frac{2G_o(1+\nu)}{3(1-2\nu)} \tag{13}$$

Software support

3M application engineers can currently provide material data card (MDC) files for 3M PSAs in formats compatible with the following finite element analysis codes:

- Abaqus™
- ANSYS® Mechanical APDL (MAPDL)
- ANSYS Workbench®
- LS-DYNA®
- RADIOSS®

Other formats may be available upon request – please contact a 3M application engineer for more information.

Material data card files are distributed using a zipped folder (*.zip) which contains subdirectories for each of the supported analysis codes. If the file format used by a code does not support the definition of units, then the subfolder associated with the program will contain additional subfolders containing material data card files for five common unit systems. The unit system associated with a file is also identified by a comment line within the file.

The contents of sample material data card files are shown below:

ABAQUS

For each material, individual input file segments (*.inp) are provided for the m-kg-s, cm-g-s, mm-N-s, mm-g-ms, and in-lbf-s unit systems. The appropriate input file segment can be pasted into the main analysis input file or included using the `*INCLUDE` keyword. Alternatively, the material model can be imported into Abaqus/CAE using `File->Import->Model`.

Sample input file:

```
** 3M Material Data
** Copyright 3M Company
** Material model exported at 10:12 on 2019-04-22
** Adhesive (3M XYZ)
** Unit system: mm-N-s
*Material, name="Adhesive (3M XYZ)"
*Density
1.000000000e-09
*Elastic, type=ISOTROPIC, dependencies=0, moduli=INSTANTANEOUS
1.451900000e+03,  4.500000000e-01
*Viscoelastic, frequency=PRONY
 5.000000000e-01,  0.000000000e+00,  1.000000000e-02
 2.000000000e-01,  0.000000000e+00,  1.000000000e+00
 1.000000000e-01,  0.000000000e+00,  1.000000000e+02
```

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ANSYS MAPDL

For each material, individual ANSYS Parametric Design Language (APDL) scripts (*.ans) are provided for the m-kg-s, cm-g-s, mm-N-s, mm-g-ms, and in-lbf-s unit systems. The appropriate script segment can be read in interactively (or from within another APDL script) using the `/INPUT` command.

Sample input file:

```
! 3M Material Data
! Copyright 3M Company
! Material model exported at 10:10 on 2019-04-22
! Adhesive (3M XYZ)
! Unit system: mm-N-s
! Note that the material ID (matId) must be modified, as appropriate
*GET,matMx,MAT,,NUM,MAX
matId = matMx + 1
MP,DENS,matId, 1.000000000e-09
MP,  EX,matId, 1.451900000e+03
MP,PRXY,matId, 4.500000000e-01
TB,PRONY,matId,,3,SHEAR
TBDATA, 1, 5.000000000e-01, 1.000000000e-02
TBDATA, 3, 2.000000000e-01, 1.000000000e+00
TBDATA, 5, 1.000000000e-01, 1.000000000e+02
```

ANSYS Workbench

For each material, a single MatML 3.1 file (*.xml) is provided in the m-kg-s unit system. The material model can be imported using `File->Import Material Model`. Documentation for the MatML file format can be found at https://www.matml.org/.

LS-DYNA

For each material, individual input file segments (*.k) are provided for the m-kg-s, cm-g-s, mm-N-s, mm-g-ms, and in-lbf-s unit systems. The appropriate input file segment can be pasted into the main analysis input file or included using the *INCLUDE keyword.

Sample input file:

```
*KEYWORD
*COMMENT
3M Material Data
Copyright 3M Company
Material model exported at 14:07 on 2019-10-03
Adhesive (3M XYZ)
Unit system: mm-N-s
Note that the material ID (MID) must be modified, as appropriate
*MAT_GENERAL_VISCOELASTIC
 1,  1.00000e-09,  4.83967e+03, 0, 3
  2.50327e+02,  1.00000e+02,  0.00000e+00,  1.00000e+02
  1.00135e+02,  1.00000e+00,  0.00000e+00,  1.00000e+00
  5.00655e+01,  1.00000e-02,  0.00000e+00,  1.00000e-02
*END
```

RADIOSS

For each material, individual input file segments (*.rad) are provided for the m-kg-s, cm-g-s, mm-N-s, mm-g-ms, and in-lbf-s unit systems. The appropriate input file segment can be pasted into the main analysis input file or included using the `#include` keyword.

Sample input file:

```
# 3M Material Data
# Copyright 3M Company
# Material model exported at 13:55 on 2019-10-03
# Adhesive (3M XYZ)
# Unit system: mm-N-s
# Note that the material identifier (mat_ID) must be modified, as appropriate
/MAT/KELVINMAX/1
Adhesive (3M XYZ)
  1.00000000e-09
  4.83966667e+03  5.00655172e+02
  2.50327586e+02  1.00131034e+02  5.00655172e+01
  1.00000000e+02  1.00000000e+00  1.00000000e-02
```

Modeling considerations

The small strain viscoelastic models provided by 3M Company are derived from small strain measurements, as documented in this paper. The following assumptions and restrictions apply:

- The material models are only appropriate for use in simulations in which the principal strain levels in the adhesives are less that approximately 10%
- The material models are only intended for use with two-dimensional or three-dimensional continuum elements
- The thickness of an adhesive domain in a model should be set equal to the thickness of the 3M PSA product being modeled (refer to the technical data sheets on 3m.citrination.com)
- Time–domain viscoelasticity can only be used in quasi–static, implicit dynamic, explicit dynamic or coupled thermal–structural load steps
- The small strain viscoelasticity models are *not* capable of simulating adhesive or cohesive damage or failure mechanisms, fatigue, aging or other degradation mechanisms

Other important modeling considerations include:

Modeling the interfaces

Since the small strain viscoelastic model documented here is *not* capable of simulating adhesive damage or failure, the use of perfectly bonded interfaces is recommended when modeling. Perfectly bonded interfaces are commonly defined using tie constraints or bonded contact definitions. Note that the strength of a real adhesive bond will depend on the adhesive as well as the substrate material, surface roughness, surface preparation and other factors. Caution should *always* be used when interpreting the results of an analysis involving an adhesive bond.

Modeling coated tapes

Single–coated tapes (SCTs) consist of a carrier film coated on one side with a PSA. Double–coated tapes (DCTs) consist of a carrier film coated on both sides with a PSA. Due to the layered construction of the tapes, the difference in the effective moduli of the film and adhesive layers, and the viscoelastic properties associated with the adhesive layer(s), an equivalent orthotropic material model cannot be derived. In general, accurate modeling of coated tapes requires explicit modeling of the individual layers of the tape. The PSA models described in this paper are appropriate for use in modeling of the adhesive layer(s). For further information, please ask a 3M application engineer for a copy of the document entitled "*3M Guide to Modeling Coated Tapes*".

Frequency domain analyses

The small strain viscoelastic material models provided by 3M are intended for use in time–domain analyses. If a frequency–domain analysis is required, please contact a 3M application engineer for assistance.

Temperature–dependent analyses

The small strain viscoelastic material models provided by 3M represent the room temperature response of the materials. Please contact a 3M application engineer for assistance if a time–varying temperature or coupled temperature–displacement analysis must be used in an analysis.

Coupled thermal–structural analyses

The small strain viscoelastic material models provided by 3M do not included thermal conductivity or specific heat definitions. Please contact a 3M application engineer for assistance if this information is required.

Finite strain analyses

3M Company can also provide customers with a finite strain viscoelastic material model for use in simulations involving higher strain levels. Please refer to the related document "*Constitutive Models for 3M Pressure Sensitive Adhesives: Finite Strain Model*" for further information.

References

"Determination of viscoelastic parameters", *Abaqus Materials Guide,* 2019, Dassault Systèmes.

Rheology: Principles, Measurements, and Applications, 1994, C.W. Macosko.

Viscoelastic Properties of Polymers, 3 ed., 1980, J.D. Ferry.

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