DESIGN DEVELOPMENT AND RAPID PROTOTYPING OF RUBBER COMPONENTS USING FEA

By

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ADVANSES®
Advanced Scientific and Engineering Services
An Independent Testing Laboratory

KARTIK SRINIVAS

- **Education**
  - B.E. Mechanical Eng. — L.D. College of Engineering -1998
  - M.S. Mechanical Eng. — Wright State University - 2001
  - Polymer Eng. Course Certifications — Univ. of Akron – 2002-2003
  - CNC Machinist Certificate — Akron Machining Institute - 2004

- **Professional Experience**
  - Mechanical Testing of Engineering Materials: MTS®, Instron® and Proprietary Servo-hydraulic and Electro-mechanical Load frames.
  - Performance Characterization of Elastomeric Products.
  - Finite Element Analysis of Engineering Products and Components
    - Automotive (Under the hood, suspension components, tires, etc.).
    - Biomedical (Spinal, knee, and hip implants, stents etc.)
    - Aerospace (Static and dynamic analysis for honeycomb structures etc.)
  - Durability Testing and Lifetime Prediction using Accelerated Test Conditions.

NABL ISO/IEC 17025:2017 ACCREDITED LAB


National Accreditation Board for Testing and Calibration Laboratories

NABL

CERTIFICATE OF ACCREDITATION

ADVANCED SCIENTIFIC AND ENGINEERING SERVICES (ADVANSES)

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for its facilities at

PLOT NO 49, MOTHER INDUSTRIAL PARK, ZAK-KADADARA ROAD, NEAR ZAK GIDC, AHMEDABAD, GUJARAT, INDIA

in the field of

TESTING

Certificate Number: TC-9168

Issue Date: 22/12/2020 Valid Until: 21/12/2022

This certificate remains valid for the Scope of Accreditation as specified in the annexure subject to continued satisfactory compliance to the above standard & the relevant requirements of NABL.
(To see the scope of accreditation of this laboratory, you may also visit NABL website www.nabl-india.org)

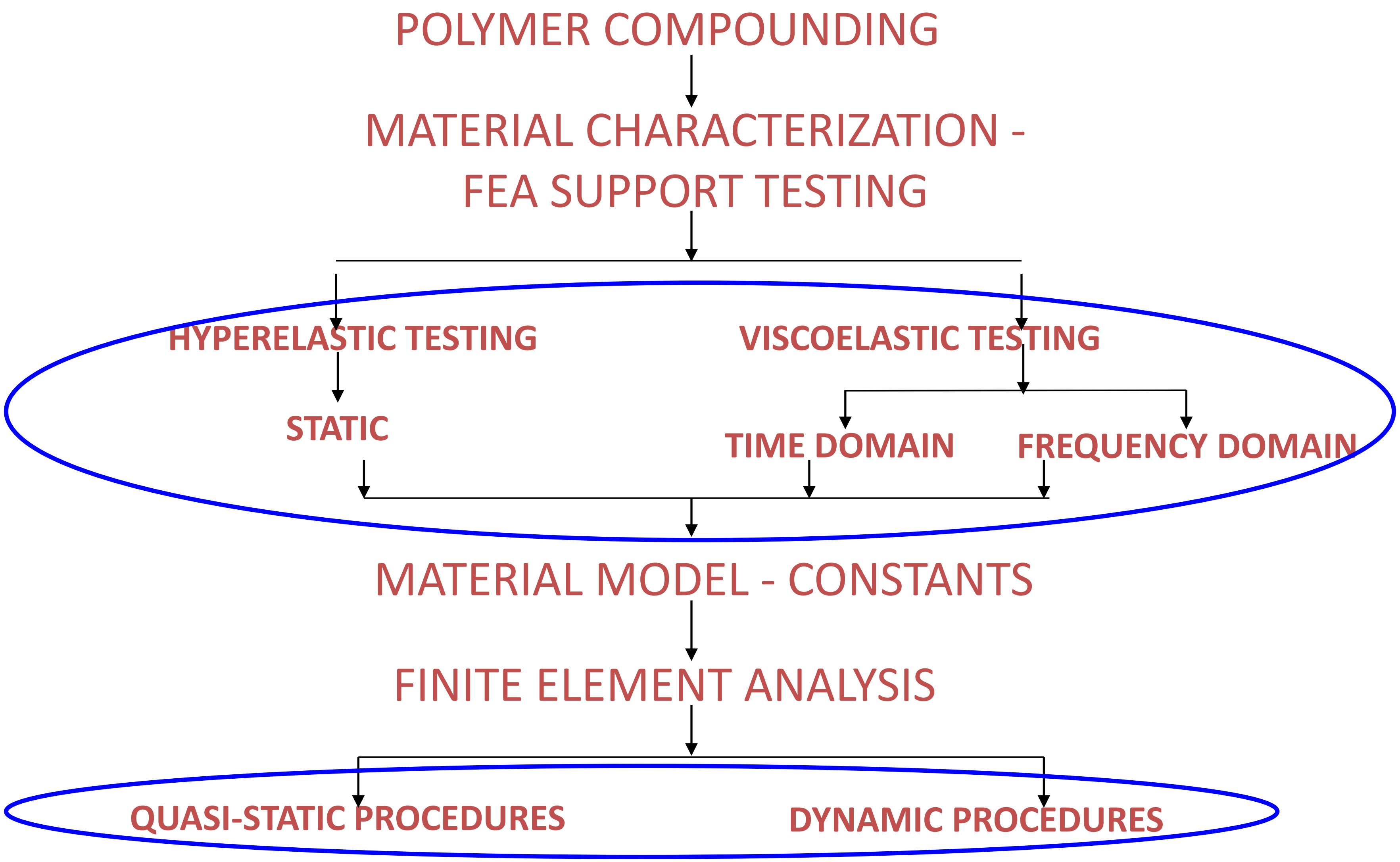
Signed for and on behalf of NABL

N. Venkateswaran
Chief Executive Officer

Accredited for;

1. Static Testing
2. Dynamic Testing
3. Fatigue Testing

POLYMER ANALYSIS METHODOLOGY



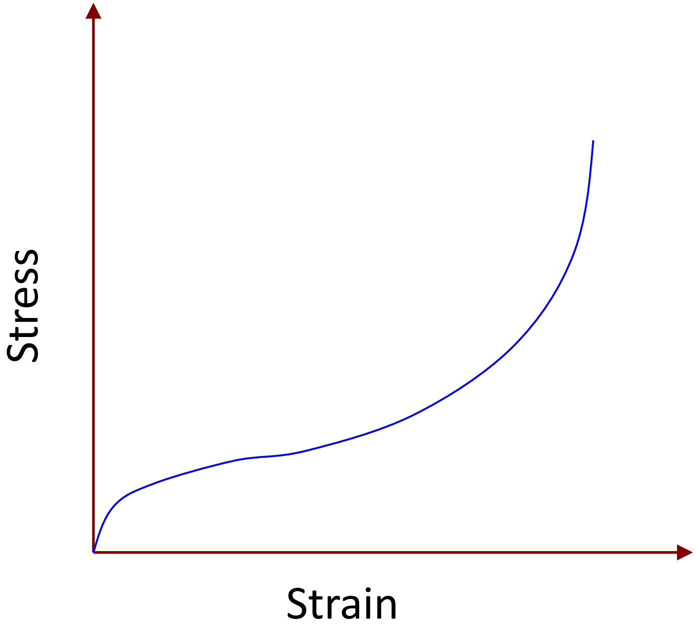
COMPLEXITIES IN THE FEA OF POLYMERS

- The Stress-Strain relationship is highly non-linear.
- Strain range can vary from 5 % to 700 %.
- Imperative to use large deflection theory.
- Stress-Strain characteristics are temperature dependent and hysteresis effects are significant.
- Rate effects are highly pronounced.
- Too many material models using different approaches.

MAJOR FEA CODES IN THE MARKET

- Abaqus® - Implicit and Explicit – Rubber
- Ansys® - Implicit – Rubber
- Calculix - Implicit and Explicit – Rubber
- Comsol® - Implicit– Rubber (50%)
- LS-Dyna® - Implicit and Explicit – Rubber
- MSC Marc-Nastran® - Implicit and Explicit – Rubber

HYPERELASTIC CONSTITUTIVE MODELS



Stretch Ratio (λ)

$\lambda = 1 + \text{Strain} = 1 + \varepsilon$

Input:

Stress-Strain Data from Main Deformation modes

$W = \text{Constants}(I_1(\lambda), I_2(\lambda), I_3(\lambda))$

$W = C10, C01, \alpha_{i,} \mu_i (I_1(\lambda), I_2(\lambda), I_3(\lambda))$

$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$

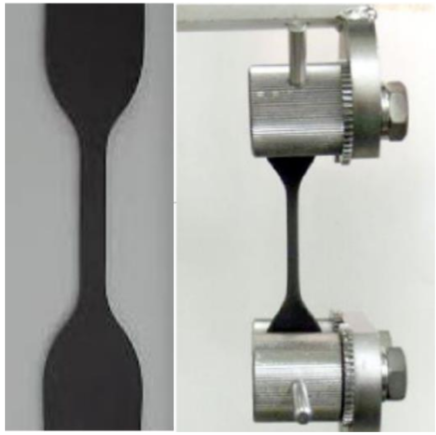
$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2$

$I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2$

HYPERELASTIC MATERIAL CHARACTERIZATION TESTING

1. **Five Deformation Modes**
   - **Uniaxial tension**
   - **Uniaxial compression**
   - **Planar shear**
   - **Volumetric compression**
   - **Equibiaxial tension**

2. **Testing speed = quasi-static procedure**
3. **Minimum of 3 specimens**



Uniaxial Tension Test

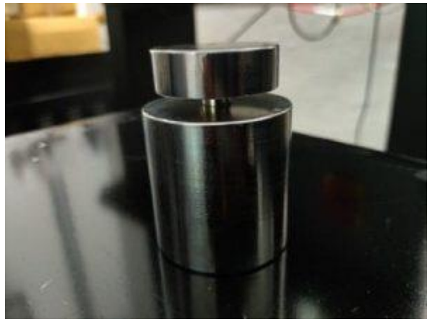
$$\lambda_1 = \lambda_T, \lambda_2 = \lambda_3 = \lambda_T^{-1/2}$$

Uniaxial Compression Test

$$\lambda_1 = \lambda_C, \lambda_2 = \lambda_3 = \lambda_C^{-1/2}$$

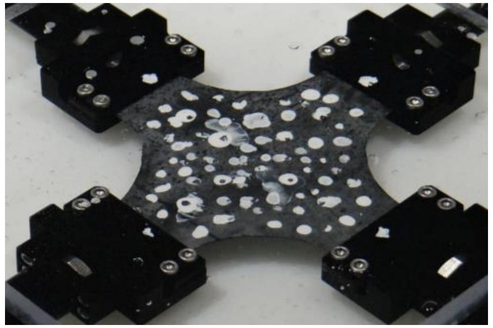
$\lambda_1 = \lambda_S, \lambda_2 = 1, \lambda_3 = \lambda_S^{-1}$

Planar Shear Test



Volumetric Compression Test

$\lambda_1 = \lambda_2 = \lambda_3 = \lambda_V$



Equibiaxial Tension Test

$\lambda_1 = \lambda_2 = \lambda_B, \lambda_3 = 1/\lambda_B^2$

STRESS AND STRAIN MEASURES

2^{nd} Piola Kirchoff stress – Cauchy's stress

Cauchy's stress = Force / Final area

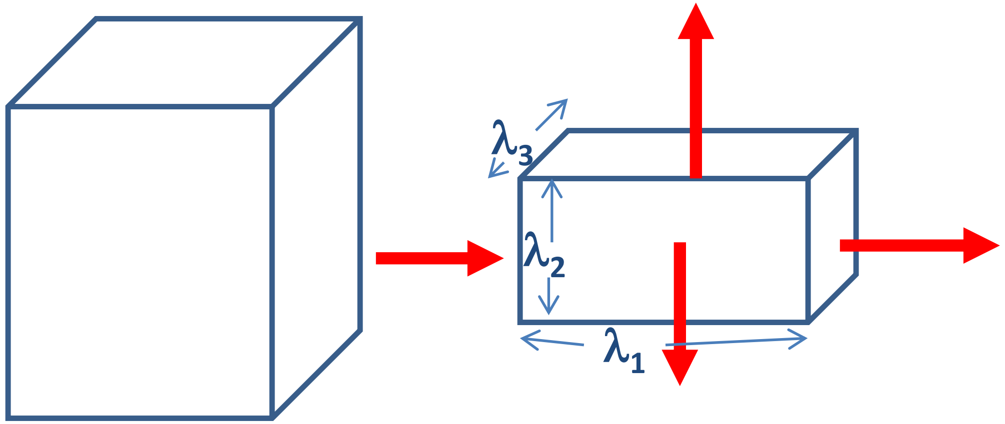
2^{nd} Piola Kirchoff stress = Force / Original area

Green Strain – True strain

True Strain = dL/L

Green Strain = dL/L + Nonlinear terms

The deformation is described by stretch ratios: $\lambda_1, \lambda_2, \lambda_3$



Strain Energy W

A simple relation for the strain energy density is:

$$\mathbf{W} = (E/6)\,(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3) \quad \text{----------- } 1$$

MATERIAL MODELS

Statistical Mechanics Based Approach

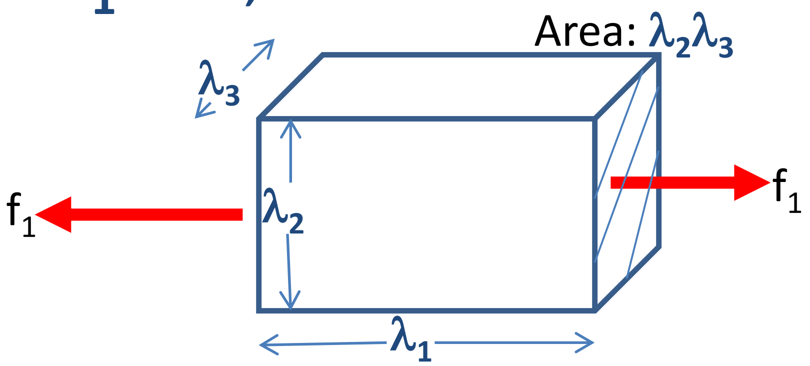
Continuum Mechanics Based Approach

1. Neo-Hooke
2. Mooney-Rivlin
3. Polynomial
4. Ogden
5. Van der Waals
6. Yeoh
7. Arruda-Boyce
8. Gent
9. Peng
10. Peng-Landel
11. Klesner-Segal
12. Hart-Smith
13. Valanis-Landel
14. User Defined …….

STRESS - STRAIN RELATIONS

We can calculate stresses from the relation for **W**.

$\Delta W = f_1 d\lambda_1$. Hence: $\mathbf{t_1 = \lambda_1\, \partial W/\partial\lambda_1 + P}$, etc.



where **P** is an undetermined hydrostatic pressure

$f_1 = t_1\lambda_2\lambda_3$

$= t_1/\lambda_1$

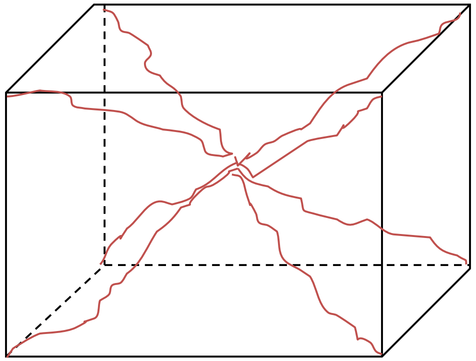
Note: we have assumed incompressibility:

$$\lambda_1\lambda_2\lambda_3 = 1$$

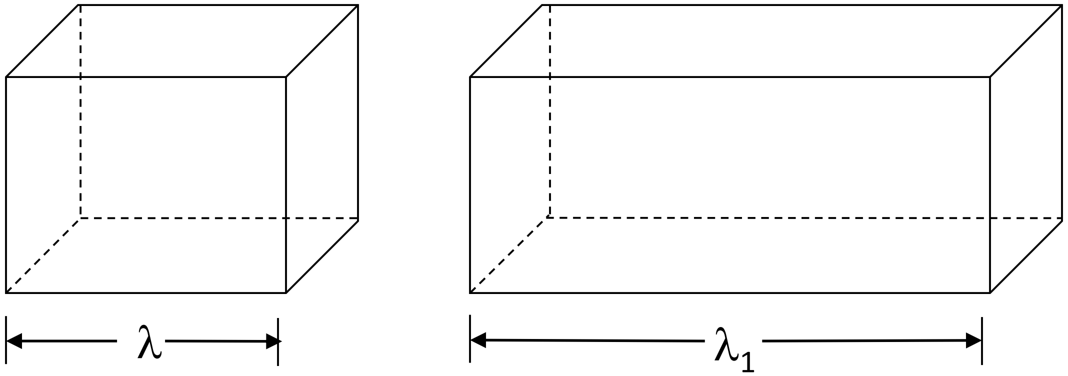
$\mathbf{t_1 = \lambda_1(\partial W/\partial\lambda_1) + p}$

$\mathbf{t_2 = \lambda_2(\partial W/\partial\lambda_2) + p}$

$\mathbf{t_3 = \lambda_3(\partial W/\partial\lambda_3) + p}$



8- Chain Network



Deformation in a Continuum Element

$$W(I_1, I_2, I_3) = \sum_{IJK=0}^{N} C_{ijk}(I_1 - 3)^i (I_2 - 3)^j (I_3 - 3)^k + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i}$$

Neo-Hookean Model: $W = C_{10}(I_1 - 3)$

Mooney-Rivlin Model: $W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$

Ogden Model: $$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}(\lambda_1^{-\alpha_i} + \lambda_2^{-\alpha_i} + \lambda_3^{-\alpha_i} - 3)$$

VISCOELASTIC MATERIAL CHARACTERIZATION TESTING

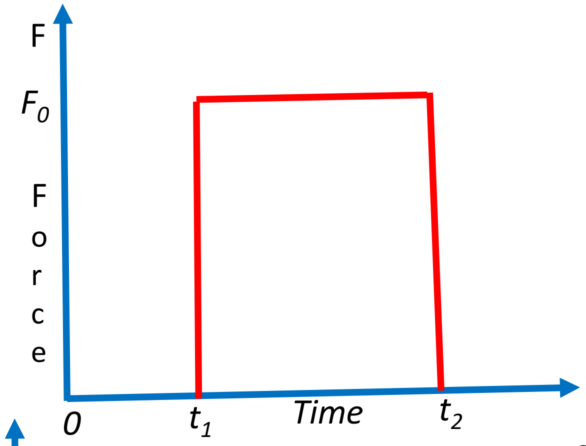
TIME DOMAIN VISCOELASTIC TESING

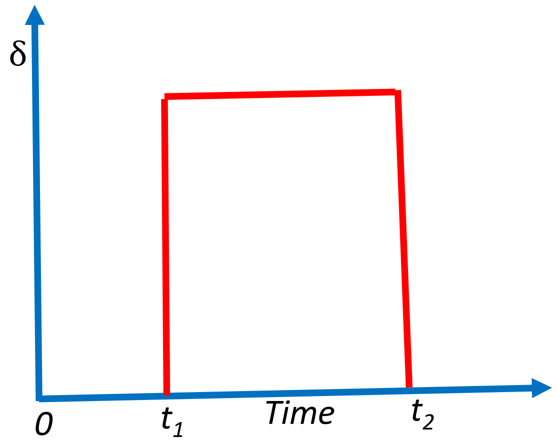
- STRESS RELAXATION
- CREEP

FREQUENCY DOMAIN VISCOELASTIC TESING

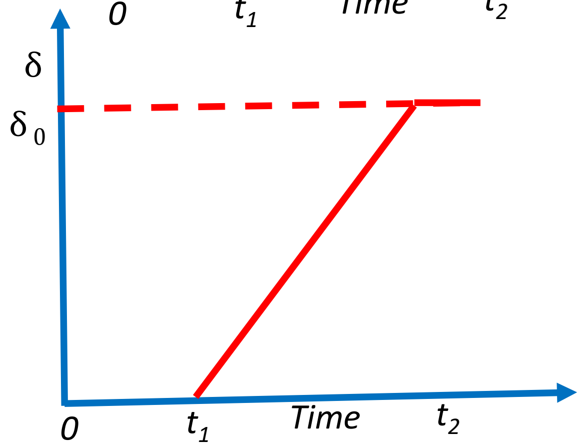
- STRAIN SWEEPS
- FREQUENCY SWEEPS

APPLIED LOAD AND RESULTANT DEFORMATION

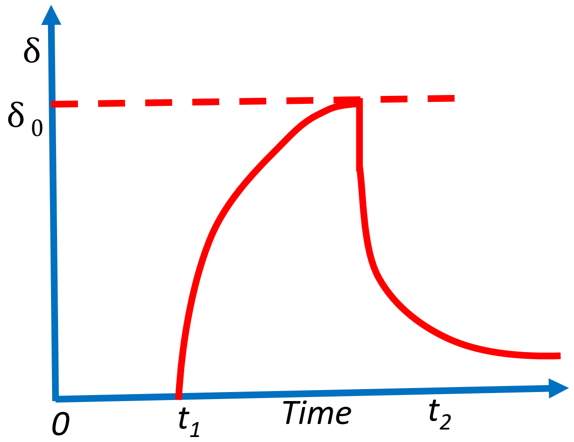




Elastic Response

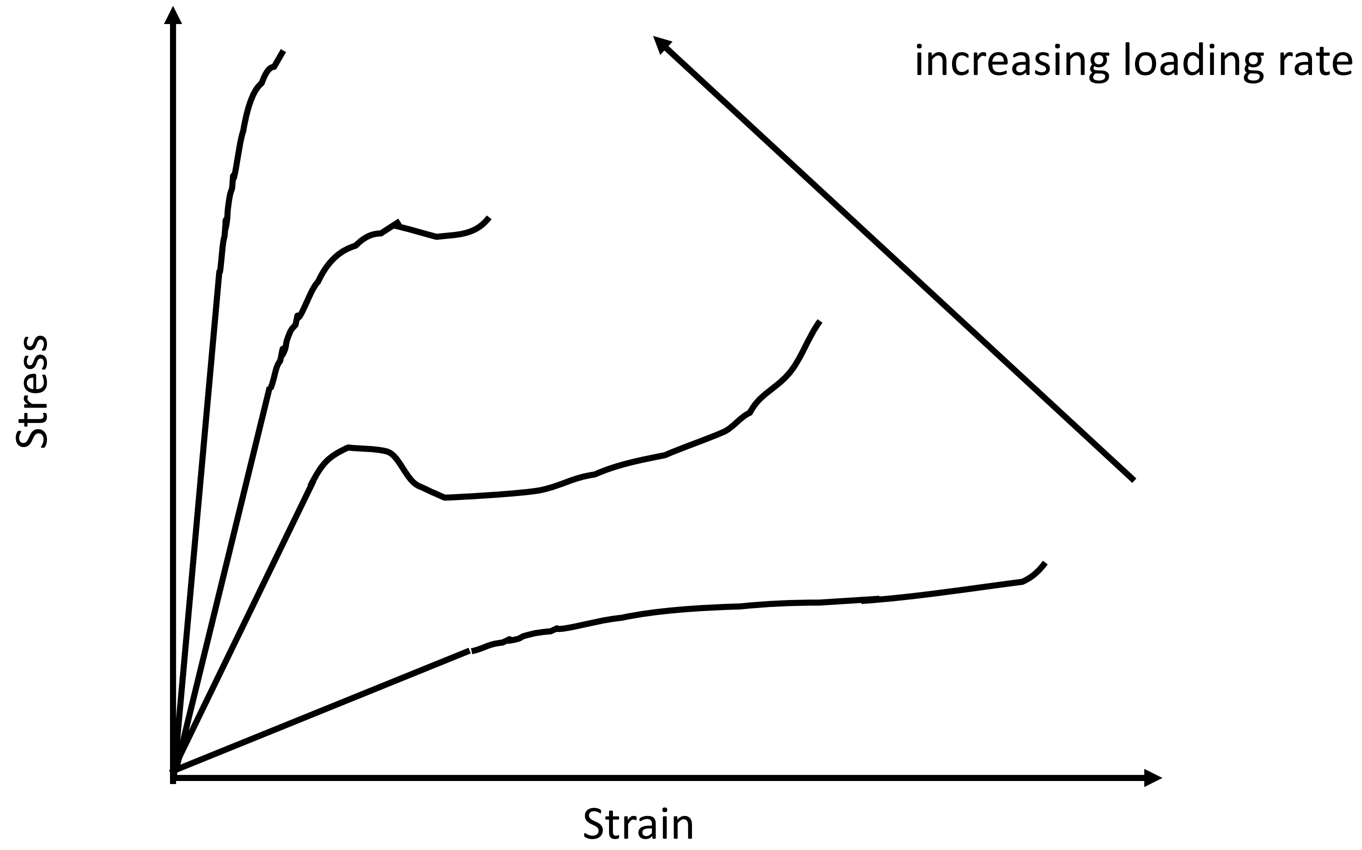


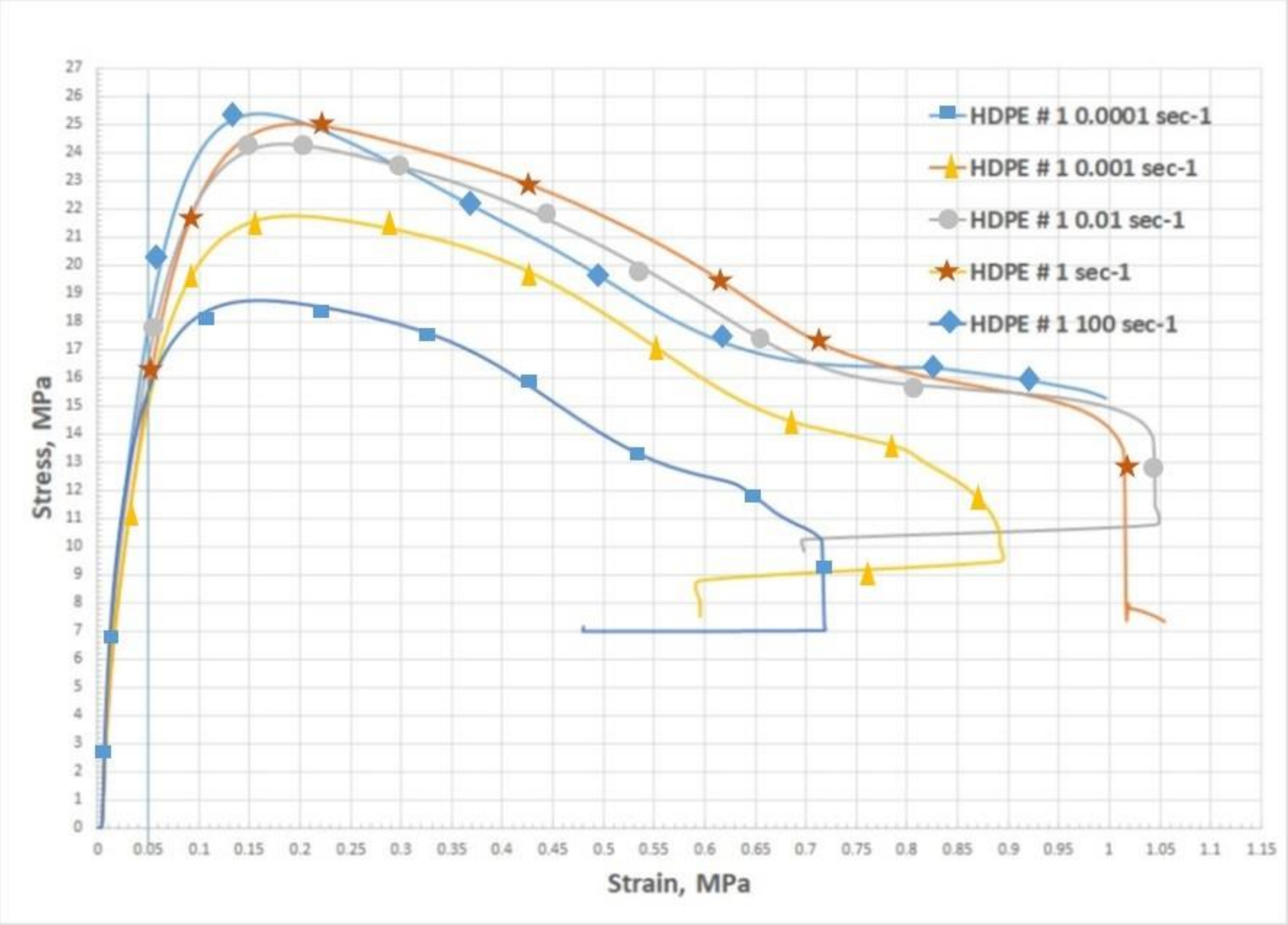
Viscous Response



Viscoelastic Response

LOADING RATE VS. MODULUS

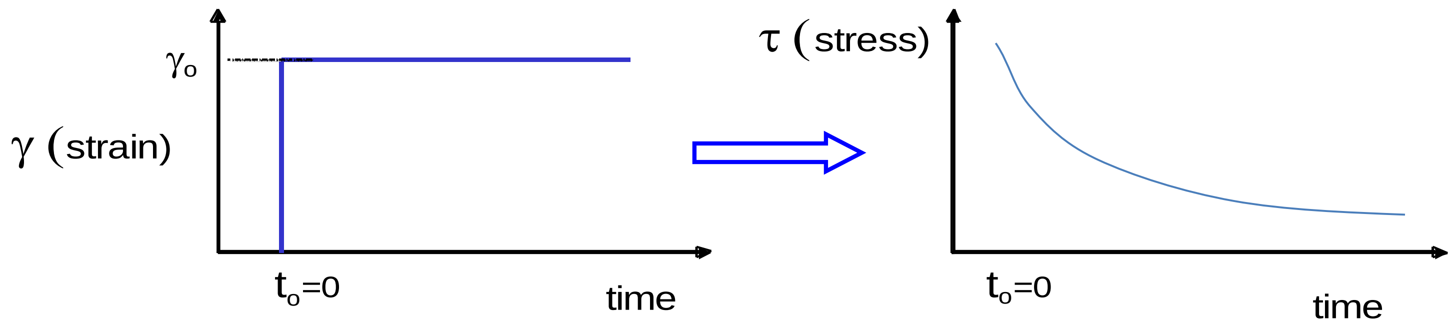




Stress, MPa
Strain, MPa
HDPE # 1 0.0001 sec-1
HDPE # 1 0.001 sec-1
HDPE # 1 0.01 sec-1
HDPE # 1 sec-1
HDPE # 1 100 sec-1

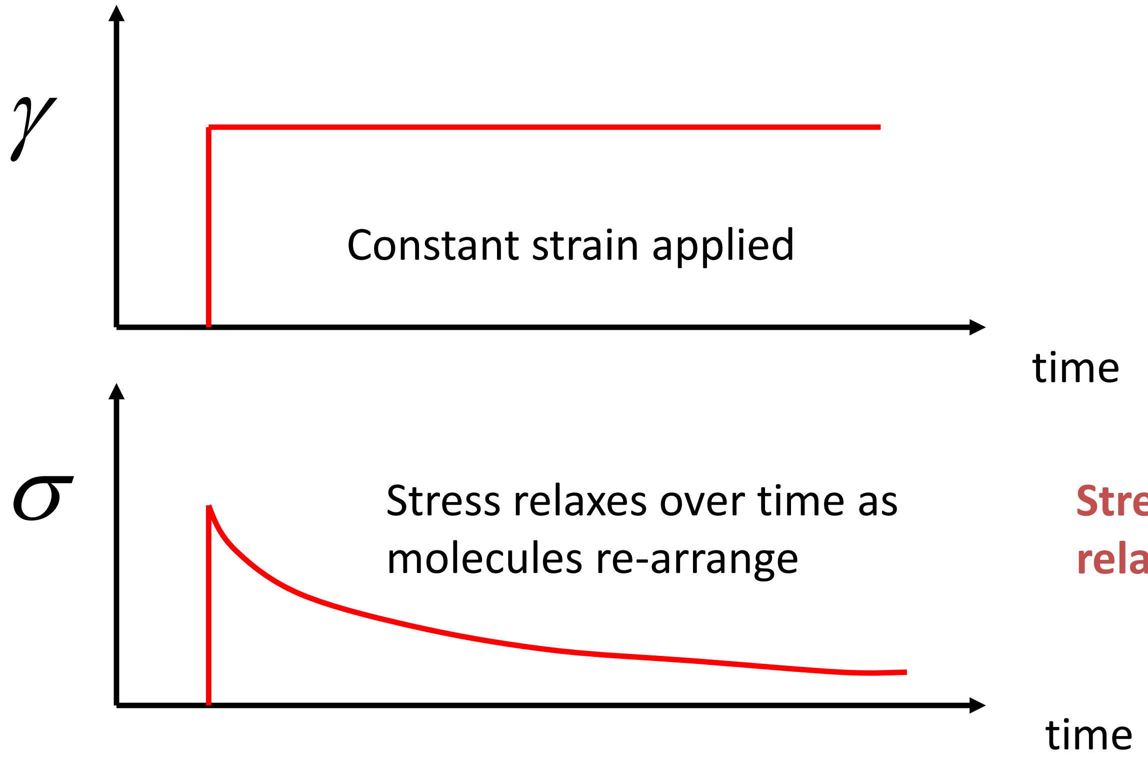
VISCOELASTICITY AND STRESS RELAXATION

Whereas steady-shear measurements probe material responses under a steady-state condition, creep and stress relaxation monitor material responses as a function of time.



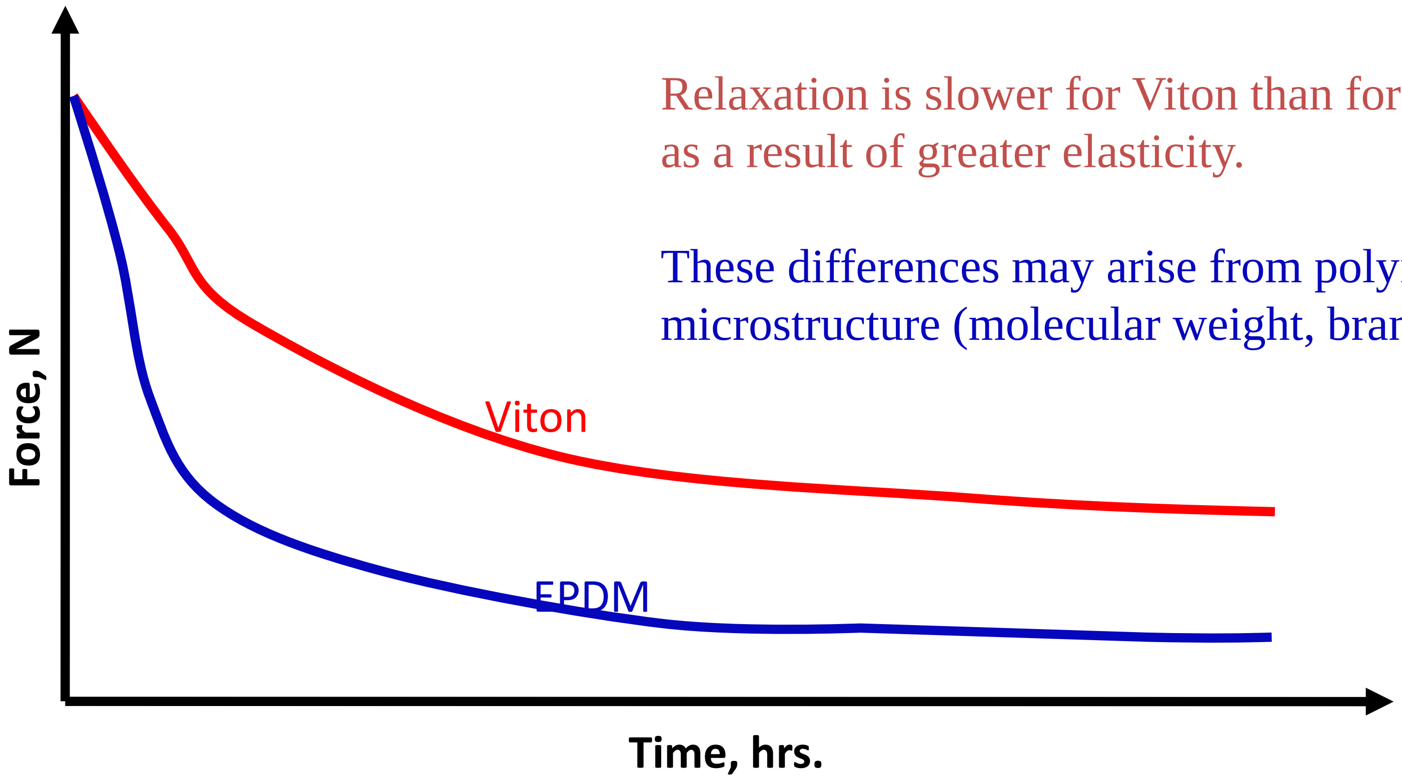
– Stress relaxation studies the effect of a step-change in strain on stress.

PHYSICAL MEANING OF THE RELAXATION TIME



Stress relaxation:

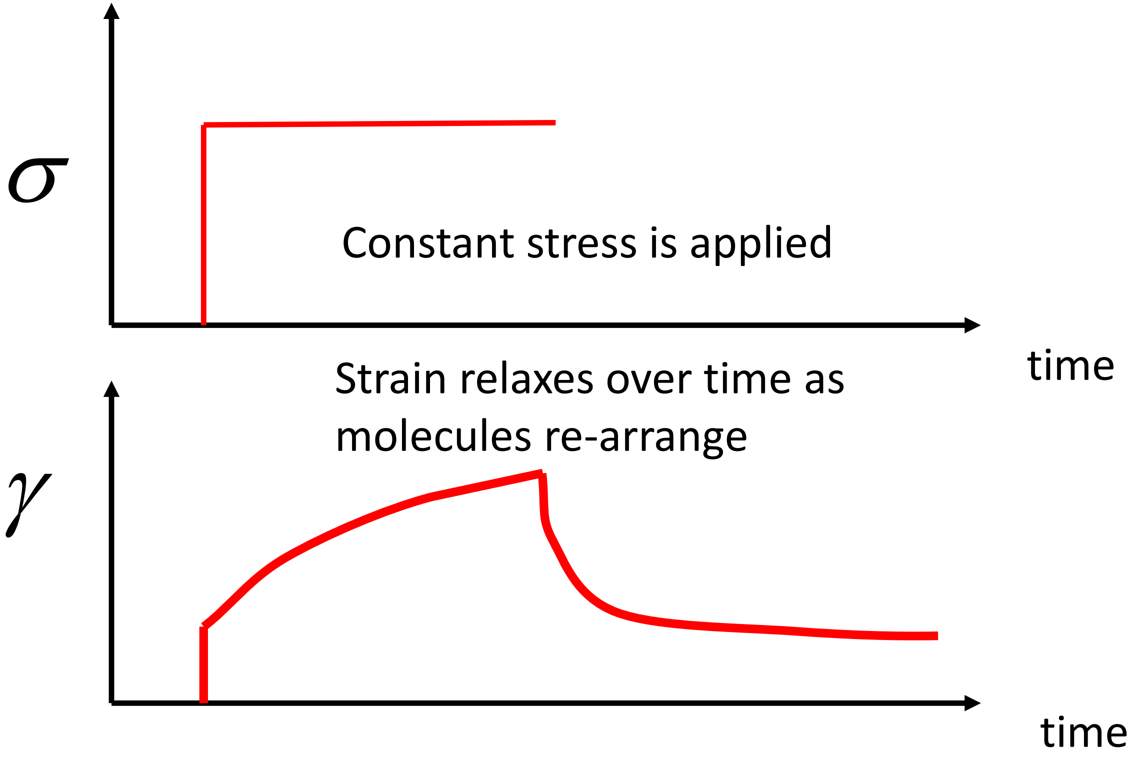
$$\sigma(t) = G\gamma e^{-t/\tau}$$



Relaxation is slower for Viton than for EPDM, as a result of greater elasticity.

These differences may arise from polymer microstructure (molecular weight, branching).

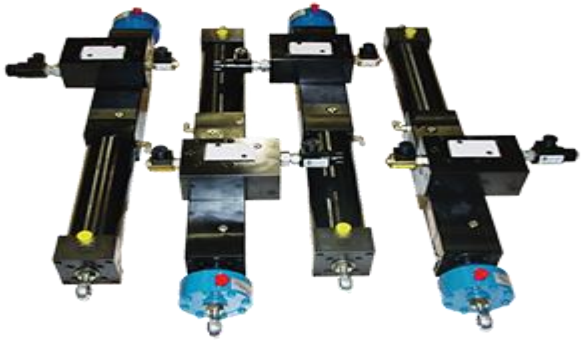
CREEP



Constant stress is applied and the strain relaxes as function of time

MATERIAL TESTING

- MODULUS (STATIC/DYNAMIC)
- TAN δ
- CRACK GROWTH PROPAGATION



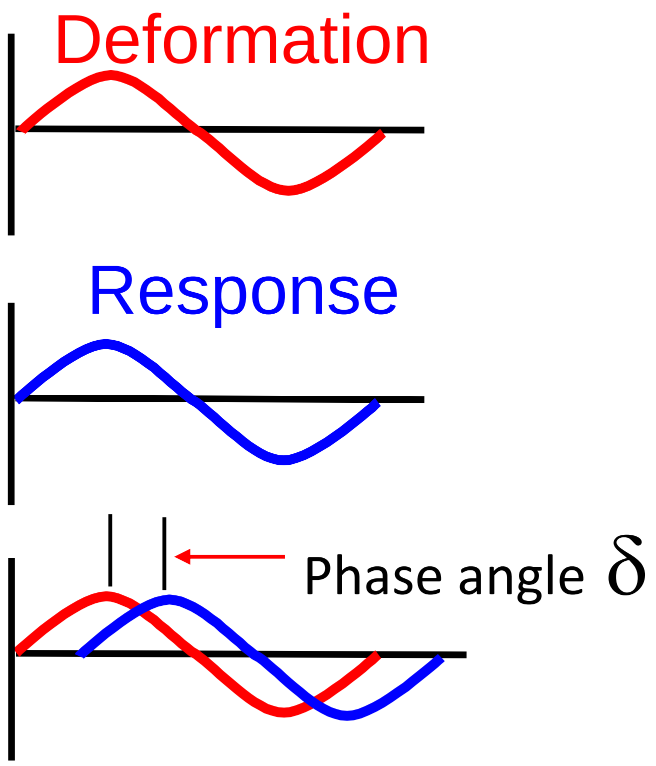
Courtesy: Dynamic Testing Equipments

DYNAMIC MECHANICAL TESTING

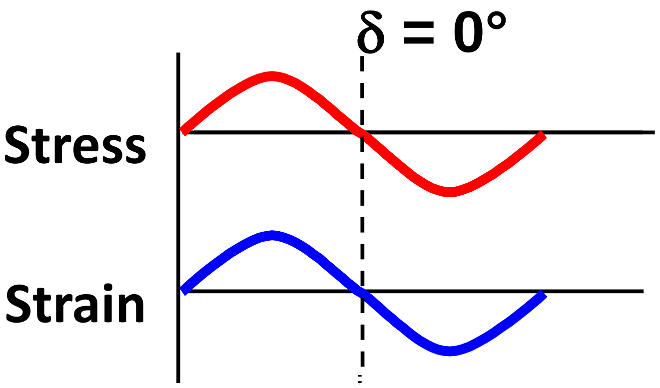
- An oscillatory (sinusoidal) deformation (stress or strain) is applied to a sample.

- The material response (strain or stress) is measured.

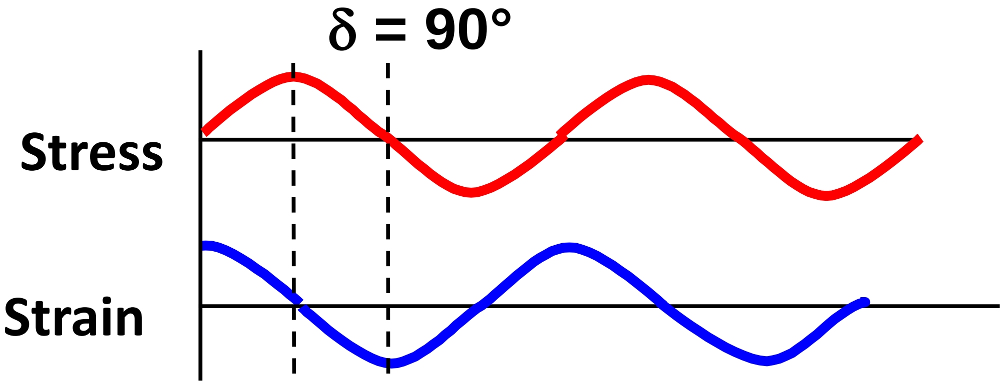
- The phase angle δ, or phase shift, between the deformation and response is measured.



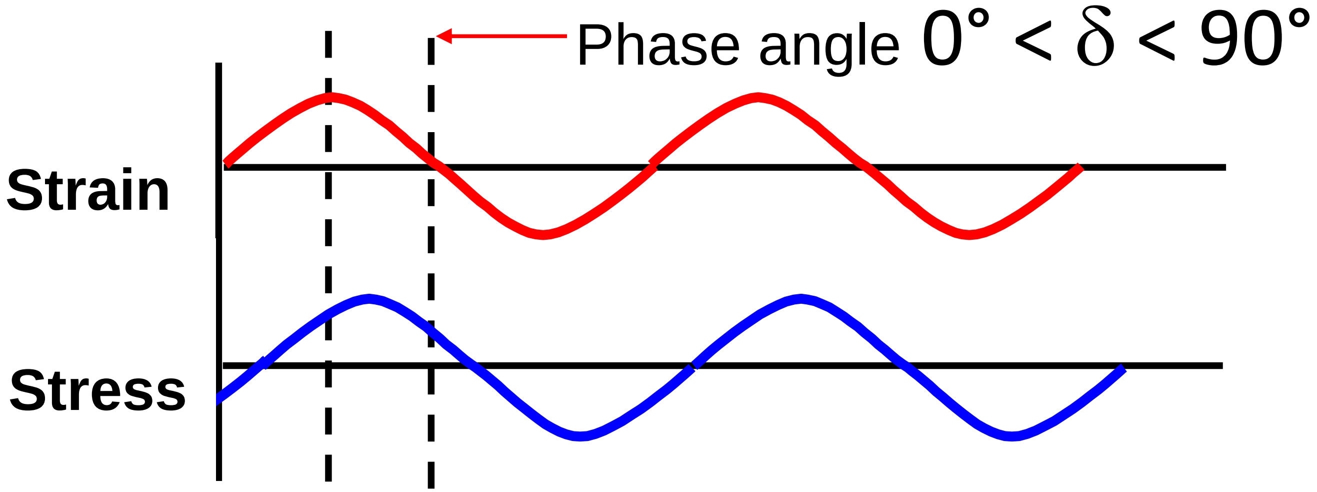
Purely Elastic Response
(Hookean Solid)



Purely Viscous Response
(Newtonian Liquid)

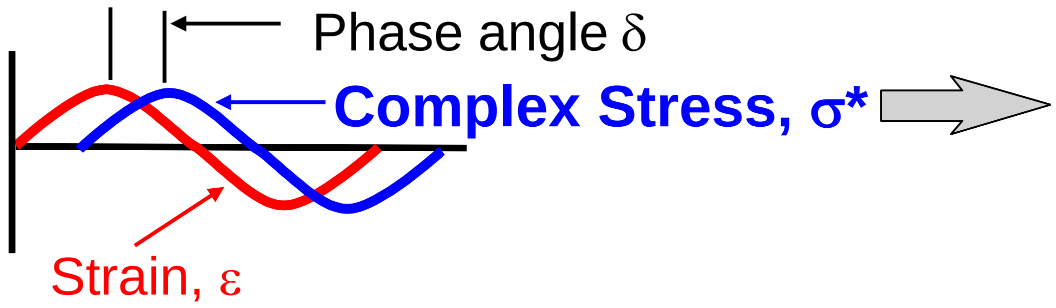


DYNAMIC MECHANICAL TESTING: VISCOELASTIC MATERIAL RESPONSE



Viscoelastic Parameters: The Complex, Elastic, & Viscous Stress

- The stress in a dynamic experiment is referred to as the complex stress σ^*
- The complex stress can be separated into two components:
  1) An elastic stress in phase with the strain. $\sigma' = \sigma^* \cos\delta$
     σ' is the degree to which material behaves like an elastic solid.
  2) A viscous stress □in phase with the strain rate. $\sigma'' = \sigma^* \sin\delta$
     σ'' is the degree to which material behaves like an ideal liquid.



$$\sigma^* = \sigma' + i\sigma''$$

VISCOELASTIC PARAMETERS

The Modulus: Measure of materials overall resistance to deformation.

G = Stress/Strain

The Elastic (Storage) Modulus: Measure of elasticity of material. The ability of the material to store energy.

G' = (stress/strain)cosδ

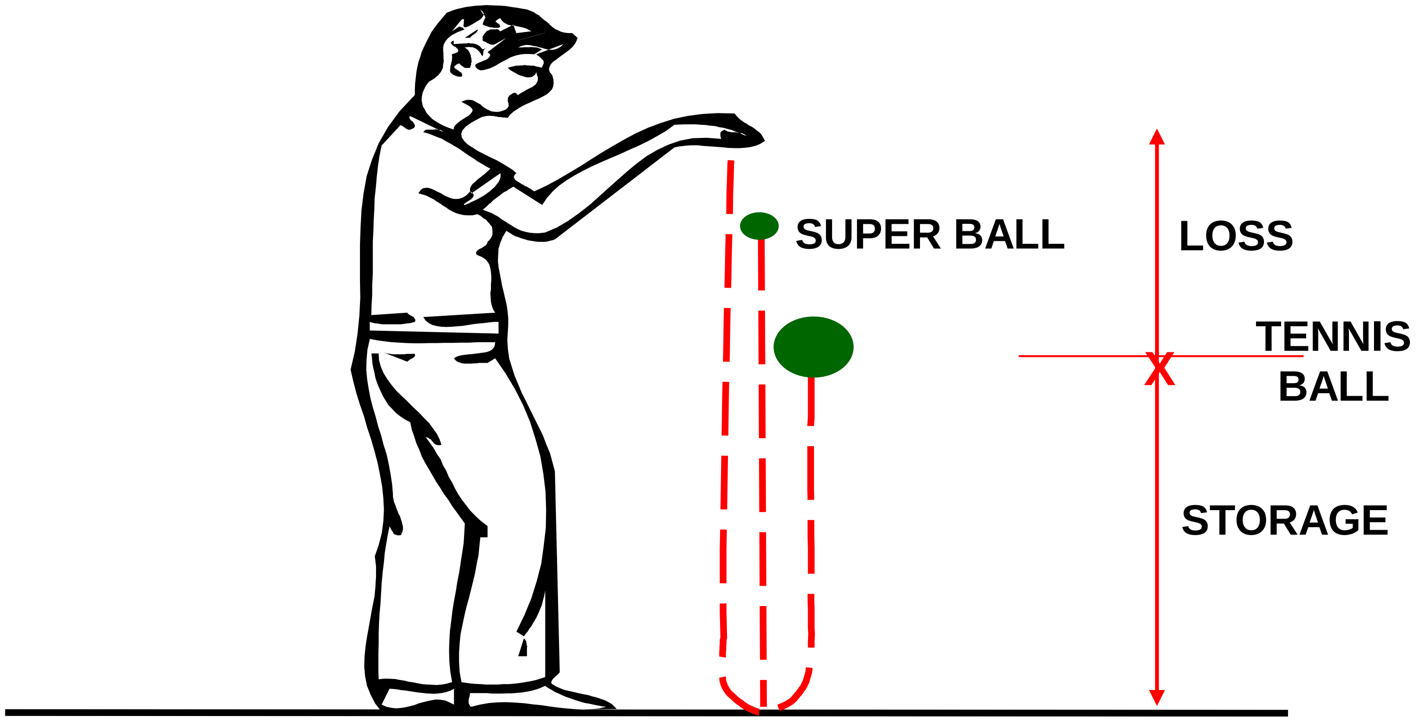
The Viscous (loss) Modulus: The ability of the material to dissipate energy. Energy lost as heat.

G" = (stress/strain)sinδ

Tan Delta: Measure of material damping - such as vibration or sound damping.

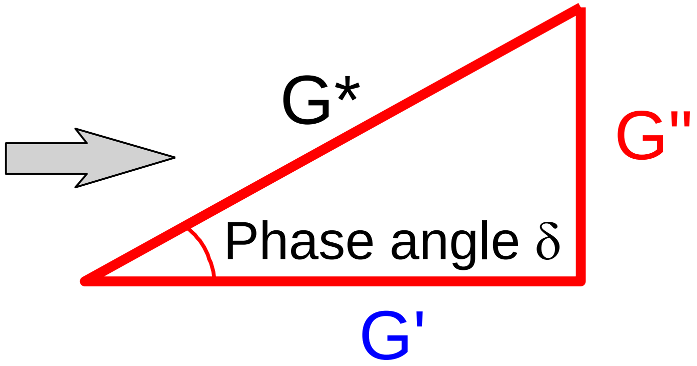
Tan δ = G"/G'

STORAGE AND LOSS OF A VISCOELASTIC MATERIAL



VISCOELASTIC PARAMETERS: DAMPING, TAN δ

Dynamic measurement represented as a vector

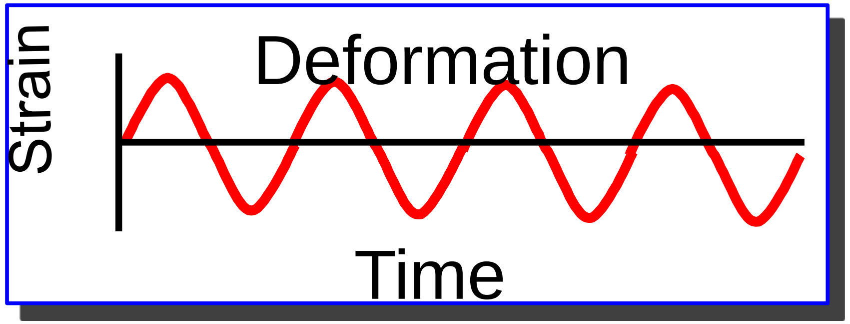


- The tangent of the phase angle is the ratio of the loss modulus to the storage modulus.

$$\tan \delta = G''/G'$$

- "TAN DELTA" (tan δ) is a measure of the damping ability of the material.

DYNAMIC TIME SWEEP

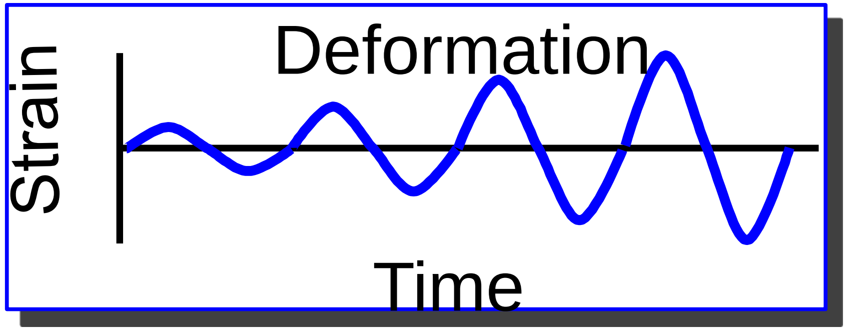


- The material response is monitored at a constant frequency, amplitude and temperature.

- INSTRUMENT MODE
  Multi-Frequency
- METHOD
  Equilibrate at ___°C
  Isotherm for ___ min.
- Frequency = single/multiple
- Amplitude = In Linear viscoelastic region

- USES
  - Cure Studies
  - Degradation

DYNAMIC STRAIN SWEEP

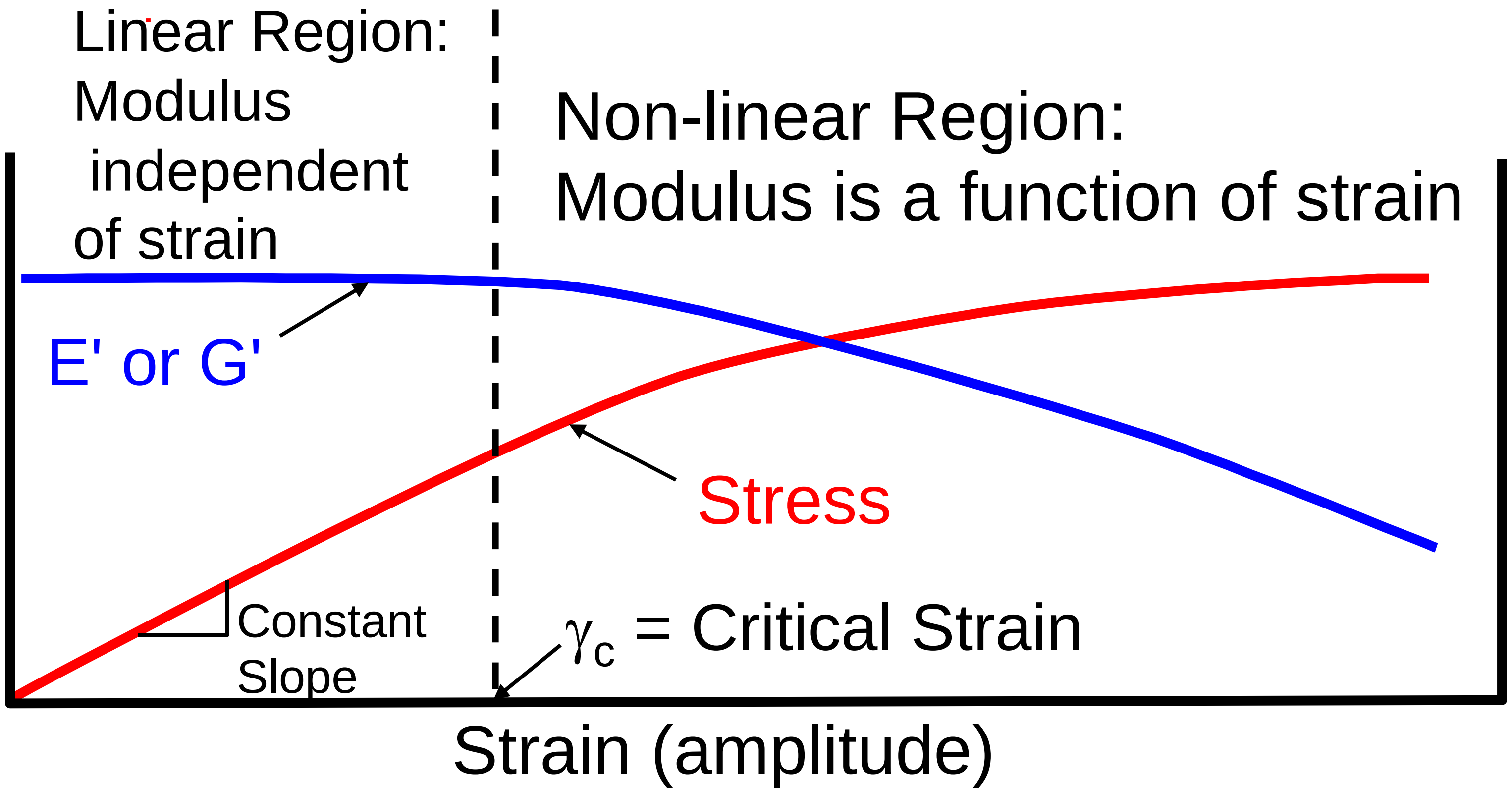


INSTRUMENT MODE
Multi-Strain
METHOD
Equilibrate at ___°C
Isotherm for ___ min.
Strain Sweep
Frequency = single only
Amplitude = Program Table up to 28 values

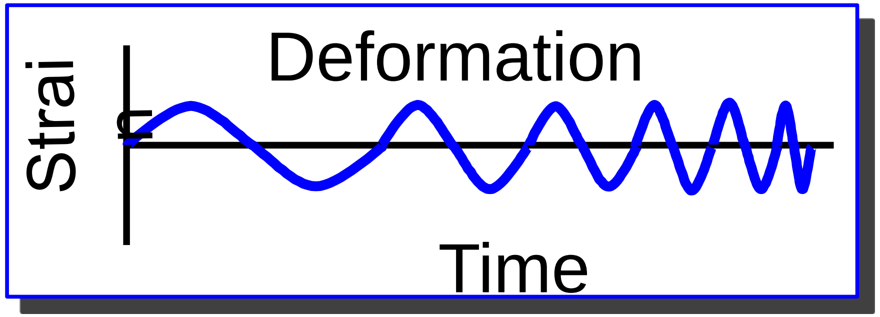
- The material response to increasing deformation amplitude is monitored at a constant frequency and temperature.
- USES

- Identify Linear Viscoelastic Region
- Resilience

DYNAMIC STRAIN SWEEP: MATERIAL RESPONSE



FREQUENCY SWEEP



- INSTRUMENT MODE

  Multi-Frequency
- METHOD

  Equilibrate at ___°C

  Isotherm for ___ min.

  Frequency Sweep
- Frequency = Program Table up to 28 values
- Amplitude = single only In Linear viscoelastic region

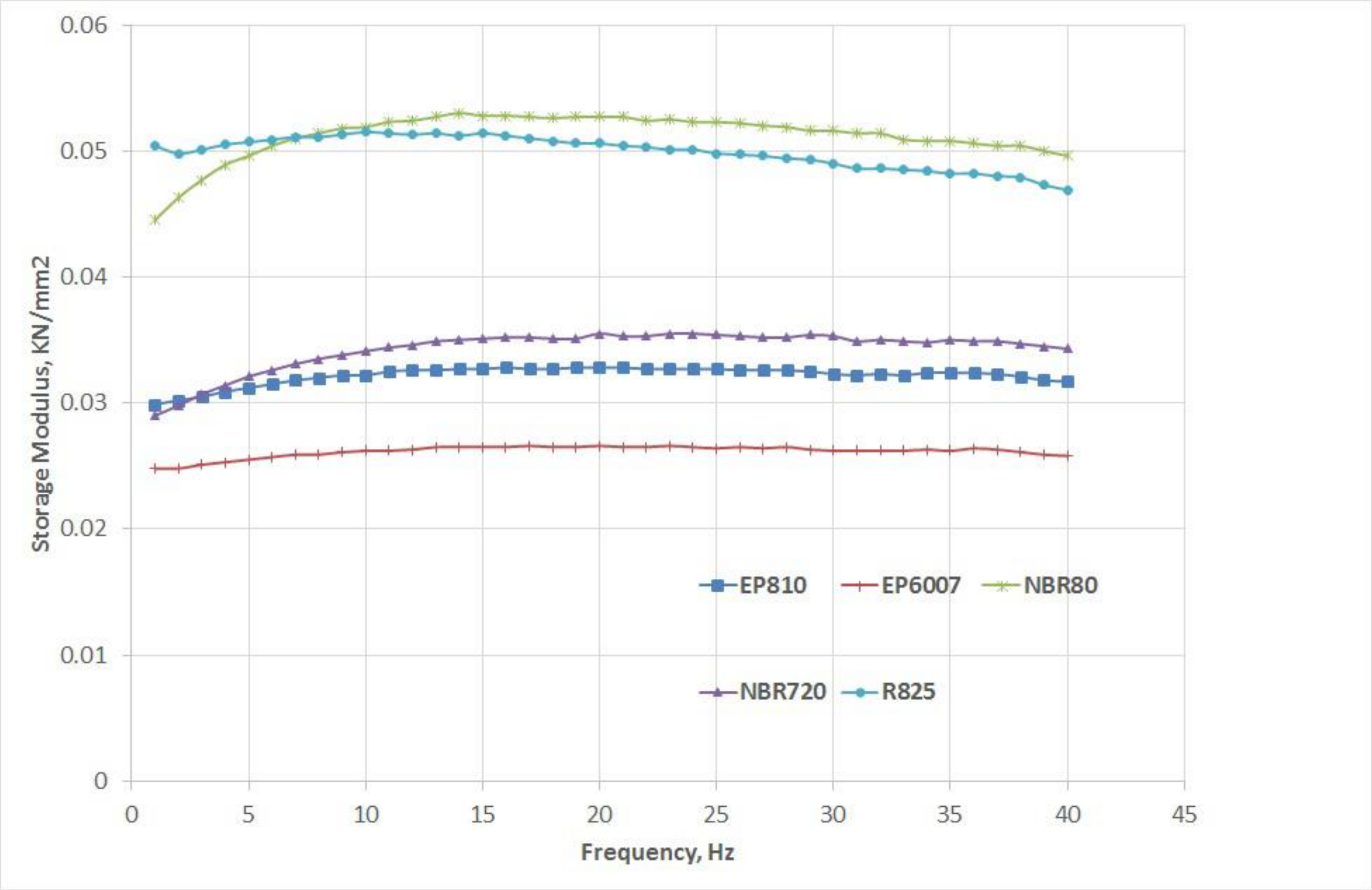
- The material response to increasing frequency (rate of deformation) is monitored at a constant amplitude and temperature.

- USES
  - High and Low Rate (short and long time) modulus properties.
  - Polymer melt processing (shear sandwich).
  - Extend range with TTS

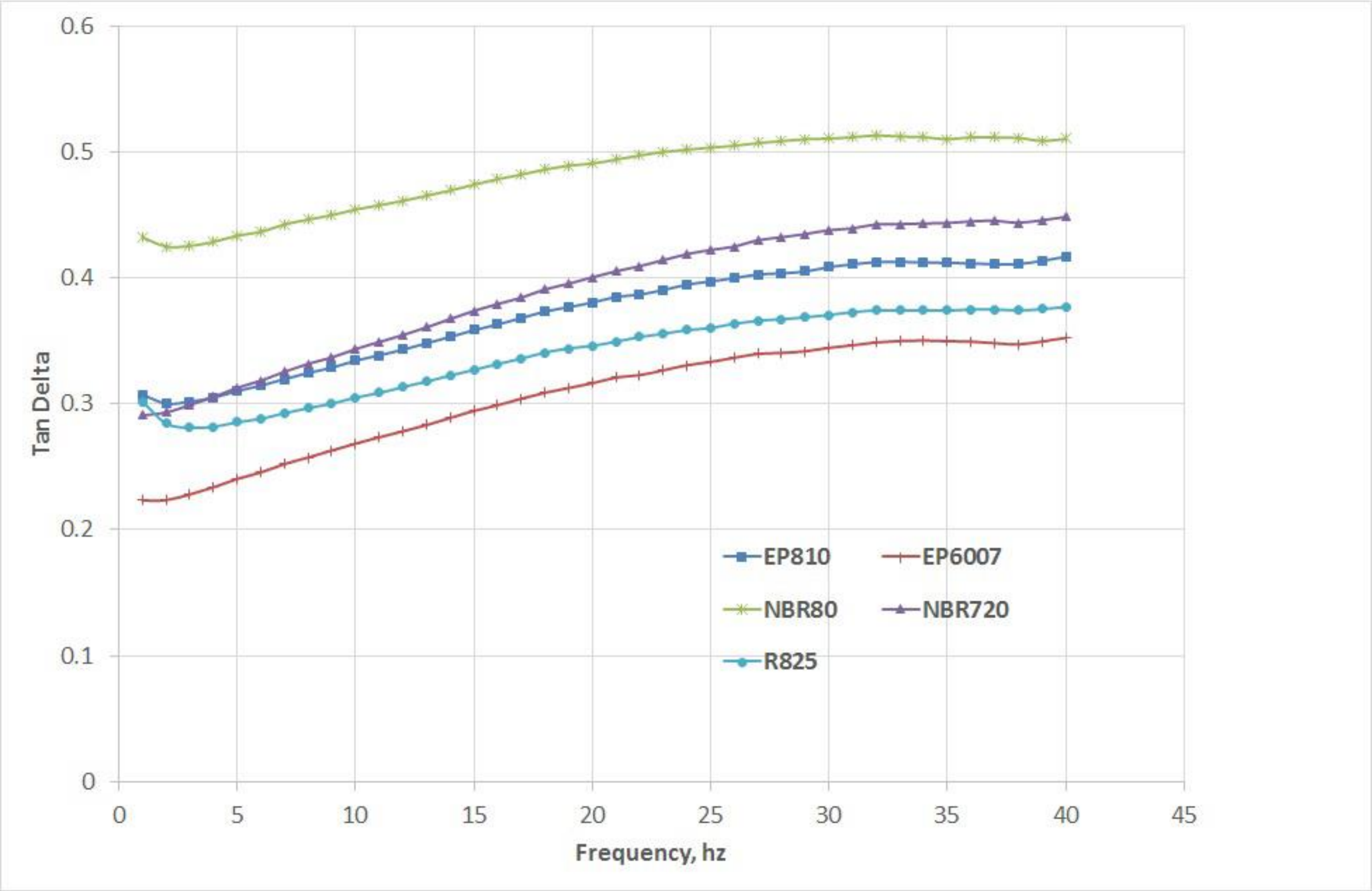
MATERIAL CHARACTERIZATION DMA TEST DATA

KS									
Step No.	**Fundamental Frequency**	**Dynamic Stiffness**	**Damping**	**Delta**	**Phase**	**Complex Modulus**	**Storage Modulus**	**Loss Modulus**	**TanDelta**
	Hz	**kN/mm**	**kNs/mm**	**Degrees**	**rad**	**kN/mm^2**	**kN/mm^2**	**kN/mm^2**	
1	1	1.66425	0.05775	14.09262	0.245963	0.04953	0.04836	0.010725	0.29016
2	2	1.66575	0.028875	14.1101	0.246268	0.04953	0.04836	0.010725	0.2912
3	3	1.685125	0.019875	14.38483	0.251063	0.050115	0.048945	0.011115	0.299
4	4	1.702	0.015375	14.73293	0.257138	0.0507	0.049335	0.011505	0.300875
5	5	1.717125	0.01275	15.13568	0.264168	0.05109	0.049725	0.011895	0.31239
6	6	1.7335	0.011	15.4504	0.26966	0.051675	0.050115	0.012285	0.31915
7	7	1.746125	0.00975	15.8461	0.276567	0.052065	0.050505	0.012675	0.32773
8	8	1.75425	0.00875	16.16373	0.28211	0.05226	0.050505	0.013065	0.33462
9	9	1.76575	0.008	16.49682	0.287924	0.05265	0.050895	0.013455	0.34177
10	10	1.773	0.007375	16.82195	0.293599	0.052845	0.05109	0.01365	0.34879
11	11	1.7815	0.00675	17.12603	0.298906	0.05304	0.05109	0.01404	0.35542
12	12	1.789375	0.006375	17.40917	0.303847	0.053235	0.051285	0.014235	0.36153
13	13	1.801625	0.006	17.70261	0.308969	0.053625	0.051675	0.014625	0.36803
14	14	1.805875	0.00575	18.03458	0.314763	0.05382	0.051675	0.01482	0.37531
15	15	1.812	0.005375	18.36453	0.320522	0.054015	0.051675	0.01521	0.38259
16	16	1.808875	0.005125	18.63523	0.325246	0.05382	0.051675	0.015405	0.38844
17	17	1.82025	0.005	18.93774	0.330526	0.05421	0.05187	0.015795	0.3952
18	18	1.812875	0.00475	19.21472	0.33536	0.054015	0.051675	0.01599	0.40131
19	19	1.820125	0.0045	19.43917	0.339278	0.05421	0.051675	0.016185	0.40625
20	20	1.824875	0.004375	19.66048	0.34314	0.054405	0.05187	0.01638	0.41119

PLOT OF STORAGE MODULUS VS FREQUENCY FROM A FREQUENCY SWEEP TEST



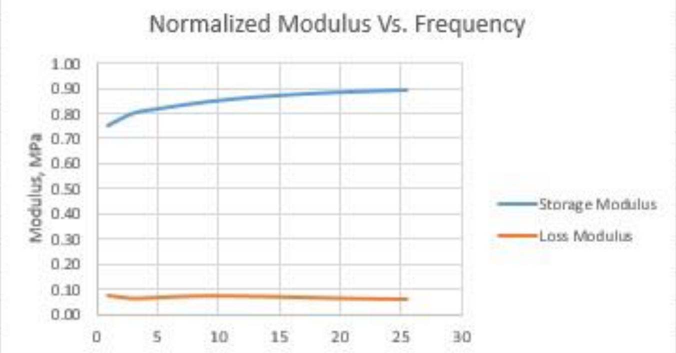
PLOT OF TAN DELTA VS FREQUENCY FROM A FREQUENCY SWEEP TEST



TIME DOMAIN AND FREQUENCY DOMAIN CALCULATIONS ON A DMA TEST DATA TO GENERATE VISCOELASTIC PROPERTIES

gi	ti	Frequency	Comp. Mod.	St. Mod.	Loss Mod.	Factor A	Factor B	Factor C	G-storage	G-loss	Gl / Ginf	1-Gs/Ginf			Frequency	Prony series sum time	relative modulus
0	0.00001	1	0.0123	0.0121	0.0022	0.5	2.5000000E-01	7.1801780E-02	7.5000000E-01	7.1801780E-02	1.4360356E-01	-5.00000E-01	0	0	1	0	1
0	0.0001	3.0417	0.0125	0.0123	0.0024		2.9869758E-01	6.4162397E-02	7.9869758E-01	6.4162397E-02	1.2832479E-01	-5.97395E-01	0	0	3.0417	0.00001	0.99989
0	0.001	5.0833	0.0128	0.0125	0.0026		3.1702684E-01	6.6567664E-02	8.1702684E-01	6.6567664E-02	1.3313533E-01	-6.34054E-01	0	0	5.0833	0.0001	0.99889
0.1	0.01	7.125	0.013	0.0127	0.0029		3.3222530E-01	6.9655339E-02	8.3222530E-01	6.9655339E-02	1.3931068E-01	-6.64451E-01	0	0	7.125	0.001	0.98938
0.1	0.1	9.1667	0.0136	0.013	0.0031		3.4530574E-01	7.0882270E-02	8.4530574E-01	7.0882270E-02	1.4176454E-01	-6.90611E-01	0	0	9.1667	0.01	0.92617
0.1	1	11.2083	0.01355	0.0131	0.0033		3.5612177E-01	7.0578545E-02	8.5612177E-01	7.0578545E-02	1.4115709E-01	-7.12244E-01	0	0	11.2083	0.1	0.82618
0.1	10	13.25	0.0135	0.0131	0.0035		3.6486380E-01	6.9439429E-02	8.6486380E-01	6.9439429E-02	1.3887886E-01	-7.29728E-01	0	0	13.25	0.2	0.79323
0.1	100	15.2917	0.0136	0.0131	0.0037		3.7189996E-01	6.7979272E-02	8.7189996E-01	6.7979272E-02	1.3595854E-01	-7.43800E-01	0	0	15.2917	0.3	0.77581
0	1000	17.3333	0.0137	0.0132	0.0039		3.7760938E-01	6.6497703E-02	8.7760938E-01	6.6497703E-02	1.3299541E-01	-7.55219E-01	0	0	17.3333	0.4	0.76454
0	10000	19.375	0.014	0.0134	0.0041		3.8231438E-01	6.5145259E-02	8.8231438E-01	6.5145259E-02	1.3029052E-01	-7.64629E-01	0	0	19.375	0.5	0.75595
		21.4167	0.0141	0.0134	0.0042		3.8626635E-01	6.3984961E-02	8.8626635E-01	6.3984961E-02	1.2796992E-01	-7.72533E-01	0	0	21.4167	0.6	0.74871
0.5		23.4583	0.0141	0.01345	0.0042		3.8965495E-01	6.3032297E-02	8.8965495E-01	6.3032297E-02	1.2606459E-01	-7.79310E-01	0	0	23.4583	0.7	0.74229
		25.5	0.0142	0.0135	0.0044		3.9262150E-01	6.2278684E-02	8.9262150E-01	6.2278684E-02	1.2455737E-01	-7.85243E-01	0	0	25.5	0.8	0.73648

G_0 =	1
G_inf=	0.5



$$G'(\omega) = \underbrace{G_0\left(1 - \sum_{i=1}^{N} g_i^P\right)}_{\text{Factor A}} + \underbrace{G_0 \sum_{i=1}^{N} \frac{g_i^P \tau_i^2 \omega^2}{1 +^G \tau_i^2 \omega^2}}_{\text{Factor B}}$$

$$G''(\omega) = G_0 \underbrace{\sum_{i=1}^{N} \frac{g_i^P \tau_i \omega}{1 + \tau_i^2 \omega^2}}_{\text{Factor C}}$$

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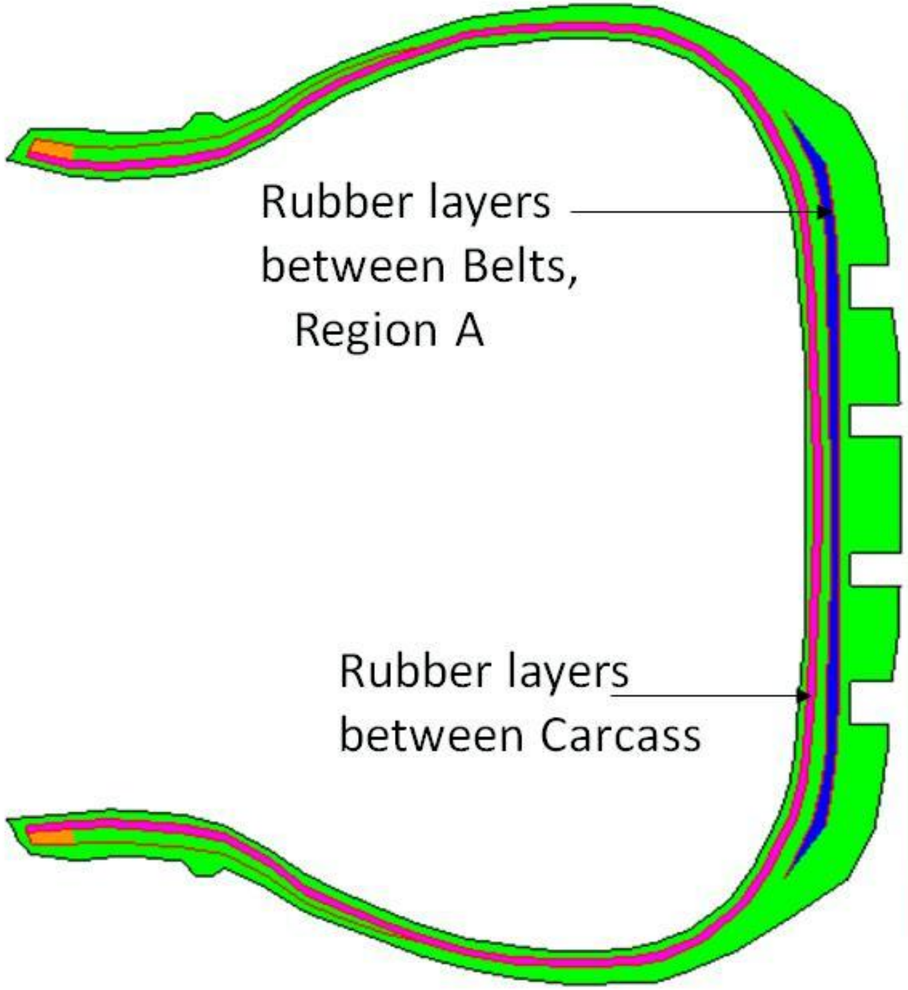
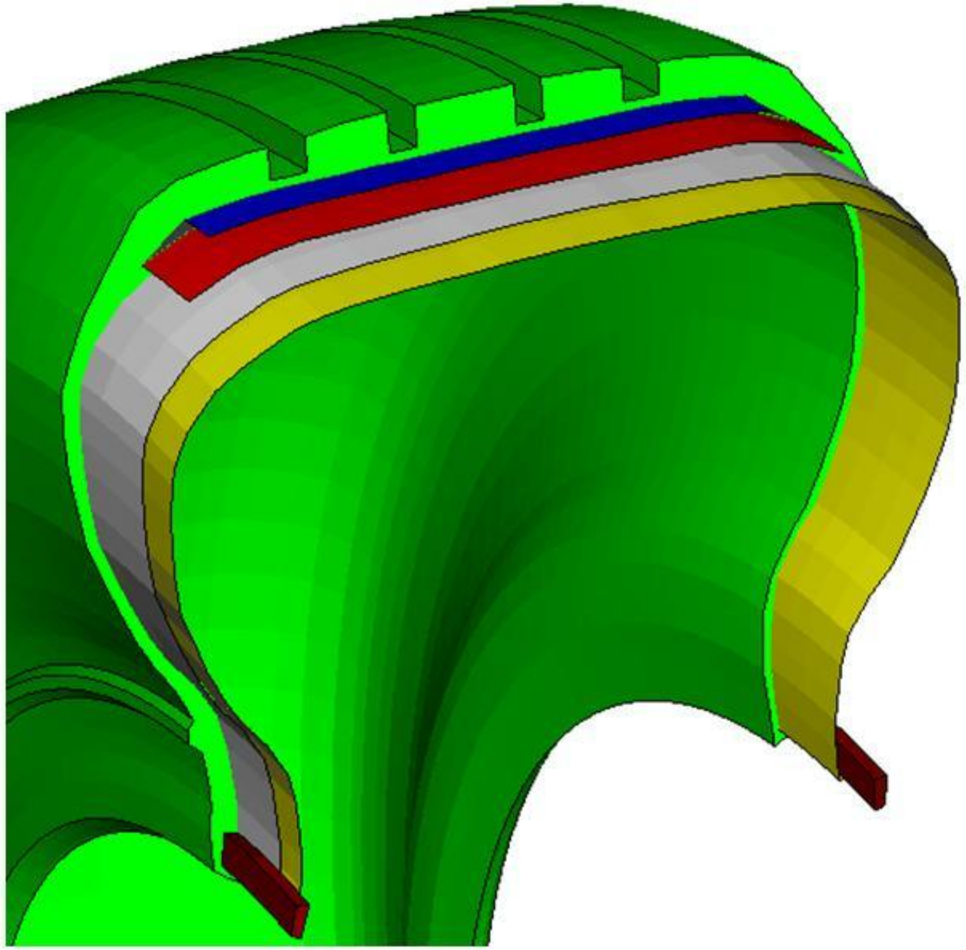
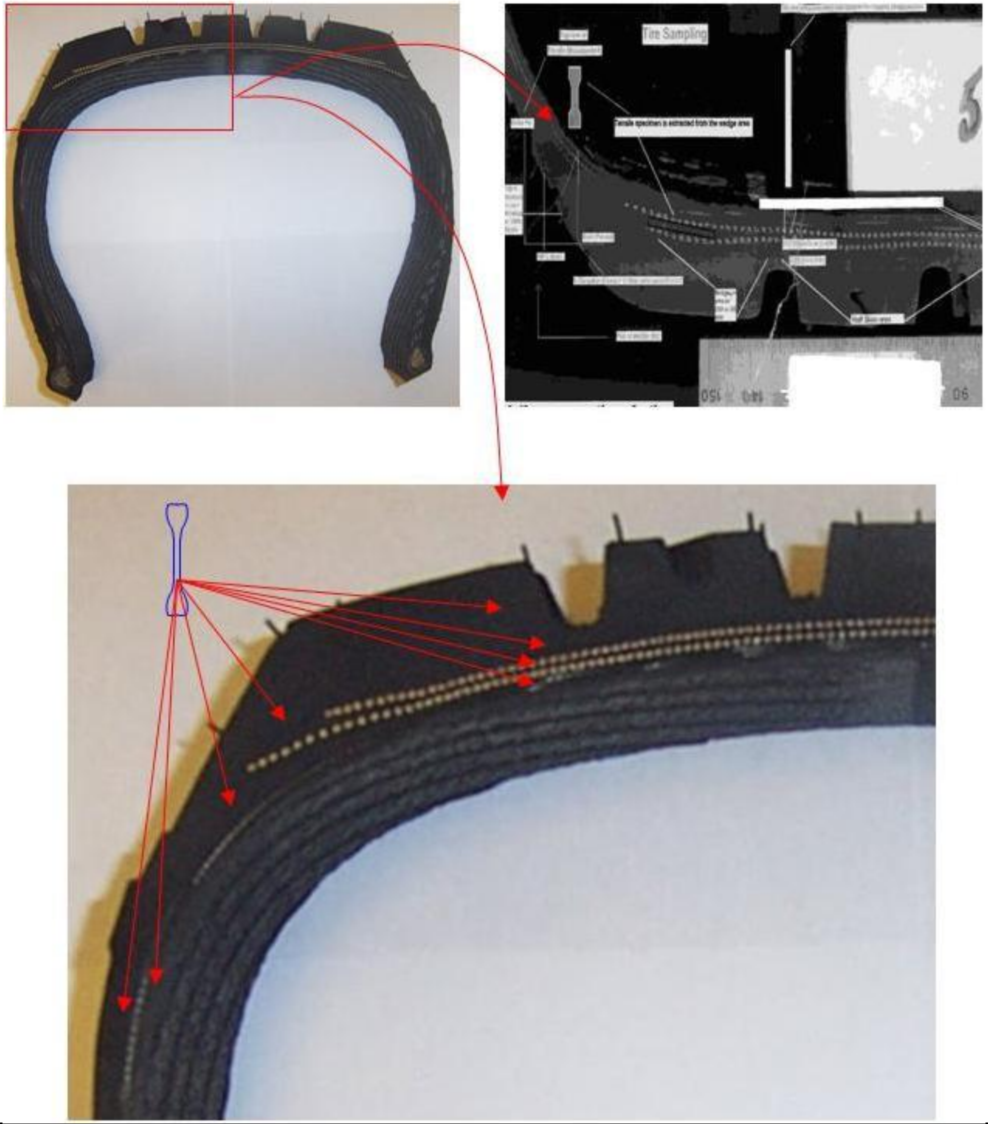
APPLICATION OF HYPERELASTIC & VISCOELASTIC DATA FOR TIRE PERFORMANCE ANALYSIS

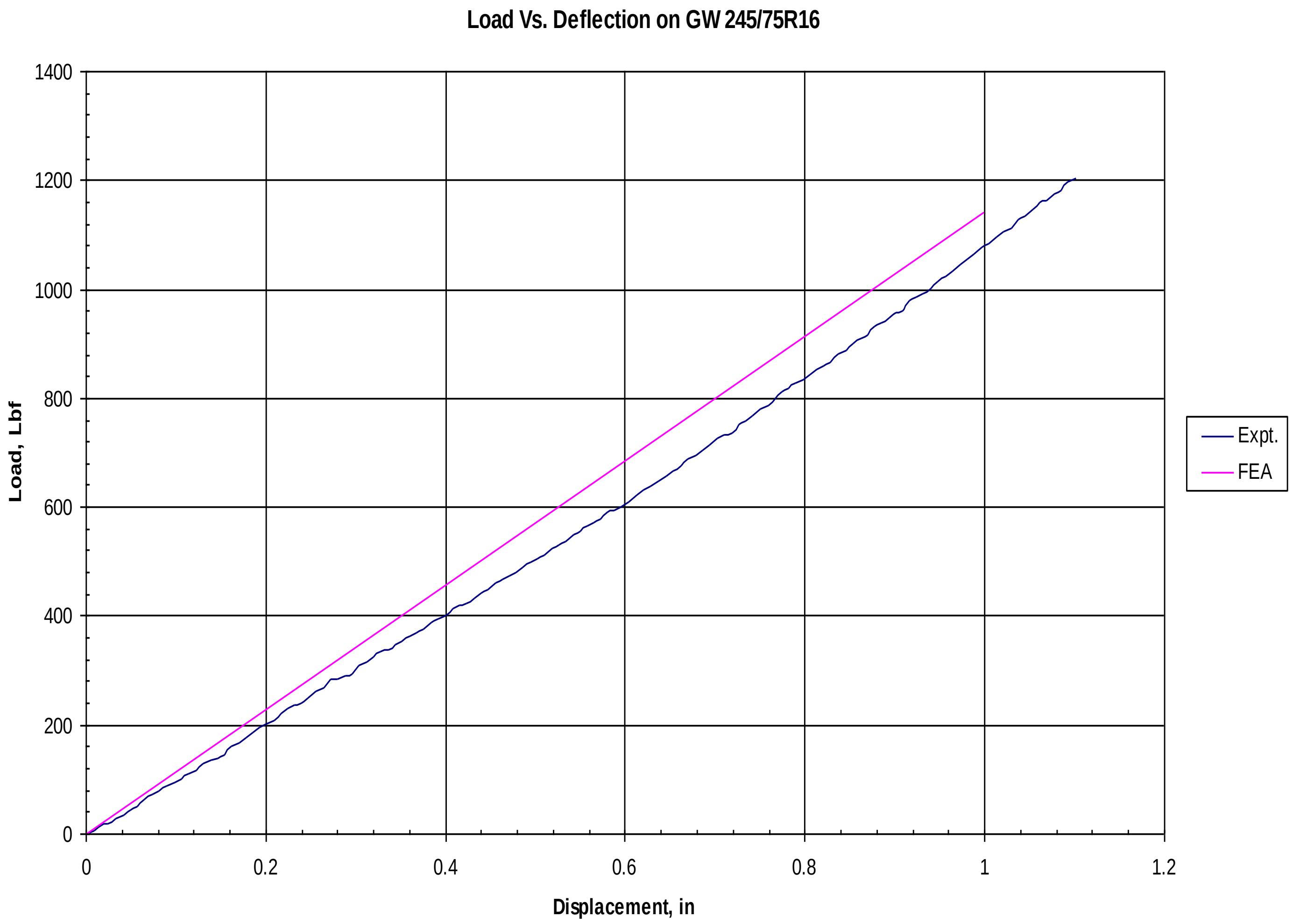




MATERIAL EXTRACTION FOR TIRE FEA

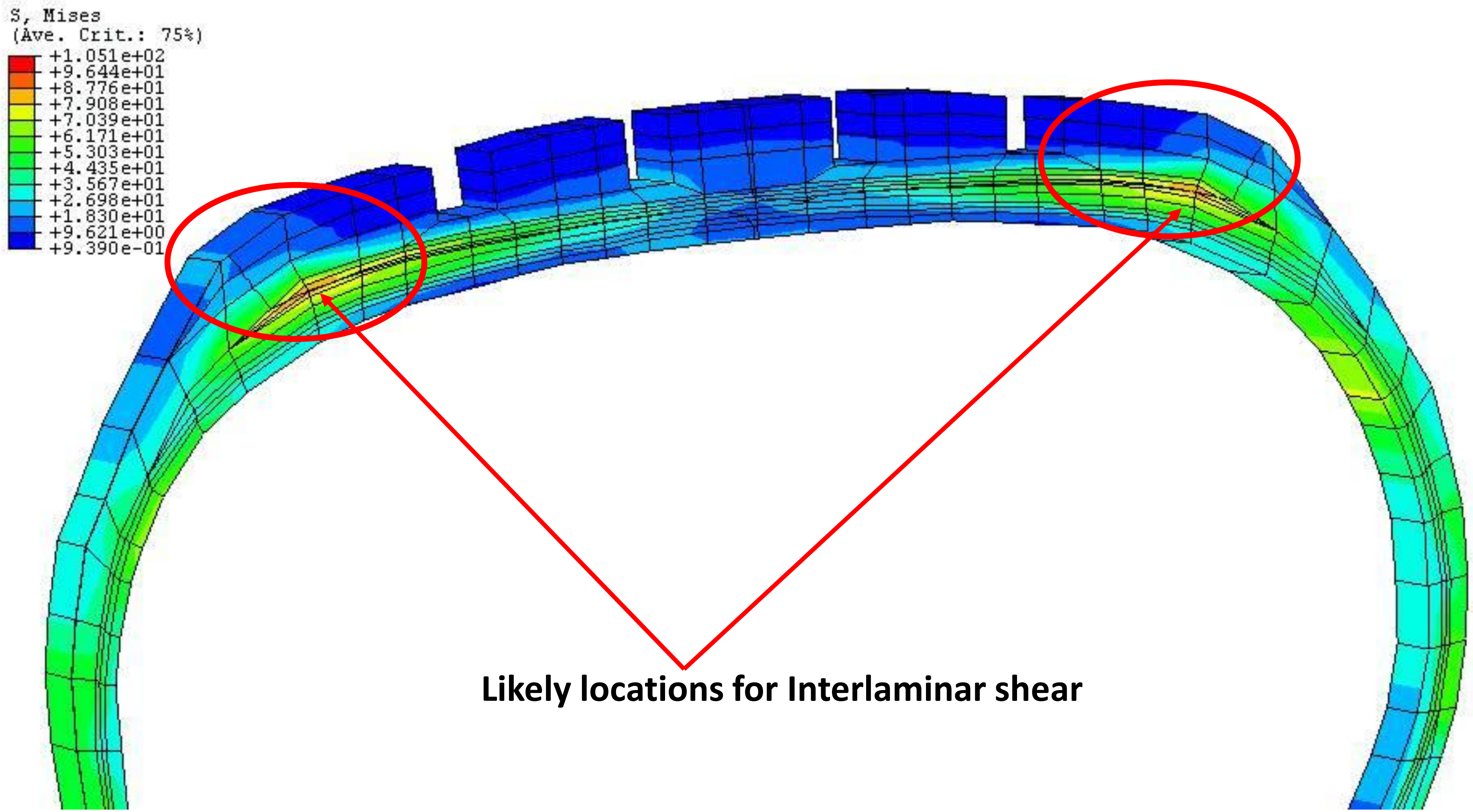


LOAD-DEFLECTION RESULTS



Comparison of Experimental and FEA Results

HYPERELASTIC TIRE ANALYSIS RESULTS

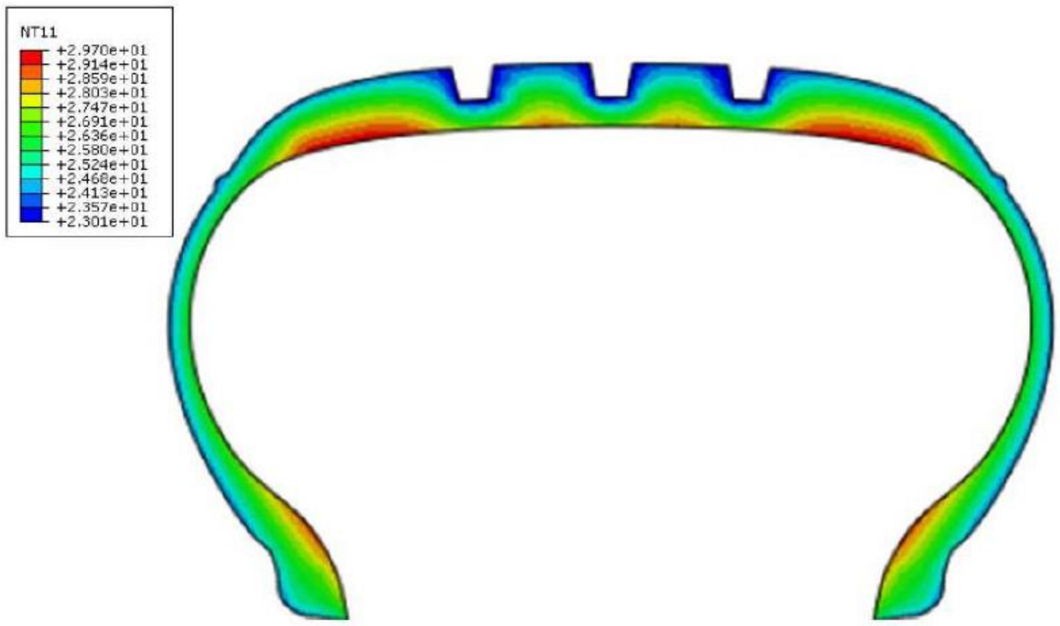


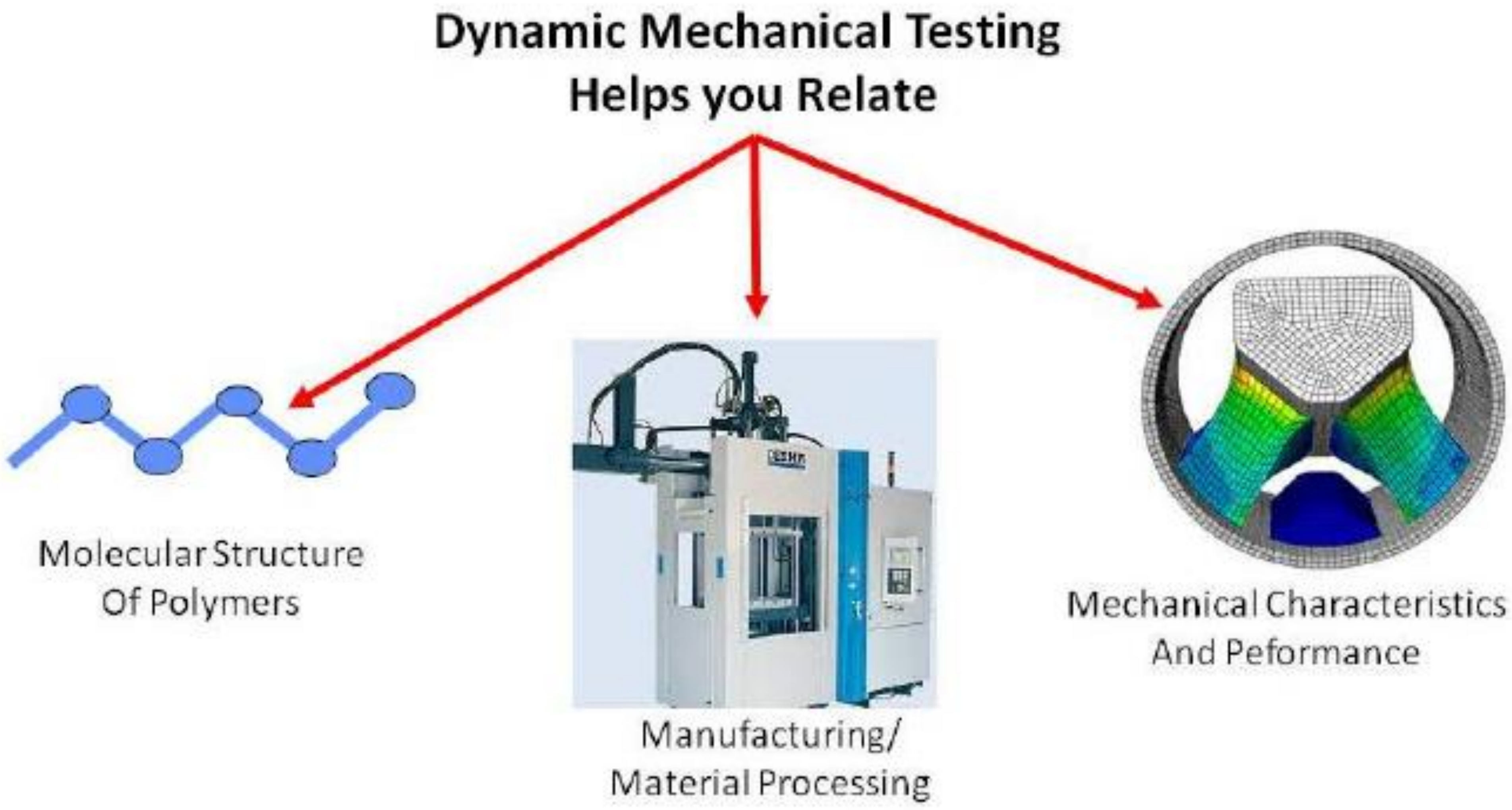
VISCOELASTIC TIRE ANALYSIS RESULTS FOR TEMPERATURE PREDICTION

Non-linear Viscoelastic tire simulation is carried out using Abaqus/Ansys/Marc etc., to predict the hysteresis losses, temperature distribution and rolling resistance of a tire. The simulation includes several steps like (a) FE tire model generation, (b) Material parameter identification, (c) Material modeling and (d) Tire Rolling Simulation.

The energy dissipation and rolling resistance are evaluated by using dynamic mechanical properties like storage and loss modulus, tan delta etc. The heat dissipation energy is calculated by taking the product of elastic strain energy and the loss tangent of materials.

Tire Temperature Prediction during Rolling




Dynamic Mechanical Testing
Helps you Relate
Molecular Structure
Of Polymers
Manufacturing/
Material Processing
Mechanical Characteristics
And Peformance

VERIFICATIONS AND VALIDATIONS

- Single Element Tests
  - Can be performed by analyst (uses curve-fitting)
  - First order check on the material property
- Closed Loop Validation
  - Compare results with the original material data from experiments
- Open Loop Validation
  - Comparison to alternate experimental modes
  - Carry out tests at component level

APPLICATION AREAS IN FEA

- Engine mounts, bushings, vibration isolators etc.
- Seals, o-rings etc.,
- Gaskets(Rubber and Composite)
- Weather strips
- Biomedical implants
- All situations where static pre-load is superimposed by service loads.

GOAL OF CAE TESTING SERVICES

- Create a step-by-step process based procedure for CAE.
- Validate for different regimes of product performance and service conditions
  - Viscoelastic
  - Hyperelastic
  - Hyperelastic rate dependent
  - Non-linear (Elasto-plastic, high strain rate)
- Validate models for failure analysis and design optimization

- Provides virtual testing and approaches to simulating complex material characteristics.
- use of FEA will reduce testing and redesign costs thereby shortening the product development time.
- Identify issues in designs before mold is made.
- Redesign components and systems before dependencies to other parts/components prohibit changes.
- Optimize design before prototyping.

EXPERIENCE BASED CONSULTING IN PRODUCT DEVELOPMENT AND MATERIAL TESTING

- Material Evaluation
- Product Design and Analysis
- Material Characterization and Durability Testing
- Failure Analysis
- Patent Development
- Feedback and Optimization of Rubber Compounds

PUBLICATIONS & REFERENCES

Srinivas, K., *Material Characterization And CAE For Non-Metallic Materials & Manufacturing Processes*, SAE Symposium on CAE Applications for Automotive Structures, Detroit, November 2005.

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Cornelius, K. C., and Srinivas, K., *Isentropic Compressible Flow for Non-Ideal Gas Model for a Venturi*, ASME Journal of Fluids Engineering, Feb 2004.

Srinivas, K., and Pannikottu, A., *Material Characterization and Finite Element Analysis of High Performance Tires*, International Rubber Expo and Conference, Mumbai, March 2005.

Srinivas, K., and Dharaiya, D., *Material And Rheological Characterization For Rapid Prototyping Of Elastomers Components*, American Chemical Society, Rubber Division, 170th Technical Meeting, Cincinnati, October 2006