Simulazione FEM Non lineare di TPE
Simulation of TPE

- Increased use in multiple industries
  - Automotive, aerospace, machinery, biomedical etc.

- Wide availability

- Low cost

- Customizable properties
  - Flexibility
  - Damping
  - Seal against moisture, heat & pressure
Thermoplastic elastomers (TPE)

Thermoplastic Elastomers (TPE) are materials, which combine the advantages of elastomers and thermoplastics.

TPE is much stiffer then a typical elastomer. TPEs usually show a softening effect.
Efficient and realistic analysis for design of hyperelastic products

- **Nonlinear material behavior**—compressible or incompressible material models, time and temperature effects, presence of anisotropy due to fillers or fibers, hysteresis due to cyclic loading and manifestation of instabilities.

- **Determination of Material Parameters from Test Data**—perhaps the single most troublesome step for most engineers in analyzing elastomers, that is, how to “curve fit” test data and derive parameters necessary to characterize a material.

- **Failure**—causes and analysis of failure resulting due to material damage and degradation, cracking, and debonding.

- **Modern automated contact** analysis techniques—friction effects, and the use of “contact bodies” to handle boundary conditions at an interface. Automated solution strategies—issues related to model preparation, nonlinear analysis, parallelization, and ease-of-use of the simulation software.

- **Automated Remeshing** - for effective solution of problems involving distorted meshes which can lead to premature termination of analysis.
Hyperelastic Materials

- **Nonlinear behavior**
  Stress-strain relationship can be defined as non-linearly elastic, isotropic, incompressible and generally independent of strain rate.
  - **Rubber / TPE**
    - isotropic and nearly incompressible
  - **Foam**
    - isotropic and highly compressible

- **Temperature dependency**

- **Manufacturing process dependency**

- **Damping**

- **Time dependent response**
  - Relaxation and creep

- **Damage and Failure**
Strain Energy Density $W$

Since for isotropic materials, the constitutive relation has to be independent of the coordinate frame selected, it is natural that the strain energy density is defined using invariants of strain.

\[
I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \\
I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2 \\
I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2
\]

$W (I_1, I_2)$
Hyperelastic Formulations

The simplest model of rubber elasticity is the Neo-Hookean model represented as:

\[ W = C_{10} (I_1 - 3) \]

The earliest phenomenological theory of nonlinear elasticity is now known as the Mooney-Rivlin model written as:

\[ W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) \]

Three term Mooney-Rivlin: (Ronald Rivlin and Melvin Mooney)

\[ W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) + C_{20} (I_1 - 3)^2 \]

Signorini:

\[ W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) + C_{11} (I_1 - 3)(I_2 - 3) + C_{20} (I_1 - 3)^2 \]

Second Order Invariant:

\[ W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) + C_{11} (I_1 - 3)(I_2 - 3) + C_{20} (I_1 - 3)^2 \]

James-Green-Simpson (Third Order):

\[ W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) + C_{11} (I_1 - 3)(I_2 - 3) + C_{20} (I_1 - 3)^2 + C_{30} (I_1 - 3)^3 \]

Others……
EXPERIMENTAL DATA FIT

**Definitions, Stretch ratios, Engineering Strain:**

\[
\lambda_i = \frac{L_i + \Delta L_i}{L_i} = 1 + \varepsilon_i \quad \text{eng. strain, } \varepsilon_i = \frac{\Delta L_i}{L_i}
\]

**Incompressibility:**

\[
\lambda_1 \lambda_2 \lambda_3 = 1
\]

**Neo-Hookean Tension case**

**Experimental Verification using Simple Extension**

\[
\lambda_1 = \lambda \quad \lambda_2 = \lambda_3 = 1 \sqrt{\frac{E}{G}}
\]

**Hence:**

\[
\psi = \frac{1}{2} G \left( \lambda^2 + \frac{2}{\lambda} - 3 \right)
\]

**Engineering Stress:**

\[
\sigma = \frac{d\psi}{d\lambda} = G \left( \lambda - \frac{1}{\lambda} \right) = G \left( 1 + \varepsilon - \frac{1}{(1+\varepsilon)^2} \right)
\]

**Theory versus experiments:**

- **Experiment**
- **Theory Neo-Hookean**
Experimental Tests

Compression and Tension very Different

Three Basic Strain Modes

Cut from Same Sheet

Testing Machine
Prove sperimentali di caratterizzazione

<table>
<thead>
<tr>
<th>POLIMERI / ELASTOMERI</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trazione (modulo e resistenza) – 0°/90° / 45°</td>
<td>ISO 527</td>
</tr>
<tr>
<td>Compressione (resistenza) – 0°/90° / 45°</td>
<td>ASTM D695 / ISO 604</td>
</tr>
<tr>
<td>Taglio (resistenza)</td>
<td>ASTM D732 / D5379</td>
</tr>
<tr>
<td>Flessione (resistenza)</td>
<td>ISO 178</td>
</tr>
<tr>
<td>DMA (da 25 a 200 °C)</td>
<td>ASTM D4065</td>
</tr>
<tr>
<td>DMA (da -100 a 200 °C)</td>
<td>ASTM D4065</td>
</tr>
<tr>
<td>Dilatazione termica (da 25 a 200 °C)</td>
<td>ASTM E 831</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LAMINE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trazione (modulo e resistenza) – 0°/90°</td>
<td>ASTM D 3039</td>
</tr>
<tr>
<td>Trazione (modulo e resistenza) ±45°</td>
<td>ASTM D 3039</td>
</tr>
<tr>
<td>Compressione (modulo e resistenza) – 0°/90</td>
<td>ASTM D3410 / ISO 14126</td>
</tr>
<tr>
<td>Taglio (resistenza)</td>
<td>ASTM D5379 / D3846</td>
</tr>
</tbody>
</table>

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<tr>
<th>LAMINATI</th>
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<tr>
<td>Trazione (modulo e resistenza)</td>
<td>ASTM D 3039/6641</td>
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</table>

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<thead>
<tr>
<th>CARATTERIZZAZIONE MICROSTRUTTURA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frazione fibre in volume</td>
<td>ISO 14127</td>
</tr>
<tr>
<td>Stratificazione</td>
<td>UNI EN ISO 1172 (fv)</td>
</tr>
<tr>
<td>Microtomografia</td>
<td>Metodo interno</td>
</tr>
<tr>
<td>Porosità</td>
<td>UNI EN ISO 1183-3</td>
</tr>
<tr>
<td>Lunghezza fibre</td>
<td>Metodo interno</td>
</tr>
</tbody>
</table>
Prove sperimentali di caratterizzazione

Prova di trazione uni-assiale

Table 2 — Dimensions of dies for dumb-bell test pieces

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Type 1</th>
<th>Type 1A</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  Overall length (minimum) (mm)</td>
<td>115</td>
<td>100</td>
<td>75</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>B  Width of ends (mm)</td>
<td>25.0 ± 1</td>
<td>25.0 ± 1</td>
<td>12.5 ± 1</td>
<td>8.5 ± 0.5</td>
<td>6 ± 0.5</td>
</tr>
<tr>
<td>C  Length of narrow portion (mm)</td>
<td>33 ± 2</td>
<td>20.7 ± 2</td>
<td>25 ± 1</td>
<td>16 ± 1</td>
<td>12 ± 0.5</td>
</tr>
<tr>
<td>D  Width of narrow portion (mm)</td>
<td>6 ± 0.2</td>
<td>5 ± 0.1</td>
<td>4 ± 0.1</td>
<td>4 ± 0.1</td>
<td>2 ± 0.1</td>
</tr>
<tr>
<td>E  Transition radius outside (mm)</td>
<td>14 ± 1</td>
<td>11 ± 1</td>
<td>8 ± 0.5</td>
<td>7.5 ± 0.5</td>
<td>3 ± 0.1</td>
</tr>
<tr>
<td>F  Transition radius inside (mm)</td>
<td>25 ± 2</td>
<td>25 ± 2</td>
<td>12.5 ± 1</td>
<td>10 ± 0.5</td>
<td>3 ± 0.1</td>
</tr>
</tbody>
</table>

* A greater overall length may be necessary to ensure that only the wide end tabs come into contact with the machine grips, thus avoiding "shoulder breakage."
EXPERIMENTAL DATA FIT

Tension Test
Prove sperimentali di caratterizzazione

Prova di compressione uni-assiale

- Si utilizza un cilindretto φ29 x 13 mm
- La superficie deve essere lubrificata per evitare gli errori che derivano dalla forma «a botte»
- Richiede una accurata misura dell’altezza
Prove sperimentali di caratterizzazione

Prova equi-biassiale

E' stato messo a punto un reometro a bolla, «Bubble Tester», basato sul gonfiaggio in condizioni controllate di una membrana di gomma. I vantaggi di questa soluzione rispetto ad altri possibili schemi (per es. il dinamometro a due assi) sono:
- Rende omogenea la distribuzione dello sforzo nella zona centrale del campione (polo)
- Non ci sono artefatti dovuti ad attrito
- La superficie di gomma bloccata nel sistema di fissaggio rimane costante


BUBBLE TEST (Cerisie lab.)
Prove sperimentali di caratterizzazione

Confronto dei dati rilevati in compressione uni-assiale e calcolati dal reometro a bolla.

Prova di compressione uni-assiale
Validazione misure sperimentali

Validazione delle misure

- Con lo stesso materiale viene stampata una sfera (Ø 34 mm) e costruito il modello FEM
Validazione misure sperimentali

- Confronto dei dati FEM con i rilievi
- Il grafico presenta anche il confronto con la soluzione esatta sotto (modello di Lindley)
Validazione delle misure: deformazione 10 mm

Risultati accurati si ottengono utilizzando i dati della prova di compressione uni-assiale (dischetto compresso 20%) e tensione equibiaisiale

Shore 39,7
Shore 59,9
Shore 71,0

Validazione misure sperimentali

Validazione delle misure: **deformazione 20 mm**

L’accuratezza migliore è ottenuta con i risultati di deformazione equi-biassiale: il contributo della deformazione a taglio nella sfera è marginale

*Sfera durezza 60 Shore A*

Material Models

- **Accurate nonlinear material behavior**
  - Mooney-Rivlin, Ogden, Arruda-Boyce, Gent, Foam
  - User defined material models

- **Anisotropic behavior**
  - Qiu and Pence, Brown and Smith, Gasser models – to model rubber belts, reinforced tubes

- **Viscoelasticity**
  - Time-dependent nonlinear behavior
  - Maxwell model, Kelvin-Voigt model, Bergstrom-Boyce

- **Temperature dependency**

- **Frequency dependent behavior (with damping)**
Elastomer Time Independent Behavior (Cont.)
Time Dependent Viscoelastic Behavior (Cont.)

Stress Relaxation
Rate Dependent Hysteresis - Viscoelasticity
Rate Dependent Hysteresis – Viscoelasticity (Cont.)
Frequency Dependent Viscoelasticity - Harmonic Analysis

*FEA of a simple extension specimen*

- Frequency Dependent Stiffness Properties
- Frequency Dependent Damping Properties
Frequency Dependent Viscoelasticity - Harmonic Analysis (Cont.)

Payne or Fletcher-Gent effect

- Automotive rubber bushing with transverse displacement
- Stiffness and damping are significantly affected by frequency and displacement
- Stiffness increases without Payne effect from 92 to 117 Hz (27%)

![Displacement vs. Frequency](image)

- Harmonic Point load of 35 N
- Harmonic Point load of 35 N without Payne effect
- Harmonic Point load of 15 N
Elastomer Damage (Mullin’s Effect)

Progressive Stiffness Loss with increasing maximum strain amplitude
Elastomer Damage (Mullin’s Effect)

Inc.: 0
Time: 0.000e+000

ciscontinuous damage
Comp 33 of Stress
Elastomer Damage (Stiffness Degradation)
Elastomer Damage (Stiffness Degradation)
Temperature effects

Typical values of \( T_g \) (in °C) are: -70 for natural rubber, -55 for EPDM, and -130 for silicone rubber.
Nonlinear Elasticity with Permanent Set – TPE specific

Multi-Network Model

- **Primary Model (0)**
  - Mooney
  - Ogden
  - Gent
  - Arruda-Boyce
  - Foam
  - Isotropic

- **Viscoelastic (1 to n) – Visco Hype**
  - Arruda-Boyce

- **Plasticity (n+1 to m) – Perm Set**
  - Ogden
  - Arruda-Boyce
  - Isotropic
Comparison of Behavior

Conventional Arruda-Boyce

Multi-Network Arruda-Boyce /Visco Hype
MSC Software Advantages

**MSC Marc** first commercially nonlinear FEA solution (1971)
Leader in solving complex problems
- 3D contact
- Parallelization
- Automatic remeshing

Nonlinear analysis for a wide range of applications:

- Aerospace & Defense
- Aviation
- Agriculture, Construction
- Shipbuilding
- Consumer Products
- Machinery, Manufacturing
- Rail Vehicles
- Automotive
- Building/Civil
- Biomedical
Multi-body Contact Analysis

Contact Analysis

• **Ease of use**
  – Time saving through easy set up
  – Prior knowledge of contact regions not required
  – Automatic self-contact

• **Accuracy**
  – Automatic convergence checks and time step adjustments
  – Friction modeling

• **Comprehensive**
  – General large sliding contact
  – Node-to-patch and segment-to-segment contact
  – Multidisciplinary (Thermal contact, electrostatics etc)
Examples

Washing machine seal

O-ring Mounting

Seal

Seal with remeshing
More Examples

Ball joint boot
Door seal
Bushing

Jounce bumper
Pin insertion
Tape peeling
Adams-Marc Co-simulation
for Nonlinear Parts Integration in System Model

Prepare Models → Create Configuration File → Run Co-simulation → Plot Results → Co-animate

Adams
Define Interaction Points
→
Adams
→
Forces
→
Position
→
Adams

1) Position/Velocity/Acceleration
2) Forces and Torques

Adams

Marc
Define Interaction Points
→
Marc
→
Plastic Strain/Stress

Use case scenario: ATV hitting an obstacle
Suspension System
Complex 3D Contact

Big Tyre has developed a non-pneumatic, non-solid segmented tire which it hopes will overcome problems and potentially revolutionize the underground mining industry.

“We were pleasantly surprised that Marc was able to handle such a demanding analysis problem in such a short period of time and deliver results that closely matched test results on the prototype.”

Bruce Louden, Big Tyre
Remeshing

• Manual and automatic

• Local
  – Automatic refining of mesh in high stress/strain gradient zones

• Global
  – Automatic recreation of a new mesh for a component

• Automatic global adaptive
  – Support for 2D and 3D elements
  – Support for boundary conditions
  – Ability to combine local and global in same analysis
  – Easy to set up
Damage and Failure

- **Damage**
  - Continuous
  - Discontinuous

- **Mechanical Wear**

- **Failure**
  - Crack propagation
  - Mesh Split
  - Deactivate
Other application examples

**TIRE**
- From AXISYMMETRIC to 3D MODEL
- Rebar elements with INSERT
- Cavity elements
- Steady state rolling
- ...

**Static analysis**
- Quasi-static
- Creep and relaxation

**Dynamic**
- Transient, time domain
- Frequency domain

**Thermal – Coupled Multiphysics**

.....
Helping Business Bottomline

Case Study: Race-Tec

CHALLENGE:
To design a CV boot that will be able to withstand articulation angles without excessive stress, deformation or contact.

APPLICATION:
Marc for nonlinear finite element analysis to quickly evaluate alternative designs and iterate to an optimal solution.

KEY RESULTS:
Consistent and Reliable Problem Solving, Accurate and Robust Nonlinear Analyses, and Considerable Cost and Time Optimization

INDUSTRY: AUTOMOTIVE | Products Used: Marc

“Nonlinear analysis with Marc helps us dramatically improve the design of CV boots and other products. Our simulation capabilities enable us to design boots that substantially outlast competitive designs. The result is that we have been able to increase our market share in our traditional markets and successfully enter new markets.”

Richard Kennison, Senior Design Engineer, Race-Tec
Driving Innovation in Tires

Case Study: Big Tyre

CHALLENGE:
Big Tyre has developed a non-pneumatic, non-solid segmented tire which it hopes will overcome problems and potentially revolutionize the underground mining industry.

APPLICATION:
Marc

KEY RESULTS:
Accurate simulation that closely matches test results, and flexibility of defining various design parameters to optimize final design.

“We were pleasantly surprised that Marc was able to handle such a demanding analysis problem in such a short period of time and deliver results that closely matched test results on the prototype.”

Bruce Louden, Big Tyre
Improving Product Performance

Case Study: ZF Lemforder

CHALLENGE:
Failure of ball joint boots can let the grease they hold to leak affecting performance and lead to excessive wear.

APPLICATION:
Marc nonlinear contact analysis was used to study the boot behavior during installation and loading cycles.

KEY RESULTS:
By conducting product tests virtually, gained insight into wear zones, contact forces and loads. Helped reduced physical prototype costs, and improved performance faster.

INDUSTRY: AUTOMOTIVE  |  Products Used: Marc
More Tests with Less Costs

Case Study: DURA

**CHALLENGE:**
Accelerate boot development to satisfy the requirements of OEMs by evaluating more design variants in less time.

**APPLICATION:**
Design variants are analyzed with Marc to predict the potential tear regions.

**KEY RESULTS:**
Reduced the required physical testing. Boot design that meets customer requirements found in less time at less cost.

**INDUSTRY:** AUTOMOTIVE  |  Products Used: Marc
Reducing Uncertainty for First Time Success

Case Study: HBW, The Netherlands

CHALLENGE:
Design an inflatable dam to protect neighboring area from flooding

APPLICATION:
Design consisting of fabric built from a composite of rubber and nylon chord analyzed with Marc for multiple environmental factors and pressure.

KEY RESULTS:
Simulations helped design modifications to reduce stresses in the material. Result accuracy was critical as no physical prototype was involved

INDUSTRY: AUTOMOTIVE | Products Used: Marc
Thank You