Applus DatapointLabs

Beyond Standards: Material Testing and Processing for Successful Simulations of Foam Materials (LAW90)

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TestCart
TestPaks
CAETestBench

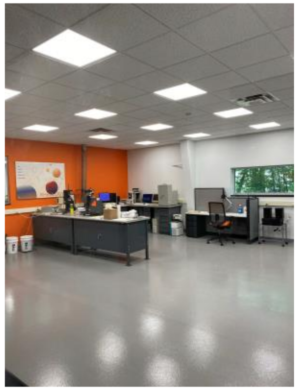
EST 1995
ISO 17025 Quality

LABORATORIES DIVISION

DatapointLabs

Technical Center for Materials




Summary Overview

Applus & DatapointLabs

Applus, DatapointLabs & Materials Characterization

Applus Overview: **€1,558B** revenue | **23,387 staff** | **70+ countries** [2020]

Relevant Divisions:

Product Development & Validation

LABORATORIES DIVISION	IDIADA DIVISION (AUTOMOTIVE)
• Testing • Engineering • Product/System Certification • Multidisciplinary Laboratories	• Design & Engineering • Data Analysis & Simulation • Homologation Services • Testing & Proving Ground

Relevant Partner Laboratories:

Materials Characterization & Quality Assurance

USA | Ithaca

Spain | Barcelona

France | St. Etiènne

Norway | Bryne

USA | Detroit

Spain | Illescas

Germany | Bremen

China | Shanghai

DatapointLabs Summary Overview (I)

Applus DatapointLabs

- Experience
  - 27 years of experience in materials testing and characterization
  - ISO 17025:2017 accredited, operating on an end-end digital platform
  - Nadcap accredited [Aerospace / Defense] (Metallic/Non-Metallic Materials Testing)

A2LA ACCREDITED
Certificate# 1242.01
ISO/IEC 17025:2017

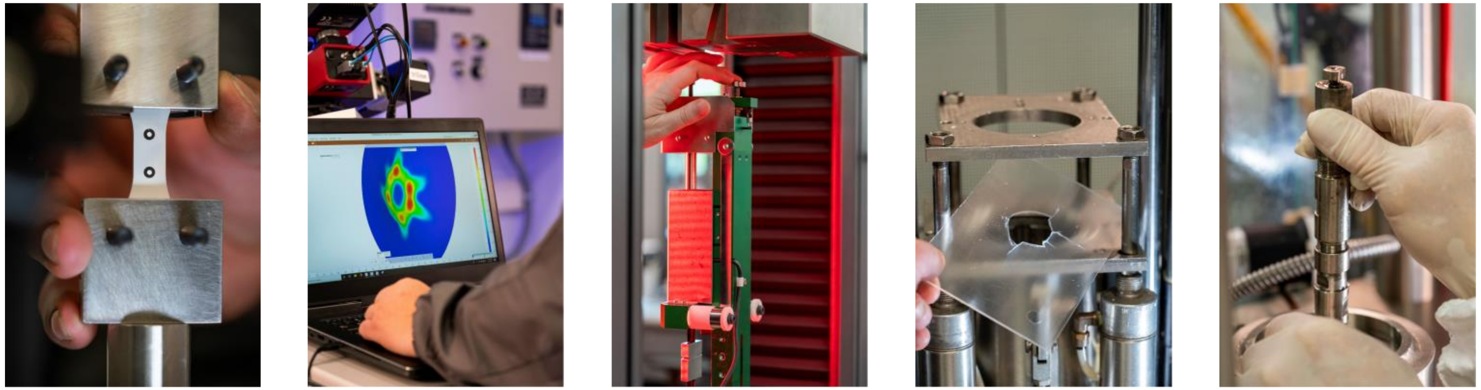
Nadcap
Administered by PRI
ACCREDITED
Certificate# 17231205927
Non Metallic Materials Testing

- Operations
  - Testing 2000+ materials per year
  - Standard 5-day turnaround
  - Comprehensive one-stop testing capability
    - 168 unique tests: all aspects of mechanical, thermal and rheological characterization

DatapointLabs Summary Overview (II)

- Capabilities
  - Materials: plastics, composites, foam, rubber, metals, additive materials, films, adhesives
  - May be characterized over a wide range of temperature and environmental conditions (elevated/cryogenic, heat aging, moisture conditioning, weathering, fluid exposure, in-vivo)
  - Characterize non-linear and post-yield behavior, dynamic situations (drop, crash, impact), hyperelasticity (rubber, foams), time-based behavior (creep, stress relaxation, viscoelasticity)

- Clientele
  - Global clientele of more than 1,800 companies in 49 countries
  - Market leader in materials testing for CAE simulation
  - Recognized as accredited materials test lab by leading OEMs

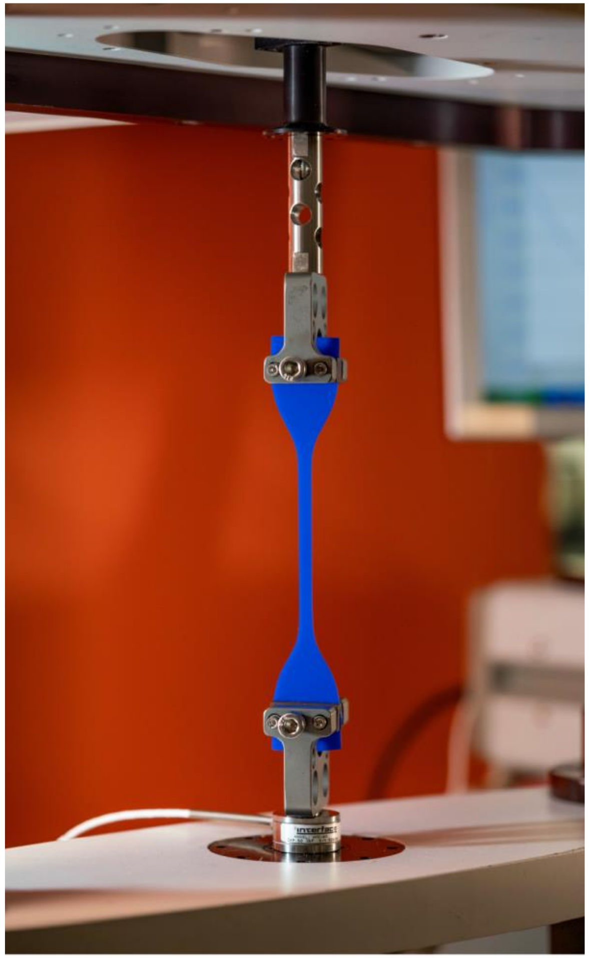


Materials Testing

Characterization Challenges
Quality Assurance
Scientific Precision
Suitability of Data
CAE-Related Issues

Tackling the Most Challenging Characterizations

- Example: plastics
  - Non-linear elasticity
  - Complex plasticity (pre-yield, post-yield)
  - Viscoelasticity (time-based behavior)
  - Properties change over product operational temperature
  - Properties change with environmental exposure
  - Distinct behavioral classes
    - Ductile (post-yield behavior)
    - Brittle (no post-yield behavior)
    - Elastomeric (hyperelastic with plasticity)



Materials Testing – Ensuring Accuracy of Data

Applus DatapointLabs

- Quality assurance of materials characterization data accuracy [ISO17025:2017]
  - Data Traceability operation of a complete digital platform for end-to-end traceability of test data
  - Independent Evaluation participation in quarterly interlaboratory round-robin proficiency testing
  - Calibration scheduled periodic calibration of test equipment to NIST-traceable calibration measures
  - Verification routine verification of test equipment using NIST-traceable standard reference materials
  - Auditing SOPs adherence to standard operating procedures (SOPs) for all calibration/verification
  - Uncertainty Budgeting determination of measurement uncertainty budgets for calibration
  - Recordkeeping complete recordkeeping of equipment calibration/verification activity & scheduling
  - Monitoring employment of control charts for statistical process control (SPC) monitoring of testing
  - Spot Intervention preventative or corrective action as dictated by the individual case
  - Test Standards adherence to ISO/ASTM testing protocols and standards whenever applicable
  - Testing SOPs adherence to SOPs informed by test standards for all standard test procedures
  - Data Statistics probing of inherent test variability through replicate testing for basic data statistics

Materials Testing – CAE-Related Issues

- Complexity of today's material data
  - Often not easily understood by design/CAE engineers
- Terminological issues regarding material properties
  - Often a lack of common vocabulary between materials engineers and CAE experts
- Appropriateness of material model to material and application
  - Selection of material model can be limited by lack of material data or model familiarity
- Difficulties in parameter conversion to material model
  - Conversion / calibration: raw material property data → material model inputs (e.g. selected points, slopes (modulus), equation coefficients, transitions, end points)
  - Conversion can be tricky, relies on skill and expertise of the analyst
- Difficulties in preparation of material file for simulation input
  - Each solver has a unique, complex, sometimes obscure file format for model import
  - Units must be converted to self-consistent unit system unique to each solver

Materials Testing for Product Development

Applus+ DatapointLabs

TestCart

Comprehensive online catalog and order system for 168 unique tests characterizing physical, thermal and flow properties of materials for use in R&D and product development

metals, plastics, composites, rubber, foam, rubber, films

TestPaks®

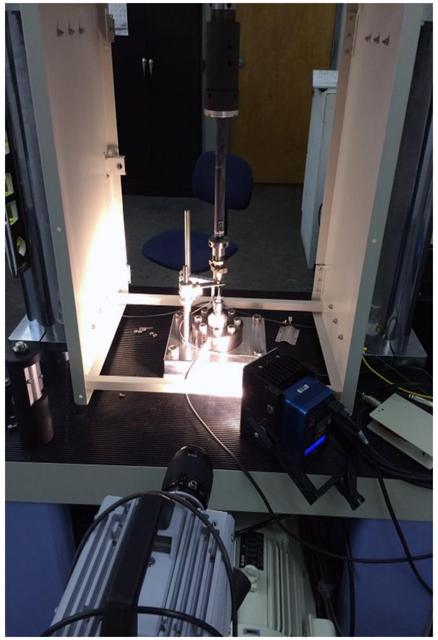
Material testing and material parameter conversion to generate 179 material cards for 36 simulation (CAE) programs, including finite-element analysis, crash and drop-test simulations, injection-molding and other process simulations

CAETestBench™

Validate your simulation against a physical part, created and tested using a rigid protocol, which can be accurately replicated in your solver – probe simulation accuracy and quantify its ability to replicate the test

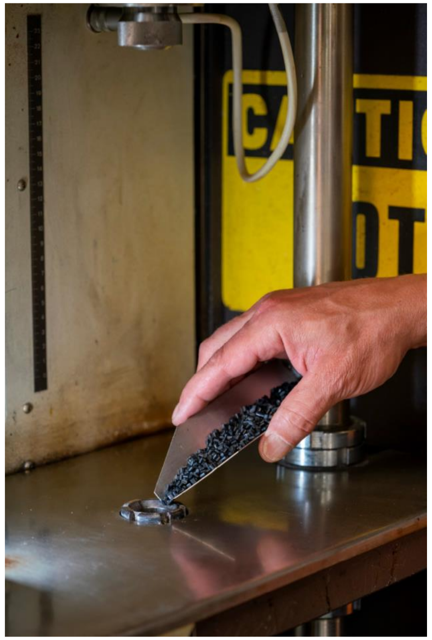
Validations range from simple tensile modes to more complex, multi-axial modes, impact and failure

Applus DatapointLabs



High strain-rate (to 1000/s) measurements using 1M fps camera with digital imaging

High-pressure dilatometer for isothermal & isobaric PVT measurements



Feeding specimen material into capillary rheometer for characterization

TestCart

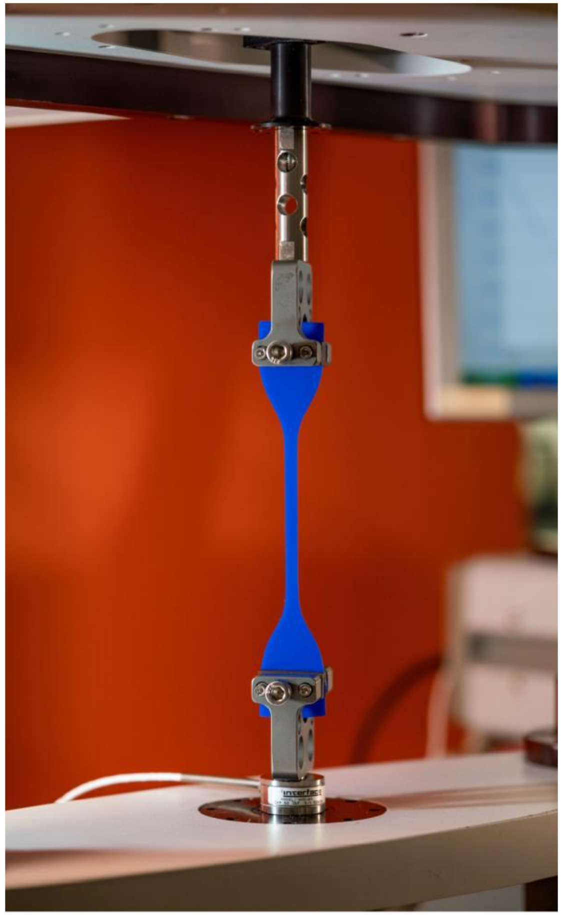
Mechanical Testing
Thermal Testing
Rheological Testing

OEM Materials Qualification

TestCart: Our testing solution

Applus DatapointLabs

Mechanical



- Stress-strain curves tensile, compressive, flexural, volumetric, shear
- Modulus tensile, compressive, shear, flexural, bulk
- Poisson's ratio tensile or compressive
- High strain rate properties up to 1000/s
- Hyperelastic and hyperfoam properties
- Creep and creep rupture tensile, compressive, flexural
- Fatigue tensile, flexural
- Impact Izod, Charpy, Dynatup
- Volumetric properties compressibility, bulk modulus
- Viscoelastic properties torsion, tensile, compressive, flexural
- Stress relaxation torsion, tensile, compressive
- Friction, wear and hardness
- Environmental exposure heat and chemical aging
- Forming limit diagrams

TestCart: Our testing solution

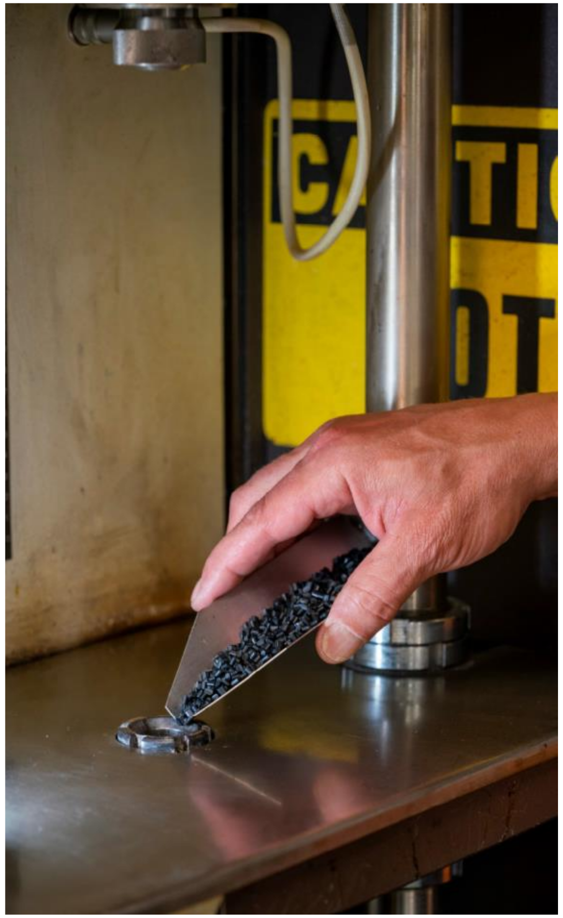
Applus+ DatapointLabs

Thermal

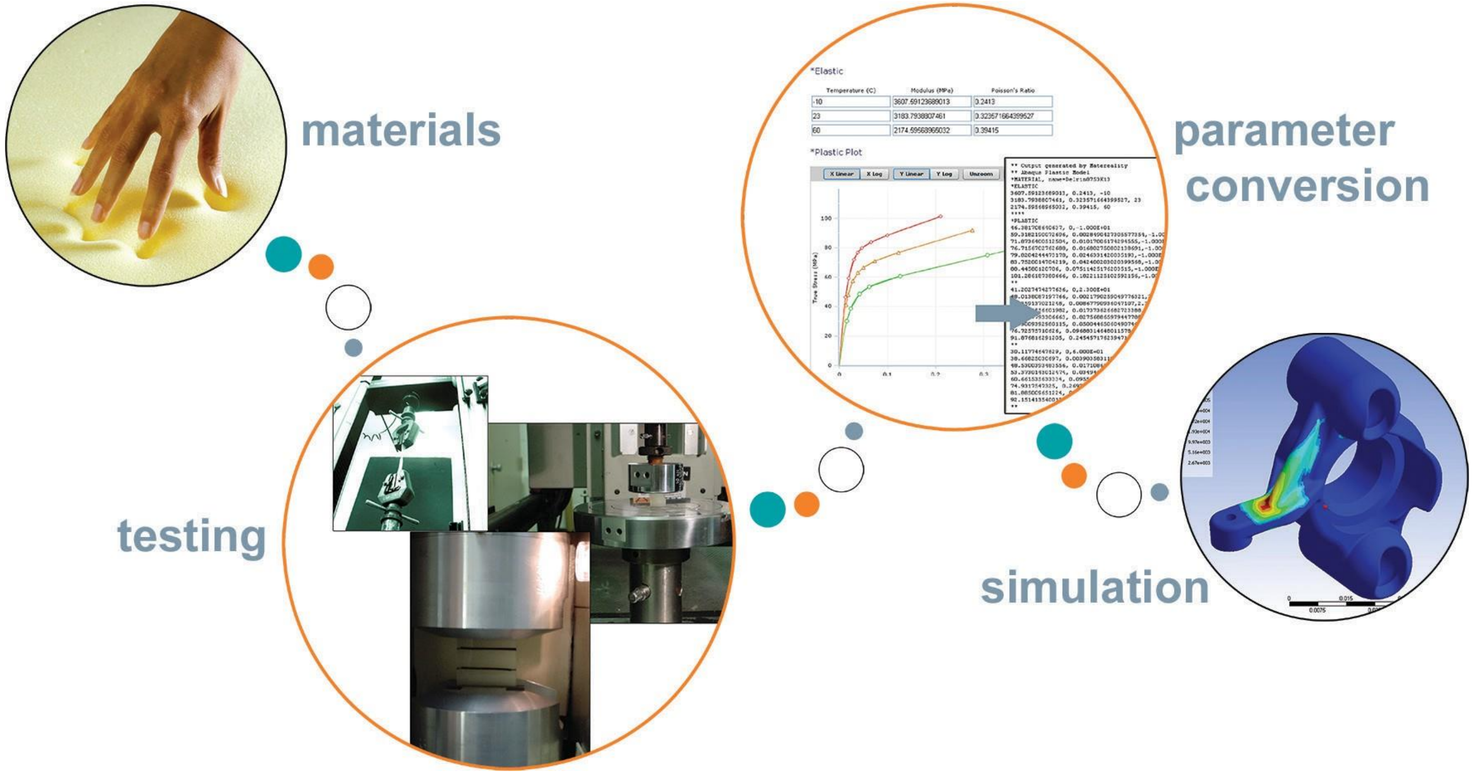
- Thermal expansion linear and volumetric
- Thermal conductivity
- Thermal diffusivity
- Thermogravimetric analysis
- Specific heat
- Transitions melting, solidification, crystallization kinetics
- Heat deflection temperature
- PVT isothermal & isobaric methods, very high-pressure PVT

TestCart: Our testing solution

Thermal



- Capillary viscosity, juncture losses, slip, die swell
- Viscoelastic properties, dynamic and steady shear
- Rheotens melt tension measurements
- Extensional viscosity   lubricated squeezing
- Melt flow rate



TestPaks

Material parameters for CAE

- Structural FEA
- Crash/dynamic FEA
- Injection molding CAE
- Extrusion
- Blow-molding

TestPaks – Material Parameters for Simulation

Applus DatapointLabs

- Reducing enterprise product risk with better CAE material data
  - Risk: divergence between simulated and actual product behavior
  - Contributing factor: disparity between material model and actual material(s)
- TestPaks: from expert materials testing to CAE-ready material files
  - Developed in collaboration with CAE software partners
  - 179 unique TestPaks for most common material models across 36 CAE software packages
  - Simply order online or email/call us, typical delivery in five business days

TestPaks – Characterization to CAE Material File

- TestPaks include
  - Exact material testing to CAE material model requirements
  - Conversion of raw characterization data to material model parameters
  - Solver-formatted, CAE-ready material files
- Your characterization data, test reports and CAE material files are deposited directly into your Personal Matereality database account

TestPaks *material properties for your CAE*

- Universal TestPaks available for some common material models
  - Single set of material tests; material files for multiple CAE solvers
  - Particularly attractive for material suppliers serving OEM customers requiring data for CAE

Serving the
Automotive Industry

General Services Offered

- Material Qualification
- Characterization for CAE

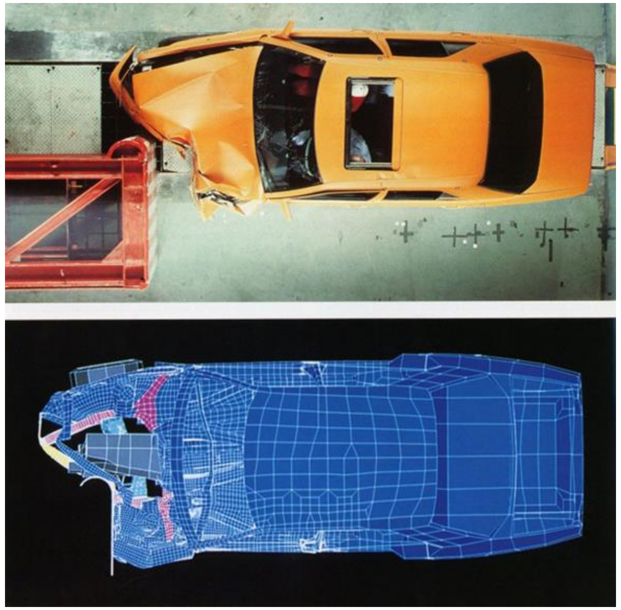
Typical TestPaks Ordered

TestPaks for LS-DYNA

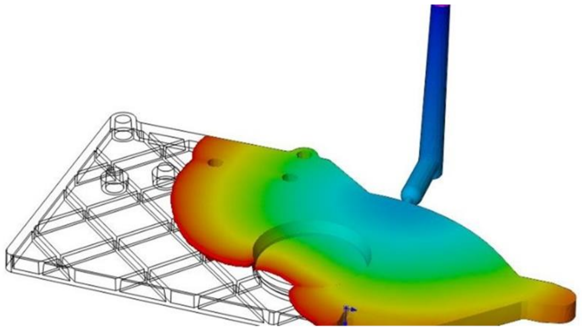
Example: Rate-Dependency

DatapointLabs - Serving the Automotive Industry

- Testing for material qualification and design properties
  - Precision data used to represent a material in new product development
  - Typical testing: stress-strain data, fatigue, creep
  - Qualification testing against automotive OEM standards
- Testing for CAE simulation and analysis
  - High strain rate properties for crash simulations
  - Injection molding simulation
  - Hyperelastic properties of rubber and foams
  - S/N curves for fatigue simulation
  - Specialized rubber properties for non-linear NVH simulations



Testing for Crash and Impact CAE



Testing for Injection Molding CAE

TestPaks for Automotive Industry

Applus DatapointLabs

G-771 LS-DYNA High Speed Tensile Rate Dependent Model (MAT_019 or MAT_024 or MAT_089)

G-771V LS-DYNA Validated High Speed Tensile Rate Dependent Model (MAT_019 or MAT_024 or MAT_089)

G-772 LS-DYNA High Speed Foam Model (MAT_083 or MAT_163)

G-776 LS-DYNA GISSMO Failure Model

G-778 LS-DYNA SAMP-1 Semi-Analytical Model for Plastic (MAT_187)

G-780 LS-DYNA Hyperelastic (MAT_027)

G-782 LS-DYNA Hyperviscoelastic Rubber (MAT_077)

G-784 LS-DYNA Simplified Rubber with Rate Dependency (MAT_181)

G-790 LS-DYNA Forming (Barlat 3-parameter model: MAT_036)

G-791 LS-DYNA Transversely Anisotropic Elastic Plastic (MAT_037)

G-792 LS-DYNA Isotropic Elastic (MAT_001)

G-793 LS-DYNA Plastic Kinematic (MAT_003)

G-794 LS-DYNA Laminated Composite Fabric (MAT_054)

Advanced failure model calibration for metals and plastics:

G-776I LS-DYNA MAT_024+GISSMO shell element failure model for metals

G-778I LS-DYNA SAMP+GISSMO shell element failure model for ductile plastics (MAT_187+GISSMO)

G-602 RADIOSS Tensile Rate Dependent Model (Laws: 2, 36, 44)

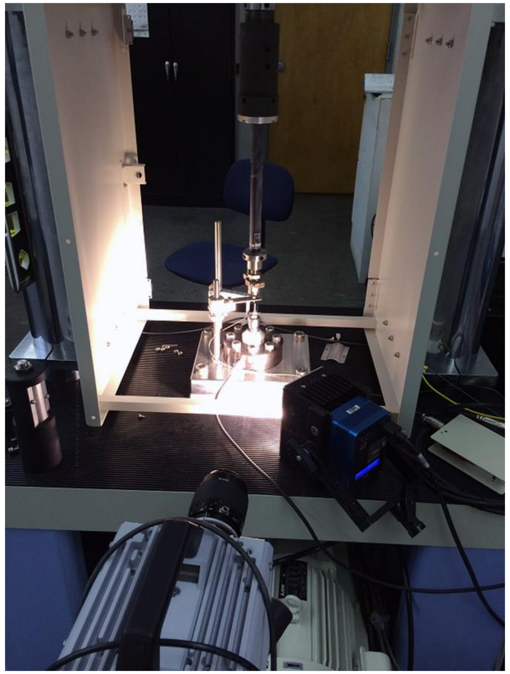
G-604 RADIOSS Rate Dependent Foam Model (Law 70)

G-606 RADIOSS Hyperelastic Model (Law 42, 69)

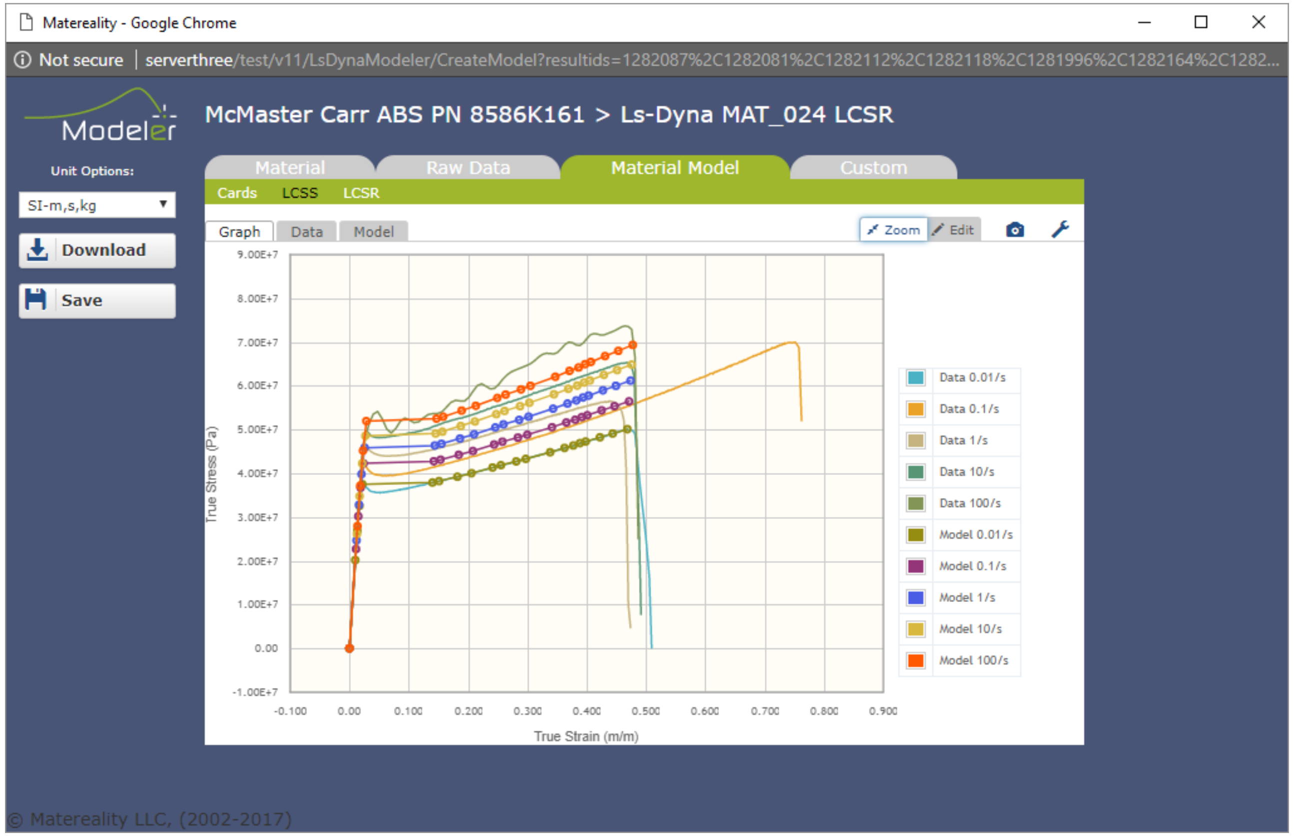
G-607 RADIOSS Hyperelastic Model with Viscoelastic (Law 42)

Crash and Drop Test Simulation Data

- High strain rate data
  - 0.01. 0.1, 1, 10, 100, 1000/s

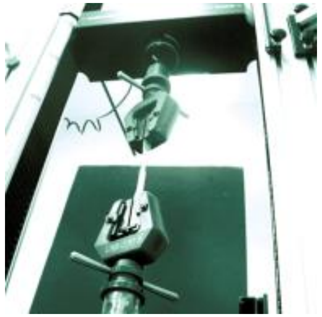


High strain-rate measurements (to 1000/s) using 1M fps, high-speed camera with digital imaging.

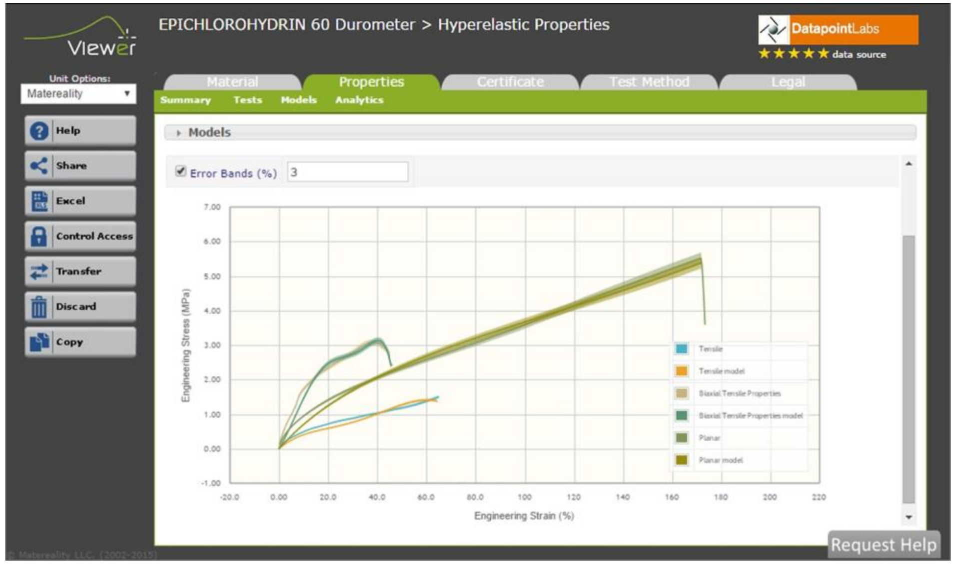


Hyperelastic Modeling of Rubber

- Test modes
  - Tensile
  - Compressive
  - Shear
  - Biaxial
  - Volumetric



Loading test specimens for a plate-twist shear modulus test.



Using Matereality's Viewer module to quantify the goodness of fit of a hyperelastic equation to raw data.

Elastomeric and Crushable Foams

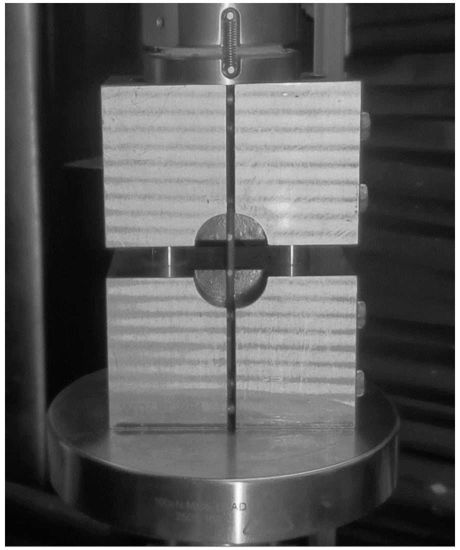
- Visco-elastic data
  - Prony series data models
- Rate dependent data
  - Hyperbolic model extrapolation

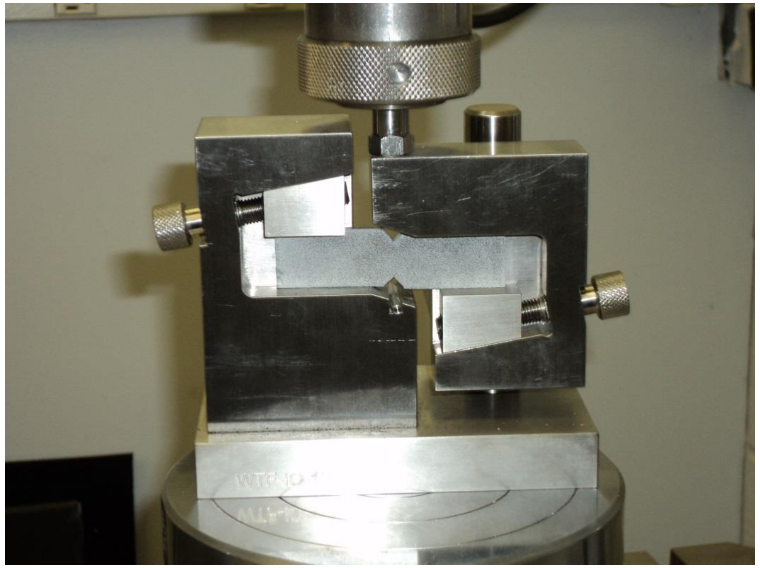
Compression test of a crushable foam.

Orthotropic Properties of Composites

- Tensile properties
- Compressive properties
- Shear properties

Properties are non-linear in certain orientations and modes of deformation





Creep, Fatigue, Long-term Behavior

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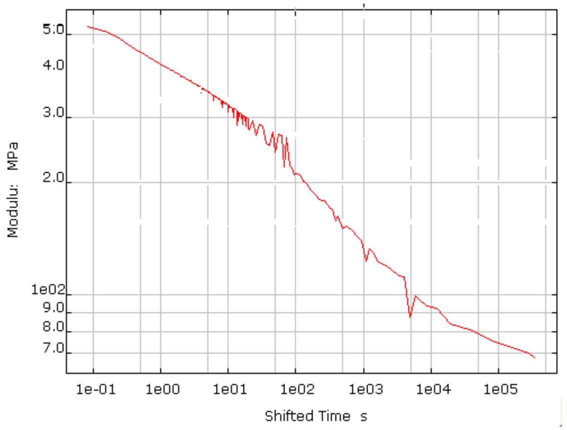
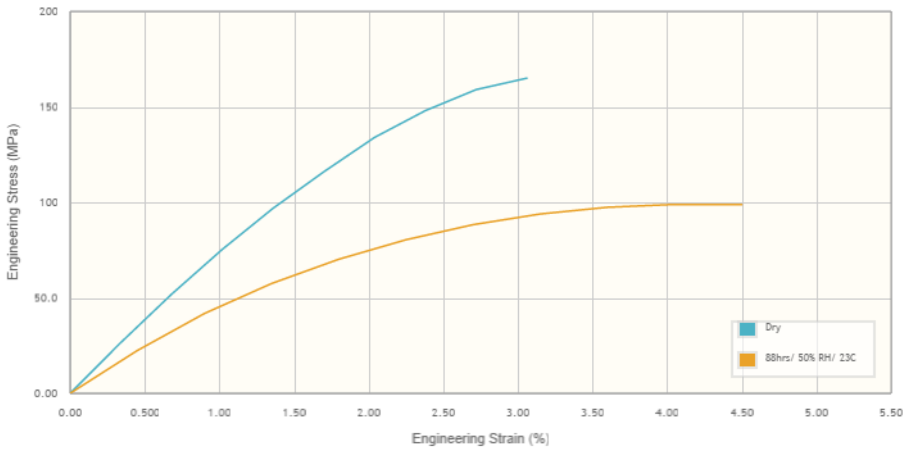
- Properties change with environmental exposure
  - More severe with some polymers
- Solution
  - Determine product use environment
  - Expose specimens to analogous environment
    - Heat aging
    - Moisture conditioning, weathering
    - Fluid exposure
    - *In-vivo*

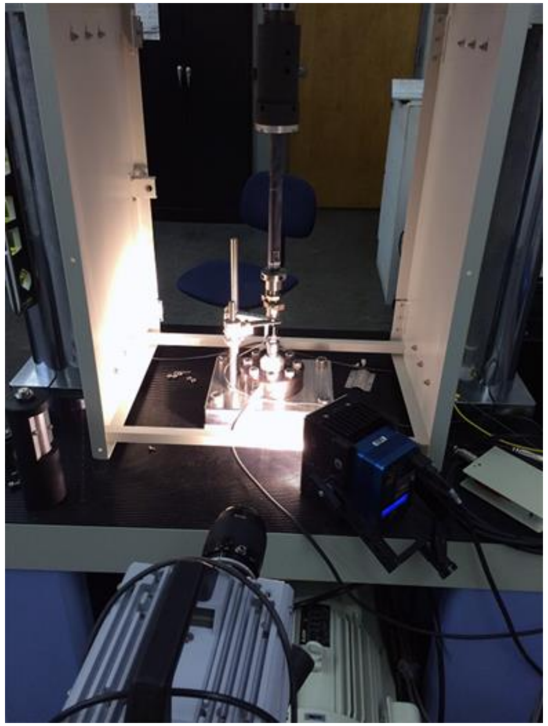
Saline cell to measure properties for 'in-vivo' applications





Example - Rate-Dependency Data for MAT_024

- Generation of rate-dependency data (LS-DYNA MAT_024)
  - Low to very high strain-rate data: 0.01/s, 0.1/s, 1/s, 10/s, 100/s, 1000/s



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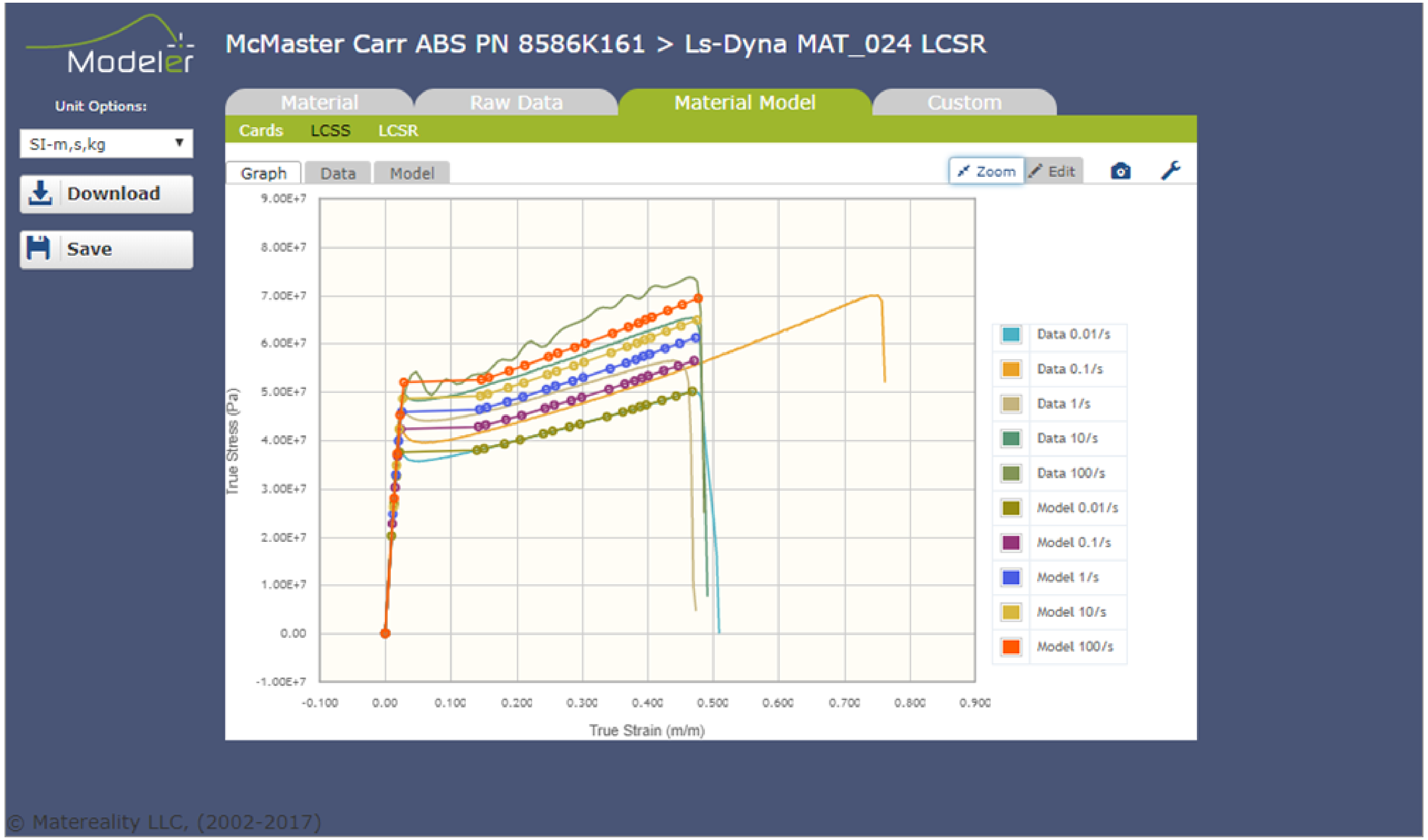
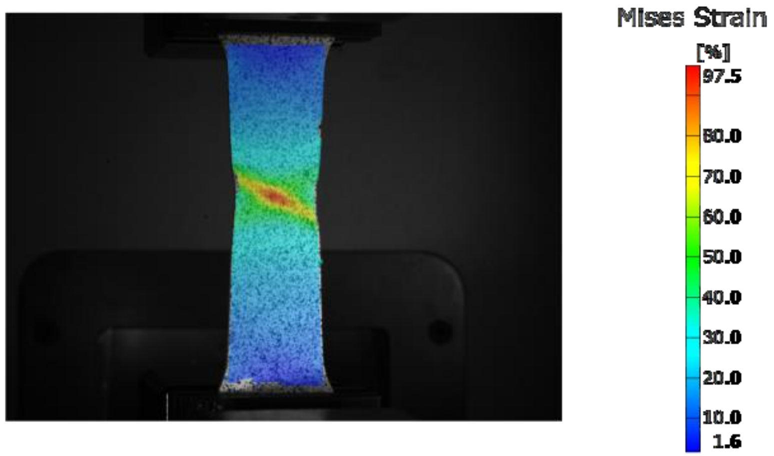


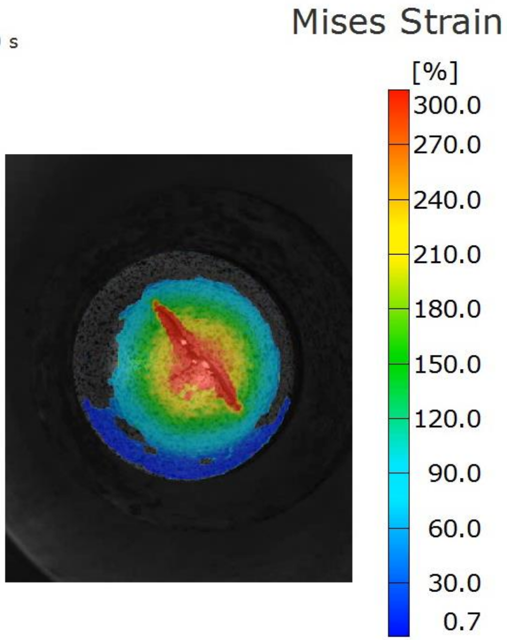
Failure of Metals and Plastics

- GISSMO, SAMP-1

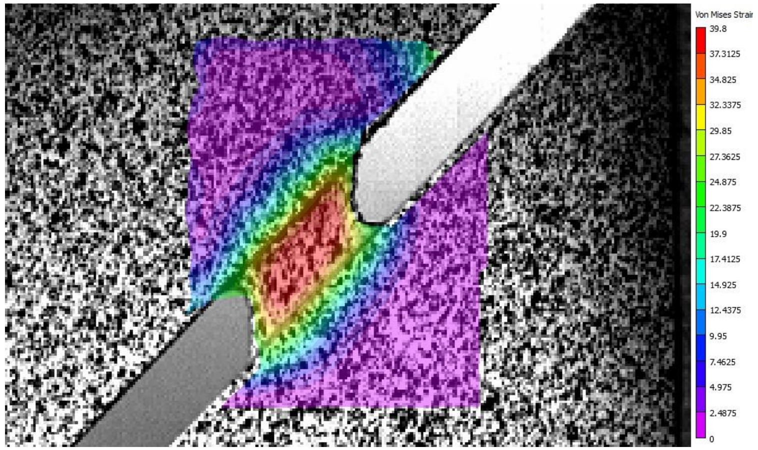
  Failure & damage models



Uniaxial



Biaxial

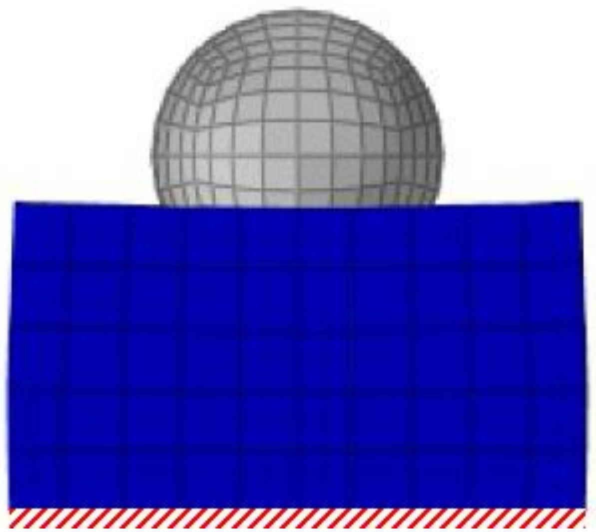


Shear

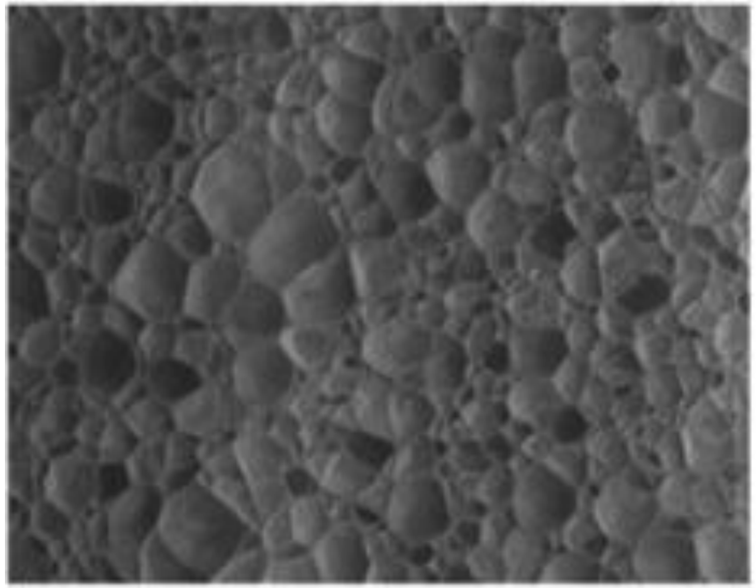
CAETestBench:

Validation of simulation

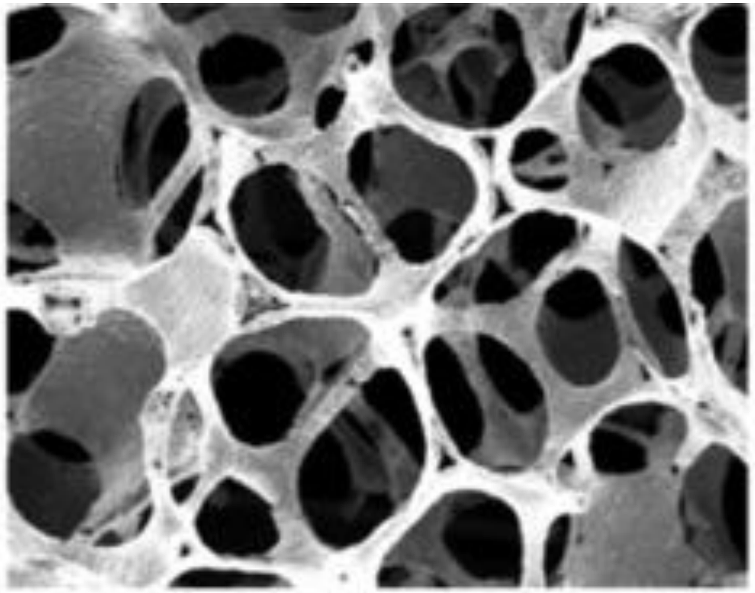
- Composites
- AM Metals
- Plastics
- Rubber
- Crash/impact



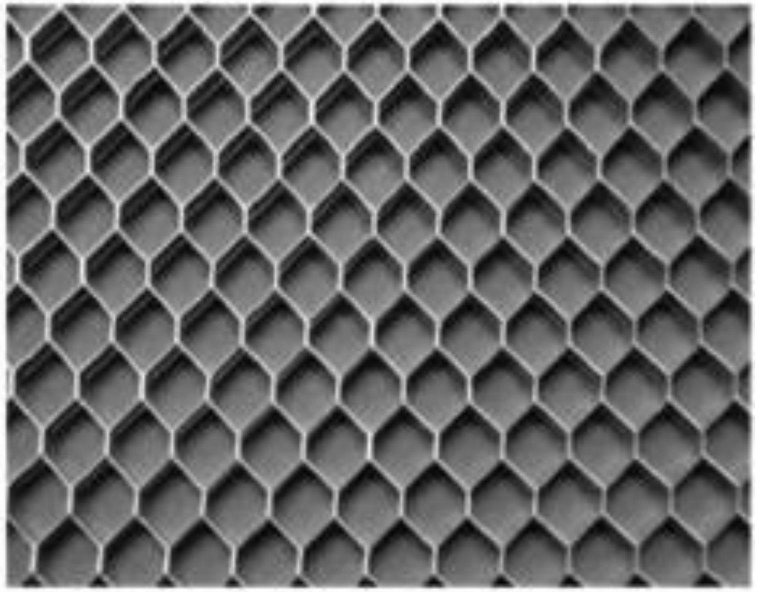
What are Foam Materials?



1 Closed-cell foam



2 Open-cell foam



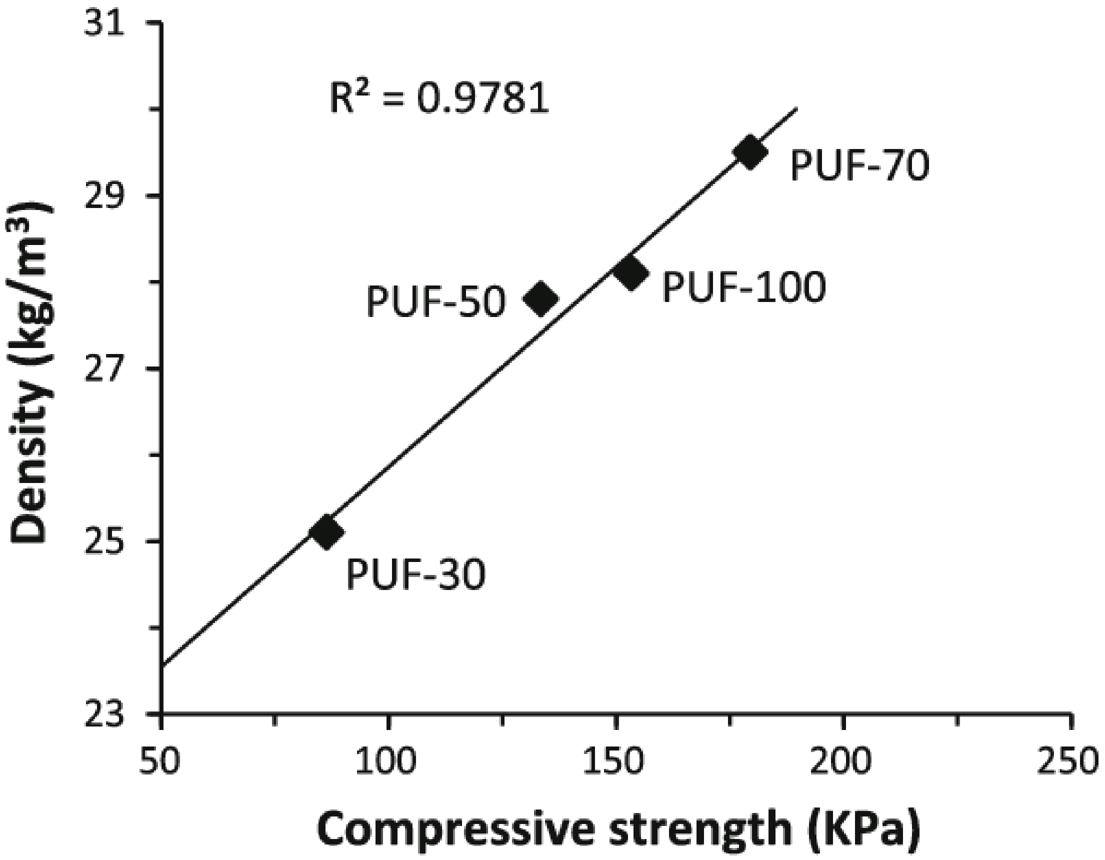
3 Honeycomb foam

Reproduced from Hitti, K., 2011. Direct Numerical Simulation of Complex Representative Volume Elements (RVEs): Generation, Resolution and Homogenization.

Mechanical Properties of Foam Materials

Mechanical properties depends on:

- Density

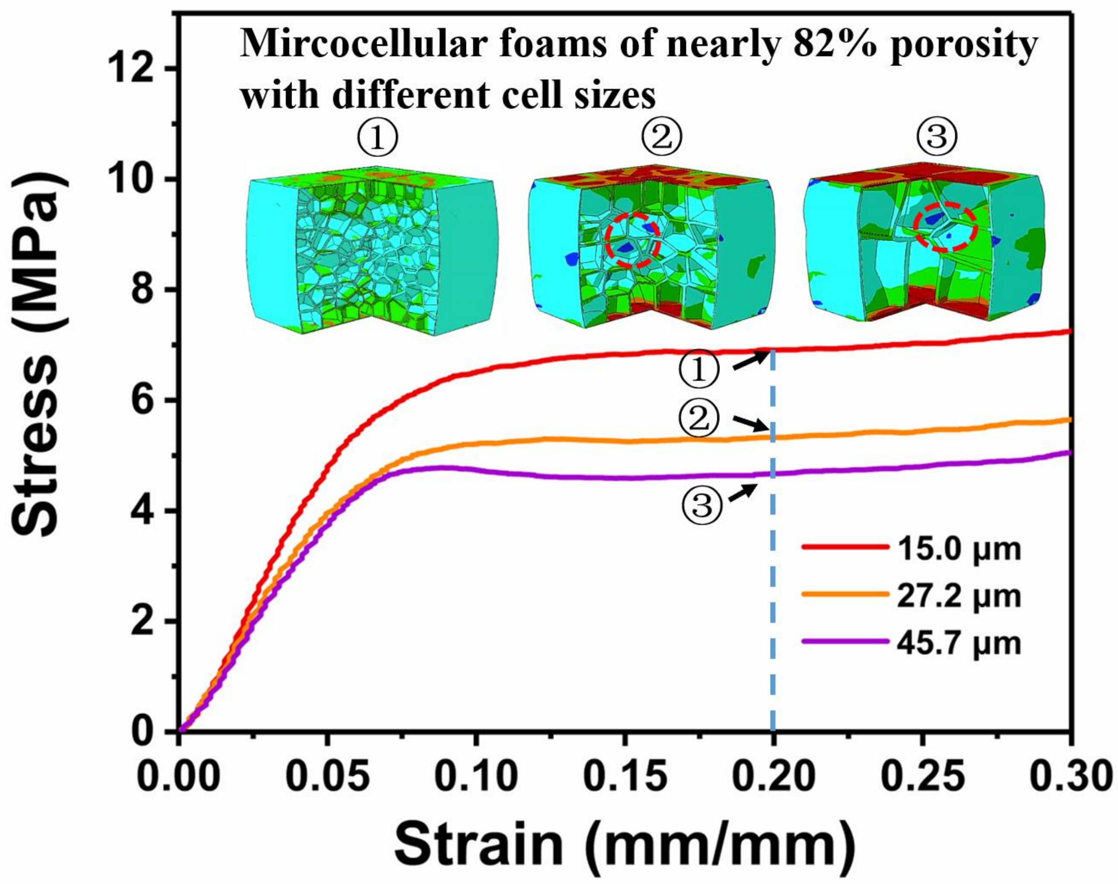


Reproduced from Luo, X. and Li Y. 2014. Synthesis and Characterization of Polyols and Polyurethan Foams from PET Waste and Crude Glycerol.

Mechanical Properties of Foam Materials

Mechanical properties depends on:

- Density
- Cell structure

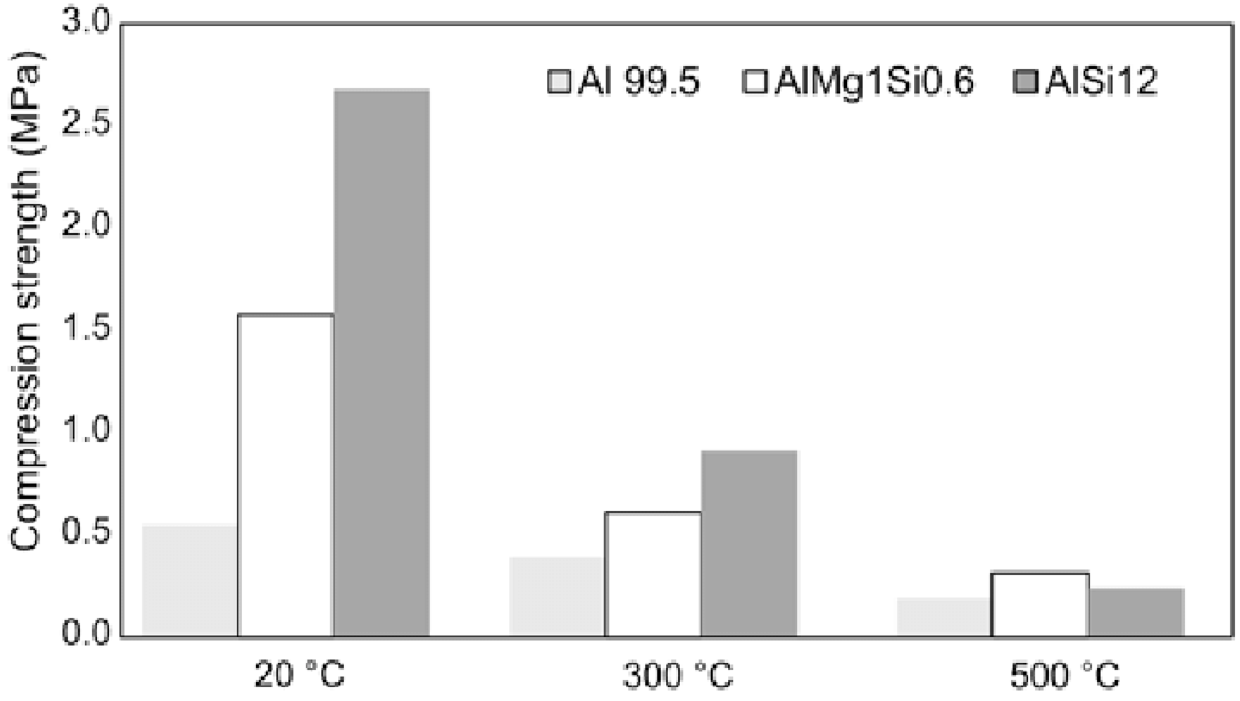


Reproduced from Zhang R., Chen J., et alt. 2020. Correlation between the structure and compressive property of PMMA microcellular foams fabricated by supercritical CO2 foaming method

Mechanical Properties of Foam Materials

Mechanical properties depends on:

- Density
- Cell structure
- Wall cell intrinsic material properties



Reproduced from Kováčik J., Orovčík L., Jerz J. 2016. High-temperature compression of closed cell aluminum foams

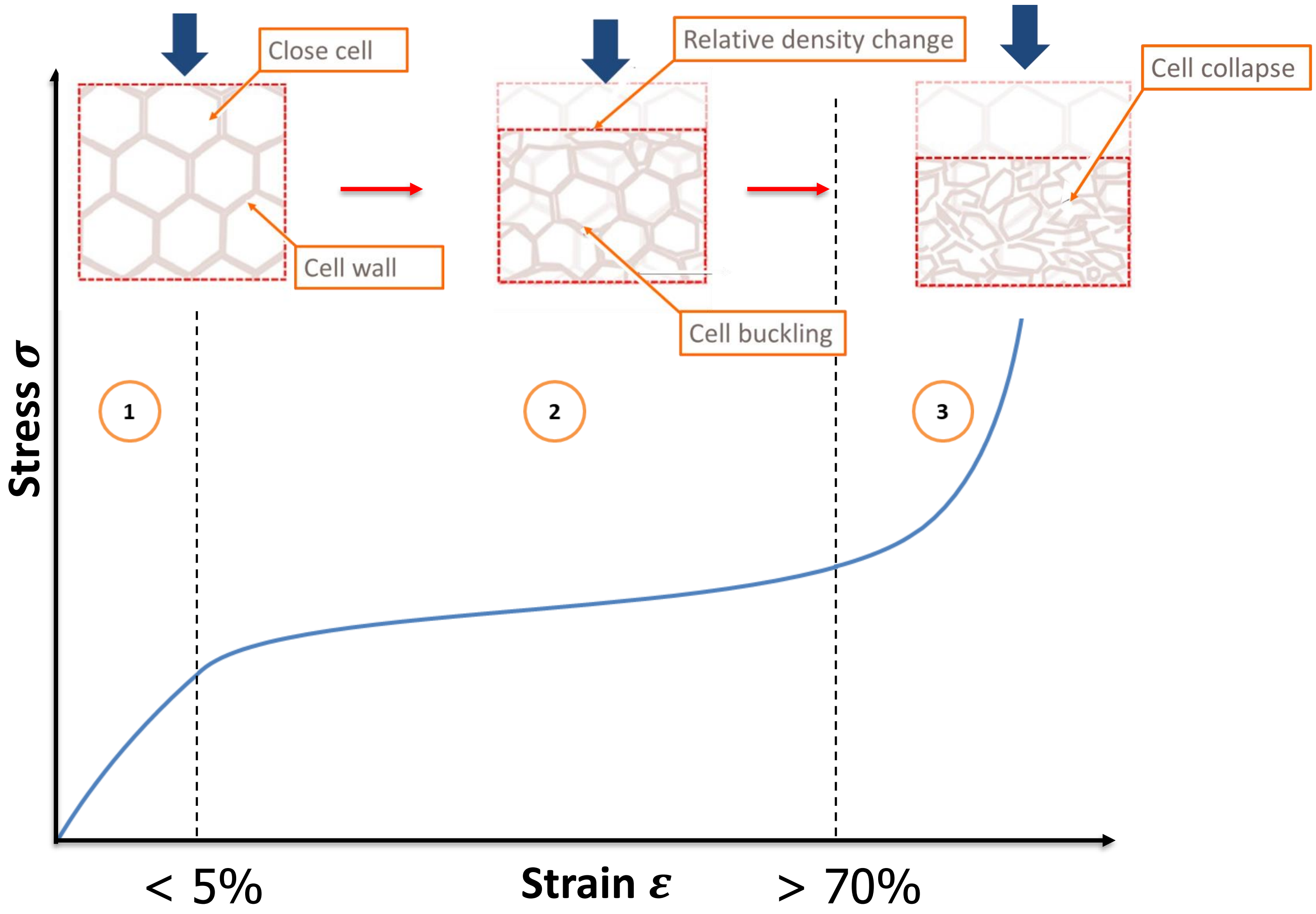
Typical Foam Behavior

- Non-linear (elastic or crushable) stress-strain response
- Zero Poisson ratio in compression
- Rate dependency
- Failure in tension and shear
- Larger deformation in compression

Typical Foam Behavior

Compression response

1. Elastic response
2. Deformation plateau
3. Densification



Reproduced from Park K., Kim H. et alt. 2019. Variation of mechanical characteristics of polyurethane foam: effect of test methods

Radioss LAW90: Definition

Radioss LAW90 describes the visco-elastic foam tabulated material

Reasons to use it

- Accurate modeling of foam behavior
- Strain-rate sensitivity
- Easy to implement
- Good correlation with experimental data
- Availability

Radioss LAW90: Definition

Visco-elastic foam tabulated material

```
#---1----|----2----|----3----|----4----|----5----|----6----|----7----|----8----|----9----|---10----|
##HWCOLOR materials 41645 3
/MAT/LAW90/41645
41645: Cold Formed - 20Kpa 75g/l
#                 Rho_I
6.31000000000000E-11
#                    E0              MAT_NU
                   0.56                0.0001
#        NL   Ismooth                  Fcut                  Shape                 Hys
          6         1 1.00000000000000E+30                     0.7                 0.1
#   fct_idL                 eps_dot                Fscale
          1                    0.01                  1.00
          2                     0.1                  1.00
          3                     1.0                  1.00
          4                    10.0                  1.00
          5                   100.0                  1.00
          5                 10000.0                  1.00
#---1----|----2----|----3----|----4----|----5----|----6----|----7----|----8----|----9----|---10----|
```

LAW definition

Density

Young Modulus

Strain-rate smoothing

Cutoff frequency for strain rate filtering

Poisson ratio

Shape factor

Hysteresis factor

Stress-strain curve

Strain-rate

Scale factor

Radioss LAW90: Definition

Minimum stiffness

```
#---1----|----2----|----3----|----4----|----5----|----6----|----7----|----8----|----9----|---10----|
##HMGROUP  4 3
/INTER/TYPE7/4
#Title
ContactImpact
# grnod_id   surf_id      Istf      Ithe      Igap                Ibag      Idel     Icurv      Iadm
       10         8         4                    2                           1
#        Fscale_gap             Gap_max             Fpenmax
              0.0                                       0.8
#             Stmin               Stmax                                      dtmin  Irem_gap   Irem_i2
            100.0
#             Stfac                Fric              Gapmin                 Tstart               Tstop
                                    0.0                 1.0                    0.0                 0.0
#      IBC                       Inacti                VisS                   VisF              Bumult
       000                            6
#    Ifric    Ifiltr              Xfreq     Iform   sens_ID   fct_IDF              Ascale_F   fric_ID
                                                2                                                   0
#---1----|----2----|----3----|----4----|----5----|----6----|----7----|----8----|----9----|---10----|
##HMGROUP  2 4
/INTER/TYPE7/2
#Title
ContactInterior
# grnod_id   surf_id      Istf      Ithe      Igap                Ibag      Idel     Icurv      Iadm
       13        12                          1000                           2
#        Fscale_gap             Gap_max             Fpenmax
                                                        0.8
#             Stmin               Stmax                                      dtmin  Irem_gap   Irem_i2
             20.0                                                                        1         3
#             Stfac                Fric              Gapmin                 Tstart               Tstop
                                                        1.5
#      IBC                       Inacti                VisS                   VisF              Bumult
       000                            6
#    Ifric    Ifiltr              Xfreq     Iform   sens_ID   fct_IDF              Ascale_F   fric_ID
```

Gap option flag
Variable gap+gap scale correction of the conducted gap

Gap option flag
Constant gap; equal to the minimum gap GAP_{min}

Minimum gap for impact activation
Set to 1-strain at densification point

Radioss LAW90: Definition

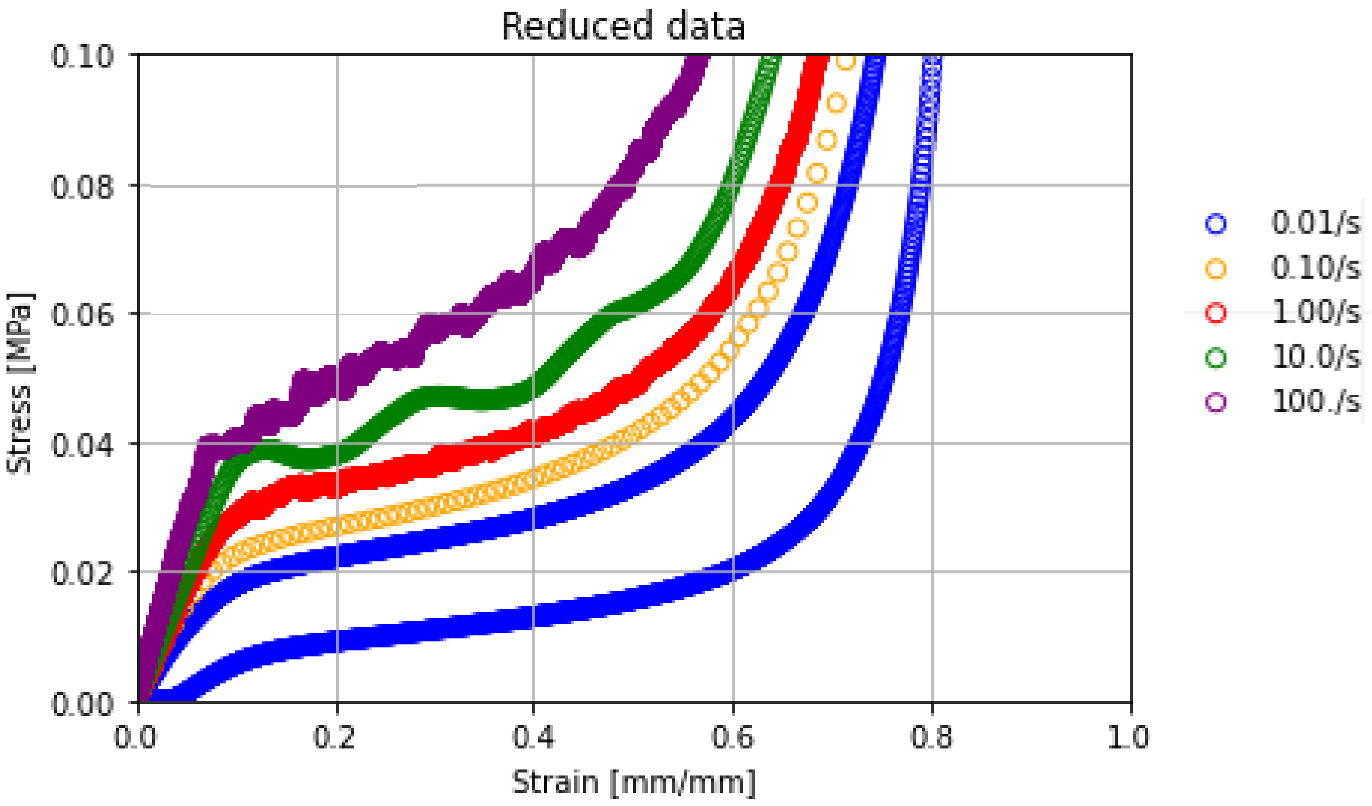
1. E0 is the Young's modulus at the highest strain rate in the stress-strain curve.
2. Poisson's ratio is expected to be 0 for large compressions, but to ensure stability in calculations, it is set to a small value, typically around 10E-3.
3. To further improve stability, an additional curve can be added to the stress-strain curve, representing a strain rate 10 times higher than the highest strain rate. This extra curve is used in the calculation to ensure that the results remain stable even at high strain rates.
4. The LAW90 model uses the hysteresis of the quasi-static curve to calculate the unloading behavior. The shape and hysteresis parameters of the curve must be fitted during the validation process to accurately predict the unloading behavior.

$$\sigma = (1 - D)\sigma \text{ with } D = (1 - Hyst)\left(1 - \left(\frac{W_{cur}}{W_{max}}\right)^{Shape}\right)$$

Radioss LAW90: Data Preparation

Applus DatapointLabs

1. Compression test data
2. Smoothing the data and point reduction
3. Extrapolating the data
4. Filtering the date



Radioss LAW90: Data Preparation

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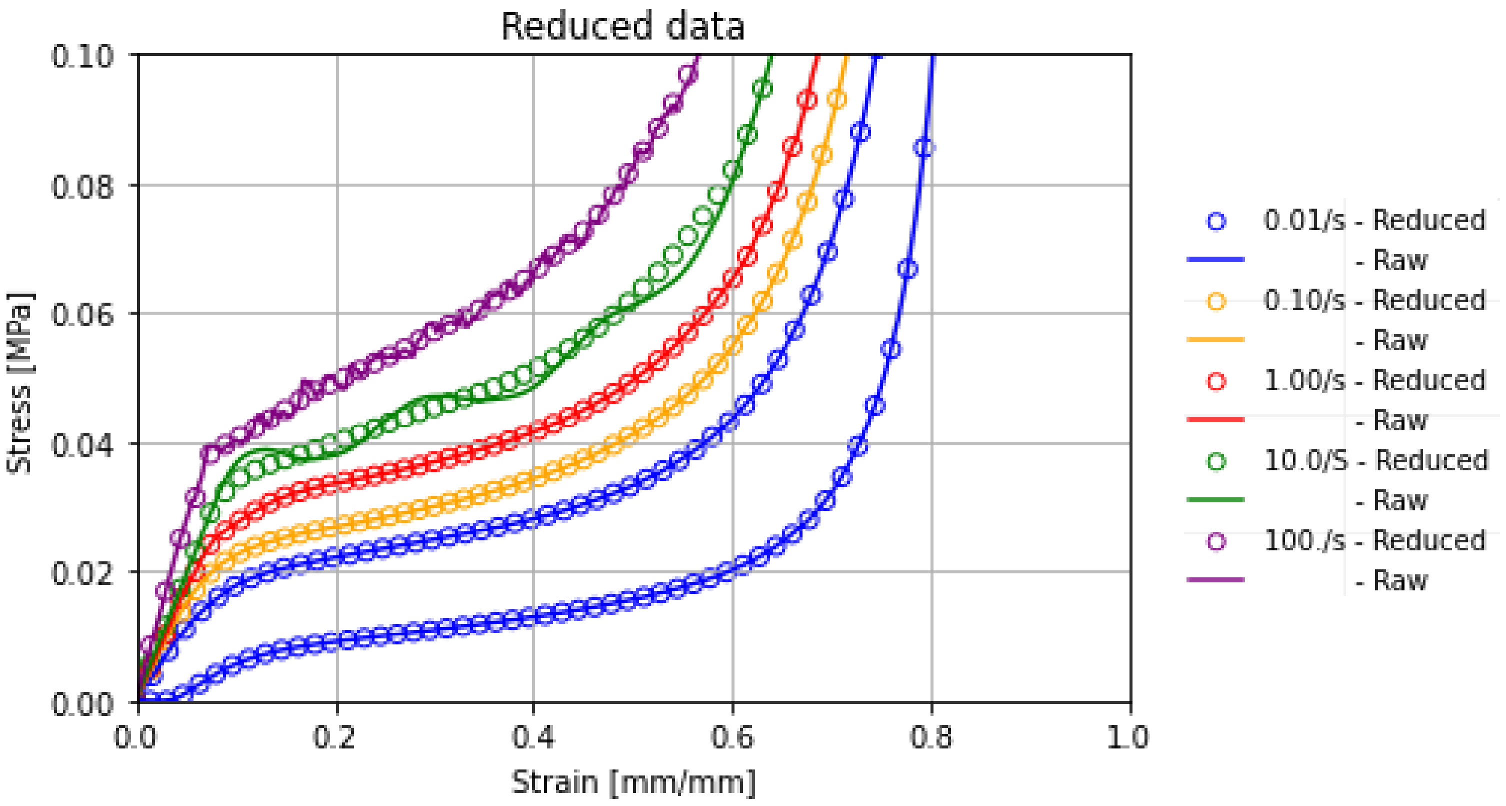
4. Filtering the date



Radioss LAW90: Data Preparation

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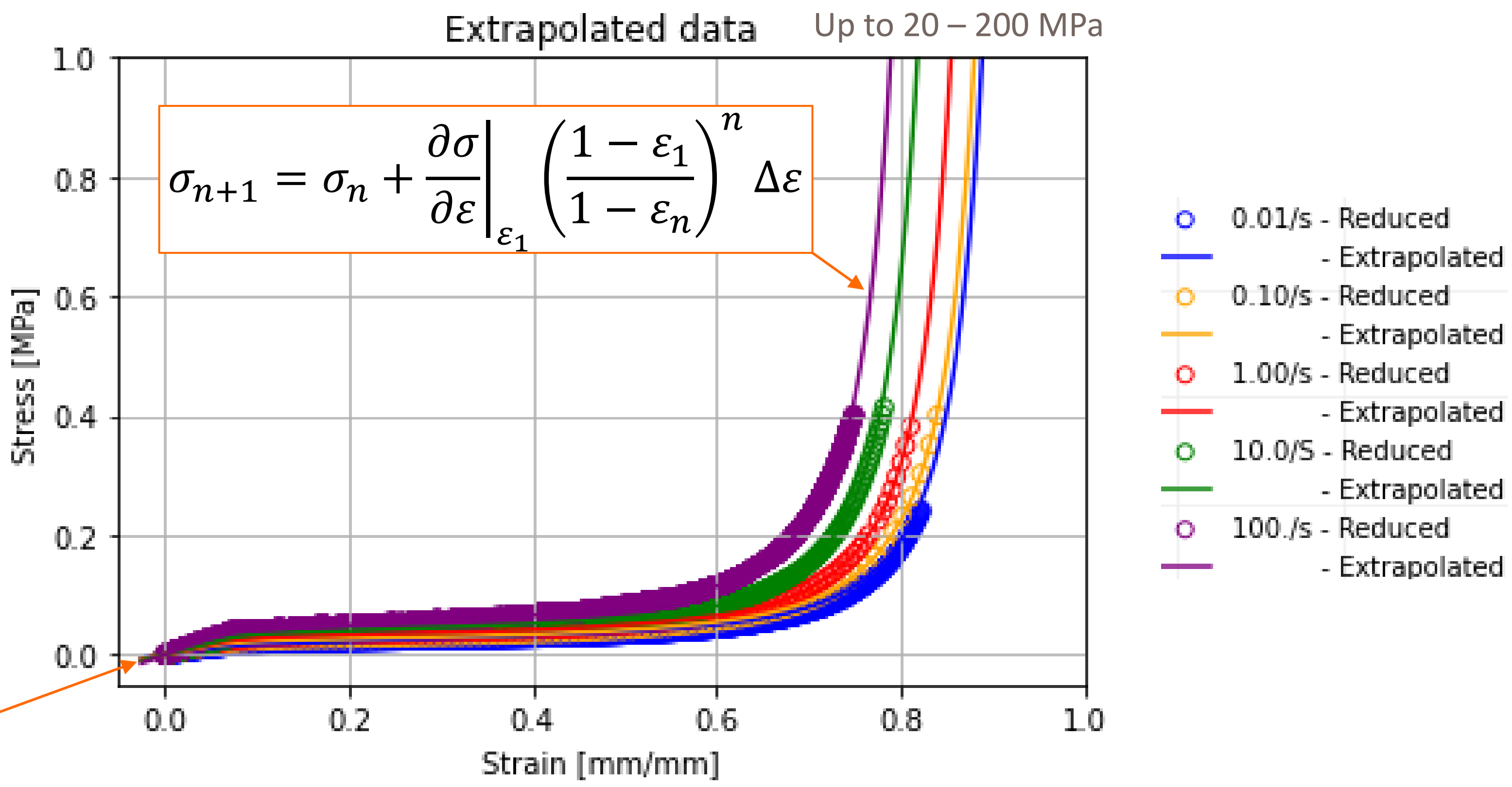


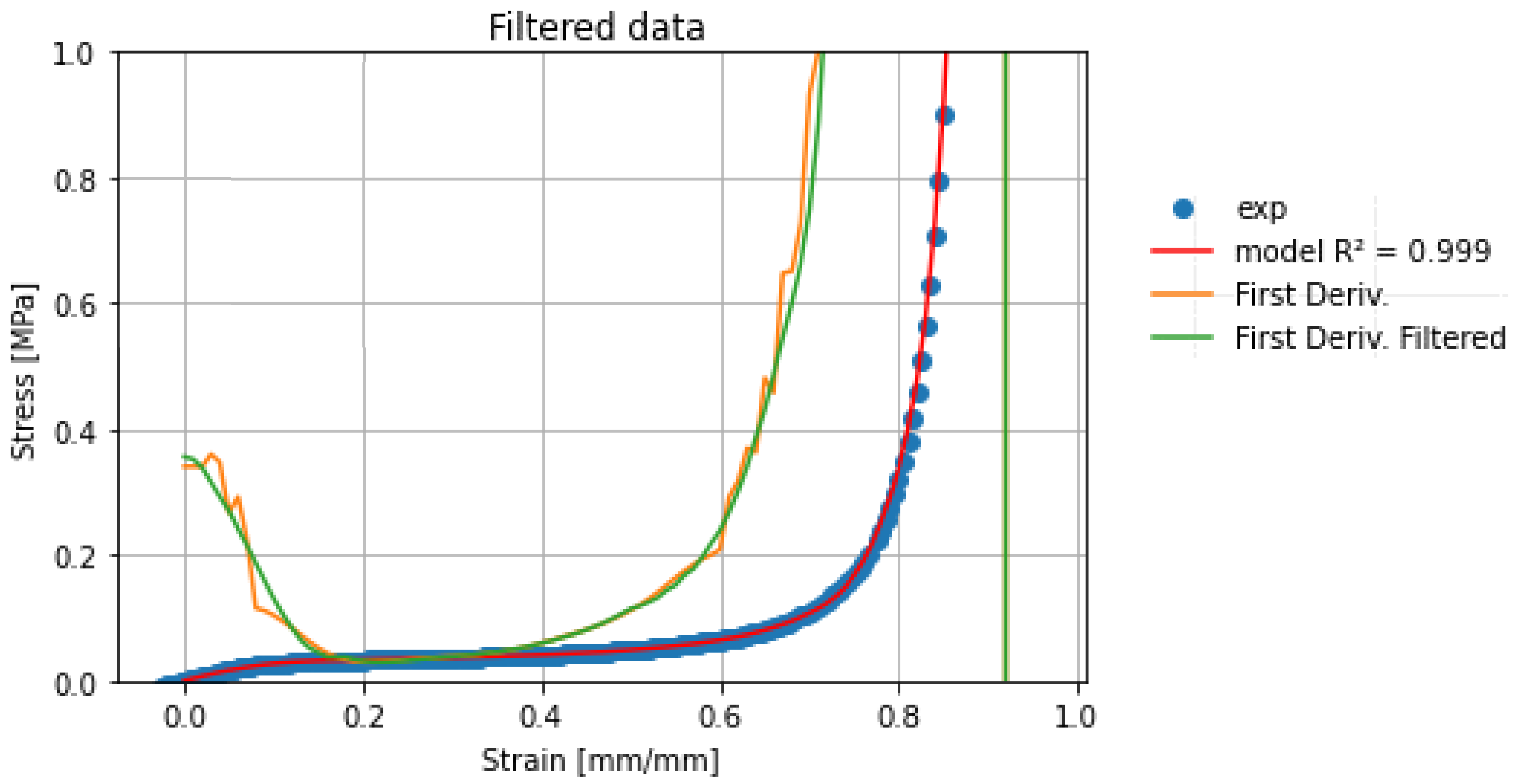
$$\sigma_{n+1} = \sigma_n + \left.\frac{\partial\sigma}{\partial\varepsilon}\right|_{\varepsilon_1} \left(\frac{1-\varepsilon_1}{1-\varepsilon_n}\right)^n \Delta\varepsilon$$

Tension:
Linear extrapolation

Radioss LAW90: Data Preparation

1. Compression test data
2. Smoothing the data
3. Extrapolating the data
4. Filtering the data
   - 1st derivative
   - Moving window filter
   - Integrate

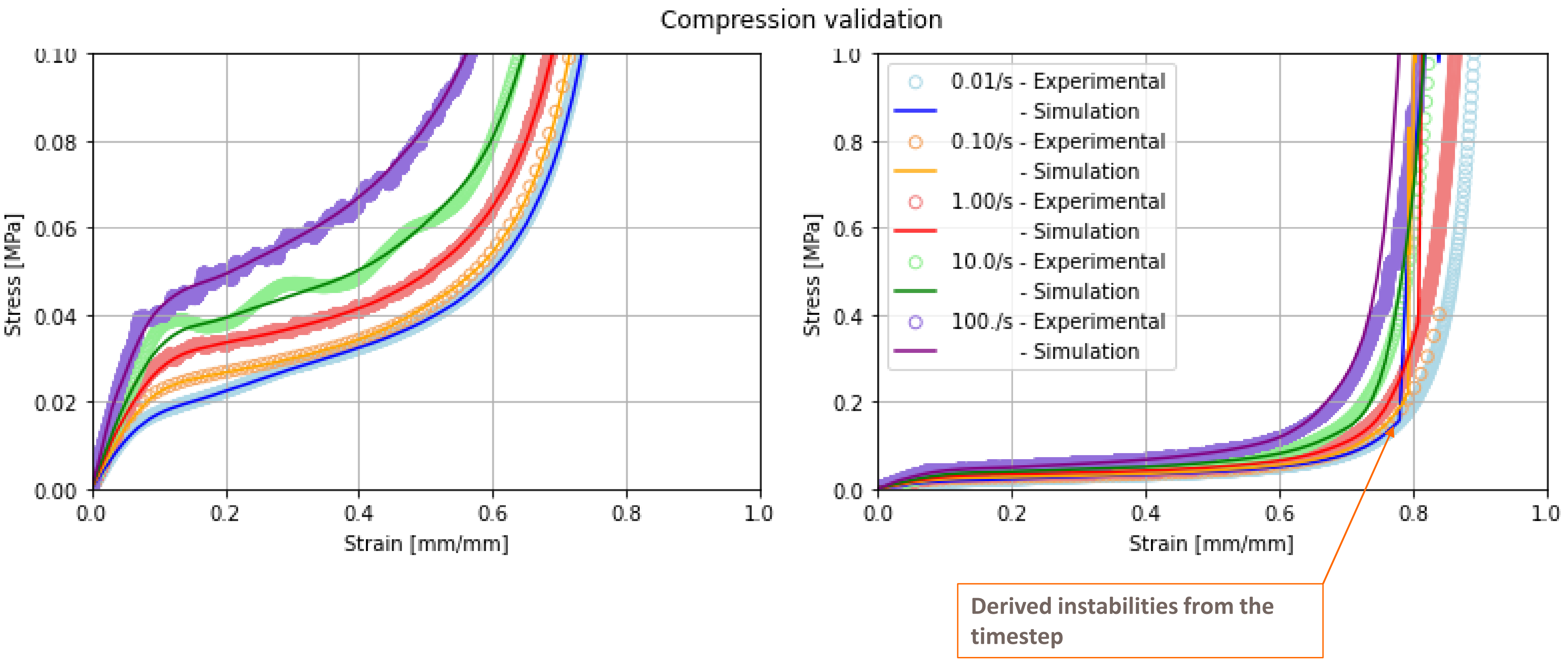
Thank you so much Marian Bulla for suggesting this additional step. Your contribution has been of great help, and we truly appreciate your input.



Radioss LAW90: Compression Validation

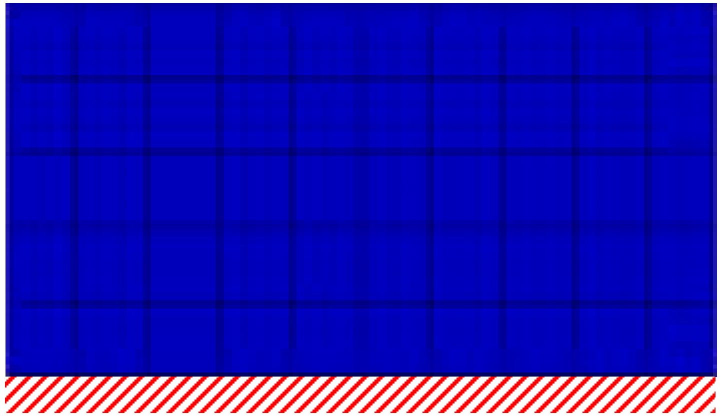
Method	ASTM D695-15 Standard Test Method for Compressive Properties Crash Material Models	
Solver	Radioss // OpenRadioss	
Specimen	form	cube
	thickness	26
Parameters	Crosshead speed	16.2 - 162000 mm/min
	material model	LAW90
	element formulation	24
	mesh type	hexahedral
	element size	10 mm
	boundary conditions	fixed base
	initial conditions	Upper surface displacements
	contact type	Type 7 (interior)

Radioss LAW90: Compression Validation



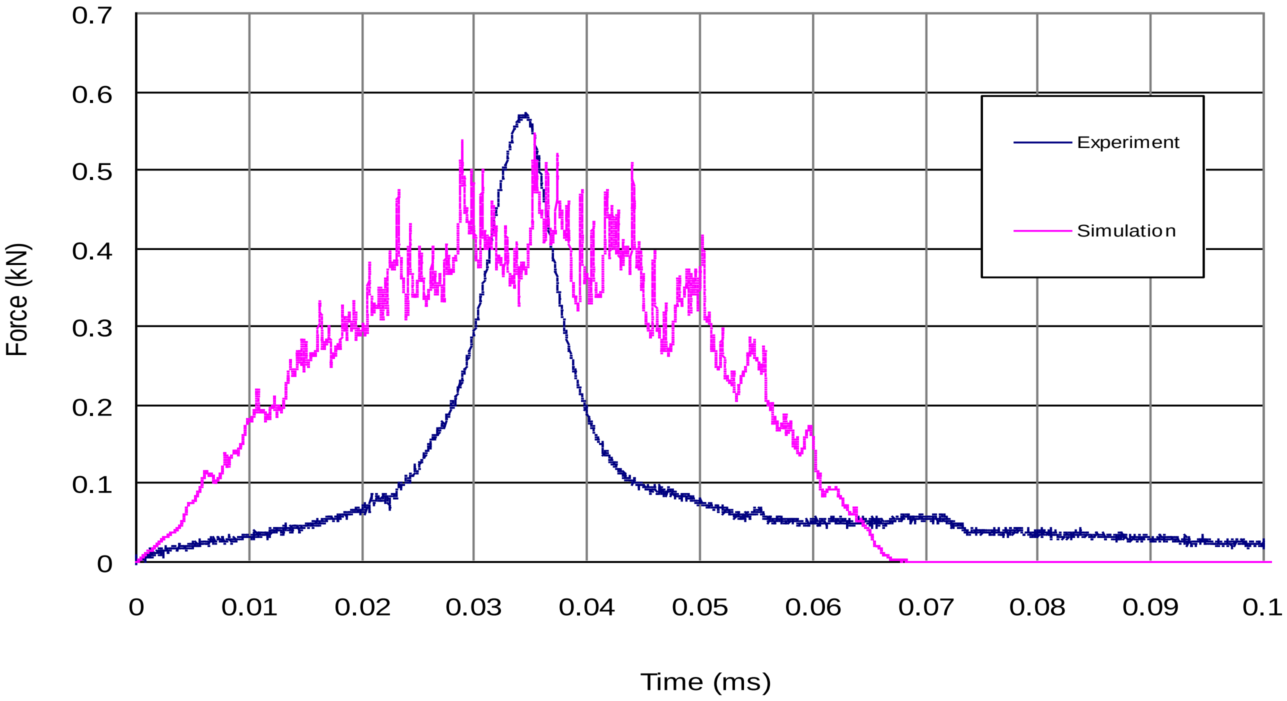
Radioss LAW90: Impact Validation

Method	DPL V-101	
	Falling Dart Impact Validation	
	Crash Material Models	
Solver	Radioss // OpenRadioss	
Specimen	form	cube
	thickness	53
Parameters	impact velocity	2.30 m/s
	dart weight	0.54 kg
	dart diameter	50.8 mm
	material model	LAW90
	element formulation	24
	mesh type	hexahedral
	element size	10 mm
	boundary conditions	fixed base
	initial conditions	acceleration
	contact type	Type 7 (impact)
		Type 7 (interior)

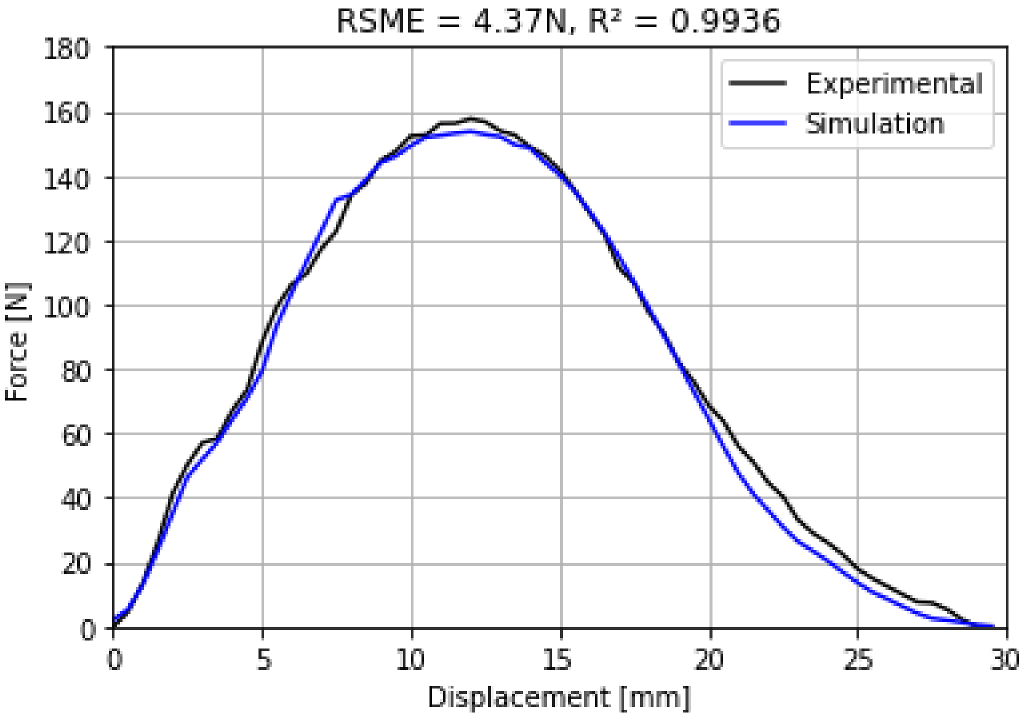


Radioss LAW90: Impact Validation

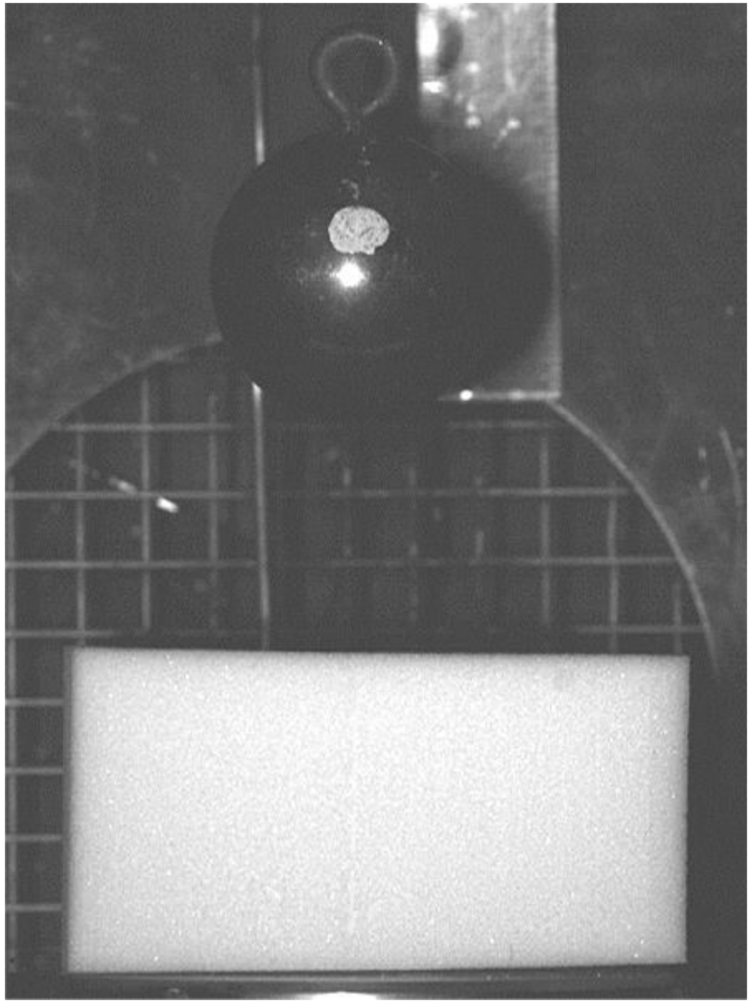
Before

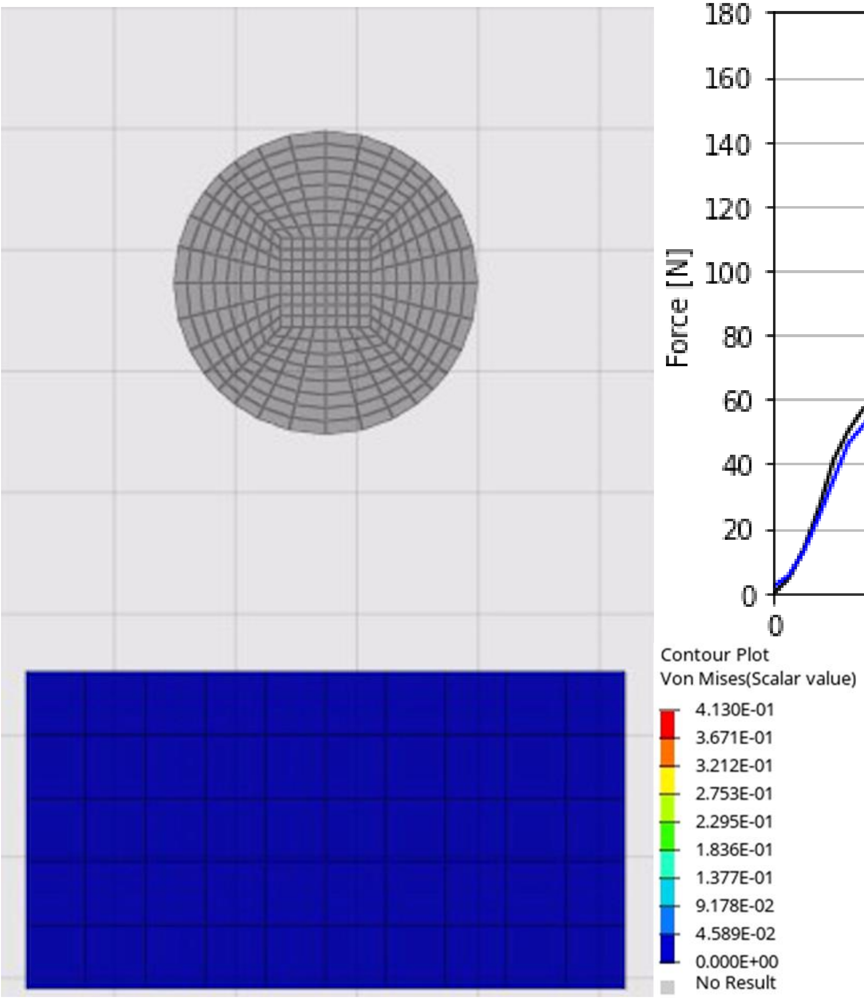


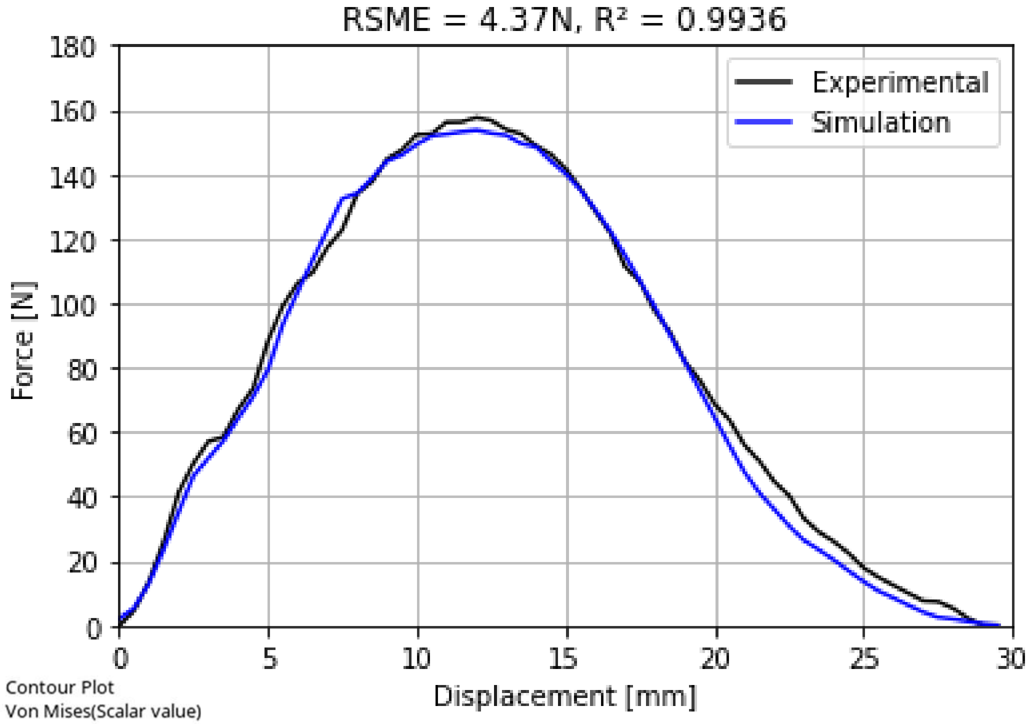
After



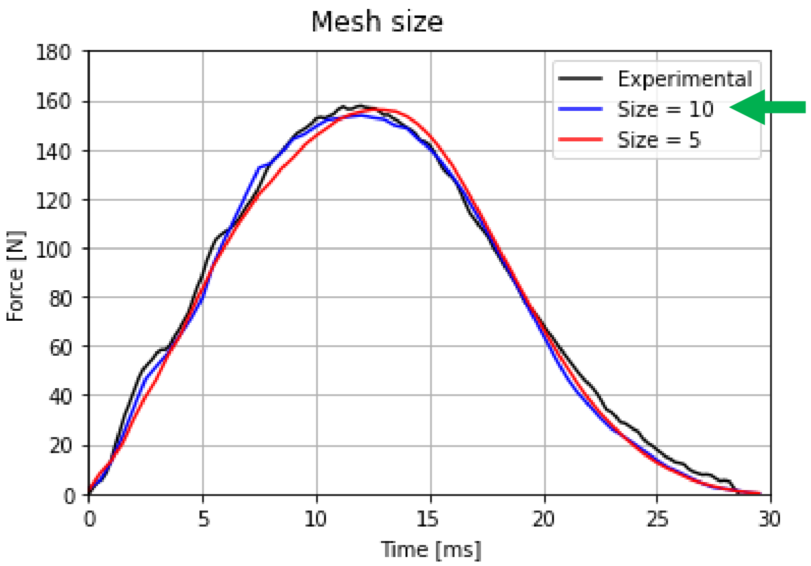
Radioss LAW90: Impact Validation

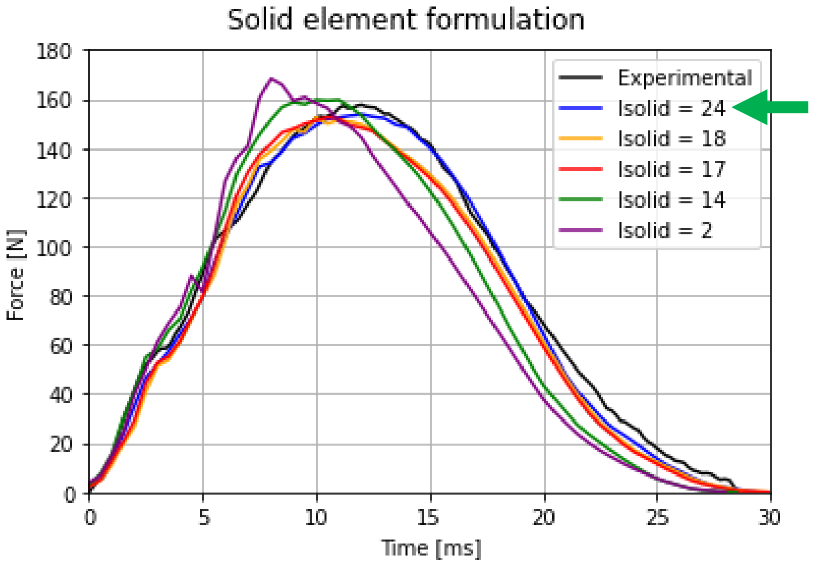


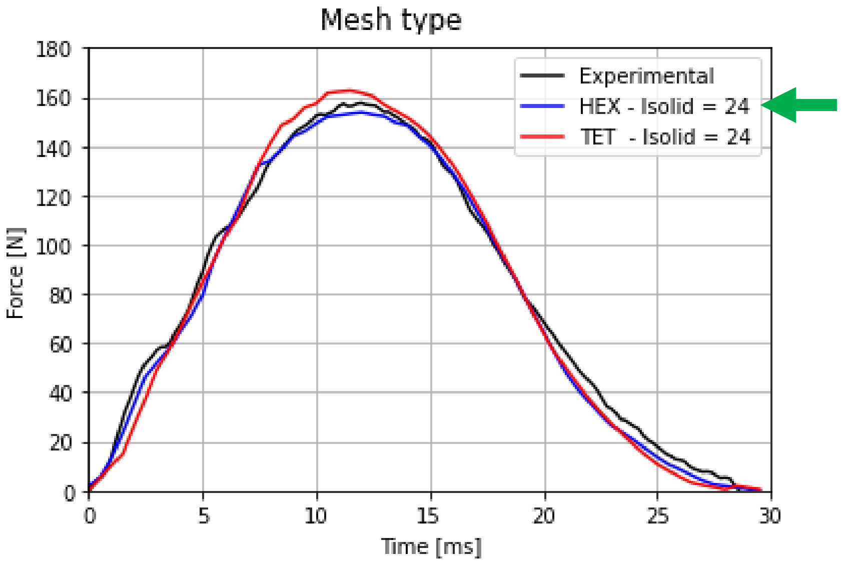


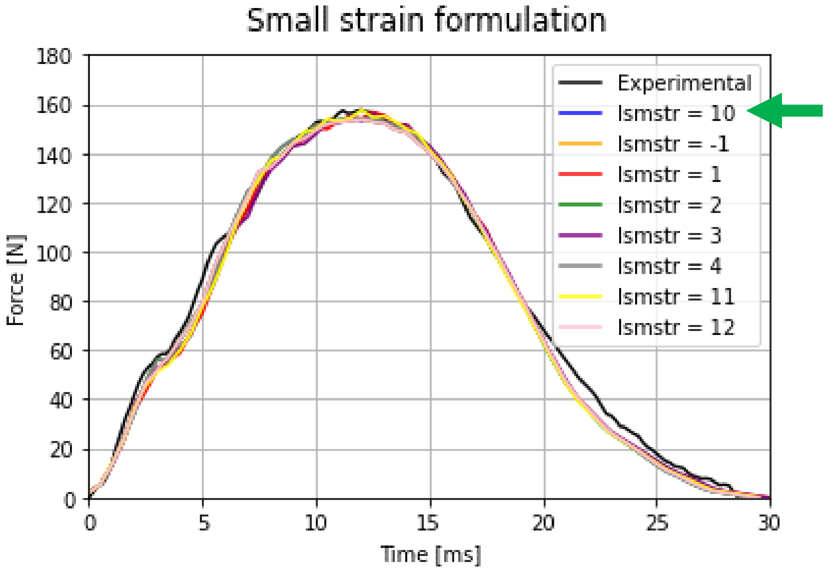


Radioss LAW90: Parameters Study

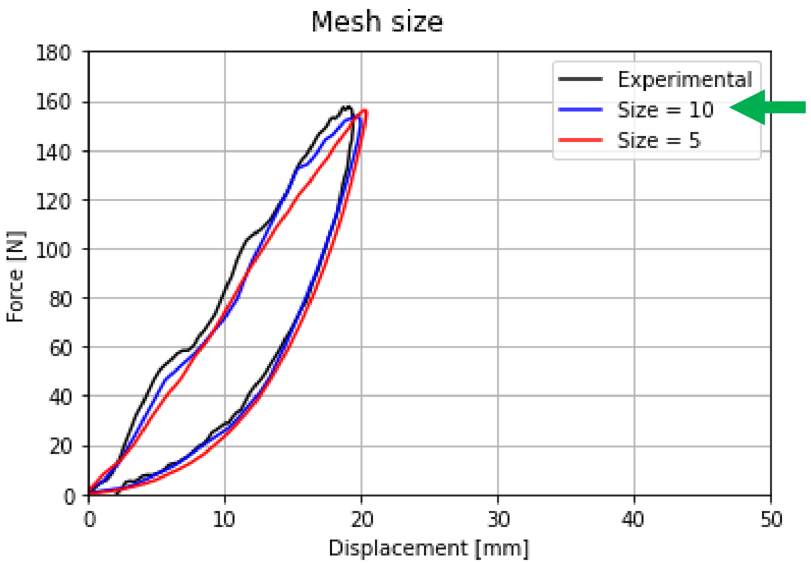


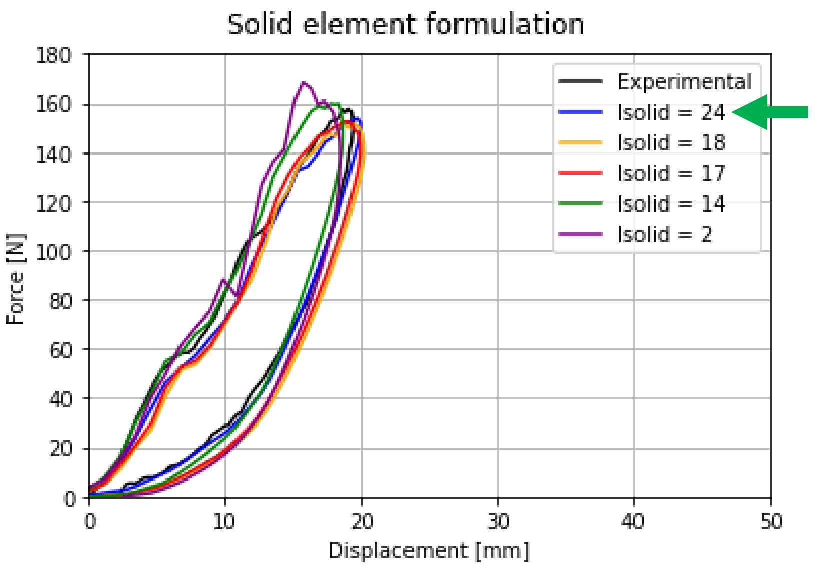


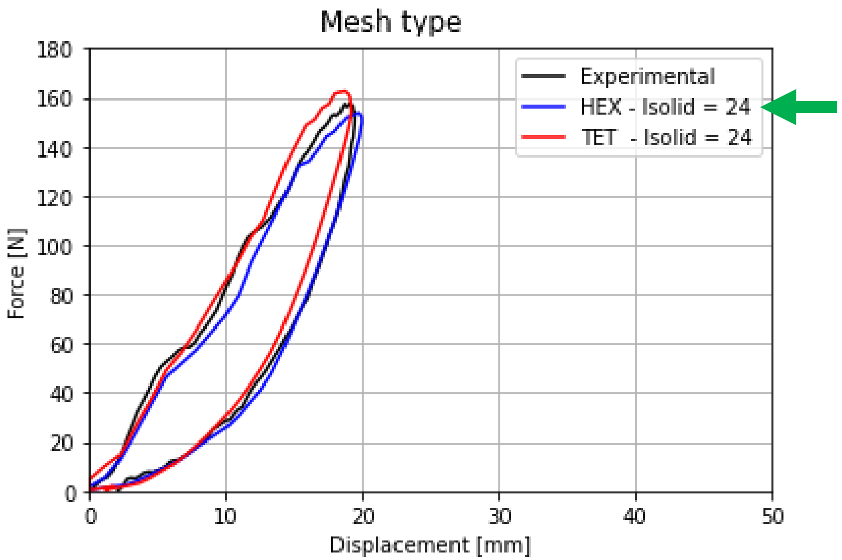


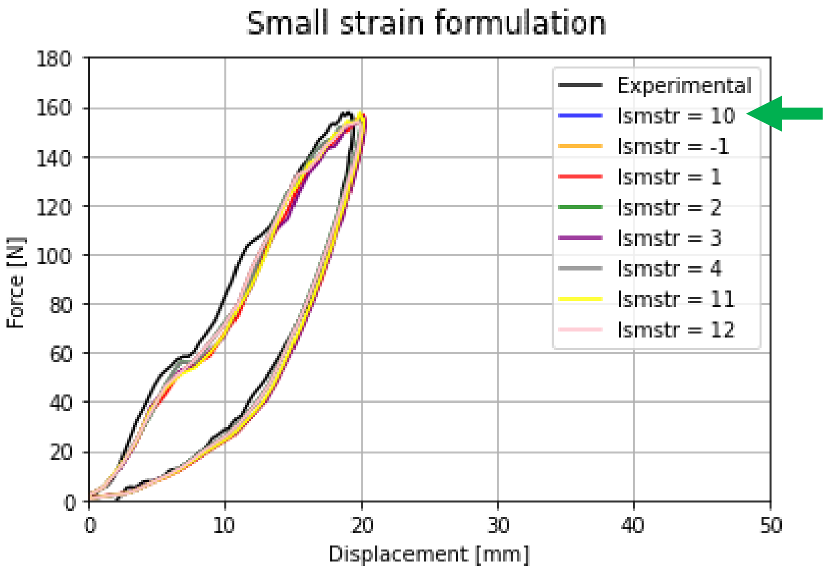


Radioss LAW90: Parameters Study









Conclusions and Remarks

- The use of the LAW90 material card has been successfully validated through compression and impact tests for simulating foam materials.
- **Experimental compression curves cannot be used directly** for material modeling, and **data pre-processing is necessary**.
- To ensure stability and accuracy, it is crucial to use **monotonically increasing imported curves**.
- When testing with strain-rate variables, the **Type 7 contact card must be used to limit the compression strain of the elements**. The strain limit corresponds to the point where densification begins in the model's curve with the highest strain-rate.
- In impact applications, it is essential to use an **impactor with smooth geometries**, as sharp geometries can cause instability due to mesh deformations.
- Various types of meshes, elements, and properties have been tested, and a **hexahedral mesh with Isolid=24, Ismrt=10, and size=10 is recommended** for succesful results.
- **For applications that require more precise unloading, the LAW70 card is recommended**. This card also uses experimental curves to calculate unloading, and it is important to prepare these curves in the same way as the load curves.

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