

Note: Page numbers followed by *f* and *t* refers to figures and tables respectively.

A

Abaqus/Explicit VUMAT
subroutine, for Neo-Hookean model, 448–450

Abaqus/Implicit UMAT
subroutine, for Neo-Hookean model, 450–454

AB model. *See* Arruda–Boyce (AB) model

Acrylate–Butadiene rubber (ABR)
Bergstrom–Boyce model, 458, 459–460, 459*f*
calibrations, 456, 458*t*
linear viscoelasticity model, 458, 459*f*
mechanical response, 455–456
stress-time response, 456, 457*f*
uniaxial compression data, 456, 456*f*
Yeoh hyperelastic model, 456, 457*f*

Addition polymerization, 11

Adiabatic thermoelastic material, 194

Almansi strain, 163

Amorphous polymers, 5–7, 6*f*

Anisotropic elasticity, 215–217

Anisotropic hyperelasticity
Bergstrom anisotropic eight-chain model, 285

Bischoff anisotropic eight-chain model, 283–285

generalized Fung model, 282
Holzapfel–Gasser–Ogden model, 285–287

invariant based anisotropy, 282–283

Anisotropic material, 199

Arrhenius model, 344–345

Arruda–Boyce (AB) model, 283
athermal shear resistance, 396
deviatoric back stress, 394–395

glassy polymers, 393–394

linear elastic response, 394

plastic flow rate, 395–396

rheological representation, 394, 394*f*

stress-strain predictions, 396, 397*f*

Atomic force microscopy (AFM), 87–88

B

Balance law, 171–184

Balance of angular momentum, 178–180

Balance of linear momentum, 175–178

BAM model, 275–277

Barcol hardness testing, 50

BB model. *See* Bergstrom–Boyce (BB) model

Bergstrom anisotropic eight-chain model, 285

- Bergstrom–Boyce (BB) model,
 27–28
 acrylate-butadiene rubber, 458,
 459–460, 459*f*
 applied strain history, 372–374,
 373*f*
 Brownian motion, 379, 380*f*
 Cauchy stress, 376–377
 chain stretch, 379–381
 chloroprene rubber, 372–374,
 373*f*, 462, 463*f*
 creep experiment, 379–381
 crosslinked polymer,
 378, 379*f*
 dynamic loading predictions,
 387–392
 eight-chain model, 376–377
 elastic and viscoelastic
 components, 376, 376*f*
 elastomers, 375
 equilibrium stress, 374–375,
 374*f*
 generic numerical
 implementation, 386–
 387
 hyperelastic response, 377
 hypothetical stress-strain curve,
 374–375
 Matlab implementation,
 382–384
 nitrile rubber, 466, 467*f*
 non-linear viscoelastic flow
 element, 375
 polyether ether ketone, 491,
 493*f*
 polymer modeling, 392–393
 Python implementation,
 384–386
 Rouse relaxation time, 379–381
 santoprene, 470–474, 473*f*,
 474*f*
 strain amplitude dependence,
 372
 time derivative, 378
 viscous components, 377–378
 viscous flow, 381–382
- Biot strain, 163
- Birefringence spectroscopy,
 95–97
- Bischoff anisotropic eight-chain
 model, 283–285
- Blatz–Ko foam model, 289
- Boltzmann’s superposition
 principle, 310
- Bulk modulus, 64–71, 241
- Buna-N. *See* Nitrile rubber
- C**
- Cauchy stress theorem,
 176–178
- Cauchy surface tractions, 176
- Chemical characterization
 techniques
 energy dispersive X-ray
 spectroscopy, 101–103
 Fourier transform infrared
 spectroscopy, 100–101
 Raman spectroscopy, 109–110
 size-exclusion chromatography,
 103–107
 thermogravimetric analysis,
 107–109
- Chloroprene rubber (CR)
 BB model with Mullins
 damage, 462, 463*f*
 calibrations, 461–462, 461*t*
 linear viscoelastic model, 462,
 463*f*
 stress relaxation response, 460,
 461*f*
 uniaxial compression data, 460,
 460*f*

- uniaxial tension, 440, 441*f*
 - Yeoh hyperelastic model, 461–462, 462*f*
 - Coefficient of determination, 444
 - Condensation polymerization, 11
 - Conductive polymers, 9
 - Confocal microscopy, 83
 - Conservation of mass, 173–175
 - Continuum mechanics
 - foundations, 219–224
 - balance laws and field equations, 171–184
 - constitutive equations, 187–194
 - coordinate transformations, 149
 - deformation gradient, 150–157
 - derivatives of scalar, vector, and tensor fields, 147–149
 - Dyadic product, 143–144
 - energy balance and stress power, 184–186
 - invariants, 150
 - large strain kinematics, 137–141
 - material symmetry, 198–199
 - multiaxial loading, 135–137
 - observer transformation, 194–198
 - rates of deformation, 164–165
 - strain, stretch, and rotation, 157–164
 - stress tensors, 165–170
 - symbols, 199
 - tensor operations, 144–147
 - uniaxial loading, 133–135
 - vector operations, 141–143
 - Coordinate transformations, 149
 - Corrugated hose failure, 127
 - CR. *See* Chloroprene rubber (CR)
 - Creep compliance
 - definition, 335
 - vs.* relaxation modulus, 336–337
- D**
- Dark field microscopy, 83
 - Deformation
 - modeling, 120–125
 - simple shear, 152
 - undeformed state, 151
 - uniaxial tension, 151
 - volumetric deformation, 153
 - Dependence of stored energy, 229–232
 - Differential interference contrast (DIC) microscopy, 83
 - Differential scanning calorimetry (DSC), 89–90
 - Digital image correlation (DIC)
 - strain measurement system, 66
 - DNF model. *See* Dual network fluoropolymer (DNF) model
 - Drucker Prager plasticity, 366–367, 367*f*
 - Drucker stability, 297
 - Dual network fluoropolymer (DNF) model, 121–122
 - Cauchy stress, 398–400
 - constant viscosity, 402
 - deviatoric viscoelastic flow, 401–402
 - kinematics of deformation, 398, 399*f*
 - material parameters, 403
 - Matlab implementation, 404
 - plastic flow, 402–403
 - polymer modeling, 404
 - strain rates, 397–398
 - structure, 398, 399*f*

- Dual network fluoropolymer
 - (DNF) model (*Continued*)
 - thermal expansion, 398–400
 - thermoplastics, 398
 - velocity gradient, 401
 - viscoelastic deformation
 - gradient, 400–401
 - volumetric viscoelastic flow, 401–402
- Dyadic product, 143–144
- Dynamic mechanical analysis (DMA), 43–47, 347
- E**
- Eigenvalue and spectral
 - decompositions, 154–157
- Eight-chain (EC) model, 250–259
- Elastomers, 24, 25*f*
- Energy balance and stress power, 184–186
- Energy dispersive X-ray spectroscopy (EDS), 101–103
- Entropy, 183
- Environmental SEM (ESEM), 86
- Environmental stress cracking (ESC), 126
- Euler–Almansi strain, 164
- Extended tube (ET) model, 273–275
- F**
- Failure model calibration, 73
- Failure modeling, 125–130
- FEA. *See* Finite element analysis (FEA)
- Fiber-reinforced composite, 217, 218*f*
- Finite element analysis (FEA)
 - deformation modeling, 120–125
 - failure modeling, 125–130
 - polymer mechanics, 115
 - properties of polymers and metals, 116–117
 - required inputs, 117–118
 - types, 119
- First law of thermodynamics, 180–182
- First Piola–Kirchhoff stress tensor, 167
- Flex circuit pressure sensor, 124
- Fluorescence microscopy, 84
- Fourier transform approach, 326
- Fourier transform infrared spectroscopy (FTIR), 100–101
- Freely jointed chain (FJC) model, 232–236
- G**
- Gaussian chains, 258
- Gel permeation chromatography (GPC), 103–107
- Generalized Fung model, 282
- Genetic algorithm, 445
- Gent model, 263–265
- Glass transition temperature, PET, 24
- Green–Lagrange strain, 163
- H**
- Hardness and indentation testing, 47–51
- HDPE. *See* High-density polyethylene (HDPE)
- Heaviside step function, 310
- Helmholtz free energy, 191–192
- Hencky strain, 163, 164

High-density polyethylene (HDPE)
 Arruda–Boyce eight-chain model, 477–478, 478*f*
 calibrations, 477, 477*t*
 elastic-plastic material model, 477–478, 478*f*
 linear viscoelastic model, 479, 479*f*
 PN model, 479, 480*f*
 power-flow model, 479, 481*f*
 stress relaxation data, 474–476, 476*f*
 stress-strain response, 474–476
 uniaxial tension data, 476*f*
 Holzapfel–Gasser–Ogden (HGO) model, 285–287
 Hooke’s law, 67–68, 211–212
 Horgan and Saccomandi model, 265–266
 Hybrid model (HM)
 backstress network, 411
 deformation map, 409, 410*f*
 energy activation approach, 412
 isotropic linear elasticity expression, 410–411
 Matlab implementation, 413–414
 polymer modeling, 414–416
 relative stiffness, 411
 rheological representation, 409, 410*f*
 strain elastic constants, 412
 ultra-high molecular weight polyethylene, 409
 viscoelastic deformation gradient, 412
 viscoplastic flow, 411–412
 Hyperelastic foam models
 Blatz–Ko foam model, 289

 hyperfoam model, 290–291
 Hyperelasticity
 code examples, 299–303
 Drucker stability, 297
 experimental testing, 296–297
 limitations, 298–299
 material parameters, 298
 Hyperfoam model, 290–291

I

I_1 and I_2 model, 250
 Impact testing, 40–43
 Incompressible biaxial deformation, 237–238
 Incompressible planar deformation, 237–238
 Incompressible uniaxial deformation, 237–238
 Interface friction, 27–28
 Invariant based anisotropy, 282–283
 Inverse Langevin function, 256–257
 Isothermal thermoelastic material, 194
 Isotropic elasticity, 211–215
 Isotropic hardening plasticity model. *See* J_2 -plasticity, isotropic hardening
 Isotropic hyperelasticity
 BAM model, 275–277
 continuum mechanics foundations, 219–224
 dependence of stored energy, 229–232
 eight-chain model, 250–259
 extended tube model, 273–275
 freely jointed chain model, 232–236
 Gent model, 263–265

Isotropic hyperelasticity

(Continued)

- Horgan and Saccomandi model, 265–266
 - I_1 and I_2 model, 250
 - Knowles hyperelastic model, 268–270
 - Mooney–Rivlin model, 243–245
 - Neo–Hookean model, 236–242
 - Ogden model, 259–261
 - predictive capabilities, 277–281
 - pure shear *vs.* planar tension, 226–228
 - response function
 - hyperelasticity, 270–272
 - uniaxial compression *vs.* biaxial tension, 225–226
 - Yeoh model, 245–248
- Isotropic material, 199

J

- Johnson–Cook plasticity model, 365–366, 366*f*
- J_2 -plasticity, isotropic hardening
 - abacus, 354
 - ANSYS, 354
 - cyclic loading, 355–357, 356*f*
 - Matlab implementation, 357–359
 - Python implementation, 359–360, 359*f*, 360*f*
 - stress-strain representation, 355, 355*f*
- UHMWPE thermoplastic
 - material, 361–362, 361*f*, 362*f*

K

- Kinematic hardening plasticity
 - model
 - Abaqus material definition, 363, 364, 365
 - backstress network, 363, 363*f*, 364*f*, 365
 - Chaboche type, 362–363
 - limitations, 365
 - MCalibration software, 363
- Knowles hyperelastic model, 268–270

L

- Lagrangian and Eulerian
 - Formulations, 139
- Large strain kinematics, 137–141
- Large strain linear viscoelasticity
 - generalization, 331–332
 - hyperelastic stress function, 332
 - numerical implementation, 332–334
- Linear elasticity
 - anisotropic elasticity, 215–217
 - isotropic elasticity, 211–215
 - transversely isotropic elasticity, 217–218
- Linear viscoelasticity
 - creep compliance, 335–337
 - differential form, 337–340
 - large strain, 331–334
 - polymer modeling, 345–349
 - shift functions, 340–345
 - small strain, 310–331
- Loss modulus, 322–323

M

- Material parameters, 437
- determination, 438–440

- error measurement functions, 442–444
- extraction, 439, 439*f*
- find_material_params, 444–445
- initial guess, 440–442, 441*f*
- mathematical minimization problem, 439–440
- Monte Carlo method, 442
- optimization algorithm, 444–445
- prior knowledge, 442
- Matlab implementation
 - Bergstrom–Boyce model, 382–384
 - dual network fluoropolymer model, 404
 - hybrid model, 413–414
 - J₂-plasticity, isotropic hardening, 357–359
 - small strain linear viscoelasticity, 329, 330*f*
 - three network model, 422
- Maxwell rheological model, 338–339, 339*f*
- MCalibration software, 445
- Mechanical stress, 134
- Metal plasticity model, 353
- Mises stress, 123, 123*f*, 170
- Monte Carlo method, 442
- Mooney–Rivlin (MR) model, 243–245
- Mullins effect models
 - Ogden–Roxburgh, 293–295
 - Qi–Boyce, 295
- Multiaxial loading, 135–137
- Multi-network Maxwell model, 340*f*

N

- Nanoindentation, 51
- Nanson's formula, 156
- Natural polymers, 4–5, 5*f*
- NBR. *See* Nitrile rubber
- Near-field scanning optical microscopy (NSOM), 83
- Nelder–Mead simplex method, 444–445
- Neo–Hookean hyperelastic material model
 - Abaqus/Explicit VUMAT, 448–450
 - Abaqus/Implicit UMAT, 450–454
 - stress, 447–448
- Neo–Hookean (NH) model, 236–242
- Neoprene. *See* Chloroprene rubber (CR)
- Nitrile rubber
 - BB model, 466, 467*f*
 - calibrations, 464, 465*t*
 - linear viscoelastic model, 466, 467*f*
 - stress-time response, 464, 465*f*
 - uniaxial compression data, 464, 464*f*
 - Yeoh hyperelastic model, 465–466, 466*f*
- Nominal strain, 164
- Nominal traction vector, 167
- Normalized mean absolute difference, 444
- Normalized root-mean square difference, 444

O

- Ogden model, 259–261
- Ogden–Roxburgh Mullins effect model, 293–295

Optical microscopy, 81–84

Orthotropic elasticity,
216–217

P

Parallel network (PN) model,
427–431, 459–460
high-density polyethylene, 479,
480*f*
polyether ether ketone,
491–492, 494*f*

Payne effect, 348–349

PEEK. *See* Polyether ether ketone
(PEEK)

Plane strain tension, 33–37

Plasticity theory. *See* J₂-plasticity,
isotropic hardening

Polarized light microscopy, 82

Polyether ether ketone (PEEK)

BB model, 491, 493*f*
calibrations, 490, 492*t*
force-displacement results,
494–495, 495*f*

Johnson–Cook plasticity
model, 491, 493*f*

PN model, 491–492, 494*f*
spherical indentation test,
495–496

TN model, 492, 494*f*
uniaxial tension and
compression data,
490, 491*f*

Polyethylene terephthalate (PET),
487–489

Polyactic acid (PLA), 7

Polymers

description, 1, 2–3
history, 7–10
manufacturing and processing,
11
mechanics, 11–15

plasticity models, 367–368
types, 4–7

Polypropylene (PP), 10

Polytetrafluoroethylene (PTFE)

calibrations, 484*t*
dual network fluoropolymer
model, 483–484, 486*f*
elastic-plastic material model,
482–483, 485*f*
mechanical behavior, 479–481
microporosity, 479–481
TN model, 484, 487*f*
volumetric compression data,
483*f*
yield stress, 479–481

PolyUMod library, 447–448

Powell method, 445

Pressure-volume-temperature
(PVT) testing, 66

Prony series, 315–316, 317*f*,
336–337, 345–346

PTFE. *See* Polytetrafluoroethy-
lene (PTFE)

Pure shear *vs.* planar tension,
226–228

Python implementation

Bergstrom–Boyce model,
384–386

J₂-plasticity, isotropic
hardening, 359–360,
359*f*, 360*f*

small strain linear
viscoelasticity, 330–
331, 331*f*

three network model, 422
viscoplasticity models, 432–
434

Q

Qi–Boyce Mullins effect model,
295

R

- Raman spectroscopy, 109–110
- Rates of deformation, 164–165
- Relaxation time spectrum, 328
- Residual error
 - strain-controlled experiment, 442, 443*f*
 - stress-controlled experiment, 443, 443*f*
- Response function hyperelasticity, 270–272
- Retardation time spectrum, 328
- Rheologically simple material, 342
- Rheological models, 338–340, 339*f*, 340*f*
- Rockwell hardness testing, 47–48

S

- Santoprene
 - BB model, 470–474, 473*f*, 474*f*, 475*f*
 - calibrations, 468, 470*t*
 - elastic-plastic material model, 469–470, 472*f*, 473*f*
 - isotropic hardening plasticity model with rate-dependence, 469, 472*f*
 - linear viscoelastic model, 469, 471*f*
 - uniaxial tensile stress-strain data, 468, 468*f*, 469*f*
 - Yeoh hyperelastic model, 468–469, 471*f*
- Scanning electron microscopy (SEM), 84–86
- Second law of thermodynamics, 183–184
- Semicrystalline polymers, 5–7, 6*f*
- Shear and bulk relaxation moduli, 312–313
- Shear modulus, 239
- Shore (durometer) testing, 48–49
- Simple anisotropic hyperelastic model, 283
- Simple shear, 37–39, 152
- Size-exclusion chromatography (SEC), 103–107
- Small-angle X-ray diffraction, 95
- Small punch testing, 77–79
- Small-strain classical theory, 135
- Small strain linear viscoelasticity applied strain history, 311, 312*f*
- Boltzmann's superposition principle, 310
- characteristic relaxation time, 313
- cyclic loading response, 320–322
- Heaviside step function, 310
- Matlab implementation, 329, 330*f*
- mat_LVE() function, 329
- monotonic loading response, 314–320, 317*f*
- Prony series, 315–316, 317*f*
- Python implementation, 330–331, 331*f*
- relaxation time spectrum, 328
- retardation time spectrum, 328
- shear and bulk relaxation moduli, 312–313
- storage and loss modulus, 322–327
- stress relaxation, 310, 311*f*, 313, 314*f*
- stretched exponential stress relaxation modulus, 316–318, 318*f*, 319*f*

Small strain linear viscoelasticity
 (*Continued*)
 test_mat_LVE function, 329,
 330*f*
 Spatial velocity gradient,
 164–165
 Spin tensor, 164–165
 Split-Hopkinson pressure bar
 (SHPB) testing, 53–63
 Stereo microscopy, 84
 Storage modulus, 322–323
 Strain matrix, 136
 Stress invariants, 169–170
 Stress-strain response, 24
 Stress tensors, 165–170
 Surface characterization
 techniques
 atomic force microscopy,
 87–88
 optical microscopy, 81–84
 scanning electron microscopy,
 84–86
 Swell testing, 97–99
 Synthetic polymers, 4–5, 5*f*

T

Tensor operations, 144–147
 Thermoelastic material,
 189–194
 Thermogravimetric analysis
 (TGA), 107–109
 Thermomechanical deformations,
 121
 Thermoplastics, 5, 6*f*, 24, 26*f*
 Thermoplastic vulcanizates
 (TPV). *See* Santoprene
 Thermosets, 5, 6*f*, 24, 27*f*
 Threaded connection gasket, 121
 Three network model (TNM),
 459–460

arbitrary rigid body rotation,
 420–421
 Cauchy–Green deformation
 tensor, 417–418
 deformation gradient, 417–418
 elastic and viscous components,
 419–420
 flow rate, 419–420
 material parameters, 421, 421*t*
 Matlab implementation, 422
 plastic strain, 418–419
 polyether ether ketone, 492,
 494*f*
 polymer modeling, 426
 polytetrafluoroethylene, 484,
 487*f*
 Python implementation, 422
 rheological representation, 417,
 417*f*
 shear modulus, 419
 viscoelastic deformation
 gradient, 418–419
 Time shifts, 342
 Time-temperature equivalence,
 341–345, 341*f*, 343*f*, 344*f*
 TNM. *See* Three network model
 (TNM)
 Transmission electron microscopy
 (TEM), 90–91
 Transversely isotropic elasticity,
 217–218
 Tresca stress, 170

U

Ultra-high molecular
 weight polyethylene
 (UHMWPE), 213–214,
 214*f*
 isotropic hardening plasticity
 model, 361–362

- Johnson–Cook model, 365–366, 366*f*
- kinematic hardening plasticity model, 362–365
- linear viscoelasticity
 - application, 346, 346*f*
- Uniaxial compression
 - vs. biaxial tension, 225–226
 - testing, 24–29
- Uniaxial loading, 133–135
- Uniaxial tension, 29–33, 151
- User material subroutines
 - Abaqus/Explicit VUMAT, 448–450
 - Abaqus/Implicit UMAT, 450–454
 - description, 447–448
 - purpose, 447–448
- V**
- Vector and tensor algebra, 141–150
- Vertical shifts, 345
- Viscoplastic deformations, 130
- Viscoplasticity models
 - Arruda–Boyce model, 393–396
 - Bergstrom–Boyce model, 372–393
 - dual network fluoropolymer model, 397–404
 - hybrid model, 409–416
 - parallel network model, 427–431
 - polymer modeling, 431–432
 - Python code examples, 432–434
 - three network model, 417–426
- V-notch shear testing, 80
- Volume characterization techniques
 - birefringence, 95–97
 - differential scanning calorimetry, 89–90
 - swell testing, 97–99
 - transmission electron microscopy, 90–91
 - X-ray diffraction, 92–95
- Volumetric deformation, 153
- Vulcanized natural rubber, 8–9
- W**
- Water filter failure, 126
- Wide-angle X-ray diffraction, 93–94
- William–Landel–Ferry (WLF) equation, 343, 344, 344*f*
- Work conjugate stress, 185
- X**
- X-ray diffraction (XRD), 92–95
- Y**
- Yeoh hyperelastic model, 456, 457*f*
 - acrylate-butadiene rubber, 456
 - chloroprene rubber, 461–462, 462*f*
 - nitrile rubber, 465–466, 466*f*
 - santoprene, 468–469, 471*f*
- Yeoh model, 245–248
- Young’s modulus, 23, 23*f*