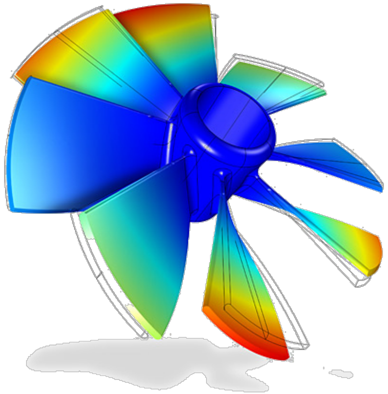
Introduction to Structural Analysis in COMSOL Multiphysics



COMSOL Products for Structural Analysis

- COMSOL Multiphysics
  - The COMSOL Multiphysics base product is required for all add-ons.
- Structural Mechanics Module
- Nonlinear Structural Materials Module
  - Available as add-on to the Structural Mechanics Module or MEMS Module.
- Geomechanics Module
  - Available as add-on to the Structural Mechanics Module.
- Multibody Dynamics Module
  - Available as add-on to the Structural Mechanics Module.
- Fatigue Module
  - Available as add-on to the Structural Mechanics Module.
- Acoustics Module
- MEMS Module
- Subsurface Flow Module

Summary of Structural Analysis Capabilities

- COMSOL Multiphysics
  - Linear static, transient, and eigenfrequency analysis with isotropic elastic materials. Solid elements.
- Structural Mechanics Module
  - Orthotropic and anisotropic elastic materials; linear viscoelasticity; piezoelectricity; geometric nonlinearity; mechanical contact; thermal strain; fluid-structure interaction (FSI); shell, membrane, plate, beam, and truss elements; rigid connectors, frequency response and prestressed analysis; linear and nonlinear buckling.
- Nonlinear Structural Materials Module
  - Elastoplasticity with large strain plastic deformation, hyperelasticity, nonlinear elasticity, viscoplasticity, and creep.
- Geomechanics Module
  - Soil, concrete, and rock mechanics material models including nonlinear elasticity, elastoplasticity, and creep.

Summary of Structural Analysis Capabilities

- Multibody Dynamics Module
  - Mix rigid and flexible components connected by joints (e.g. hinge, ball joint) or springs. Joints can have constraints, locking, springs, damping, friction, prescribed motion.
- Fatigue Module
  - High cycle fatigue (stress based) , Low cycle fatigue (strain based, energy based) and Cumulative damage.
- Acoustics Module
  - Acoustics, orthotropic and anisotropic materials; geometric nonlinearity; acoustic-structure interaction; elastic and poroelastic waves; piezoelectricity; frequency domain and prestressed analysis.
- MEMS Module
  - Orthotropic and anisotropic materials; geometric nonlinearity; mechanical contact; thermal strain; fluid-structure interaction (FSI); piezoelectricity; frequency response and prestressed analysis; linear viscoelasticity; rigid connectors; linear and nonlinear buckling, electromechanics; thermoelasticity; piezoresistivity; thin-film damping; electric fields.
- Subsurface Flow Module
  - Porous media flow with poroelastic deformation.

Product Suite – COMSOL® 5.2a

COMSOL Multiphysics®

COMSOL Server™

ELECTRICAL
- AC/DC Module
- RF Module
- Wave Optics Module
- Ray Optics Module
- Plasma Module
- Semiconductor Module
- MEMS Module *

STRUCTURAL & ACOUSTICS
- Structural Mechanics Module *
- Nonlinear Structural Materials Module *
- Geomechanics Module *
- Fatigue Module *
- Multibody Dynamics Module *
- Rotordynamics Module *
- Acoustics Module *

FLUID & HEAT
- CFD Module
- Mixer Module
- Subsurface Flow Module
- Pipe Flow Module
- Microfluidics Module
- Molecular Flow Module
- Heat Transfer Module

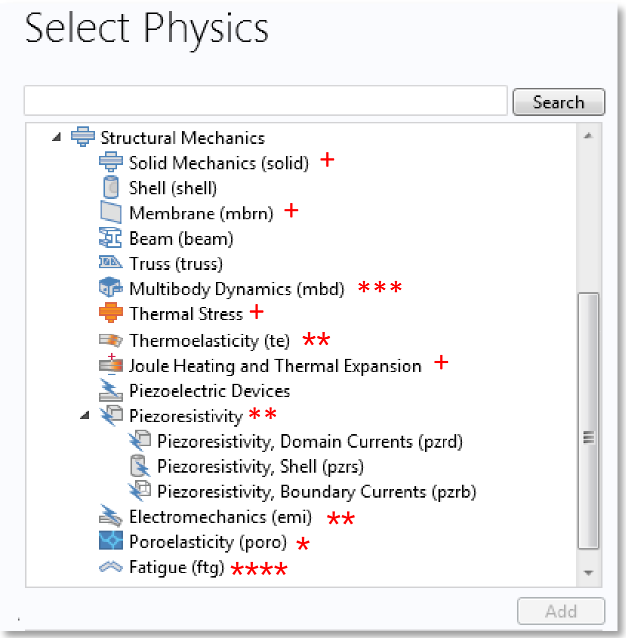
CHEMICAL
- Chemical Reaction Engineering Module
- Batteries & Fuel Cells Module
- Electrodeposition Module
- Corrosion Module
- Electrochemistry Module

MULTIPURPOSE
- Optimization Module
- Material Library
- Particle Tracing Module

INTERFACING
- LiveLink™ for MATLAB®
- LiveLink™ for Excel®
- CAD Import Module
- Design Module
- ECAD Import Module
- LiveLink™ for SOLIDWORKS®
- LiveLink™ for Inventor®
- LiveLink™ for AutoCAD®
- LiveLink™ for Revit®
- LiveLink™ for PTC® Creo® Parametric™
- LiveLink™ for PTC® Pro/ENGINEER®
- LiveLink™ for Solid Edge®
- File Import for CATIA® V5

* Products with structural analysis capabilities

Physics Model Wizard



+ Additional features with Nonlinear Structural Materials and Geomechanics Modules
* Subsurface Flow Module necessary
** MEMS Module necessary
*** Multibody Dynamics Module necessary
**** Fatigue Module necessary

Not shown (only available in 2D):
- Plate
- Beam Cross Section

Structural Mechanics Module

Analysis Capabilities

- Study Types
  - Stationary
  - Eigenfrequency
    - Prestressed
  - Transient
    - Direct and modal
  - Frequency response
    - Direct and modal
    - Prestressed
  - Linear buckling
  - Parametric
  - Modal reduced order

- Element Types
  - Solid (3D, 2D axisymmetric , 2D plane stress, and 2D plane strain)
  - Shell (3D)
  - Membrane (3D and 2D axisymmetric)
  - Plate (2D)
  - Beam (3D and 2D)
  - Truss (3D and 2D)

All study types and space dimensions are not available for certain physics interfaces.

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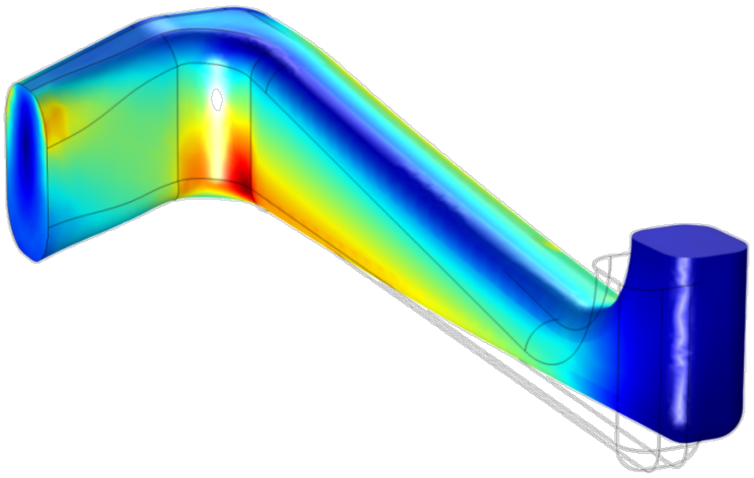
Solid Mechanics



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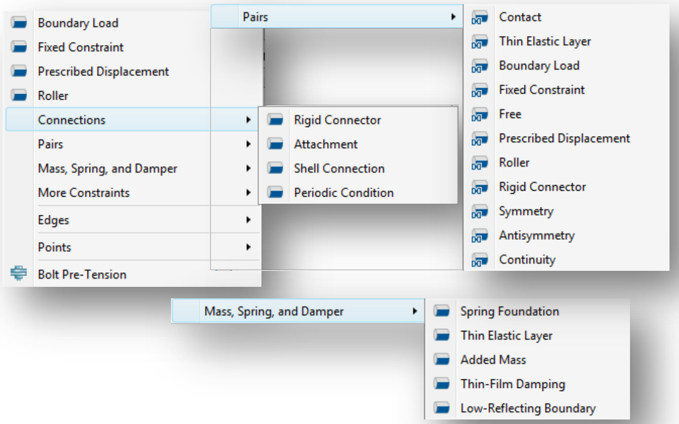
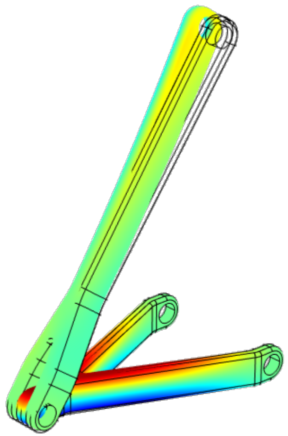
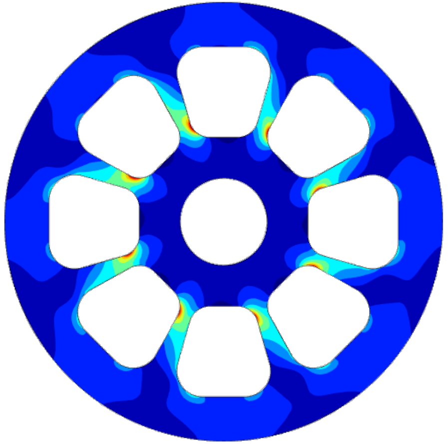
Solid Mechanics

- Contact with friction
- Low-reflecting boundary
- Periodic condition
- Rigid connector





Hinged assembly: Static loading.



Engine pulley:
Rotation affected stresses.

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Material Models for Solids

- Linear elastic materials:
  - Isotropic, orthotropic, and anisotropic
  - Thermal expansion
  - Hygroscopic swelling
  - Initial stress and strain
  - External stress
  - Damping
    - Isotropic, orthotropic, and anisotropic loss factors
    - Rayleigh Damping
    - Viscous Damping
- Linear viscoelastic material with thermal effects

Material Models for Solids

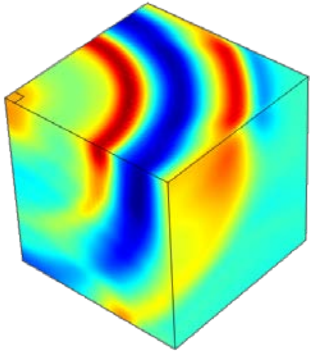
- Piezoelectric material
  - Mechanical, electrical and coupling damping
  - Requires AC/DC module
- User defined material
  - Coded in C (or other programming language called from a C wrapping function)
  - Can be distributed as a shared library (dll, so, dylib)
- Nonlinear materials are available in the Nonlinear Structural Materials and Geomechanics Modules.

Loads and Constraints for Solids

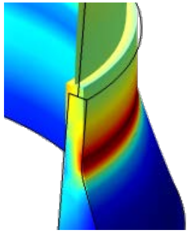
- Follower pressure load
- Prescribed velocity and acceleration
- Lumped and distributed spring with damping
- Thin elastic layer
- Mechanical contact with friction
- Periodic boundary conditions including cyclic symmetry and Floquet periodicity
- Rigid connector
- Shell connection
- Added lumped and distributed mass

Advanced Boundary Conditions

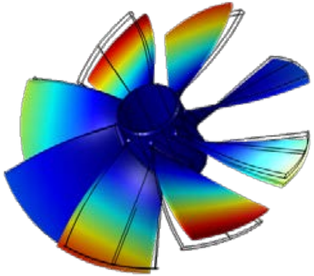
- Periodic boundary conditions
  - Continuity
  - Antiperiodicity
  - Floquet periodicity
  - Cyclic symmetry
- Low-reflecting boundary
- Shell connection



Blast loads: Elastic wave propagation in rock using symmetry and low-reflecting boundary.



Shell-Solid transition



Impeller: Vibration analysis using dynamic cyclic symmetry.

Thermal Expansion, Initial Stress and Strain

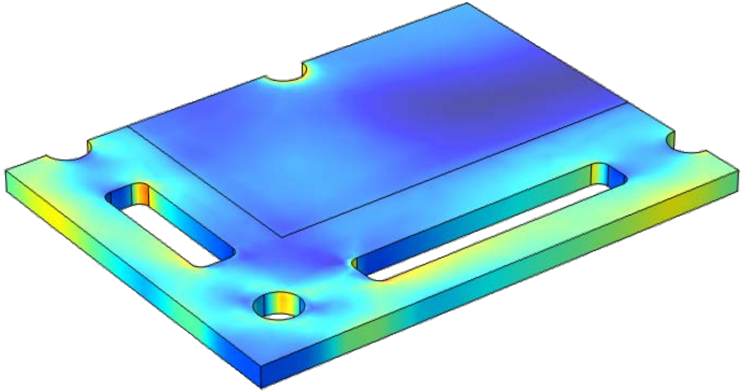
- Initial Stress and Strain Tensors
  - Initial stress and strain tensor components can be functions of space or any field quantity from different physics.
  - External stress
    - User defined, or imported from other physics interface
    - Can be a pure load contibution, like a pore pressure
  - Thermal expansion
    - Isotropic or anisotropic coefficient of thermal expansion
    - Temperature can be computed by another physics interface
  - Hygroscopic swelling
    - Isotropic or anisotropic coefficient of hygroscopic selling
    - Moisture concentration can be computed by another physics interface

Infinite Domains

- Infinite elements
  - Allows for accurate truncation of a large piece of material where only part is modeled
- Perfectly Matched Layers (PML)
  - Absorption of elastic waves in the frequency domain
- Low-reflecting boundaries
  - Absorption of elastic waves in the time domain

Thermal Stress

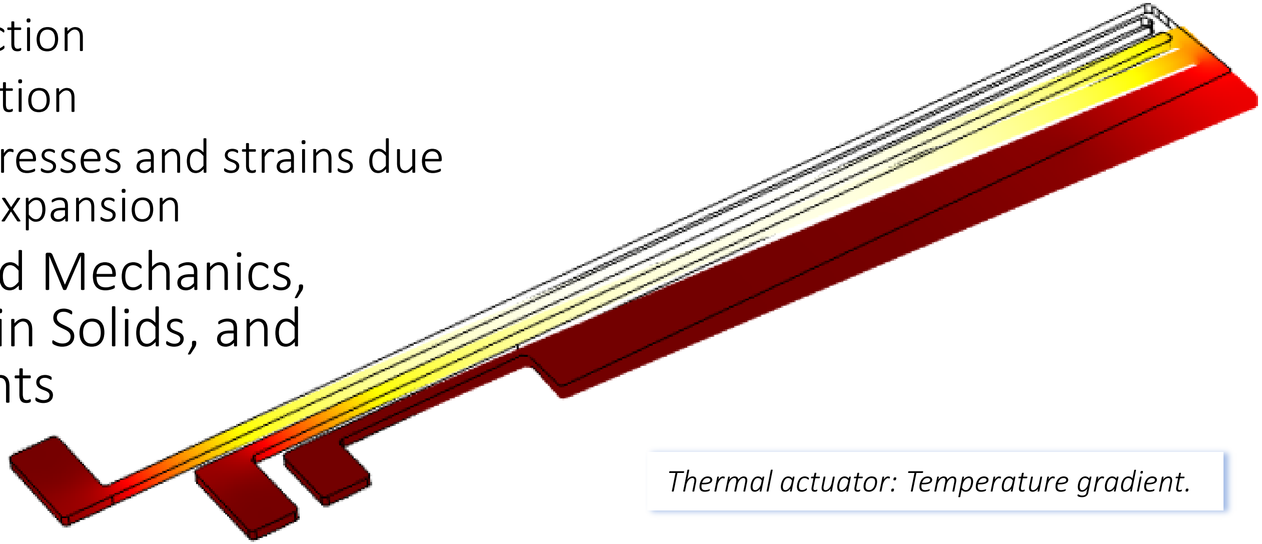
- Coupled structural and thermal analysis
- Combines Solid Mechanics and Heat Transfer in Solids



Bipolar plate in a fuel cell: Thermal stresses in a constrained plate.

Joule Heating and Thermal Expansion

- Physics coupling:
  - Electric current conduction
  - Heat conduction
  - Heat generation
  - Structural stresses and strains due to thermal expansion
- Combines Solid Mechanics, Heat Transfer in Solids, and Electric Currents

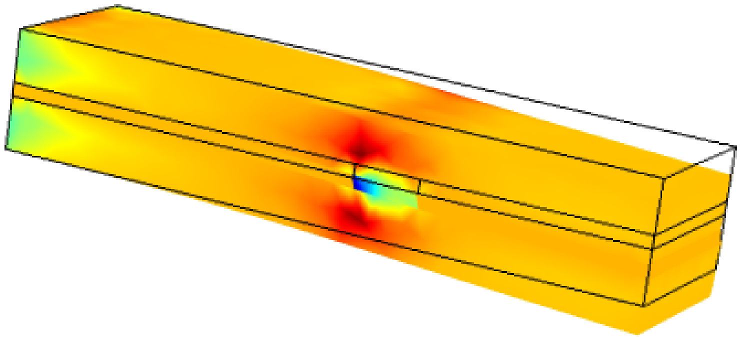


Thermal actuator: Temperature gradient.

Piezoelectric Devices

- Constitutive modeling
  - Piezoelectric material
  - Mechanical damping
  - Coupling loss
  - Dielectric loss
  - Conduction loss

- Combines Solid Mechanics and Electrostatics



Sandwich beam with piezoelectric ceramic actuator: Bending deflection due to shear stress.

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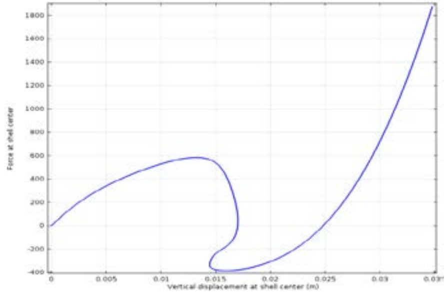
Piezoelectric Devices

- Mixed piezoelectric, dielectric, and elastic modeling domains
- Fully coupled static, transient, frequency-response, and eigenfrequency analysis
- Combine with AC/DC or MEMS Module for adding electrical circuits
- Combine with Acoustics Module for piezo-acoustic interactions

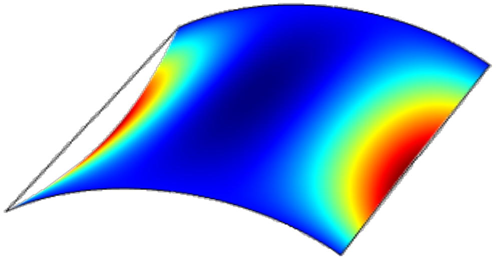
Shell, Plate, and Membrane

Shell

- High accuracy elements
- Stress evaluation at arbitrary through-thickness position
- Offset of surface
- Curvature dependent properties



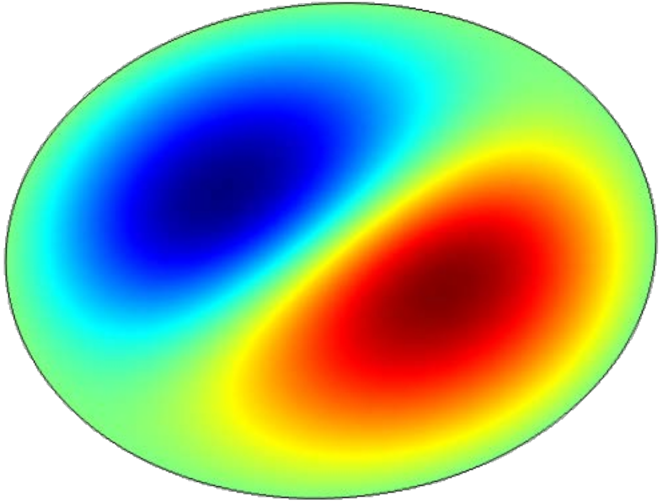
Shell post-buckling: Snap- through phenomena.



Hanging roof: Deflection due to gravity load.

Membrane

- Thin structures with low bending stiffness
- Microphone membranes
- Thin cladding
- Fabric
- Pre-stressed



Vibrating membrane: Second eigenmode of a membrane.

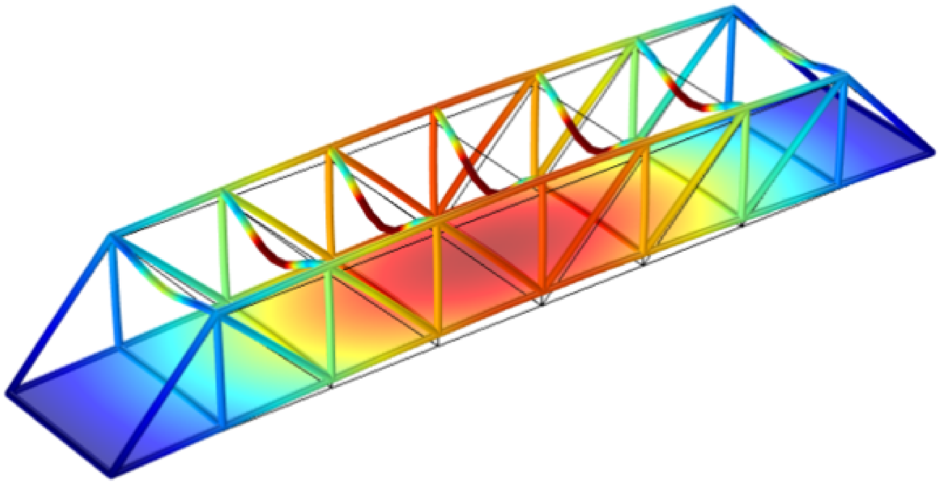
Shell, Membrane, and Plate Features

- Surface and body load
- Added lumped and distributed mass
- Distributed spring with damping
- Rigid connectors (shell only)
- Solid and beam connection (shell only)
- Shell offset
- Linear elastic material
  - Isotropic, orthotropic, and anisotropic
  - Initial stress and strain
  - External stress
  - Thermal expansion
  - Hygroscopic swelling
  - Damping

Material Models for Membranes

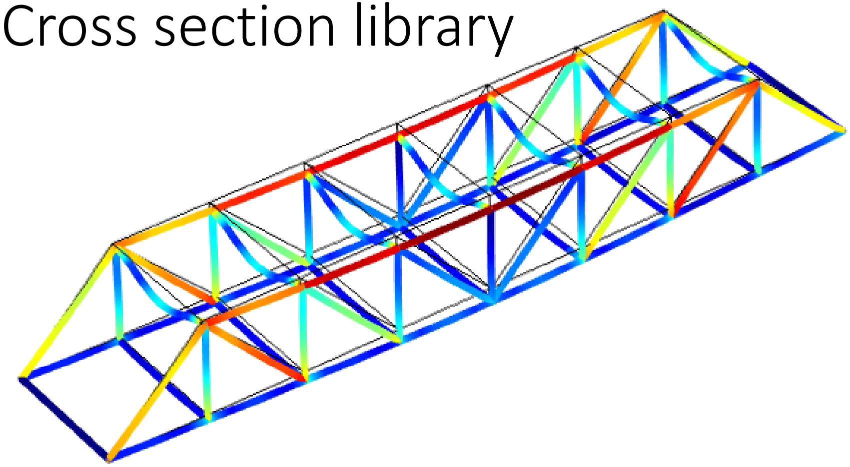
- Linear elastic material
- Linear viscoelastic material with thermal effects
- With the Nonlinear Structural Materials and Geomechanics Modules:
  - Nonlinear elastic
  - Hyperelastic
  - Plasticity
  - Creep
  - Viscoplasticity

Beam and Truss

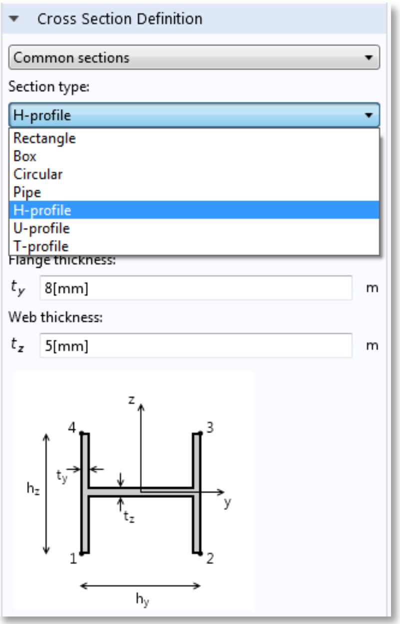


Beam

- Euler or Timoshenko type elements
- Cross section library



Pratt bridge: Stress distribution in structure caused by two trucks.



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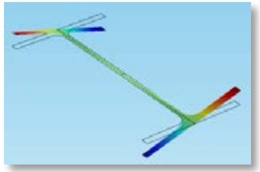
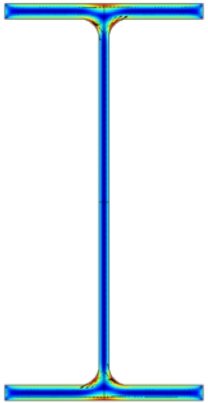
Beam Cross Section

- Draw a beam cross section in 2D
  - Simple sections or arbitrary number of internal holes
- Compute all cross section properties
  - Area
  - Center of gravity and shear center locations
  - Moments of inertia and bending stress distribution
  - Torsional rigidity and torsional stress distribution
  - Shear stress distribution and shear area
  - Warping function and warping constant
- Compute detailed stress distribution given the section forces



Warping function



Torsional stresses in an I300 beam

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Truss

- Discretization flexibility for connection with other physics
- Can be used also for cables
- Straight edge constraint

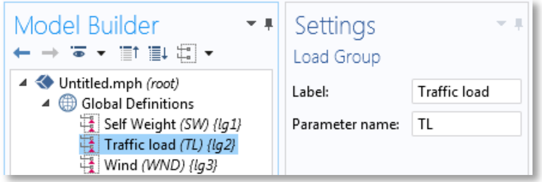
Truss tower: Critical buckling load.

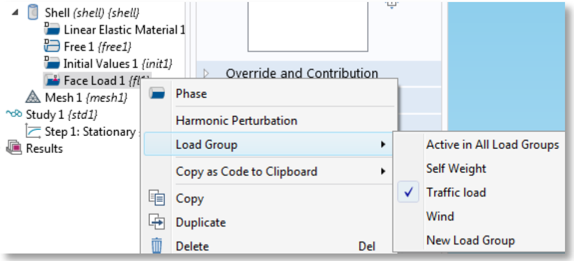
Beam and Truss Features

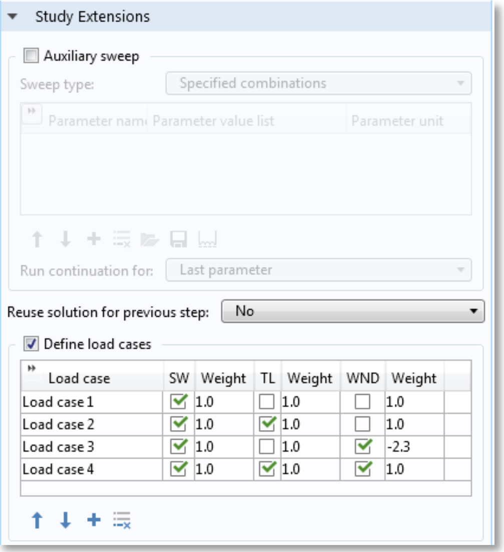
- Linear elastic material
  - Initial stress and strain
  - External stress
  - Thermal expansion
  - Hygroscopic swelling
  - Damping
- Plasticity (Truss only)
- Edge and body load
- Added lumped and distributed mass
- Spring foundation with loss factor and viscous damping
- Two-point spring/damper (Truss only)
- Standard cross sections (Beam only)

Load Cases

- Load and Constraint groups
- Weight factor for load scaling







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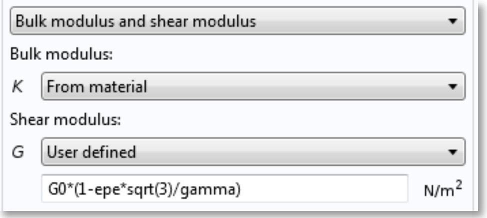
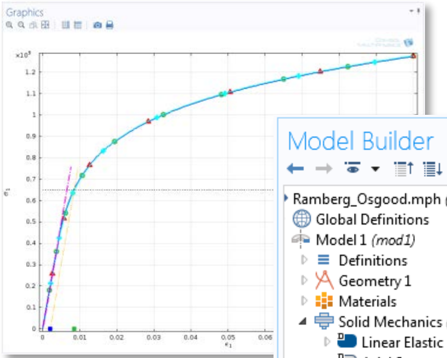
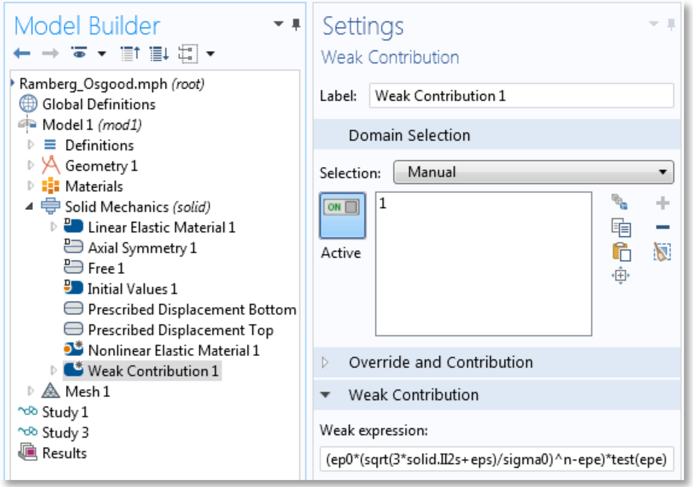
User Defined Material Models

- Equation- based modeling
- PDF formulation
- Distributed ODEs
- Additive physics
- Inelastic strains
- External materials
  - C-code; shared libraries







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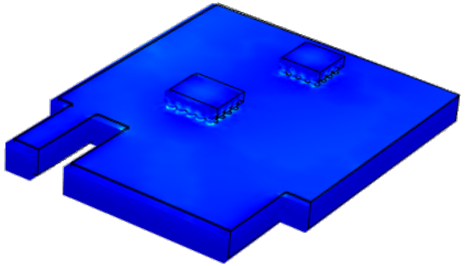
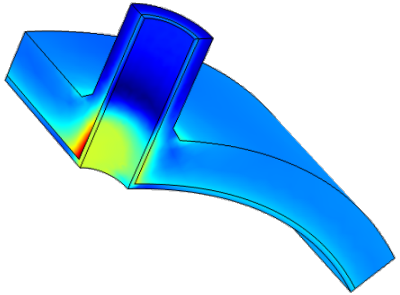
Other Modules for Structural Analysis



Thermal creep in viscoplastic solder joints: Requires Nonlinear Structural Materials Module.

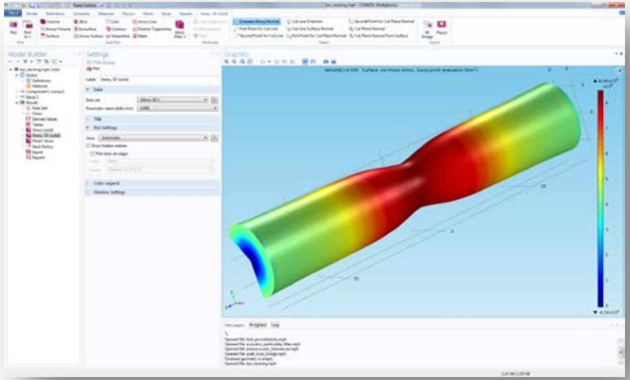
Tunnel excavation: Requires Geomechanics Module.



Thermo-elastoplastic pressure vessel with internal cladding: Requires Nonlinear Structural Materials Module.

Nonlinear Structural Materials Module

- Adds several nonlinear material model families:
  - Nonlinear elastic
  - Hyperelastic
  - Elastoplastic
  - Creep and viscoplasticity



Necking of a metal bar. This example is a classical benchmark for large strain plastic deformation.

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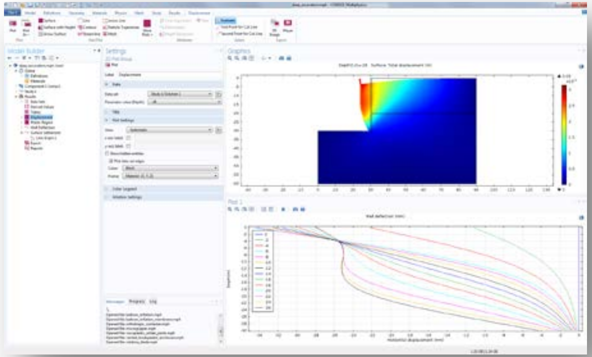
Geomechanics Module

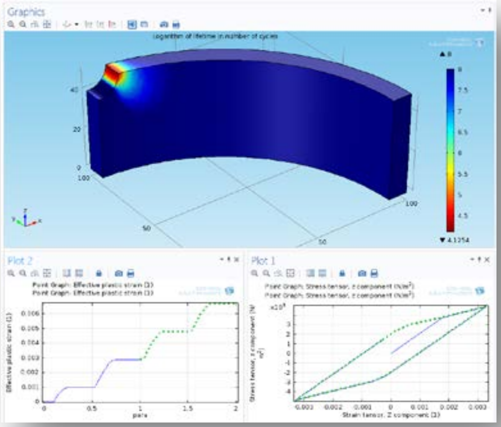
- Adds several nonlinear material model families targeted at geomechanical and civil engineering:
  - Nonlinear elastic
  - Elastoplastic
  - Soil plasticity
  - Concrete
  - Rocks
  - Cam-Clay
  - Creep



Deep excavation example

Fatigue Module

- Postprocessing of stress and strain results for fatigue evaluation
  - High cycle fatigue; stress based models
  - Low cycle fatigue; strain and energy based models
  - Cumulative damage for variable load amplitudes



Life time prediction for a hole subjected to cyclic plasticity

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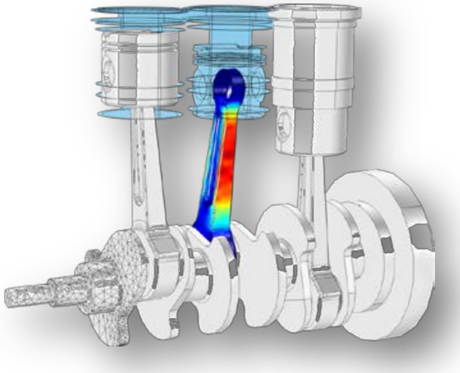
Multibody Dynamics Module

- Analyze combinations of rigid and flexible bodies
- Library of joints for mechanical connections
  - Hinge, Ball, Planar, Screw, Slot, ...
  - Joint conditions: Friction, Spring, Damping, Locking, Prescribed Motion, Applied Force
- Springs and Dampers
- Combine with Solid Mechanics, Shell and Beam models



Dynamic analysis of a three-cylinder engine

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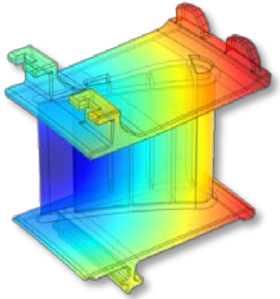
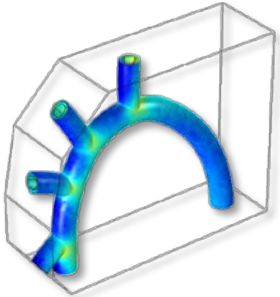
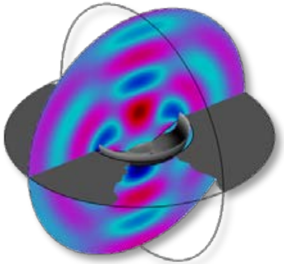
Structural Analysis and Multiphysics



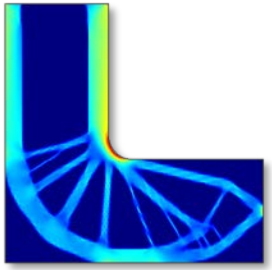
Thermally stressed stator blade: Requires Heat Transfer Module or CFD Module.



Deformation in a blood vessel: Requires CFD Module.

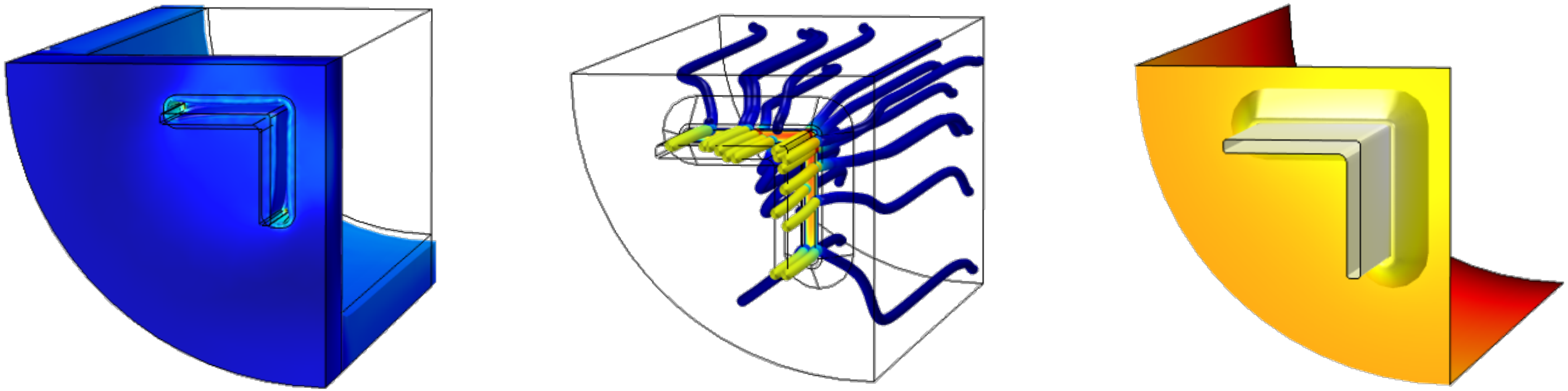


Baffled membrane: Requires Acoustics Module.



Topology optimization of angled bracket: Requires Optimization Module.

Structural Analysis and Multiphysics



Fluid Structure Interaction in Aluminum Extrusion: Requires Heat Transfer Module.

Material Library

- Data for more than 2500 materials.
- A given material entry store data for up to 24 different properties by default – can be extended by user.
- Contains a total of almost 20,000 property functions (material curves).
- Search through UNS number, or DIN number.

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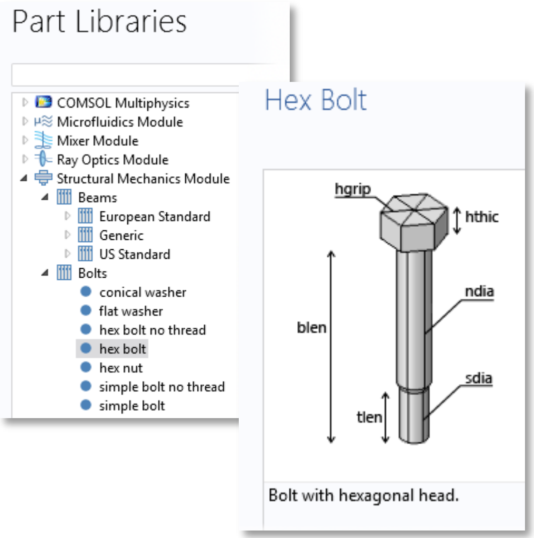
Part Libraries

- Parametrized geometries
  - Bolt, nuts and washers
    - Predefined selections for positioning, contact conditions, and prestress
  - Beam cross sections
    - Common generic sections (C, I,L, T)
    - European standard (HEA, INP, UPE, ...)
    - US Standard (C, HP, MC, ...)

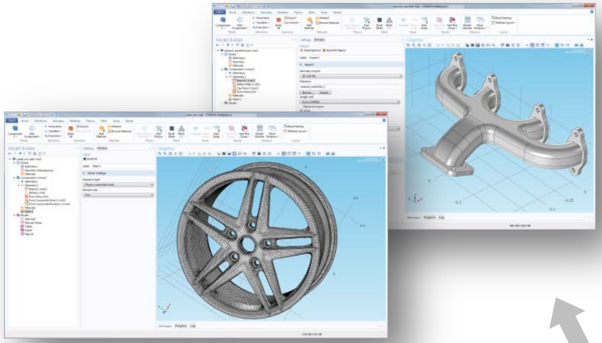


CAD & Mesh Interoperability

Mesh File Formats
NASTRAN® (read & write)
STL (read & write)
VRML

3D CAD File Formats
ACIS® (read & write)
AutoCAD®
CATIA® V5
IGES
Inventor®
NX™
Parasolid® (read & write)
PTC® Creo® Parametric™
PTC® Pro/ENGINEER®
SOLIDWORKS®
STEP

LiveLink™ Interfaces
LiveLink™ *for* AutoCAD®
LiveLink™ *for* Inventor®
LiveLink™ *for* PTC® Creo® Parametric™
LiveLink™ *for* PTC® Pro/ENGINEER®
LiveLink™ *for* Revit®
LiveLink™ *for* SOLIDWORKS®
LiveLink™ *for* Solid Edge®



ECAD File Formats
GDSII
NETEX-G
ODB++
ODB++(X)

3rd Party Products
Mimics®
Simpleware

Geographic Information System (GIS)
Digital Elevation Map (DEM)

2D CAD File Formats
DXF™ (read & write)

Support for implementation of the ODB++ Format was provided by Mentor Graphics pursuant to the ODB++ Solutions Development Partnership General Terms and Conditions (www.odb-sa.com).

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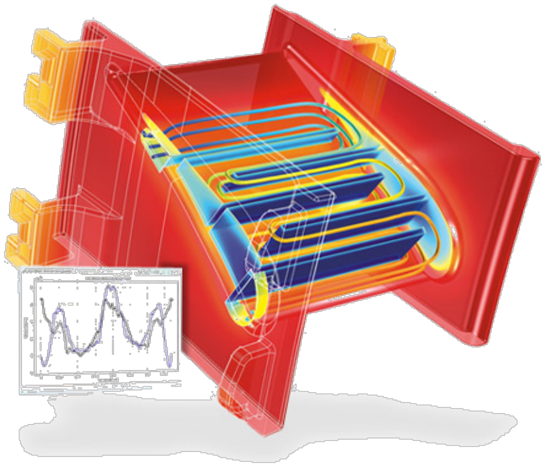
Examples

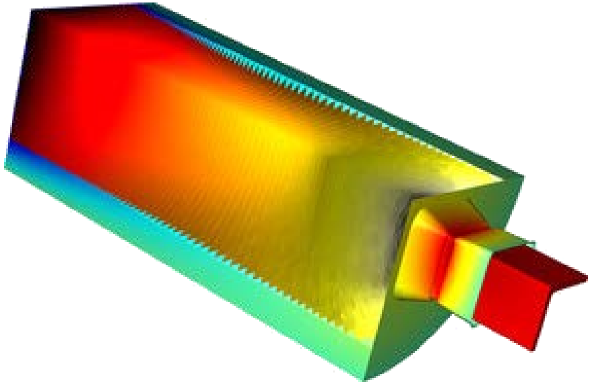
Thermal Stress in a Turbine Stator Blade

- A stator blade in the turbine stage of a jet engine is heated by combustion gases, where the resulting temperature gradients introduce significant stresses.
- To prevent the stator from melting, air is passed through a cooling duct in the blade.
- Shown is the temperature distribution throughout the blade and in the flow stream.
- COMSOL Multiphysics and the Structural Mechanics Module together with either the Heat Transfer Module or CFD Module are required.



Fluid-Structure Interaction in Metal Extrusion

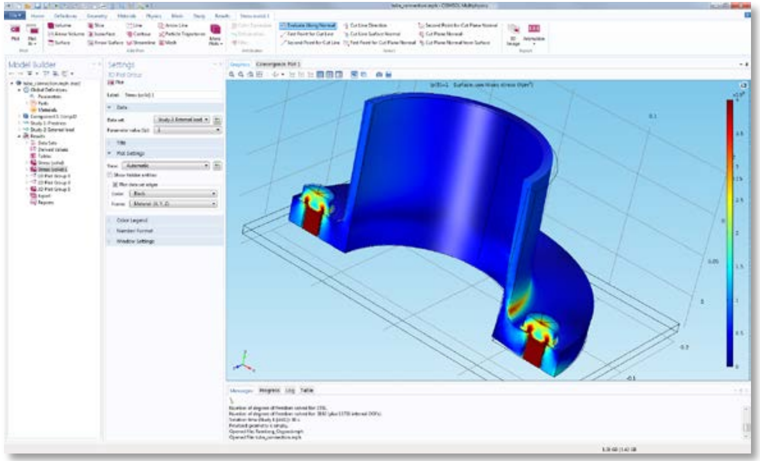
- Fluid-structure interaction (FSI) with non-Newtonian flow, heat transfer, and viscous heating.
- The stress in the die due to fluid pressure and thermal loads are computed.
- A comparison between the available experimental data and the numerical results of the simulation shows good agreement.
- COMSOL Multiphysics and the Structural Mechanics, Heat Transfer, and CFD Modules as well as the Material Library are required.



COMSOL

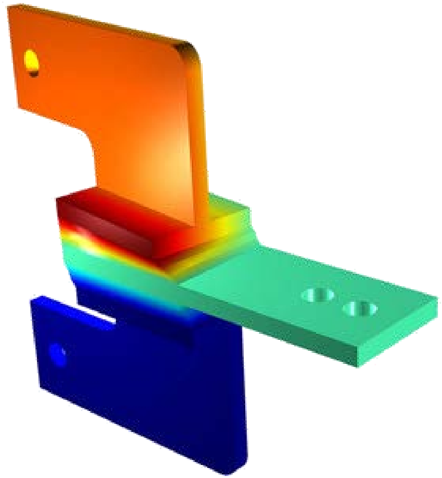
Prestressed Bolts in a Tube Connection

- A prestressed tube connection subjected to an external bending moment is analyzed.
- The bolts are imported from the Part Libraries.
- The built-in functionality for adding a bolt prestress is used.
- Contact between the mating flanges is modeled.
- The stress in the bolts as a function of the applied external force is calculated.
- The geometry is imported from an IGES file and therefore this example requires the CAD Import Module or one of the LiveLink products for CAD, in addition to COMSOL Multiphysics and the Structural Mechanics Module.



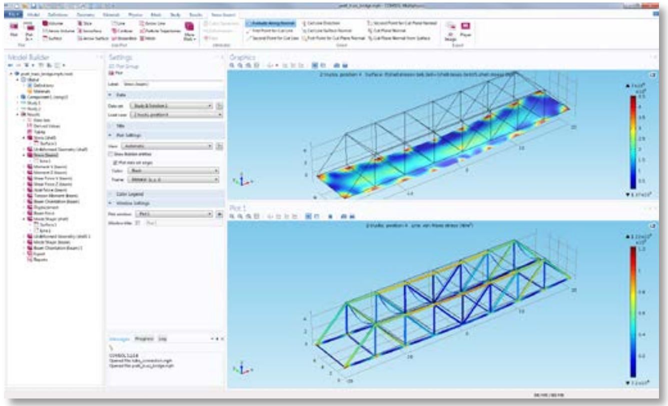
Viscoelastic Structural Damper

- Damping elements involving layers of viscoelastic materials are often used for reduction of seismic and wind induced vibrations in buildings and other tall structures.
- The forced response of a typical viscoelastic damper is studied. The analysis involves two cases: a frequency response analysis and a time-dependent analysis.
- The viscoelastic material model is available with the Structural Mechanics Module and the MEMS module.



Pratt Truss Bridge with Beam and Shell Elements

- This example is inspired by a classic bridge type called a Pratt truss bridge.
- A truss structure supports only tension and compression. You would normally model it using bars, but here 3D beams are used, so it also includes bending moments. In the model, shell elements represent the roadway and both the Shell and Beam interfaces are used.
- The load case functionality is used for investigating the effect of trucks at different locations on the roadway.
- COMSOL Multiphysics with the Structural Mechanics Module are required.



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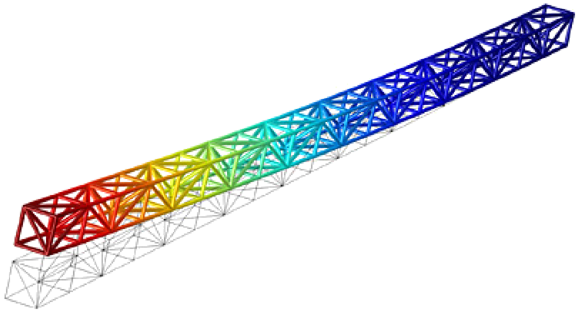
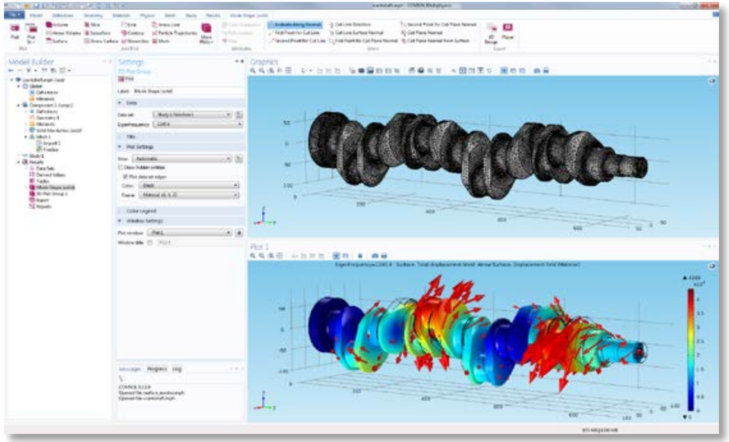
Linear Buckling of a Truss Tower

- In this example, the critical buckling load of a truss tower is computed using a linear buckling analysis.
- The Truss interface is used to model the tower.
- The solution is compared with an analytical estimate of the critical load obtained from Euler buckling.
- COMSOL Multiphysics and the Structural Mechanics Module are required.



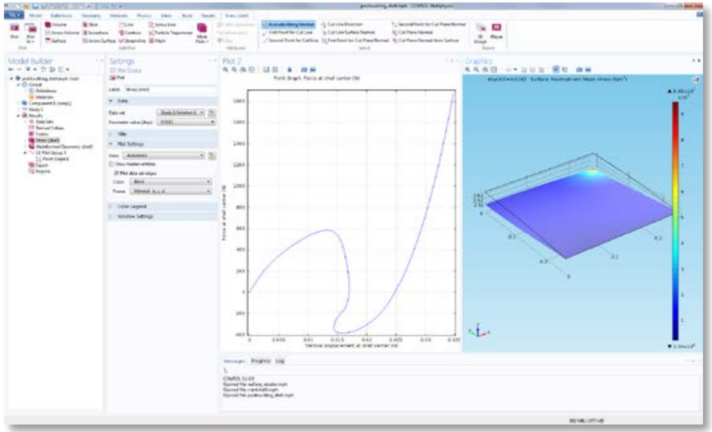
Modal Analysis of a Crankshaft

- This example shows a modal analysis of a crankshaft.
- The simulation is in this case based on an imported mesh on NASTRAN format and not on a mesh generated by COMSOL.



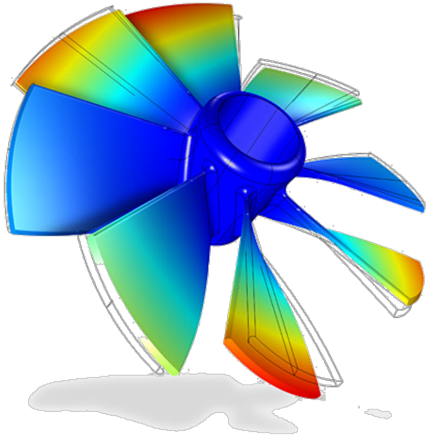
Postbuckling Analysis of a Hinged Cylindrical Shell

- This example shows how to trace a postbuckling path where neither load nor displacement increases monotonously.
- The results correspond very well to published values.
- COMSOL Multiphysics and the Structural Mechanics Module are required.



Vibration of an Impeller

- This tutorial demonstrates how to reduce model size by using dynamic cyclic symmetry on a sector.
- The fundamental frequencies are computed for the whole impeller geometry, and then compared with the values computed for a single sector using the Floquet periodicity boundary conditions.
- It also demonstrates how to set up a frequency response analysis for one sector of symmetry, and how to postprocess the results into the full geometry.
- The results for one sector are in very good agreement with the computations on the whole geometry, while both the computational time and memory requirements are significantly reduced.



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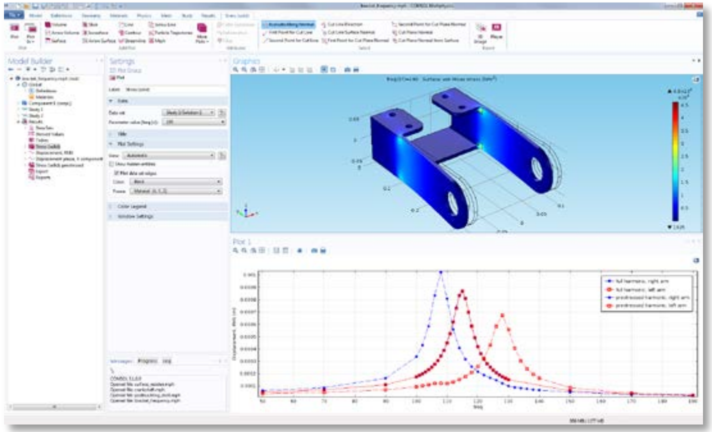
Prestressed Analysis

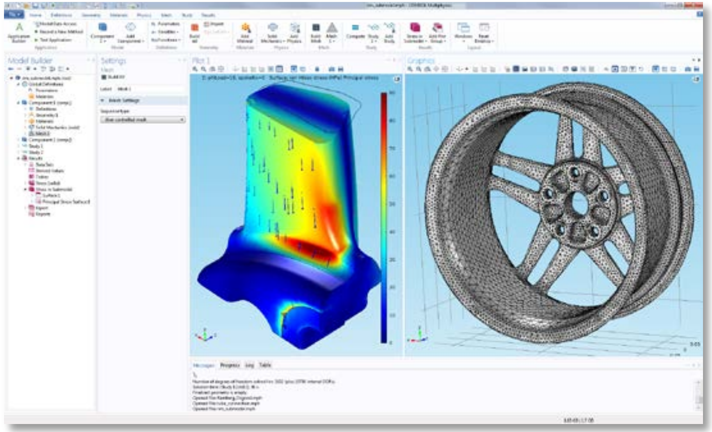
- Structures be prestressed by mechanical, thermal, or arbitrary multiphysics-based loads.
- Prestressed analysis types include eigenfrequency and frequency response.
- This functionality is available in the Structural Mechanics, MEMS, and Acoustics Modules.



COMSOL

Submodel in a Wheel Rim

- In this example the submodeling technique is used to accurately resolve the stress concentrations in a wheel rim.
- First a global model is solved to obtain the displacements, which are then used as boundary conditions in a local model of the region where the stress concentrations occur.
- Several loadcases are computed in order to simulate how the load is moving with respect to the rotating wheel.
- This example can also be extended by a fatigue analysis, which requires the Fatigue Module.



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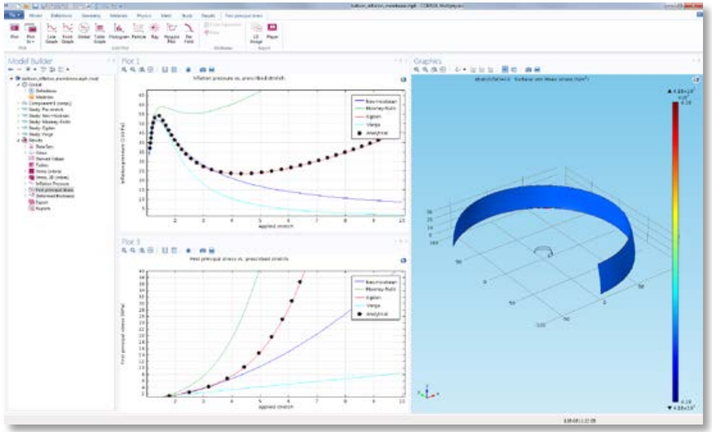
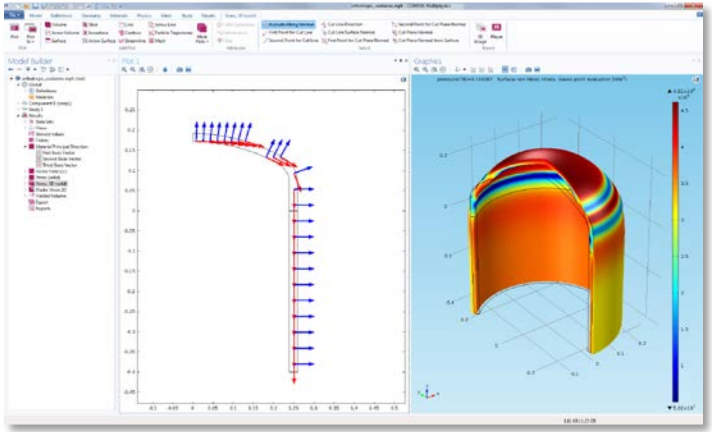
Inflation of a Spherical Rubber Balloon

- This example shows inflation of a spherical rubber balloon for four different hyperelastic material models: Neo-Hookean, Mooney-Rivlin, Ogden, and Varga.
- There are two variants of this example, one using the Solid Mechanics interface, and one using the Membrane interface.
- Hyperelastic material models are available when combining COMSOL Multiphysics with the Structural Mechanics and Nonlinear Structural Material Modules.



Pressurized Orthotropic Container

- The stress and plastic strain in a thin-walled container made of rolled steel are analyzed.
- The material is represented by an elastic isotropic model combined with Hill orthotropic plasticity.
- This example also illustrates how to handle structures where the material behavior varies with shape, such as for rolled steel or composites. Here, the principal directions of the material follow the geometrical shape of the structure.
- COMSOL Multiphysics with the Structural Mechanics and Nonlinear Structural Material Modules are required.



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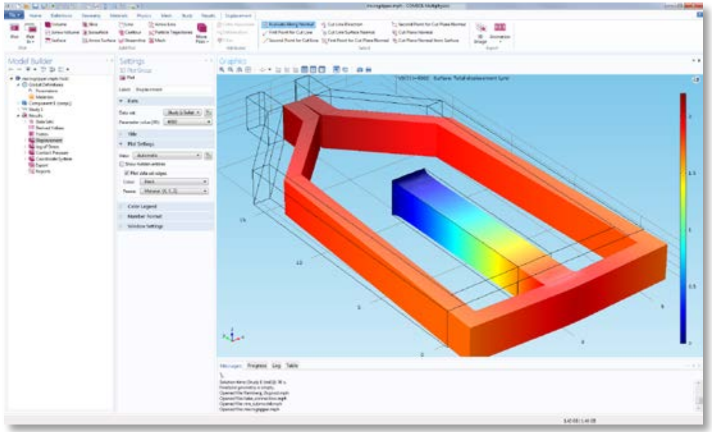
Piezoelectrically Actuated Microgripper

- This tutorial shows a piezoelectrically actuated microgripper with mechanical contact.
- The microgripper contains a piezoelectric actuator that operates in the longitudinal mode.
- Elongation in the longitudinal direction creates a lifting movement to the structure, and simultaneous contraction in the transversal direction closes the gripper and allows it to move objects.
- The example uses the Piezoelectric Devices interface and requires COMSOL Multiphysics and one of the Structural Mechanics, MEMS, or Acoustics Modules.



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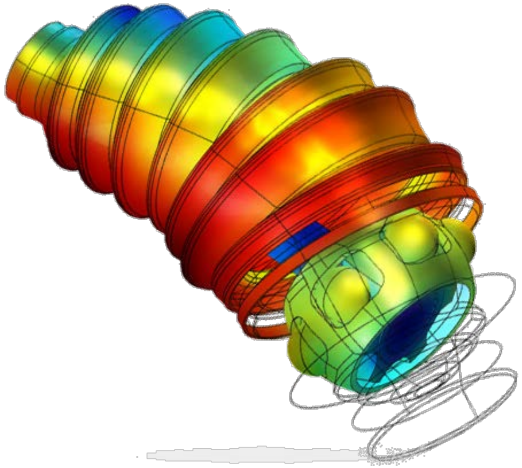
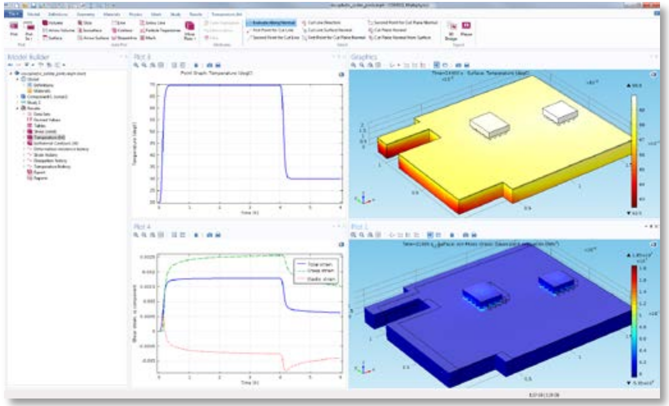
Hyperelastic Materials in a Continuous Velocity Joint

- The visualization shows the von Mises stress and deformation in the ball bearing, cage and rubber seal of a continuous velocity joint.
- The hyperelastic material model used requires COMSOL Multiphysics and the Structural Mechanics and Nonlinear Structural Materials Modules.
- This example is courtesy of Metelli S.p.A., Italy.



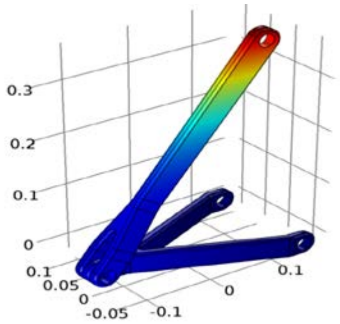
Viscoplastic Creep in Solder Joints

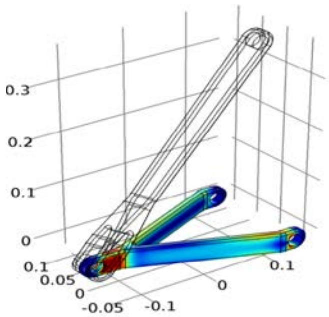
- Viscoplastic creep in solder joints under thermal loading using the Anand viscoplasticity model is studied in this example.
- This material model requires COMSOL Multiphysics and the Structural Mechanics and Nonlinear Structural Materials Modules.
- The geometry includes two electronic components (chips) mounted on a circuit board by means of several solder ball joints.
- In the Fatigue module, there is an extension of this example where the lifetime is computed based on the thermal cycling.



Hinge Joint Assembly

- A hinge between two mechanical components is modeled. One part is considered as rigid and the other as flexible.
- The connection is established using a Hinge Joint and a Cylindrical Joint. This is to enable the sliding between hinge barrel and hinge pin.
- The example uses the Multibody Dynamics interface and requires COMSOL Multiphysics , Structural Mechanics, and Multibody Dynamics Modules.





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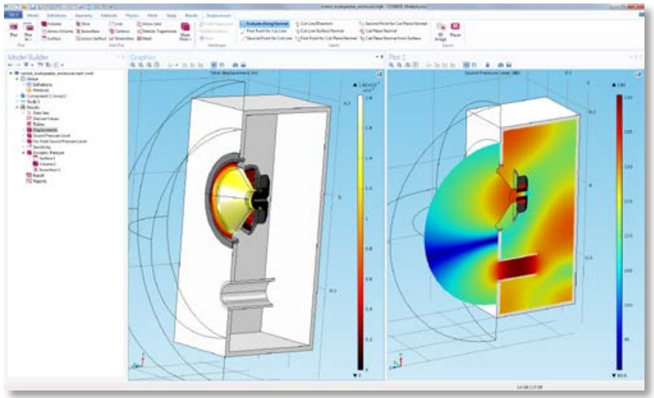
Acoustic-Structure Interaction: Loudspeaker Driver in a Vented Enclosure

- The acoustic behavior of a woofer mounted in a bass reflex enclosure and placed in the corner of a room is studied.
- The frequency is swept through a logarithmically spaced range of 40 values from 10 Hz to 3.5 kHz.
- The time-harmonic Acoustic-Shell Interaction interface is used. This multiphysics interface provides automatic coupling between the Shell equation for the moving parts and the Pressure Acoustics equation in the surrounding air.
- COMSOL Multiphysics with the Acoustics Module and the Structural Mechanics Module are required.



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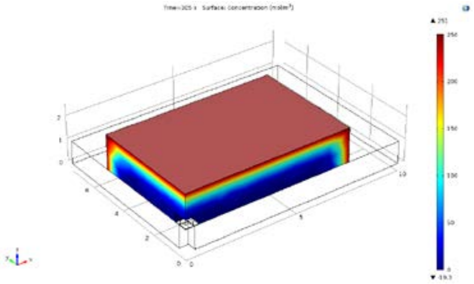
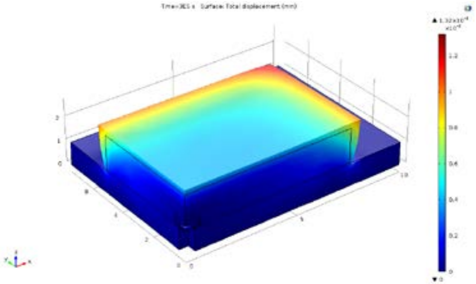
MEMS Pressure Sensor Drift due to Hygroscopic Swelling

- This example studies the moisture diffusion across the mold compound that protects a MEMS pressure sensor.
- The hygroscopic swelling induced by the moisture diffusion induces a drift in the measured characteristics of the sensor.
- The pre-defined coupling between the Transport of Diluted Species and Solid Mechanics interfaces is used.



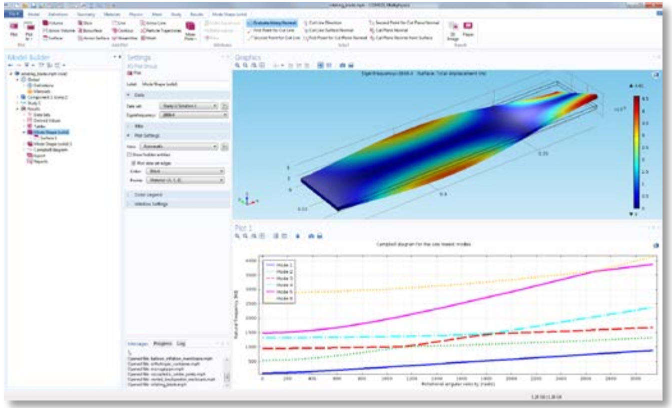
Moisture concentration



Displacement

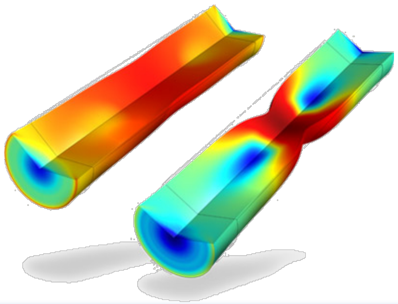
Rotordynamics:
Eigenfrequencies of a Rotating Blade

- The eigenfrequencies of a rotating blade are studied in this benchmark example.
- The combined effect from stress stiffening and spin softening affects the eigenfrequencies.
- A Campbell diagram shows the six lowest natural frequencies vs. angular velocity.
- COMSOL Multiphysics and the Structural Mechanics Module are required.

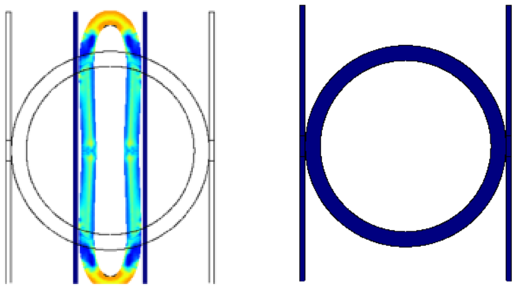


Large Strain Plastic Deformation

- The Nonlinear Structural Materials Module and the Geomechanics Module both feature large strain plastic deformation.
- Note: each of these two modules have COMSOL Multiphysics and the Structural Mechanics Module as prerequisites.



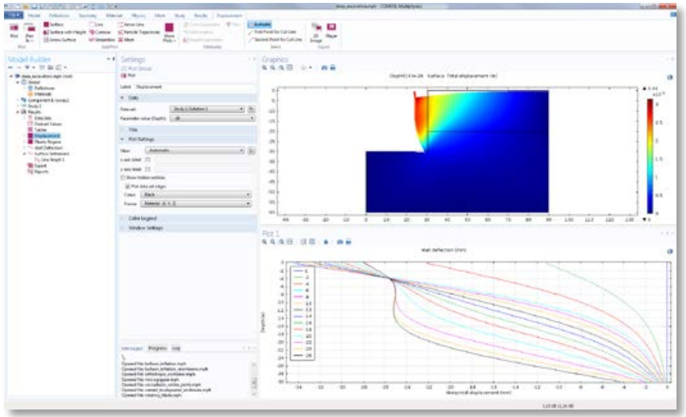
Necking of a metal bar. This example is a classical benchmark for large strain plastic deformation.



Flattening of a pipe with large strain elastoplastic deformation.

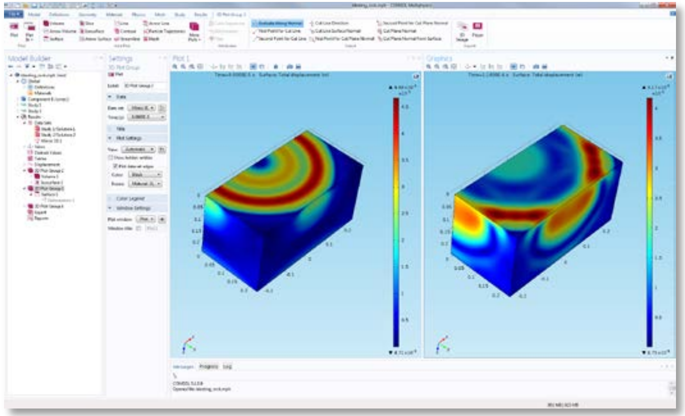
Geomechanics:Deep Excavation

- This example shows how to model a deep excavation. The main application area for this kind of modeling is civil engineering.
- The excavated soil is modeled with boundary loads that are subsequently removed one-by-one to simulate the soil excavation.
- This requires COMSOL Multiphysics with the Structural Mechanics and Geomechanics Modules.



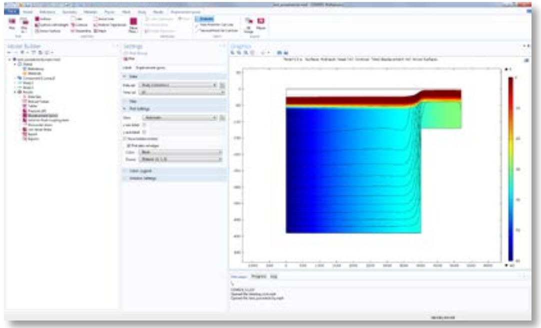
Elastic Waves

- Elastic wave propagation can be modeled both in the frequency domain and time-domain.
- In the frequency domain, outgoing waves are absorbed with perfectly matched layers (PMLs). These are artificial materials that absorb elastic energy using an optimized anisotropic and lossy material model.
- In the time-domain, low-reflecting boundary conditions absorb the outgoing wave energy.
- The example to the right shows a time domain analysis of elastic wave propagation in rock using low-reflecting boundaries.
- This capability is available in the Structural Mechanics Module and the Acoustics Module with the Solid Mechanics interface and in the Acoustics Module with the Elastic Waves interface.

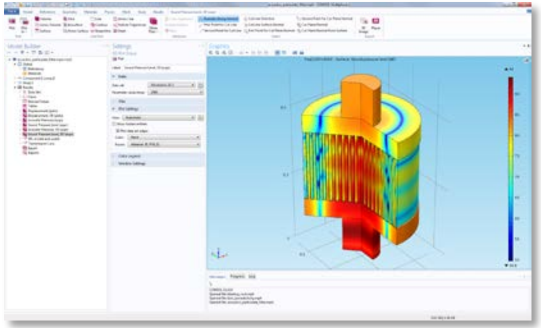


Poroelasticity and Poroelastic Waves

- The Subsurface Flow Module adds functionality for porous media flow and quasi-static Biot poroelasticity.
- The Acoustics Module adds capability for poroelastic waves and allows for combining with elastic waves.



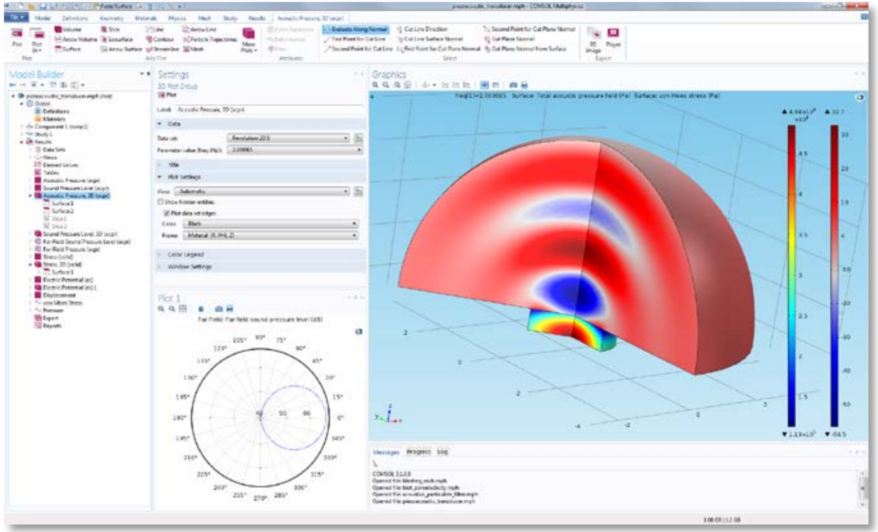
Soil compaction with Biot poroelasticity using the Subsurface Flow Module.



Poroelastic waves in a diesel filter using the Acoustics Module.

Piezo-Acoustic Interaction

- This example shows a simulation of a piezoacoustic transducer.
- The Acoustics Module allows for piezo-acoustic interactions where solid acceleration and acoustic pressure are bidirectionally coupled.



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