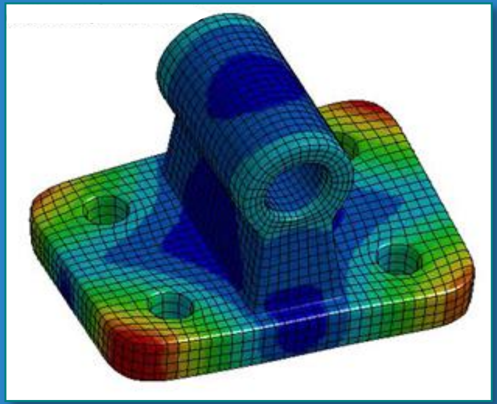
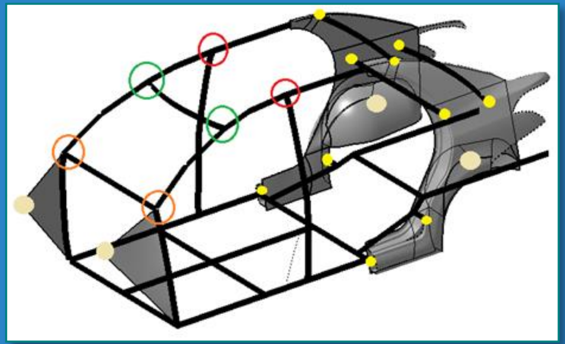
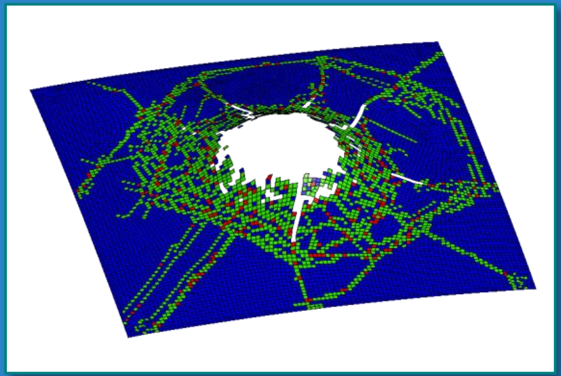
Recent Developments in LS-DYNA
Part II

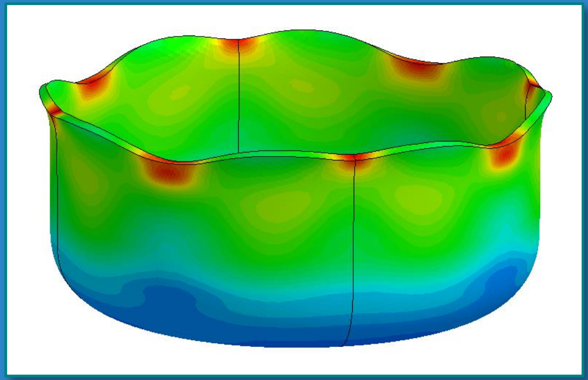
contributions from various developers
(LSTC, DYNAmore, NTNU)

presented by Thomas Borrvall & Tobias Erhart - 16 May 2019 - Koblenz



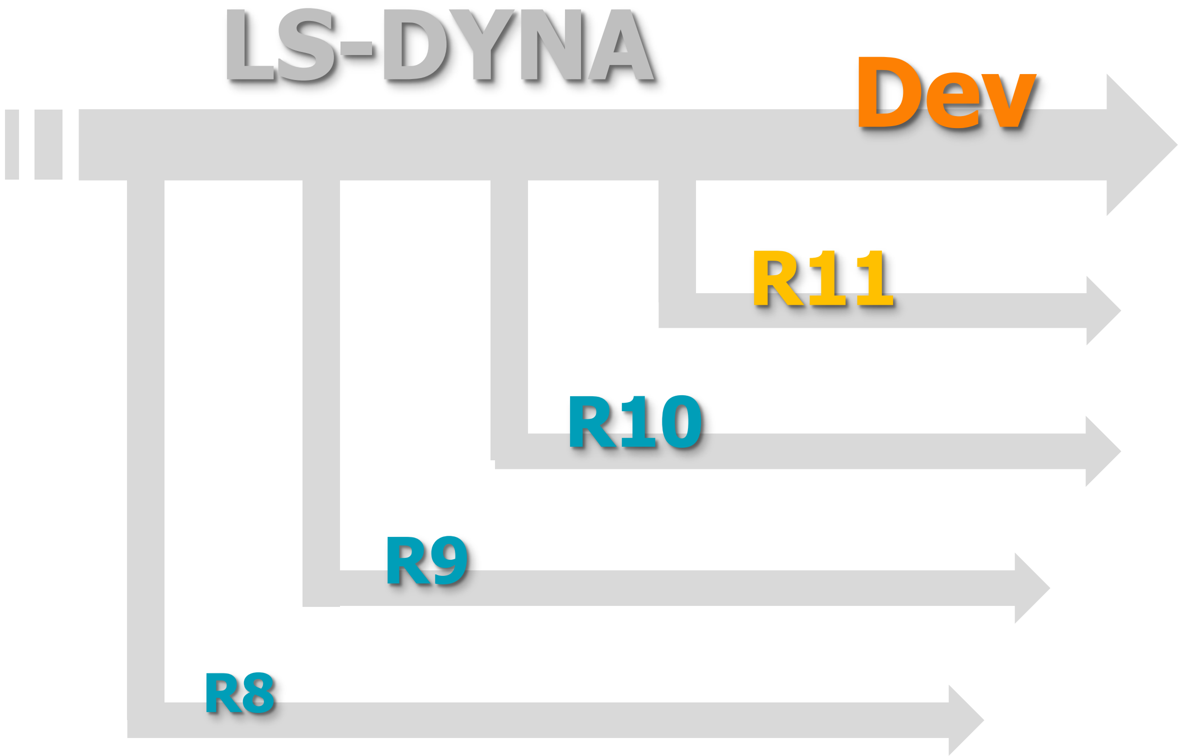






Outline (TB)

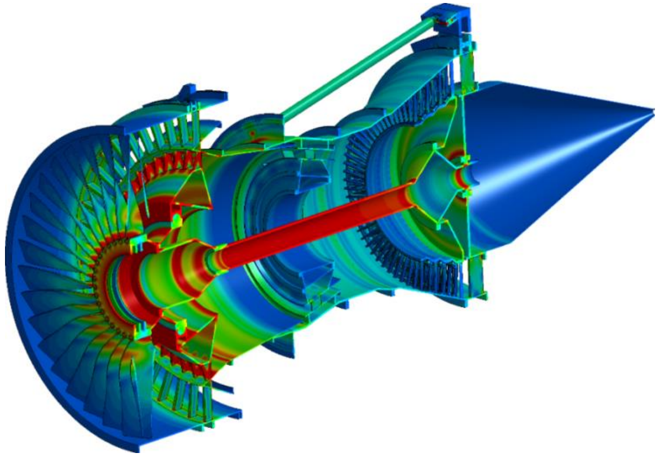
- Linear Implicit
- Nonlinear Implicit
- Mortar Contact
- Materials
- Pressure Tube



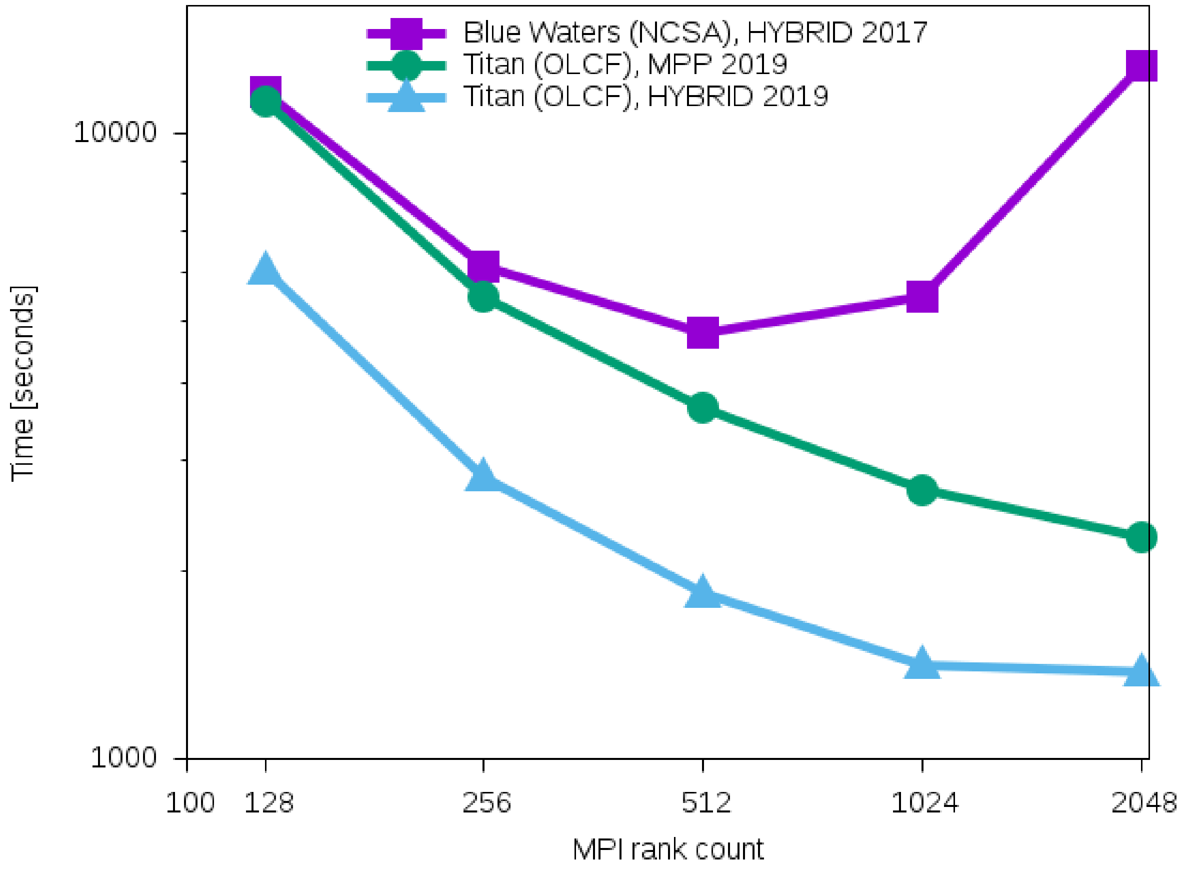
Linear Implicit (1)

Grimes, Ashcraft, Lucas, Rouet, Wiesbecker, Vecharynski

- Rolls Royce representative engine models, an HPC challenge
  - Collaboration with Rolls-Royce, Cray Inc., NCSA and OLCF
  - Improve scalability for implicit static, dynamic and thermal problems (MPP and HYBRID)
  - Focus on ordering, symbolic factorization, numeric factorization and numeric solution
  - Approx. 67 million solid elements, 200 Million degrees of freedom in the largest model



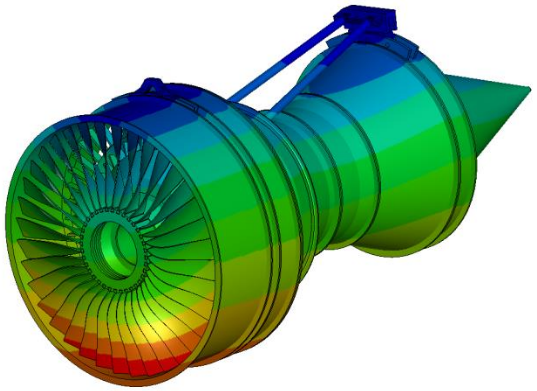
- Scalability
  - Results of the 35 million element model
  - 3 loads steps were calculated
  - Developed a new scalable sparse matrix reordering/partitioning code



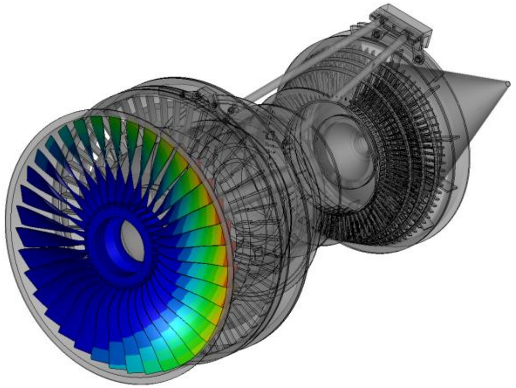
Linear Implicit (2)

Grimes, Ashcraft, Lucas, Rouet, Wiesbecker, Vecharynski, Blankenhorn

- Eigenvalues computation
  - The customer requested 2000 eigenmodes after the model has been spun up to the operational state.
  - It takes 14 implicit time steps to get to the desired state.
  - Block Shift and Invert Lanczos needs all of the current improvements

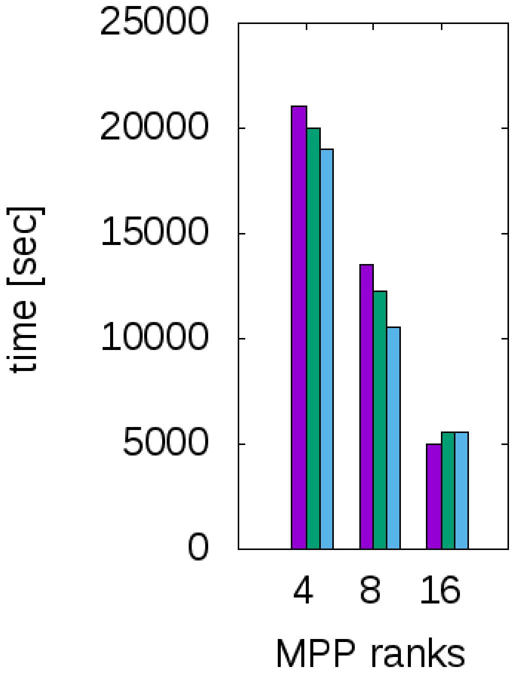


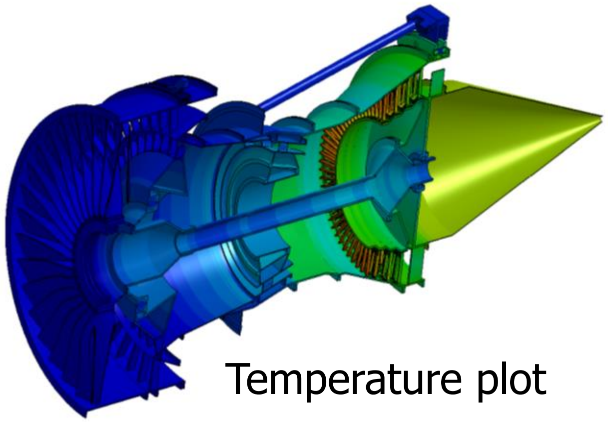
1. eigenmode



2. eigenmode

- Scalability thermal solver
  - The model also requires to solve for the temperature field
  - We investigated using the thermal capabilities in LS-DYNA and the scalability of three equation solvers.

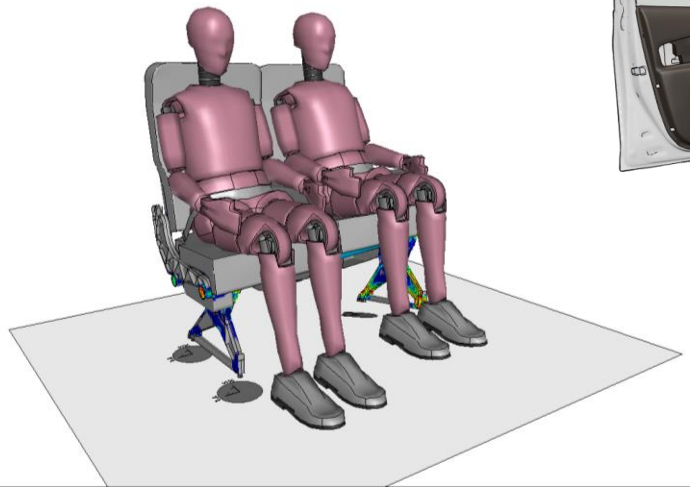


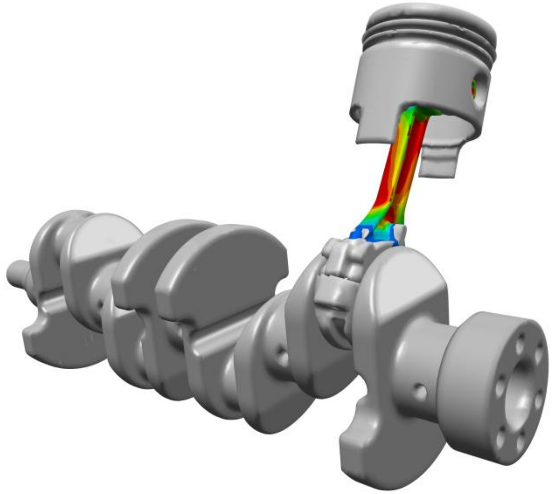


Temperature plot

Nonlinear Implicit

Borrvall, Bengzon, Jonsson, Pathy





Many a little makes a mickle...

- Tangent moduli and stiffness matrices added and improved
  - *MAT_PLASTIC_KINEMATIC, *MAT_SHAPE_MEMORY, *MAT_SOFT_TISSUE, *MAT_SAMP, *AIRBAG, *CONSTRAINED_INTERPOLATION,...
- Account for bending in bolt prestress to preserve structural integrity
  - ISHEAR=2 on *INITIAL_STRESS_SECTION
- Option to output rigid body constraints to bndout
  - SPC2BND=1 on *CONTROL_OUTPUT

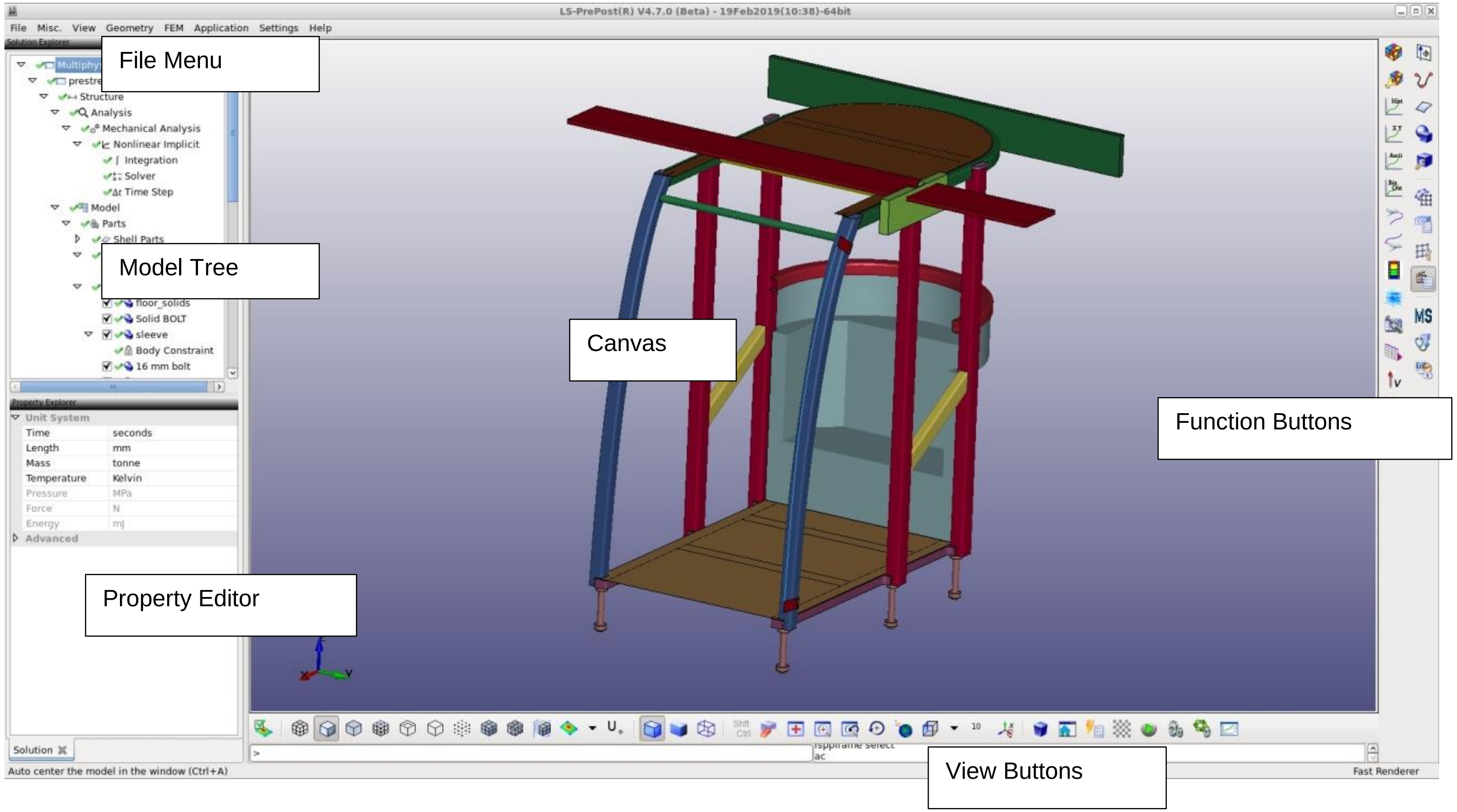
...also for explicit...

- Various options and changes, for user's convenience and hopeful improvement
  - Geometric stiffness by part, Automatic generation of keyoints, Convergence tolerance by curve
  - Rework of residual norm calculations and influence of prescribed motions in convergence checks

Nonlinear Implicit – Solution Explorer

Borrvall, Yu, Chengju, Zhanqun, Jernberg

A complementary pre- and post-processing environment for Nonlinear Implicit...

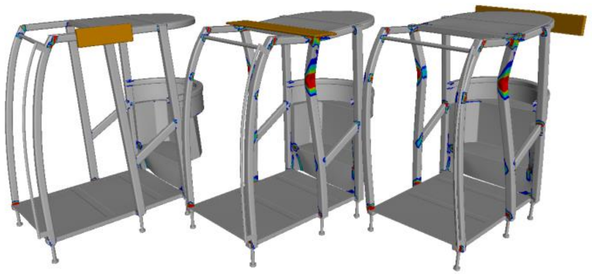


- Simple

  Concepts recognized by FE engineers

- Integrated pre and post

  Output found in convenient places



- Cases

  Complex process simplified

- Errors and Warnings

  Acts as guidance towards a decent input

Mortar Contact - General

- Towards physical behavior and completeness

  Contacts physical surfaces of solids/shells/beams/tshells

  Sliding and tied/tiebreak/weld versions

  User defined options

- Developed with implicit in mind

  Consistent FE treatment of kinematics/kinetics

  Robustness is primary, efficiency secondary

  Explicit serves more as a life wire

- Recent developments include

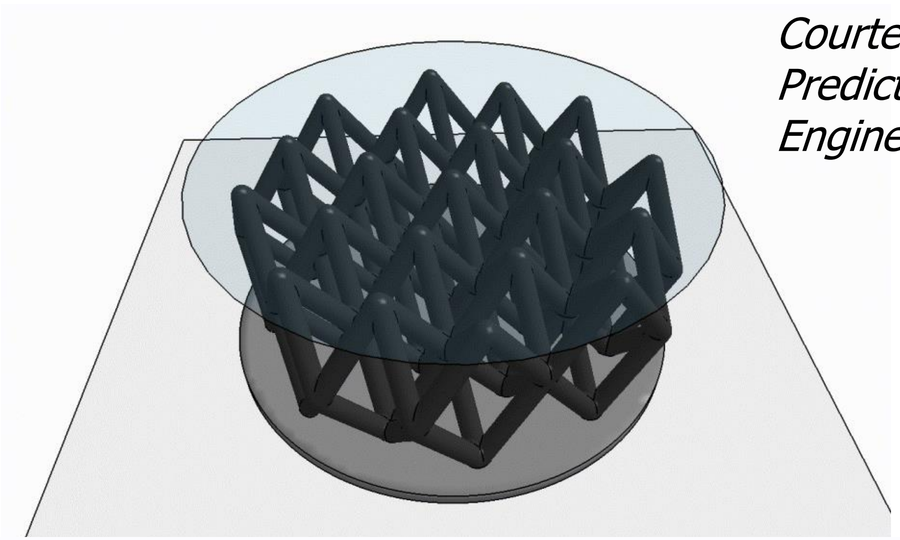
  Expansion of friction models and tied/tiebreak/weld features

  - Tiebreak models supported, including thermal softening

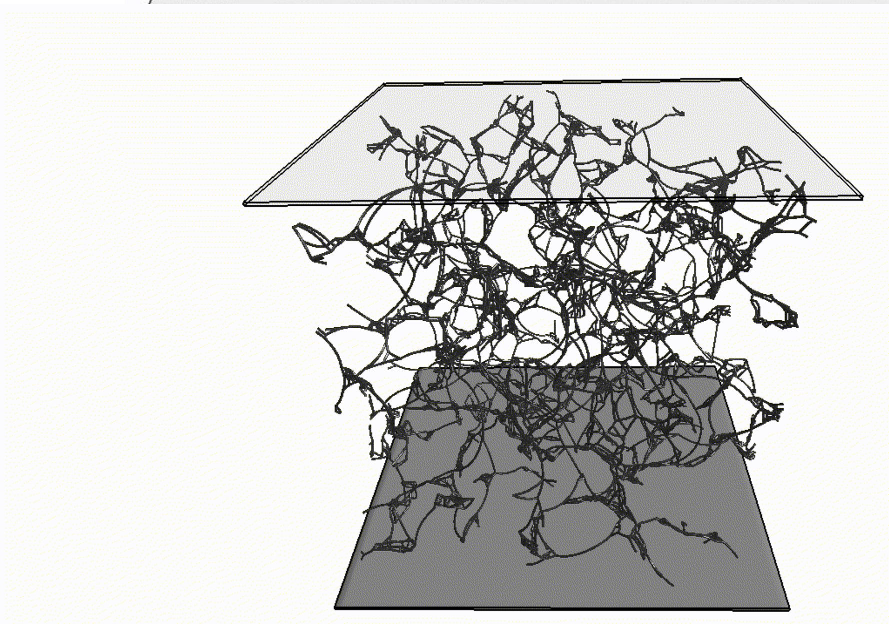
  - History and material history available in weld and friction

  Treatment of initial penetrations, explicit in particular to avoid spurious negative energies

  Efficiency considerations



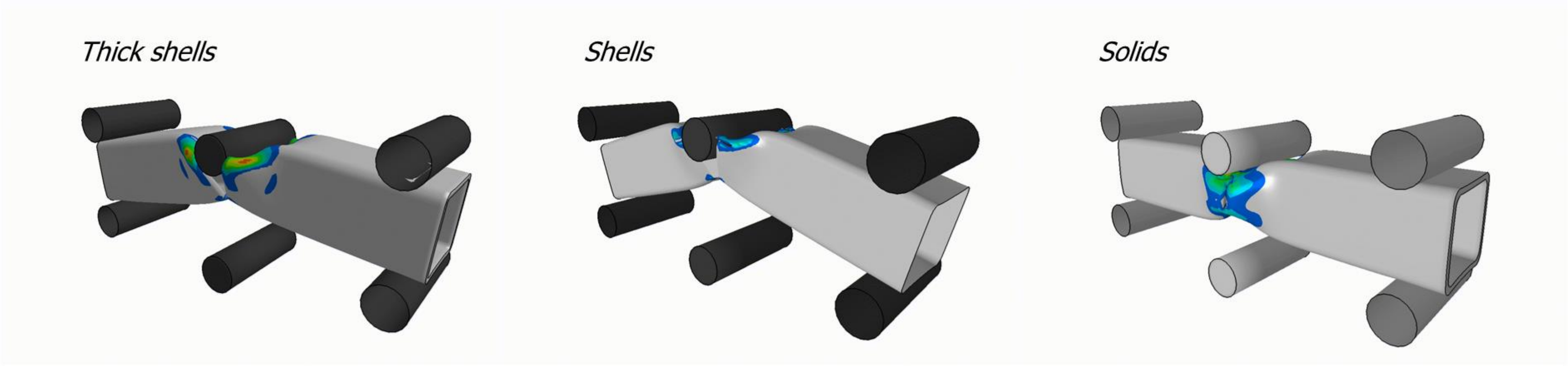
Courtesy of Predictive Engineering



Courtesy of Royal Institute of Technology

Mortar Contact - Erosion

Borrvall, Klöppel



- Exposed segments due to erosion added to the contact

  Works for solids, shells and thick shells
- For shells, edges of eroded elements are exposed
- Supported for automatic surface to surface and single surface

Miscellaneous Material and Element Developments

Borrvall, Bengzon

- *MAT_ADD_INELASTICITY - to amend ”any” material model with an inelasticity feature

  Plasticity (partially supported, incremental models)

  Von Mises isotropic hardening viscoplasticity

  Creep (partially supported, incremental models)

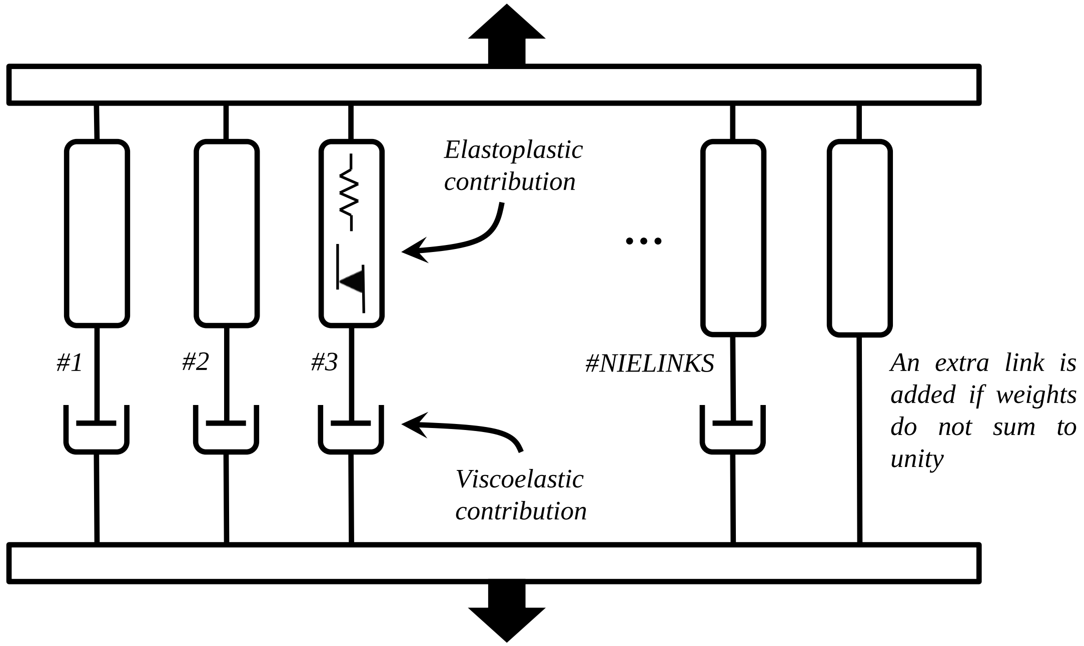
  Norton creep variants

  Viscoelasticity (supported)

  Prony series

  Thermal expansion (not supported)

  Intention is not to replace any material models, but to complement with potentially missing features and accept an incurred cost when doing so



- *DEFINE_MATERIAL_HISTORIES – new outputs

  Effective stress for anisotropic yield surfaces

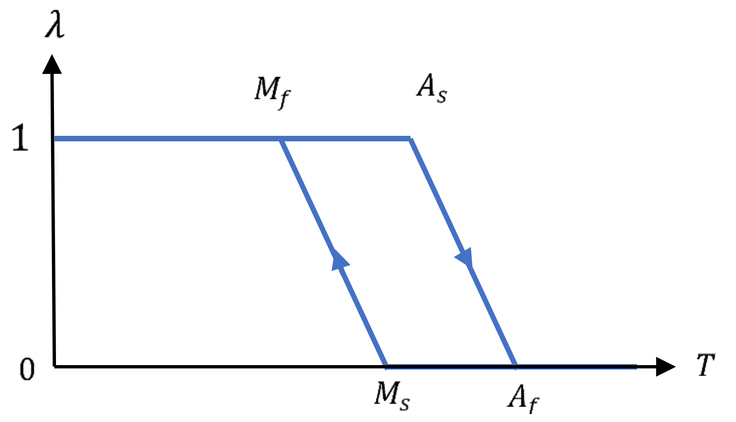
  Instability in *MAT_ADD_EROSION

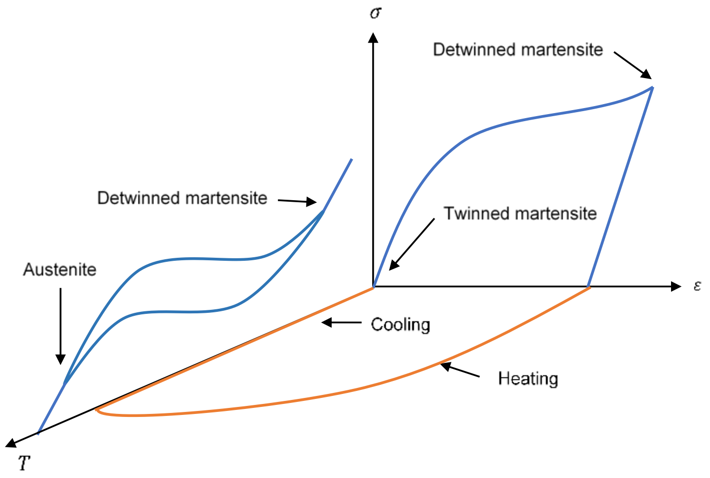
- *MAT_ADD_DAMAGE_DIEM

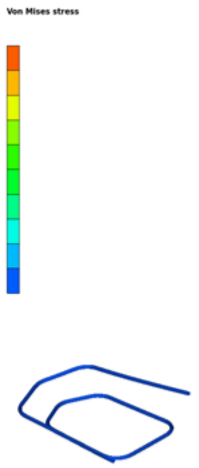
  Supported for thick shells and H-L beams

*MAT_SHAPE_MEMORY_ALLOY

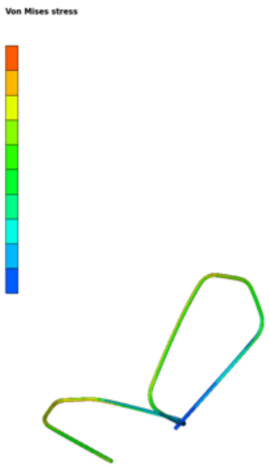
- A new micromechanics-inspired model for shape memory alloys
- Medical applications: self-expanding stents, heart valve frames
- Based on strain split $\varepsilon = \varepsilon_e + \lambda \varepsilon_m$ and minimizing Helmoltz' free energy
- Supports implicit/explicit/thermal for solids



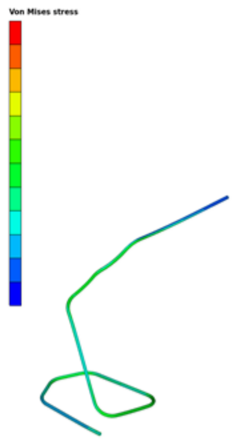




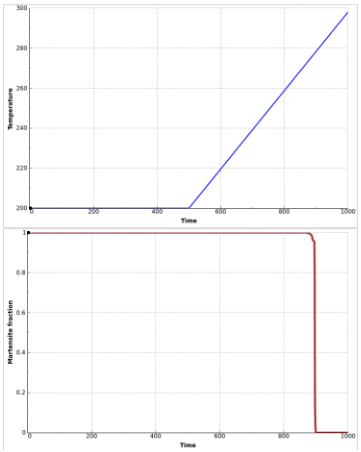
High temperature – austenite phase



Low temperature – martensite phase



Temperature effect



*DEFINE_PRESSURE_TUBE

- Models acoustic pressure waves in a thin long tube
- Embedded in bumber to detect collisions with pedestrians

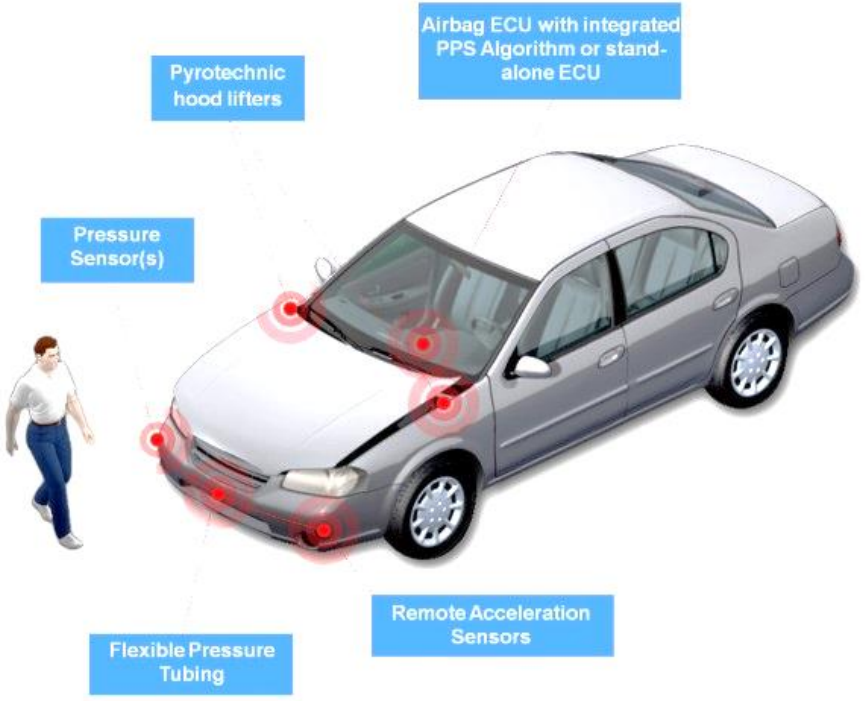
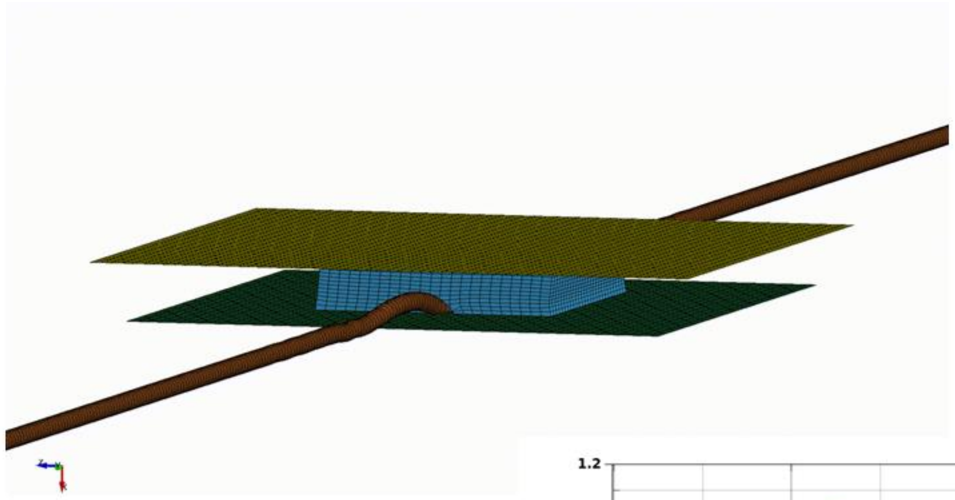
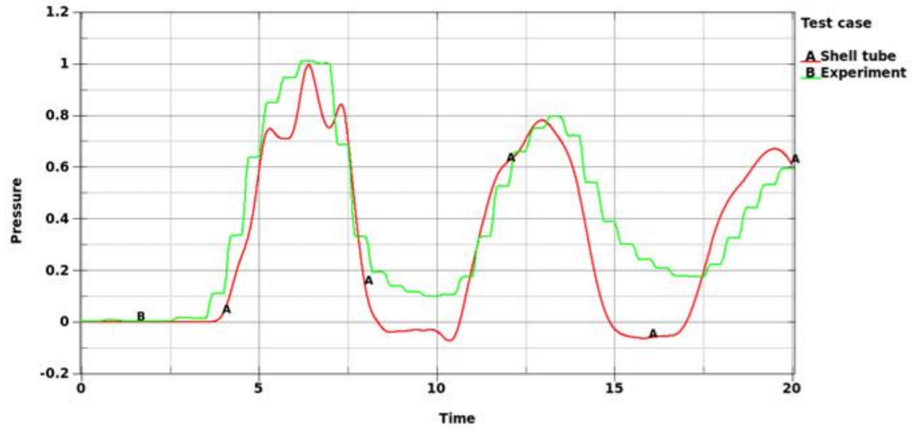


Photo: ZF TRW.





New features

- Automatic generation of shell/solid tubes from beams

  Increased pressure accuracy and tube radial response

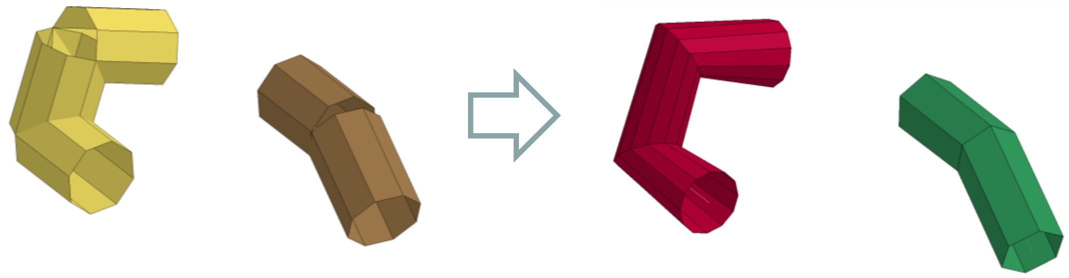
- Automatic generation of shell/solid boundary conditions from beams

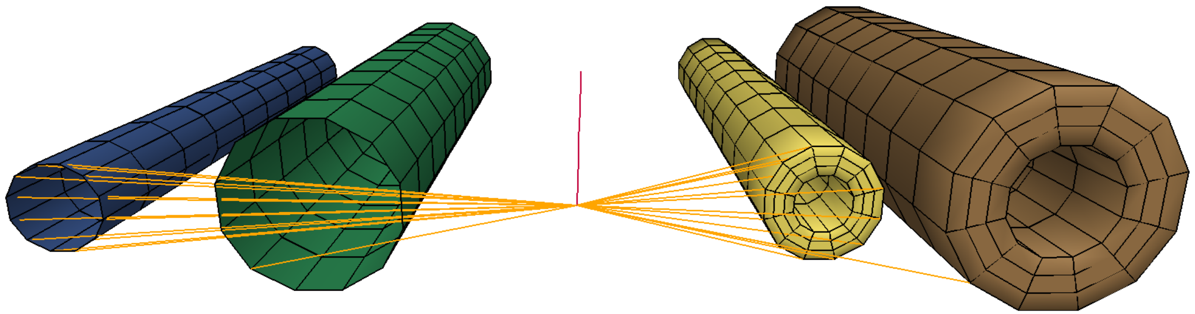
  *BOUNDARY_SPC/*PRESCRIBED_BOUNDARY_MOTION
  /*CONSTRAINED_NODAL_RIGID_BODY
  /*CONSTRAINED_RIGID_NODES/etc.

- New pressure boundary conditions

  Open/closed/non-reflective/partially damped

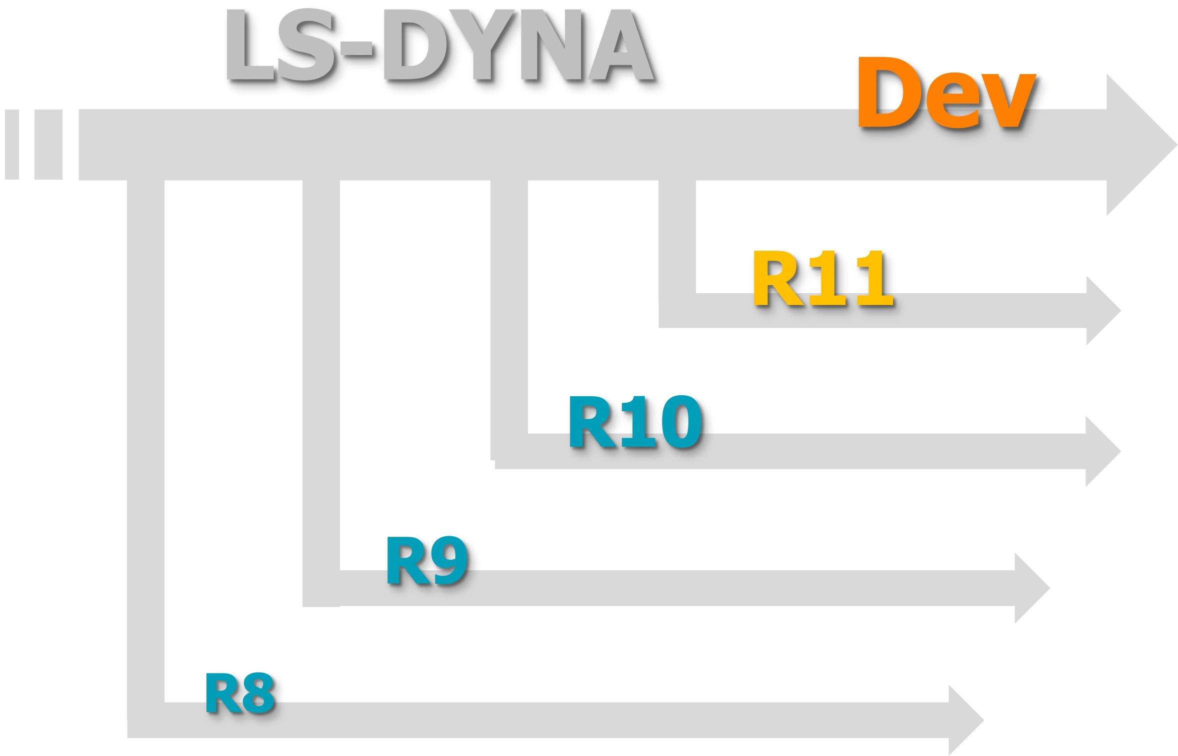
  End cavities and interior boundary conditions





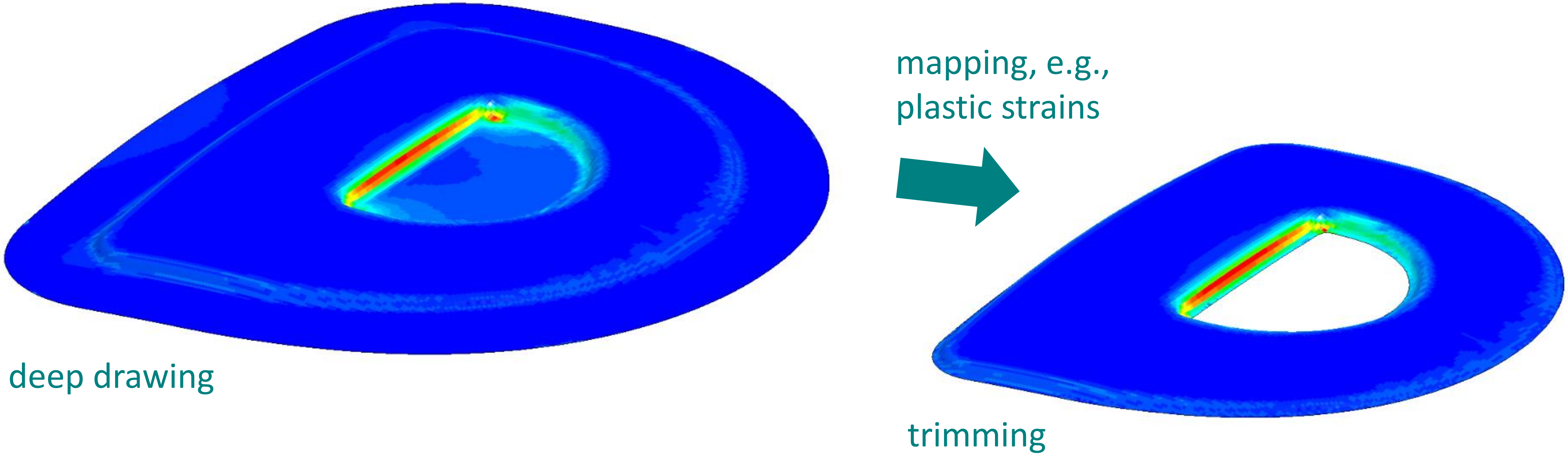
Outline (TE)

- Isogeometric Analysis (IGA)
- Element Technology
- Contact
- Connections
- Material Models
- Forming Applications
- Thermal Analysis
- Structured ALE
- Post-processing



Isogeometric Analysis | Multistage

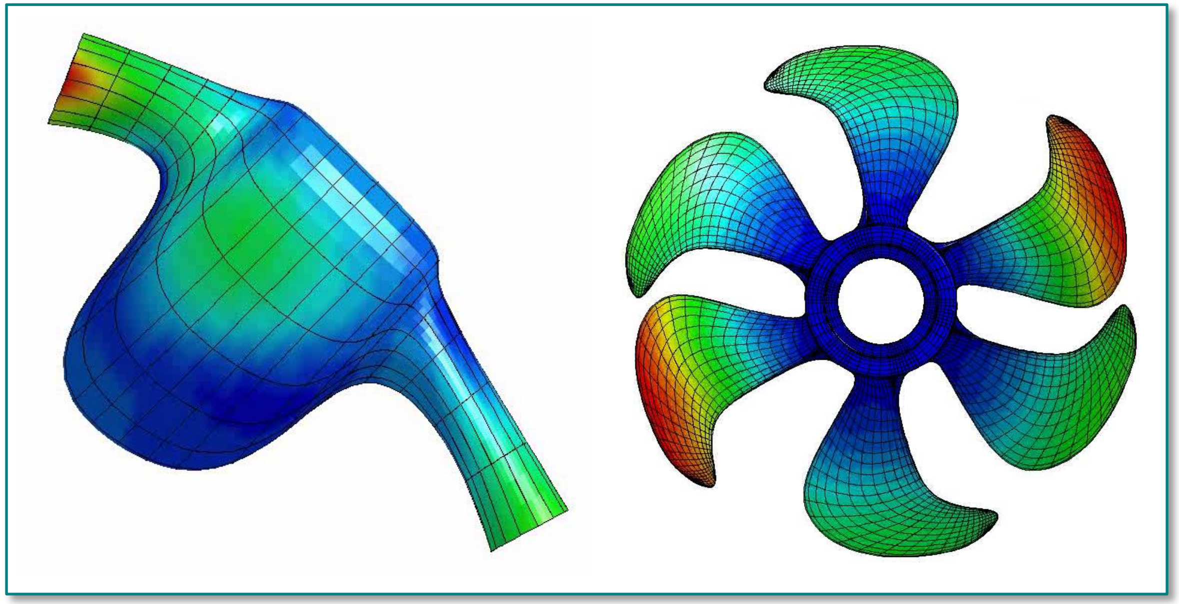
- Enable multistage analysis, e.g., forming processes
  - prepare for next step with *INTERFACE_SPRINGBACK_LSDYNA
  - start from last step with *INITIAL_STRESS/SHELL_NURBS_PATCH
    stresses, strains, thickness change, history variables
  - trimming step with *CONTROL_FORMING_TRIMMING



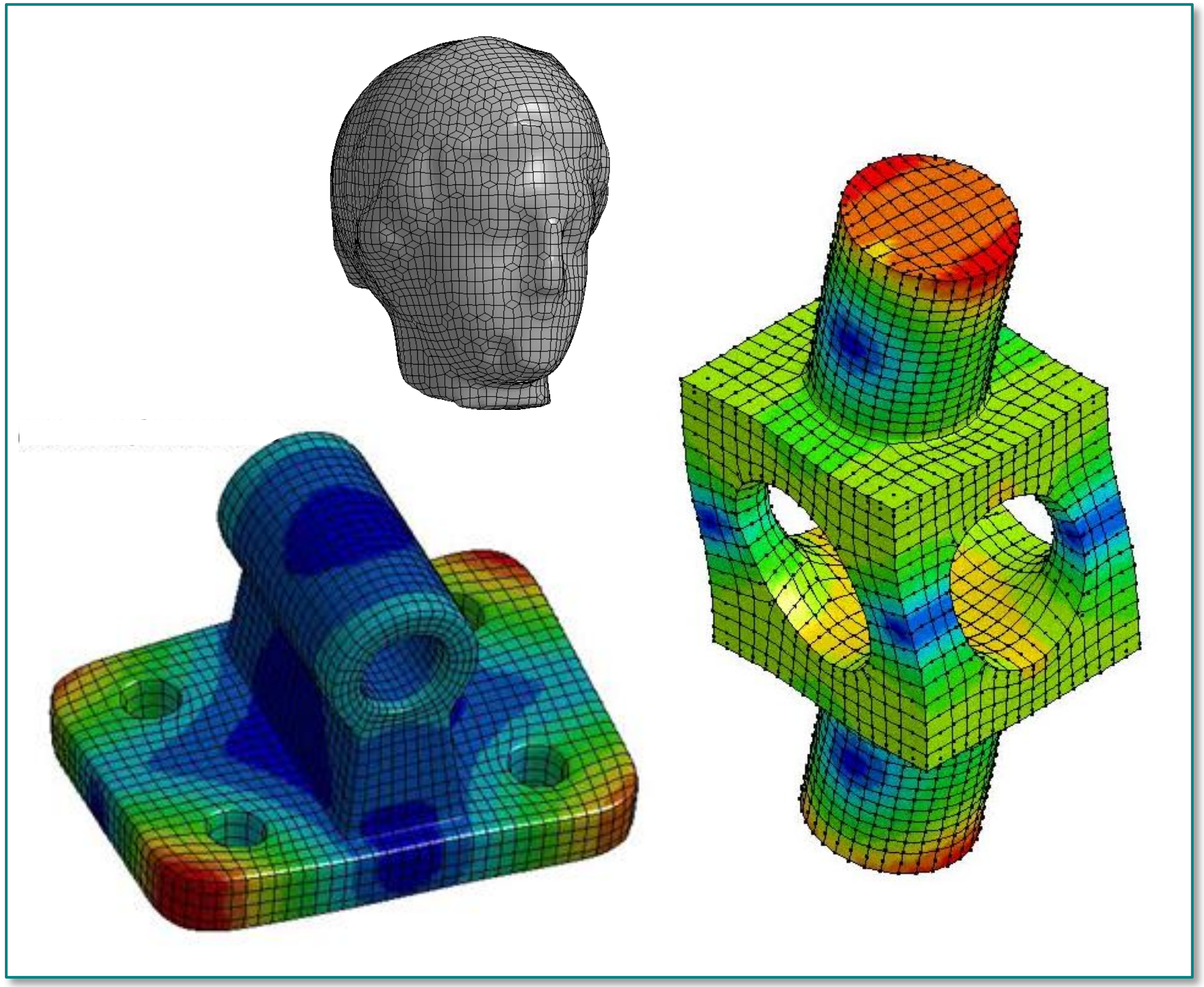
Isogeometric Analysis | Spline Techniques

Benson, Hartmann, Li, Nagy

- Support ”Bezier-Extraction“-Format
  - allows study of different spline technologies
  - shell & solid NURBS



T-splines, U-splines
Coreform LLC · Ford Motor Co., Ltd.



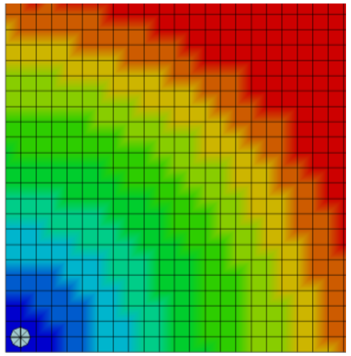
Truncated hierarchical T-spline
Carnegie Mellon University · Honda Motor Co., Ltd.

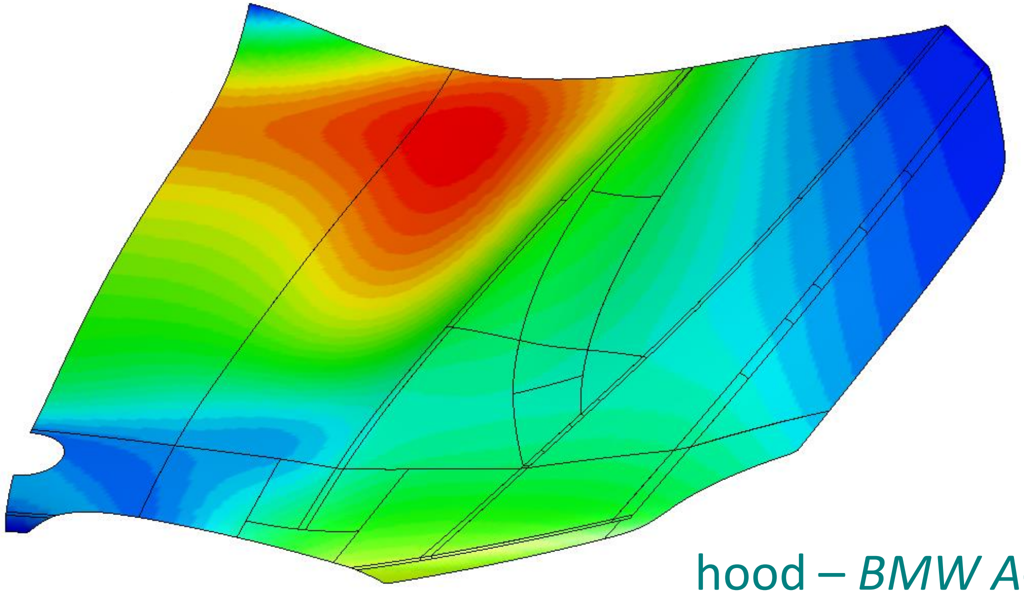
Isogeometric Analysis | Miscellaneous

Benson, Hartmann, Li, Nagy

- Support HAZ-option for NURBS shells
- *LOAD_NURBS_SHELL
  - line loads along curves
  - pressure loads on patch and areas
- *CONTACT_NURBS_TIED_EDGE_TO_EDGE
  - tying of (un-)trimmed NURBS patches
  - penalty formulation
  - explicit & implicit
  - currently only SMP (Dev-Version)
  - … work in progress

spotweld with
heat affected zone



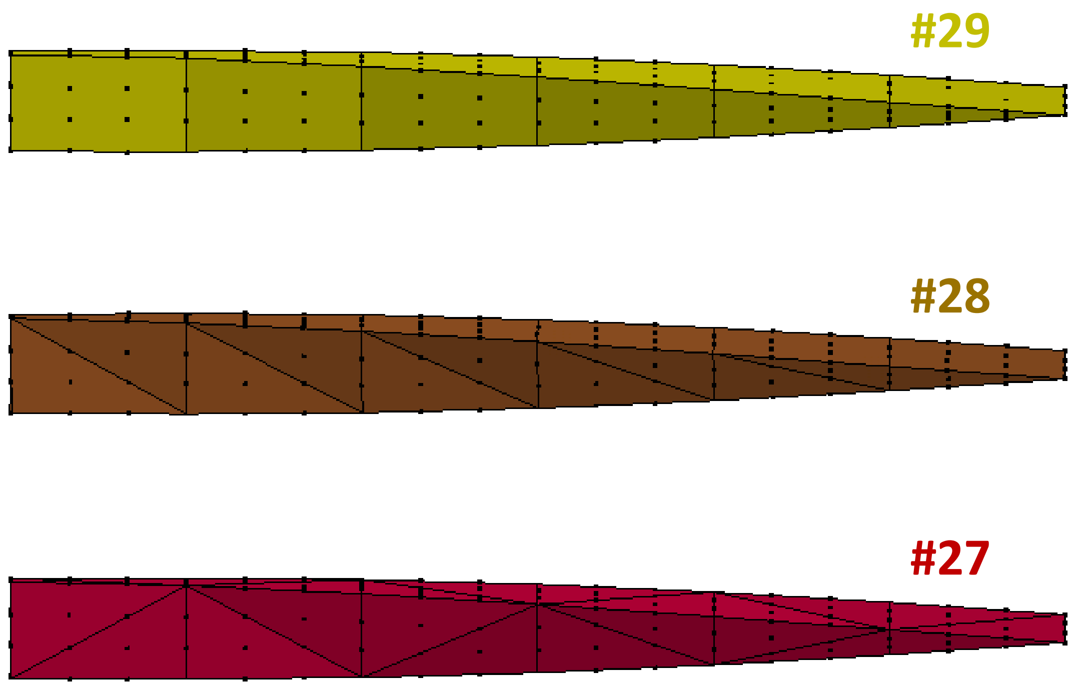


hood – *BMW AG*

Finite Elements | Cubic Solids

Benson, Teng

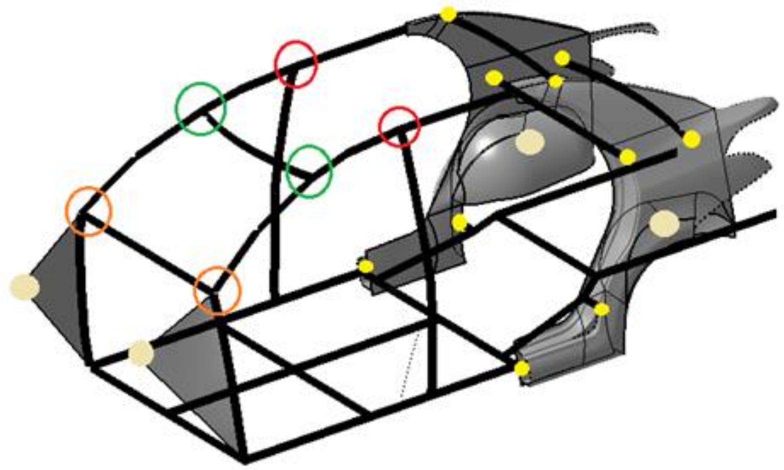
- New element formulations 27, 28, and 29
  - ELFORM=27 is a 20-node tetrahedron
  - ELFORM=28 is a 40-node pentahedron
  - ELFORM=29 is a 64-node hexahedron
- Element input
  - *ELEMENT_SOLID_T20
  - *ELEMENT_SOLID_P40
  - *ELEMENT_SOLID_H64
- Keyword to convert linear to cubic
  - *ELEMENT_SOLID_H8TOH64
- … work in progress

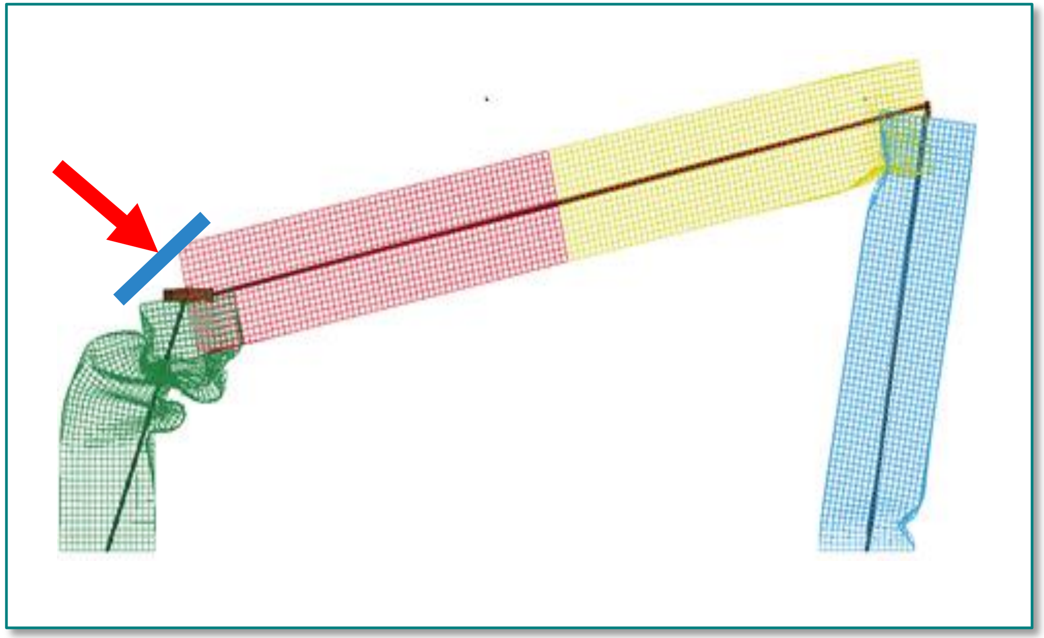


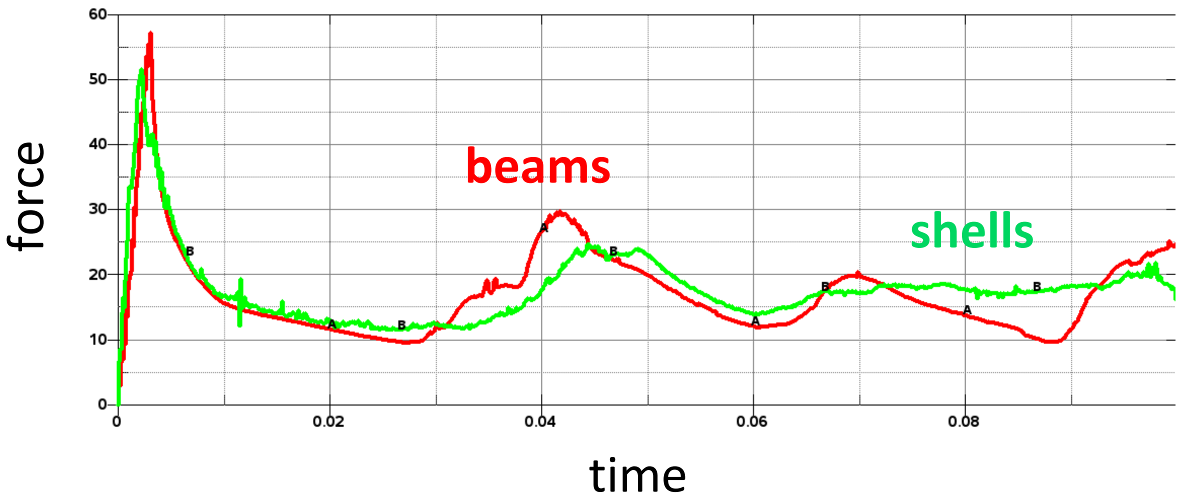
high accuracy in twisted beam problem
with only one solid over the thickness

Elements | Crushable Beam

- CAE models for concept design
- Replace detailed FE model (shells, solids) by simple beam frame structure
- Complex structural behavior embedded in material model: *MAT_119 enhanced (IFLAG=2)



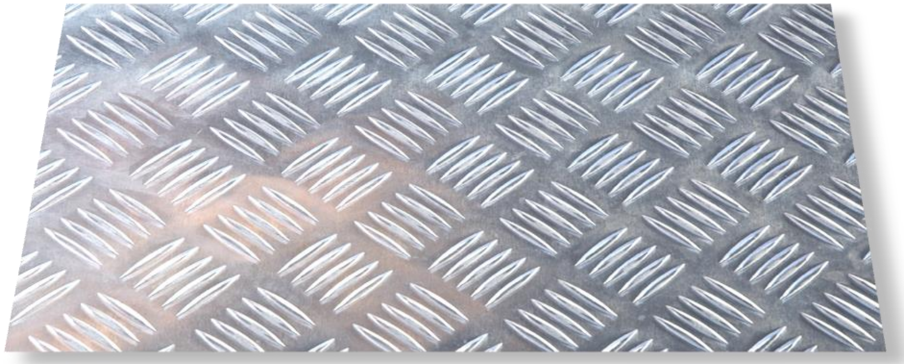




Contact | SOFT=2 (segment based)

- Spotwelds share nodes with shells
  - support SPOTHIN and SWRADF in this case as well
- Different friction coefficient for the inner and outer surface of shell elements
  - new keyword *DEFINE_FRICTION_SCALING

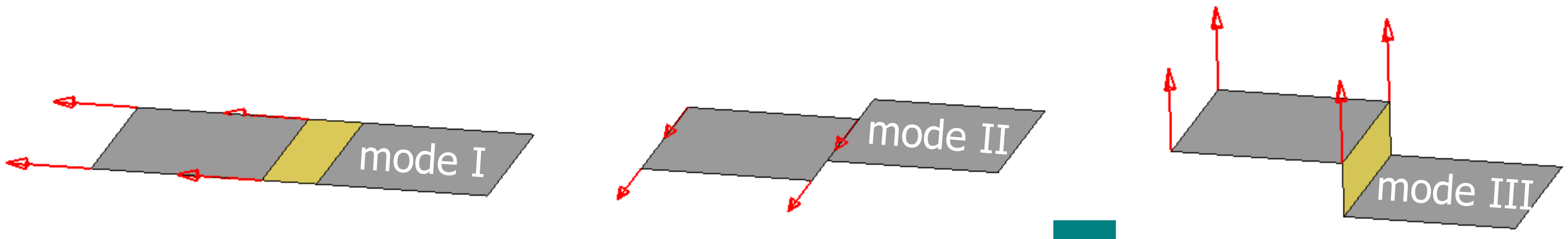
- Frictional torque correction with FTORQ=2
- Support orthotropic friction



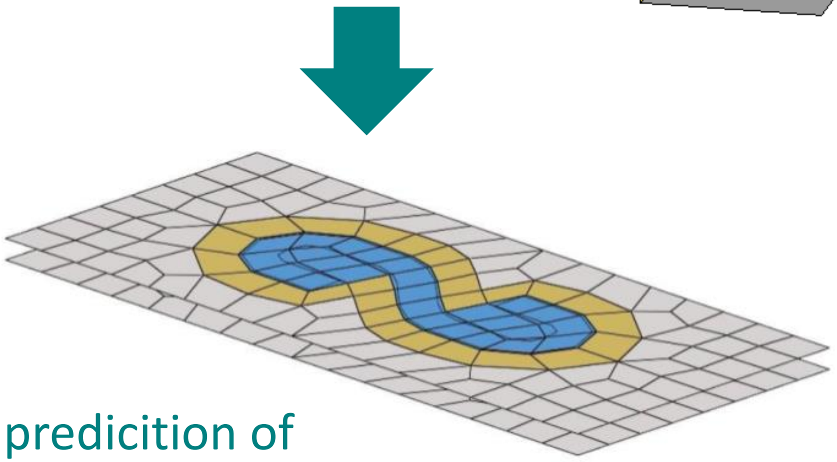
- Support MPP groupable contact

Connections | Linear and planar

Erhart, Karlsson



- New option for cohesive shell elements
  - clear distinction of three separation modes



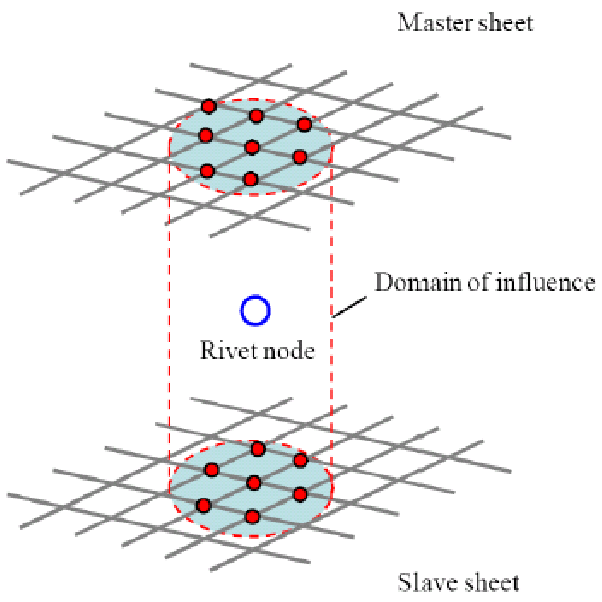
predicition of
laser weld plug out

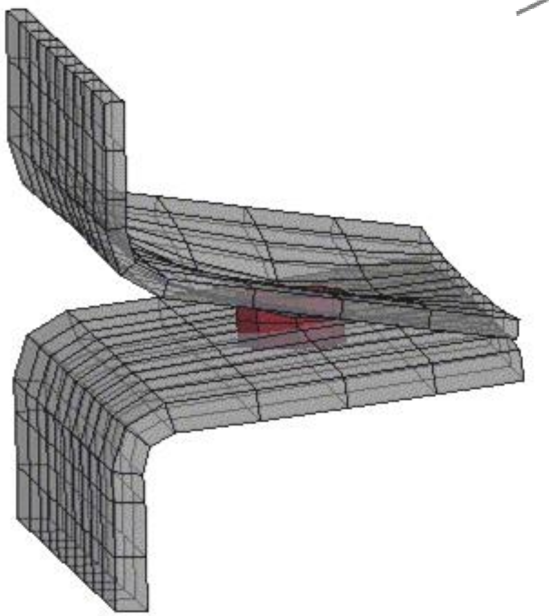
- *MAT_240 now fully supports all three modes
  - new option _3MODES
  - also: thermal properties using new option _THERMAL
- Equivalent tiebreak model to *MAT_240
  - new options 13 and 14
  - allows rate dependence

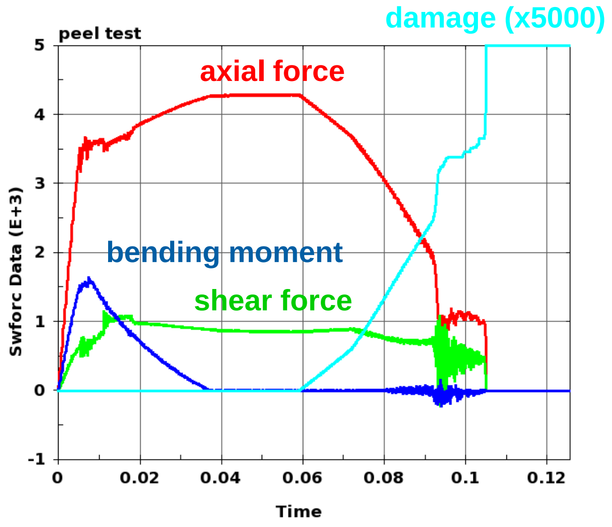
Ford Motor Co., Ltd.

Connections | Point-shaped

- *CONSTRAINED_INTERPOLATION_SPOTWELD ("SPR3")
  - separate input for material data via new *MAT_265 (*MAT_CONSTRAINED_SPR3, also for _SPR2)
  - separate stiffnesses for tension, shear, bending
  - alternative deformation kinematics
  - exponential damage evolution
  - now also works for beam connections
  - "self-connection" of a shell part
  - accuracy improvements
  - new option for visualization beams
  - more output
  - etc.

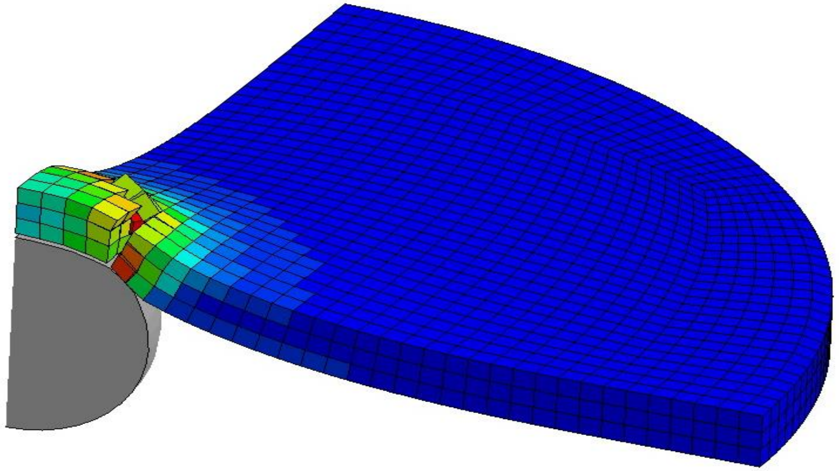






Materials | Failure and Damage

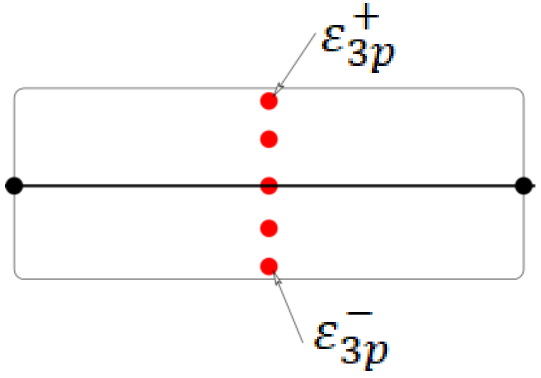
- New keywords *MAT_ADD_DAMAGE_{GISSMO|DIEM}
  - separated from *MAT_ADD_EROSION to make input clearer: pure failure vs. damage
- Now available for more elements/methods
  - beams, higher order solids, SPH, SPG, and *CONSTRAINED_TIED_NODES_FAILURE
- ADD_EROSION: new failure criteria
  - e.g. maximum temperature, minimum step size
- GISSMO: new features
  - e.g. damage limitation, mid-surface treatment, stochastic variation of failure strain, crash front methodology (“SOFT”), temperature dependence



Materials | Regularized Failure Model

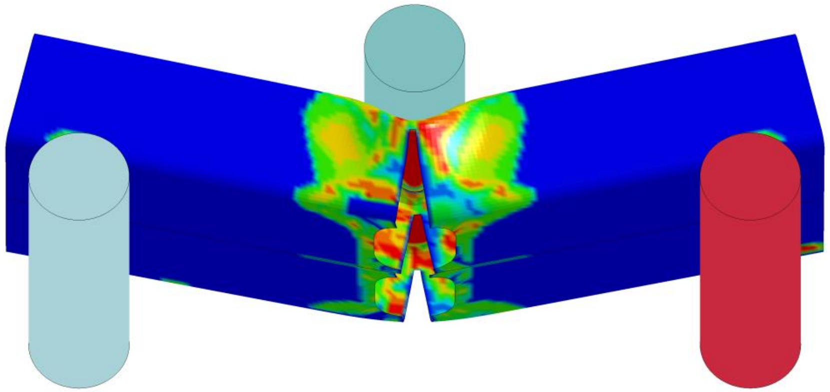
Berstad (NTNU)

- New model *MAT_258: "NON_QUADRATIC_FAILURE"
- Non-quadratic yield surface: Hersey/Hosford
- Voce hardening and J-C type visco-plasticity
- Fracture criterion: Extended Cockcroft-Latham
- Bending-enhanced regularization
  - Fracture parameter W_c depends on characteristic element size, shell thickness, and a bending indicator Ω
  - Better distinction between pure membrane loading and bending

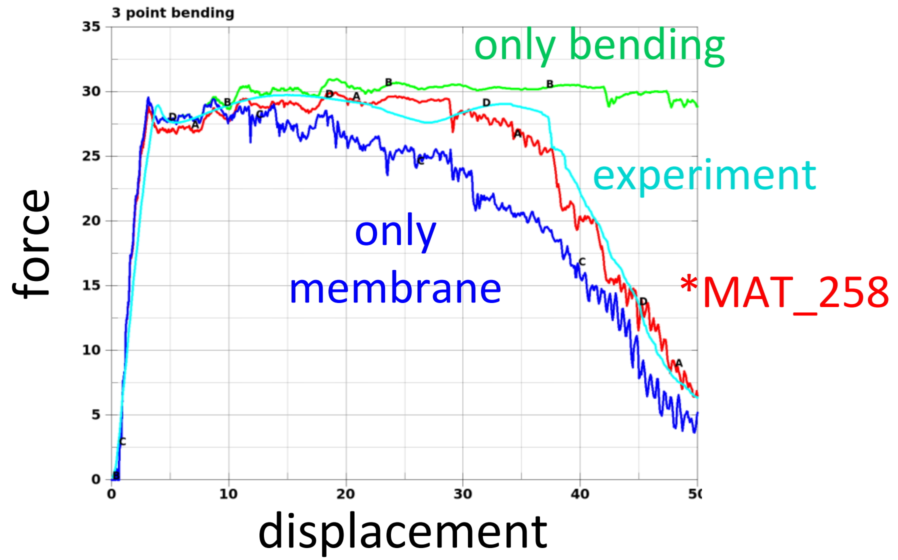


$$W_c = \Omega W_c^b + (1-\Omega) W_c^m$$

$$\Omega = \frac{1}{2} \frac{\left|\varepsilon_{3p}^{+} - \varepsilon_{3p}^{-}\right|}{\max\left(\left|\varepsilon_{3p}^{+}\right|, \left|\varepsilon_{3p}^{-}\right|\right)}$$

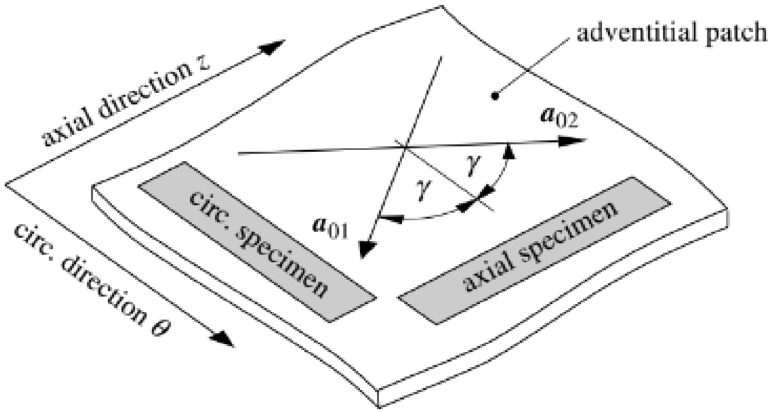


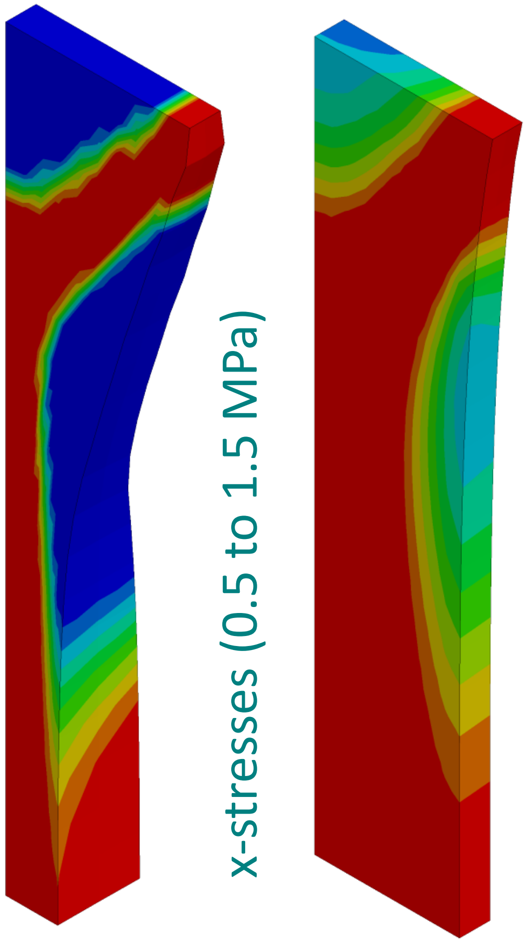
3-point bending of aluminum profile with hole: critical fracture value



Materials | Biological Soft Tissues

- New model *MAT_295: “ANISOTROPIC_HYPERELASTIC”
- Modular material model for e.g. biological soft tissues or fiber-reinforced elastomers featuring:
  - Nearly-incompressible and compressible models
  - Rotationally non-symmetric fiber dispersion
  - Electro-mechanical coupling (muscle activation)
- Example problem - Gasser et al. (2006)
  - Uniaxial tension of an iliac adventitial strip (axial case)
  - Nearly-incompressible formulation
  - Two fiber families with and without fiber dispersion





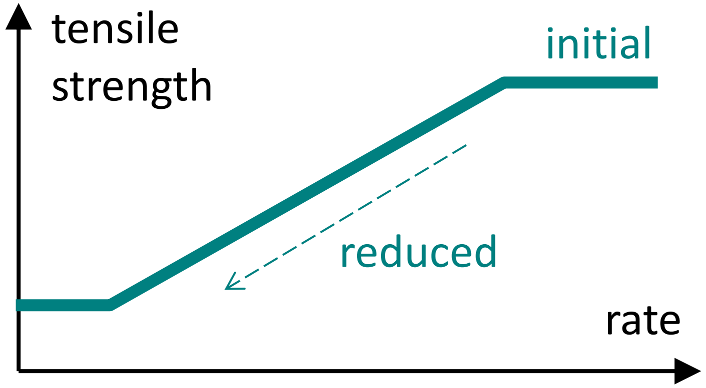
without fiber disp.

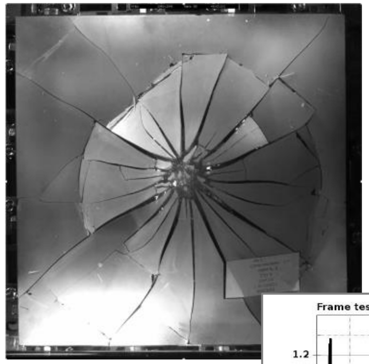
with fiber disp.

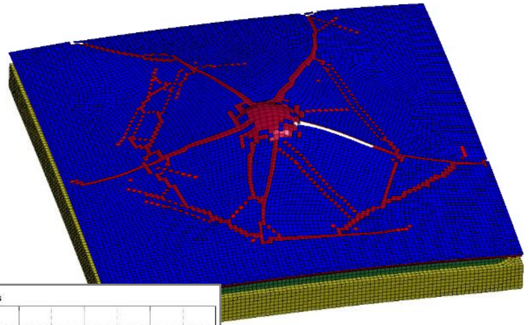
Materials | Glass

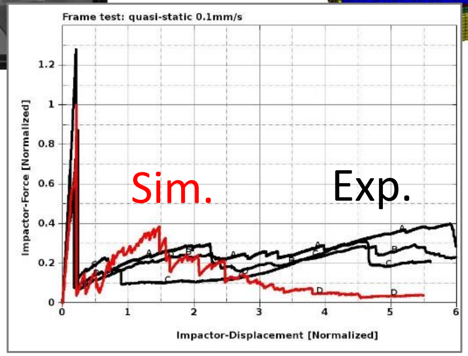
A. Erhart

- Improvements for *MAT_280 (GLASS)
  - nonlocal extension: rate-dependent strength reduction in elements around cracks
  - better agreement with tests (static & dynamic)
  - project with Jaguar Land Rover, Volvo, EMI, and others

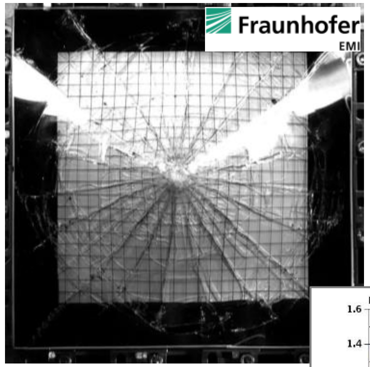


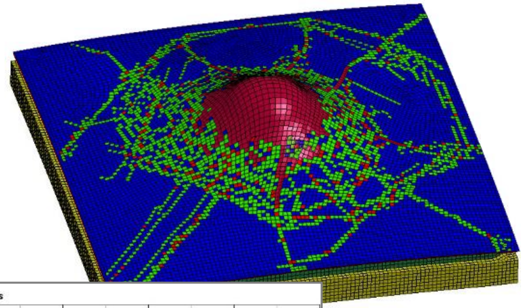


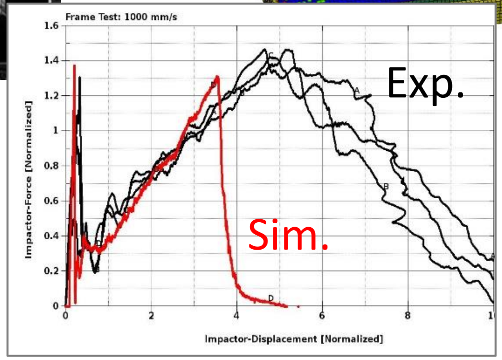




static
(0.1 mm/s)





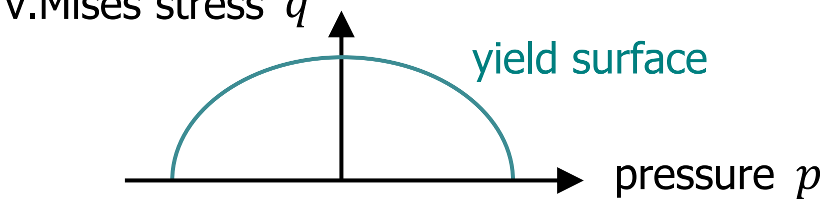


dynamic
(1000 mm/s)

Materials | Foam

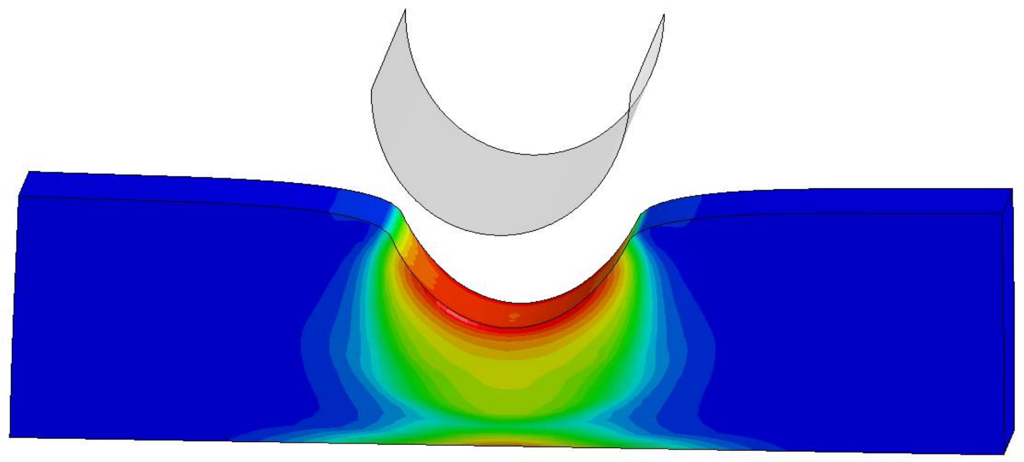
A. Erhart

- *MAT_063 (CRUSHABLE_FOAM) MODEL=1
  - alternative formulation for crushable foams
  - elliptical yield surface (*p*-*q* space)
  - individual elastic and plastic Poisson's ratio
  - rate dependent hardening
  - stabilizing (penalty) stiffness for very high compression

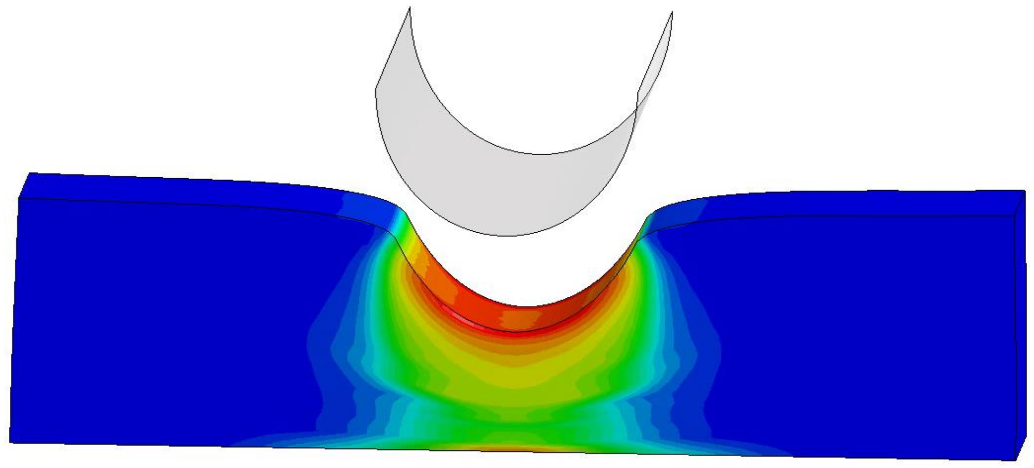


$$F = \sqrt{q^2 + \alpha^2 p^2} - B(\sigma^y) = 0$$

100 mm/s

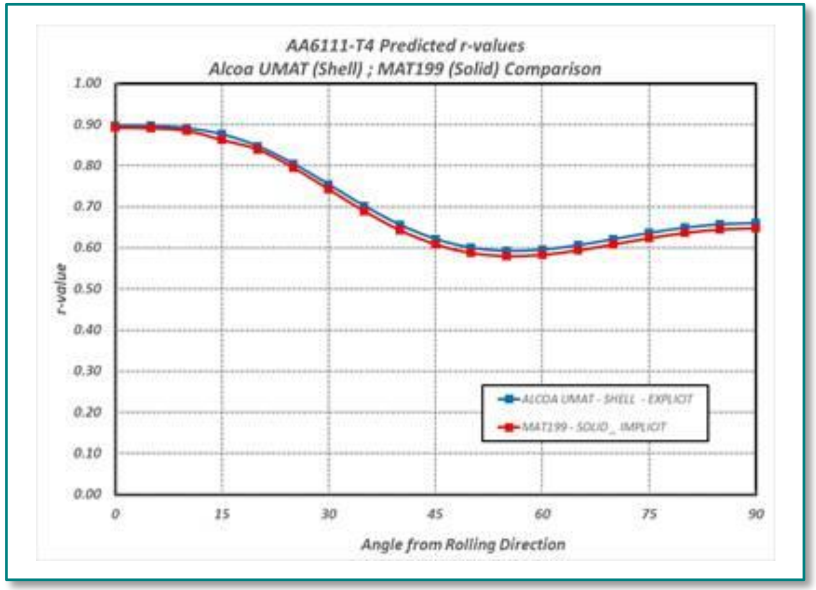


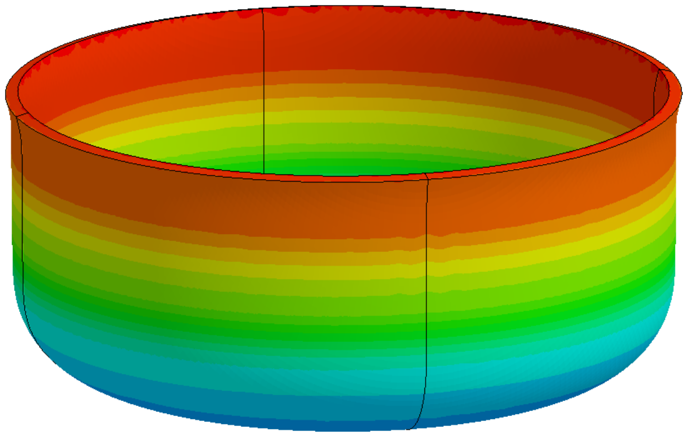
2000 mm/s



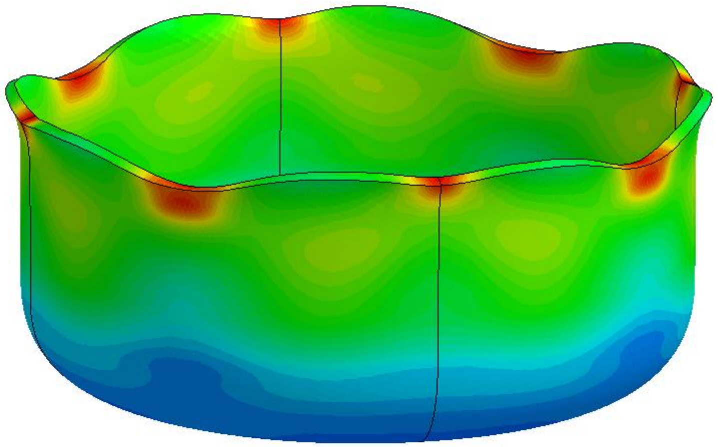
Materials | Anisotropic Yield (1)

- Most forming materials use plane stress assumption
- New 3D material model 199 for solids & explicit analysis
  - keyword *MAT_BARLAT_YLD_2004
  - based on ”Linear transformation-based anisotropic yield functions” by Barlat et al. (2005)
  - uniaxial tests in 0, 15, 30, 45, 60, 75, and 90 degree; biaxial tests; out-of-plane properties
  - capable to predict 6 and 8 ears in cup drawing





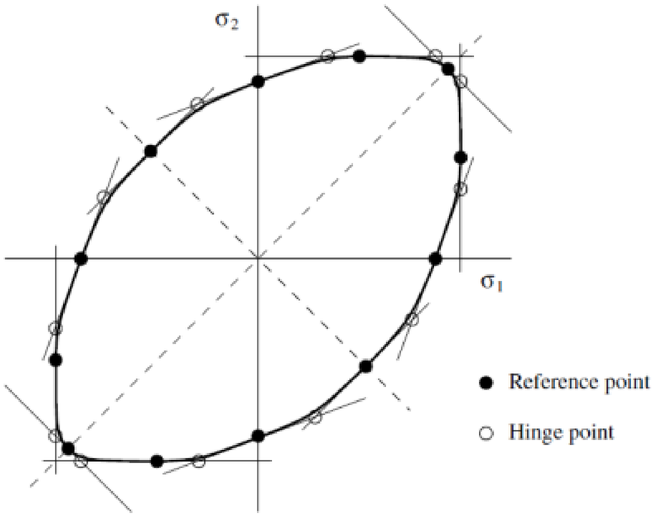
*MAT_024



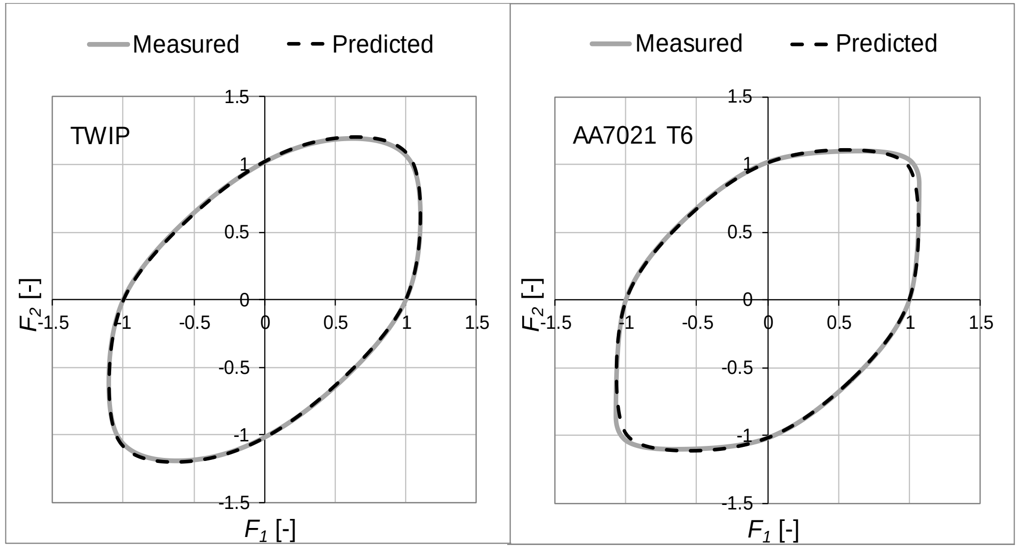
*MAT_199

Materials | Anisotropic Yield (2)

- Vegter material (*MAT_136) allows describing complex yield surfaces with a B-Splines representation
- New option _2017:
  - only data from uniaxial tensile tests (0°,45°,90°) required
  - biaxial, plane strain and shear points are predicted using the method proposed in [2]
  - strain rate effects are accounted for
- Material is able to accurately predict advanced yield loci while only requiring standard tensile test data
- Applicable to steel, stainless steel, and aluminium types



TATA

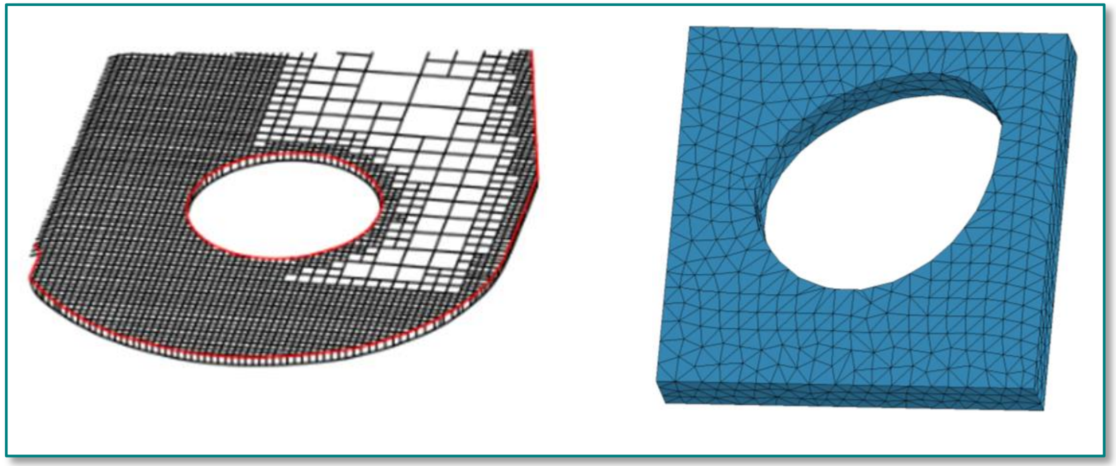


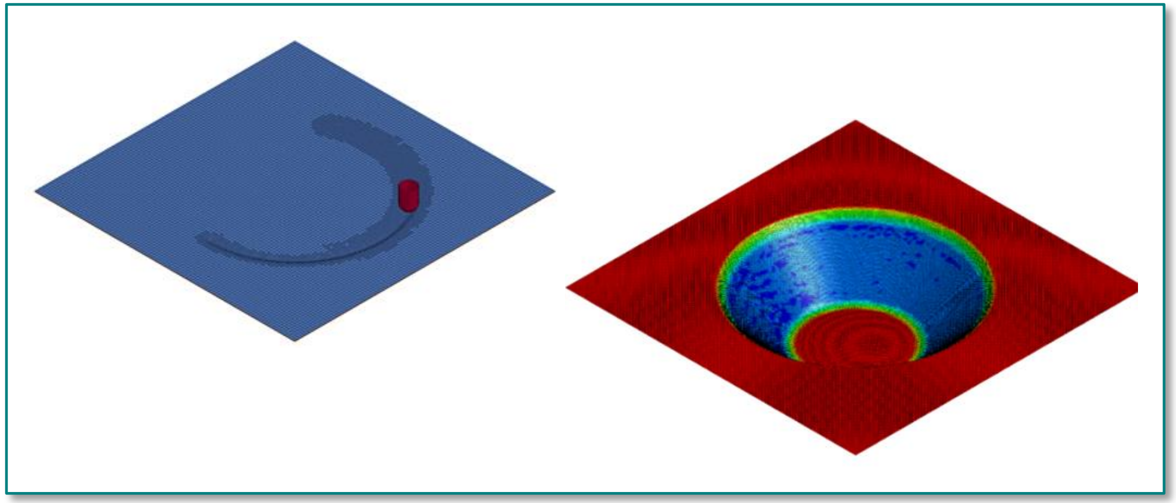
[1] Vegter, Boogaard; 2006 [2] Abspoel et al, 2017

Metal forming (1)

Zhu, Fan, Zheng

- Trimming of shells, solids, tshells, and laminates
  - now available for tetrahedral elements
  - mesh refinement along trimming curves

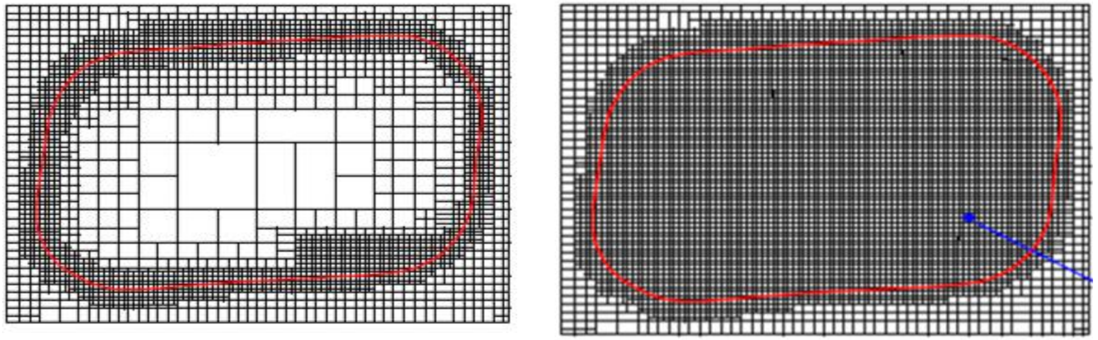




- Mesh fusion (adaptive re-coarsening)
  - completely reworked & extended to MPP
  - uses average information of merged elements
  - with tube adaptivity for incremental forming

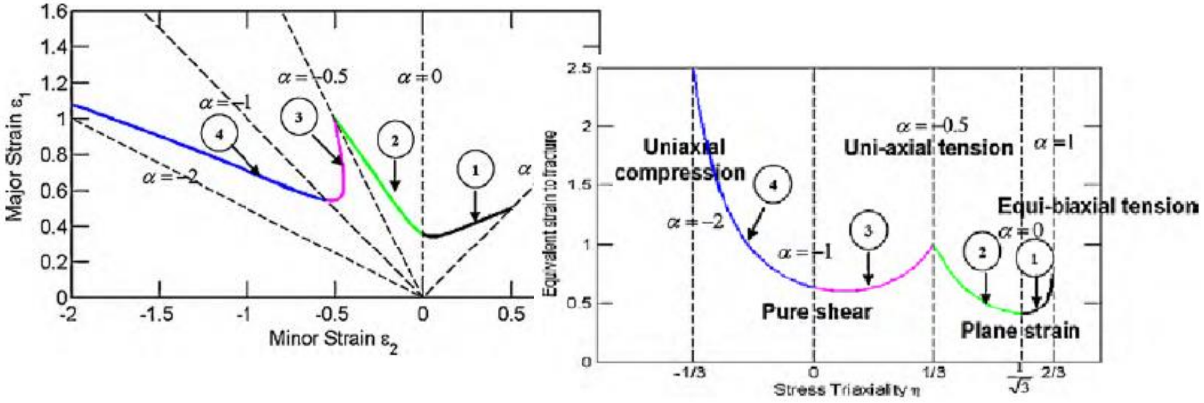
Metal forming (2)

- New mesh refinement options
  - along given curve or inside domain
  - *CONTROL_ADAPTIVE_CURVE: ”ITRIOPT”



- Analytical hardening functions
  - new keyword *DEFINE_CURVE_STRESS
  - automatic creation of stress-strain curves for Swift, Voce, Hockett-Sherby, …
  - or weighted combinations of them

- Automatic conversion FLD to triaxiality curve (and vice versa)
  - *DEFINE_CURVE_TRIAXIAL_LIMIT_FROM_FLD

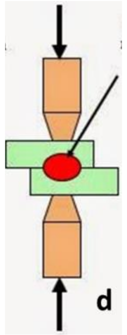


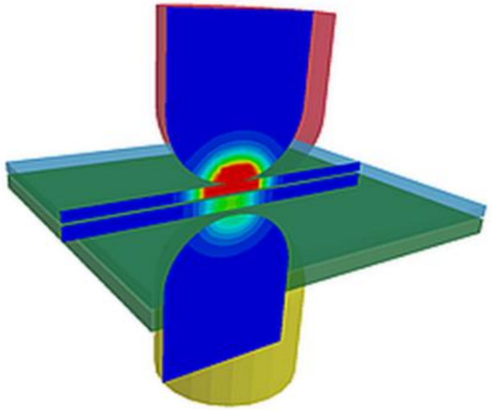
Thermal Analysis | RSW

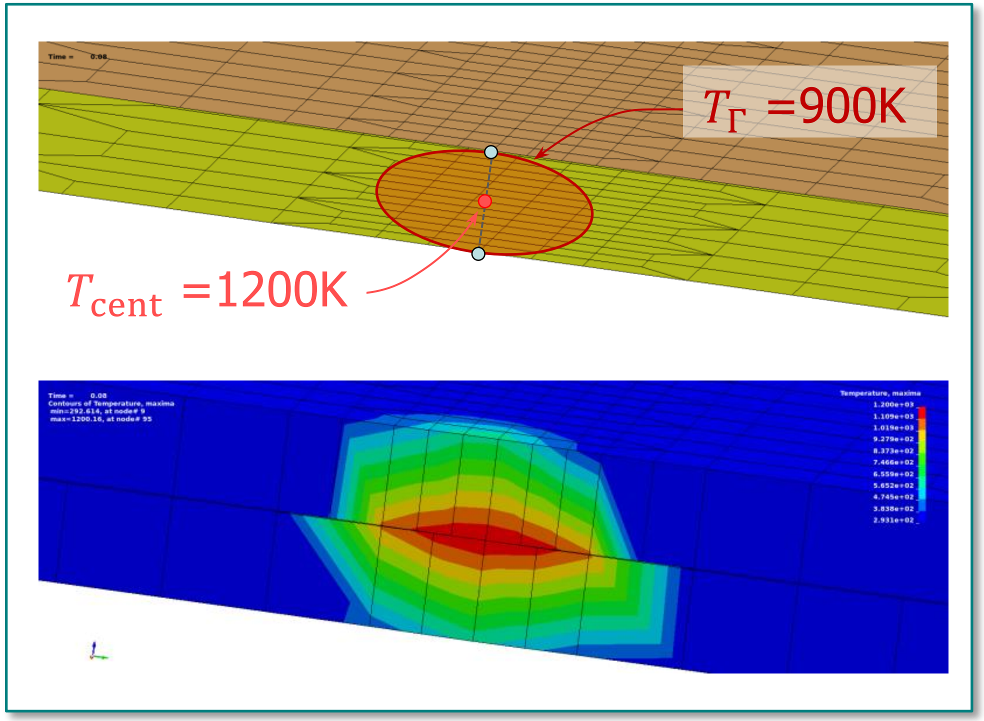
Klöppel

- Resistance Spot Welding
- Keyword *BOUNDARY_TEMPERATURE_RSW
  - simplified and fast boundary conditions
  - direct definition of the temperatures for nodes in the weld nugget
  - temperature preset at the center and the boundary
  - quadratic approximation of the temperature field
  - birth and death time
  - nodes outside the nugget are not affected
  - position is given with respect to two nodes
  - nugget can move over time

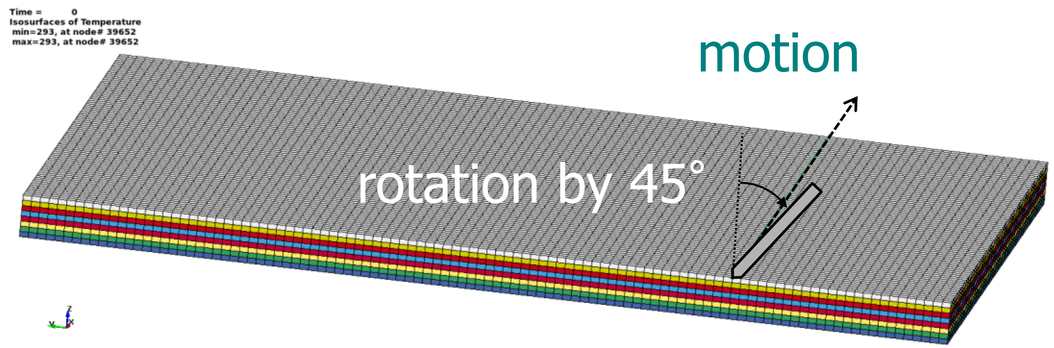
- … applicable to solid and thermal thick shell models

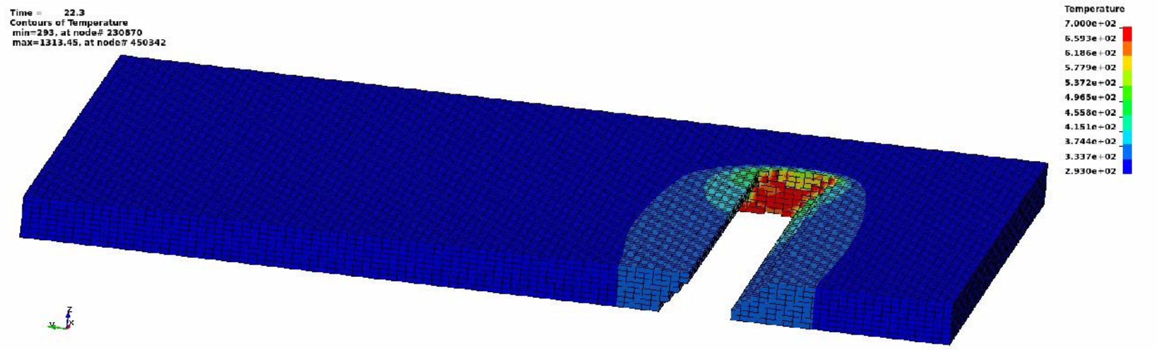






Thermal Analysis | Laser Cutting



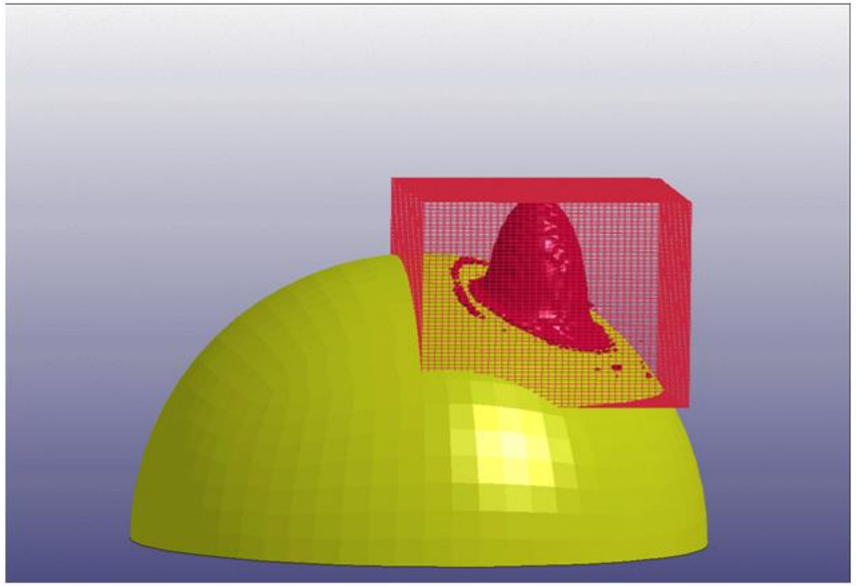


- New keyword *BOUNDARY_FLUX_TRAJECTORY
  - aims to simulate a moving surface heat source, e.g. a laser, on a structure
  - keyword allows for an easy definition of surface fluxes
    motion along a nodal path given by *SET_NODE
    geometry and heat distribution of heat source either from list or given as user-defined function
    tilting of heat source is accounted for
  - after element erosion flux propagates to exposed segments (for laser cutting)

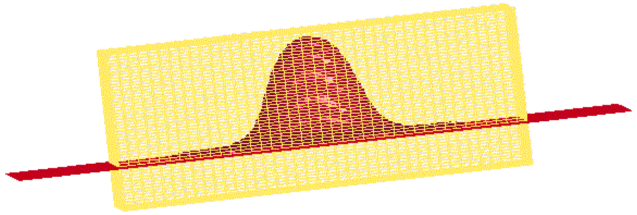
Structured ALE (S-ALE)

Hao Chen

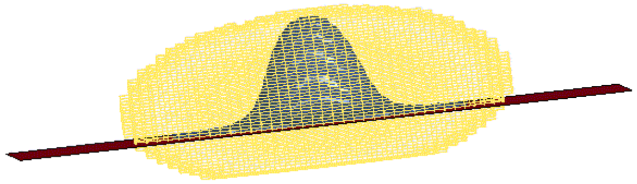
- Mesh tracking
  - new option FOLLOW_GC of *ALE_STRUCTURED_MESH_MOTION moves the ALE mesh with the gravity center of certain AMMG groups



- Mesh trimming
  - *ALE_STRUCTURED_MESH_TRIM trims off unnecessary elements
  - results stay consistent



CPU time reduced by 40 %



Post-processing

- Output of history variables
  - up to now, numbers from 1 to …
    for each material model / element type
  - meaning of variables described in manual
    or on www.dynasupport.com

***MAT_024**	1	effective strain rate (VP=0); effective plastic strain rate (VP=1)
	4	current hardening slope
	5	current yield stress
		Remark: 4 and 5 apply only to non-strain-rate option.

- Names of history variables in databases
  - new option HISNOUT on *CONTROL_OUTPUT
    - HISNOUT=1: info written to d3hsp
    - HISNOUT=2: info written to d3hsp and new file hisnames.xml
  - user-relevant names listed for each PART separately
  - at first, most common materials supported
    1, 3, 4, 15, 24, 34, 36, 54, 58, 63, 81, 82, 83, 89, 98, 100, 106, 120, 123, 138, 169, 183, 187, 188, 224, 240, 252, 254, 270, 277, 280, GISSMO, DIEM
  - can be combined with *DEFINE_MATERIAL_HISTORIES

```
<?xml version='1.0' encoding='UTF-8'?>
<hisnames>
  <part>
    <id>45000</id>
    <title>front rail                          </title>
    <ele_type>shells </ele_type>
    <mat_law>24</mat_law>
    <mat_add>GISSMO</mat_add>
    <extra_history>
      <order_id>1</order_id>
      <label>effective strain rate             </label>
      <order_id>4</order_id>
      <label>hardening slope                   </label>
      <order_id>5</order_id>
      <label>yield stress                      </label>
      <order_id>6</order_id>
      <label>damage                            </label>
      ...
    </extra_history>
  </part>
  . . .
```

Summary

Our ultimate goal for the past two decades is the development of one highly scalable software, LS-DYNA, for large scale, multi-physics, full model, linear and nonlinear, static and transient, simulations in the engineering design process.

Only one model is needed and created

Multi-Physics and Multi-Stage

Structure + Fluid + EM + Heat Transfer

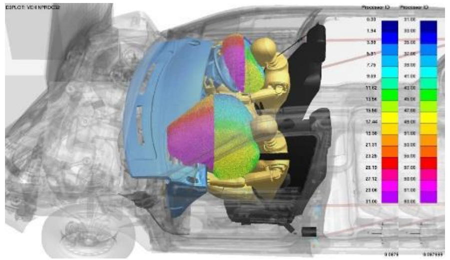
Implicit + Explicit ….

Multi-Scale

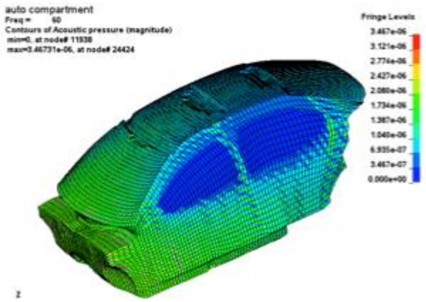
Failure predictions, i.e., spot welds

Multi-Formulations

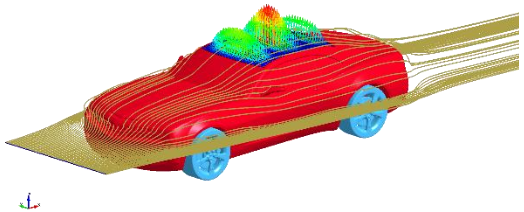
Linear + Non-Linear + Peridynamics + …



Crash



NVH



Structure + Fluid

LSTC | Future

New features and algorithms are continuously implemented to handle new challenges and applications

Electromagnetics,

Acoustics,

Compressible and incompressible fluids

Isogeometric shell & solid elements, isogeometric contact algorithms

Discrete elements

Meshless methods SPH, SPG, and EFGElement

Peridynamics

Simulation based airbag folding and THUMS dummy positioning

Control systems and links to 3rd party control systems software

Composite material manufacturing

Battery response in crashworthiness simulations

Sparse solver developments for scalability to huge # of cores

Multi-scale capabilities

LSTC
Livermore Software Technology Corp.

DYNA MORE

Thank you!