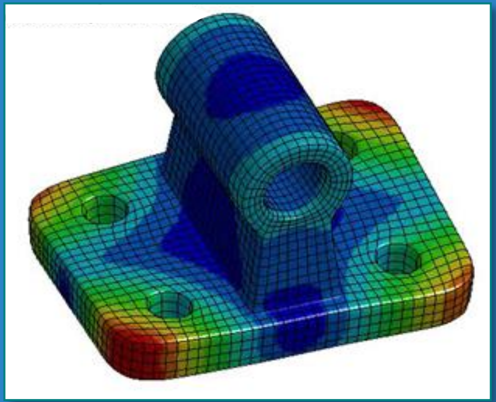
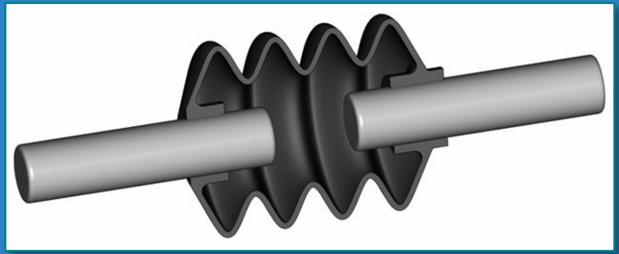
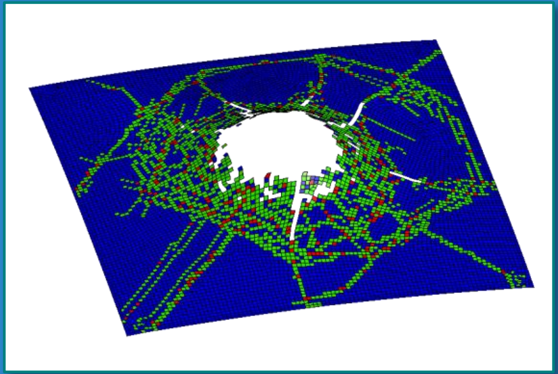
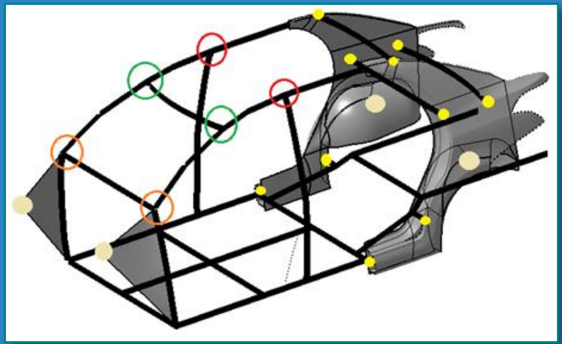
Structural Mechanics & Crash Applications

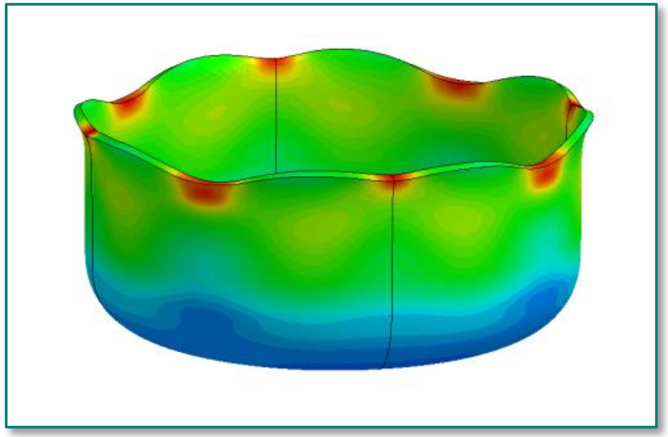
contributions from various developers
(LSTC, DYNAmore, Arup, NTNU)

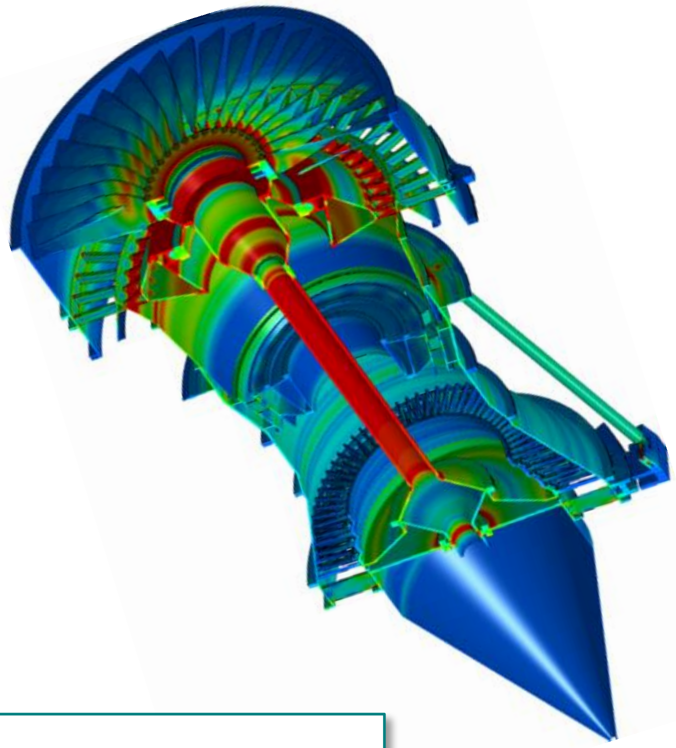
presented by Tobias Erhart

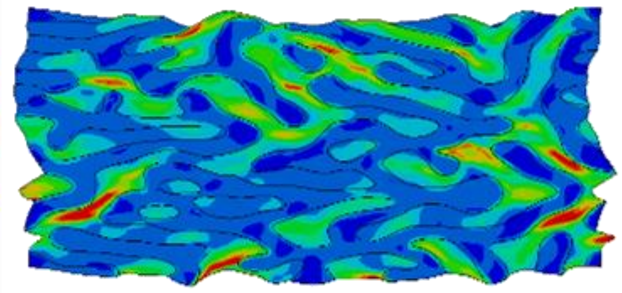





Outline

- Isogeometric Analysis (IGA)
- Linear & Nonlinear Implicit
- Contact
- Element Technology
- Material Models
- Forming Applications
- Thermal Analysis
- Civil Engineering Topics
- Multi-Scale Mechanics

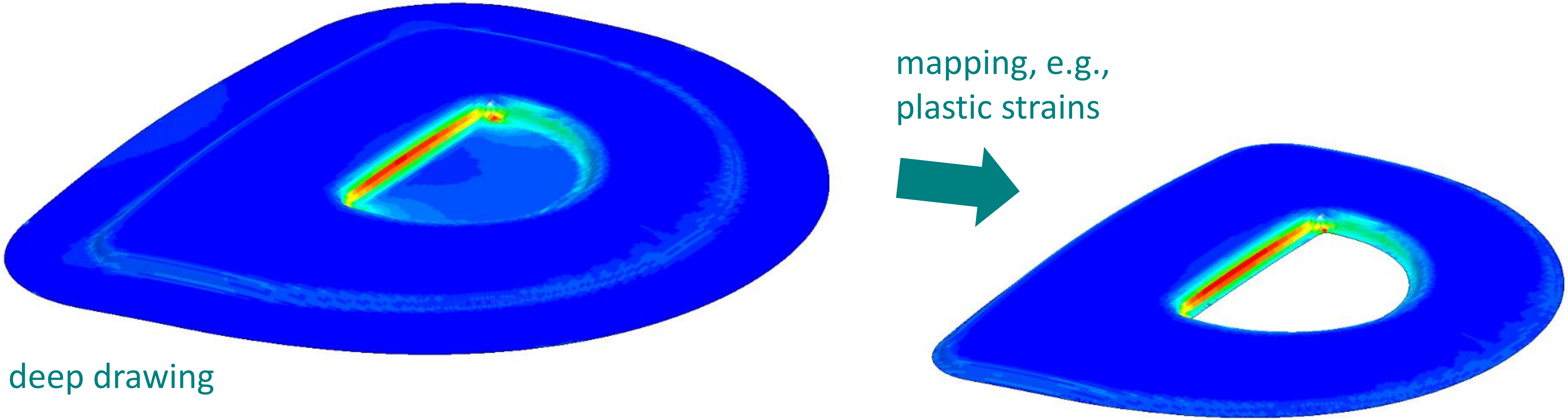






Isogeometric Analysis | Multistage

- 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



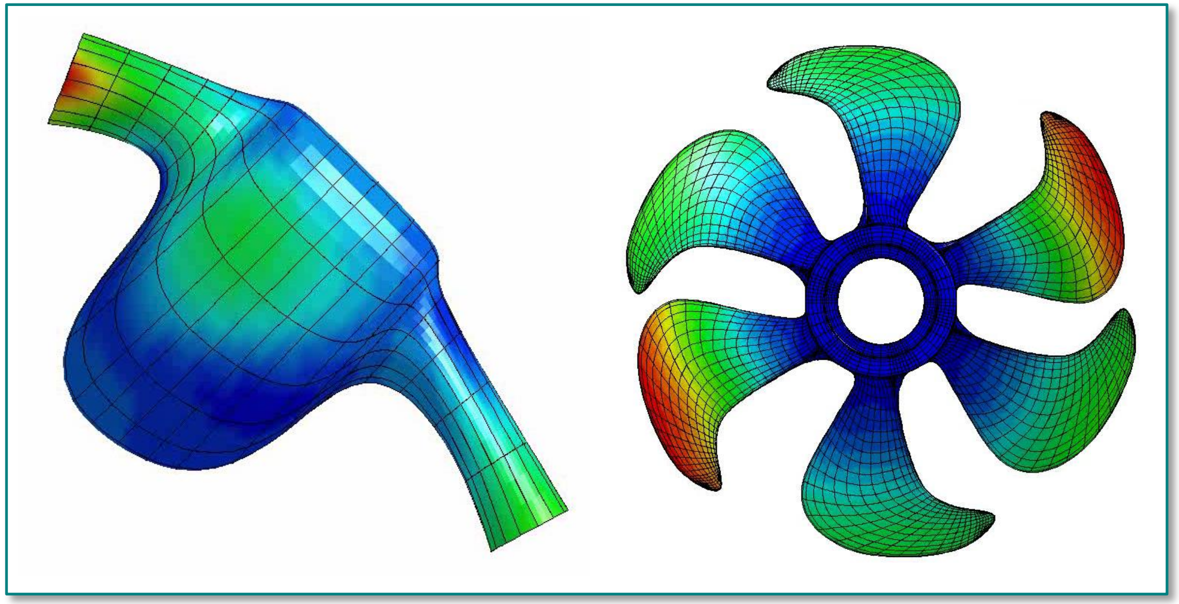
mapping, e.g.,
plastic strains

deep drawing

trimming

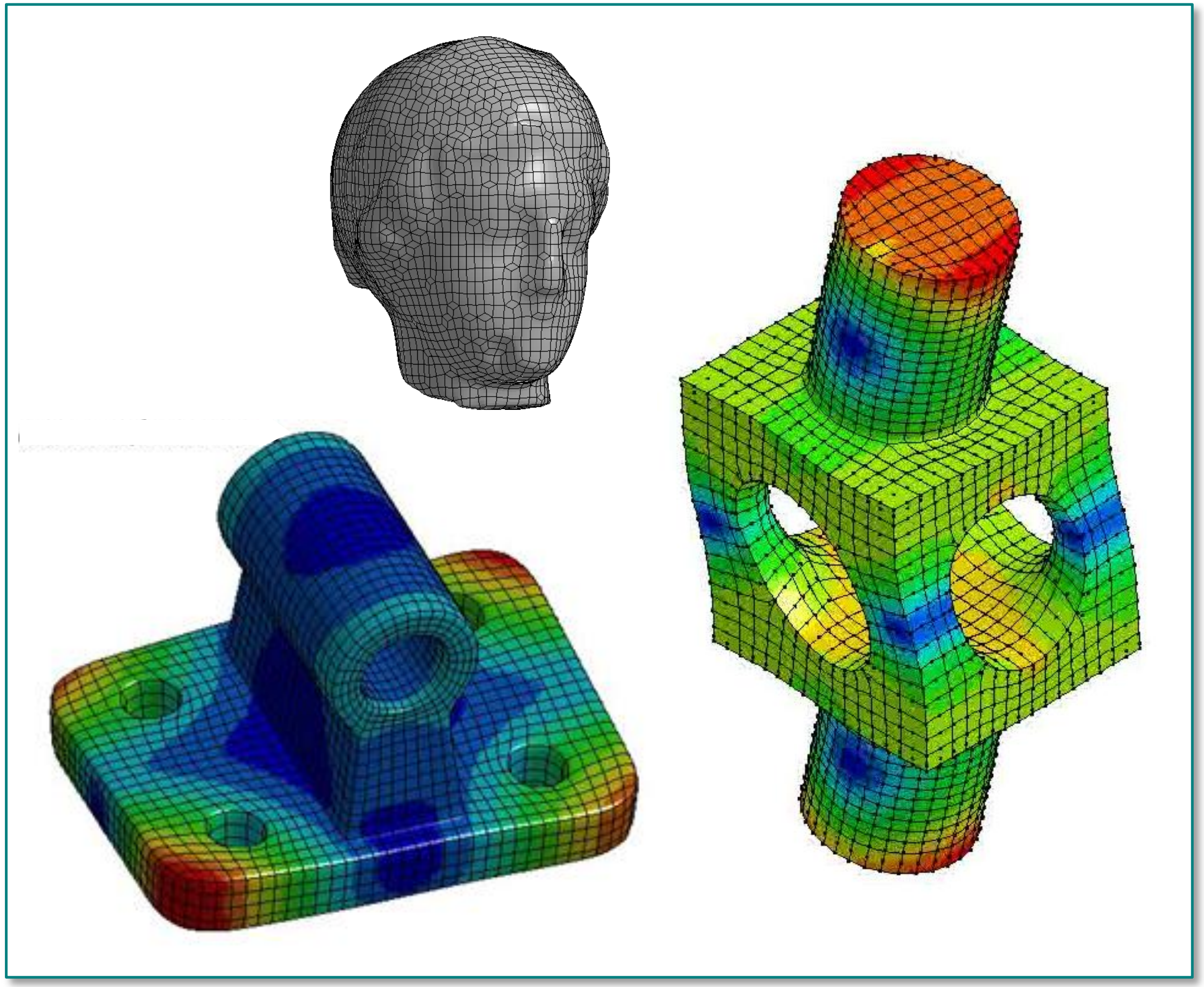
Isogeometric Analysis | Spline Techniques

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



T-splines, U-splines

Coreform LLC · Ford Motor Co., Ltd.



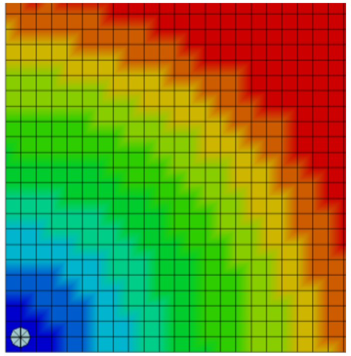
Truncated hierarchical T-spline

Carnegie Mellon University · Honda Motor Co., Ltd.

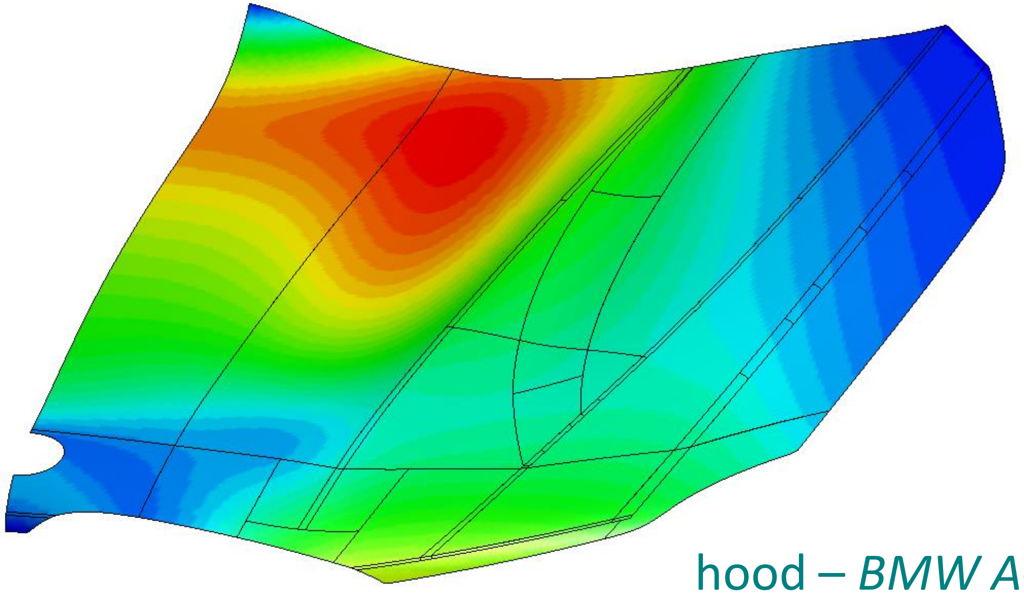
Isogeometric Analysis | Miscellaneous

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

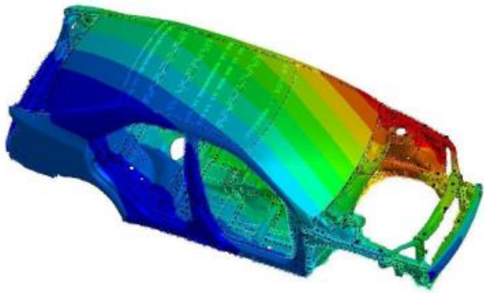


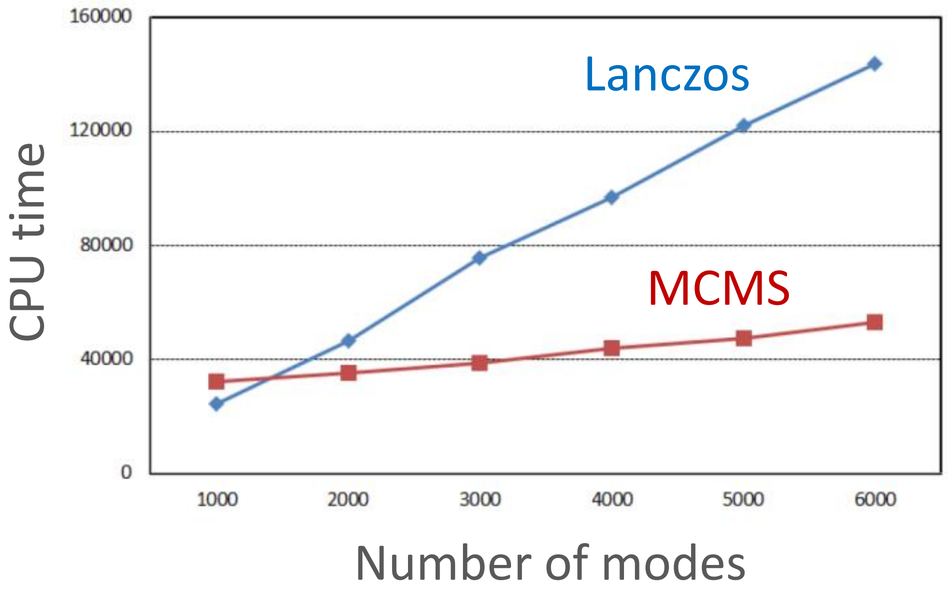
hood – *BMW AG*

Linear Implicit (1)

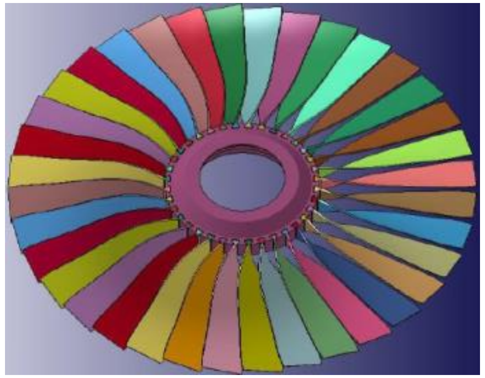
Grimes, Ashcraft, Lucas, Rouet, Wiesbecker, Vecharynski, Li

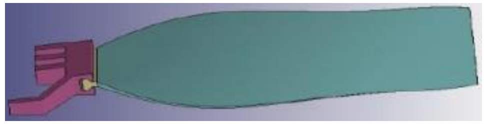
- New eigenvalue extraction method: MCMS
  - Multilevel Component Mode Synthesis
  - less accurate than Lanczos, but far less computer resources
  - useful for NVH applications that want thousands of modes





- Sectoral symmetry
  - for models with significant rotational symmetry: highly reduced eigenvalue problem





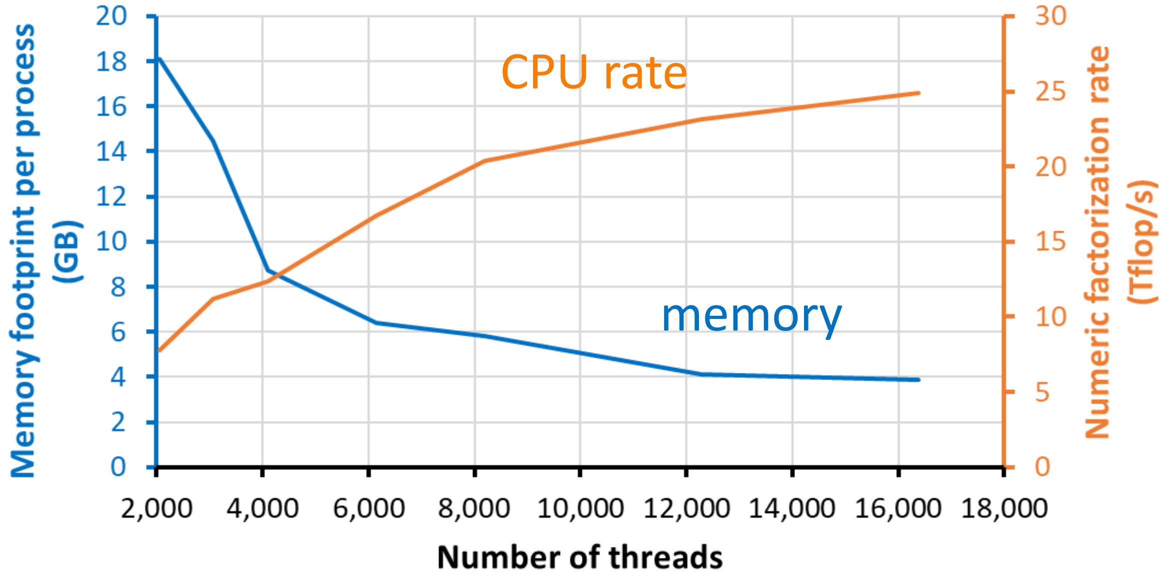
huge CPU/memory savings

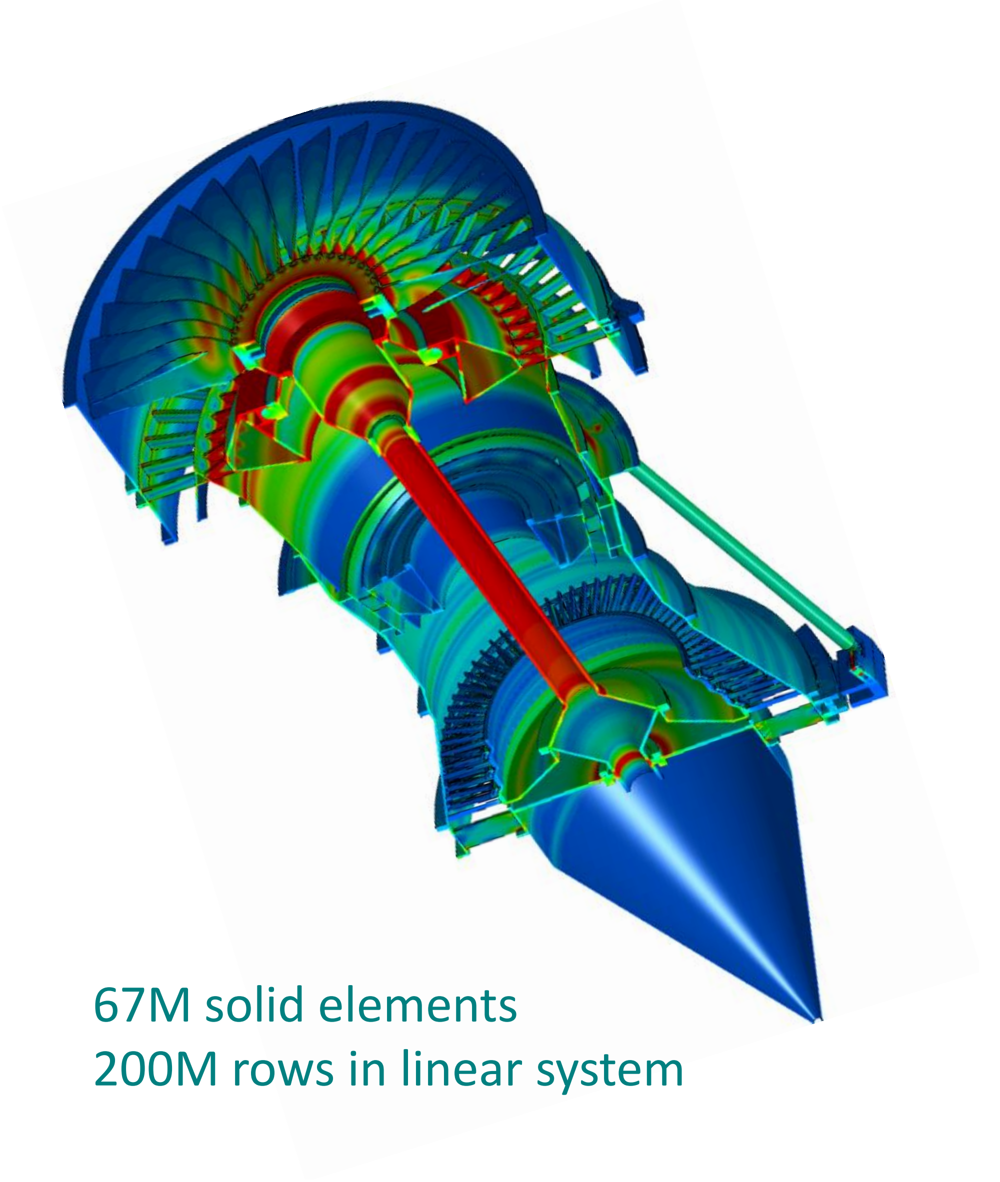
- And always…

Linear Implicit (2)

Grimes, Ashcraft, Lucas, Rouet, Wiesbecker, Vecharynski, Li

- …working on larger and larger models!
  - e.g. jet engine model from Rolly Royce
  - original attempt: 158 hours on 448 cores
  - current best: 12 hours on 2304 cores
  - continuing efforts to improve scalability

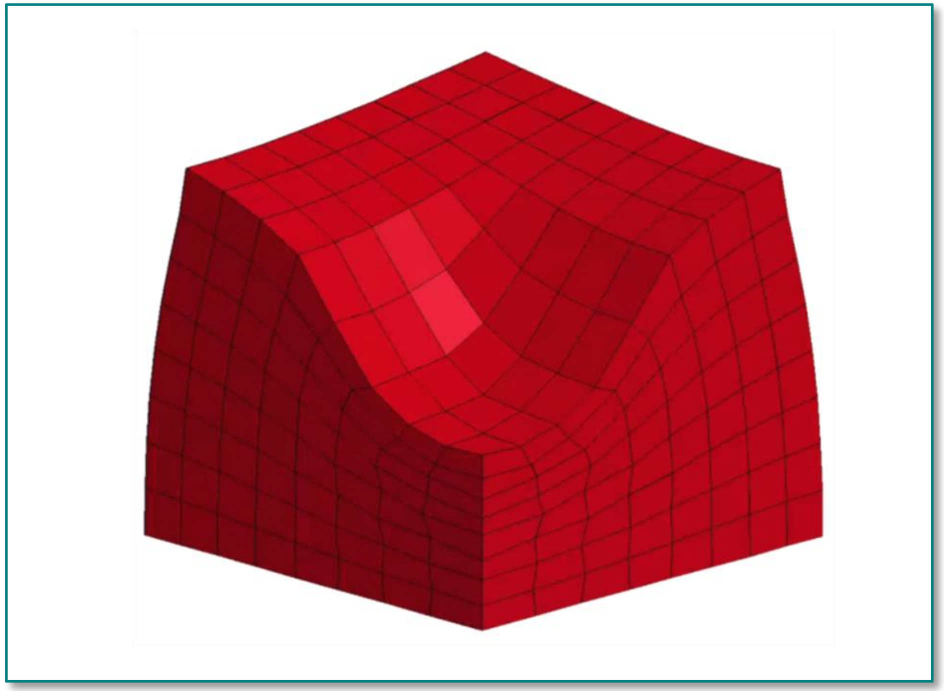




67M solid elements
200M rows in linear system

Nonlinear Implicit (1)

- Improvements on many different fronts
- e.g., new hexahedral solid element
  - enhanced assumed strains (EAS) approach
  - generalization of linear solid #18 to nonlinear analysis
  - higher computational cost justified in implicit
  - very good coarse mesh accuracy
  - paper presented in Detroit, June 2018 (Bengzon, Borrvall, Basu)



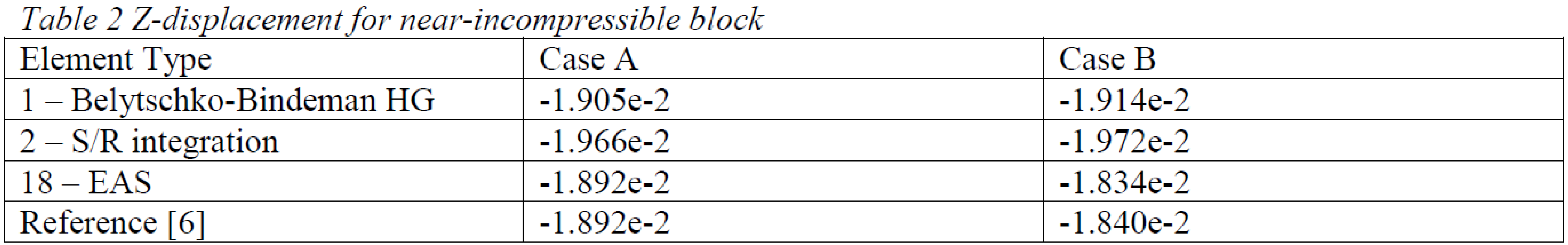
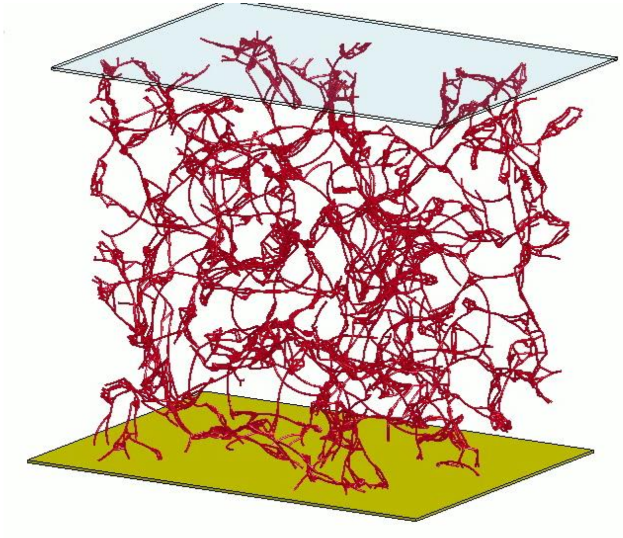


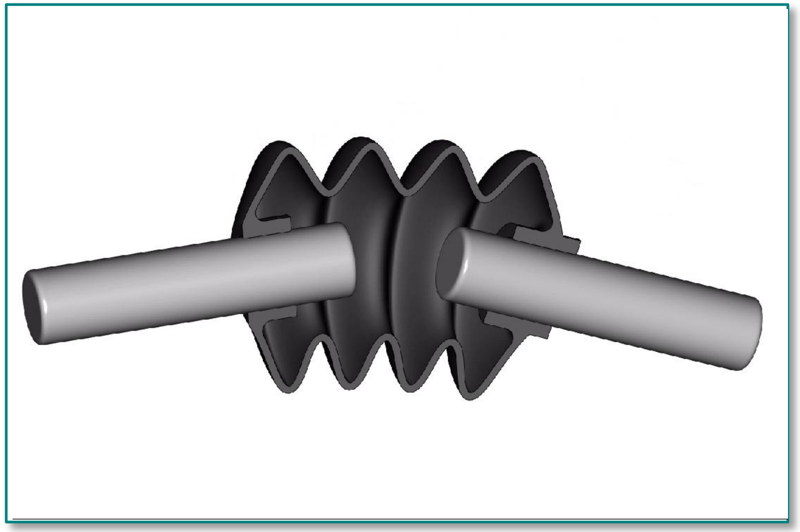
Table 2 Z-displacement for near-incompressible block

Element Type	Case A	Case B
1 – Belytschko-Bindeman HG	-1.905e-2	-1.914e-2
2 – S/R integration	-1.966e-2	-1.972e-2
18 – EAS	-1.892e-2	-1.834e-2
Reference [6]	-1.892e-2	-1.840e-2

Nonlinear Implicit (2)

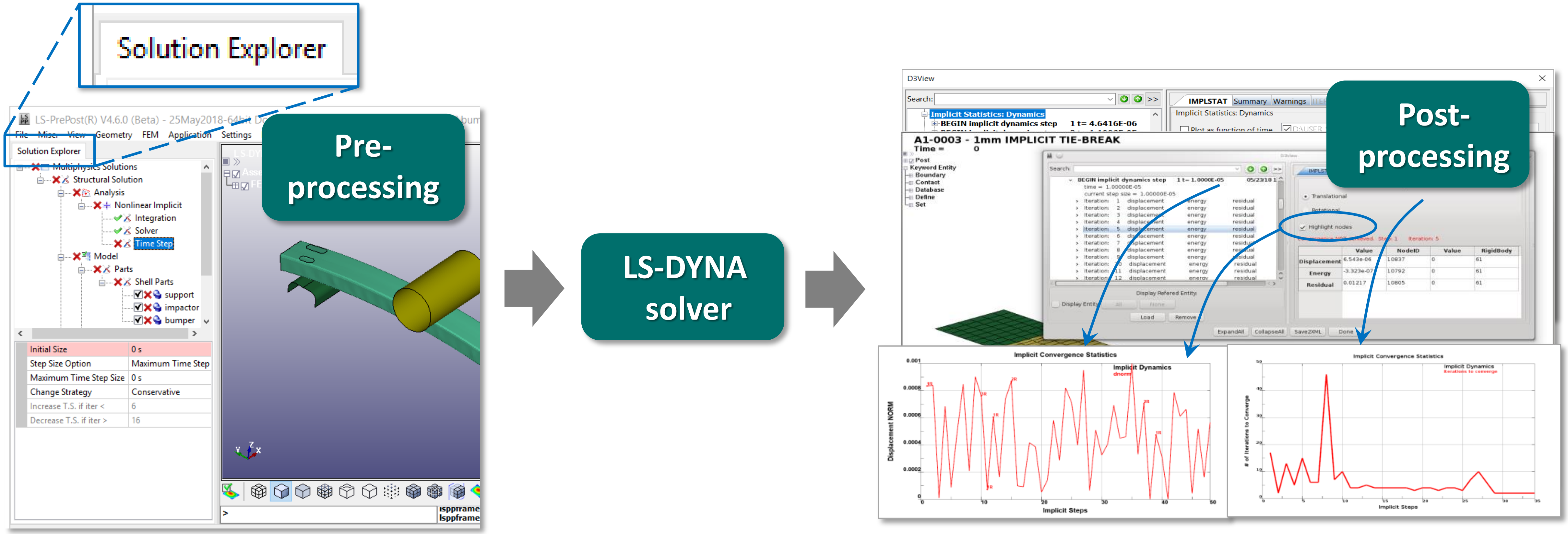
- Convergence tolerances
  - maximum values, consistent norms
- Time stepping
  - step change based on accuracy, automatic keypoints
- Process splitting by *CASE
  - ”complex” process divided into ”simple” steps
- Accurate prestressing
  - initial stress section accounts for bending (*INITIAL_STRESS_SECTION with IZSHEAR=2)
- Mortar contact
  - frictional torque, tiebreak, tied weld, user friction, …





Nonlinear Implicit (3)

Borrvall, Bengzon, Wenhui, Jernberg, Chengju, Zhanqun, Zhansheng



Pre-processing

LS-DYNA solver

Post-processing

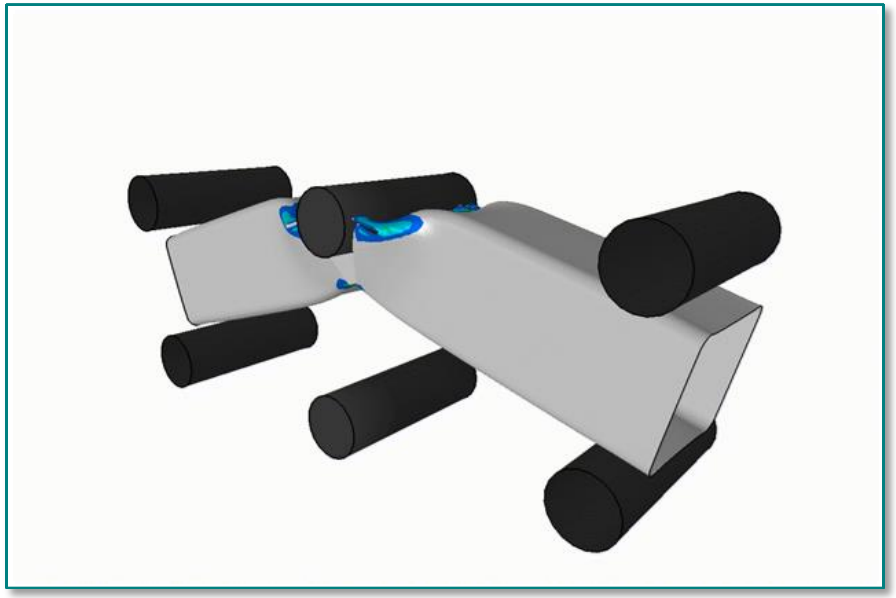
Initial Size	0 s
Step Size Option	Maximum Time Step
Maximum Time Step Size	0 s
Change Strategy	Conservative
Increase T.S. if iter <	6
Decrease T.S. if iter >	16

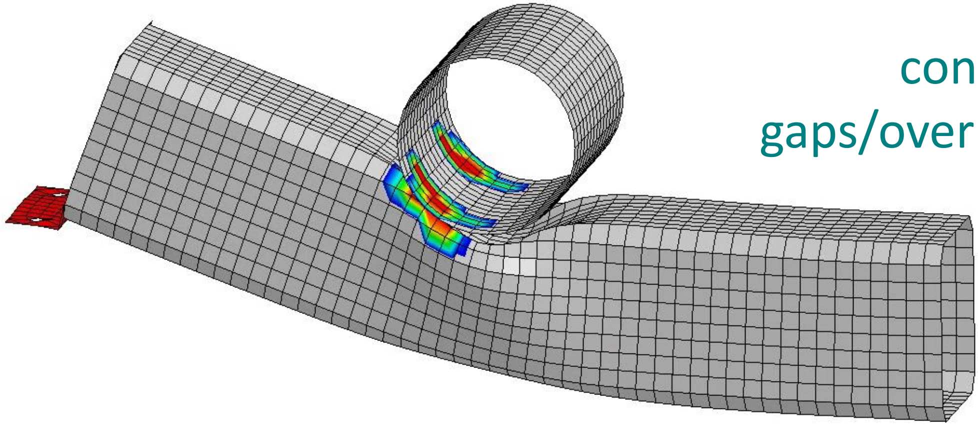
- Working on user-friendly Pre- and Post-processing (LS-Prepost)
  - model tree, parameter editor, suggested presets, error functionality, diagnostics
  - motivation: attract newcomers, facilitate migration, widen user community

Contact

Wainscott, Bindeman, Han, Yeh, Borrvall

- Mortar with element erosion
  - Exposed segments due to erosion added to the contact
- New command line options
  - `soft=1to2(2to1)` converts all contacts from SOFT=1(2) to SOFT=2(1)
- 2D seatbelt elements inside retractor
  - new option to activate/deactivate surface-to-surface contact
- Add gap calculation to SOFT=2 contact
  - written to intfor,
    overlaps reported as negative gaps



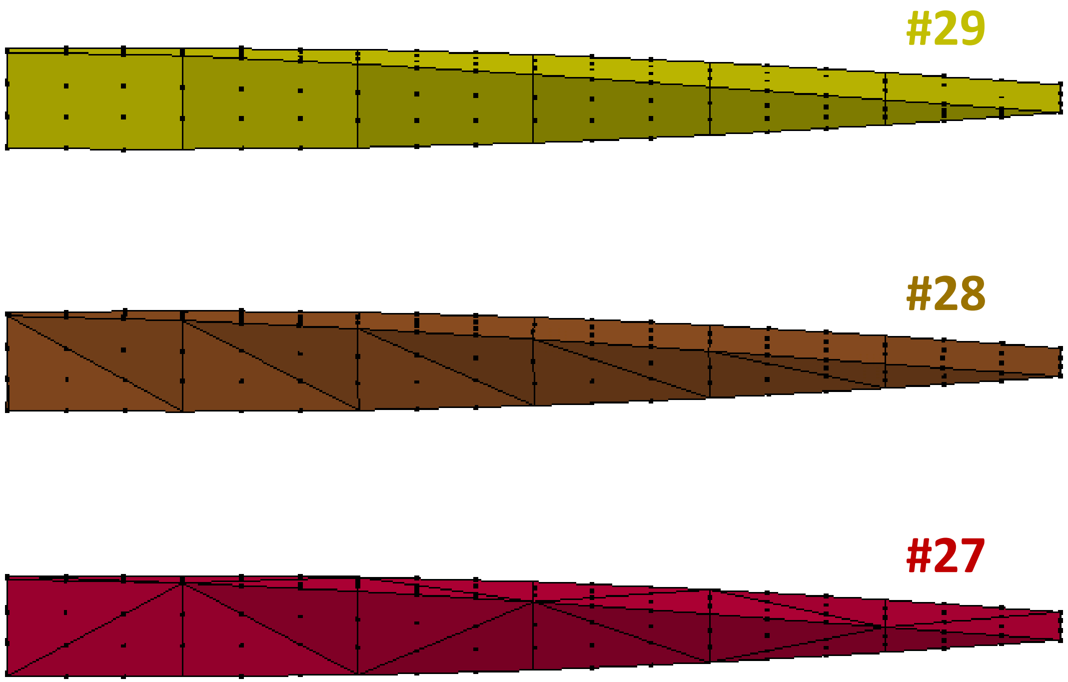


contact
gaps/overlaps

Elements | Cubic Solids

Benson, Teng

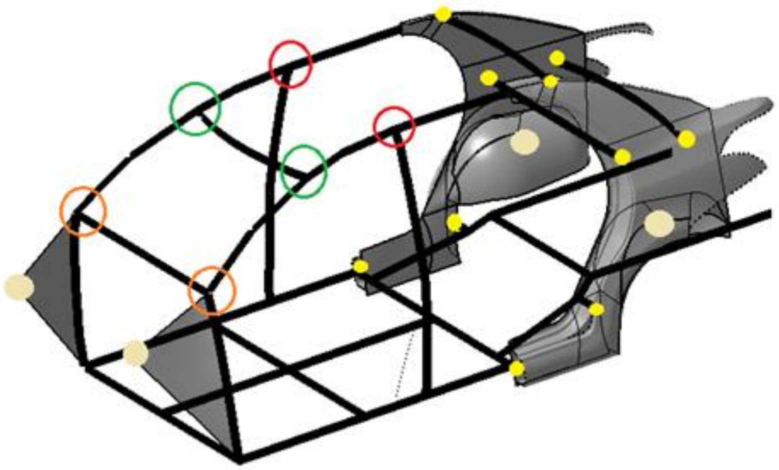
- New element formulations 27, 28, and 29
  - ELFORM=27 is a 20-node tetrahedron
  - ELFORM=28 is a 40-node pentahedron
  - ELFORM=29 is a 64-node hexahedron
- Element input
  - *ELEMENT_SOLID_T20
  - *ELEMENT_SOLID_P40
  - *ELEMENT_SOLID_H64
- Keyword to convert linear to cubic
  - *ELEMENT_SOLID_H8TOH64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

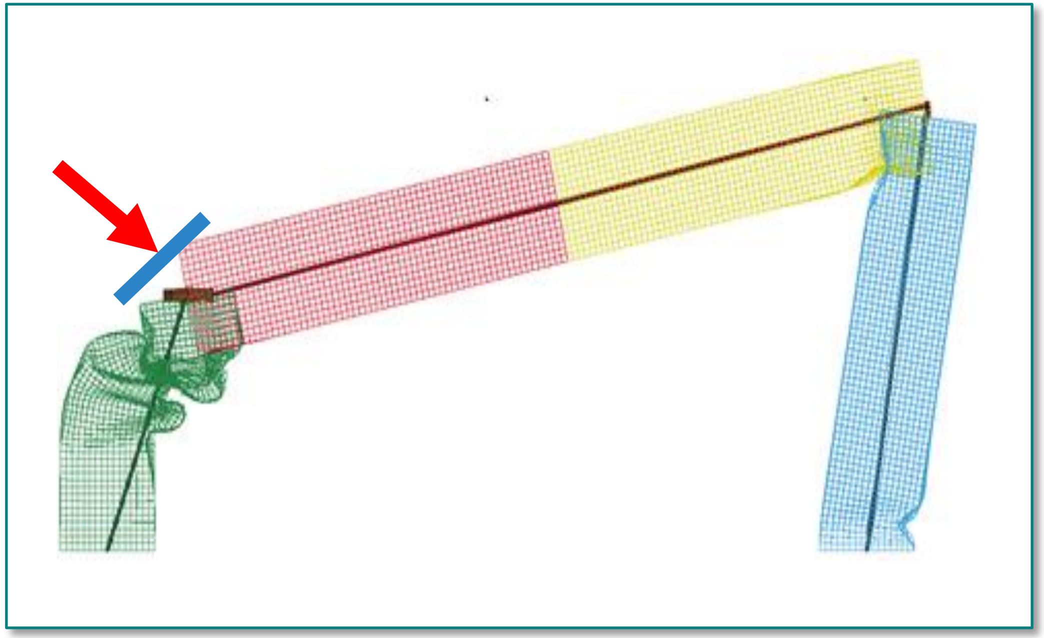


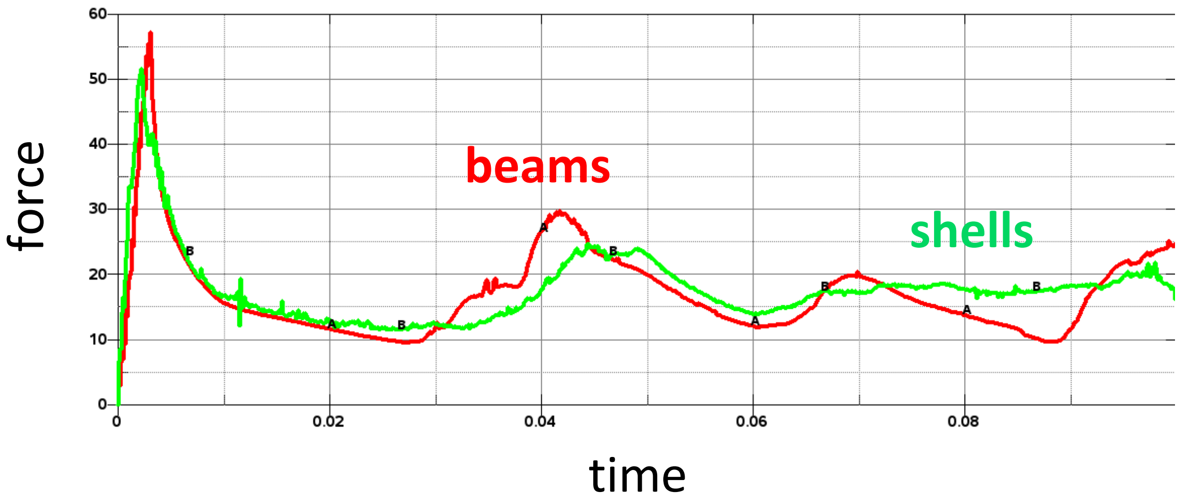
high accuracy in twisted beam problem
with only one solid over the thickness

Elements | Crushable Beam

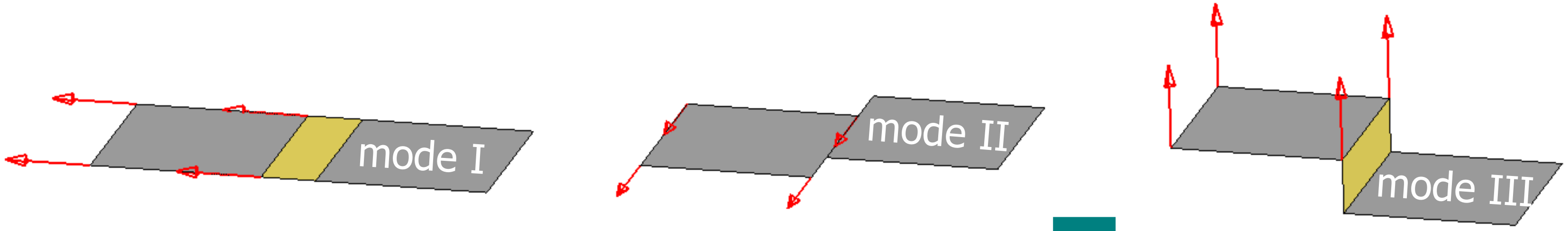
- CAE models for concept design
- Replace detailed FE model (shells, solids) by simple beam frame structure
- Complex structural behavior embedded in material model: *MAT_119 enhanced (IFLAG=2)



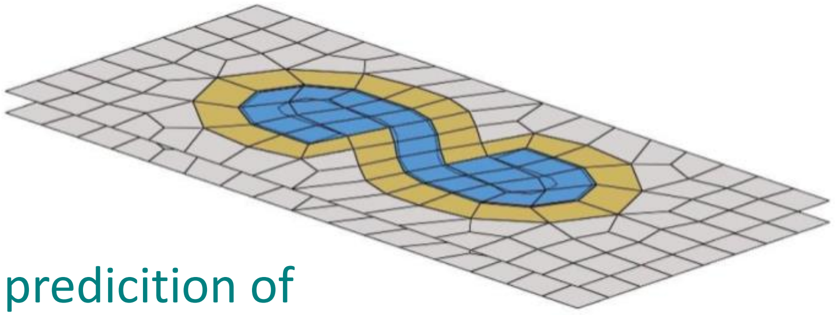




Connections | Linear and planar



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



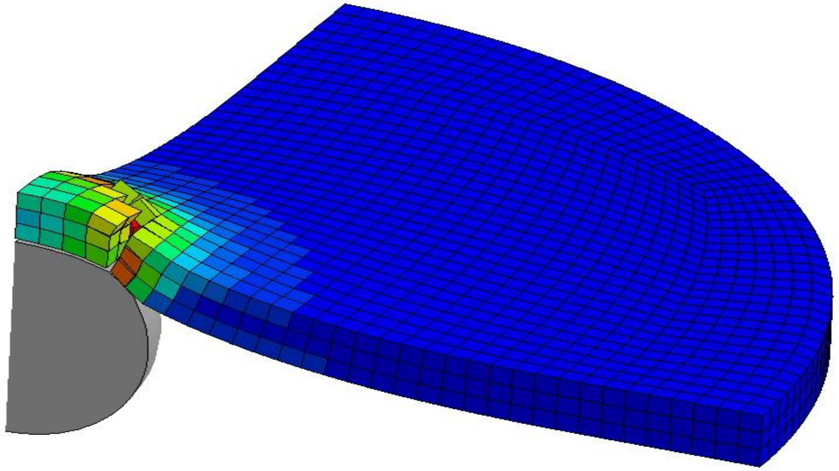
predicition of
laser weld plug out

Ford Motor Co., Ltd.

Materials | Failure and Damage

Borrvall, Erhart, Lum

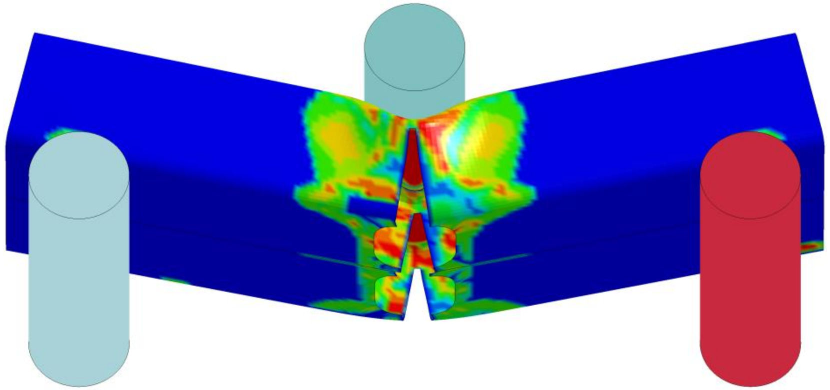
- New keywords *MAT_ADD_DAMAGE_{GISSMO|DIEM}
  - separated from *MAT_ADD_EROSION to make input clearer: pure failure vs. damage
- Now available for more elements/methods
  - beams, higher order solids, SPH, *CONSTRAINED_TIED_NODES_FAILURE
- ADD_EROSION: new failure criteria
  - e.g. maximum temperature,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



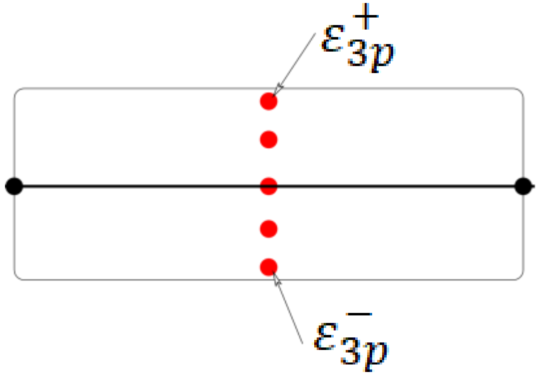
Materials | Regularized Failure Model

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

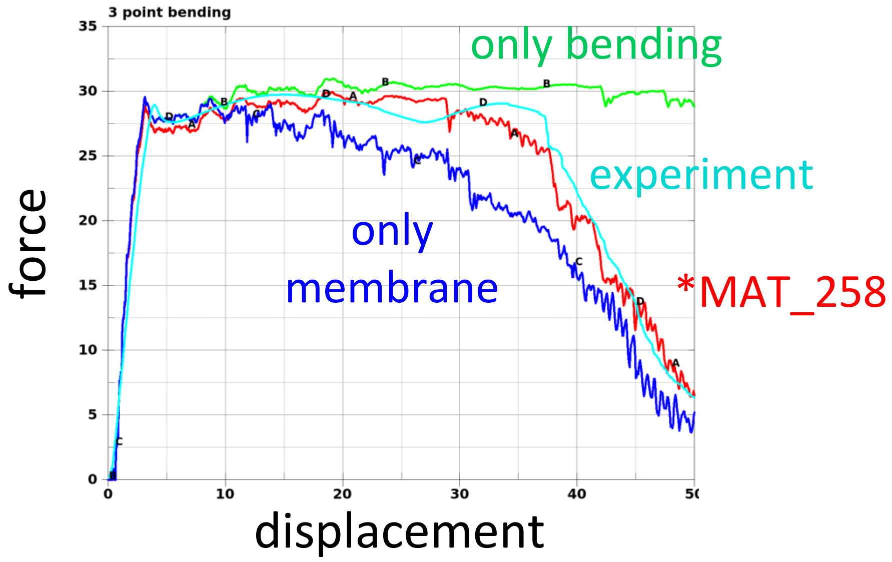


3-point bending of aluminum profile with hole: critical fracture value



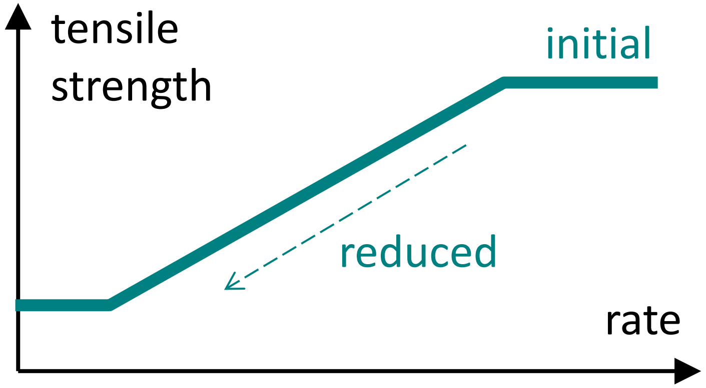
$$W_c = \Omega W_c^b + (1-\Omega) W_c^m$$

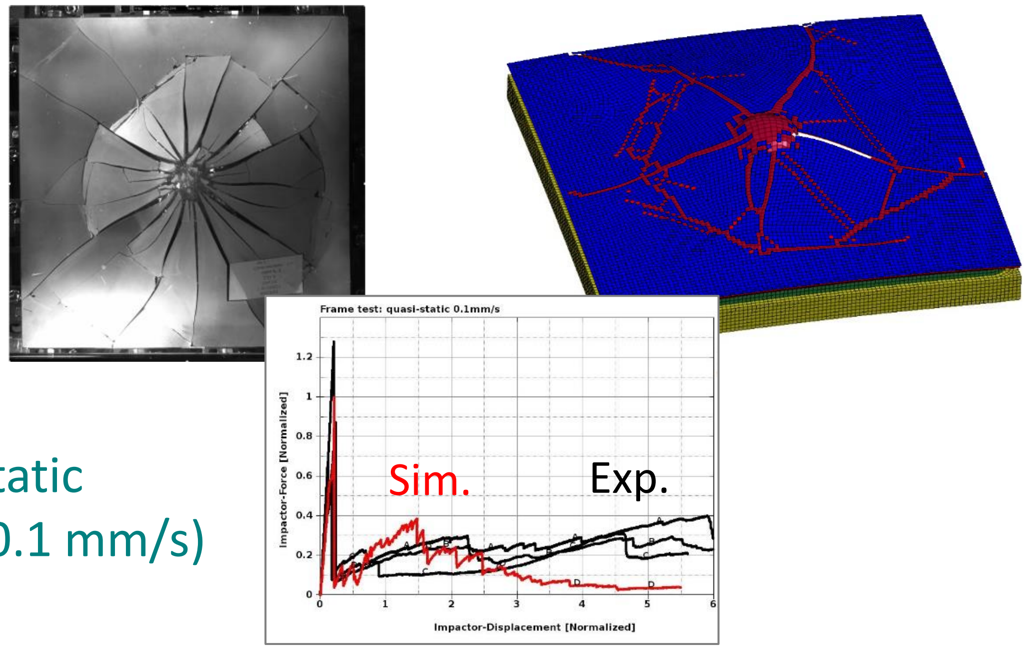
$$\Omega = \frac{1}{2}\frac{\left|\varepsilon_{3p}^{+} - \varepsilon_{3p}^{-}\right|}{\max\left(\left|\varepsilon_{3p}^{+}\right|, \left|\varepsilon_{3p}^{-}\right|\right)}$$



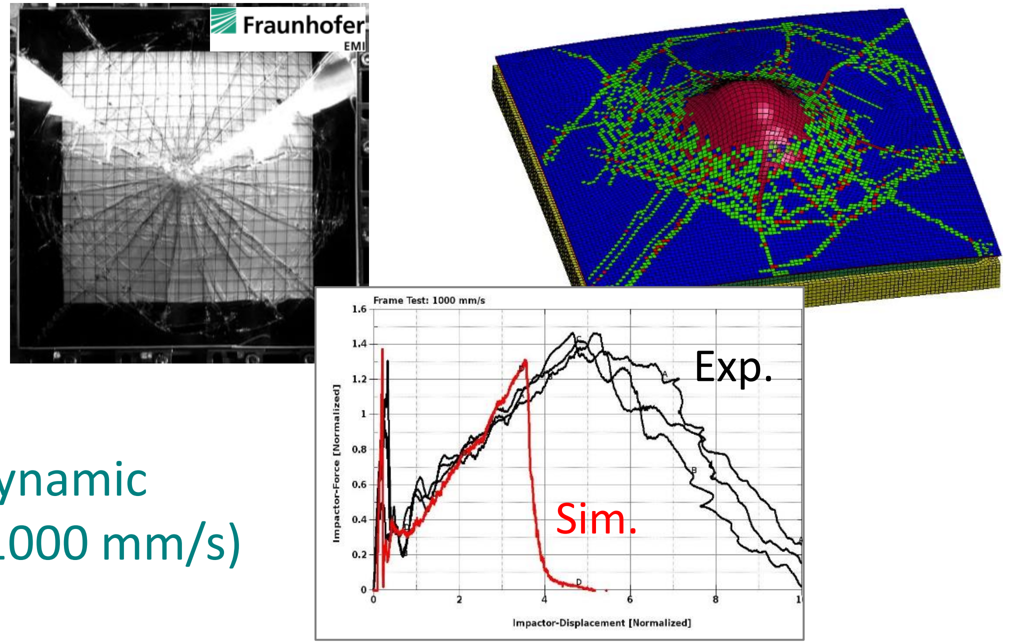
Materials | Glass

- 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





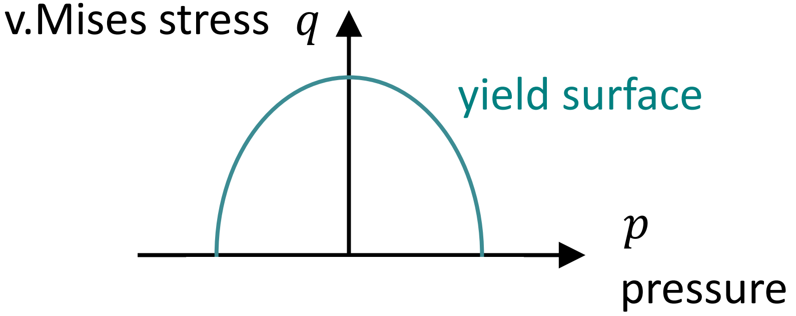
static
(0.1 mm/s)



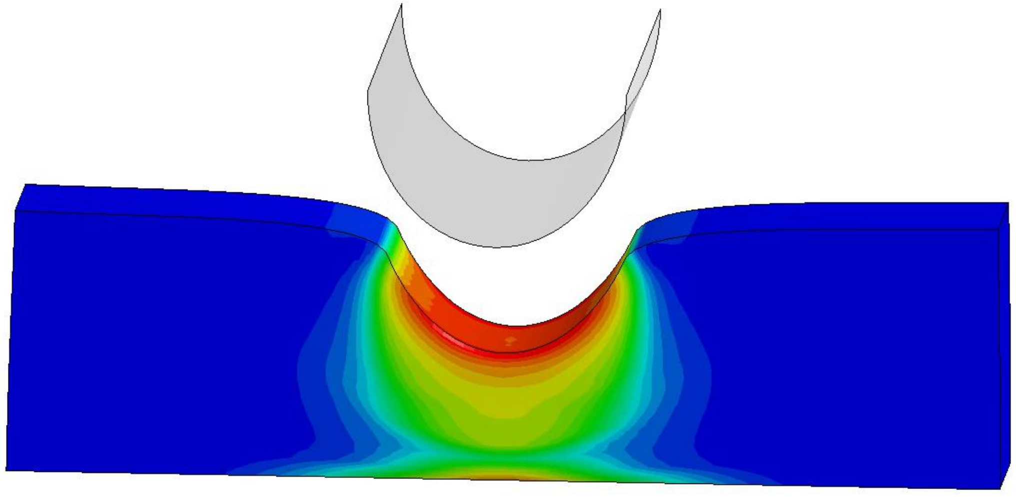
dynamic
(1000 mm/s)

Materials | Foam

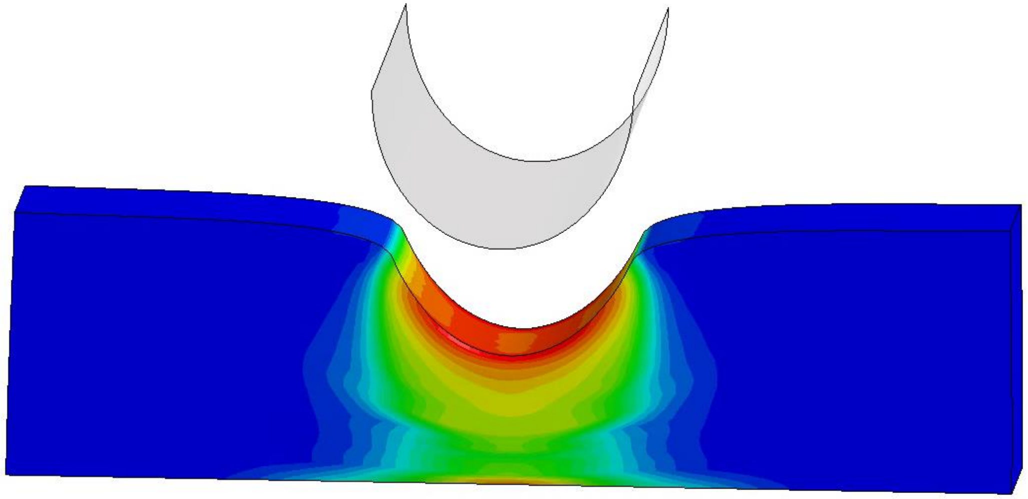
- *MAT_063 (CRUSHABLE_FOAM) MODEL=1
  - alternative formulation for crushable foams
  - elliptical yield surface (*p*-*q* space)
  - individual elastic and plastic Poisson’s ratio
  - rate dependent hardening



100 mm/s

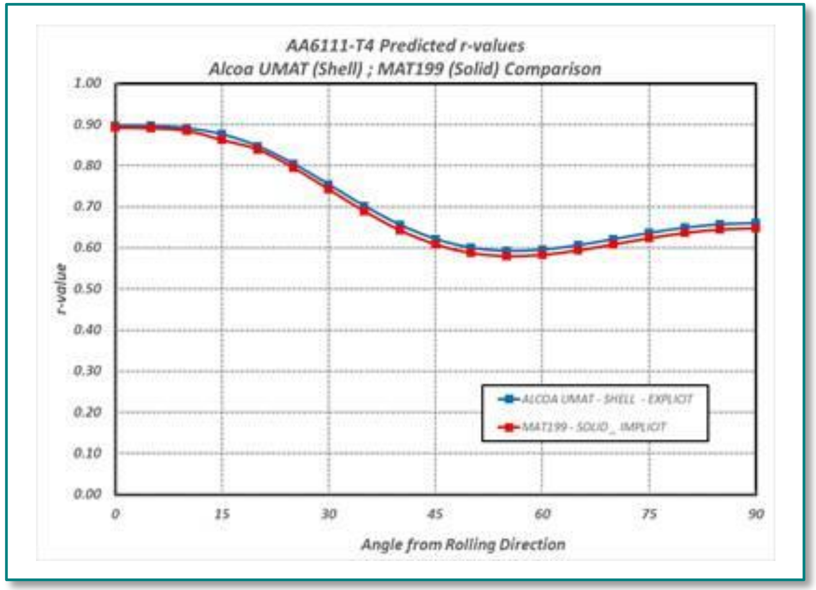


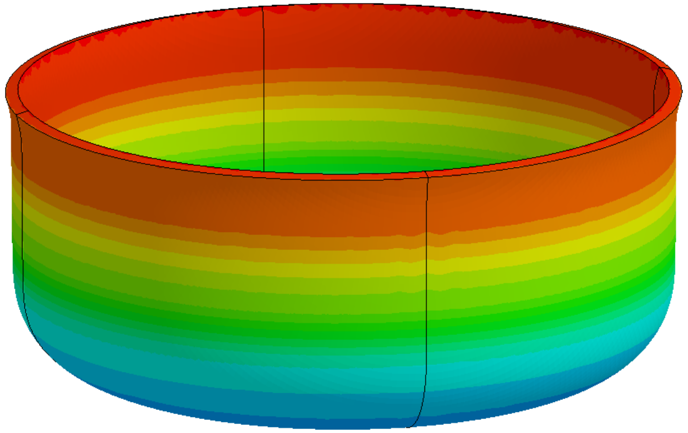
2000 mm/s



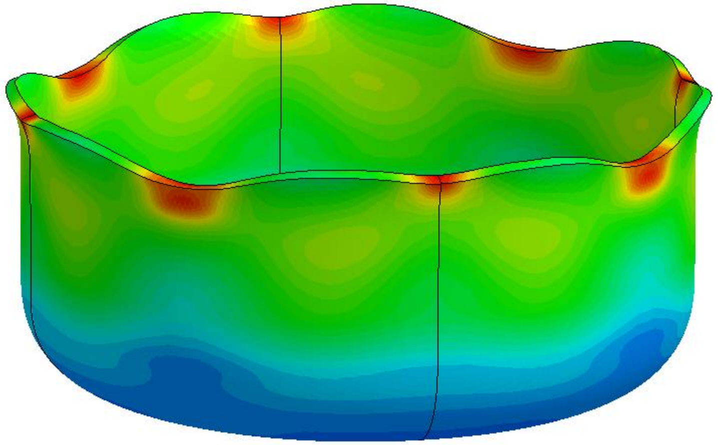
Materials | Anisotropic Yield (1)

- 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





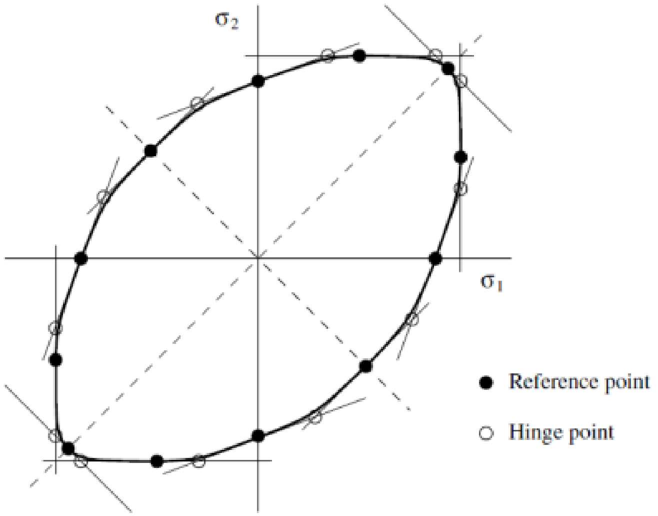
*MAT_024

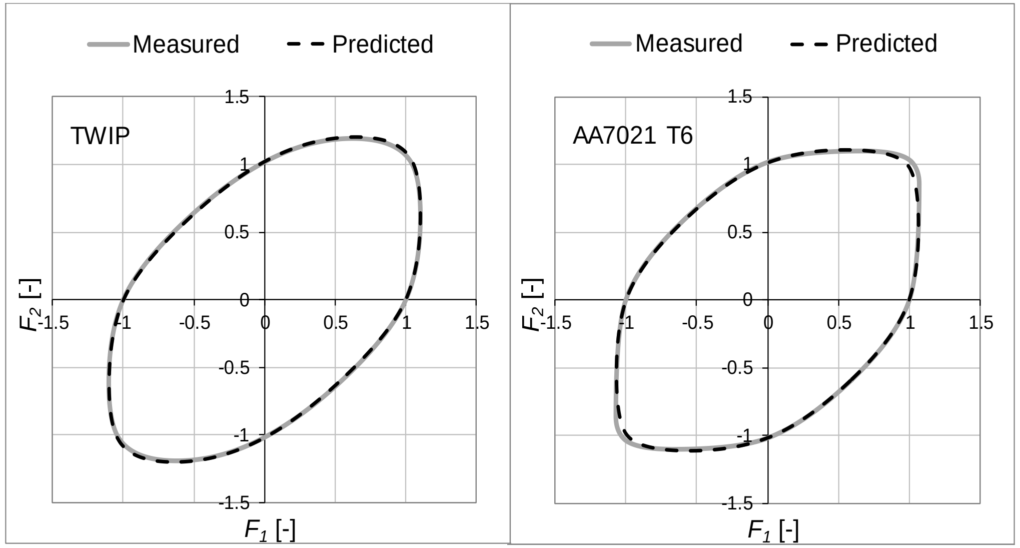


*MAT_199

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

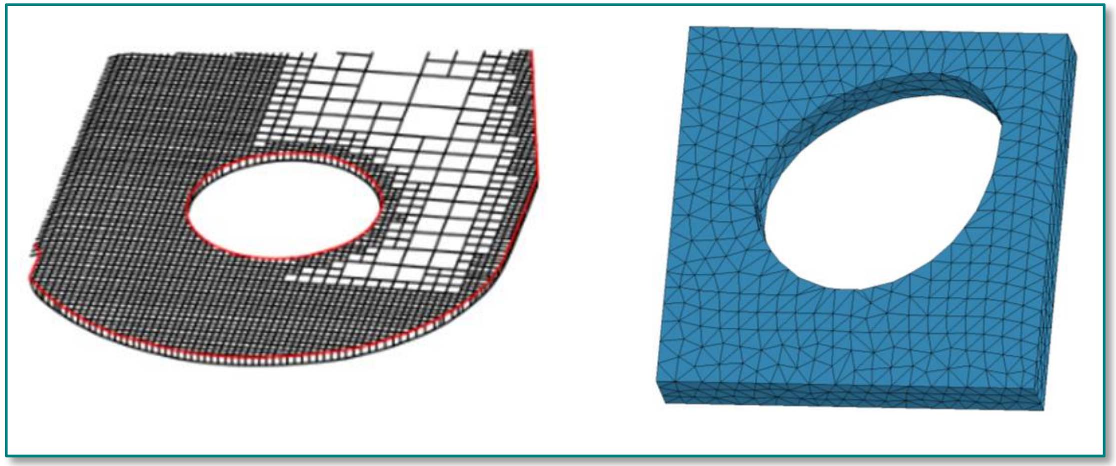


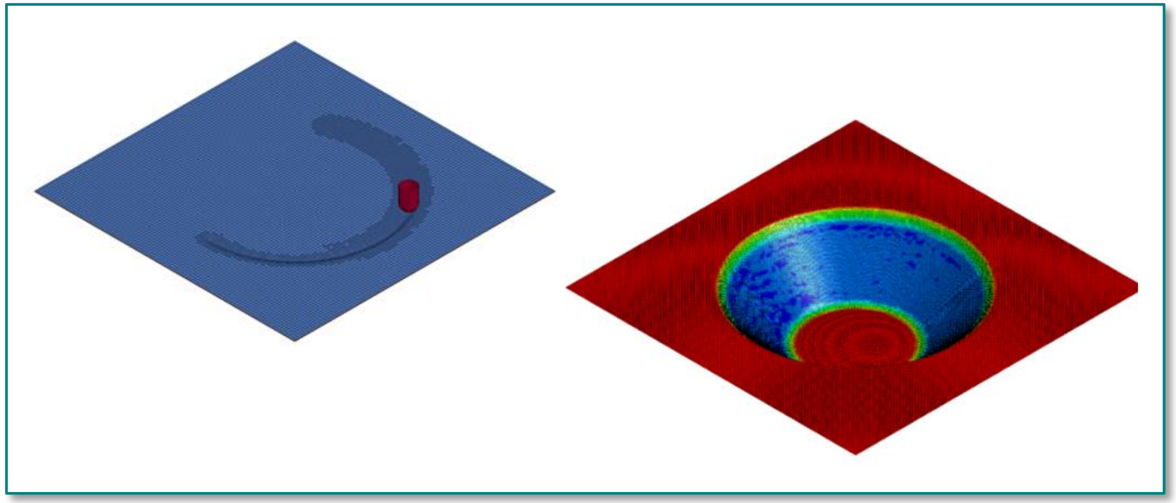


[1] Vegter, Boogaard; 2006 [2] Abspoel et al, 2017

Metal forming (1)

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

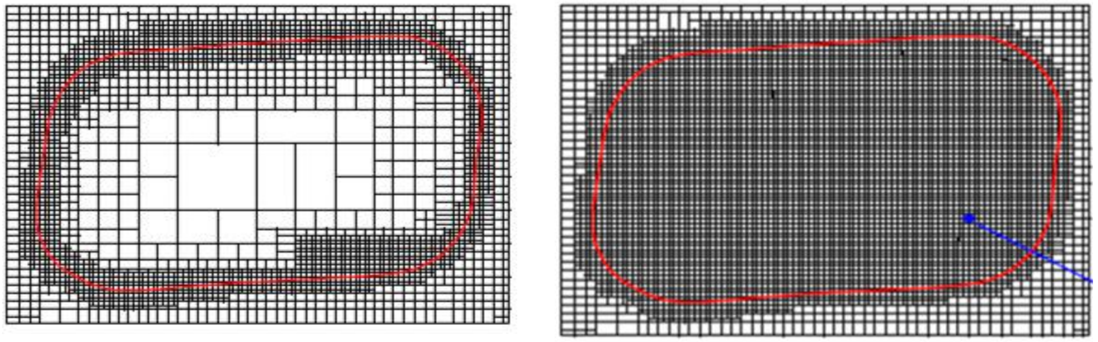




- Mesh fusion (adaptive re-coarsening)
  - completely reworked & extended to MPP
  - uses average information of merged elements
  - with tube adaptivity for incremental forming

Metal forming (2)

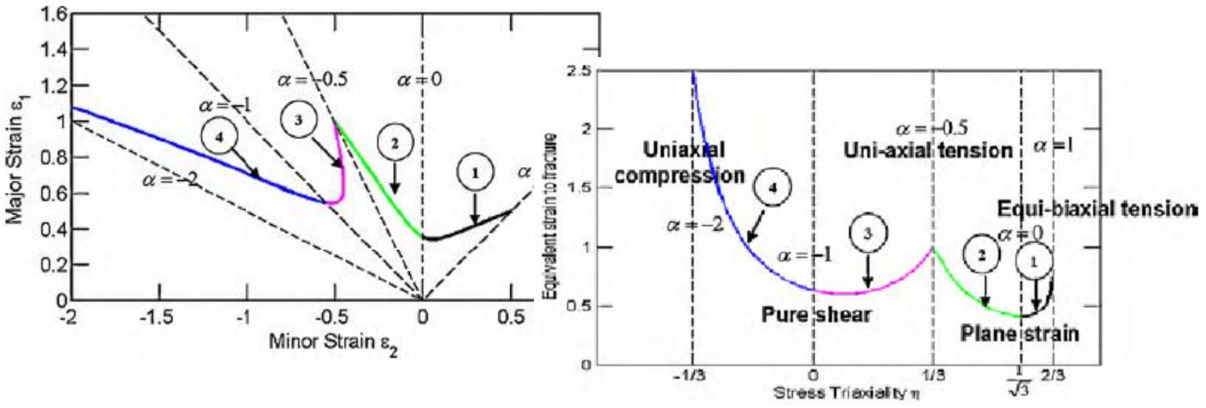
- New mesh refinement options
  - along given curve or inside domain
  - *CONTROL_ADAPTIVE_CURVE: ”ITRIOPT”



e.g. for stoning

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

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

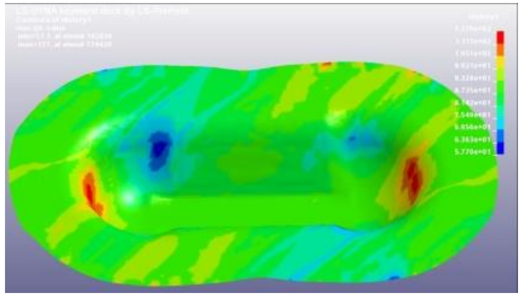


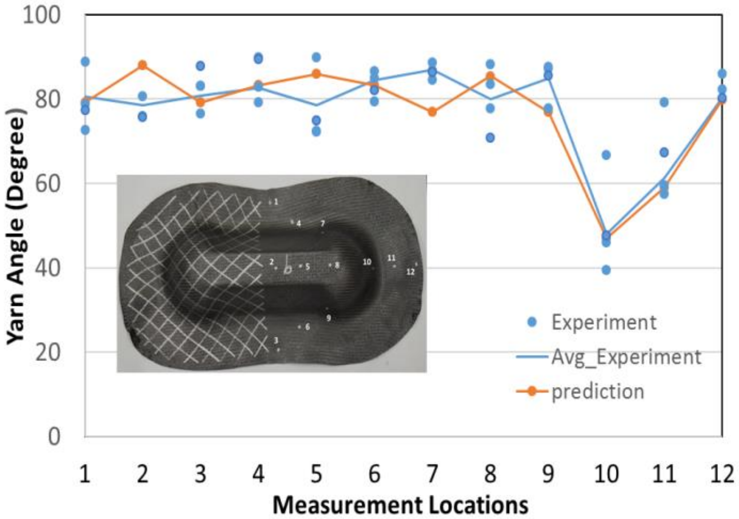
Metal forming (3)

Zhu, Fan, Zheng

- One-step analysis
  - improvements towards higher accuracy and speed
  - now also availabe for woven carbon fiber composites

    anisotropy is very important (optimal component performance); new algorithm predicts fiber angles, determines initial blank size, …

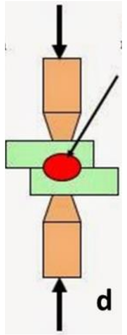


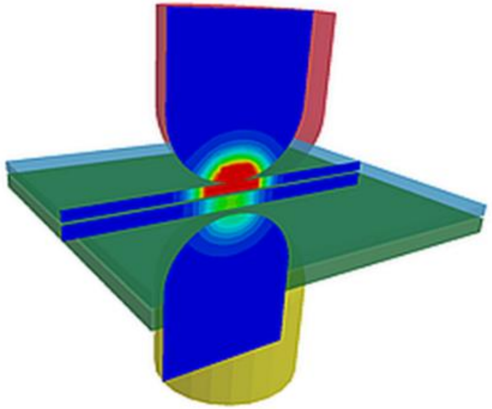


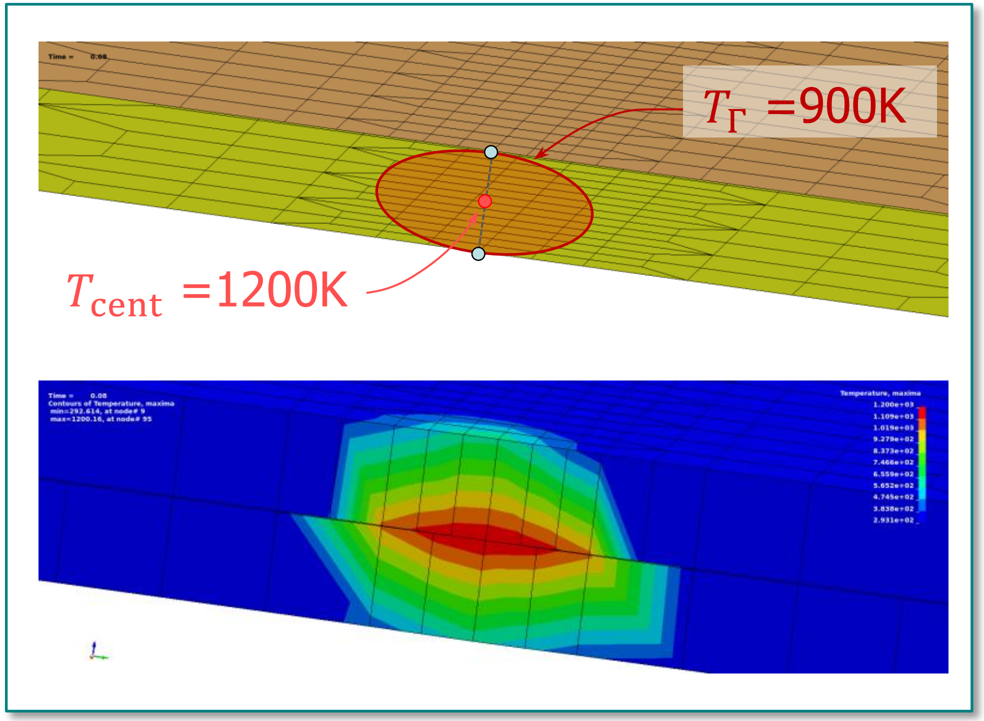
- Enhancements for springback compensation
  - maintain tangency along the boundary between binder and addendum
  - allow springback compensation to be used in flanging tools
  - keep tangency around trimming curves

Thermal Analysis | RSW

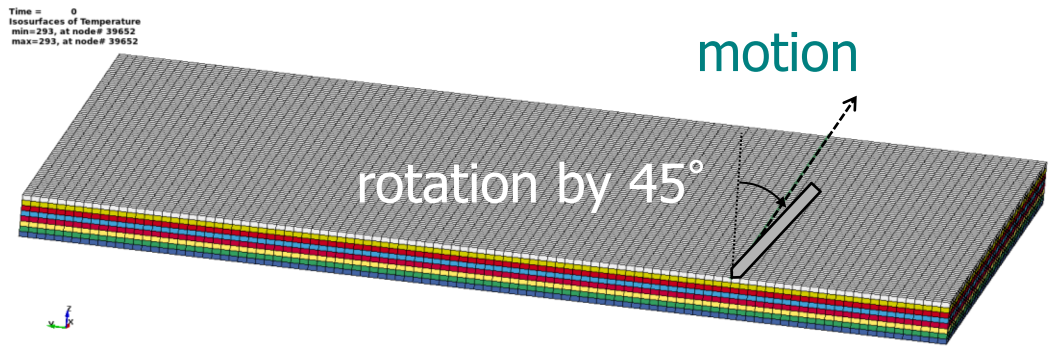
- Resistance Spot Welding
- Keyword *BOUNDARY_TEMPERATURE_RSW
  - simplified and fast boundary conditions
  - direct definition of the temperatures for nodes in the weld nugget
  - temperature preset at the center and the boundary
  - quadratic approximation of the temperature field
  - birth and death 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

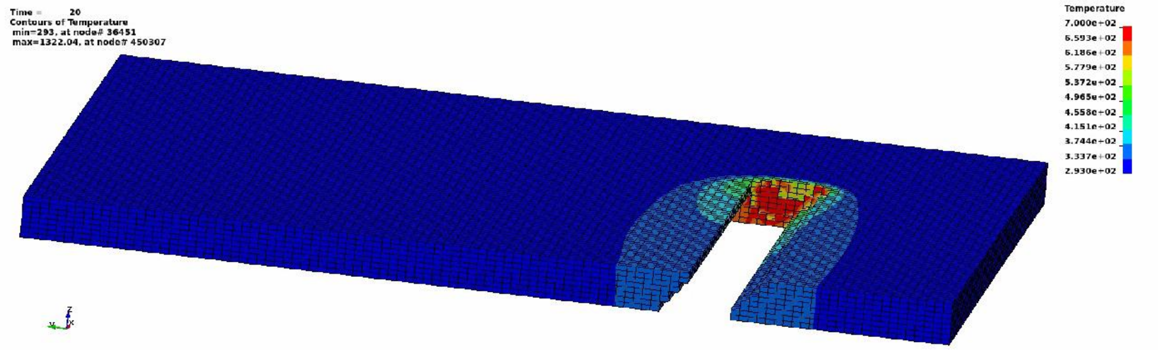






Thermal Analysis | Laser Cutting

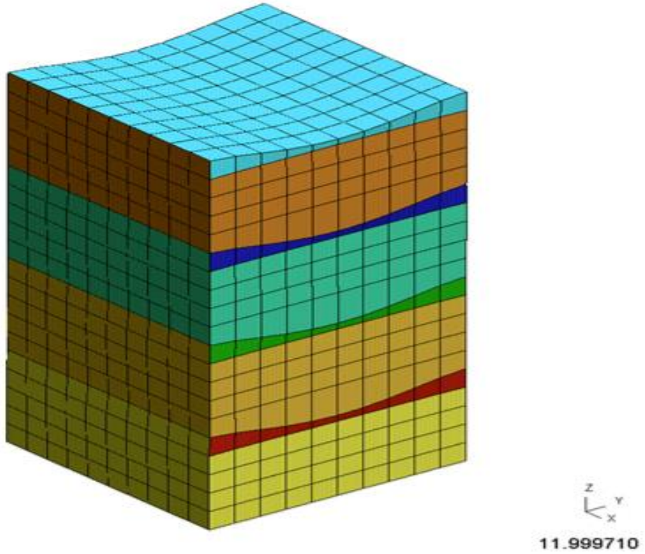




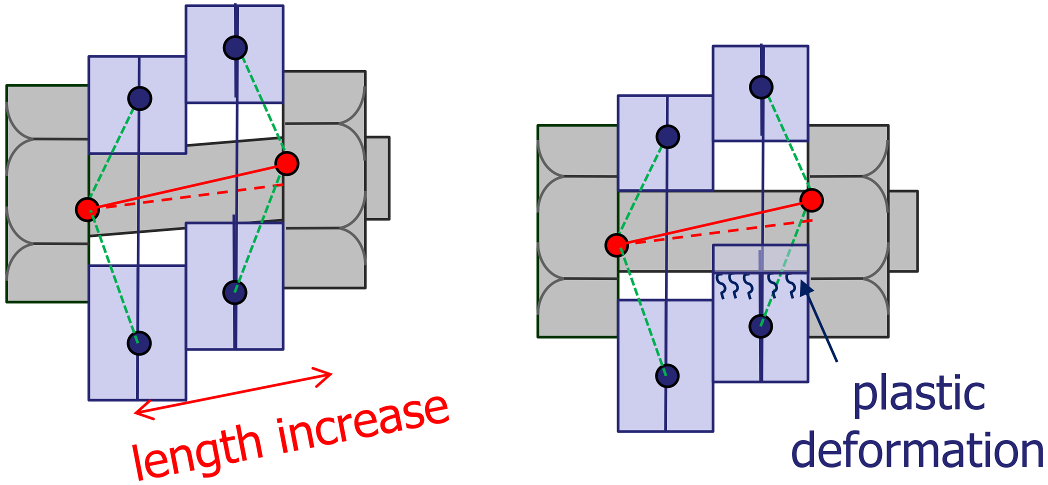
- New keyword *BOUNDARY_FLUX_TRAJECTORY
  - aims to simulate a moving surface heat source, e.g. a laser, on a structure
  - keyword allows for an easy definition of surface fluxes

    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)

Civil Engineering Topics



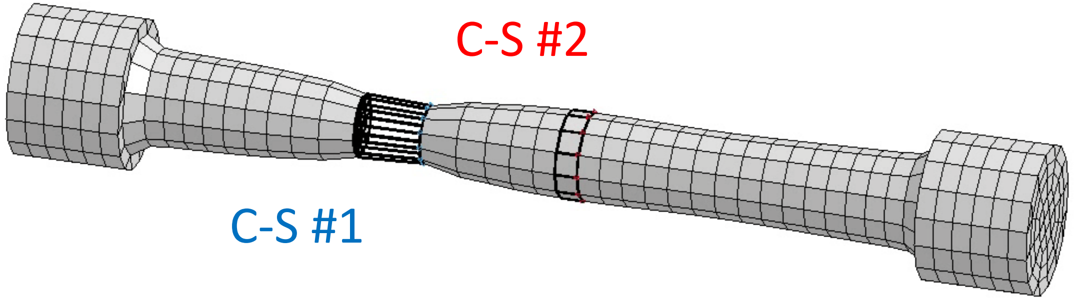
- Improvements for staged construction
  - break the analysis into periods of time that can be referenced in loading definitions and rerun separately
  - e.g. introduce and remove parts sequentially
  - accelerated analysis shows ”real time”
  - ongoing improvements
- Bolt modeling with *MAT_BOLT_BEAM
  - represented by discrete beam element type 6
  - takes clearance gap into account
  - new flag AXSHFL: shear-induced length increase treated as axial load (0) or is ignored (1)
  - now with element erosion after failure
- Reinforced concrete models, soil, …



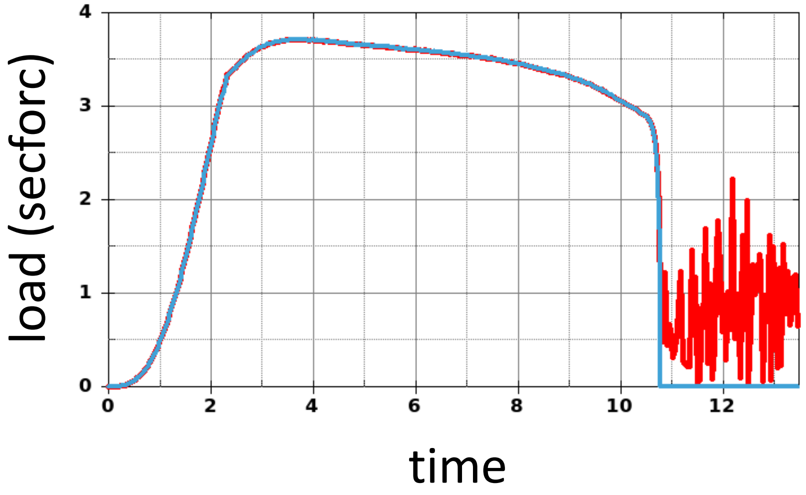
Miscellaneous

Tsay, Schmied, Wang, Borrvall, Yeh, …

- Cross sections output
  - new variable ICRFILE on *CONTROL_OUTPUT to get nodes/elements in output file



- Work on shell elements with thickness stretch (#25, #26, #27)
  - reduce spurious stresses observed in these actually very promising elements



- User interfaces
  - non-local search, unsymmetric tangents, mortar contact, user supplied LES, …

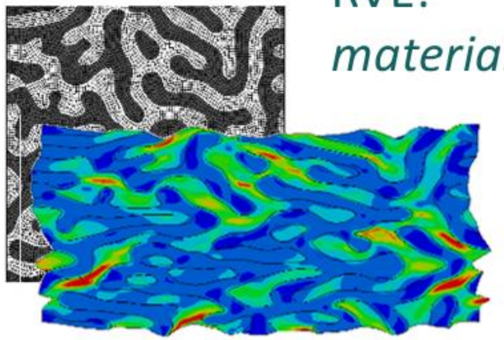
- *SENSOR: New entities to be controlled / traced
  - energies, number of failed elements, curve values, thermal loads, …

Multi-Scale Mechanics

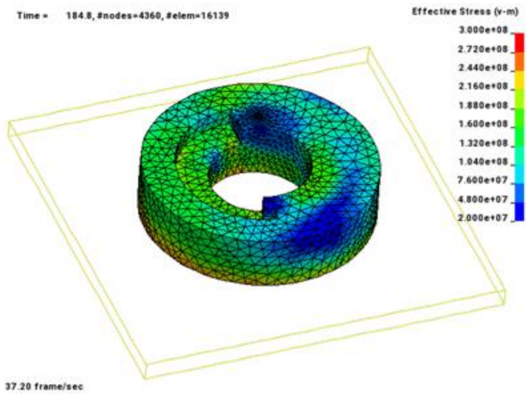
Wu et al.

- Several numerical methods under constant development
  - 3D Adaptivity, DDD, EFG, Immersed, MEFEM, Peridynamic, Reduced-order, RVE, SPG, SPH, XFEM

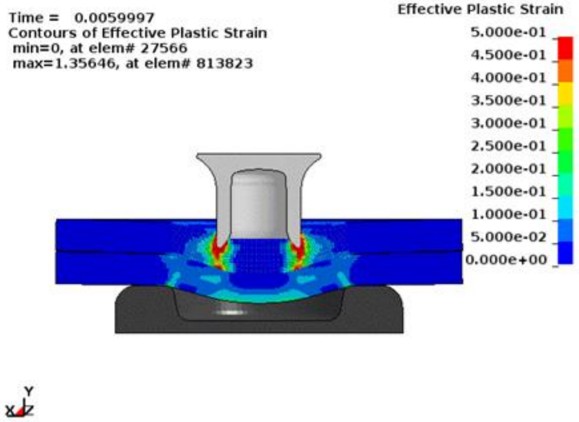
RVE:
material design



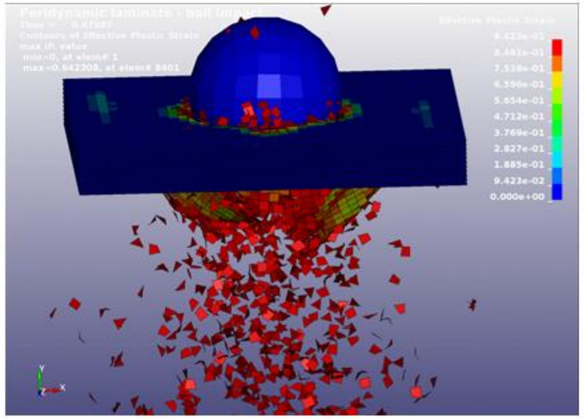
Adaptive EFG:
3-d printing



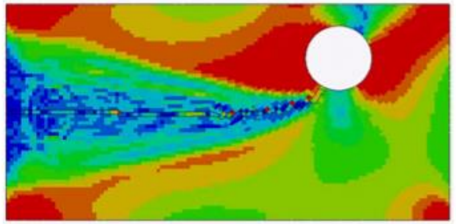
SPG:
self-pierce riveting



Peridynamic:
CFRP plate impact



XFEM:
crack propagation



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

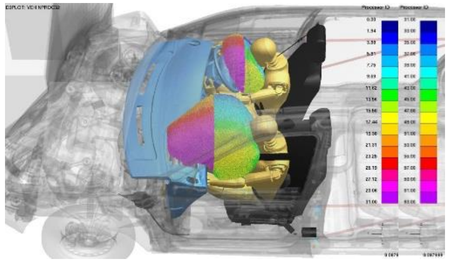
Implicit + Explicit ….

Multi-Scale

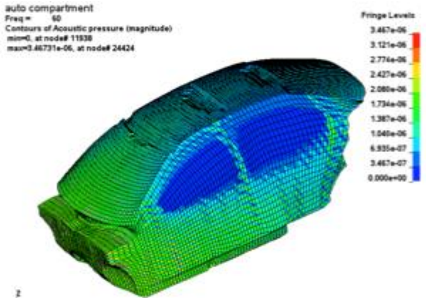
Failure predictions, i.e., spot welds

Multi-Formulations

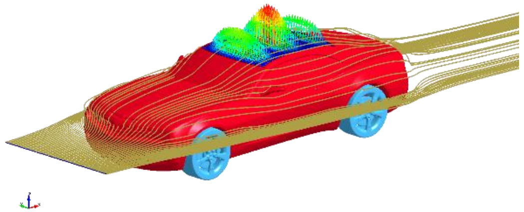
Linear + Non-Linear + Peridynamics + …



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

Upcoming Conference

LSTC
Livermore Software
Technology Corp.

DYNA MORE

Announcement and Call for Papers

12th LS-DYNA EUROPEAN CONFERENCE & USERS MEETING

14 - 16 May 2019 ▪ Koblenz, Germany

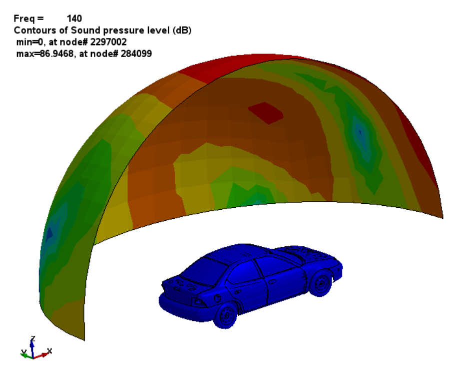
Livermore Software Technology Corp.

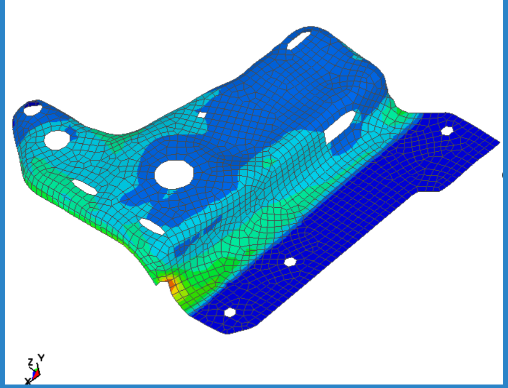
Thank you!

LS-DYNA® LS-PrePost® LS-OPT® LS-TASC® Dummies & Barriers

NVH and Fatigue Analysis

Yun Huang, Zhe Cui





Overview of NVH and Fatigue solvers

Vibration solvers

- **F**requency **R**esponse **F**unction
- **S**teady **S**tate **D**ynamics
- **R**andom **V**ibration
- **R**esponse **S**pectrum **A**nalysis

Fatigue solvers

- **R**andom **V**ibration **F**atigue
- **SSD** fatigue
- Time domain fatigue
  - *Stress based*
  - *Strain based*

Acoustic solvers

- **B**oundary **E**lement **M**ethod
  - *Collocation*
  - *Indirect*
  - *Rayleigh Method*
  - *Kirchhoff Method*
- **F**inite **E**lement **M**ethod
- **A**coustic **E**igenvalue **A**nalysis
- **S**tatistical **E**nergy **A**nalysis

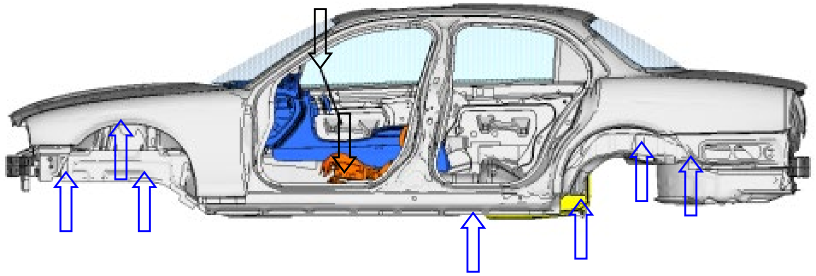
Applications

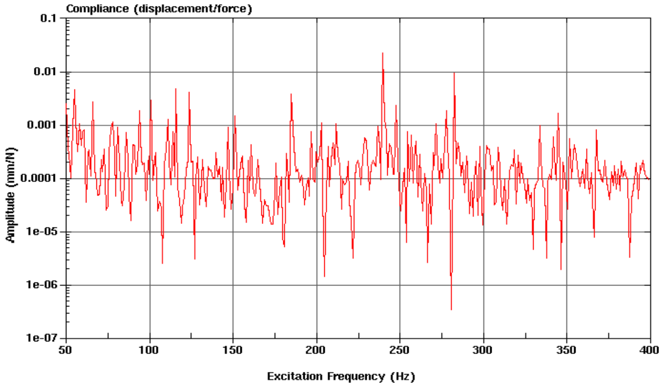
- NVH analysis of automotives and airplanes
- Civil and hydraulic Engineering
- Earthquake engineering
- Acoustic simulation
- Fatigue and durability

FRF (Frequency Response Function)

FRF for NVH

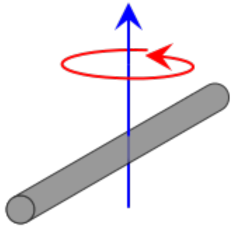
- Locate load transfer path or energy flow for road/engine excitations
- Estimate structural properties such as dynamic stiffness
- Locate natural frequencies, normal modes
- Basis for frequency response analysis
- Mechanical FRF and Acoustic FRF





Recent updates

- Implemented rotational input and output
- Implemented structural damping

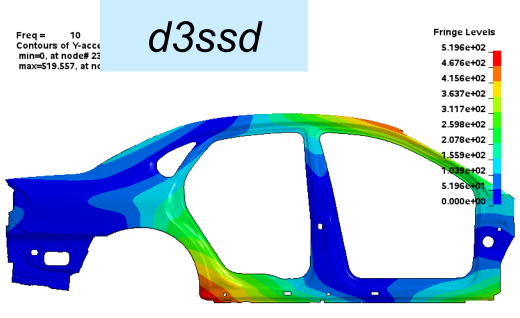


SSD (Steady State Dynamics)

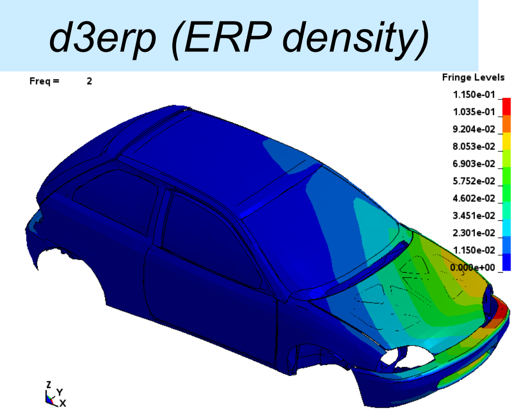
- SSD analyzes the structural response due to Harmonic excitation:
  - The unbalance in rotating machinery
  - Periodical load, e.g. in fatigue test
  - Uneven base, e.g. the force on tires running on a zig-zag road

$$\boxed{F\,(t) = F_0 \sin\left(\omega t + \phi\right)}$$

Typical harmonic excitation



Acceleration of auto side frame under harmonic excitation

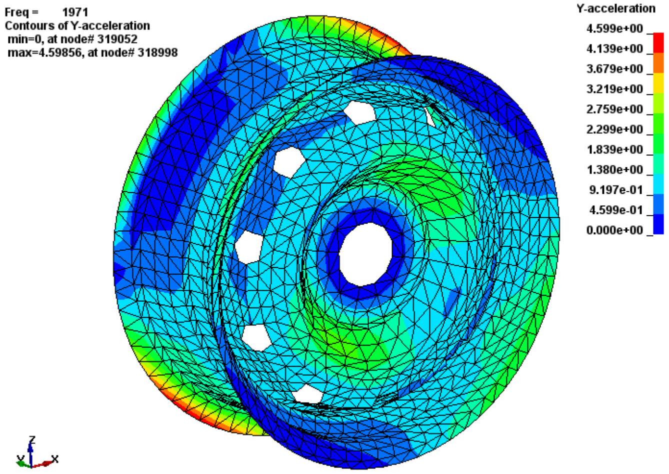


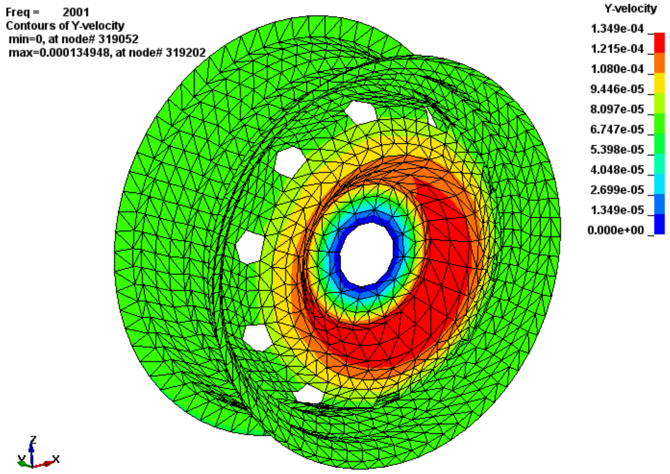
- ERP calculation is available by *FREQUENCY_DOMAIN_SSD_***ERP**:
  - It is a simple and fast way to characterize the structure borne noise
  - It gives user a good look at how panels contribute to total noise radiation
  - It is a valuable tool in early phase of product development

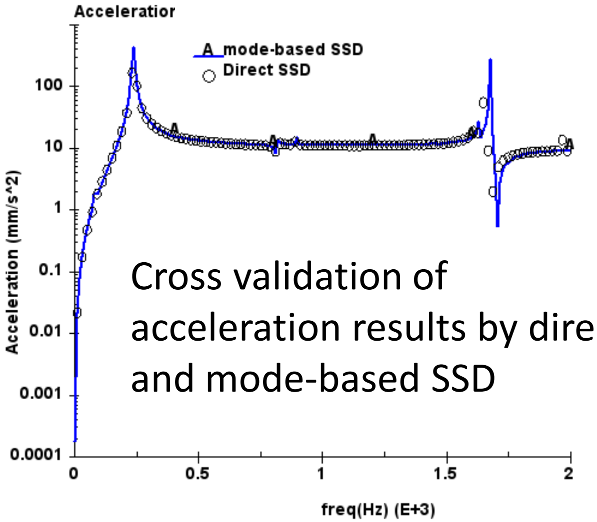
SSD – direct solver

- DIRECT solver is available by *FREQUENCY_DOMAIN_SSD_***DIRECT**
  - Solves the dynamic system in physical space, not modal space
  - No expensive eigenvalue analysis
  - No error due to mode truncation
- Frequency-dependent material properties can be considered, using the keyword *MAT_ADD_PROPERTY_DEPENDENCE:
  - it defines how a property of a material model changes with frequency
  - stiffness and damping matrices can be updated at each frequency

<u>Response of a rim model using direct SSD</u>



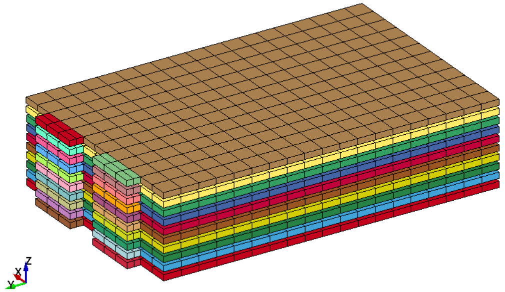


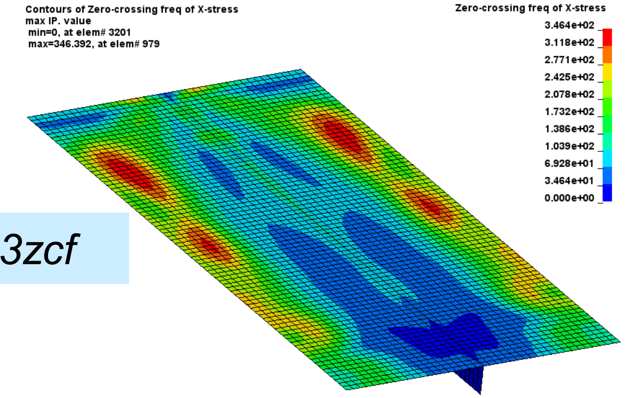


Cross validation of acceleration results by direct and mode-based SSD

Random vibration

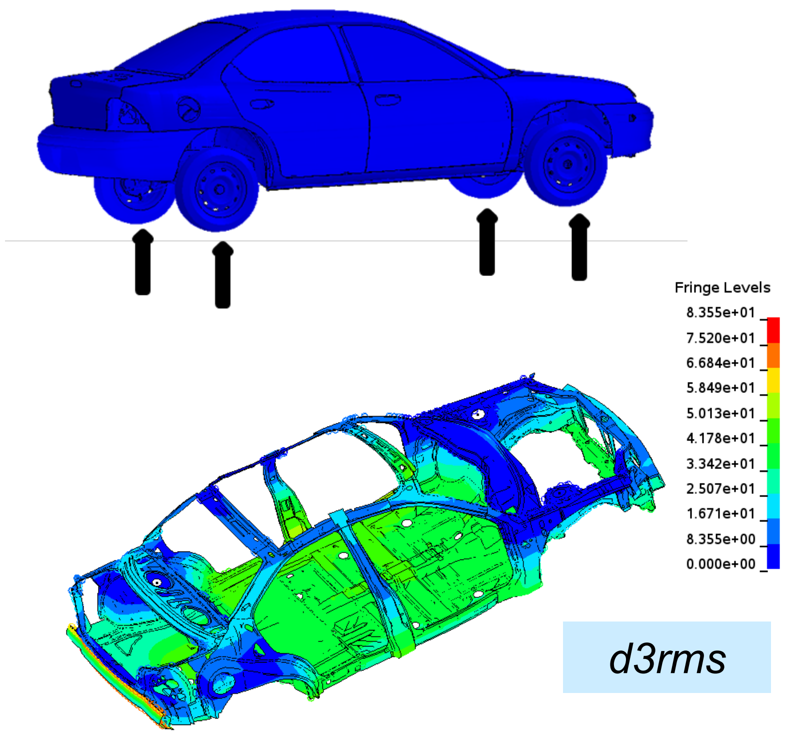
- Random vibration analysis is needed when
  - Loading Condition is not definite
  - Multiple Input Sources
  - For Random Fatigue and Durability Analysis





d3zcf

- Examples
  - Wind-turbine
  - Air flow over a wing or past a car body
  - Vibration and safety of batteries
  - Earthquake ground motion
  - Wheels running over a rough road



d3rms

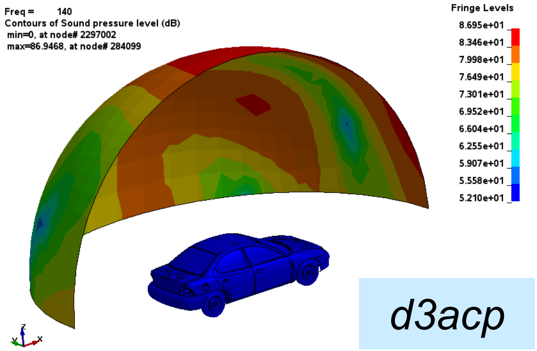
Response spectrum analysis - DDAM

- US Navy-developed analytical procedure for shock resistance analysis of on board equipment
- It evaluates the design of equipment subject to dynamic loading caused by Underwater Explosions (UNDEX)
- The analysis uses a form of Shock Spectrum Analysis that estimates the dynamic response of a component to shock loading caused by the sudden movement of a naval vessel
- The analytical process simulates the interaction between the shock-loaded component and its fixed structure

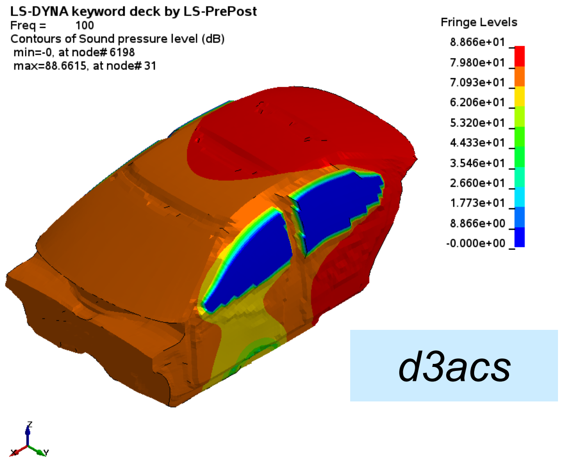
"NAVSEA 0908-LP-000-3010 (Revision 1), Shock Design Criteria for Surface Ships". Naval Sea Systems Command. September 1995. Retrieved 2012-06-26.

Acoustic analysis by BEM / FEM

- A series of BEM have been implemented
    - Variational indirect BEM
    - Collocation BEM (Burton-miller formulation).
    - Rayleigh method
    - Kirchhoff method
    - ATV/MATV techniques are available for multi load cases
    - Acoustic panel contribution analysis
    - Incident acoustic waves can be easily defined
- FEM acoustic solver provides alternative solution for interior acoustic problems (e.g. compartment)
    - Fast solution based on sparse matrix
    - 3 types of elements (Hex, Tet and Pentahedron)
    - Velocity, pressure and impedance boundary conditions
    - Acoustic Eigensolvers can be activated

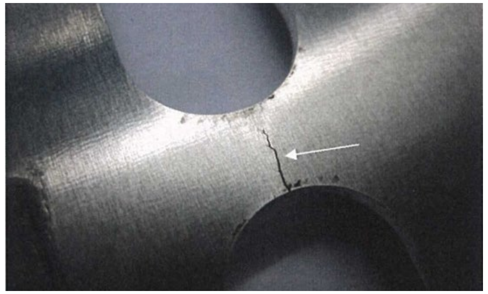


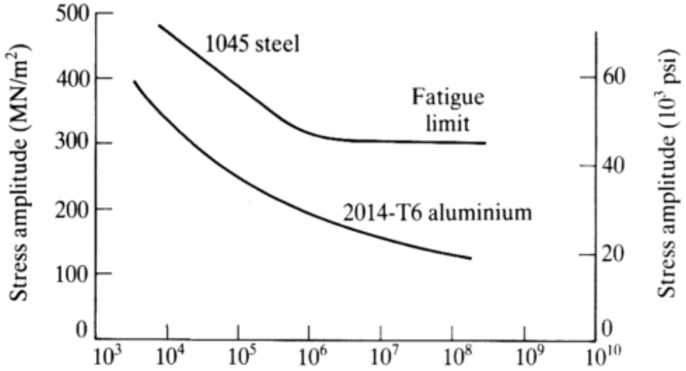
d3acp



d3acs

Fatigue analysis





Frequency domain fatigue solvers

- **Random vibration environment**
- **SSD environment**

Time domain fatigue solvers

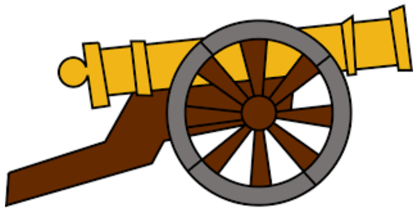
- **Based on stress (high cycle, low stress)**
- **Based on strain (low cycle, high stress)**

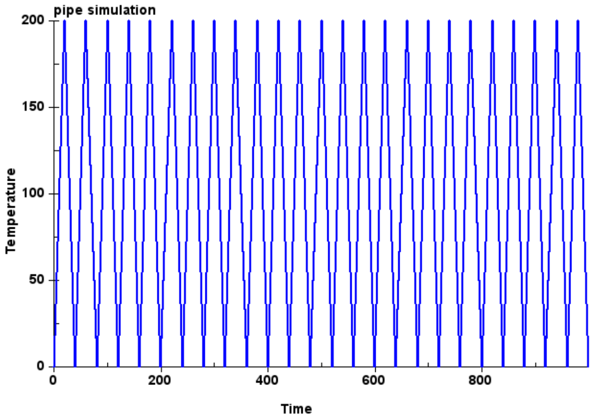
- Advantage for running fatigue analysis with LS-DYNA
  - Integration of vibration and fatigue solver in one code
  - A wide selection of stress / strain solvers in LS-DYNA (implicit, explicit, etc.)
  - Manufacturing effects (e.g. residual stress in metal forming) can be considered
  - User chooses to run fatigue analysis on whole model, part, set of parts, or set of elements of interest.
  - Future integration with LS-OPT / LS-TASC for multidisciplinary optimization

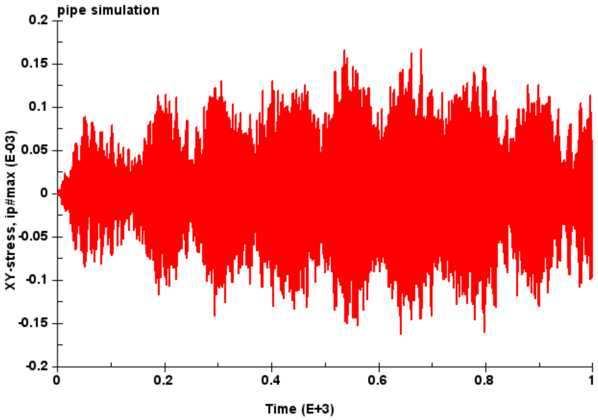
GM: Jong S. Park, Ramakrishna Dospati, Ye-Chen Pan, Amit Nair, Random vibration fatigue life simulation of Bolt-on Metal Brackets using LS-DYNA, the 15th International LS-DYNA Users Conference, June 10-12, 2018, Dearborn, MI.

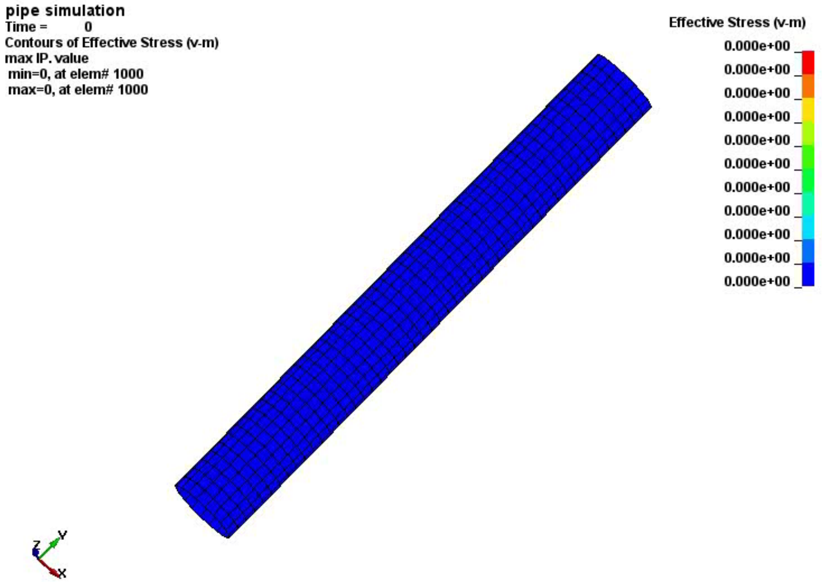
Time domain fatigue – Stress based Example

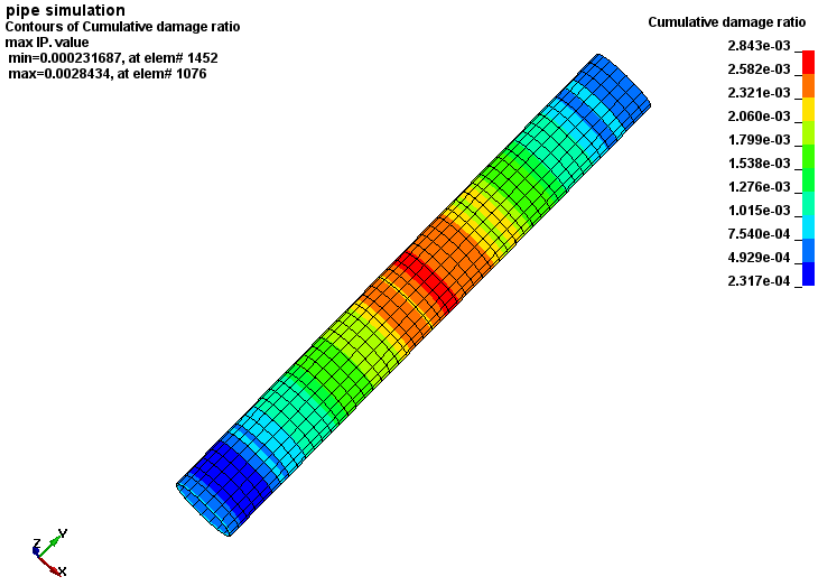
This example studies the fatigue life of a metal pipe, under cyclic thermal stress condition, which is caused by gunfire or other events which are characterized by cyclic temperature change.





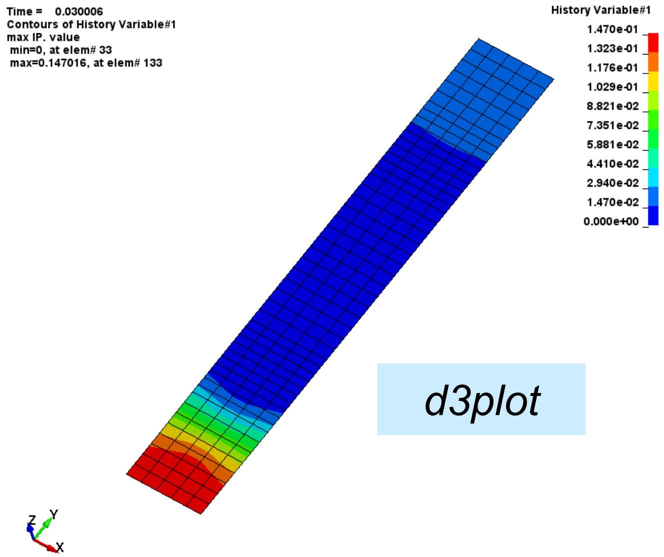




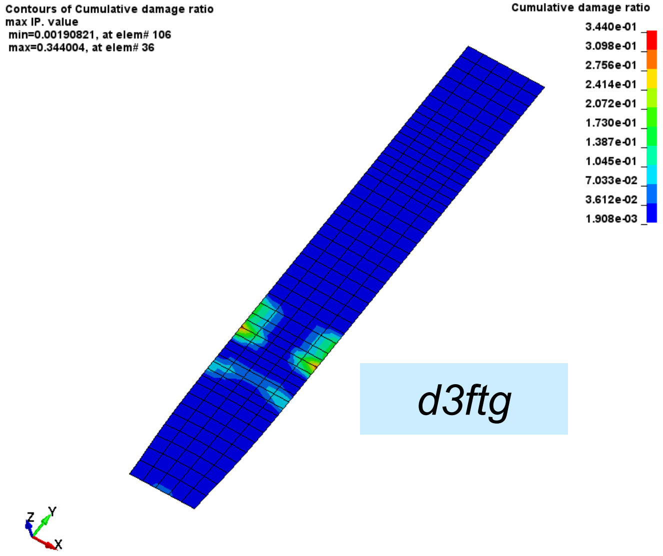


Initial Fatigue Damage Ratio

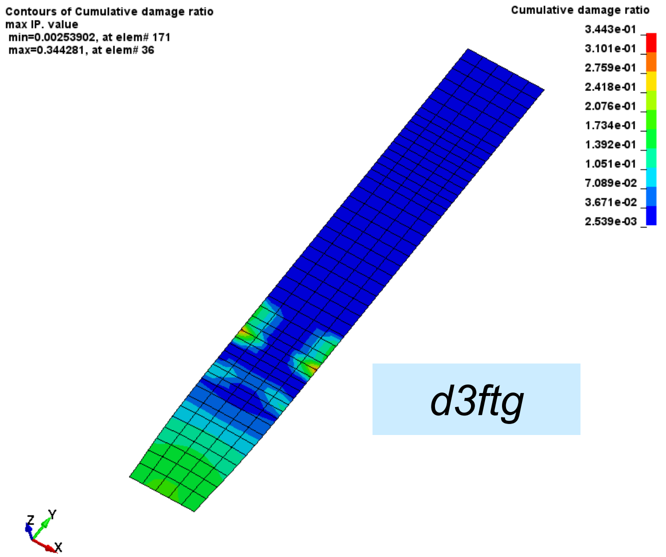
- Defined by *INITIAL_FATIGUE_DAMAGE_RATIO
  - Initial damage ratio can come from past fatigue analysis (d3ftg)
  - Initial damage ratio can come from transient preload (d3plot), e.g. *mat_add_erosion, *mat_add_damage_gissmo, etc.
- Summed up by *FATIGUE_SUMMATION



Damage from transient preload case (d3plot)



Damage ratio from fatigue load



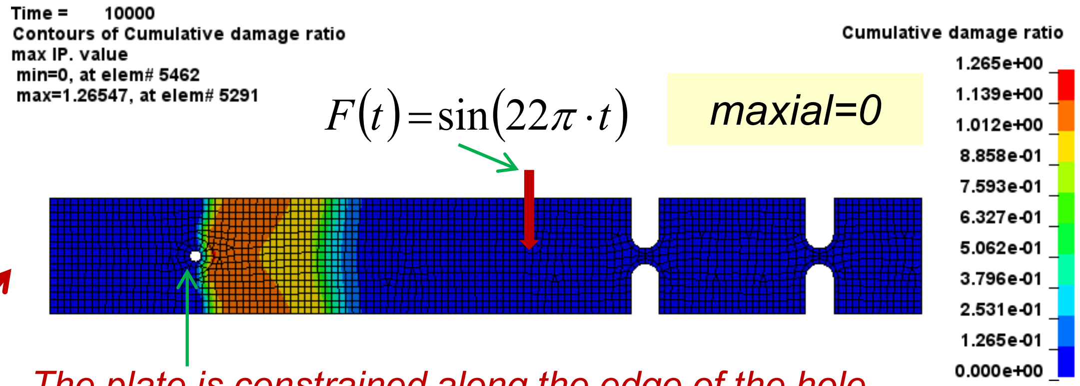
Cumulative damage ratio from transient preload + fatigue load

Multi-Axial Fatigue Analysis

- Stress / strain state is always three dimensional
  - A scalar index (e.g. Von-Mises stress, 1st principal stress) can be used
  - Fatigue damage is computed on multiple planes and the max value is picked
  - A critical plane is located and fatigue analysis is performed on the critical plane

```
*FATIGUE_ELOUT
$#     ssid      sstype
$
$#       dt
$
$#    stres       index
                                 1
*FATIGUE_MULTIAXIAL
$#   maxial      nplane
          1         180
```

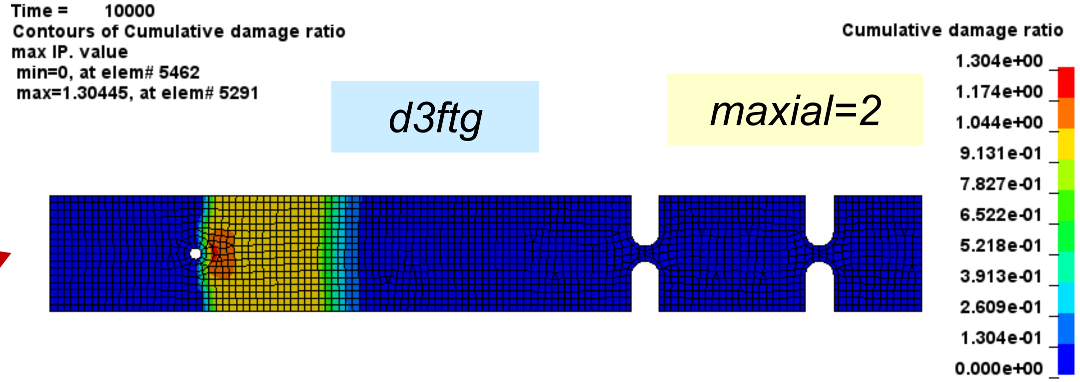
maxial	nplane	Max damage ratio
0		1.26547
1	18	1.30282
1	36	1.30282
1	72	1.30327
1	180	1.30327
2		1.30445



$F(t)=\sin(22\pi \cdot t)$

maxial=0

The plate is constrained along the edge of the hole



d3ftg

maxial=2