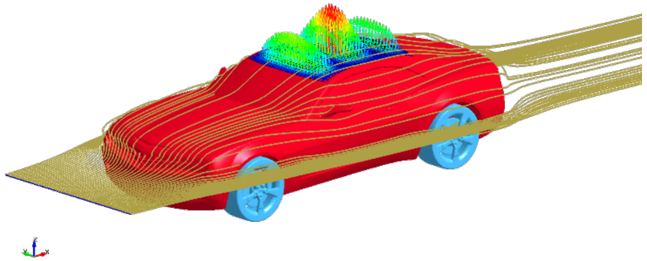
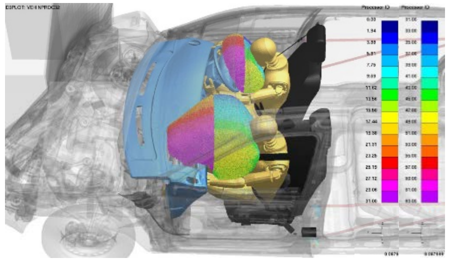
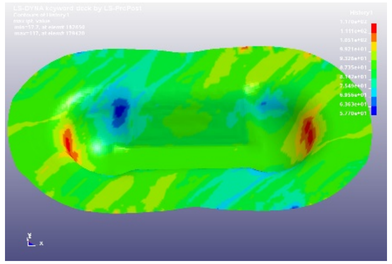
Recent and Ongoing Developments in LS-DYNA®

LSTC
Livermore Software Technology Corp.

John O. Hallquist, Pierre L'Eplattenier, Facundo Del Pin, Jason Wang, Edouard Yreux, John Zhao, Yun Huang, Isheng Yeh, Nielen Stander







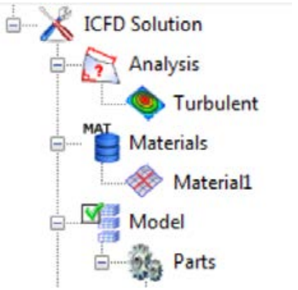
Nordic LS-DYNA Users Conference

Göteborg, Sweden

October 18, 2018

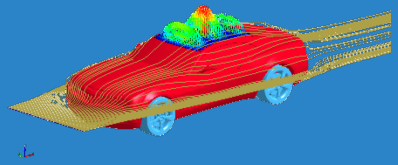
LSTC | Products

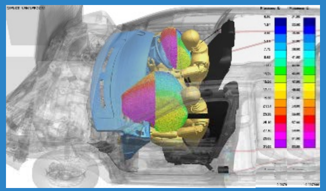
Multi-Physics Solver, Pre-and-Post Processor, Optimization, and Library of Validated Dummies and Barriers

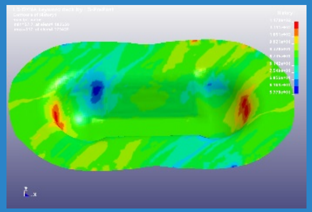


LS-PrePost

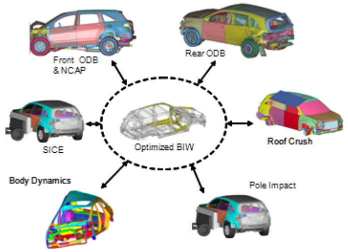
Dummies & Barriers



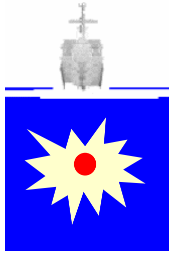




LS-DYNA®



LS-OPT/LS-TaSC



USA

No additional license cost

LS-DYNA | One Code, One Model

Single Model for Multiple Disciplines – Manufacturing, Durability, NVH, Crash, and FSI

Multi-Physics

Structure + Fluid + EM + Heat Transfer

Multi-Stage

Implicit + Explicit ….

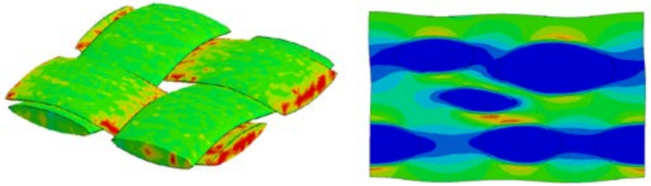
Multi-Formulations

Linear + Non-Linear + Fatigue …

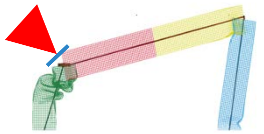
Multi-Scale

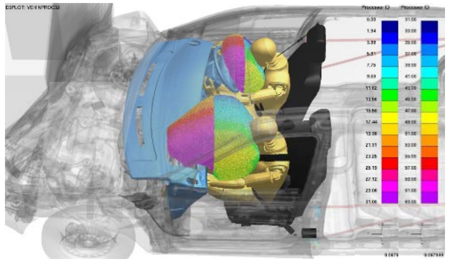
Failure predictions, i.e., spot welds, composites, crystal plasticity

Composites (C.-T. Wu)

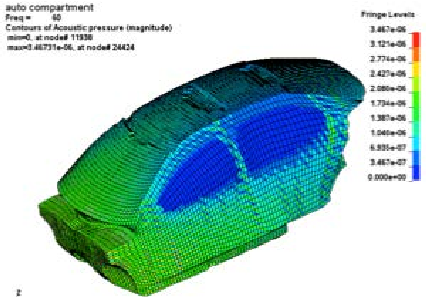


Crushable beam (Yeh)

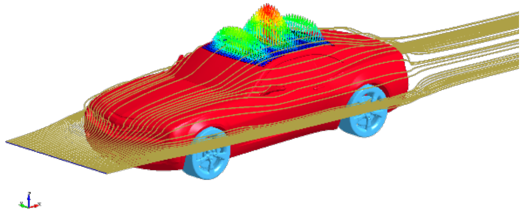




Crash



NVH

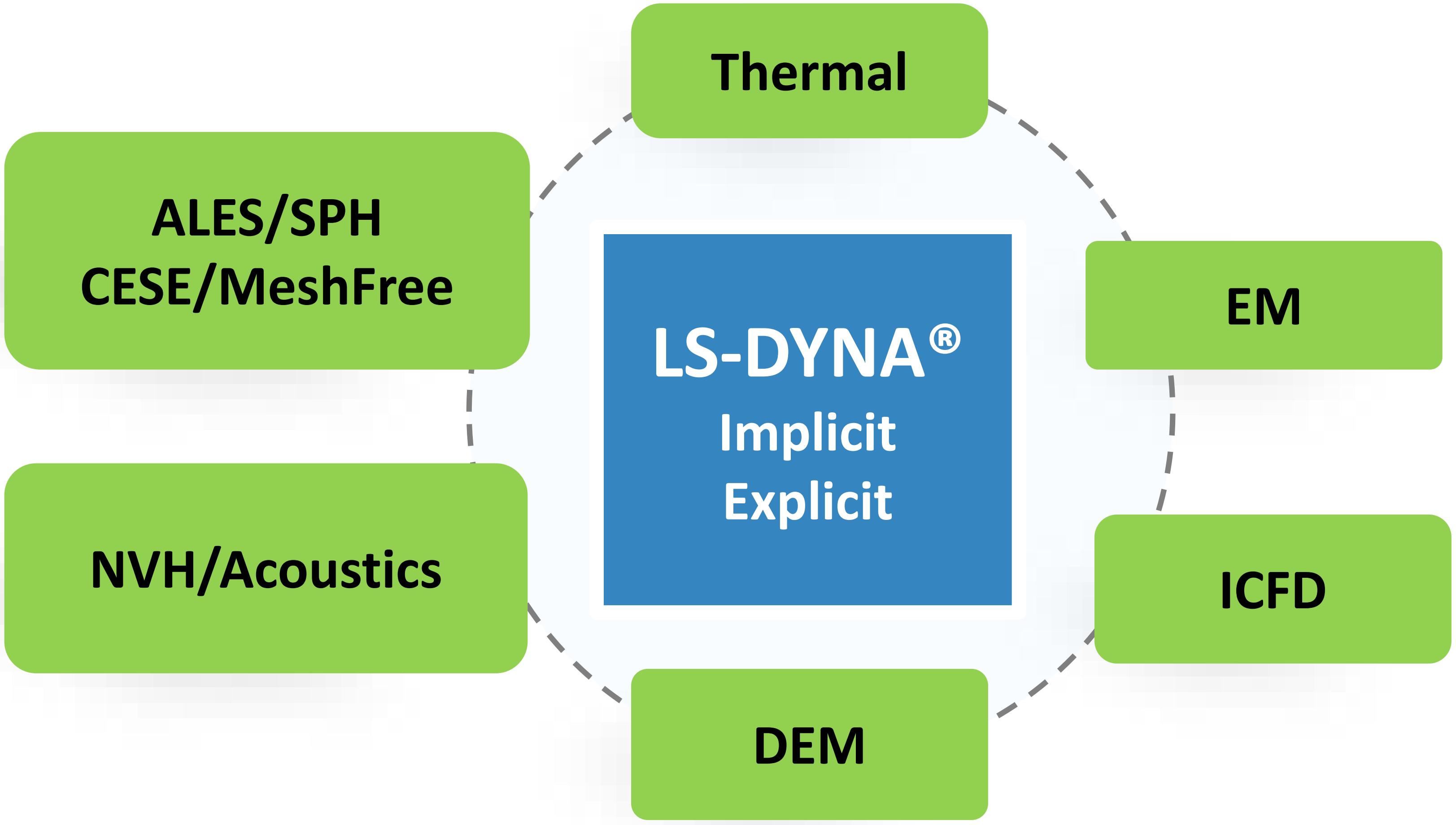


Structure + Fluid

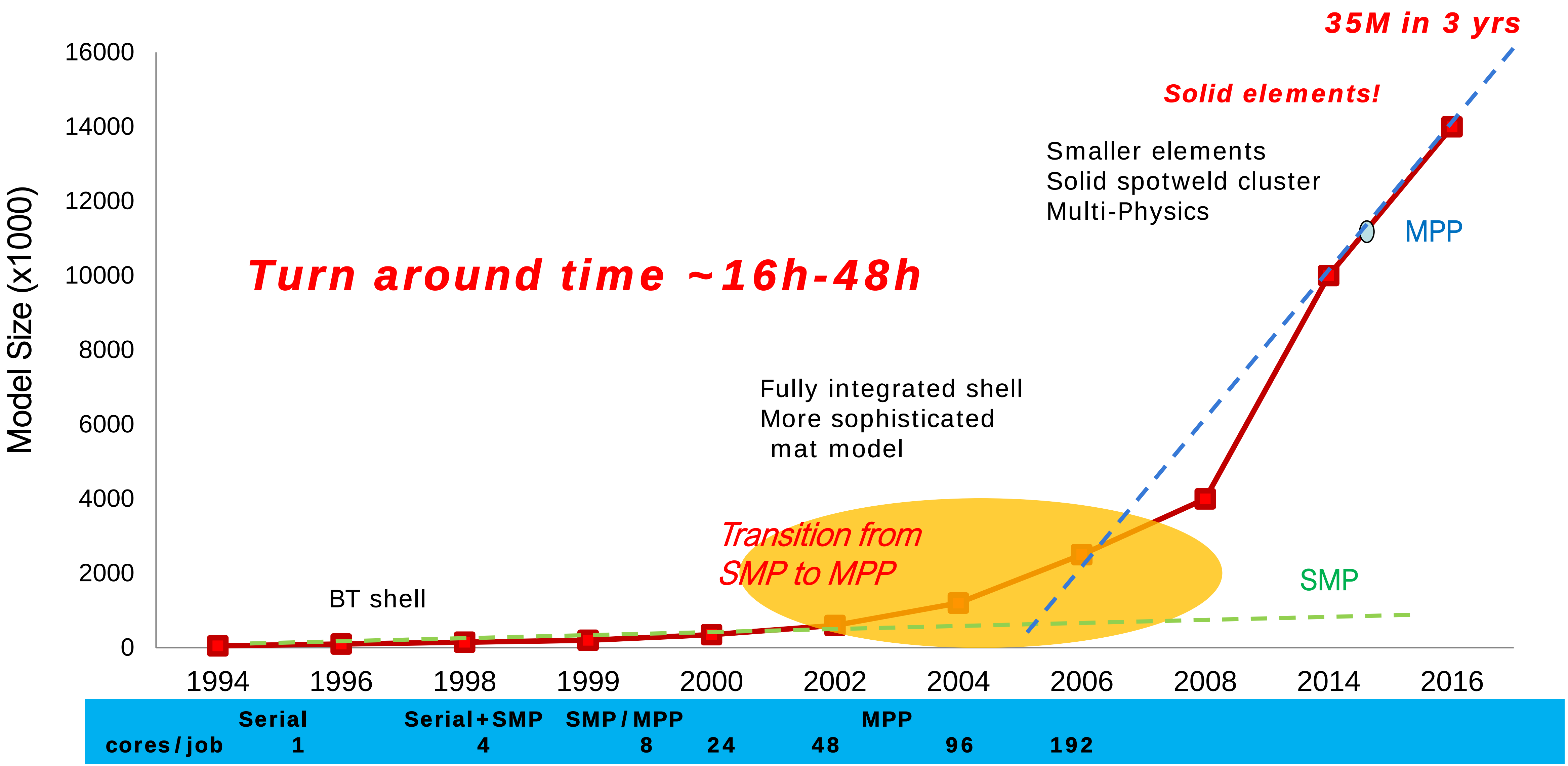
LS-DYNA | Strongly Coupled Multi-Physics Solver

Computers capable of multi-physics simulations are becoming affordable.

Scalability is rapidly improving for solving multi-physics problems



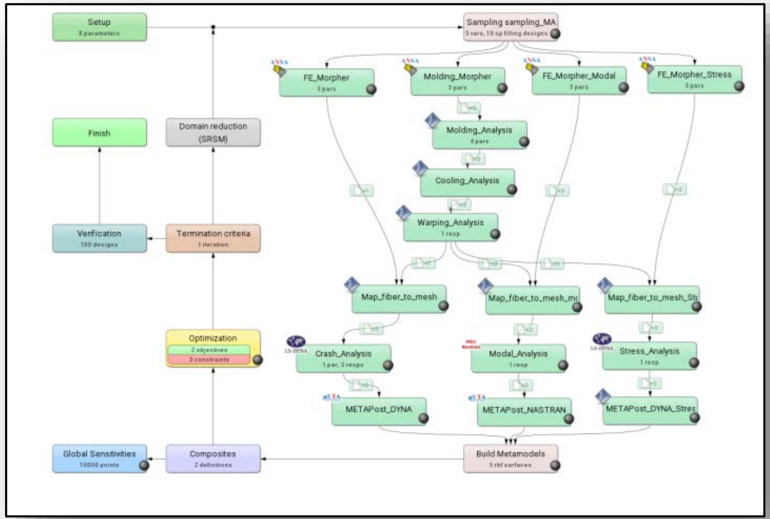
Model size for Safety Analysis



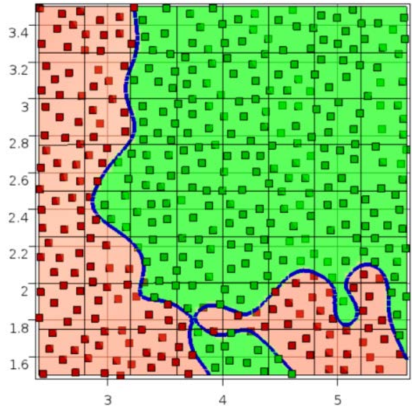
LS-OPT® | Optimization, Probabilistic Analysis & System Calibration

LS-DYNA® can be incorporated in a *multi-stage, multi-case, multi-level* process

- **Multi-case, Multi-stage, Multi-level**



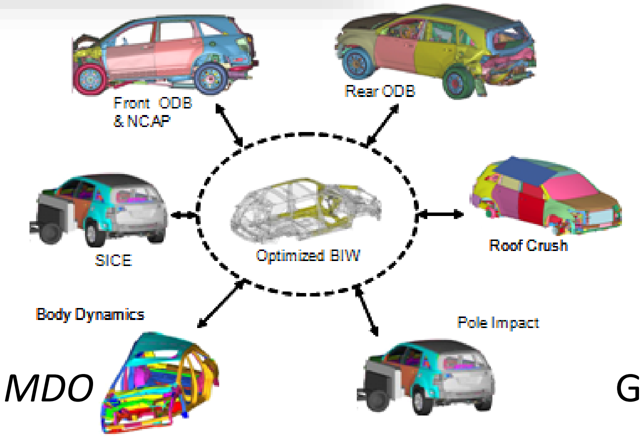
- **Statistics & Uncertainty**
  - Robust Design
  - Sensitivity Analysis
  - LS-DYNA® Statistics
  - Outlier Analysis
  - *Classification*



SVM Classifier

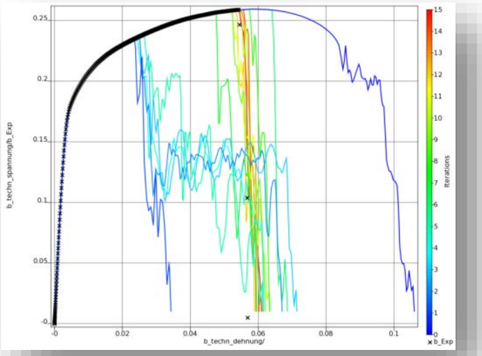
- **Material Calibration**
  - Hysteresis: Loading-Unloading
  - *Noise handling e.g. GISSMO*
  - *Full-field Calibration w. Digital Image Correlation*

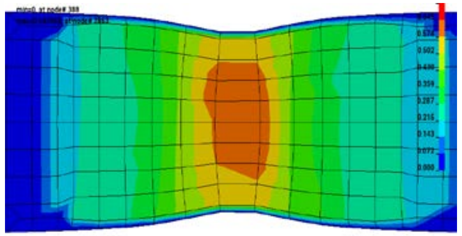
- **Optimization**
  - MDO
  - MOO
  - Discrete variables



Multi-case MDO

GISSMO





Digital Image mapping

Outline

Electromagnetics
Pierre L'Eplattenier

ICFD
Facundo Del Pin

Particle Methods
Jason Wang

Implicit Analysis
Roger Grimes

Composites
John Zhao

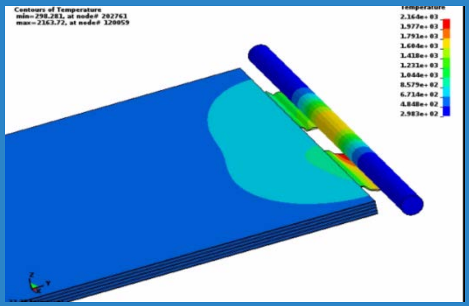
Acoustics and Fatigue Analysis
Yun Huang

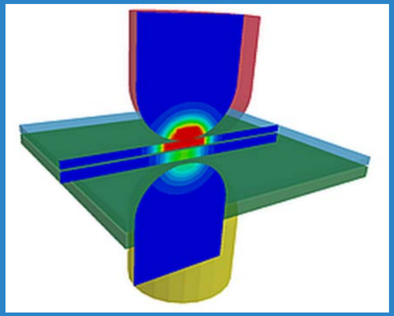
Crashworthiness: Beams
Isheng Yeh

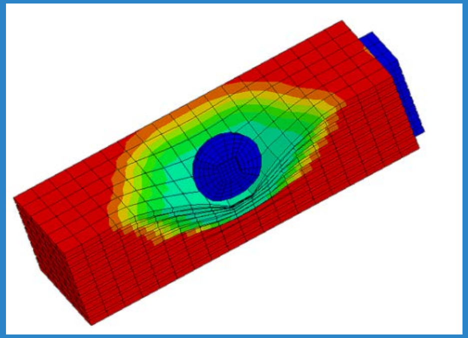
Optimization
Nielen Stander

Electromagnetics

Dr. Pierre L’Eplattenier





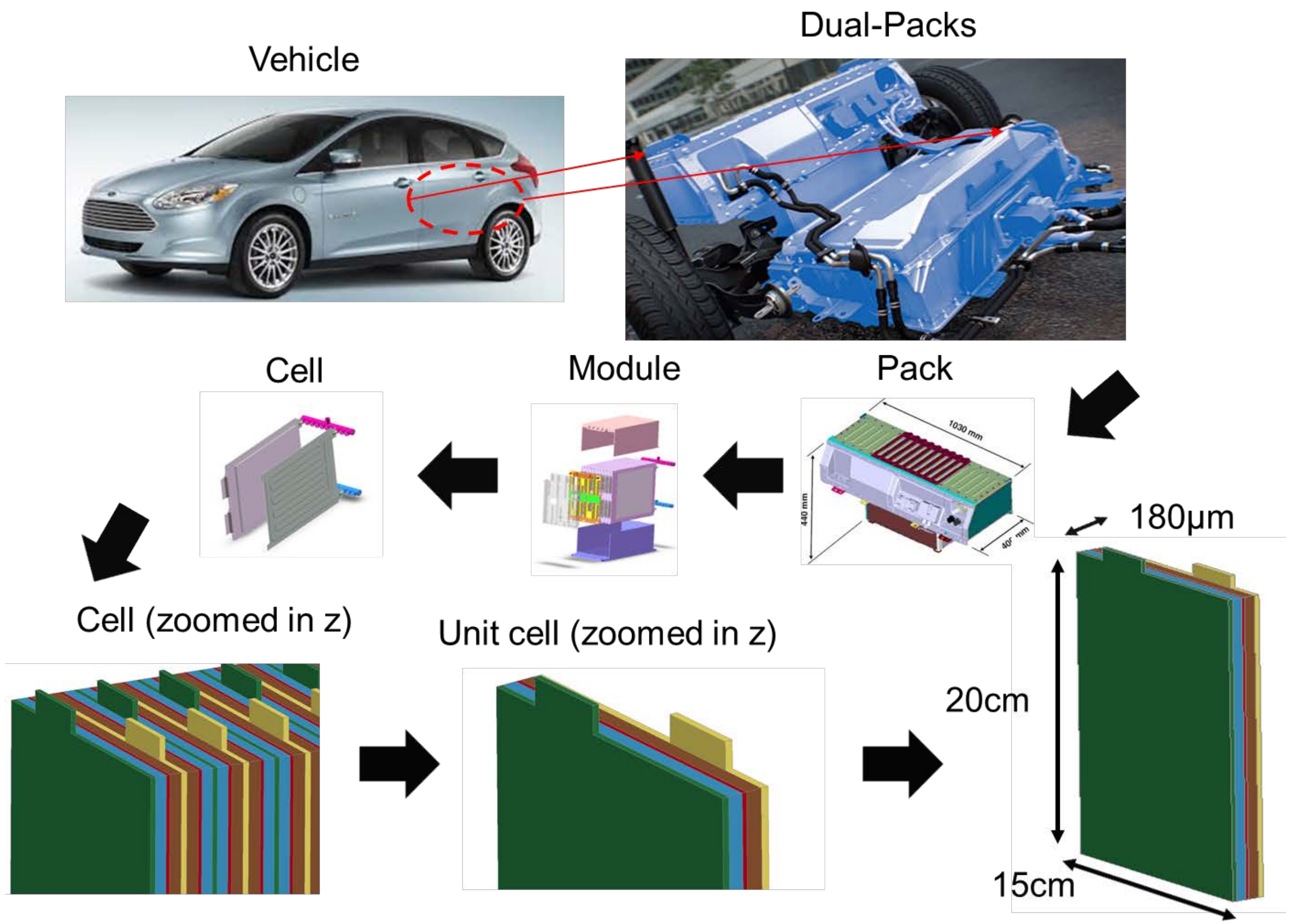


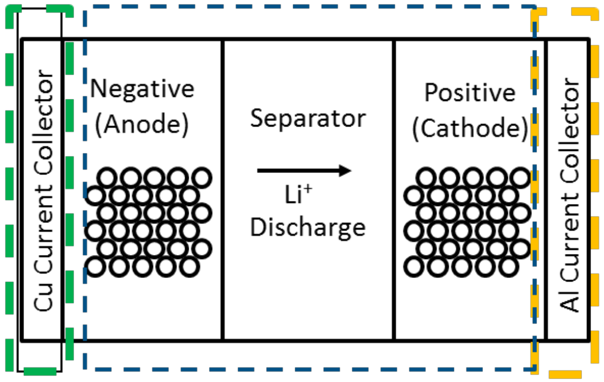
Outline

- Battery abuse
- Resistive spot welding

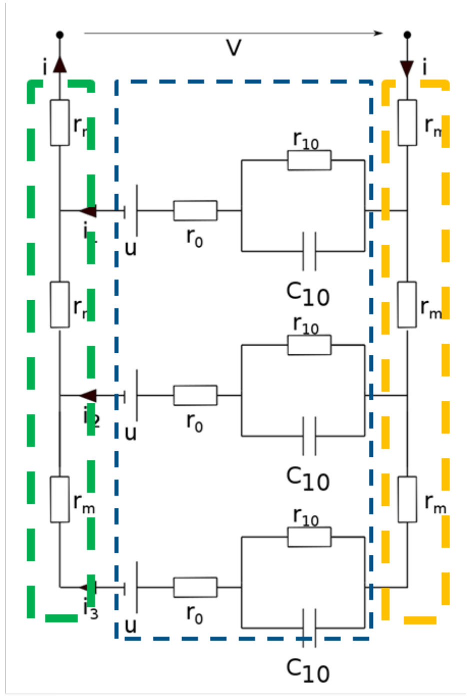
Battery – Distributed Randles circuit model

Electro-chemistry in the electrodes simulated by equivalent electrical circuits (Randles circuits)





- Current collectors transport electrons to/from tabs; modeled by resistive elements
- Jelly roll (anode – separator – cathode) transports Li+ ions; modeled with Randle circuit



r_0: Ohmic & kinetic

r_{10} & c_{10}: Diffusion

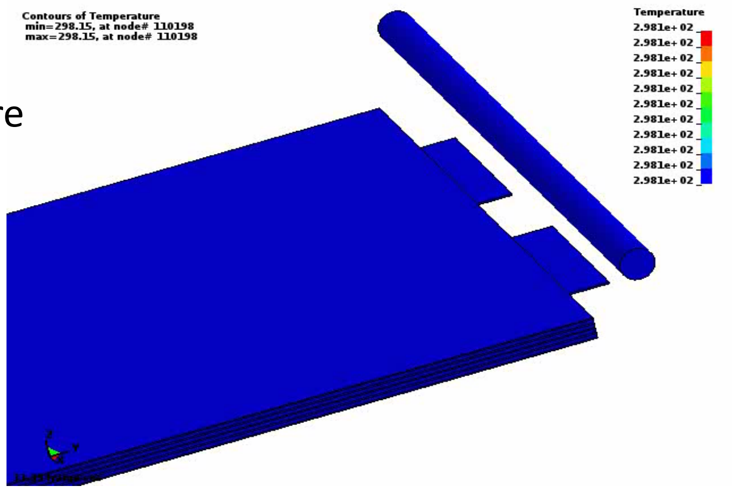
u: Equilibrium voltage (OCV)

r_m: Current collectors

Battery abuse simulations

- Battery abuse simulations on cells, modules, packs
- Pouch cells, cylindrical cells available, soon prismatic cells
- Coupled with mechanical and thermal solvers
- Solid, shells and composite thick shells
- External and internal shorts
- Battery packaging application in LS-PrePost

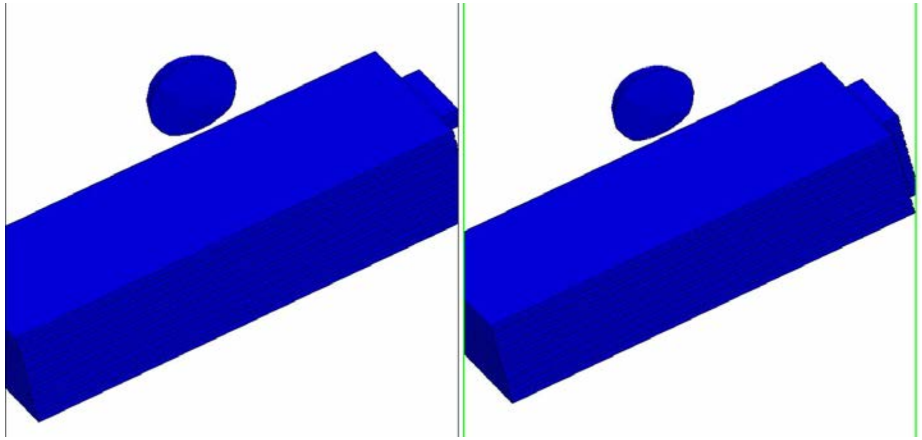
Temperature



External short
5 cells module

Potential

Current density



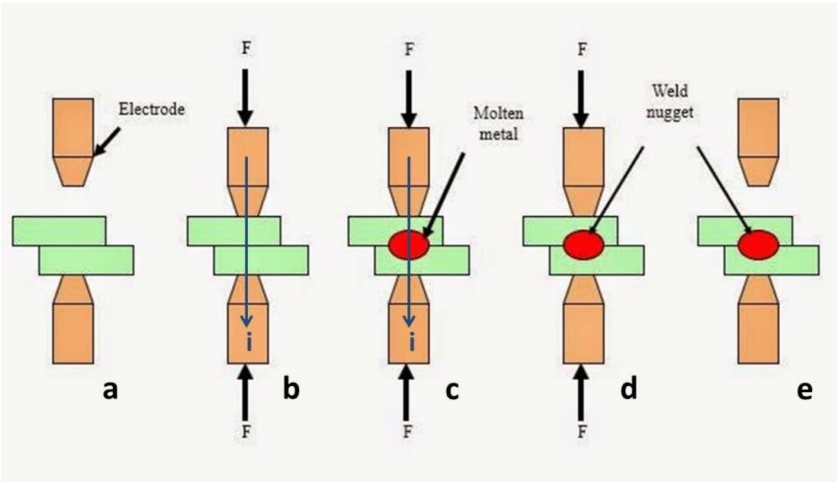
Internal short
10 cells module

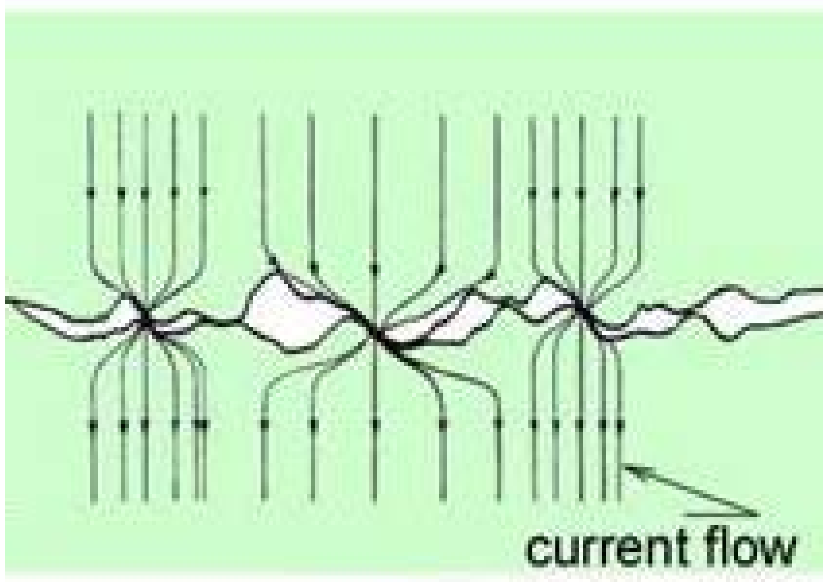
Resistive spot welding

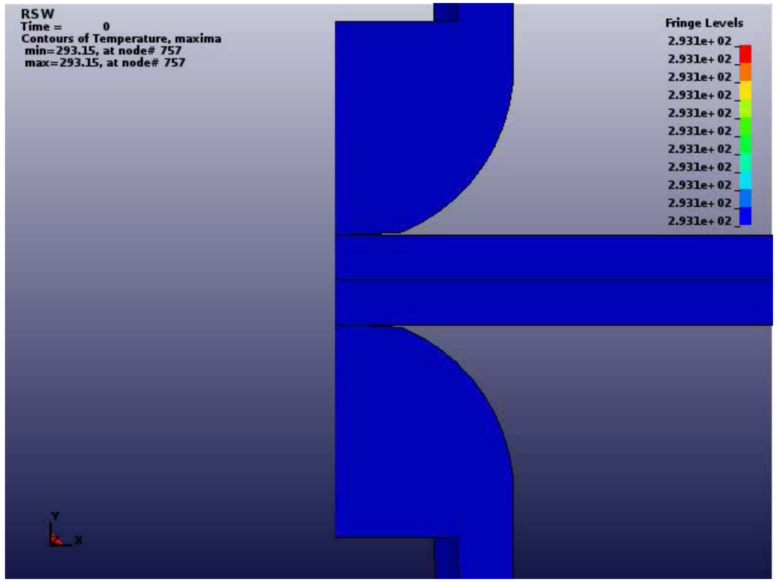
New model in LS-DYNA for local contact resistance depending on local parameters, using *DEFINE_FUNCTION

$$r(T,P) = r_0 \left(\frac{p - p_k}{p_0 - p_k} \right)^{\varepsilon_p} \cdot \left(\frac{T - T_{\lim} + (293{,}15\ K - T) \cdot 2^{-\frac{1}{\varepsilon_T}}}{293{,}15\ K - T_{\lim}} \right)^{\varepsilon_T}$$

Electrodes on each sides of sheets using Pressure and Current Flow resulting in molten weld nugget

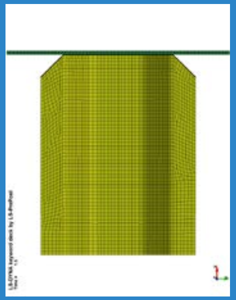


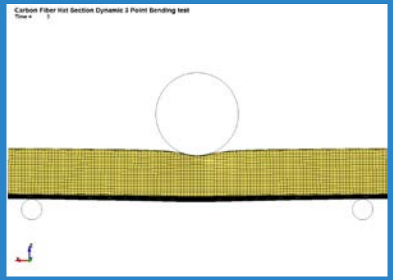


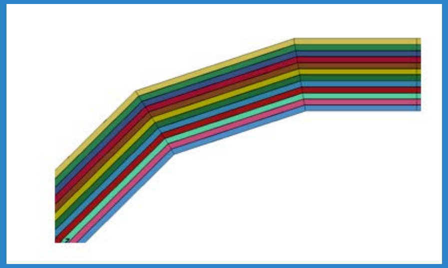


Composites

Dr. John Zhao







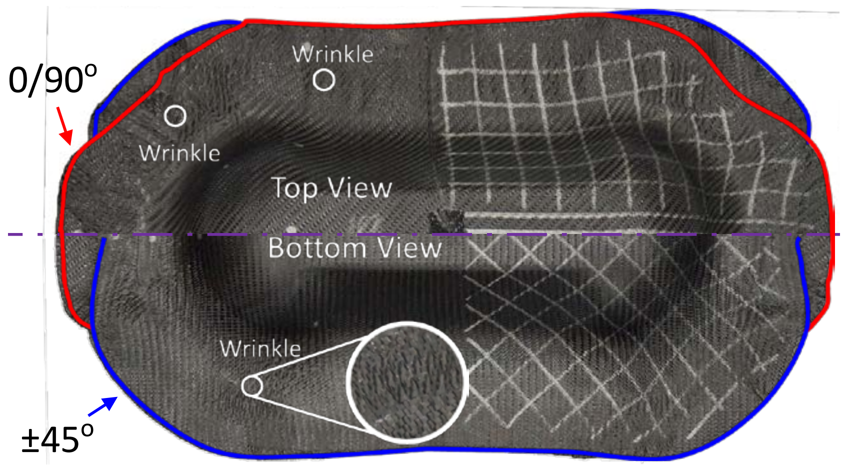
Continuous long fiber compression molding

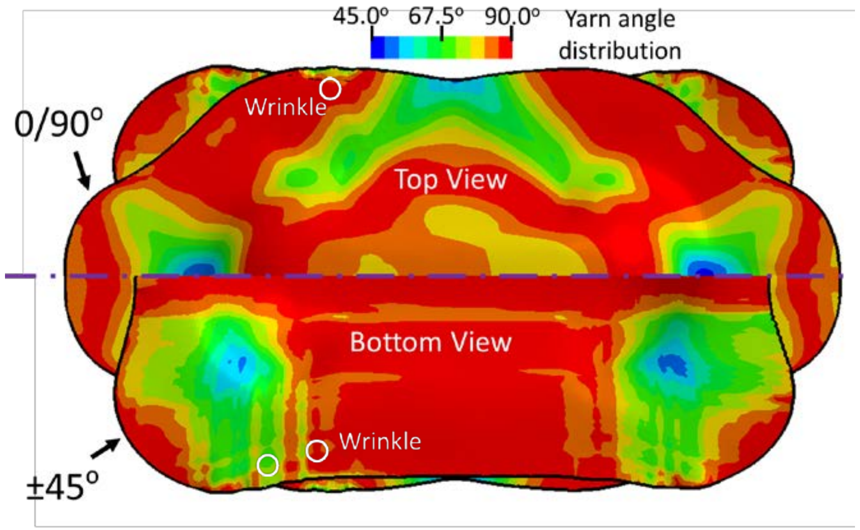
Transfer the fiber orientation from the manufacturing process to the crash analysis.

- MAT_277 developed by DOW and Ford for resin curing process. Curing curve determines mechanical properties.
- MAT_278 micro mechanics model for woven prepreg compression molding. Deformation gradient to update angle changes.
- MAT_293 non-orthogonal model for compression molding developed . Easy integration of test results.
- For woven long fiber composite, fiber angle after forming is crucial information for accurate prediction of crash performance

Layers differ in:
- Geometry
- Drawing distance

Sliding between layers

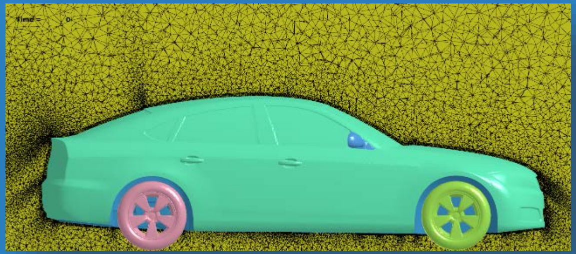
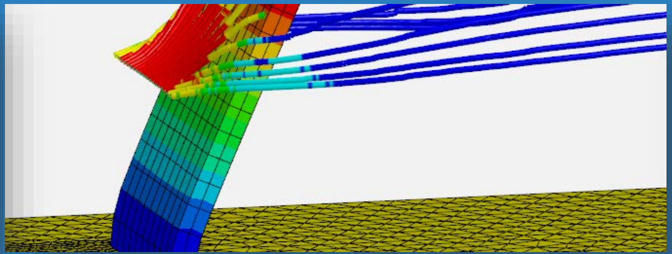
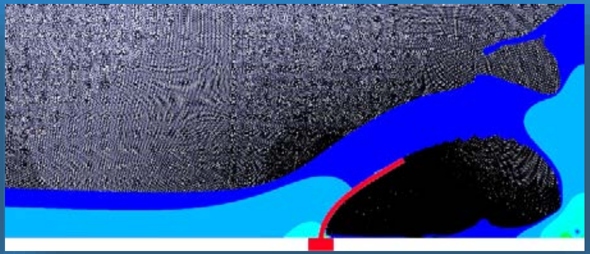




ICFD
Recent Developments

Facundo Del Pin

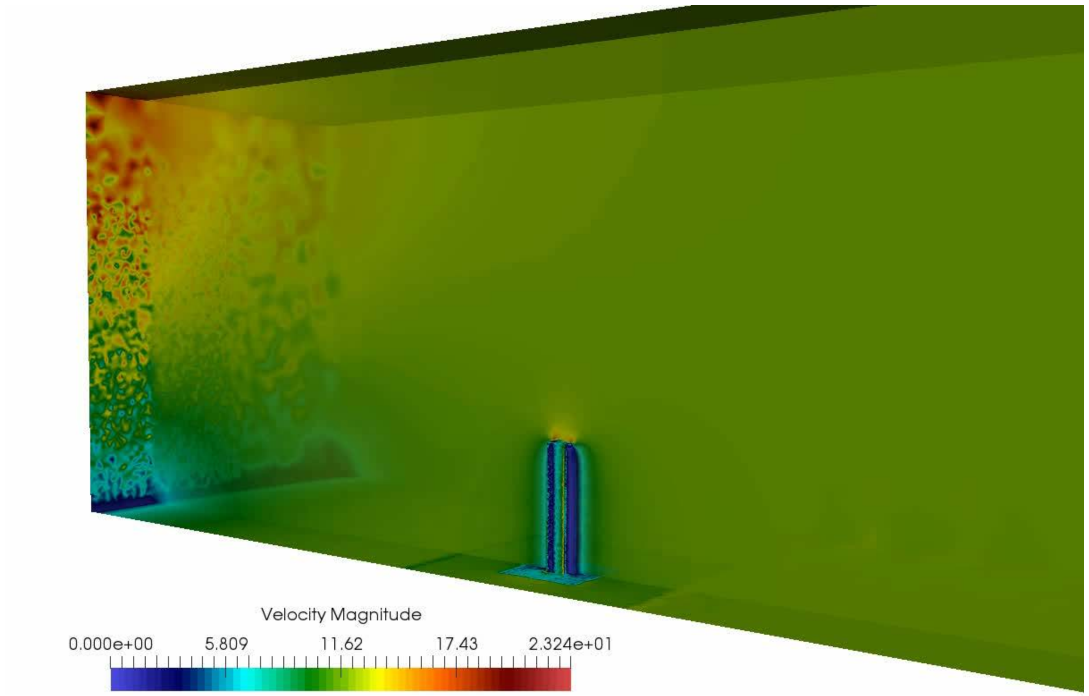
Iñaki Çaldichoury
Rodrigo R. Paz
Chien-Jung Huang

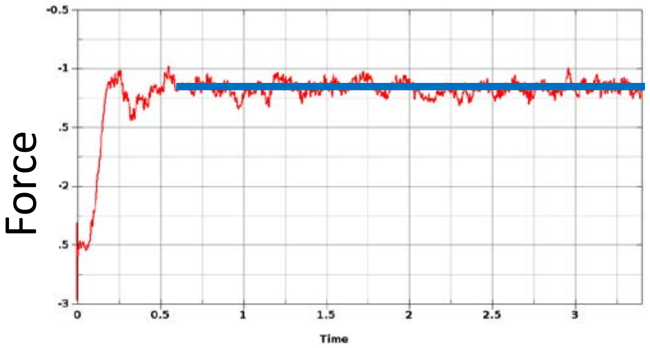




Steady State for Fluid-Structure Interaction

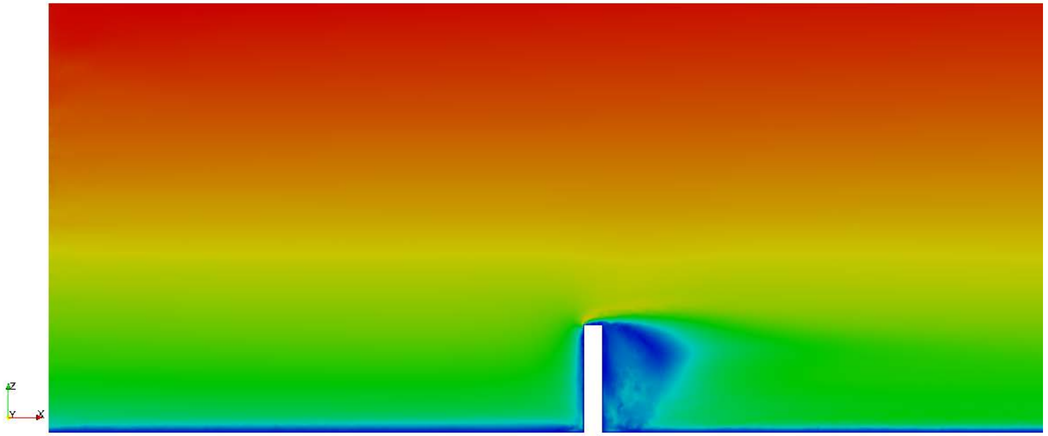
Delpin, Caldichoury, Paz, Wang

The steady state solver or the potential flow solver allow for a fast linearization of Fluid Structure Interaction (FSI) and/or Conjugate Heat transfer (CH) problems





Steady state analysis allows engineers to study physical problems in a time average fashion.

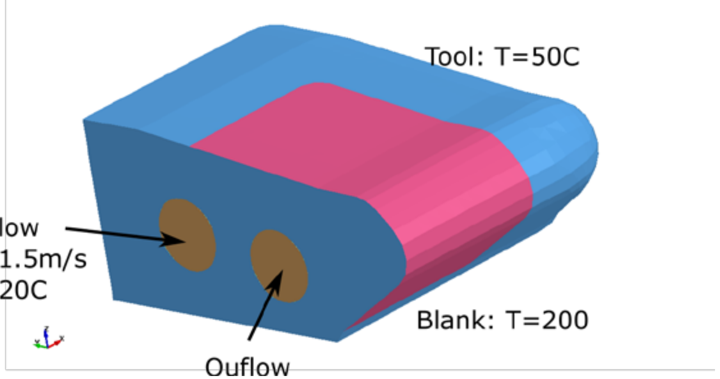


These simulations provide valuable insight faster which is useful for prototyping.

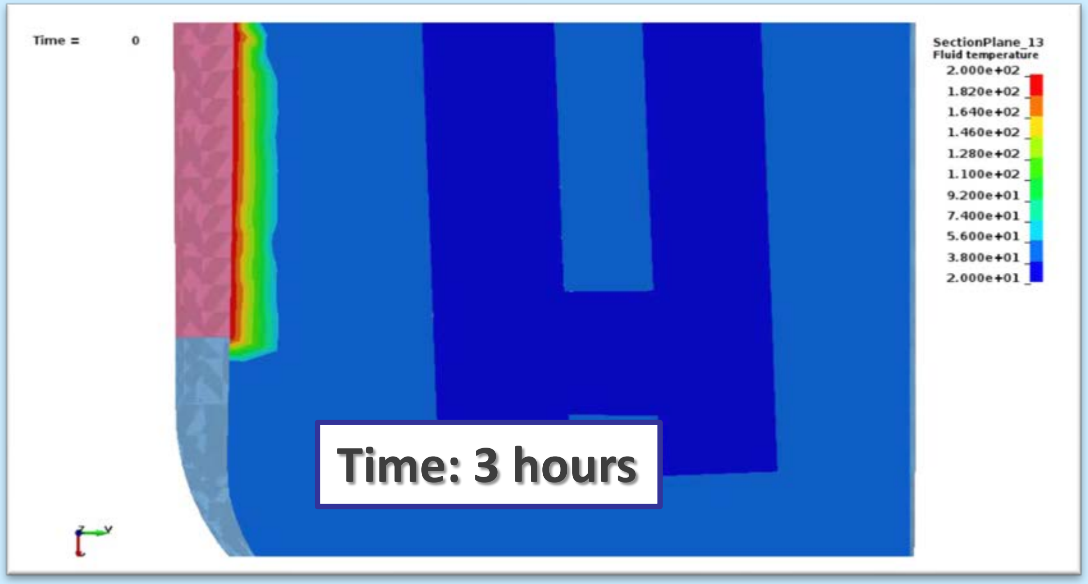
Conjugate Heat: Cooling problem

Delpin, Caldichoury, Paz, Wang

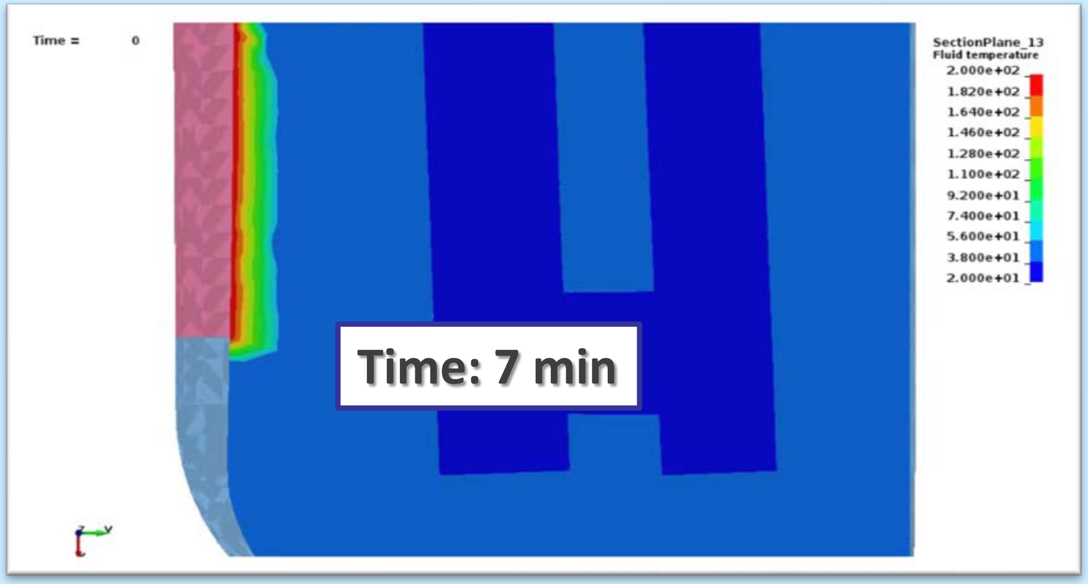
- Conjugate heat solver: Transfer heat from solid to fluid
- Run steady state Navier-Stokes or Potential flow. Use ***ICFD_CONTROL_GENERAL** to set it up.
- Once steady state reached or Potential flow finishes the conjugate heat solver will use the *steady velocity* for the *thermal analysis*.



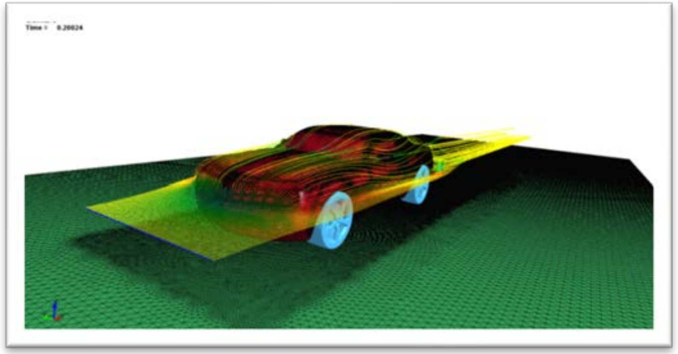
Navier Stokes Temperature (coupled)



Potential Flow Temperature



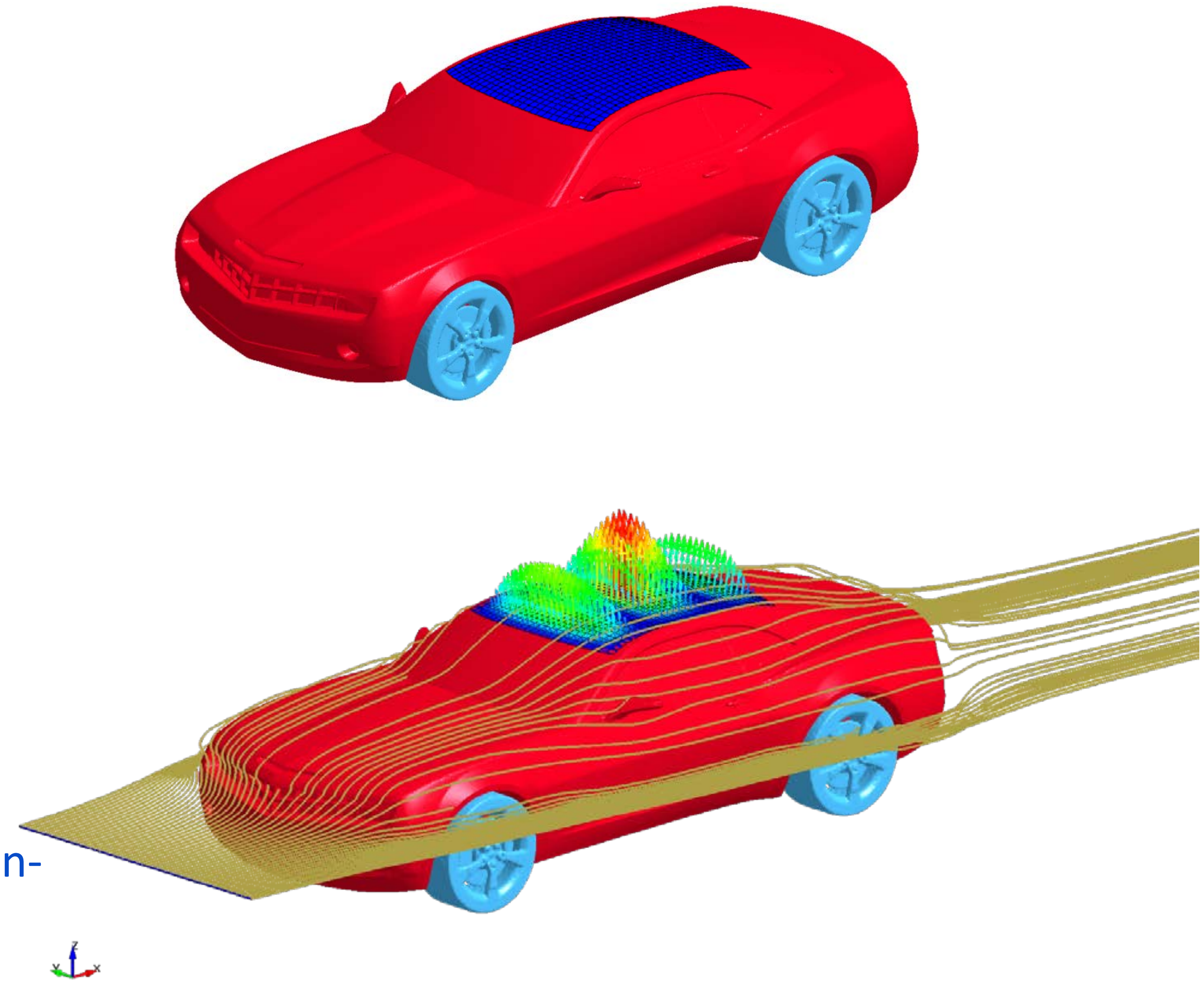
Steady State + Fluid Structure Interaction



- CFD analysis of full vehicle.
- Couple parts of the structure to analysis the response in a realistic environment.

3 different options to solve the same problem:

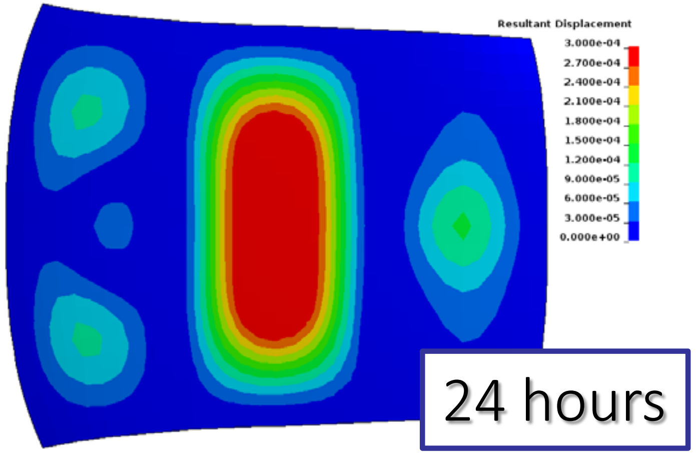
- Solve Full Navier–Stokes with FSI non linear coupling
- Solve Potential flow. Provides forces for a non-linear structural analysis
- Solve the structural analysis alone using the output from Navier-Stokes



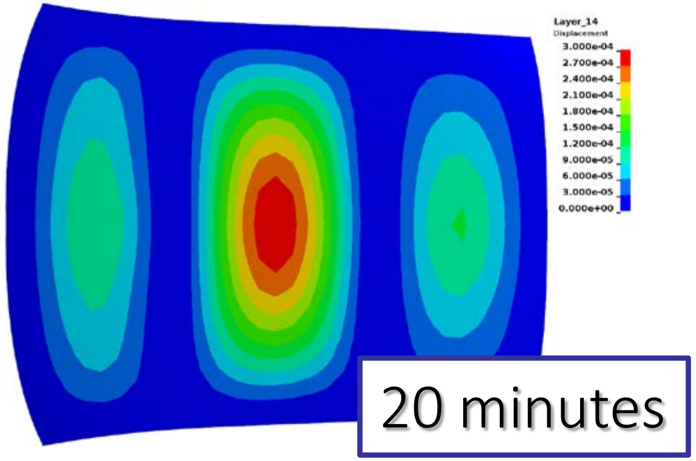
Steady State + Fluid Structure Interaction

Delpin, Caldichoury, Paz, Wang

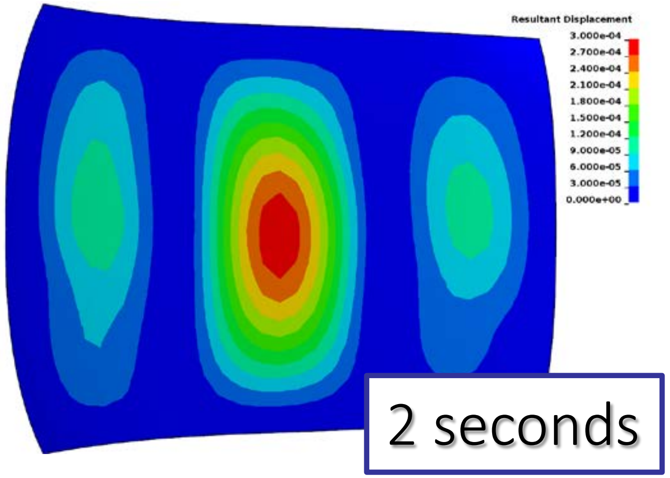
Coupled Navier Stokes



Potential Flow

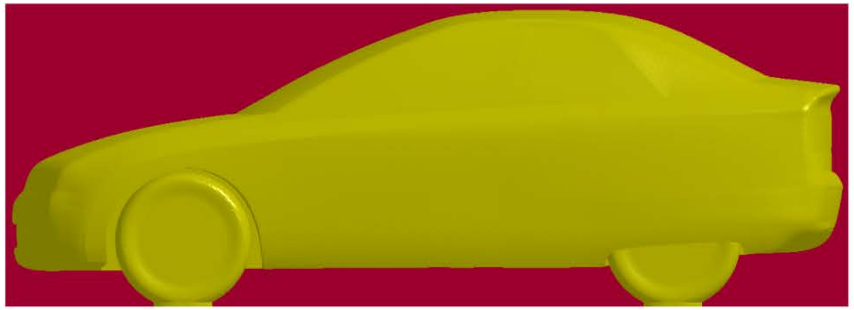


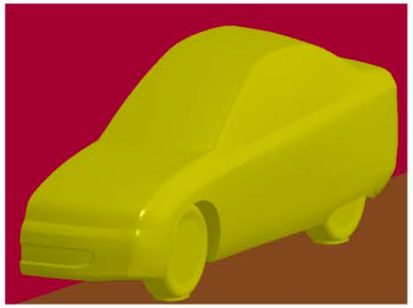
Using *LOAD_SEGMENT from Navier-Stokes solution



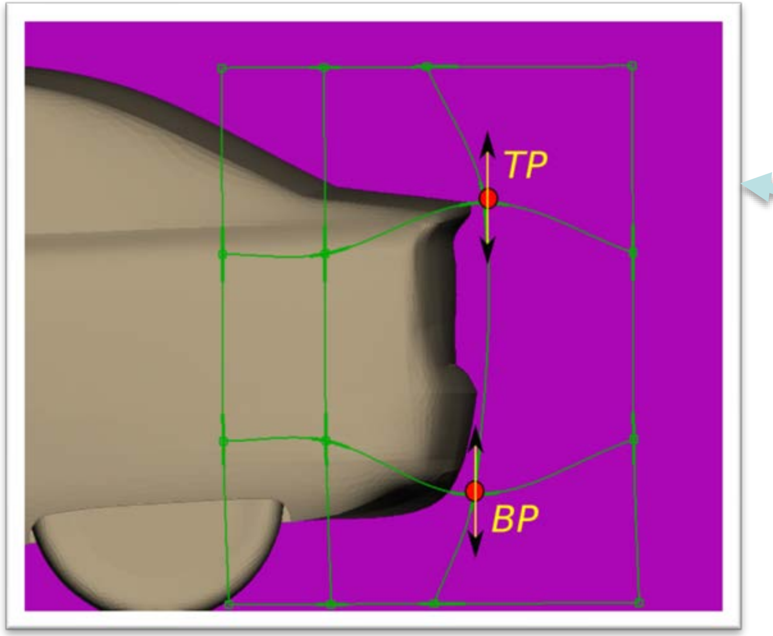
ICFD with LS-Opt and ANSA for shape optimization

Delpin, Caldichoury, Paz, Wang

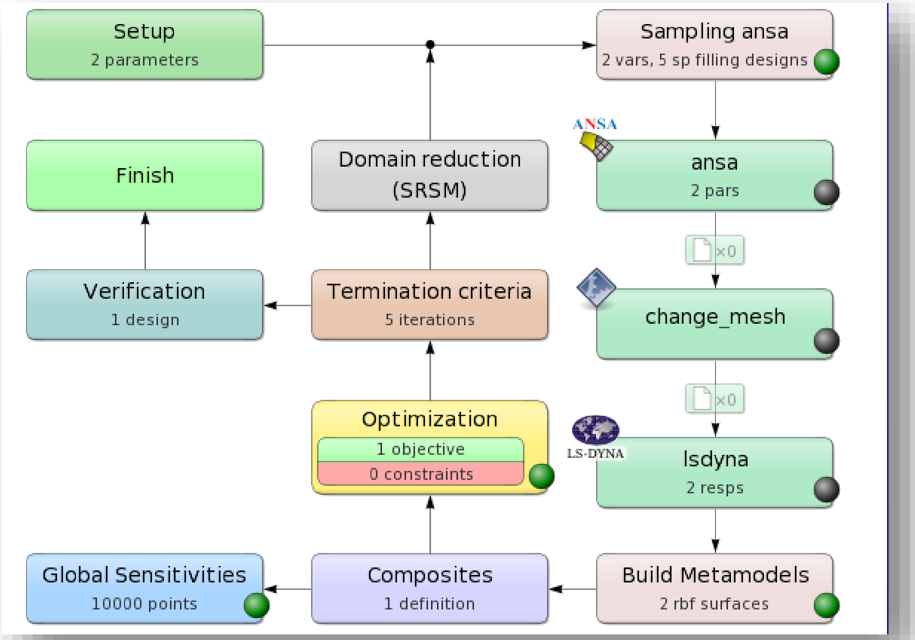




ANSA morphing



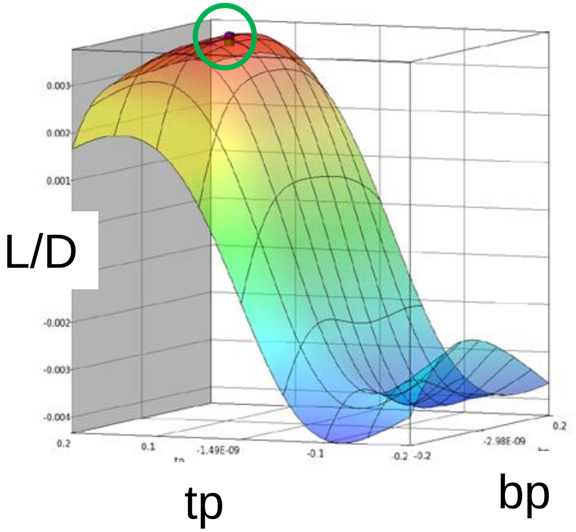
LS-OPT® Workflow

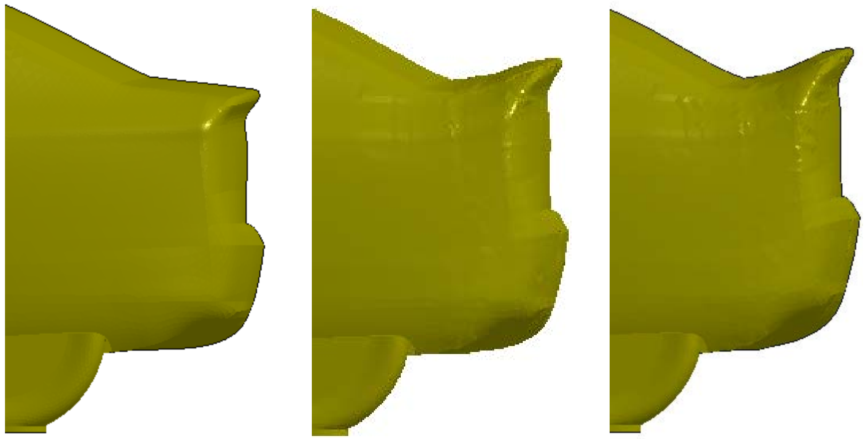


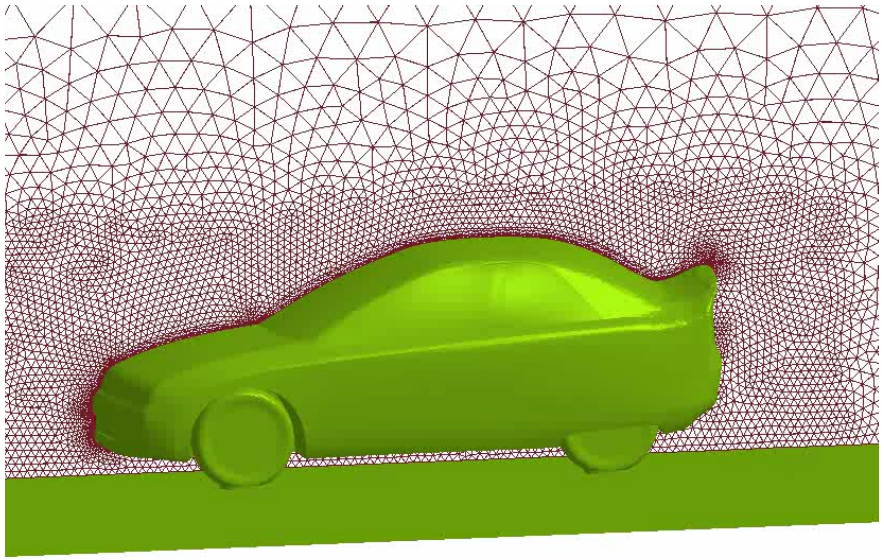
Optimal design for (Down Force) / Drag Ratio

Delpin, Caldichoury, Paz, Wang

Initial design	Optimal design (6.1)	"Best" design (5.2)	
0.0	0.022	0.062	bp
0.0	0.105	0.132	tp
-	0.00376	0.00366	L/D pred
0.00094	0.00364	0.00384	L/D comp

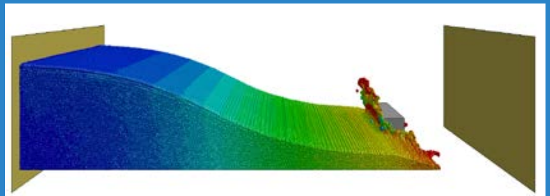


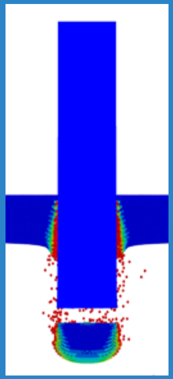


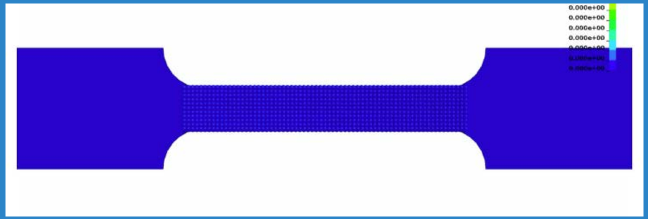


SPH/CPM Enhancements in LS-DYNA

Dr. Jason Wang
Dr. Edouard Yreux







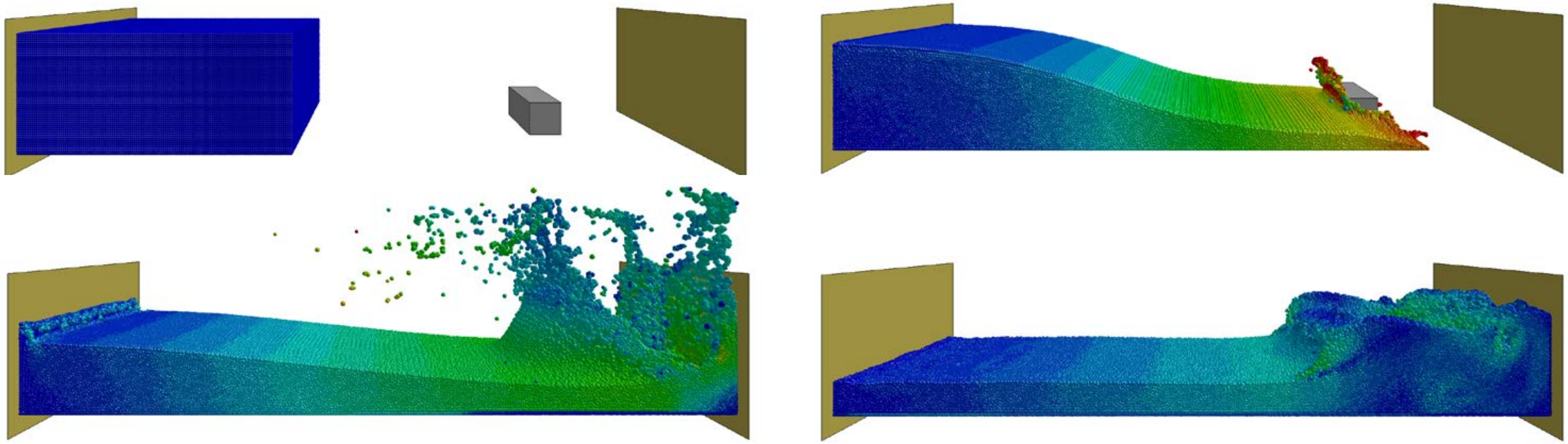
Smooth Particle Hydrodynamics (SPH) | Fluid Simulation

- Density smoothing (to avoid noise) : $\tilde{\rho}_I = \frac{\sum_J \rho_J \phi_{IJ}}{\sum_J \phi_{IJ}}$ with $\phi_{IJ} = W_{IJ} m_J / \rho_J$

- Murnaghan Equation of State for weakly compressible modeling (1944)

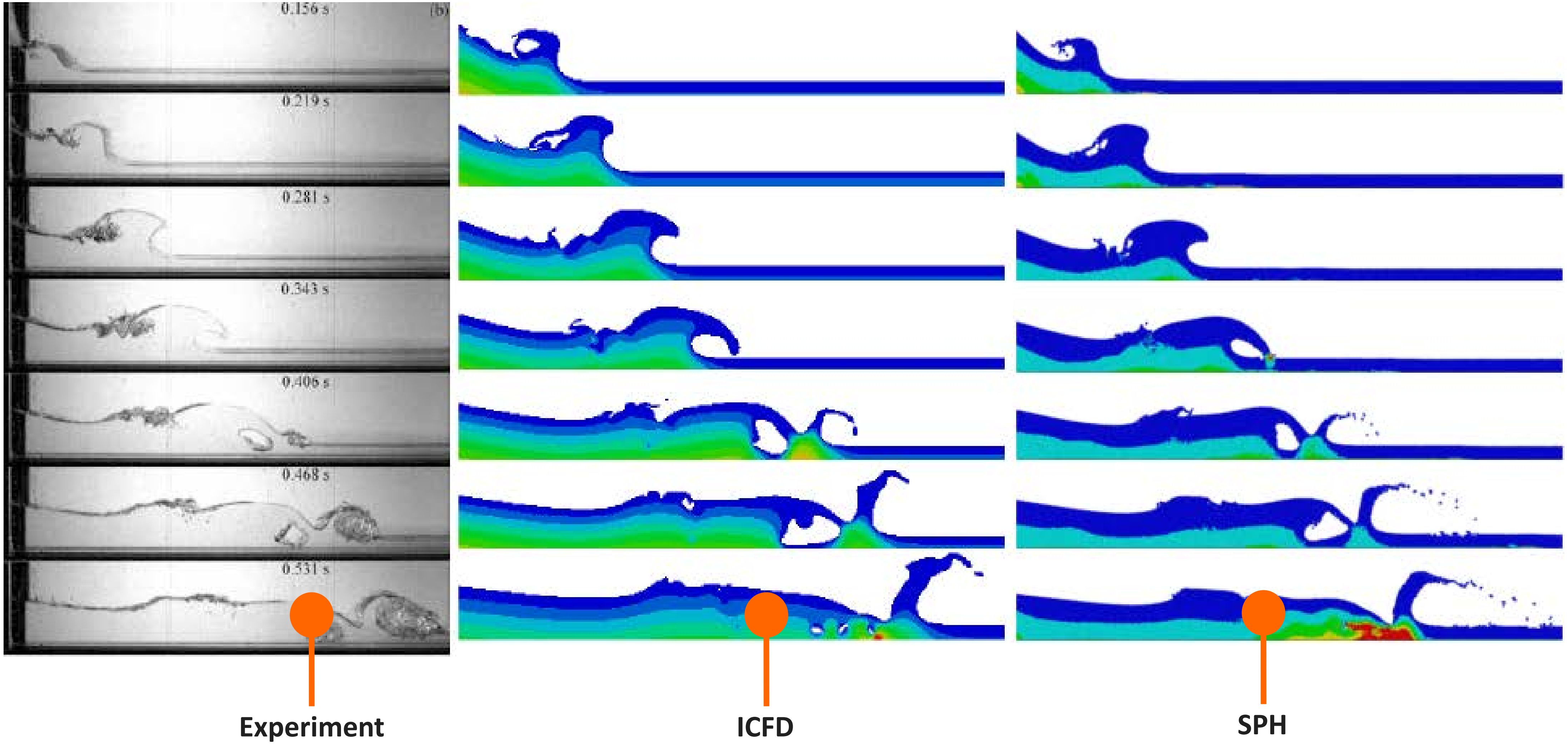
$$p = k_0 \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right]$$

- Low artificial viscosity is applied for stability



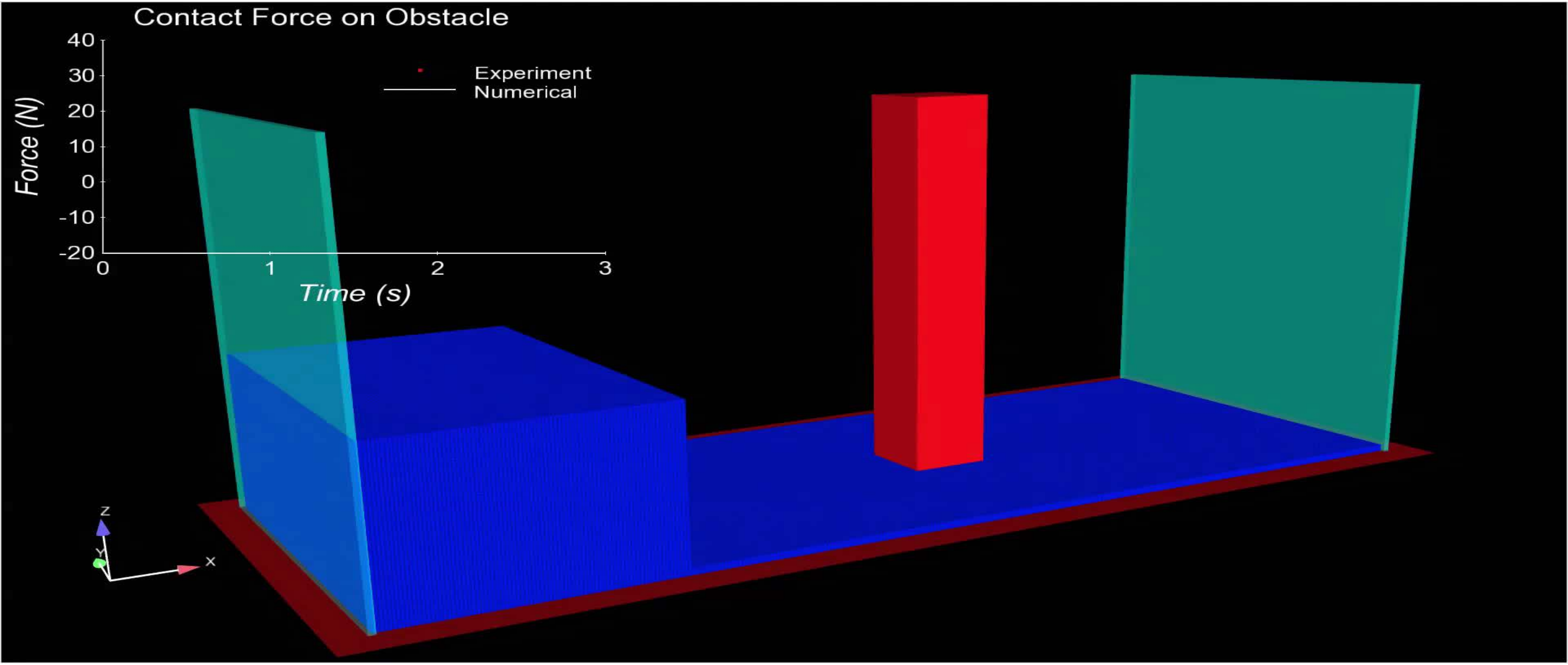
Smooth pressure field - Low compressibility - Reasonable timestep size

SPH | Fluid Formulation



Validated in 2D and 3D formulations

SPH | Fluid Formulation

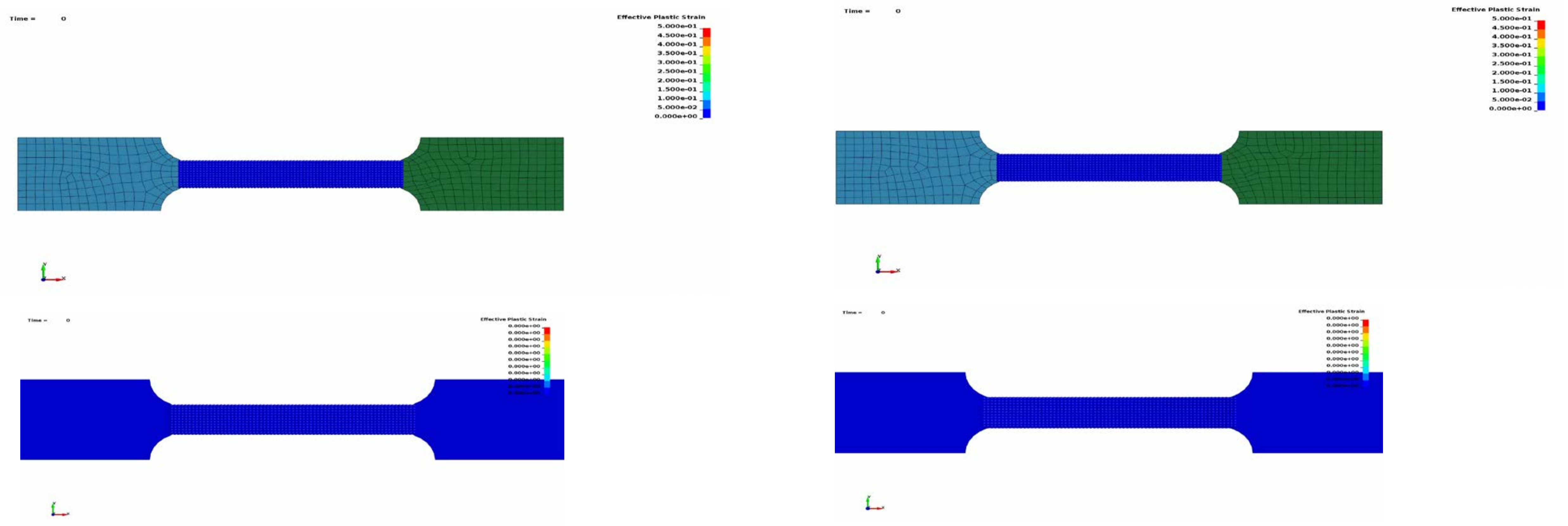


Validated in 2D and 3D formulations

SPH | MLS-Based formulation

Wang, Yreux

- Quasi-Linear Moving Least-Squares formulation for accuracy and consistency
- Increase support size of the kernel function. Stabilized nodal integration for better stability.
- More CPU-Intensive than regular SPH. A larger support size will increase cost.

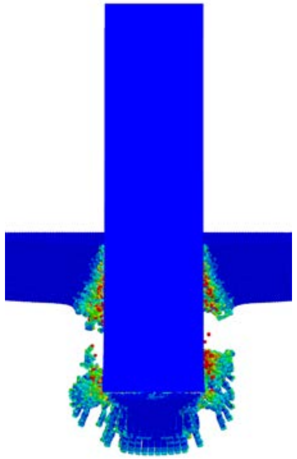


Higher accuracy – Better consistency – Alleviated tensile instability

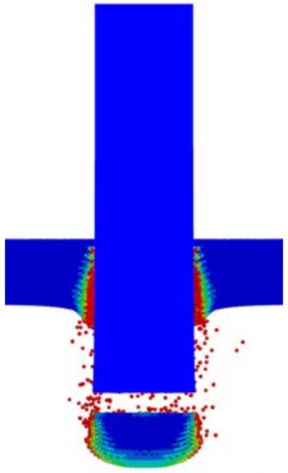
SPH | MLS-Based formulation

Validated for high-velocity impact simulations

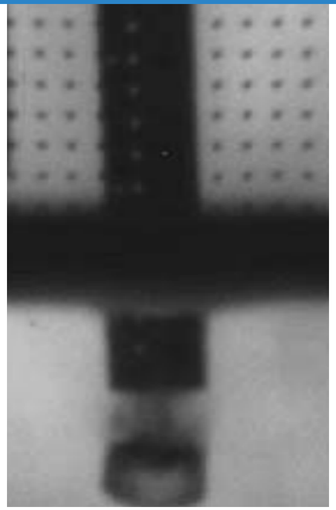
- Quasi-Linear Moving Least-Squares formulation for accuracy and consistency
- Stabilized nodal integration for better stability
- More CPU-Intensive than regular SPH



Traditional SPH



MLS-Based SPH



Experiment

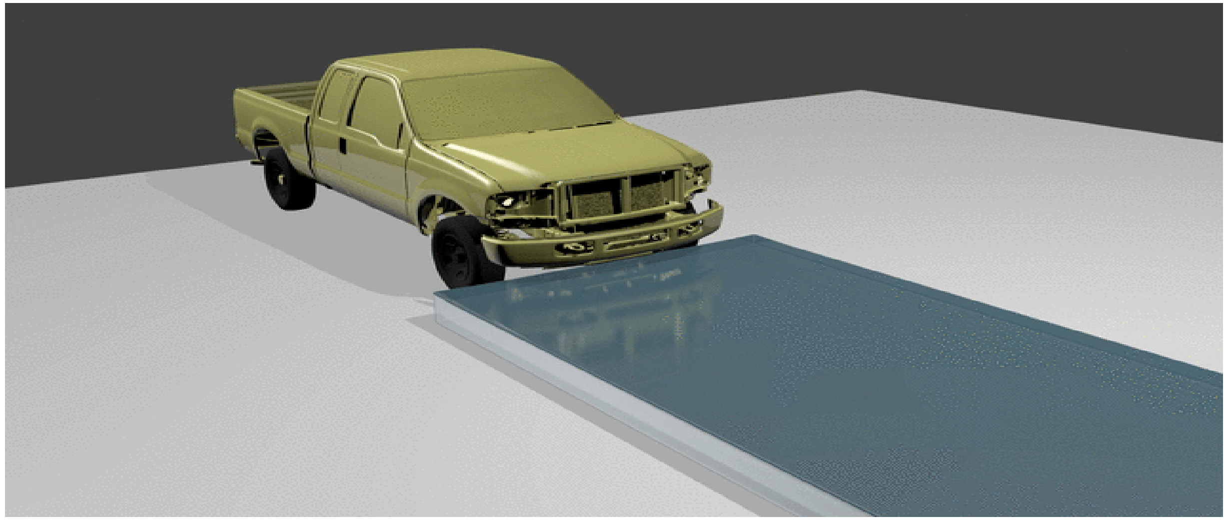
Comparision With Experimental Data					
	Experimental	Form 0		Form 12	
Projectile Residual Velocity	199.7 m/s	207.9 m/s	3.9%	201.6 m/s	0.9%
Plug Residual Velocity	242.3 m/s	212 m/s	12.5%	248 m/s	2.4%
Plug Mass	27.6 g	35.9 g	23.1%	28.9 g	4.7%
Plug Height	11.4 mm	17.6 mm	54.4%	11.3 mm	0.9%
Crater, front diameter	20.7 mm	20.4 mm	1.4%	20.6 mm	0.5%
Crater, exit diameter	20.9 mm	30.8 mm	47.4%	23.7 mm	13.4%

T Borvik et al. “Perforation of 12 mm thick steel plates by 20 mm diameter projectiles with flat, hemispherical and conical noses: Part I: Experimental study”. International Journal of Impact Engineering 27.1 (2002).

SPH | Implicit formulation | Wading problem

- Implicit, incompressible SPH formulation allows larger timestep size
- Tailored for wading-type problems
- Example with 9.1 million particles:

Implicit SPH
Color-coded by velocity

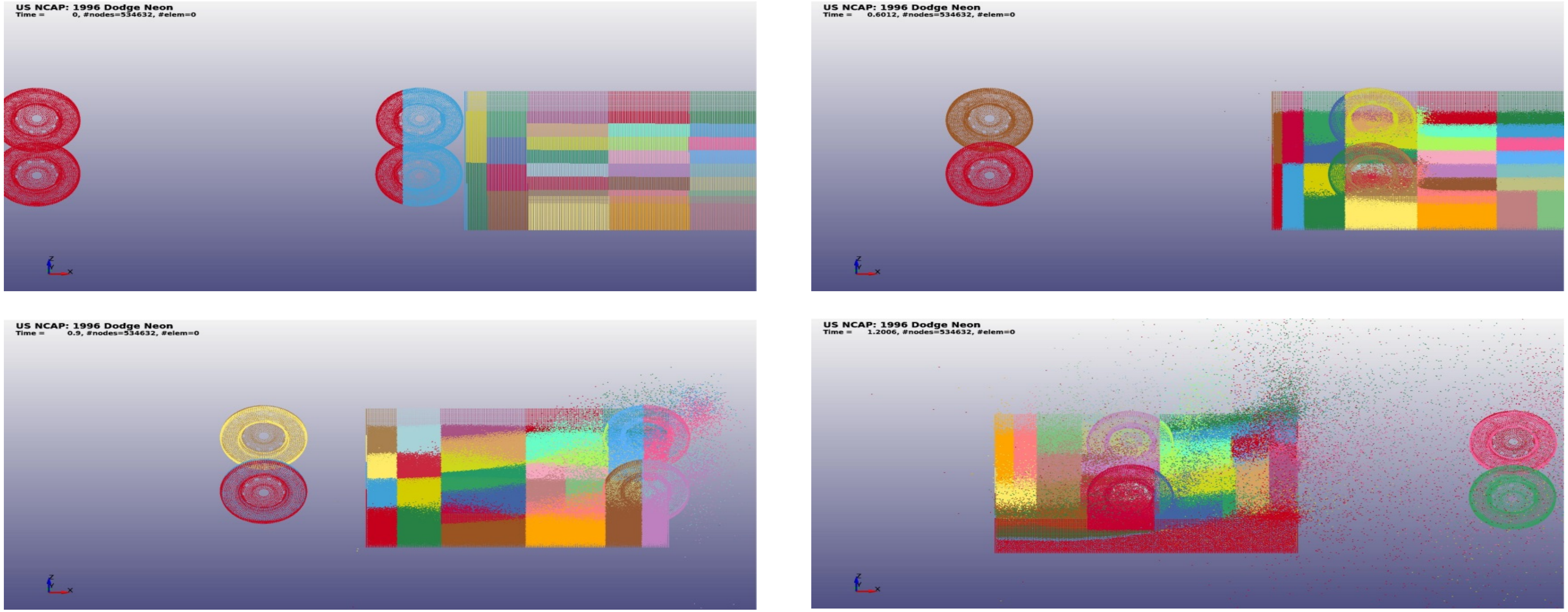


Blender rendering

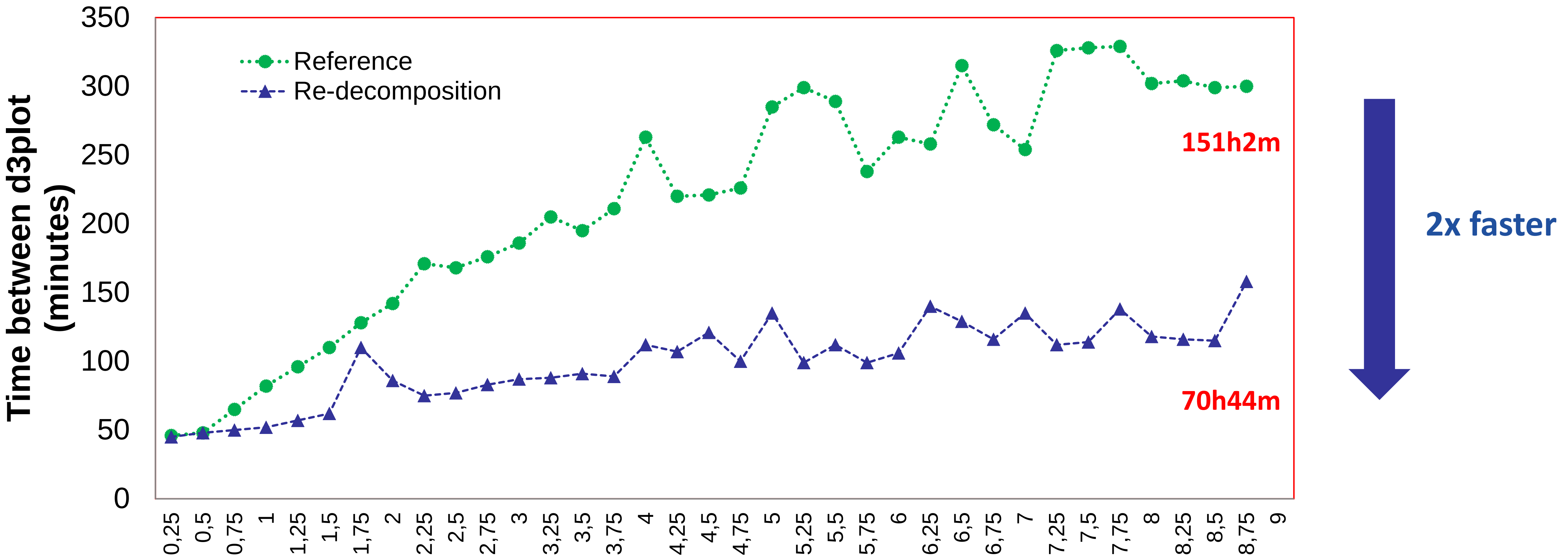
SPH | re-decomposition (dynamic partitioning)

Wang, Yreux

- Large deformation can cause load unbalancing among processors
- Re-decomposed the model several times during simulation using a fulldeck restart
- decomp { defgeo } : The model is decomposed using the current deformed geometry



Re-decomposition

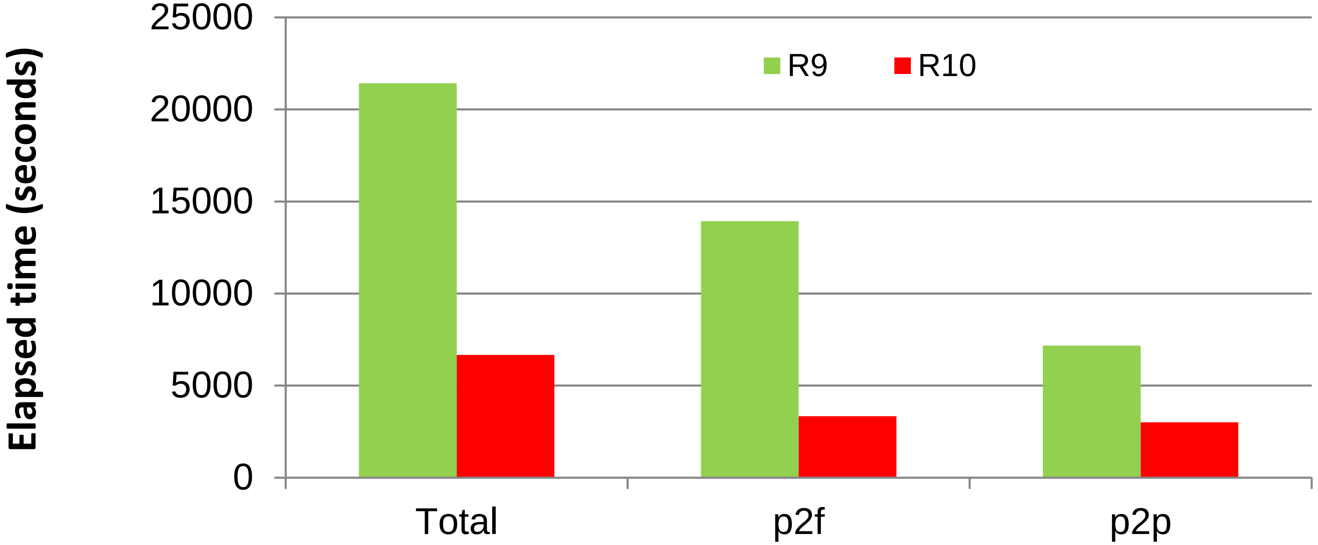


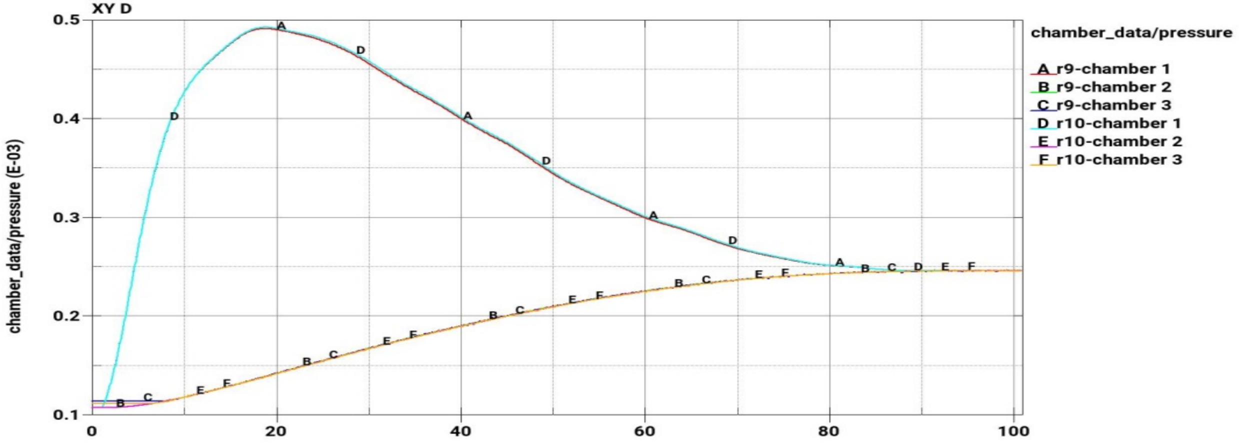
- More development work to make an automated process similar to adaptive simulation.
- Currently it uses fulldeck restart capability, user has full control to get better performance.
- Testing other problems, i.e. bird strike, small offset, ODB, etc.

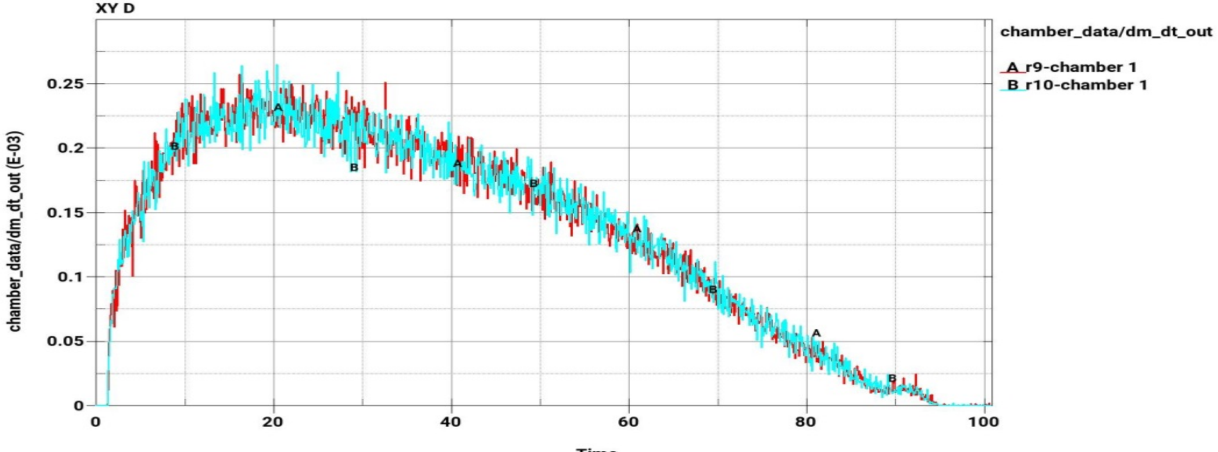
CPM | New CPM for AIRBAG Simulations

- Main cost for airbag simulation, (1)airbag self contact, (2)p2f and (3)p2p
- New and faster particle to fabric (p2f) contact algorithm
- Redistribute CPM particles among processors to achieve better scaling and efficient particle to particle (p2p) collisions

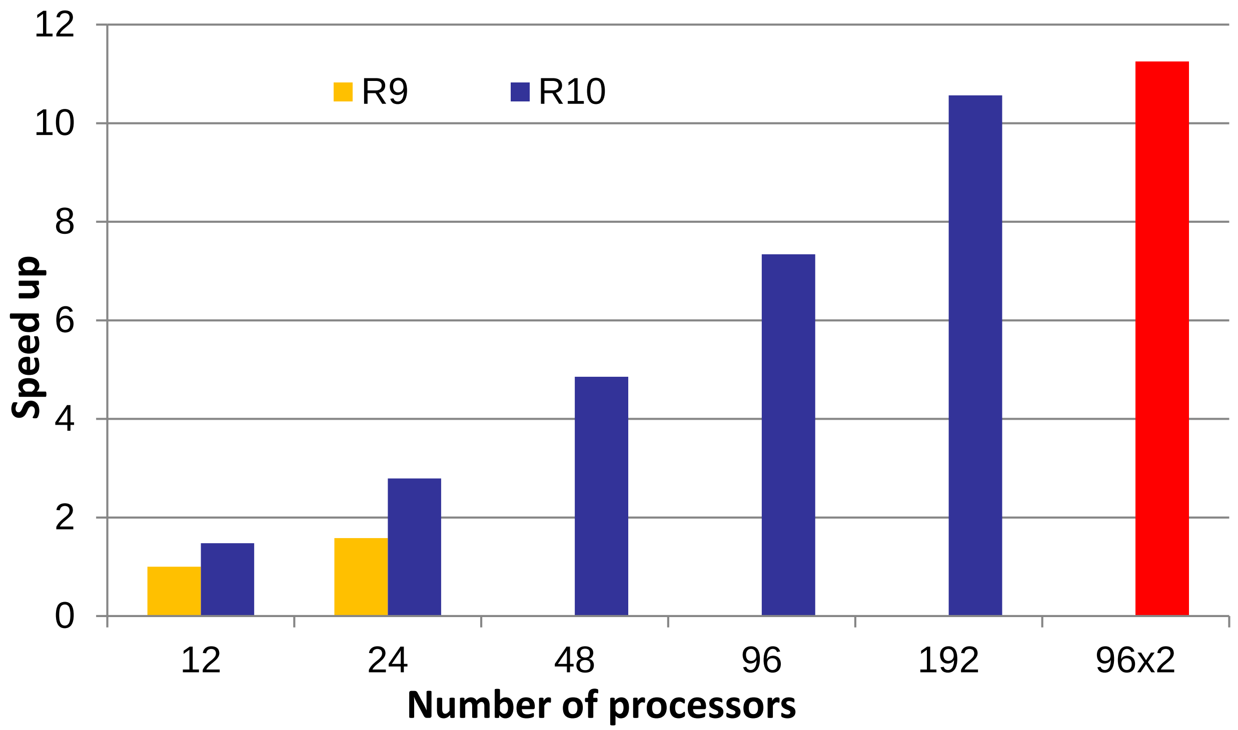
- ***Speedup: 3x*** *for tank test*
- ***Validation****: Pressure history is consistent between releases*



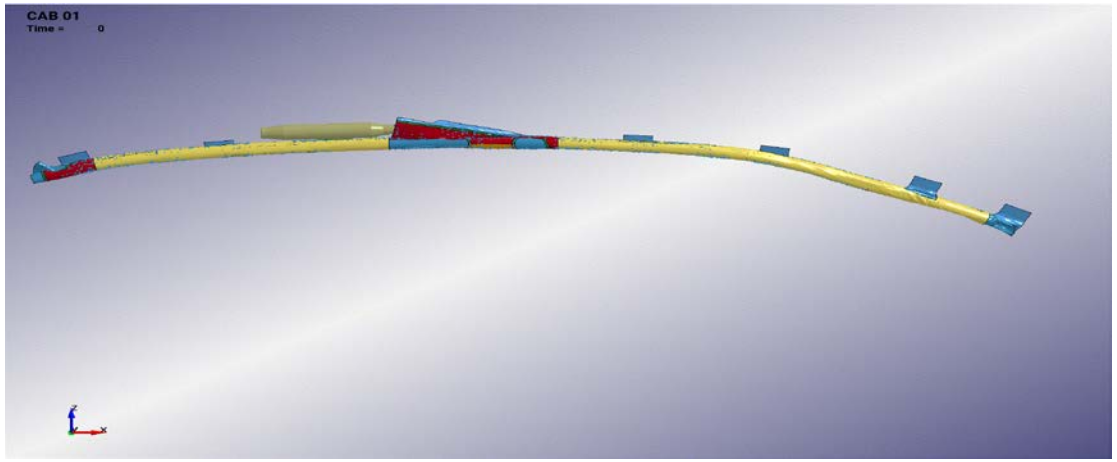




CPM | CAB Performance Improvement

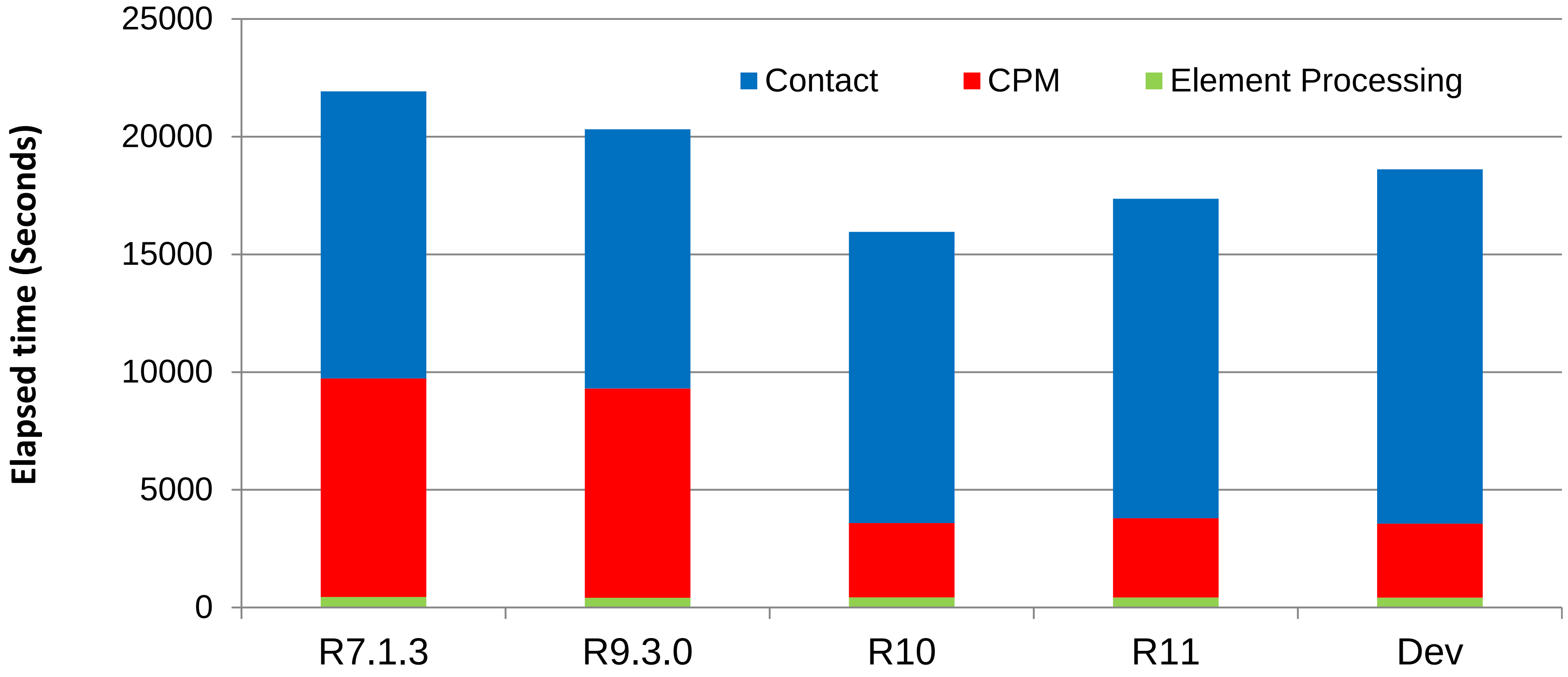


CAB

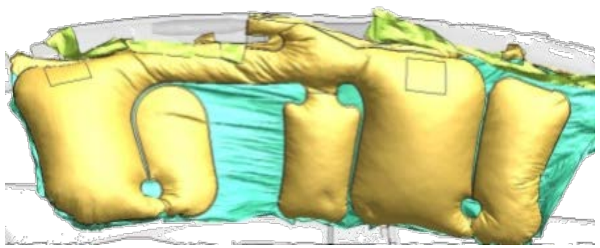


- OpenMP (HYBRID) enabled as the default algorithm. See 96x2 (red bar)
- Reduced amount of data transferring between processors for better scaling
- It is more efficient for the full vehicle simulation which uses more than 200 processors
- Same input faster turn around time (no additional user input)

Special decomposition



CAB



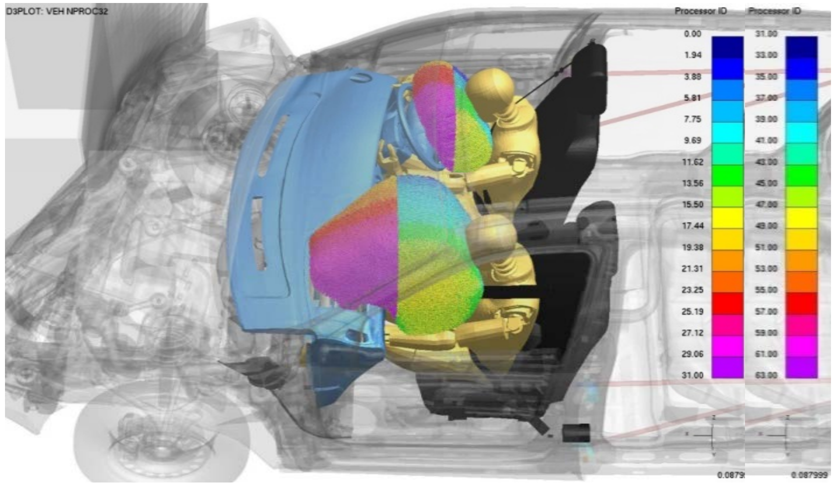
- Performance was measured with 96 processors
- CPM is about 3x faster from R7 to R10
- Self contact about the same
- The overall speed up is about 20%.

Special decomposition: airbag-dedicated processor group

*CONTROL_MPP_DECOMPOSITION_ARRANGE_PARTS

Part/Part Set ID, TYPE, NPROC, FRSTP

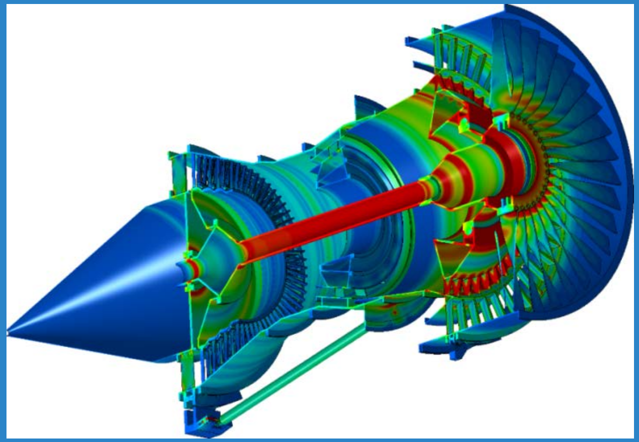
pfile options: region { parts/partset   ID   NPROC   FRSTP }



- New decomposition allows distributing workload into user defined processors group.
- Multiple CPM airbags can be arranged into subset of processors.
- Each CPM airbag and its self contact runs independently to achieve best parallel efficiency.

Linear Implicit Analysis

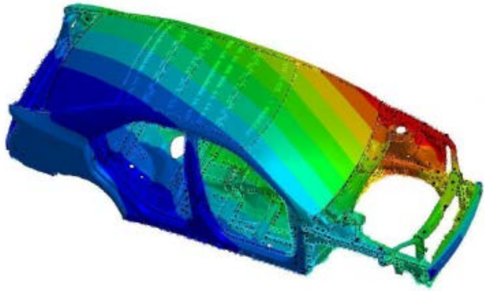
Grimes, Ashcraft, Lucas, Rouet, Wiesbecker, Vecharynski, Li

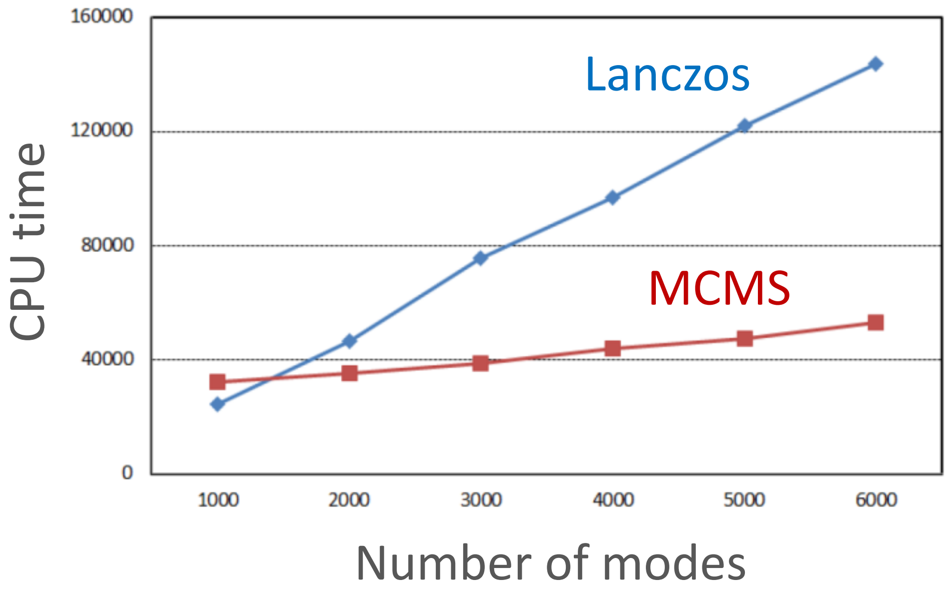


Linear Implicit (1)

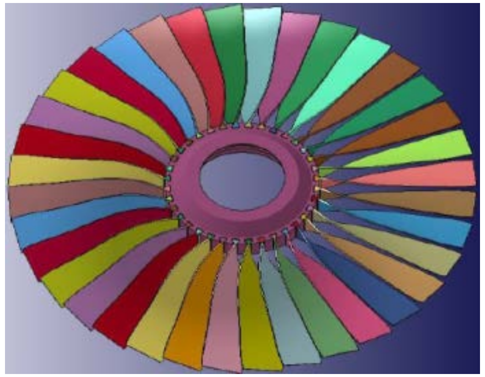
Grimes, Ashcraft, Lucas, Rouet, Wiesbecker, Vecharynski, Li

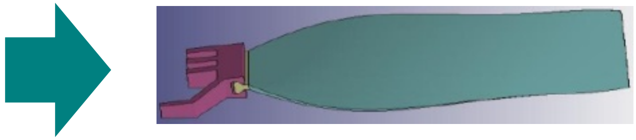
- New eigenvalue extraction method: MCMS
  - Multilevel Component Mode Synthesis
  - Based on multilevel substructuring (AMLS)
  - less accurate than Lanczos, but far less computer resources
  - useful for NVH applications that want thousands of modes





- Sectoral symmetry
  - 1,000,000 elements per blade
  - for models with significant rotational symmetry: highly reduced eigenvalue problem





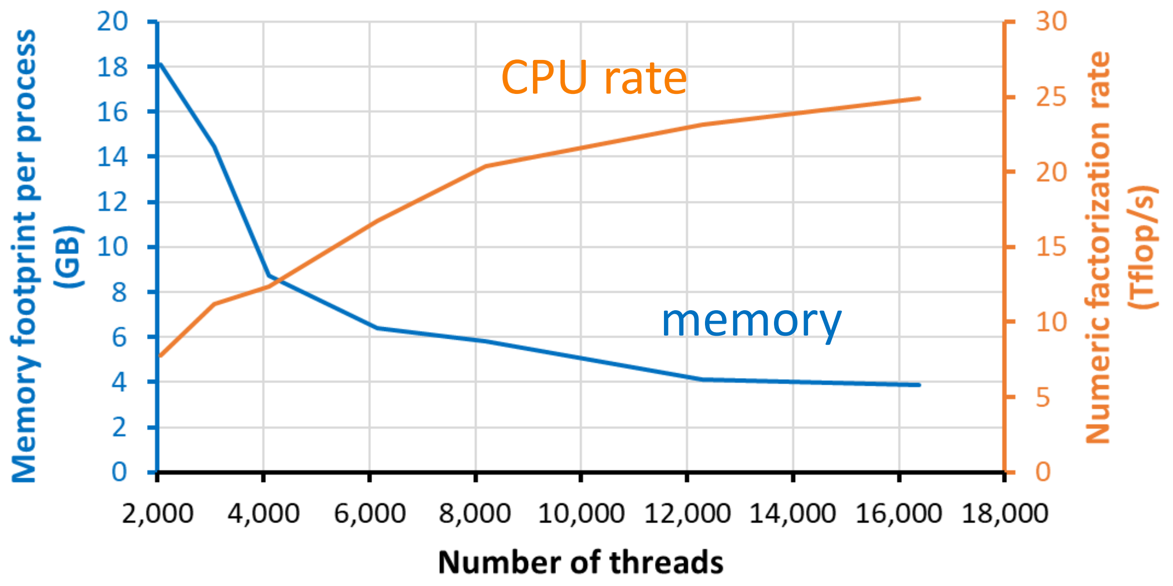
huge CPU/memory savings

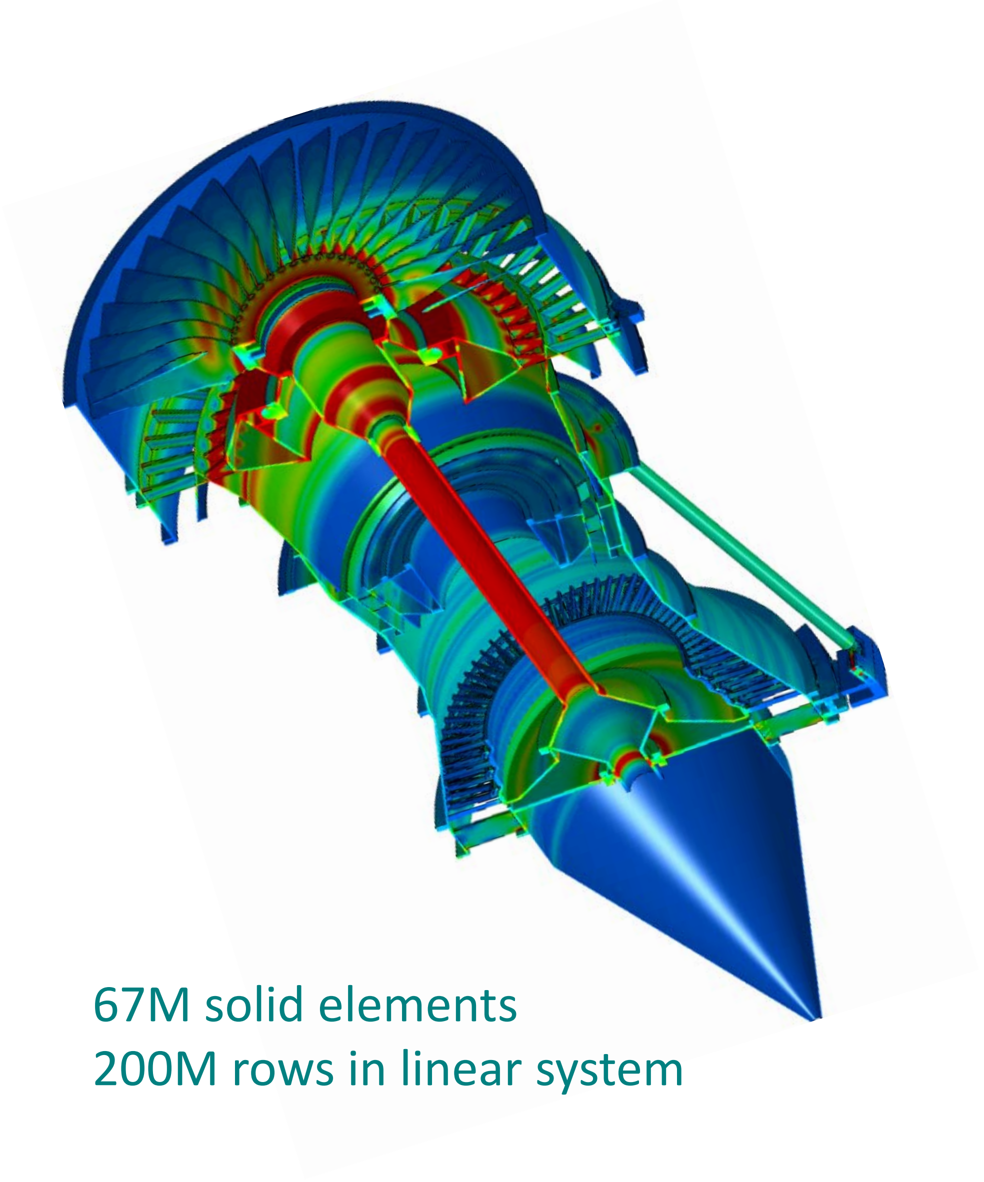
- And always…

Linear Implicit (2)

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

- …working on larger and larger models!
  - e.g. static loading of jet engine model from Rolls-Royce
  - original attempt: 158 hours on 448 cores
  - current best: 12 hours on 2304 cores
  - continuing efforts to improve scalability
  - Eigenvalue problem not analyzed yet

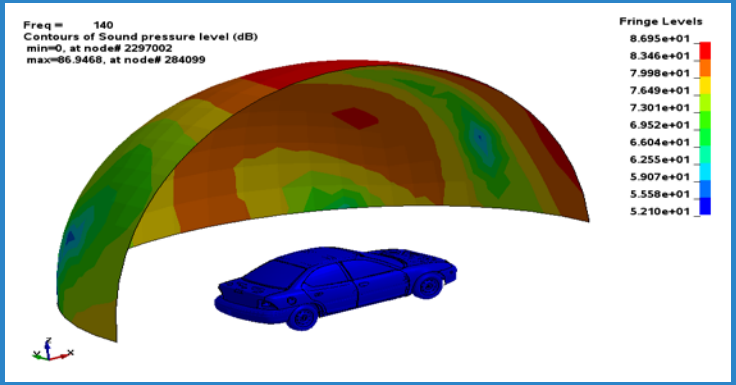


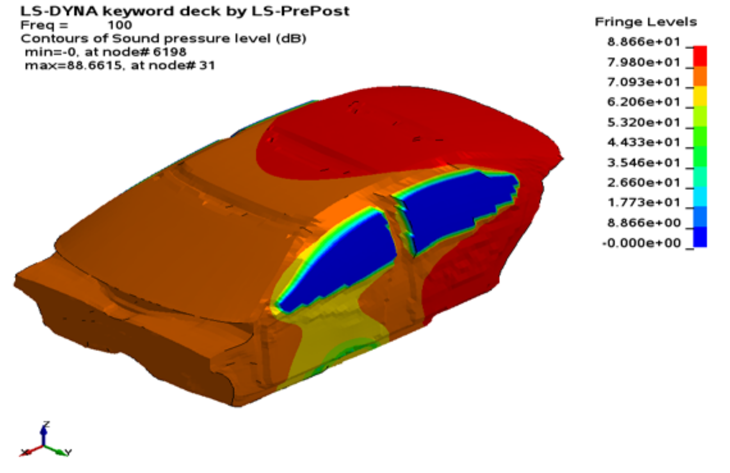


67M solid elements
200M rows in linear system

Acoustic and Fatigue Analysis

Dr. Yun Huang





Overview of NVH and Fatigue (Durability) analysis features

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 (Frequency)
- SSD fatigue (Frequency)
- Time domain fatigue
  - Stress based
  - Strain based

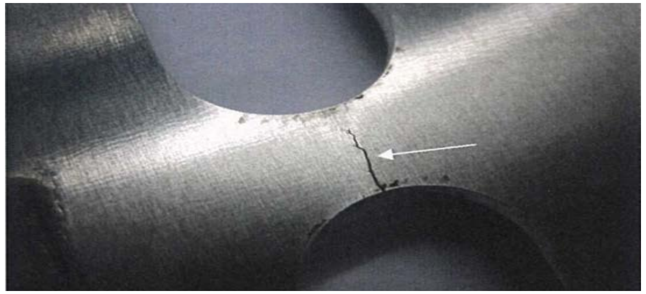
Acoustic solvers

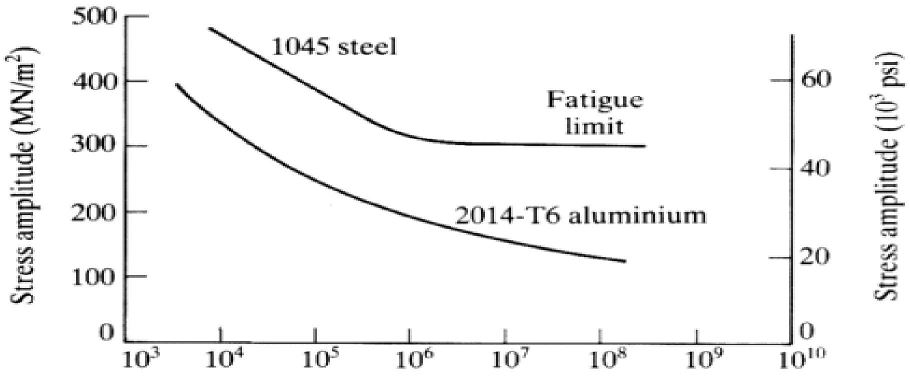
- **B**oundary **E**lement **M**ethod
  - *Collocation*
  - *Indirect*
  - *Rayleigh Method*
  - *Kirchhoff Method*
- **F**inite **E**lement **M**ethod
- **A**coustic **E**igenvalue **A**nalysis
- **S**tatistical **E**nergy **A**nalysis

Applications

- NVH analysis of automotive and aerospace
- Civil and hydraulic Engineering
- Earthquake engineering
- Acoustic simulation
- Fatigue and durability

Fatigue analysis





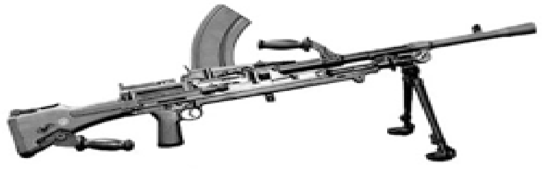
- Frequency domain fatigue solvers
  - random vibration environment
  - SSD environment
- Time domain fatigue solvers
  - based on stress *(high cycle, low stress)*
  - based on strain *(plastic deformation)*
- Advantages
  - Integration of vibration and fatigue solver in one code
  - A wide selection 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

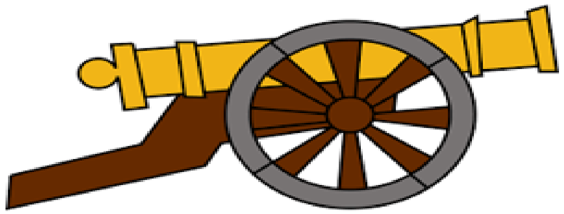
GM: Jong S. Park, Ramakrishna Dospati, Ye-Chen Pan, Amit Nair, *Random vibration fatigue life simulation of Bolt-on Metal Brackets using LS-DYNA*, the 15th International LS-DYNA Users Conference, June 10-12, 2018, Dearborn, MI.

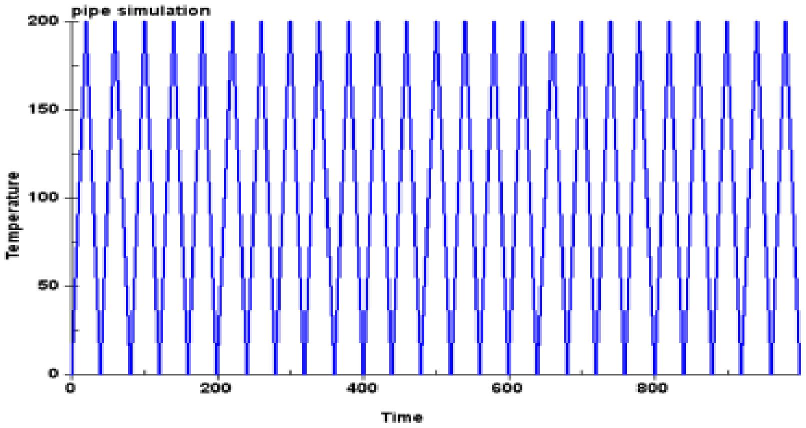
Time domain fatigue – Stress based example

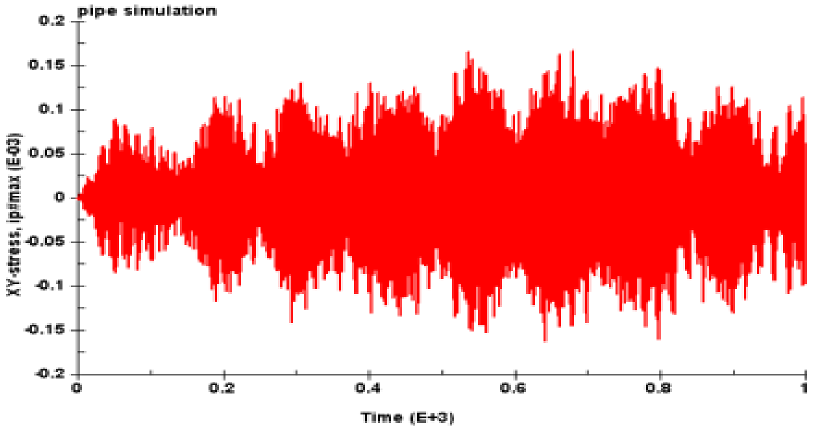
Huang

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

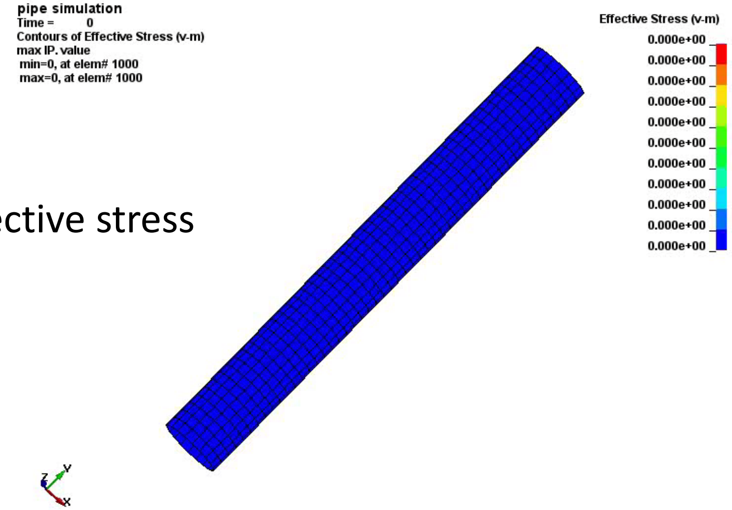




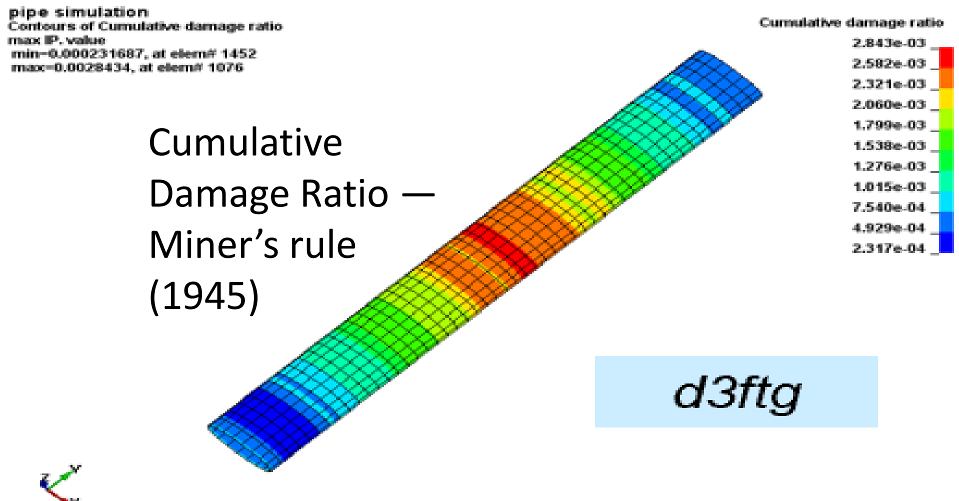




Effective stress



Cumulative Damage Ratio — Miner's rule (1945)

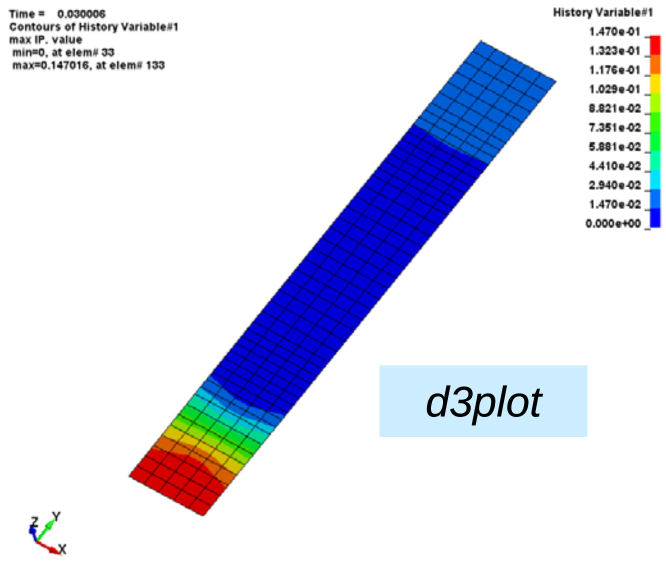


d3ftg

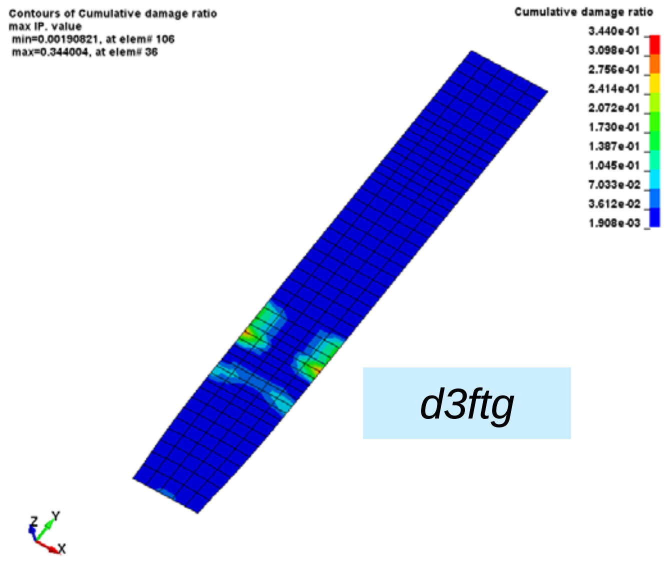
Initial Fatigue Damage Ratio

Accumulate damage using previous damage due to loading or fatigue

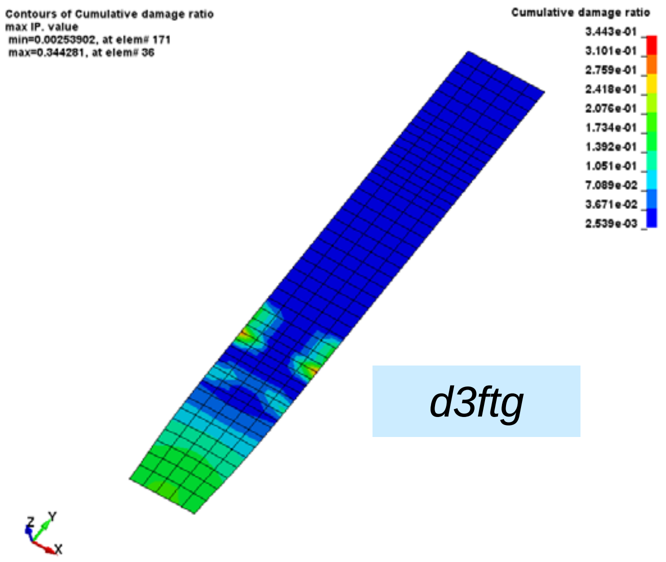
- Defined by *INITIAL_FATIGUE_DAMAGE_RATIO
    - Initial damage ratio (e.g. Miners's rule) can come from *past fatigue* analysis (d3ftg)
    - Initial damage ratio can come from *transient preload* (d3plot), e.g. *mat_add_erosion, *mat_add_damage_gissmo, etc.
- Summed up by *FATIGUE_SUMMATION



Damage from transient preload case (d3plot)



Damage ratio from fatigue load



Cumulative damage ratio from transient preload + fatigue load

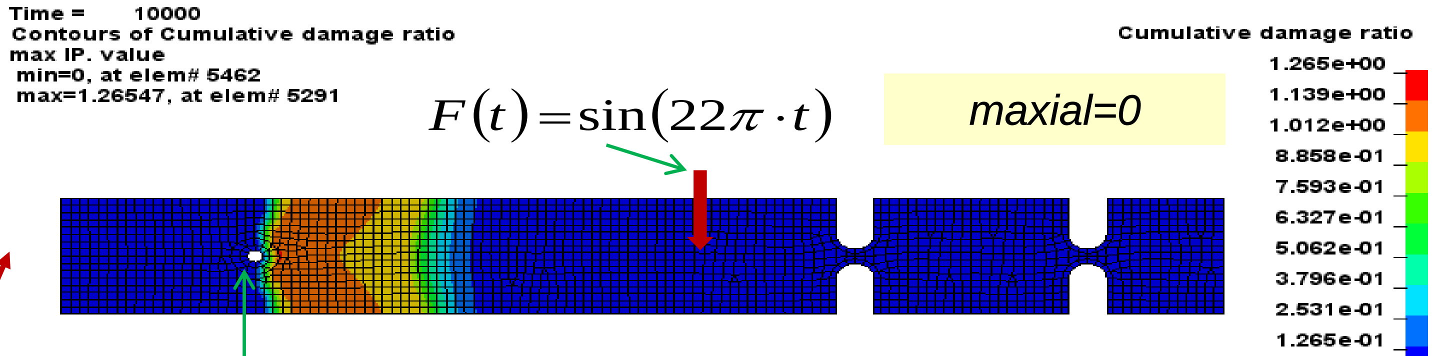
Multi-axial fatigue analysis

Stress / strain state is always three dimensional (two-dimensional on surface): *scalarize* the problem, using ...

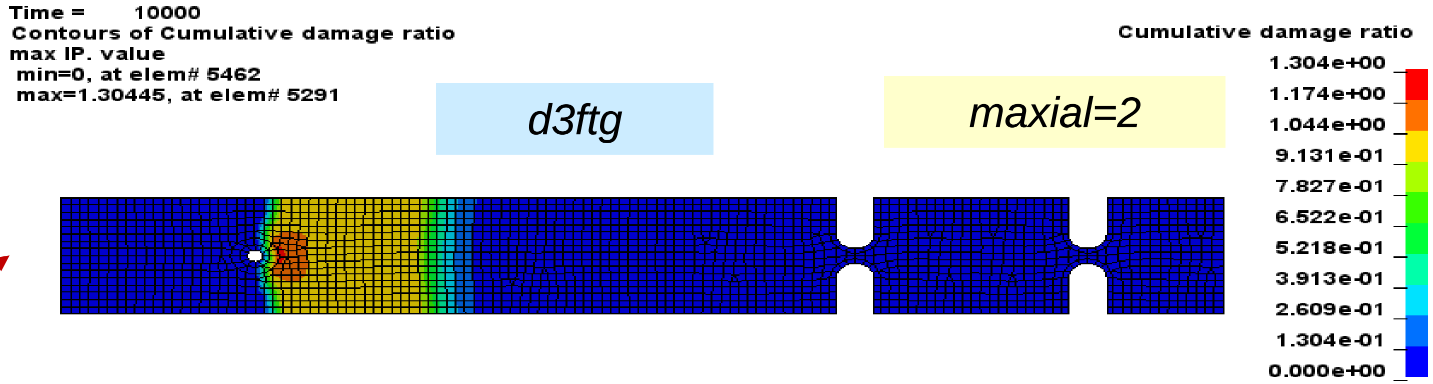
- A scalar index (e.g. von-mises stress, 1st principal stress) can be used
- Fatigue damage is computed on multiple planes and the max value is picked
- A critical plane is located and fatigue analysis is performed on the critical plane

```
*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

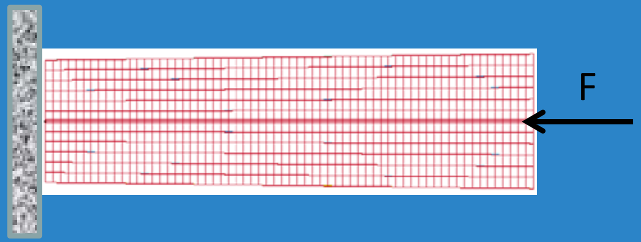


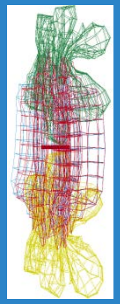
The plate is constrained along the edge of the hole



Crushable Nonlinear Beam

Dr. Isheng Yeh



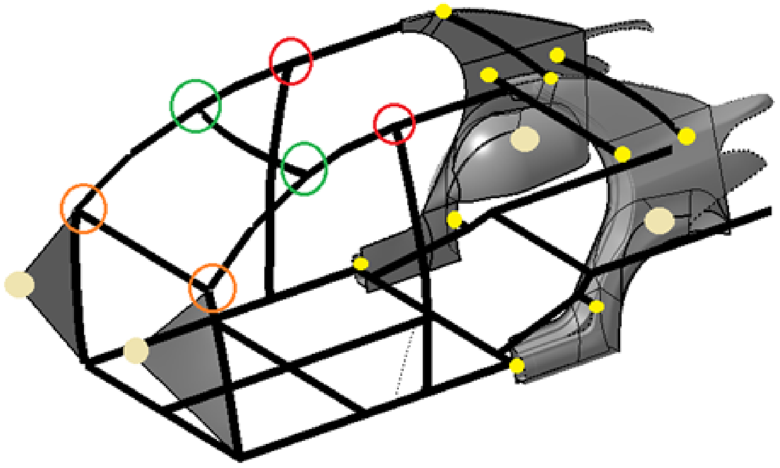


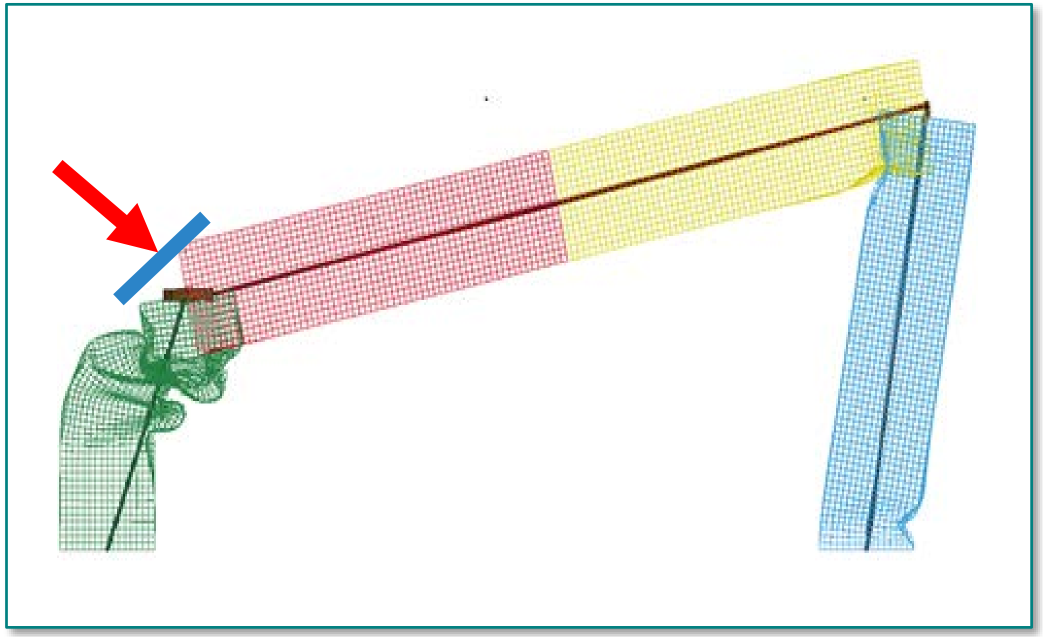
Elements | Crushable Beam

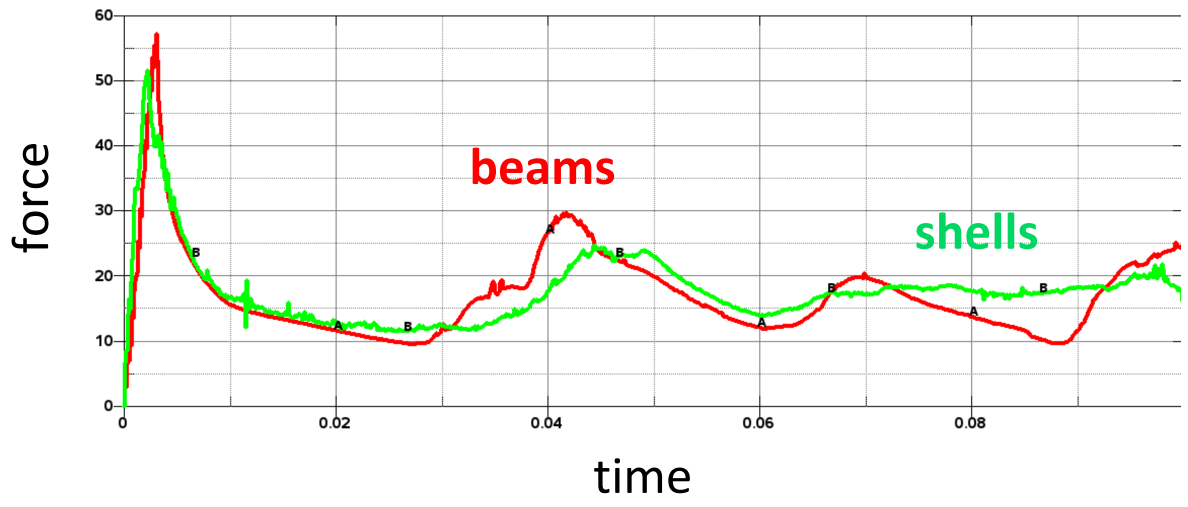
Isheng Yeh

Efficient non-linear beam models to replace detailed FE analysis for preliminary design

- 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)



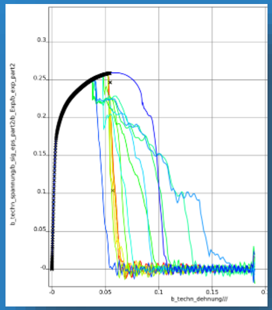


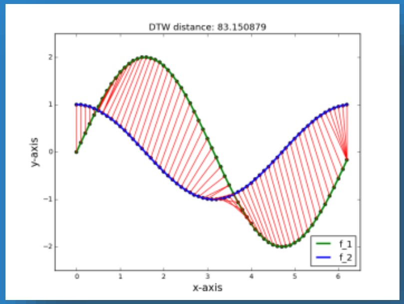


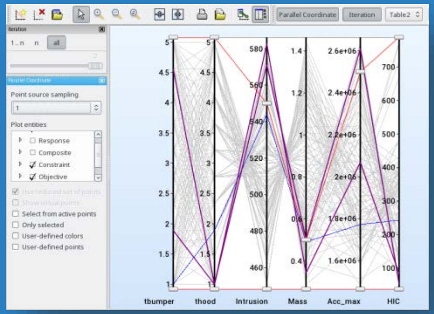
LS-OPT ®

Dr. Nielen Stander[1], Dr. Anirban Basudhar[1], Imtiaz Gandikota[1]
Katharina Witowski[2], Åke Svedin[2], Charlotte Keisser[2]
Sophie Du Bois[1], Denis Kirpicev[1]

[1]Livermore Software Technology Corporation
[2]DYNAmore GmbH

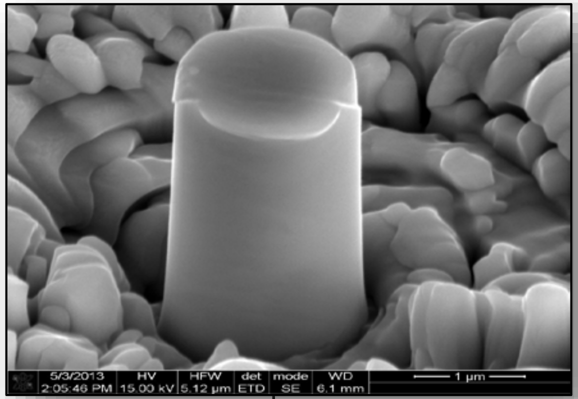




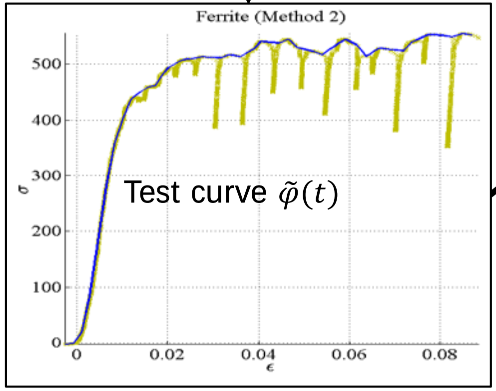


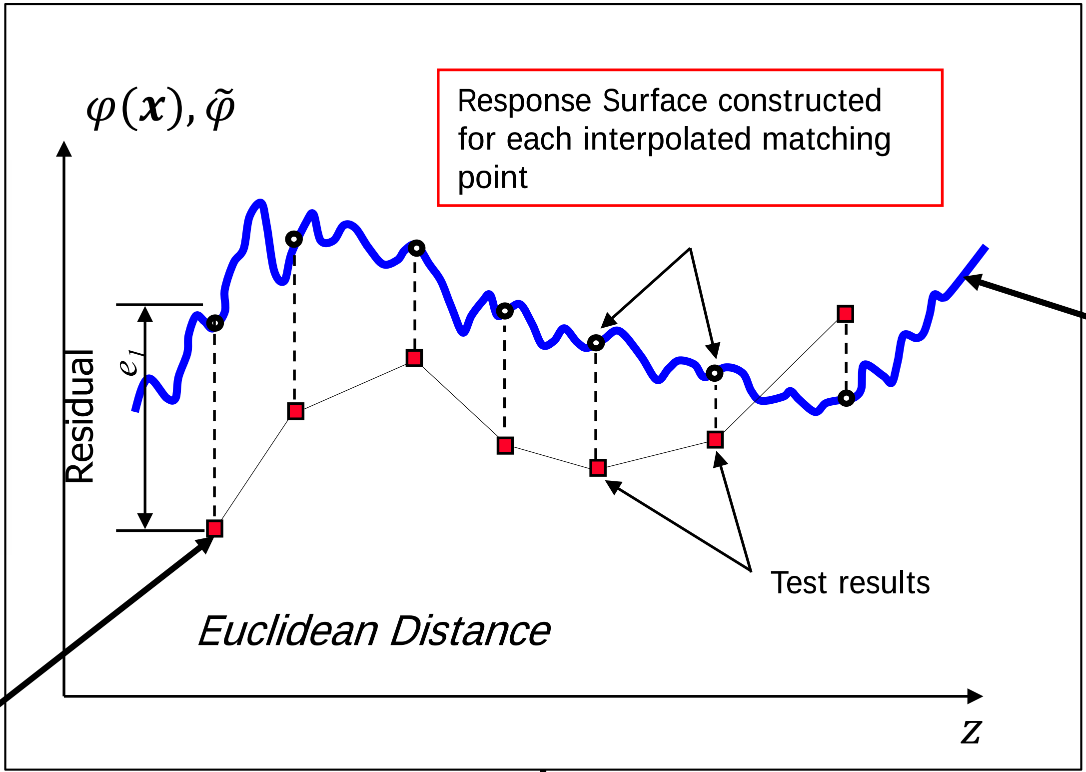
Material Calibration: Introduction

Experiment (single crystal micropillar)



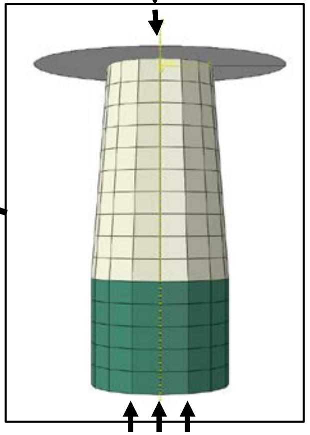
Result





Material parameters $\boldsymbol{x}$

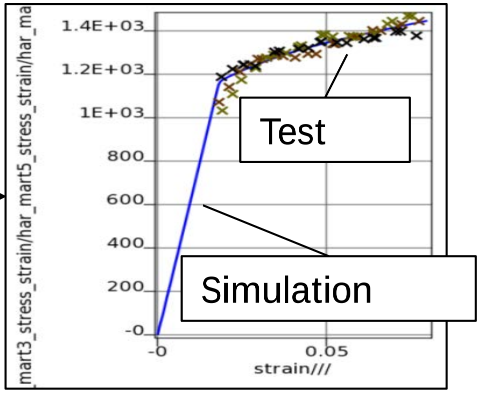
Computed curve: $\varphi(\boldsymbol{x}, t)$



FE model

$$\min_{\boldsymbol{x}} \sum_{j=1}^{n} (\varphi_j(\boldsymbol{x}) - \tilde{\varphi}_j)^2$$

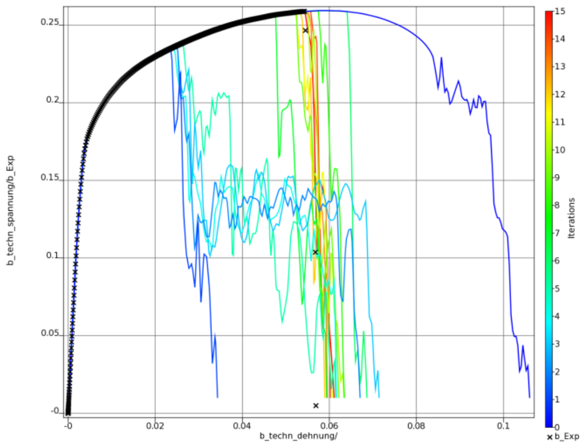
$$\boldsymbol{x}^*$$



Prof. S. Kumar,
Dr. H. Ghassemi-Armaki
(Brown U.)
Prof. F. Pourboghrat (OSU)

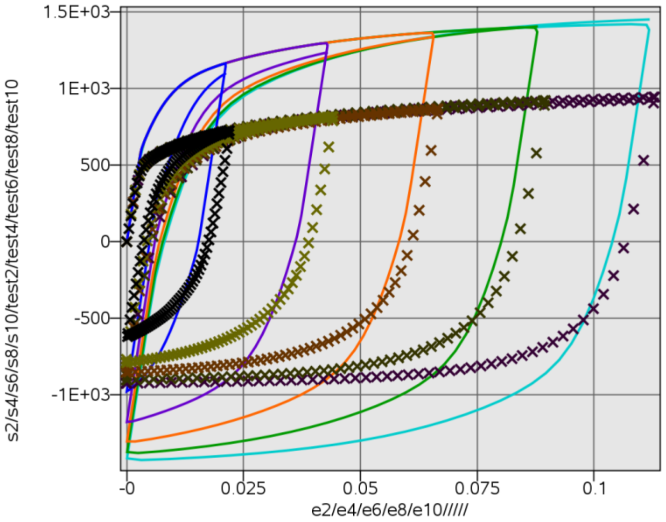
Calibration | Computational challenges

Curve matching presents challenges due to the nature of the experimental or computational curves



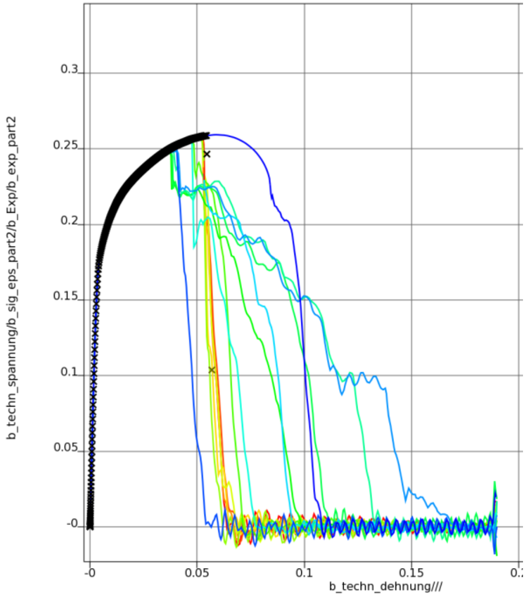
Noise

Failure model:
GISSMO — discrete process



Hysteresis

Loading/Unloading
Material 125



Partial Matching

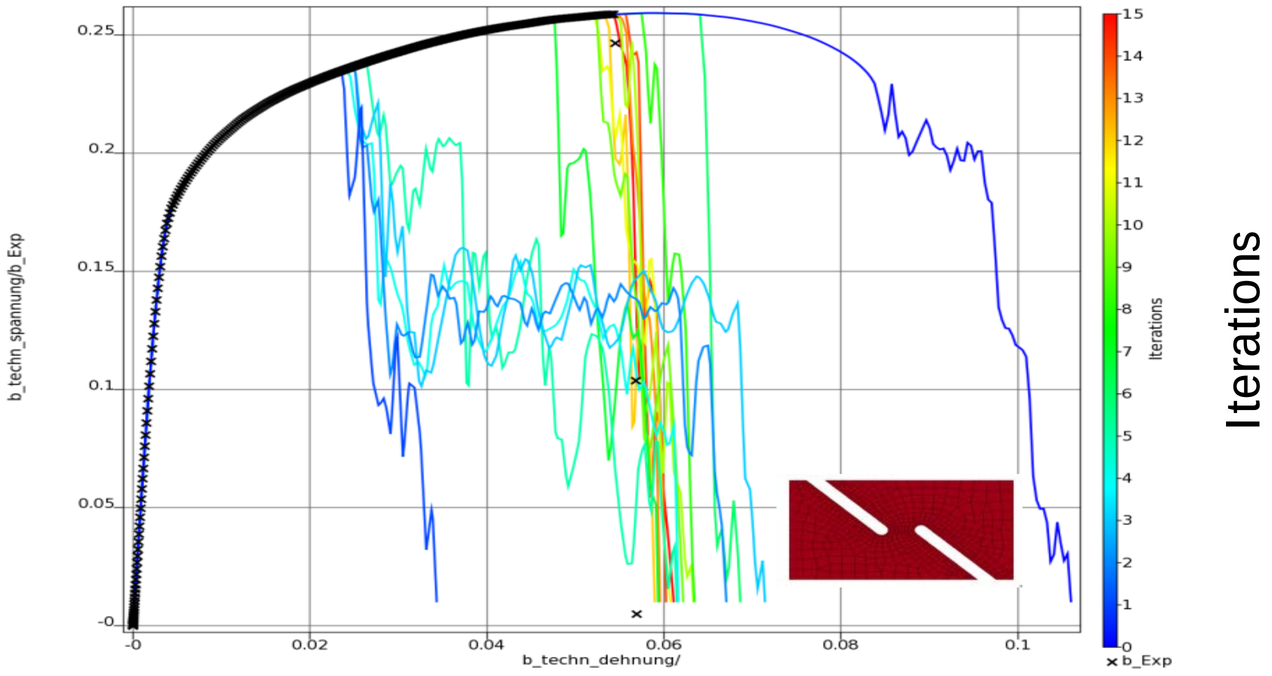
Failure model:
GISSMO — oscillation after failure

Example: GISSMO model

The GISSMO failure model requires special treatment for curve matching

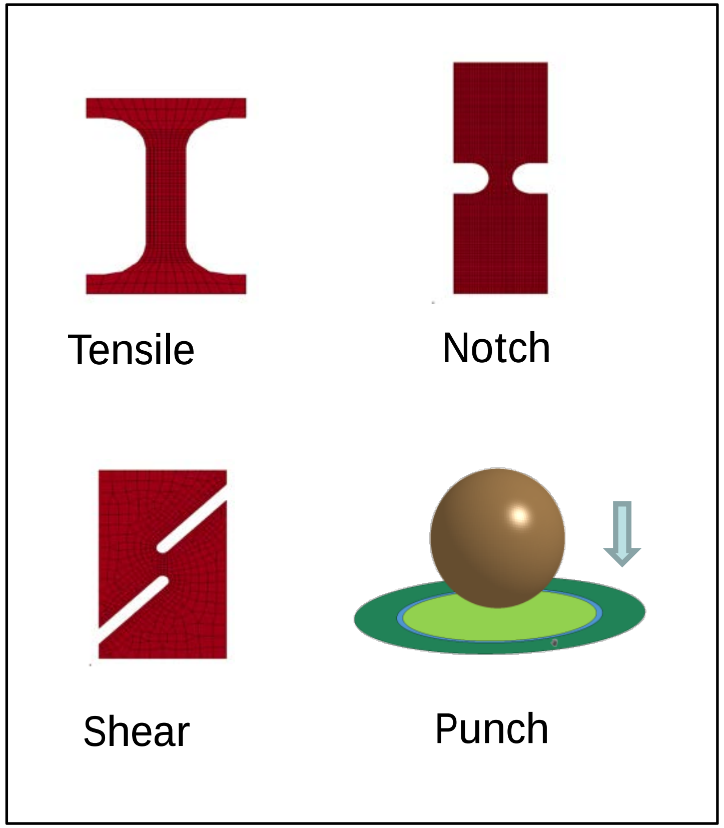
- Parameters: 7, Material Model: GISSMO
  - Uses discrete (element-by-element) erosion
- Curve Matching
  - Dynamic Time Warping (DTW)
  - Does not address partial curves ⇨ Truncate Force history at failure
- Optimization
  - SRSM (fast local optimizer)

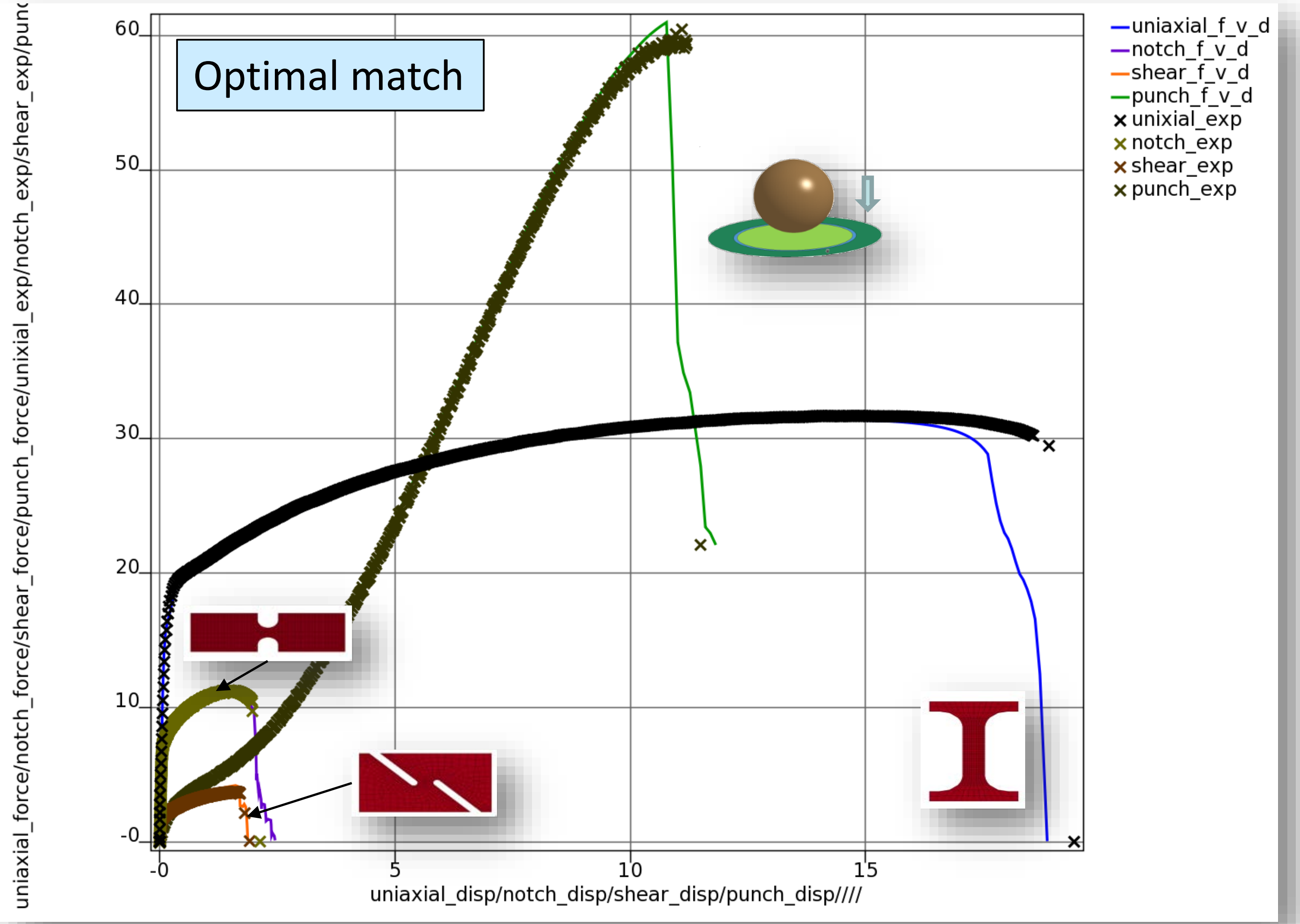
Shear: single case calibration history



Calibration: GISSMO model

In industry, the calibration of the GISSMO model typically involves multiple cases





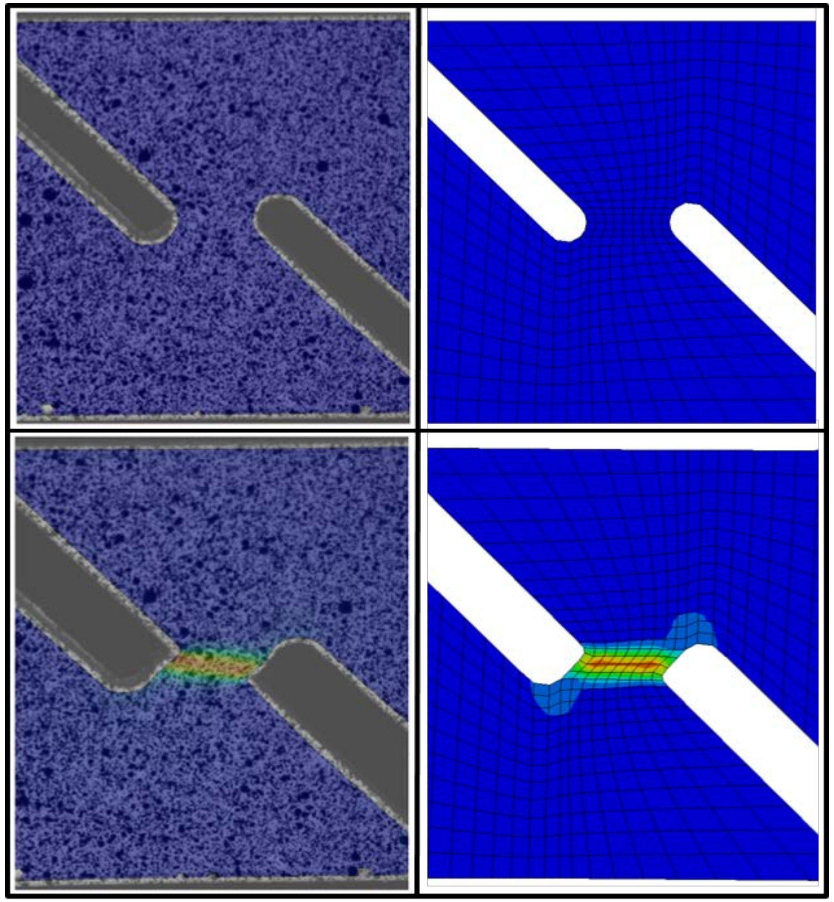
Courtesy: FCA

Digital Image Correlation (DIC)

Optical method for tracking changes in images

Tensile testing equipment

Measurement system



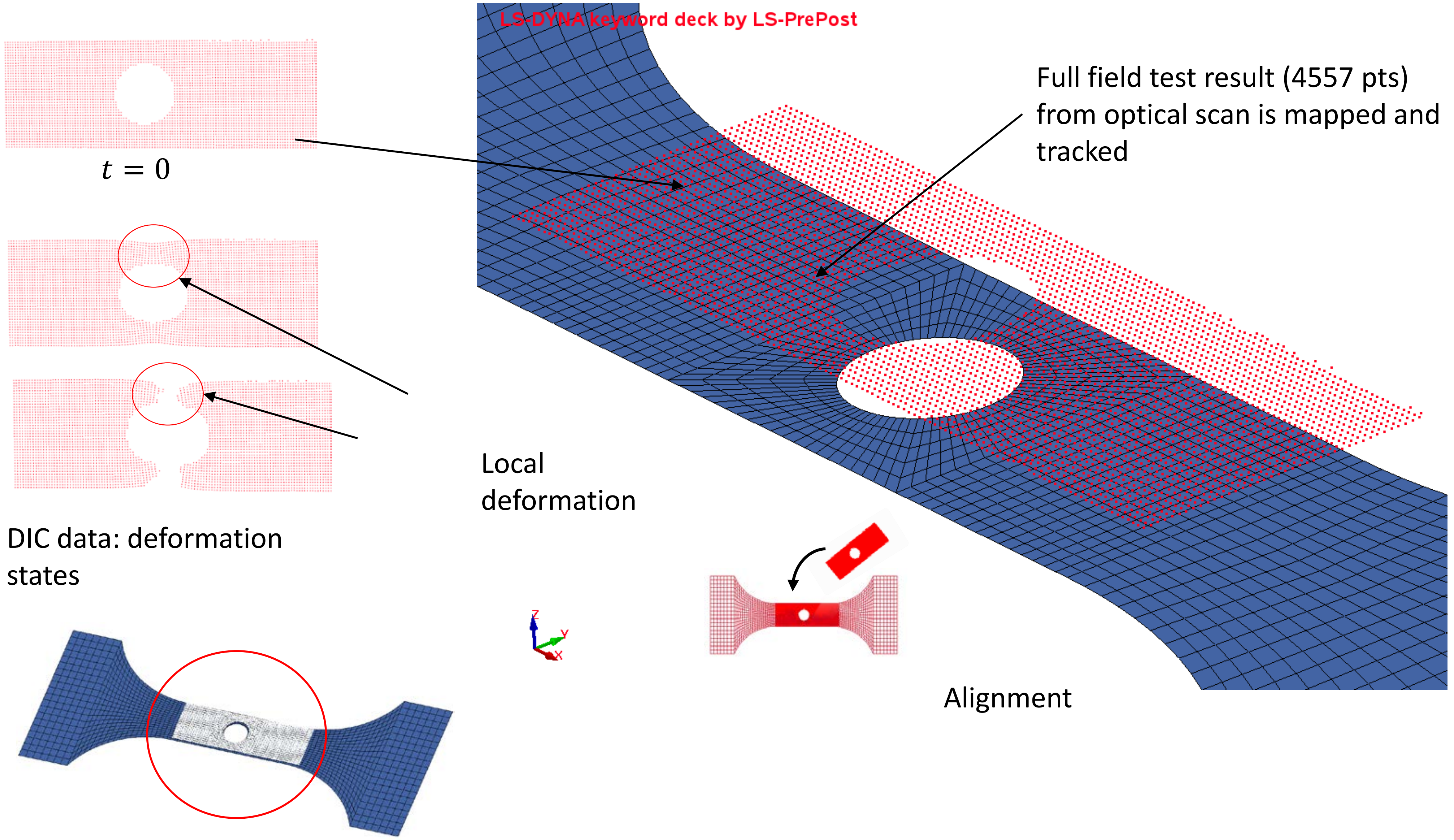
Experiment

Simulation

Aramis at DYNAmore GmbH, Stgt

DIC | Matching in time and space

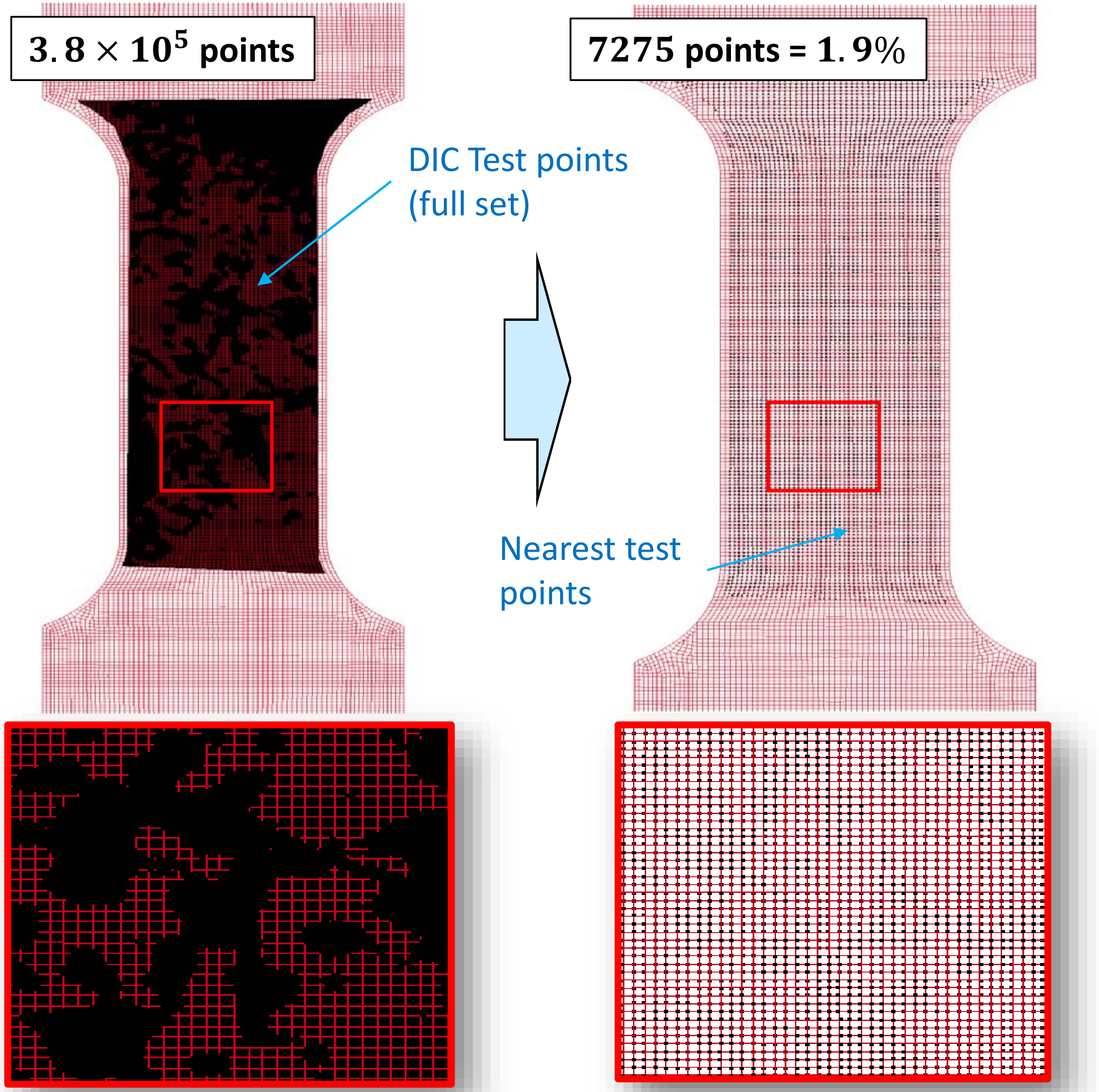
Test data can be mapped to the Finite Element model for Full-field calibration



Digital Image Correlation: *Nearest Neighbor Cluster*

- **Nearest Neighbor Clustering**
  - Pre-processing feature
  - Reduce resources for large point set ($\sim 10^6$)
    - Storage space
    - CPU time: mapping is done at each time step (vanishing nodes/points)
  - Nodal map
  - Can also apply a proximity tolerance for removing outlier points
- **Algorithm** $(\boldsymbol{t = 0})$
  - Nearest node to each point → *reduced node set*.
  - Prune *reduced node set* → *nearest points*
  - 1-to-1 map

Enlarged

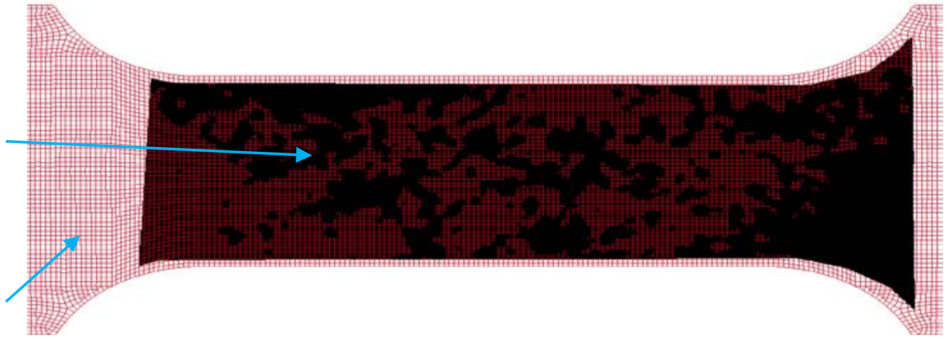


Example 2: Tensile test

The contour comparison uses *Dynamic Time Warping:* 3.8×10^5 DIC points

DIC Test points

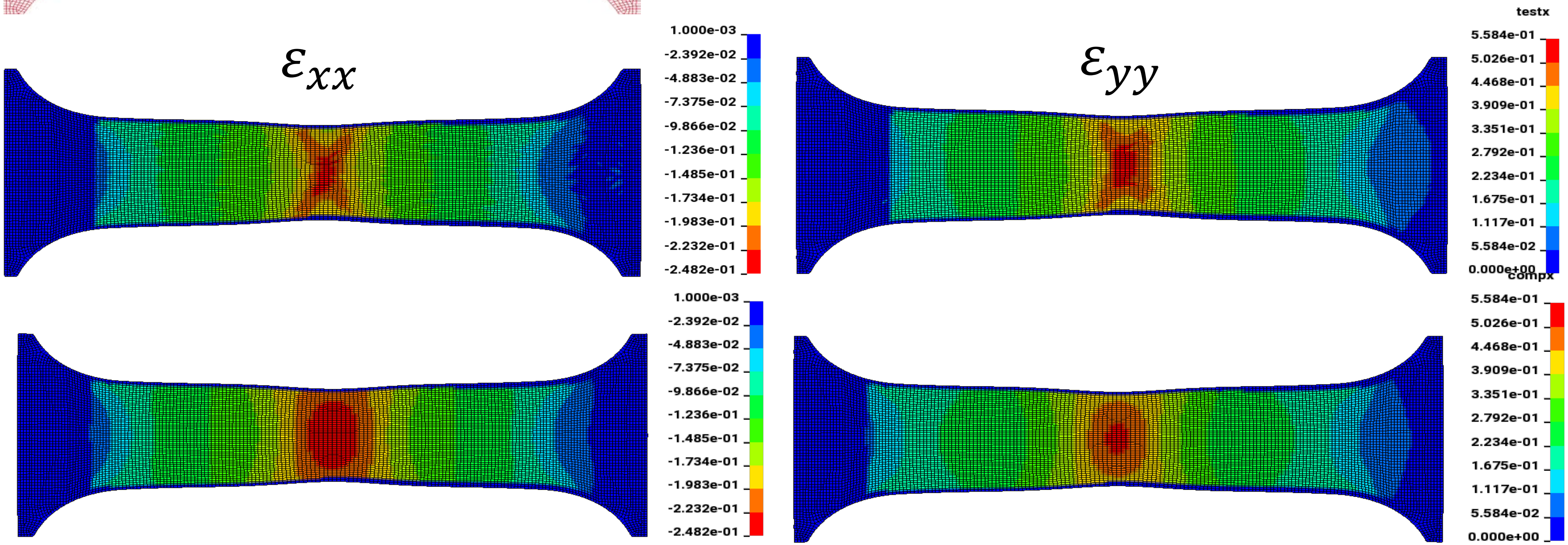
FE model



- Reduces 380,000 DIC points to 7275 points with nodal neighbors
- Reduces extraction time from 2 hours → 6 minutes

DIC

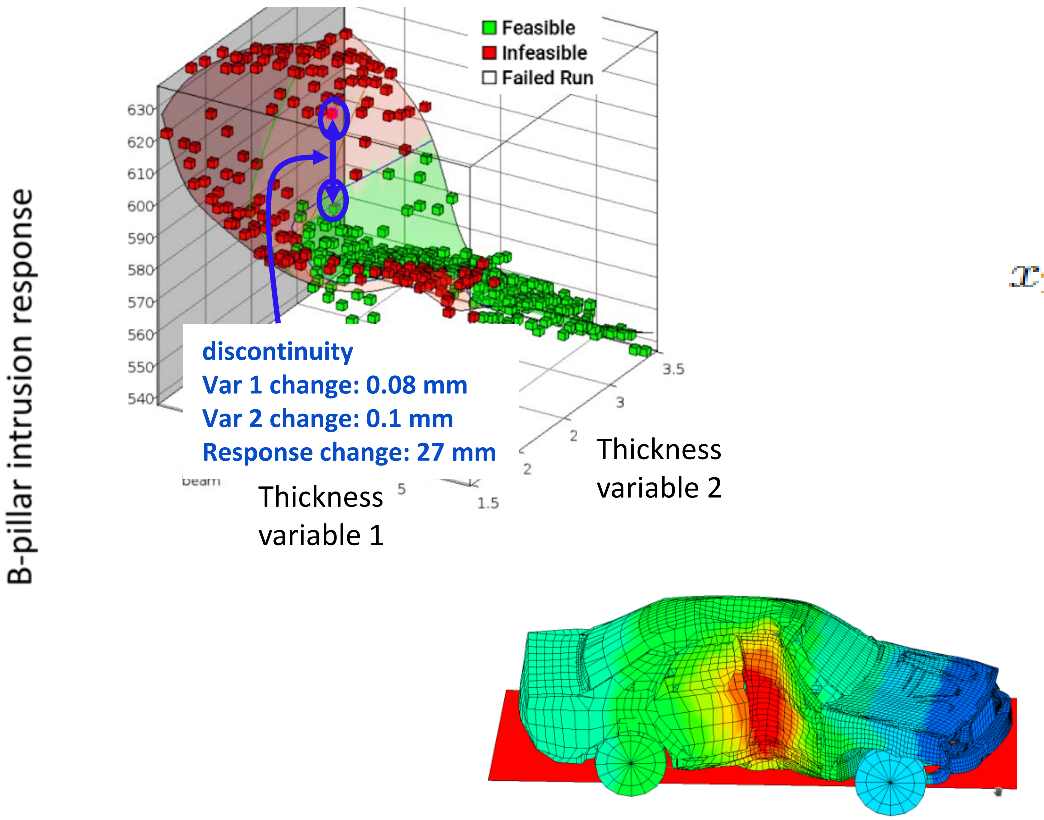
Computed

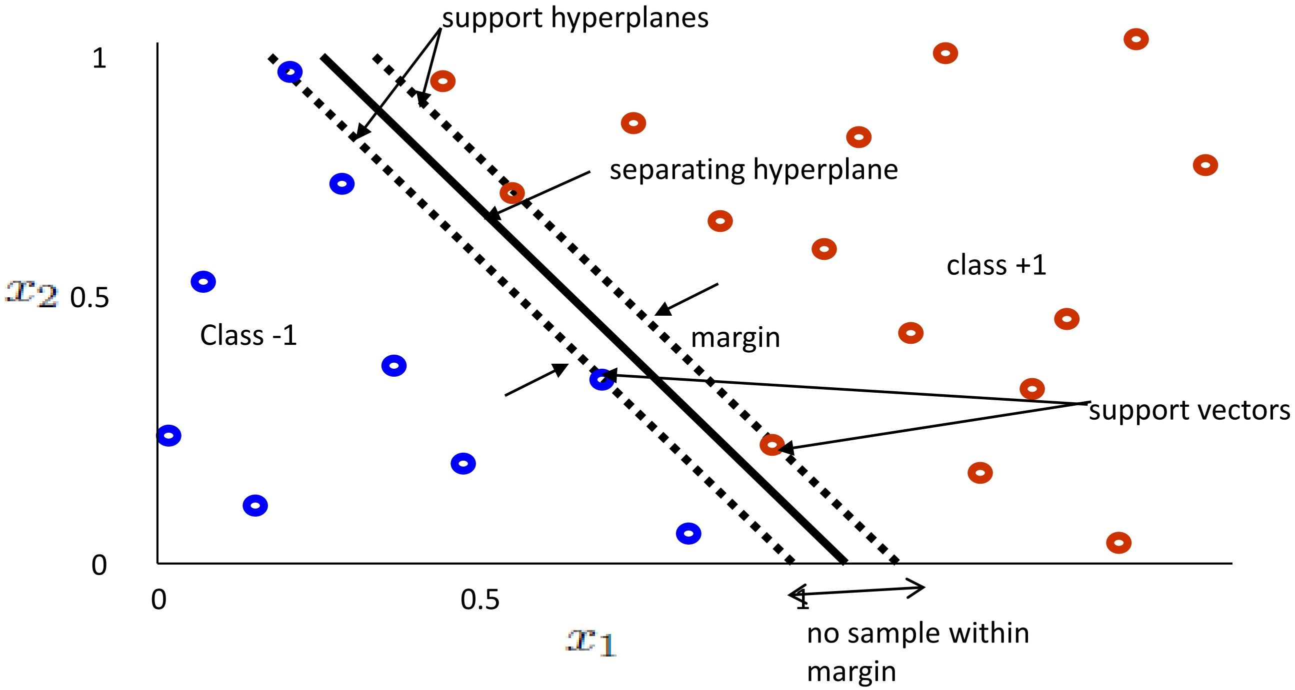


Support Vector Machine Classification

- *Metamodel* approximation hampered by *discontinuities/noise*, hence global approximation using a metamodel may be inaccurate

- *Support Vector Machines (SVM)* treats the problem as a *classification* of feasible/infeasible patterns in the design space (instead of regression)

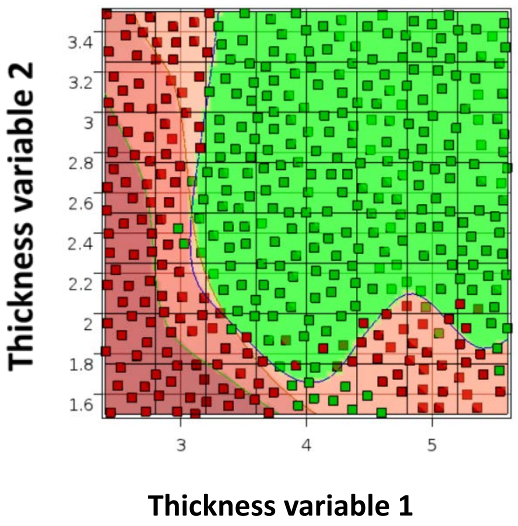




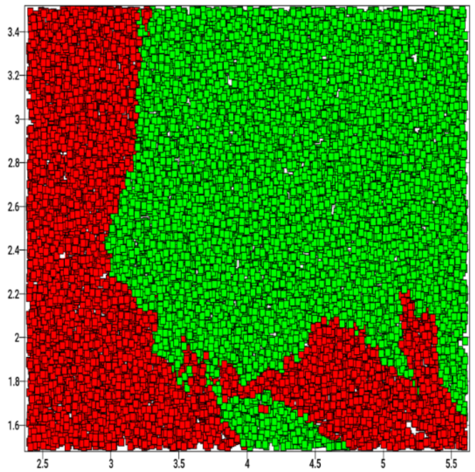
Optimal SVM maximizes the margin

Support Vector Machine Classification

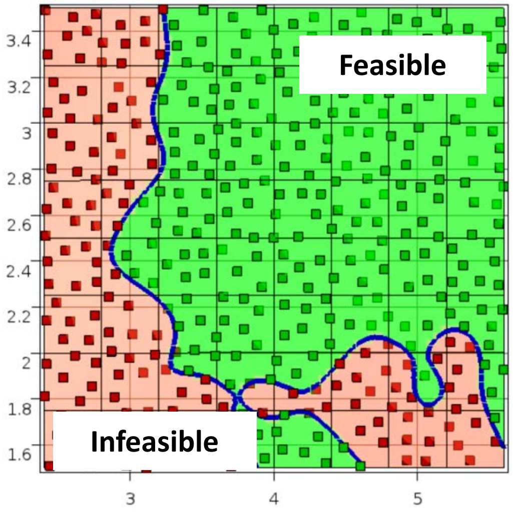
- Handles noisy and discontinuous/binary constraints
- Able to approximate highly nonlinear boundaries accurately
- Single classifier represents multiple constraints (allows computation savings)
- 3 intrusion constraints represented by a single SVM classifier (bottom right)



Neural Net approximation of constraint
(inaccurate)



Actual constraint feasibility
(LS-DYNA)



SVM Classifier
(accurate)

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

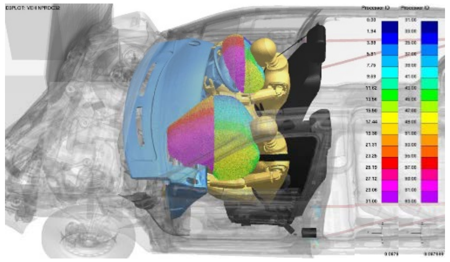
Implicit + Explicit ….

Multi-Scale

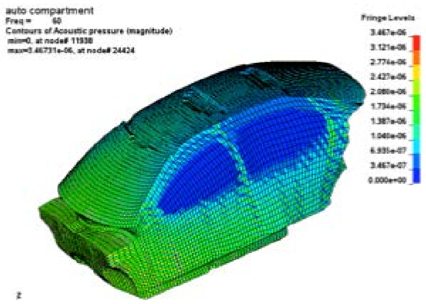
Failure predictions, i.e., spot welds

Multi-Formulations

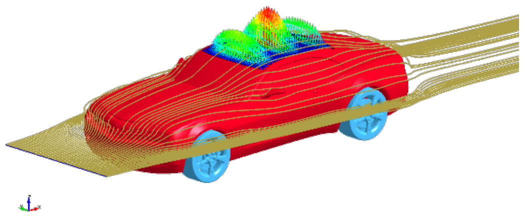
Linear + Non-Linear + Peridynamics + …



Crash



NVH



Structure + Fluid

Announcement and Call for Papers

12th LS-DYNA EUROPEAN CONFERENCE & USERS MEETING

14 - 16 May 2019 ▪ Koblenz, Germany

LSTC
Livermore Software
Technology Corp.

Thank you!