Recent and Ongoing Developments in LS-DYNA

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LSTC
Livermore Software Technology Corp.

16th Oasys LS-DYNA Users' Meeting March 12th 2019

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Announcement

As of March 04, 2019 Nathan Asher Hallquist has been appointed Executive Vice President of LSTC.

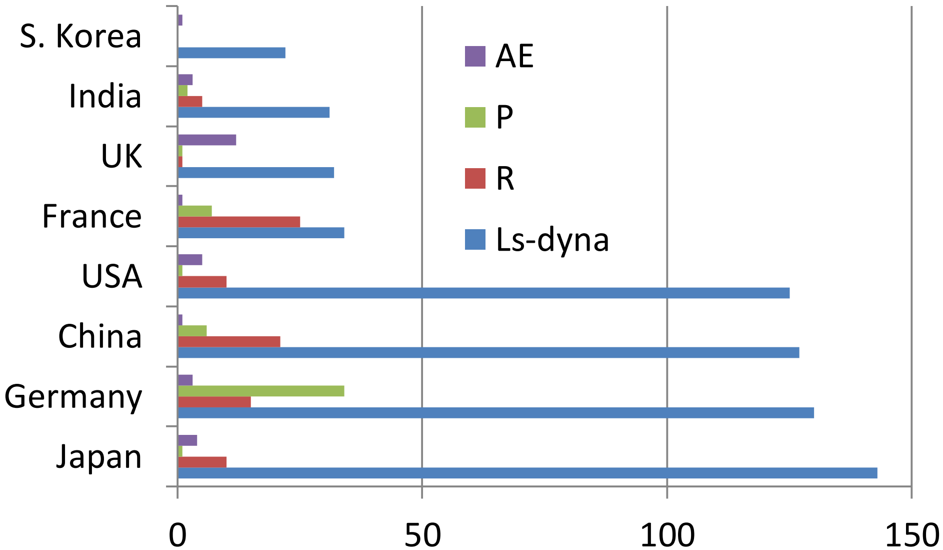
Outline

- Introduction
- Applications and development updates on
  - Metal forming
  - Implicit
  - Frequency Domain Analysis
  - Material: composite
  - CFD: ICFD, ALE, SPH & CESE
  - Meshless method
- Summary & Future

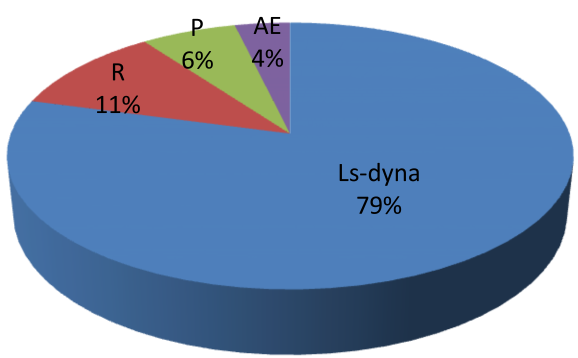
Introduction

Growth of LS-DYNA

- Continues leading explicit FEA

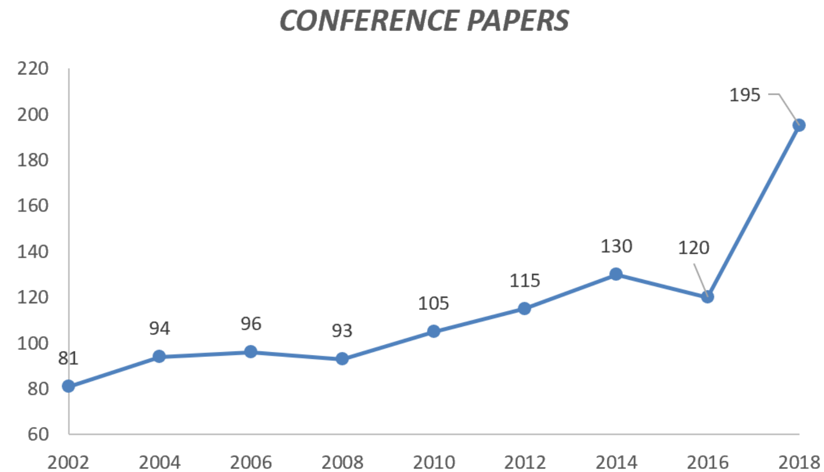


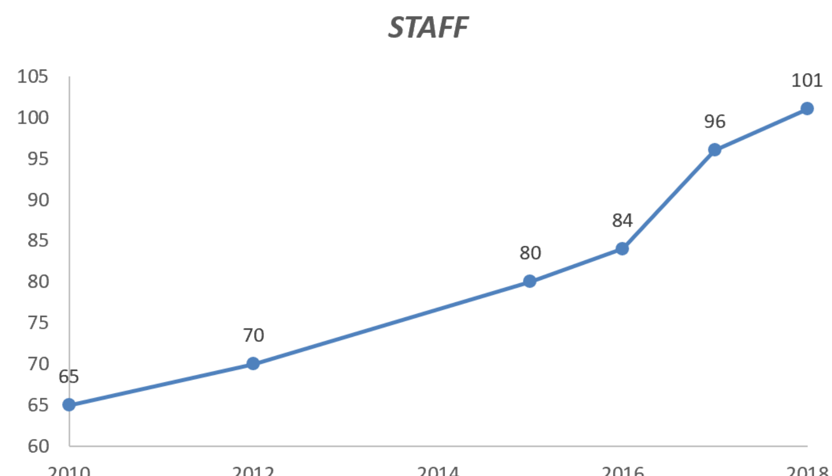
Explicit CAE openings in Indeed, 05/04/2018



Global Market Share

- Keeps growing





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LS-DYNA Applications

Development costs are spread across many industries

Automotive
Crash and safety
NVH & Durability
FSI

Structural
Earthquake safety
Concrete and composite structures
Homeland security

Aerospace
Bird strike
Containment
Crash

Electronics
Drop analysis
Package analysis
Thermal

Manufacturing
Stamping
Forging
Welding

Defense
Weapons design
Blast and penetration
Underwater Shock Analysis

Consumer Products

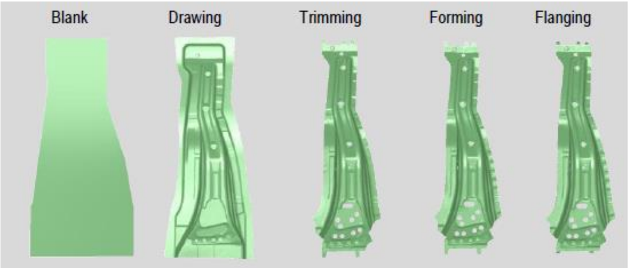
Biosciences

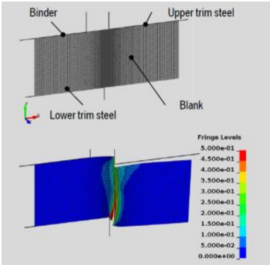
Forming Simulation

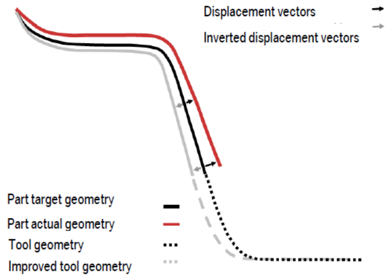
L. Zhang, X. Zhu, F. Ren

LS-DYNA for forming

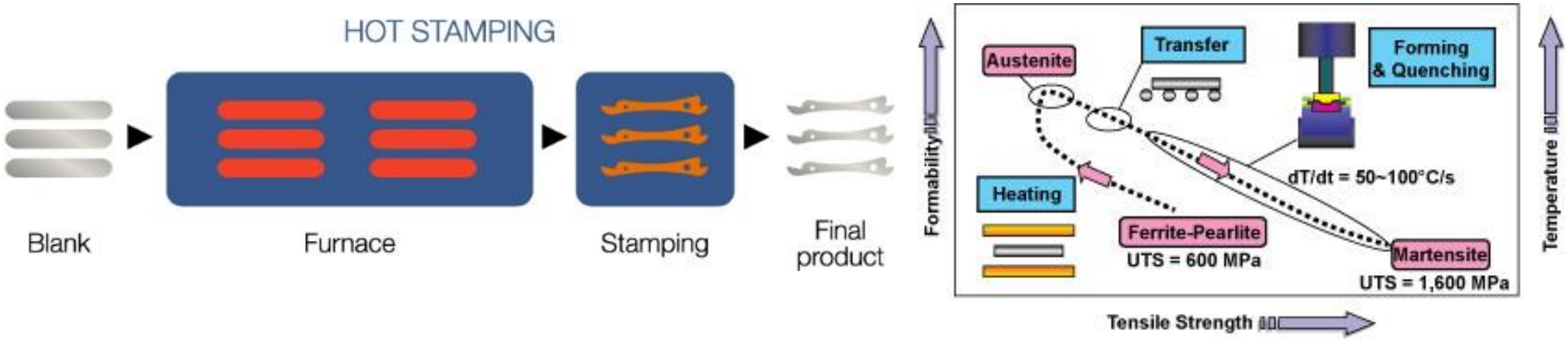
- Users include, not limited to,
  - Audi, BMW, Volvo, Honda, Mazda, Nissan, Toyota, Unipres,..
- Usage of LS-DYNA for Metal Forming in BMW
  - cold forming, trimming and springback compensation







  - simulation of indirect press hardening.



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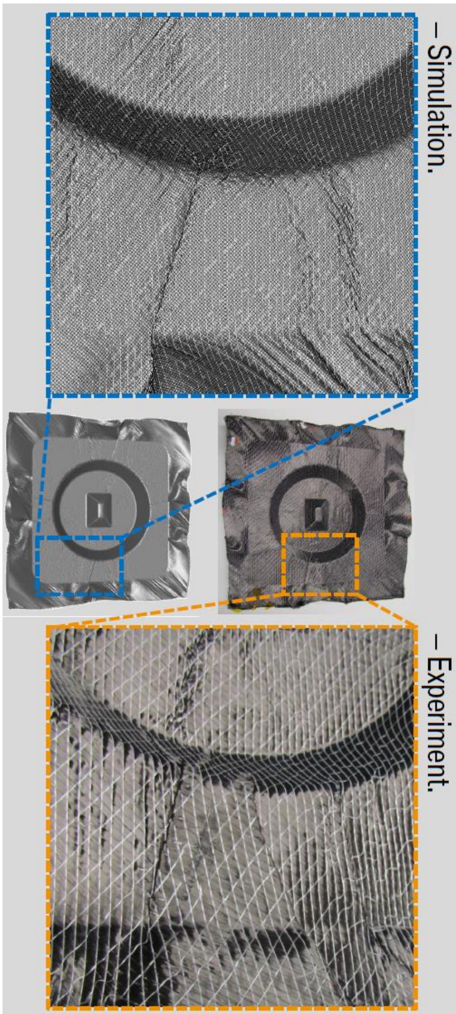
DR. M. FLEISCHER (BMW) "Usage of LS-DYNA in metal forming". 10th European LS-DYNA Conference – 2015.

LS-DYNA for forming in BMW

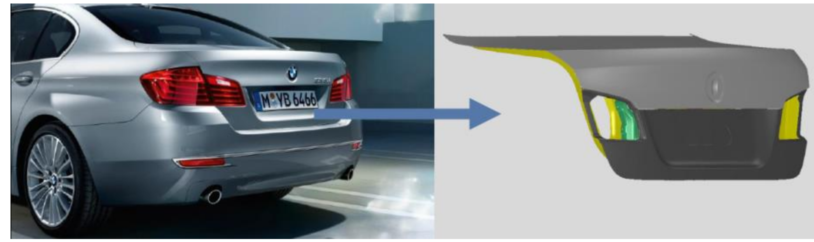
– Draping of CFRP

Ls-dyna

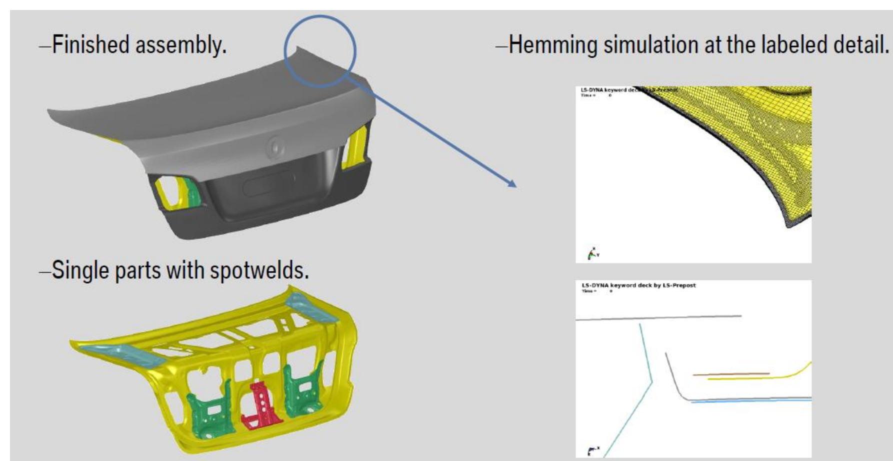
Test



– Assembly process,

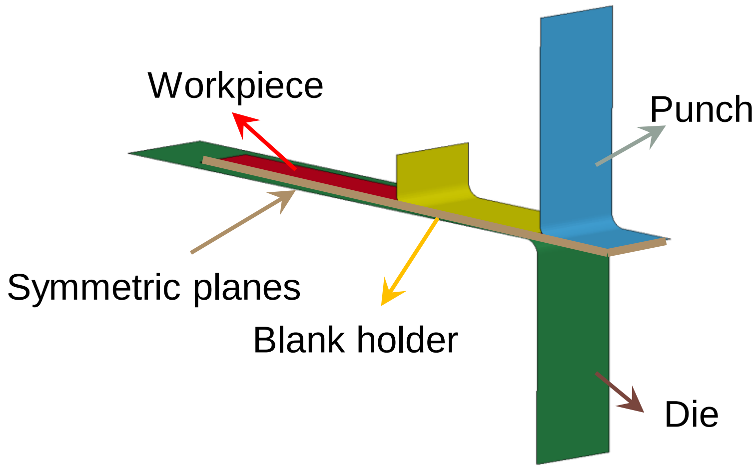


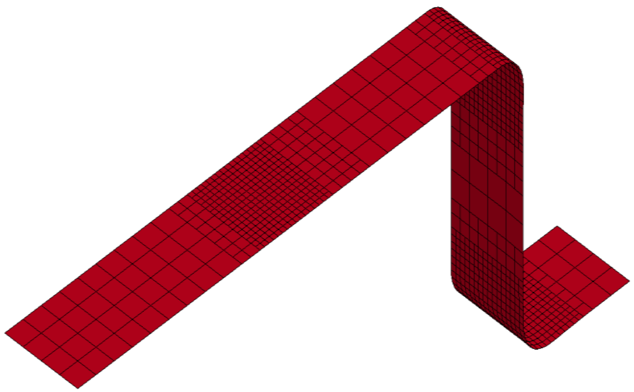
- Insertion of single parts
- Modeling of spotwelds, weldlines & adhesive
- Hemming simulation of the outer parts



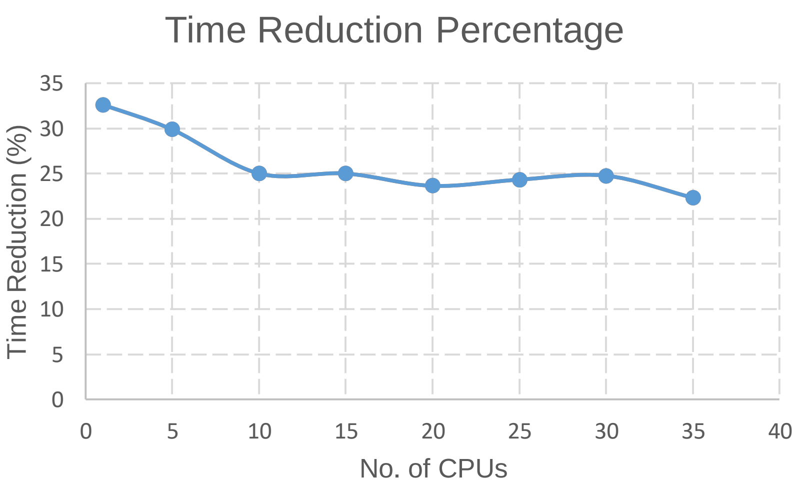
MPP Fusion

- As per BMW's request, Fusion is extended to MPP





- MPP performance
  - Reduce simulation time > 25%
  - Forming error < 2%
  - Springback error < 10%



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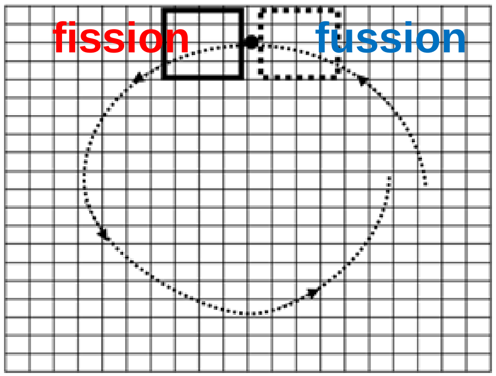
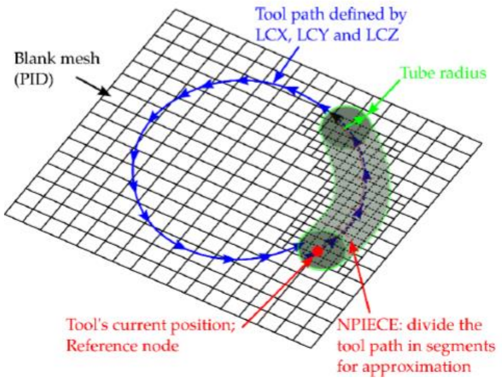
Tube-adaptive method

- Box-adaptive method
  - Cannot handle arbitrary loading path
  - Need to perform mesh fission/fusion every single time step



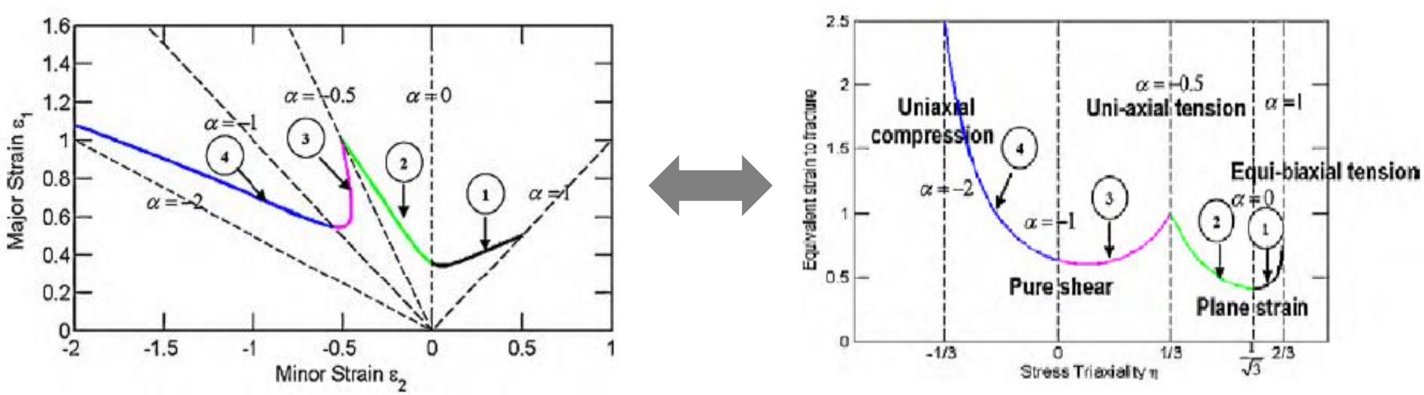


- Tube-adaptive method
  - Arbitrary loading path
  - Optimal adaptive time interval and tube radius
  - Reduce computational cost while maintaining accuracy

Radius	2	4	6	8	10	12	14	16
Thick. Diff.(%)	6.4	4.4	5.2	1.8	0.3	0.7	0.9	0.6
Time Red.(%)	50	50	49	47	46	45	44	40

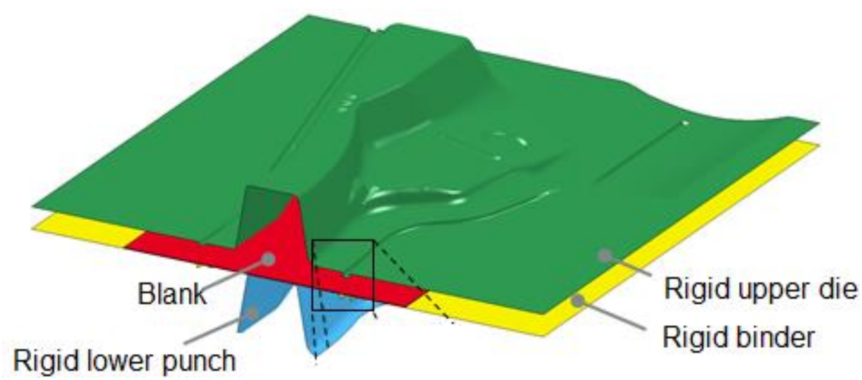
Translations between FLD and Triaxial Limit

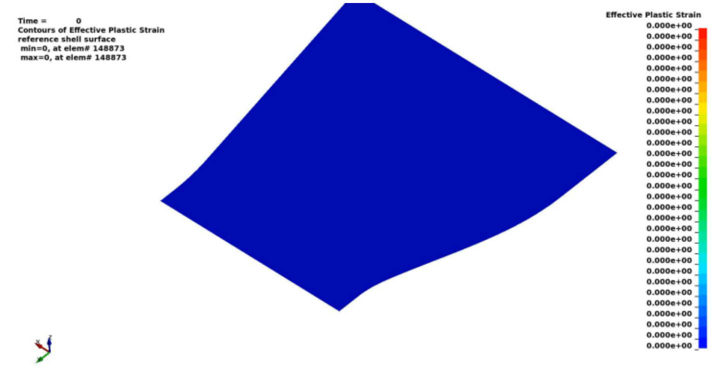
- Increasingly, as more Advanced High Strength Steels (AHSS) are being used, stamping engineers need to worry about material failure such as shear fracture during forming, in addition to the traditional necking failure.
- Two keywords are created to conveniently translate the two types of failure limits.
  - *DEFINE_CURVE_FLD_FROM_TRIAXIAL_LIMIT
  - *DEFINE_CURVE_TRIAXIAL_LIMIT_FROM_FLD



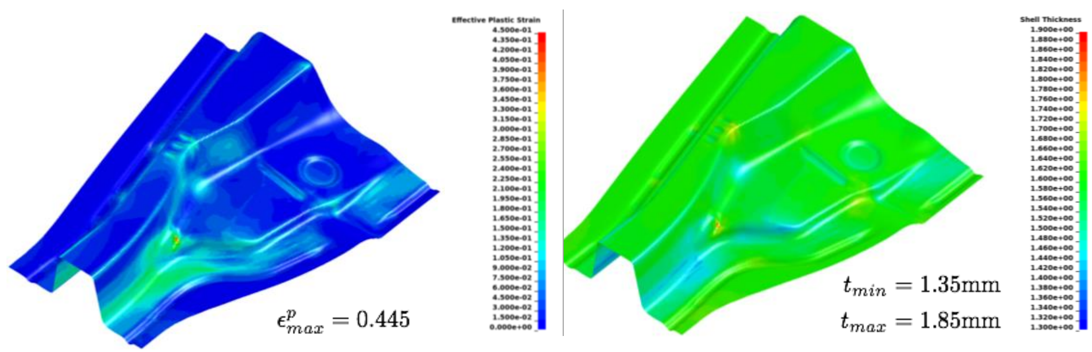
IGA for Metal Stamping

- NUMISHEET 2005 benchmark in 2017

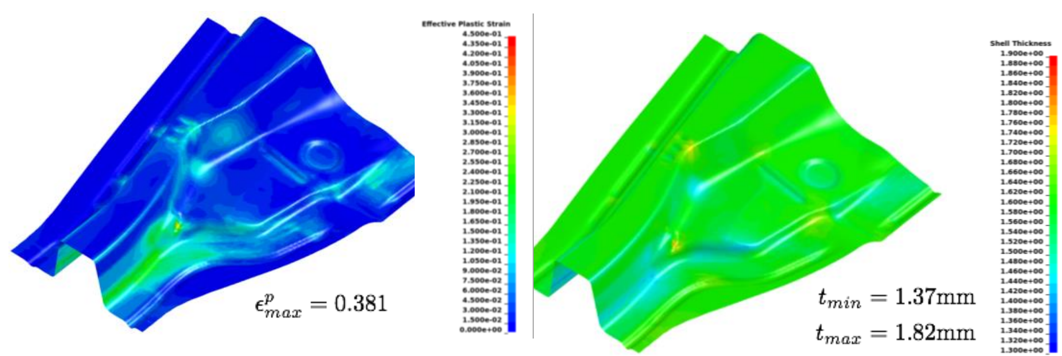




FEA:
- Avg. mesh = 2mm
- 3.7 hr



IGA:
- No adaptivity
- Mesh = 4mm
- 2.2 hr



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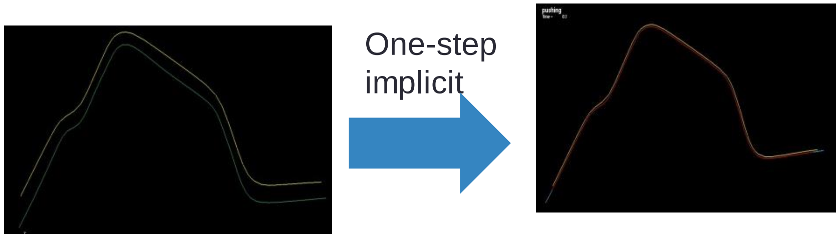
Implicit

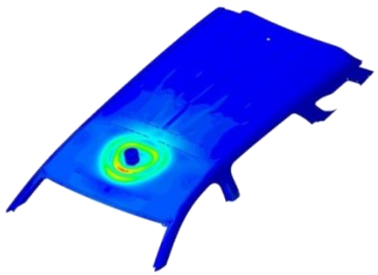
Thomas Borrvall, F. Bengzon

LS-DYNA for Implicit analysis

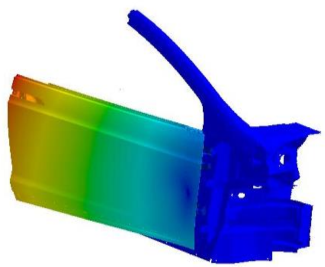
- Spring-back compensation



- Static structure analysis



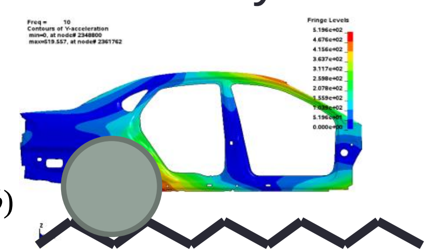
Oil canning simulation



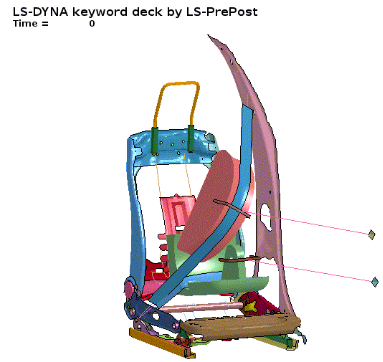
door sag simulation

- Frequency domain solver for NVH, fatigue, random vibration analysis..

$$F(t) = F_0 \sin(\omega t + \phi)$$



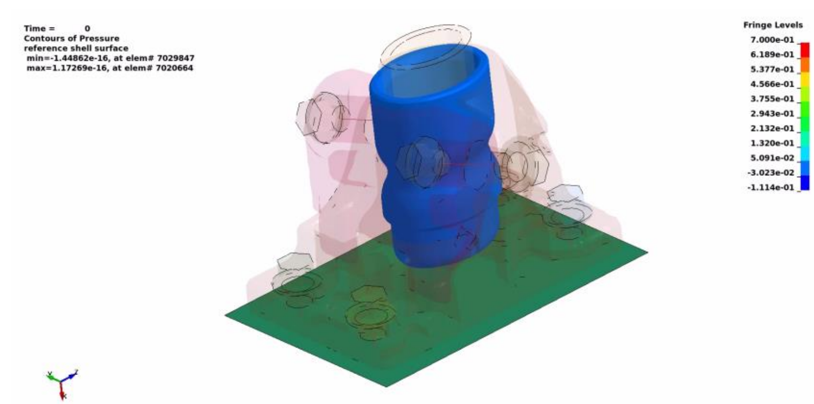
- Safety analysis



207/210

Positioning BioRid & HPM, Daimler

- Other



Fitting of rubber cylinder between two steel components, *VOLVO GTT*

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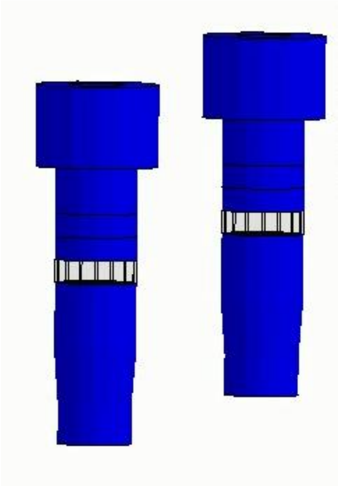
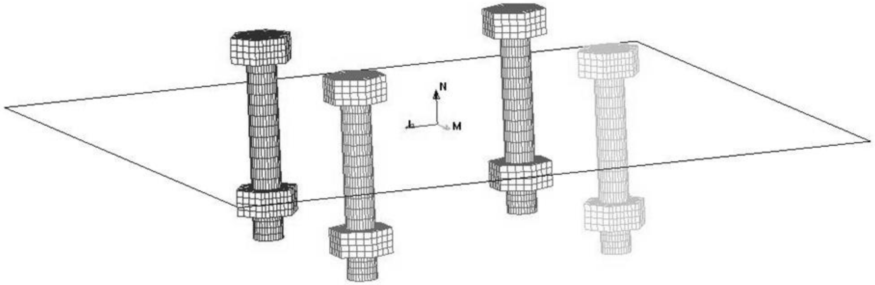
Improvement for implicit

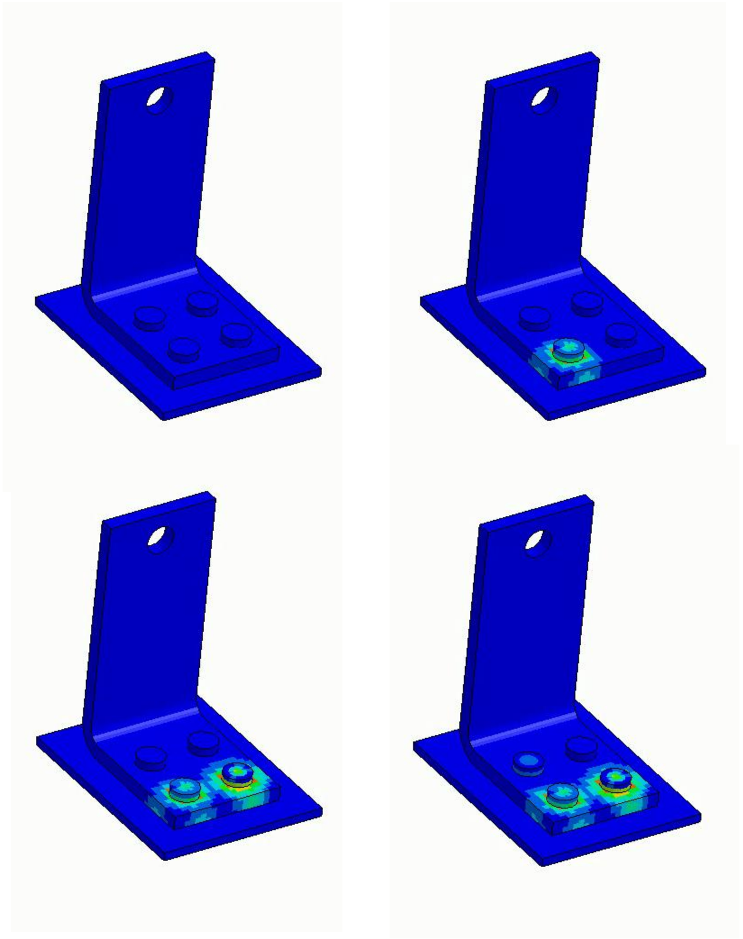
- Prescribed motion
  - exact integration of velocity and acceleration curves
  - avoid zero residual force for use on rigid bodies
- Mortar contact
  - frictional torque due to (shell) offsets
  - extensions of friction, tiebreak and tied weld
  - Rejections
- Prestress
  - initial stress section accounts for bending
    - IZSHEAR=2 on *INITIAL_STRESS_SECTION
  - mean cross sectional stress prescribed
  - preserves structural integrity of bolts





Improvement for implicit

- Process splitting (*CASE)
  - implicitly requested by users
  - a ”complicated” process is divided into ”simple” steps
  - each ”step” is simple and clean
    - no birth/death, simple curves etc.
  - system state transferred between cases through dynain.lsda
    - stress, history, stabilization, contact friction, tied contact
  - flexible
    - each case is essentially a keyword input, allows for ”any” modifications
  - ”restart” can be made from any case
    - saves the agony of rerunning the entire process



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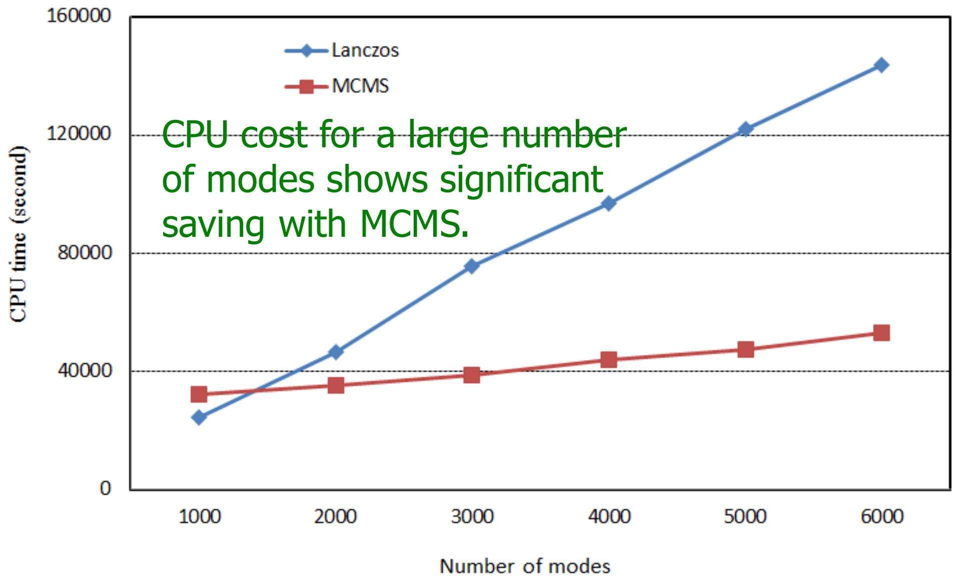
Frequency Domain Analysis

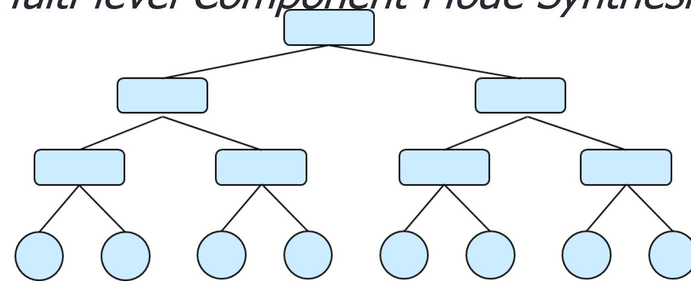
Z. Cui & Y. Huang

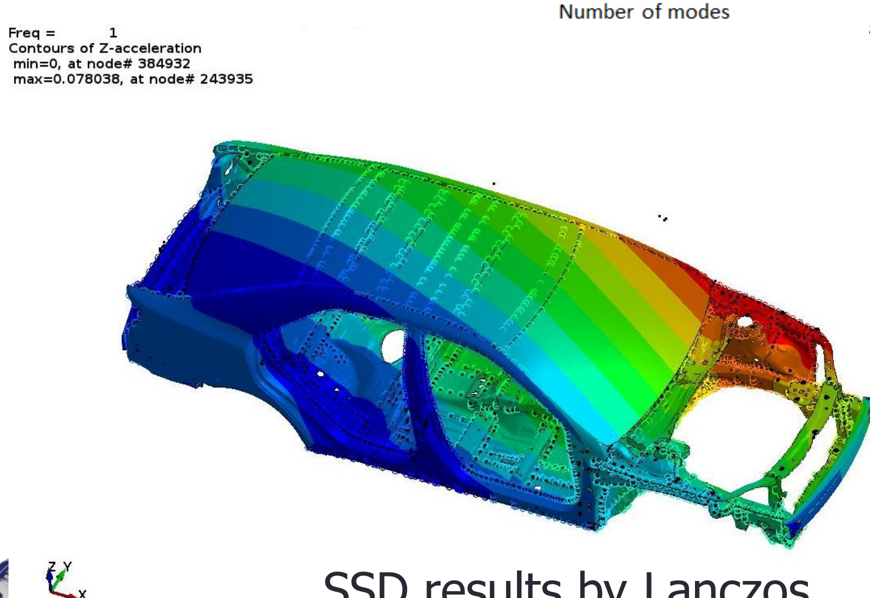
Using MCMS for NVH analysis



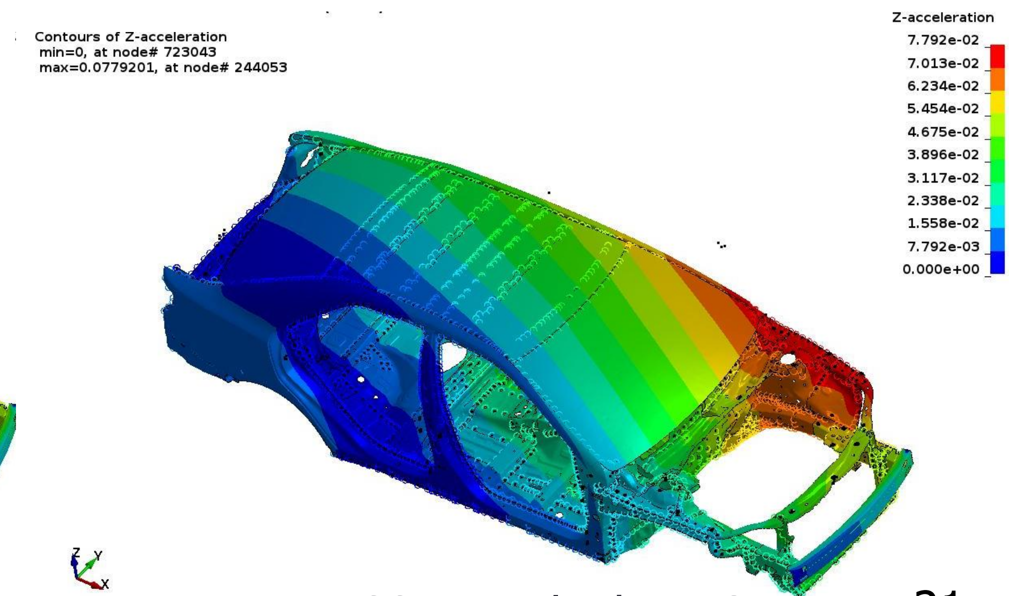
MCMS (developed by Roger Grimes)

Multi-level Component Mode Synthesis



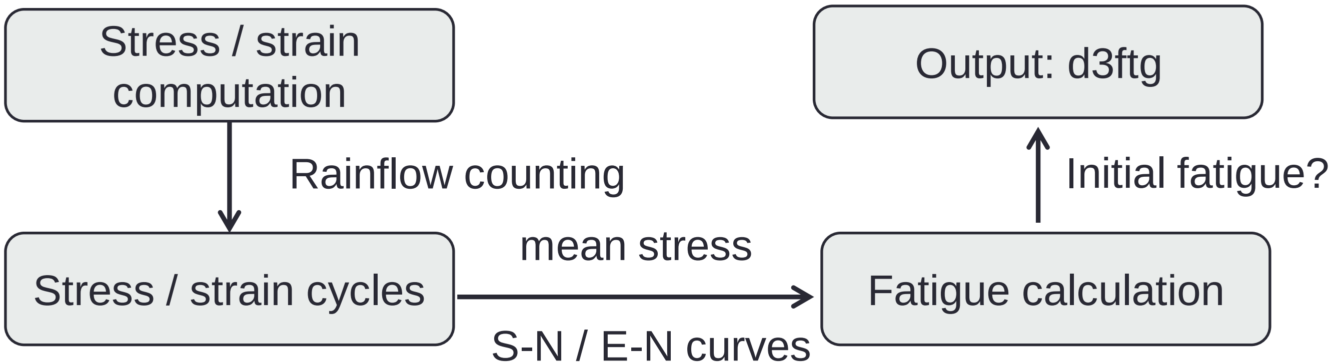


SSD results by Lanczos

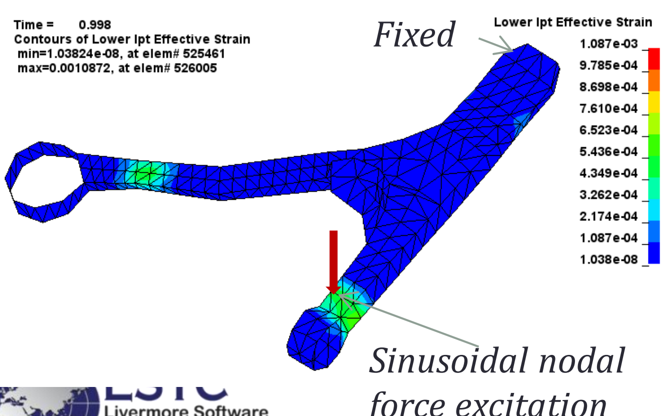


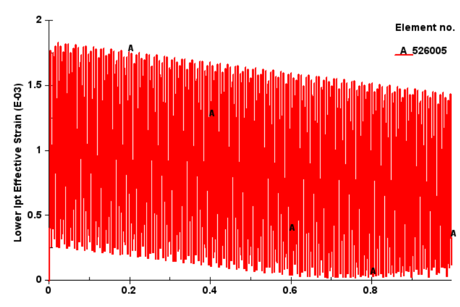
SSD results by MCMS

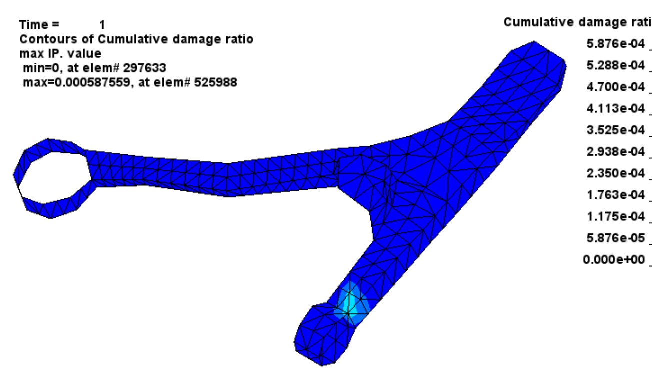
Time domain fatigue analysis



- Calculate damage ratio and fatigue life in time domain
- Advantages
  - A wide selection of stress / strain solvers (linear / nonlinear, thermal, multi-physics, fluid-structure interaction, EM, CFD, explicit / implicit, etc.)
  - Integration of vibration and fatigue solvers in one code.







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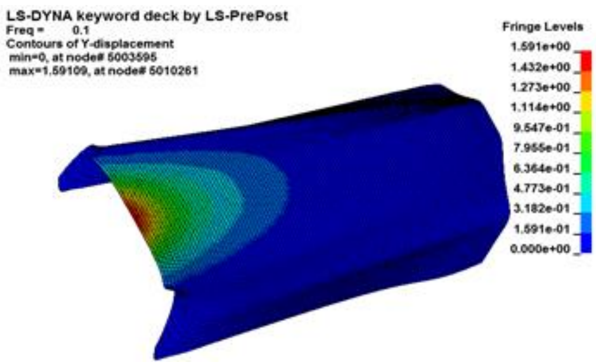
IGA for Frequency domain SSD

NURBS Shell Model

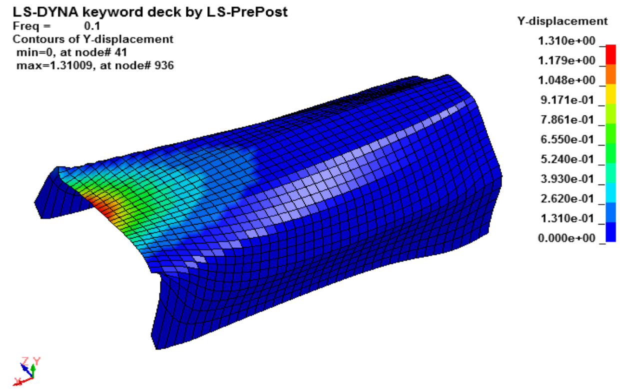
Full Gauss integration rule

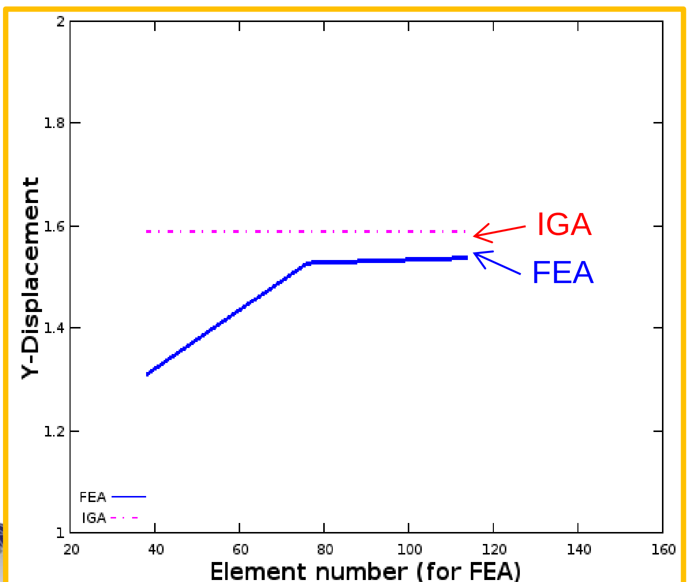
*Piecewise linear plasticity (*MAT_024)*



FEA baseline model

Fully integrated shell with assumed strain formulation





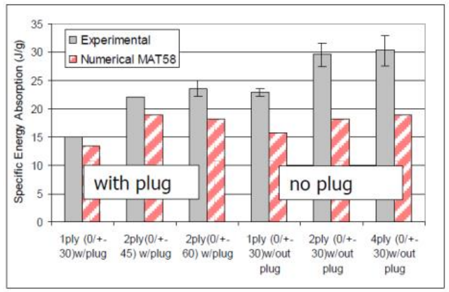
Analysis tool	Number of elements	CPU (s)
IGA	1444	47
FEA	1444	6
FEA	5776	23
FEA	12996	54

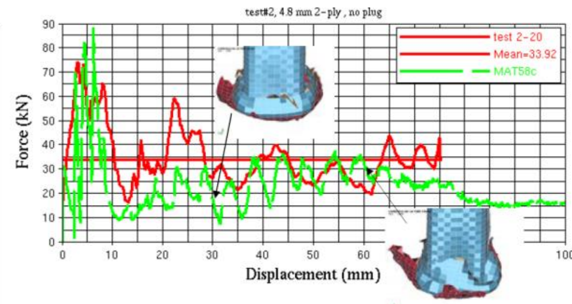
Material

Composite

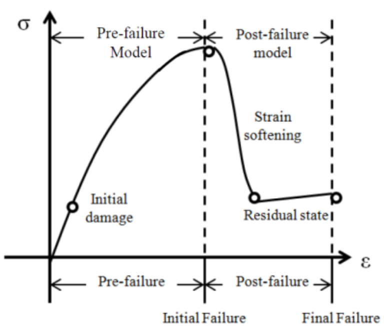
LS-DYNA composite material - application

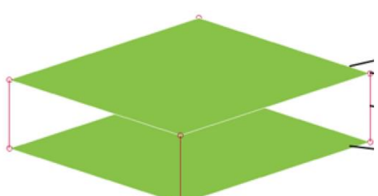
- Traditional material model like MAT58 with CDM tends to underestimate the energy absorption (EA) by 10%~40%

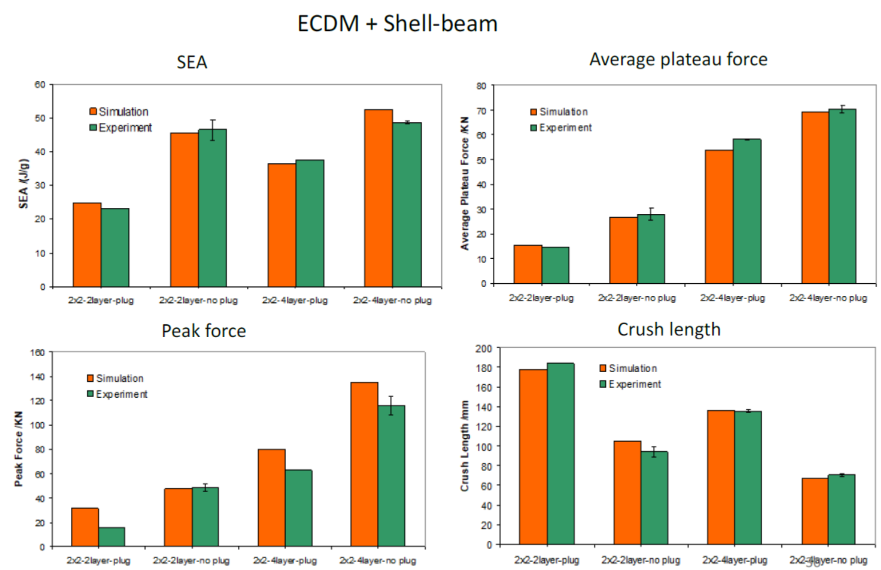




- enhanced continuum damage mechanics (ECDM) model and a shell-beam (SB) method are developed as a remedy



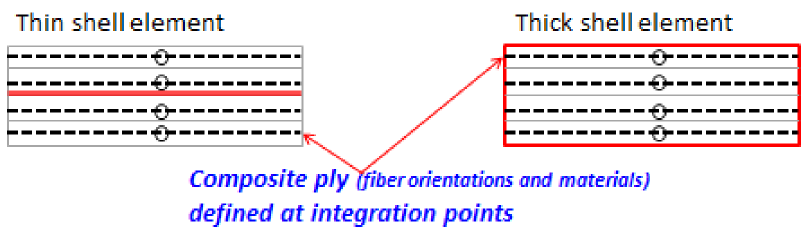


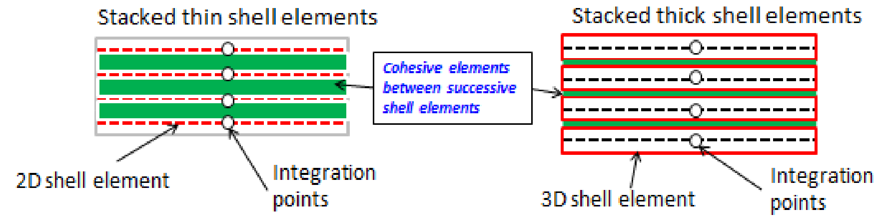


"Modeling the Post-Peak Behavior for Crashworthiness Prediction of Composite Structures", X. Xiao and D. Shi Composite Vehicle Research Center, MSU, 15th ls-dyna int. conf.

LS-DYNA composite material - application

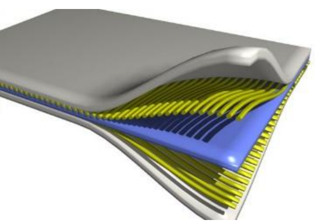
- Pre-preg compression molded (PCM) CF composites is modeled in meso-scale using MAT_54

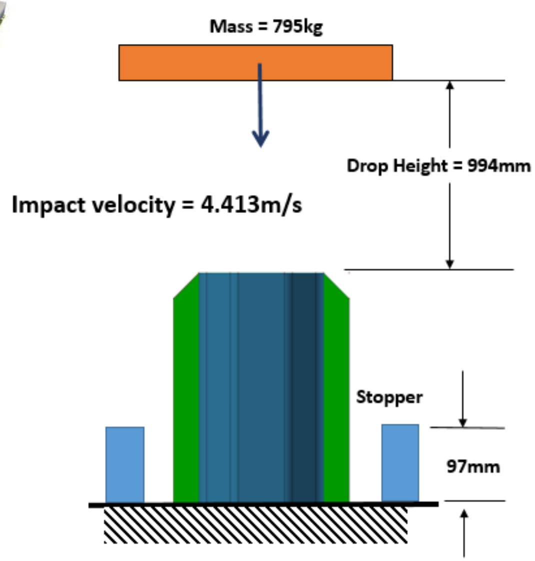


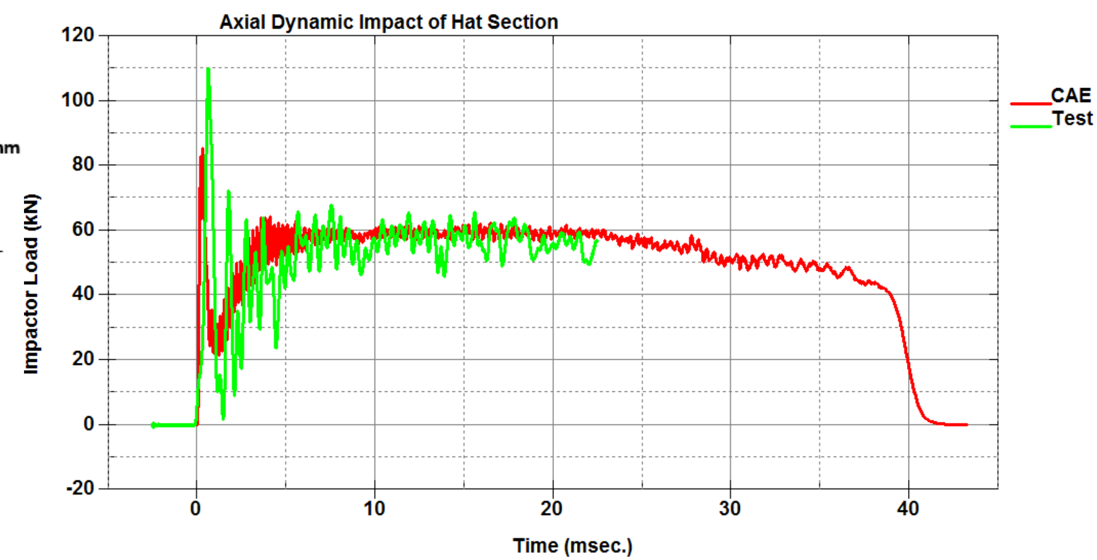


- *Composite ply (fiber orientations and materials) defined at integration points*
- *Cohesive layer thickness equals ply thickness*

- *Composite ply (fiber orientations and materials) defined at integration points*
- *Cohesive layer has zero thickness*

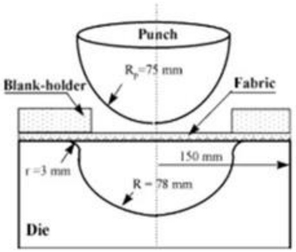


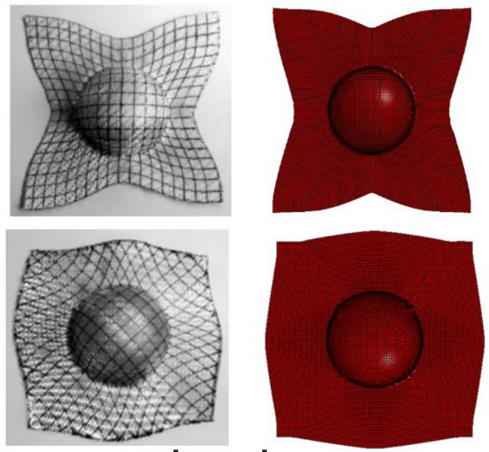




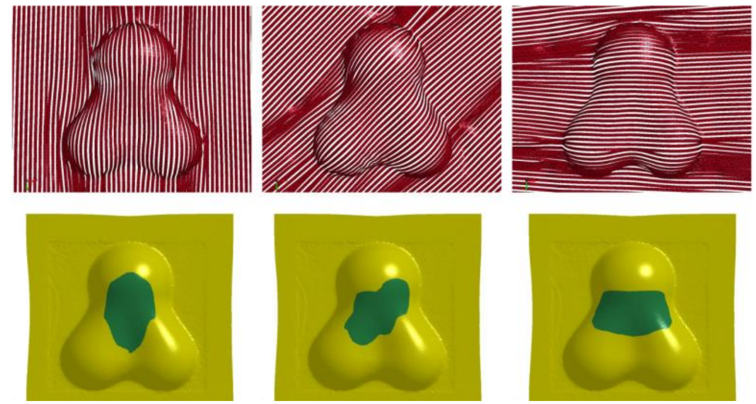
LS-DYNA composite material - application

- Draping and RTM



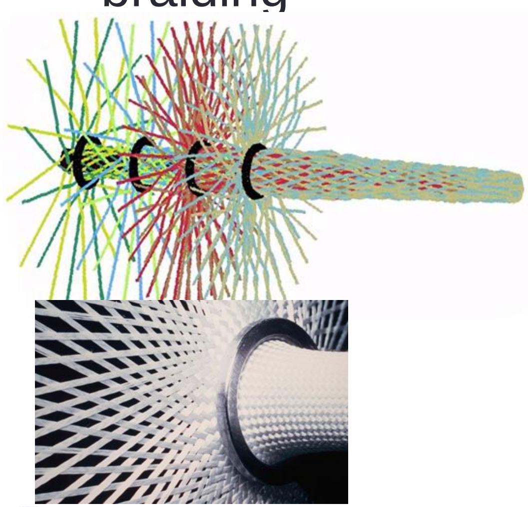


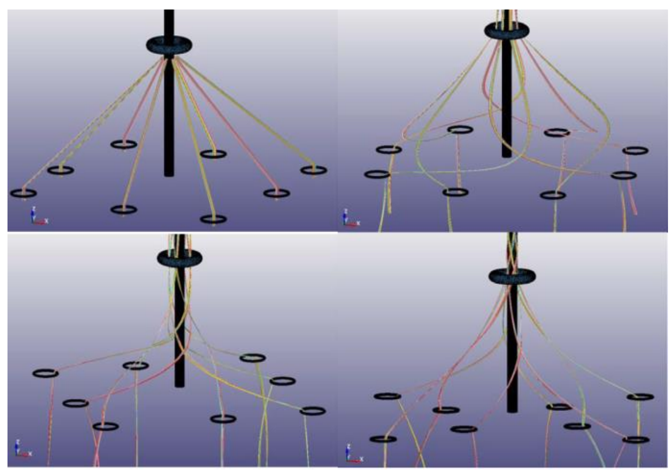
draping

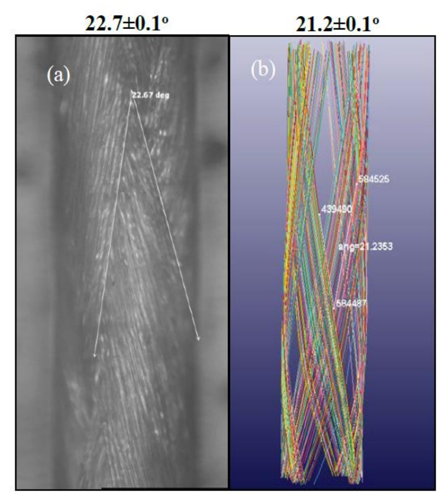


RTM with ALE

- braiding



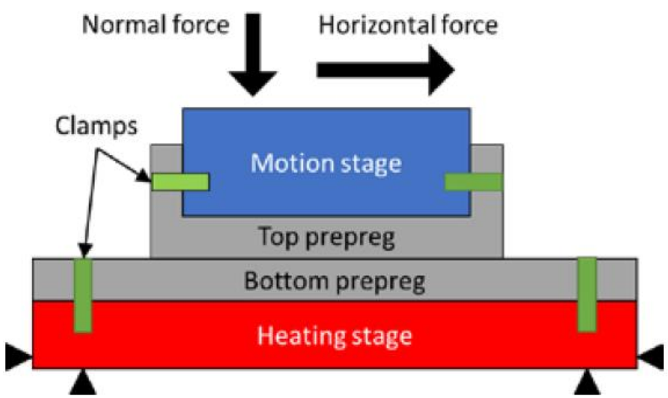


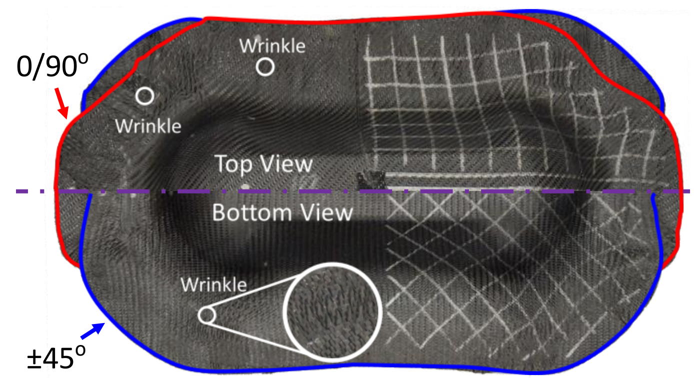


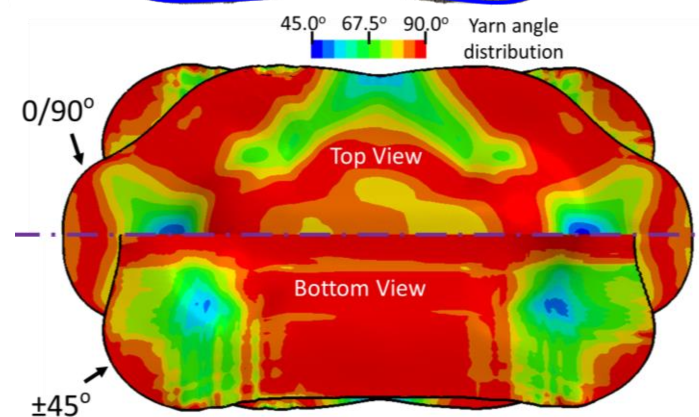
"Simulation of the Braiding Process in LS-DYNA", Seyedalireza Razavi *Imperial College London, Department of Aeronautics, London, UK* 15th International LS-DYNA® Users Conference

MAT_293 for the preforming of woven composites

- For woven prepregs forming simulation, which are woven CFRPs impregnated with uncured thermoset resin in desired fiber orientations
- decouple the strong tension and weak shear behavior of the woven composite under large shear deformation
- For woven long fiber composite, fiber angle after forming is critical for accurate predication of crash performance







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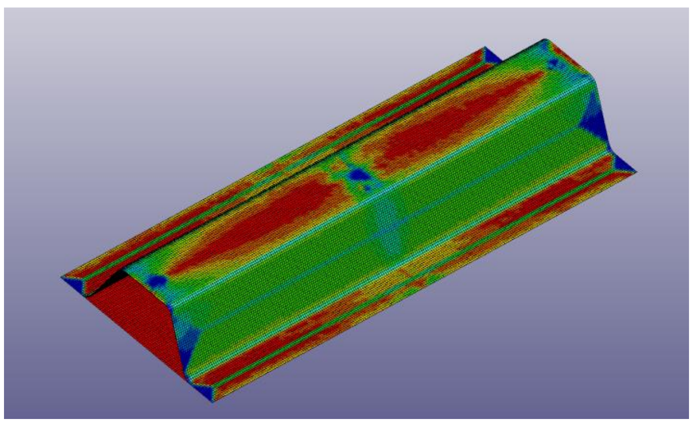
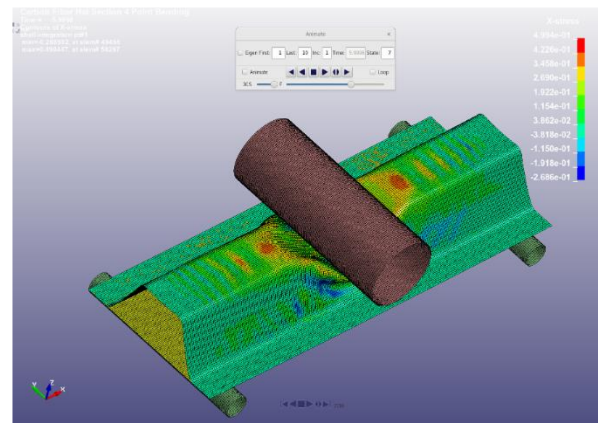
Short fiber from molding to crash

- New interface program to utilize Moldflow and MoldEx3D molding result for LS-DYNA crash analysis is recently implemented in LS-PrePost
- Enhance MAT_157 with *INITIAL_STRESS card for elasticity tensor Cij



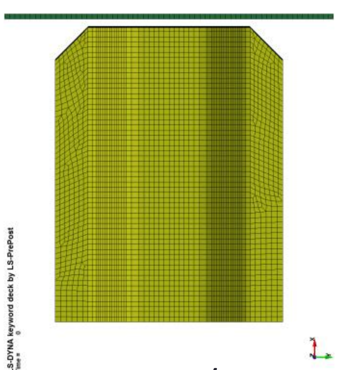
Fiber orientation result from Moldflow



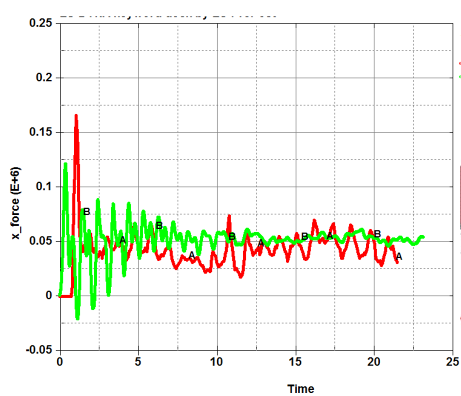
LS-DYNA 3 point bending simulation

Thick shell and cohesive element for delamination

- Model description
  - CFRP modeled as thick shell; each thick shell represents a ply
  - Cohesive element thickness of 0.01mm; TS size 4mmx4mm
  - Both UD and Woven tested
  - MAT_054 is used

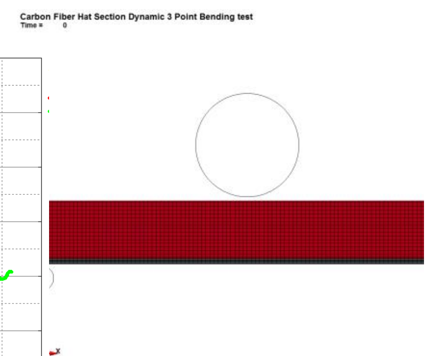


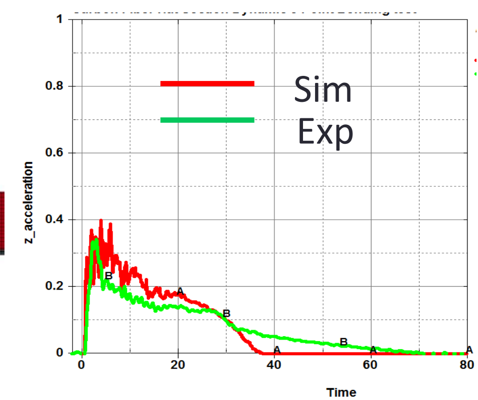
V=4.4m/s



axial

3 point bending





3-point bending

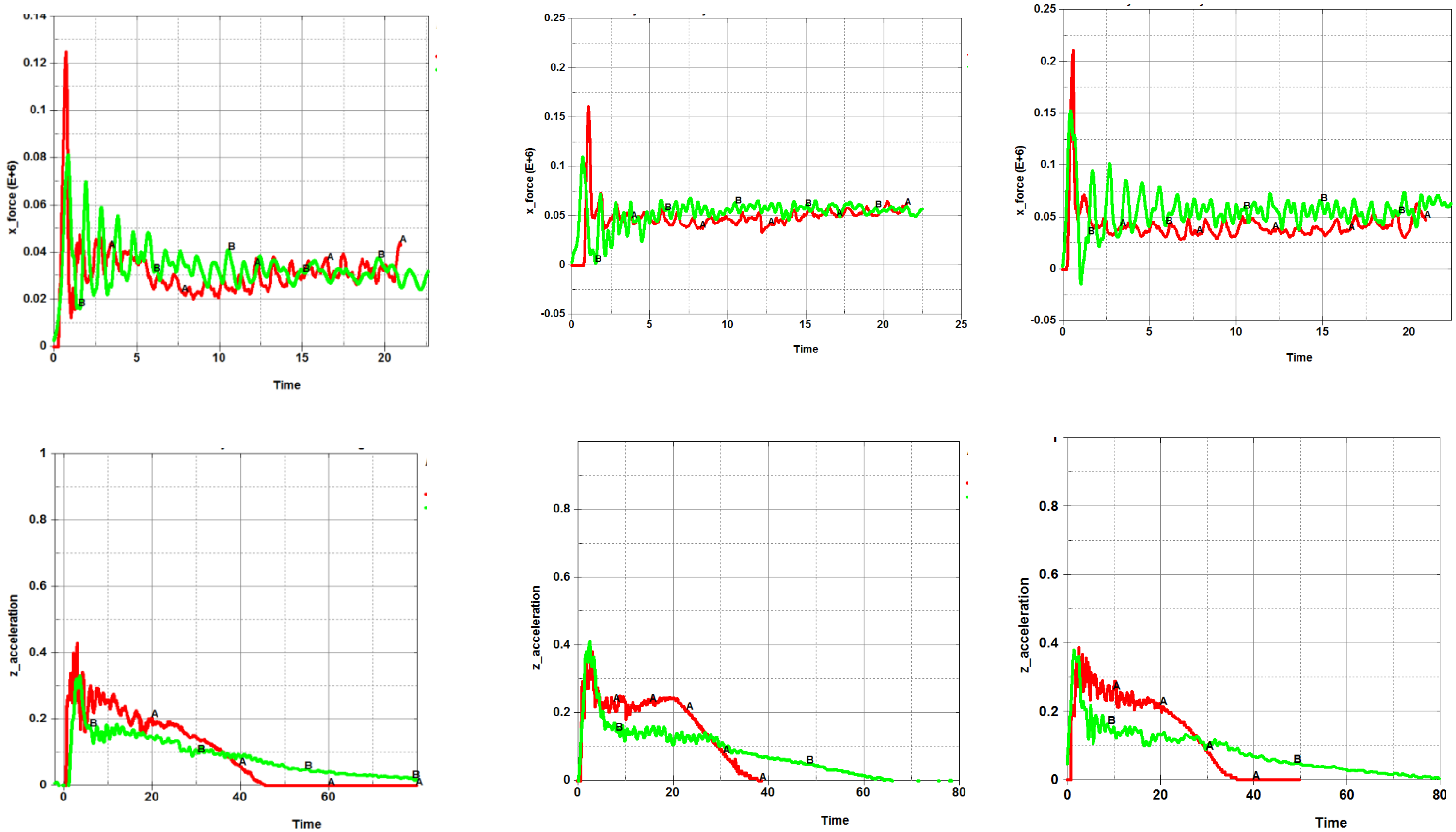
Woven 0-90

Thick shell and cohesive element for delamination

Sim
Exp

Axial crush

3 point bending



Woven 45-45

UD [0/60/-60/0/60/-60]$_S$

UD [0/90/90/0/0/0]$_S$

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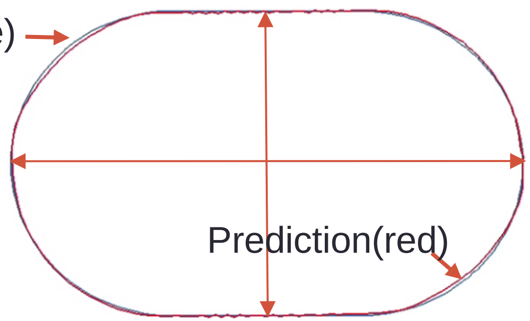
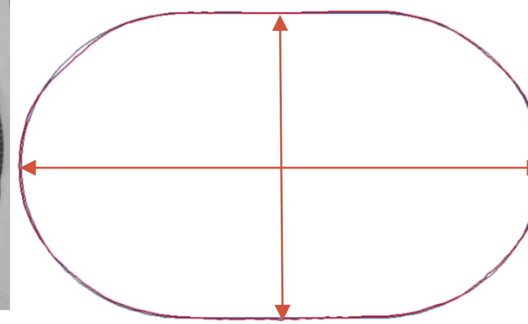
One-Step Analysis for Woven Carbon Fiber Composite

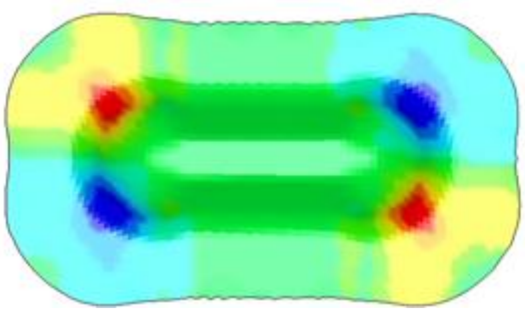
- *DEFINE_FIBER
  - defines carbon fibers and their related properties in a matrix for a one-step inverse forming simulation.
  - Can predict the desired composite shape and fiber orientations
  - works *only* with the keyword *CONTROL_FORMING_ONESTEP

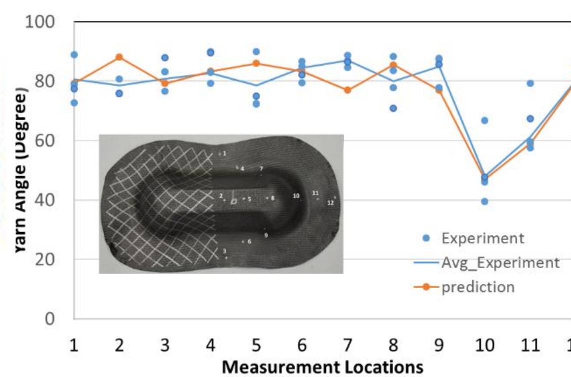
Predicted shape

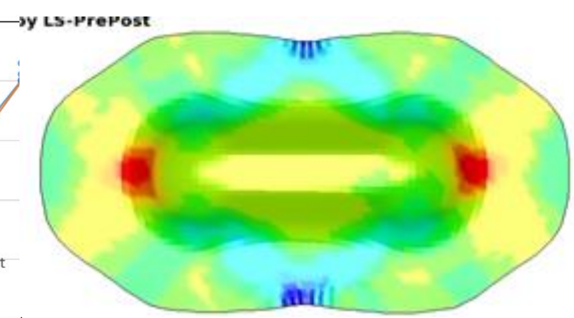




Predicted fiber angle







0, 90 deg

45, 135 deg

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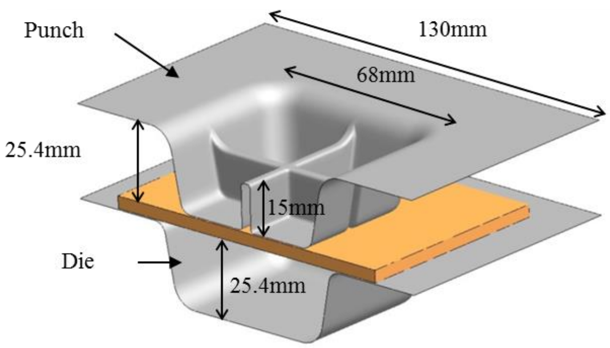
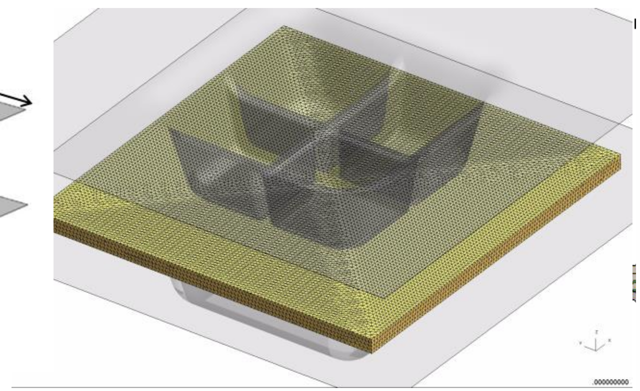
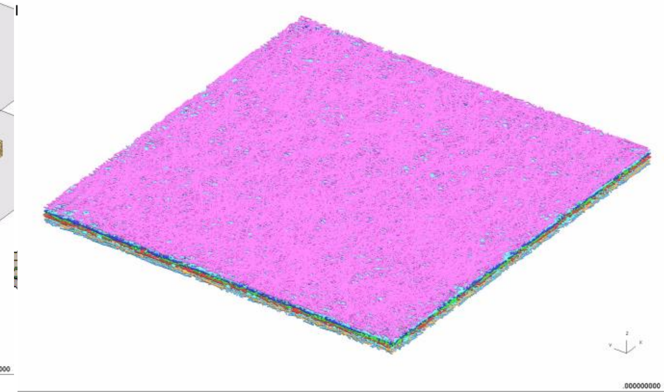
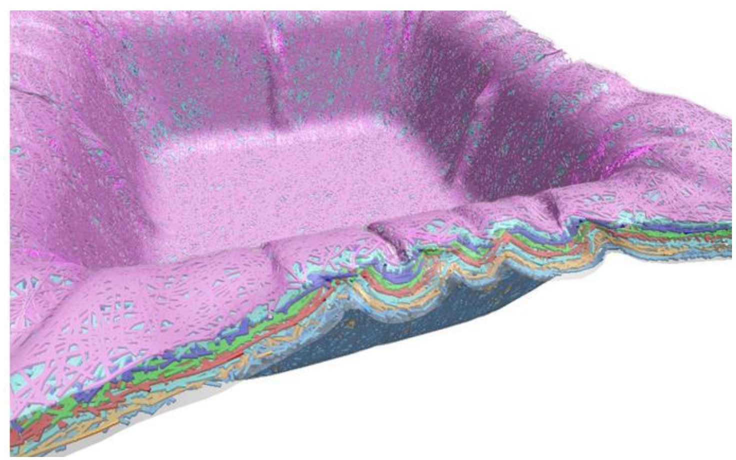
*CONSTRAINED_BEAM_IN_SOLID

- Was designed for RC; Extended to simulate FRP manufacturing process
- Thermal-mechanical Adaptive EFG method with local refinement









Courtesy : Shinya Hayashi, JSOL

CFD Technique

Zeng-chan Zhang, Kyoung-Su Im, and Grant Cook, Jr.
Hao Chen
Inaki Caldichoury, Pieree L'Eplattenier
Edouard Yreux

CFD solvers in LS-DYNA

- Available CFD solvers in ls-dyna

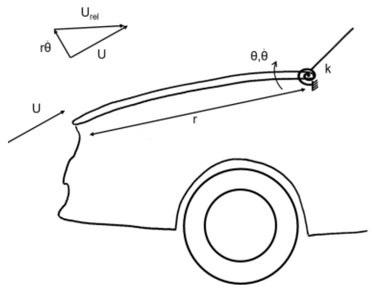
Solver	CESE	ICFD	ALE	SPH
Low speed aerodynamics	-	√	-	-
High speed aerodynamics	√	-	-	-
Explosive with EOS	-	-	√	√
Airbag-piston	√	-	√	-
Free surface problem (slamming)	-	√	√	√
FSI	√	√	√	√
Chemistry reaction	√	-	-	-
Stochastic particles	√	-	-	-

ICFD

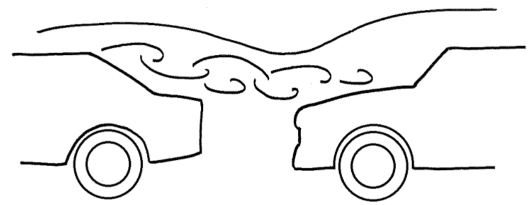
Facundo Del Pin
Iñaki Çaldichoury
Rodrigo R. Paz
Chien-Jung Huang

ICFD applications

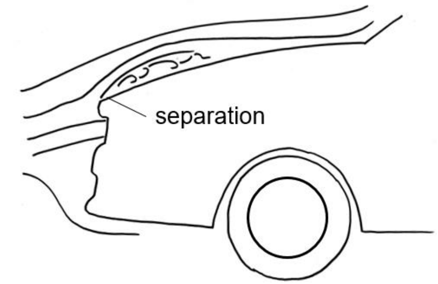
– Hood flutter vibration



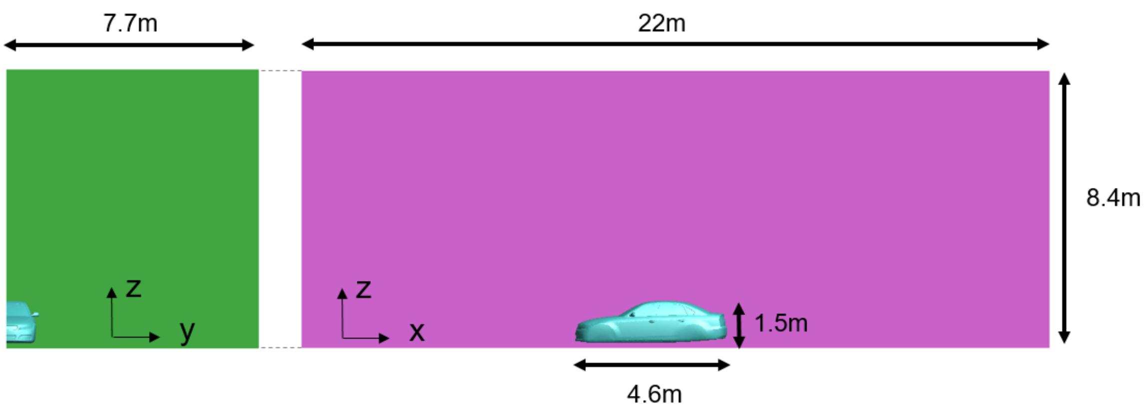
Hood attached to a rotational spring

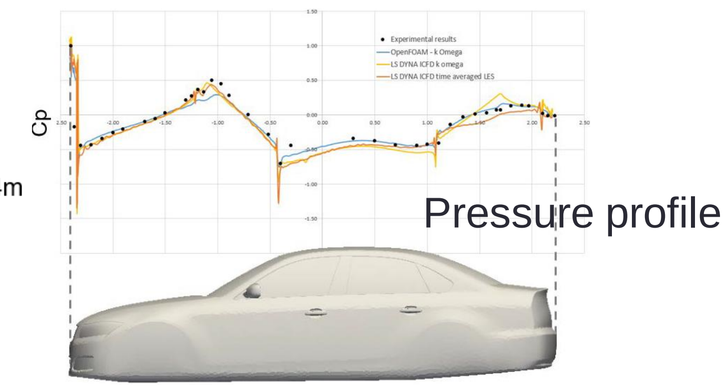


Extraneously induced excitation

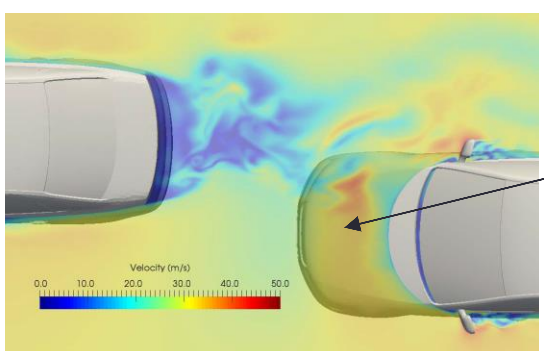


“Instability induced excitation”

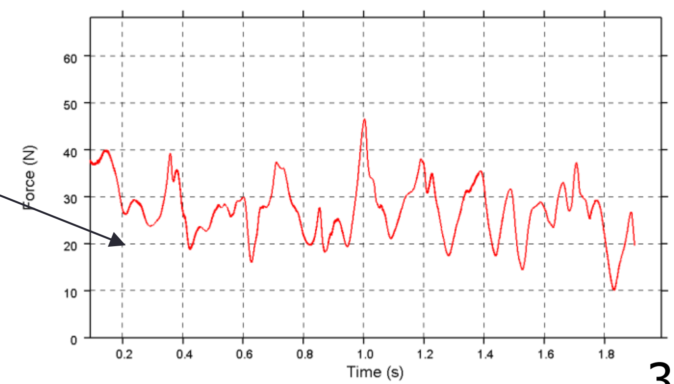




Flow field around the front of the following car



Force on the hood of the following car



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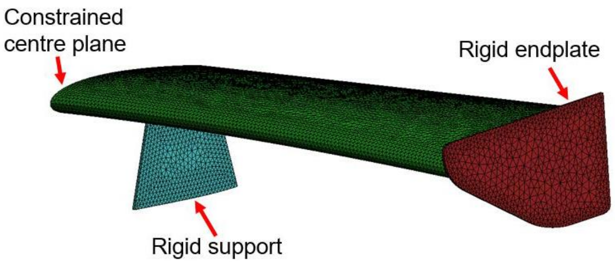
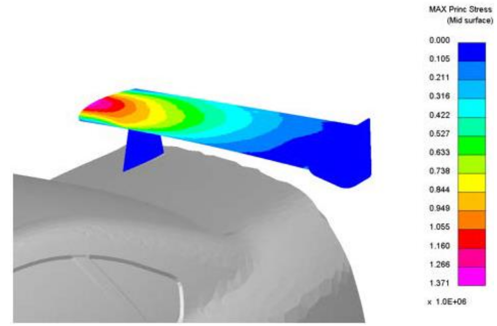
“Fluid Structure Interaction Simulation of Hood Flutter”, J. Dilworth, ARUP, 15th ls-dyna int. conf.

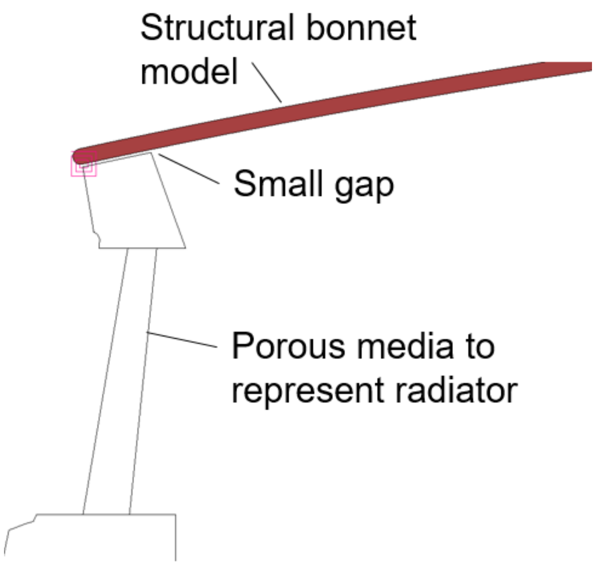
ICFD applications

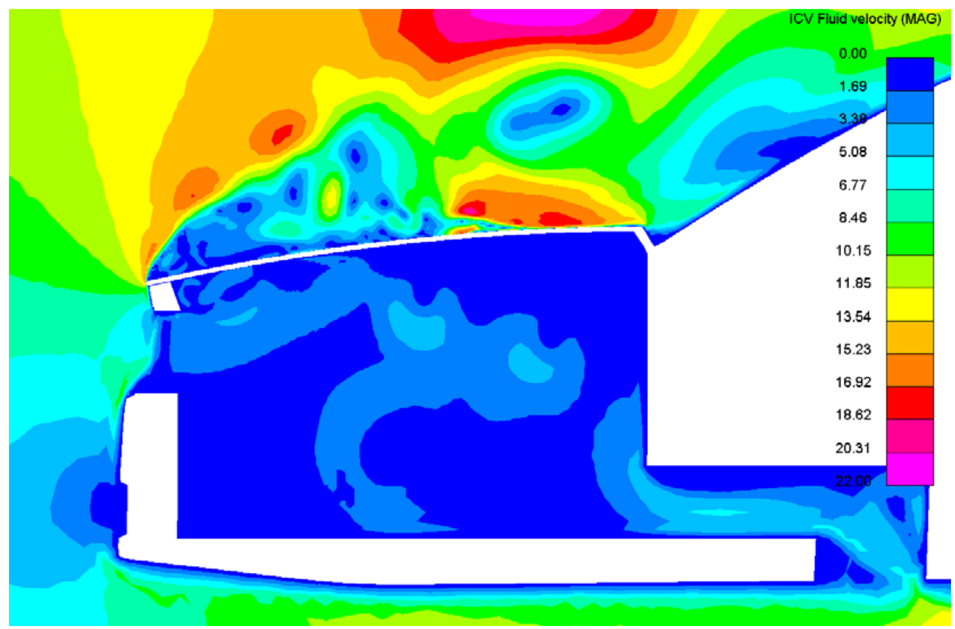
– Stress on a deformable spoiler





– 2D simulation of a deformable hood

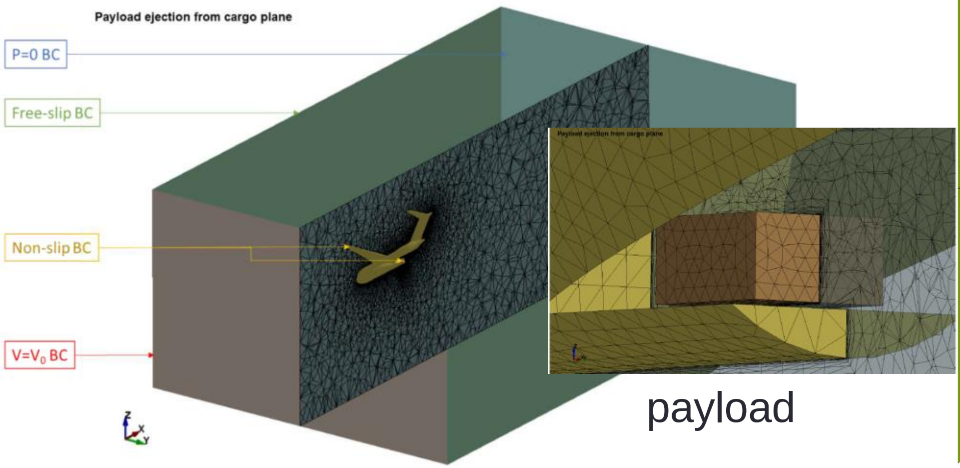




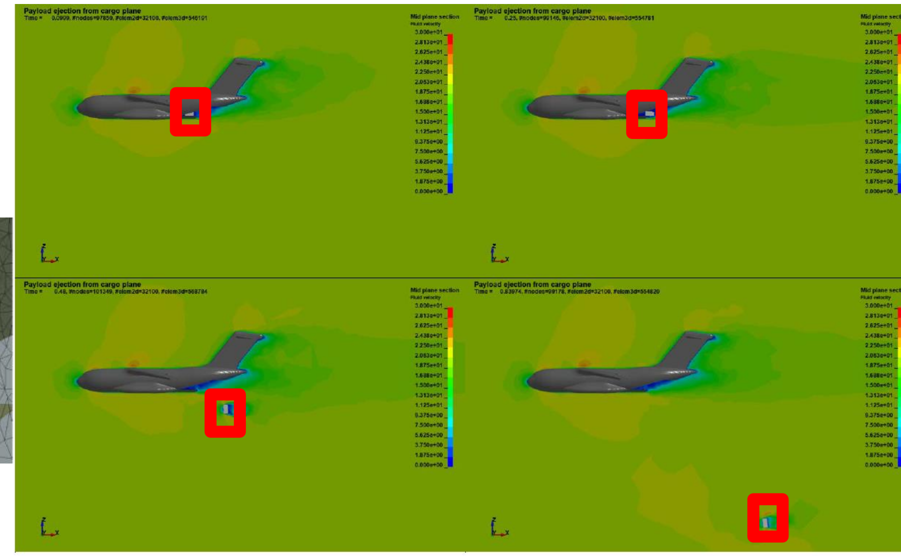
“Fluid Structure Interaction Simulation of Hood Flutter”, J. Dilworth, ARUP, 15th ls-dyna int. conf.

ICFD applications

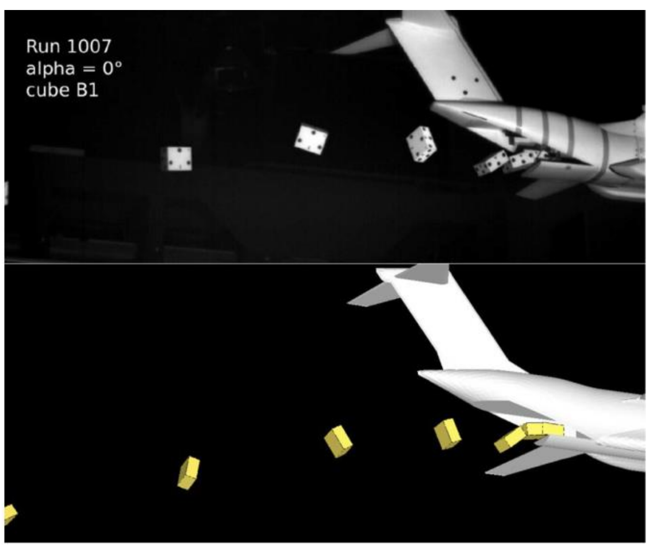
- Airdrop simulation



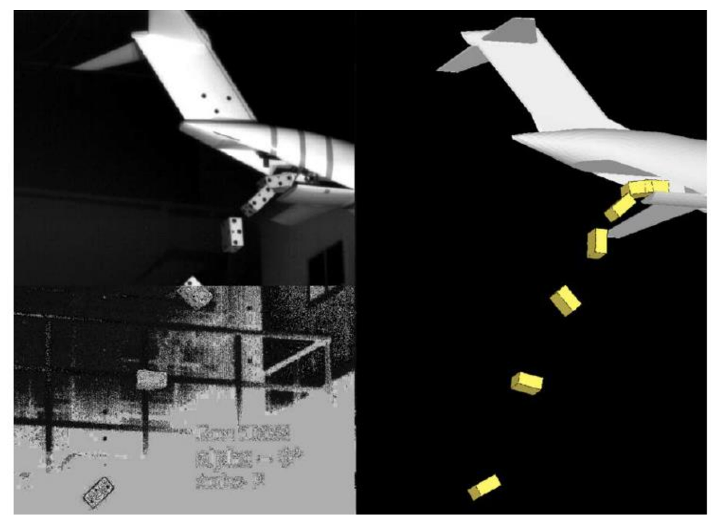
payload



Light payload



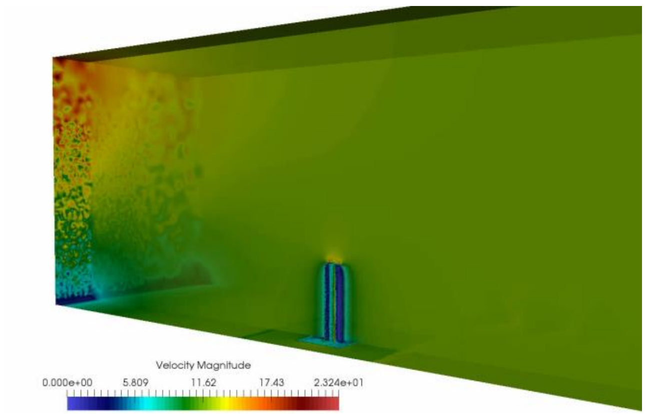
Heavy payload

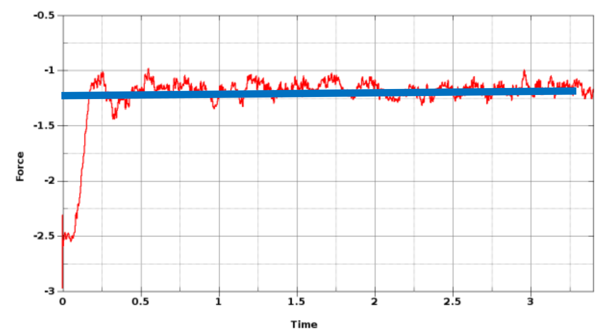


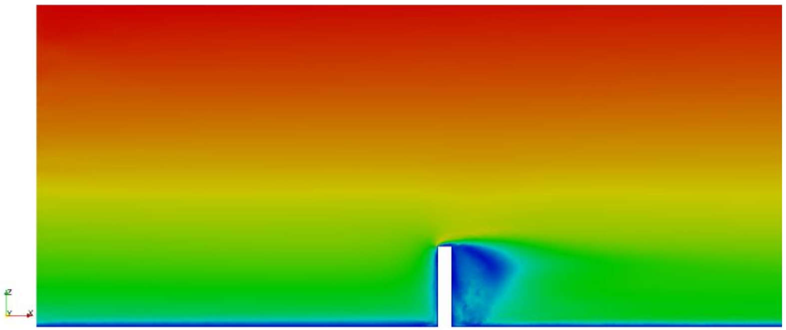
“Airdrop Sequence Simulation using LS-DYNA® ICFD Solver and FSI Coupling”, Morgan Le Garrec, 15th International LS-DYNA® Users Conference

Steady State for Conjugate Heat and FSI

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.

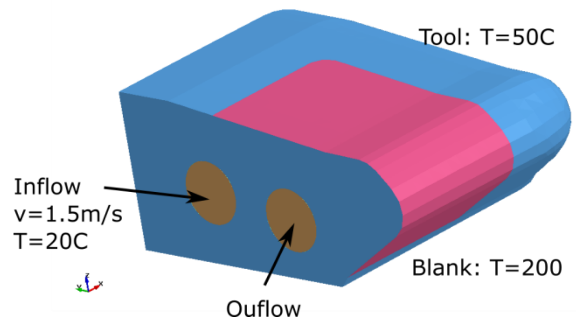
These simulation provide valuable insight faster useful for prototyping.

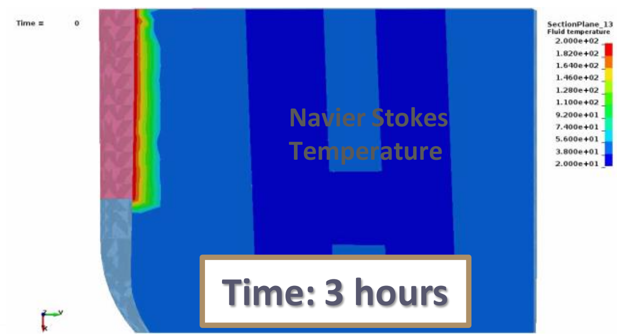
Steady State for Conjugate Heat and FSI

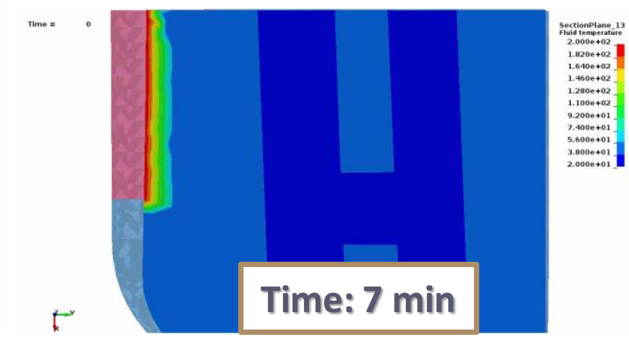
- Conjugate heat transfer for die cooling

Navier Stokes

Potential Flow

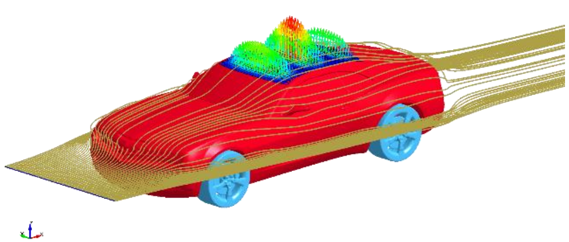


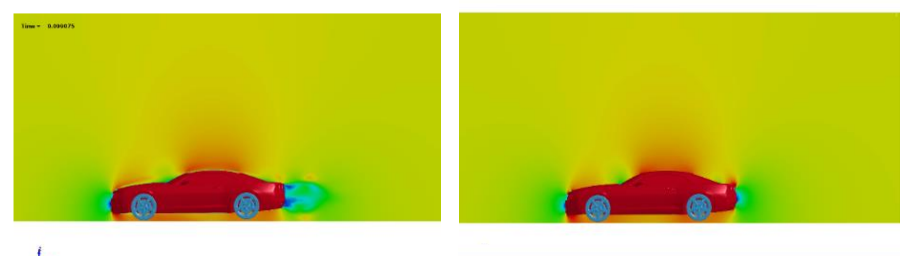


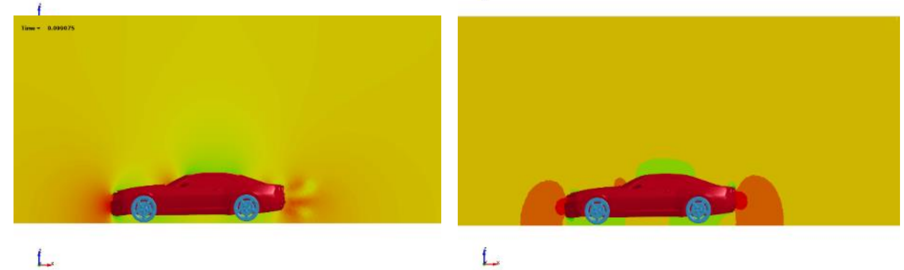


Temperature

- FSI







Velocity

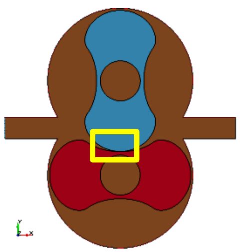
Pressure

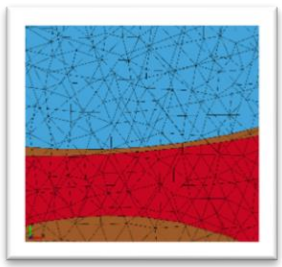
24 hours

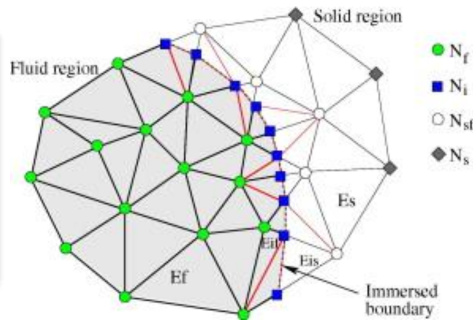
20 minutes

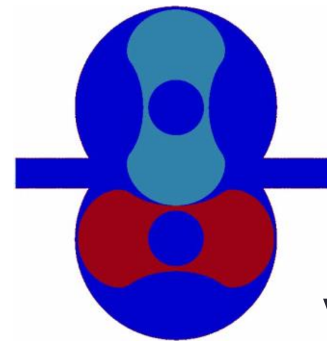
Immersed Interface & sliding mesh

- Immersed interfaces
  - simplifies the pre-processing of complex geometries.
  - provide sharp interfaces and allow structural contact.



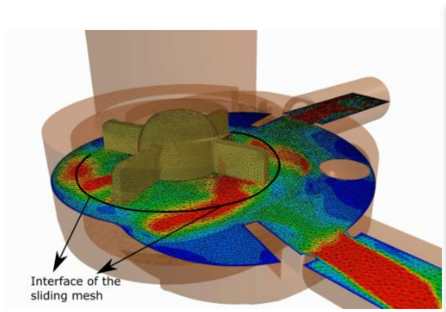


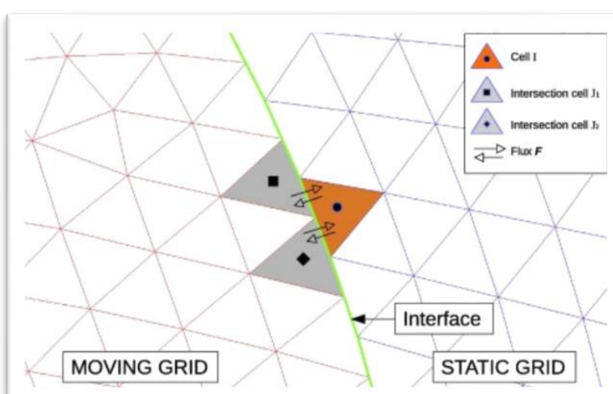


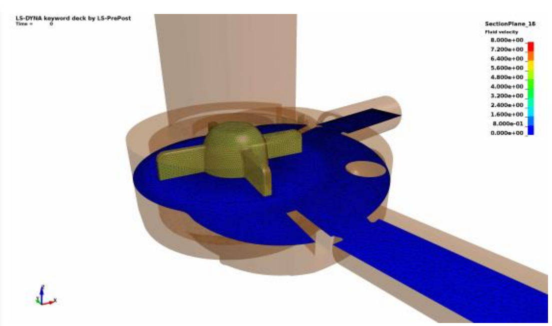


velocity

- Sliding mesh
  - for the simulation of transient rotating mechanisms without re-meshing.
  - the domain is split into at least two volume meshes. One mesh will have the rotating components and the other the rest of the domain
  - prevents excessive re-meshing in problems that involve rotating parts

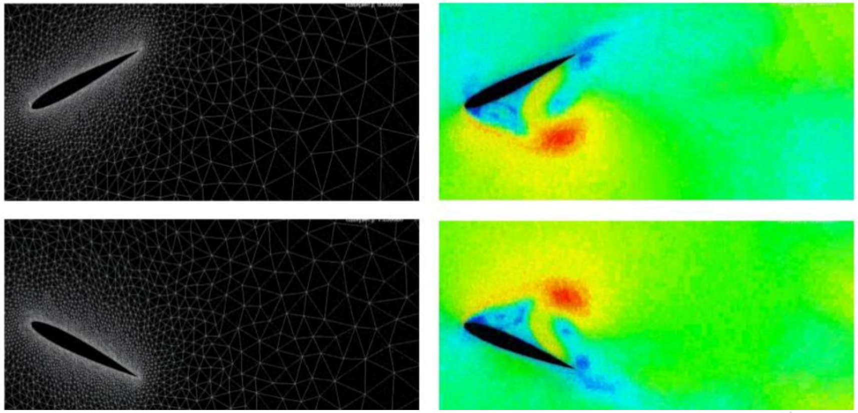


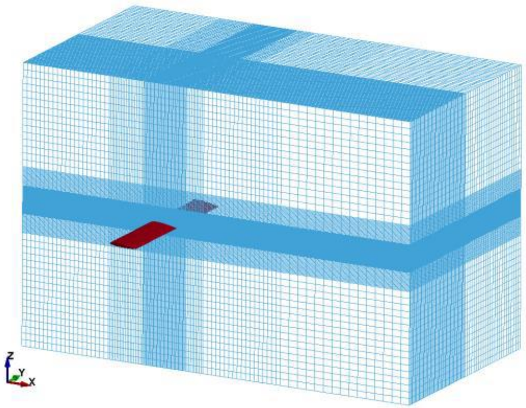


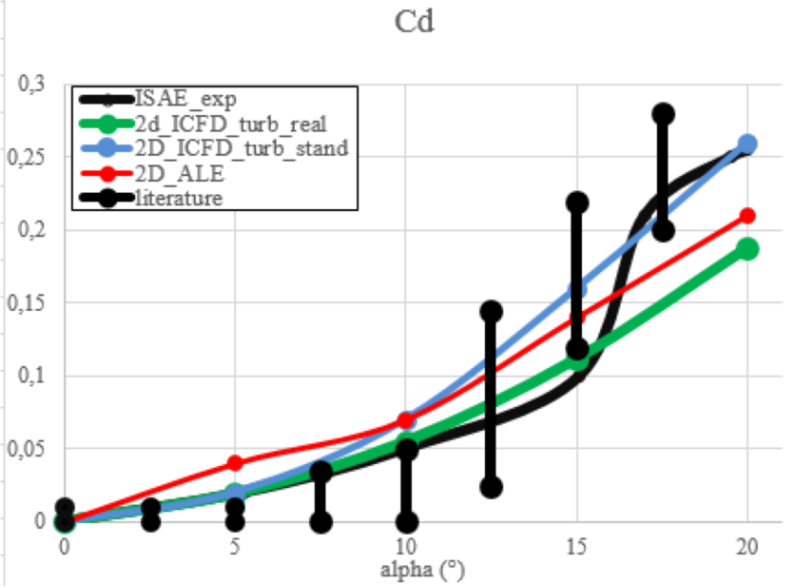


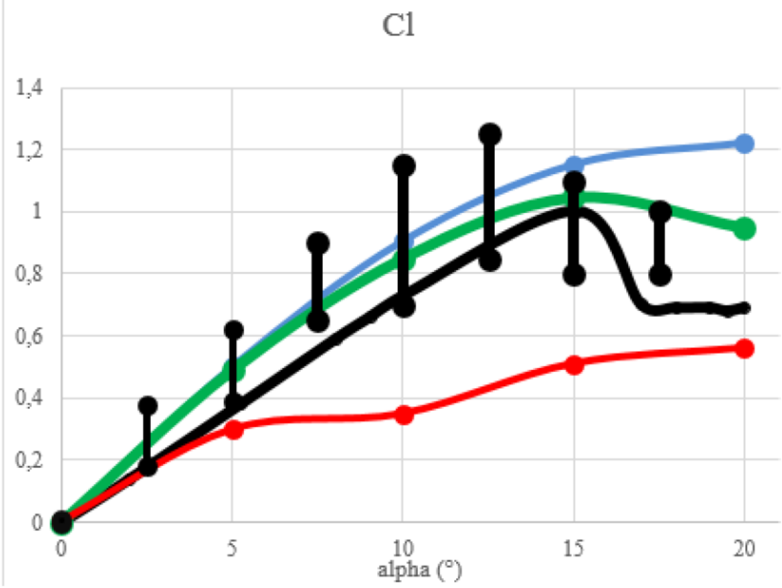
Compare ALE and ICFD based on airfoil simulation

- Based on NACA0012





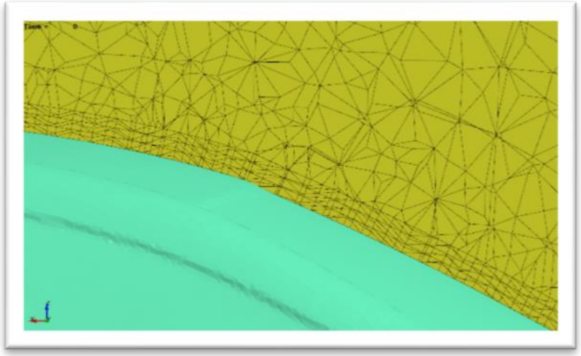




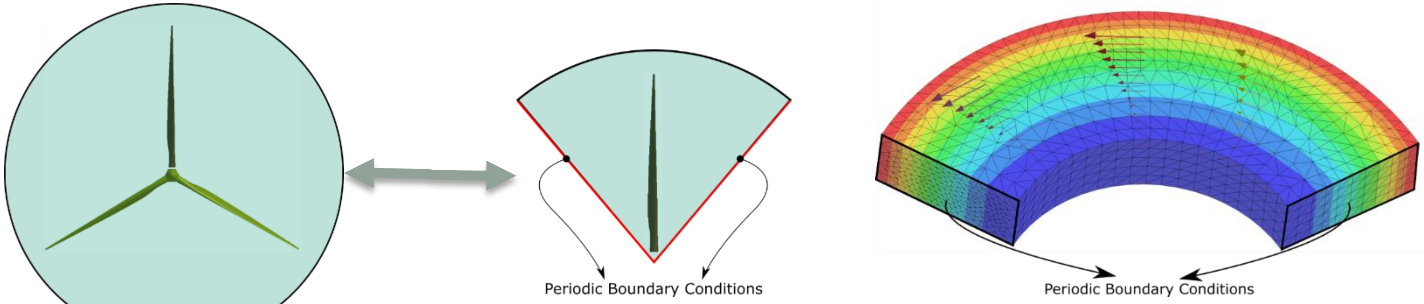
"Computational Fluid Dynamic of NACA0012 with LS-DYNA (ALE & ICFD) and Wind Tunnel Tests", B.Perin 14th International LS-DYNA Users Conference

Boundary Layer and periodic boundary condition

- Boundary layer and new RANS turbulence model
  - improvements in speed and quality of boundary layer mesh generation
  - Most commonly encountered RANS Turbulence models are available



- Periodic boundary condition
  - allow a domain reduction of the areas with a repeating fluid pattern. It is widely used in the simulation of turbomachinery.



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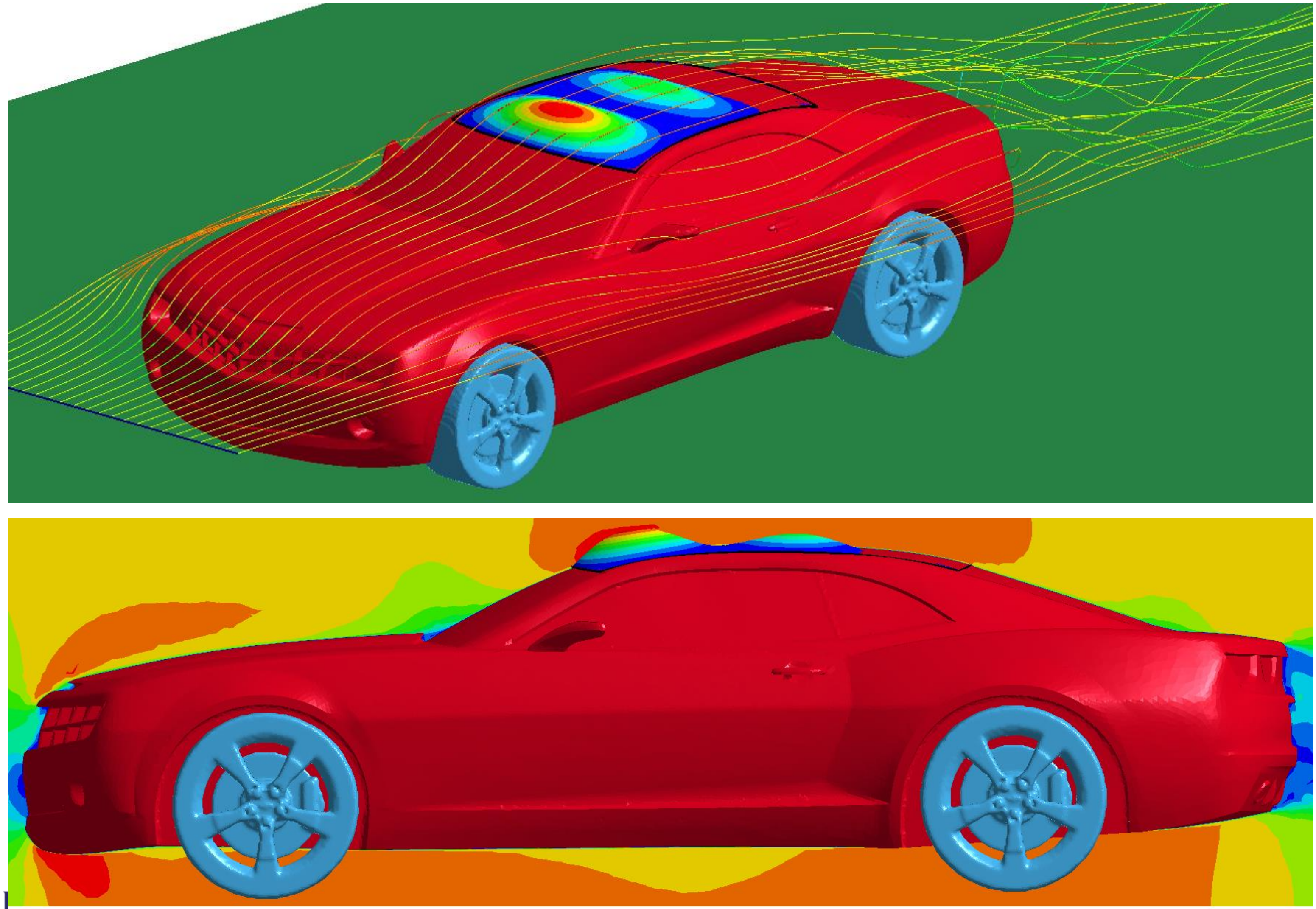
Coupling IGA with ICFD



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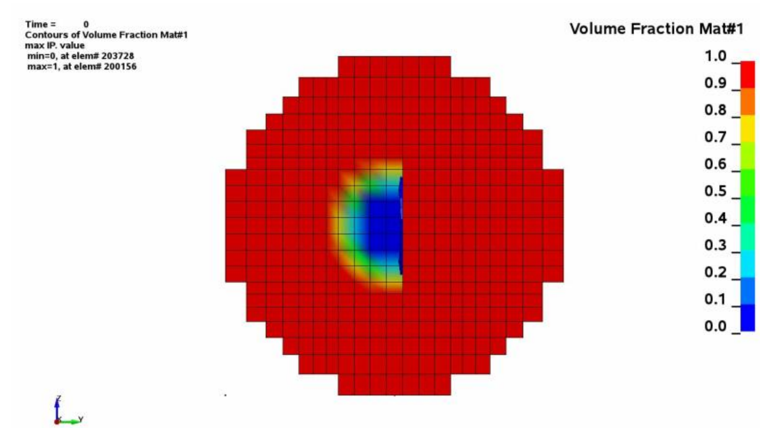
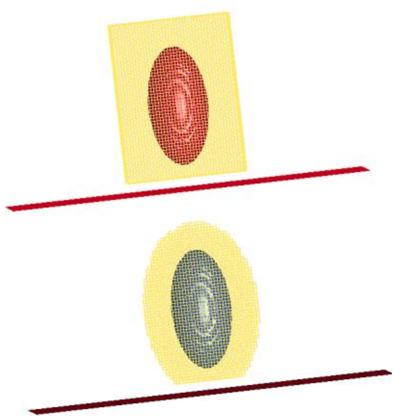
ALE

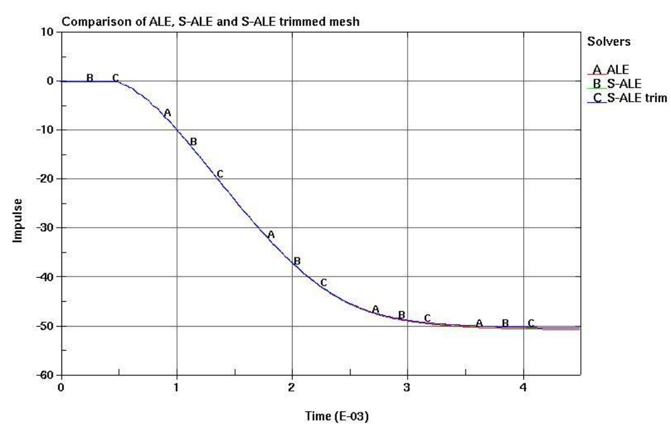
S-ALE: Mesh Trimming

- ALE_STRUCTURED_MESH_TRIM trims off unnecessary elements.



http://ftp.lstc.com/anonymous/outgoing/hao/sale/models/meshtrim/saletrim.tar





Results consistency

method	# of ele	time
ALE	84800	1.0
S-ALE	84800	0.6
S-ALE_TRIM	43219	0.35

CPU time / MPP 4 cores

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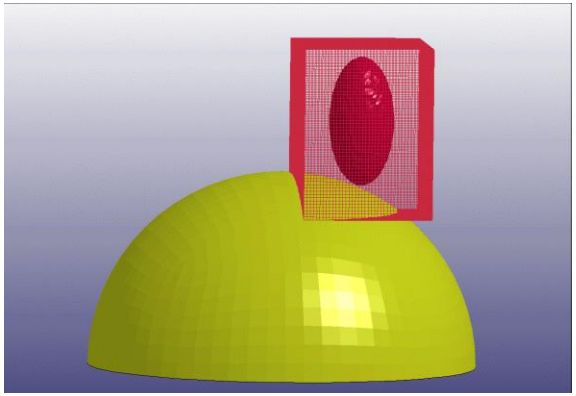
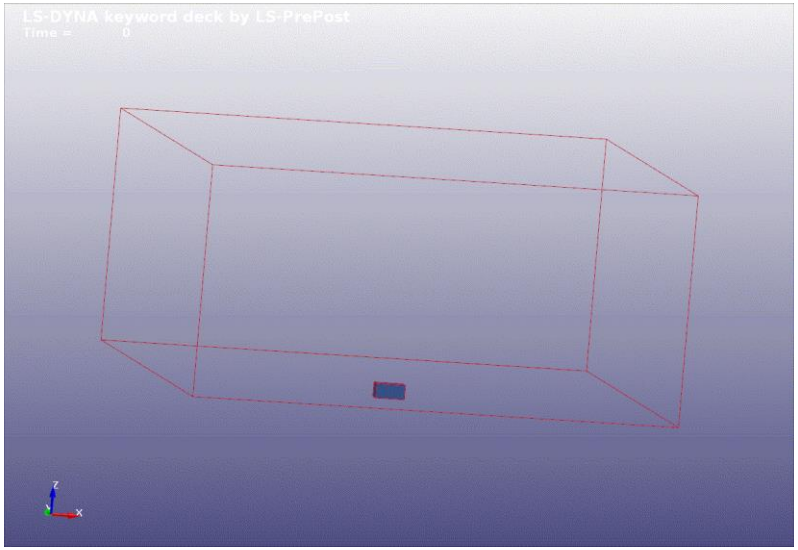
S-ALE: FOLLOW_GC & mesh merging

- New option of FOLLOW_GC of ALE_STRUCTURED_MESH_MOTION move the ALE mesh with the gravity center of certain AMMG groups; and expand/contract with those fluids.



http://ftp.lstc.com/anonymous/outgoing/hao/sale/models/meshmotion/birdstrike/bird_sale.tar

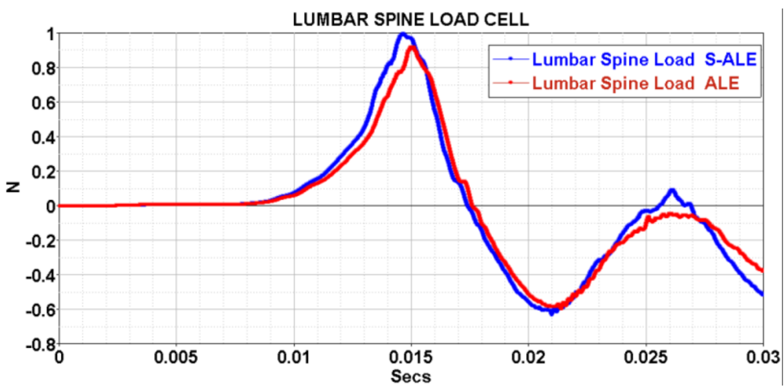
- Multiple ALE_STRUCTURED_MESH cards. Can share the same PID
  - A finer mesh for HE and solid can share the same PID with the coarser air mesh separately created by other ALE_STRUCTURED_MESHS card



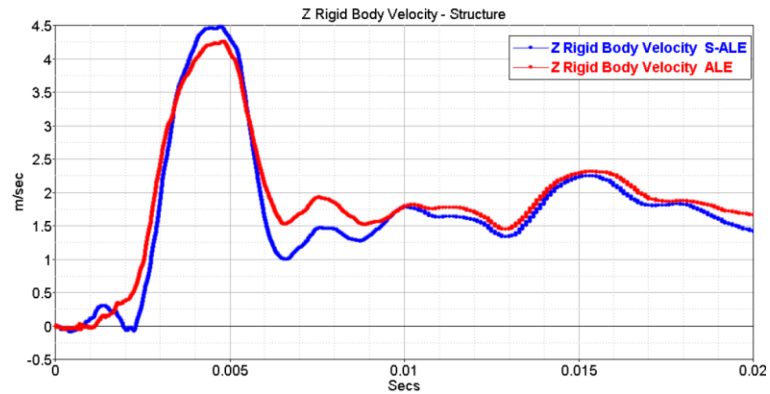
two meshes setup reduced mesh usage from 6 million to 4 million.

S-ALE vs. ALE for blast simulation

- Save 28% of CPU with comparable results



Solider response

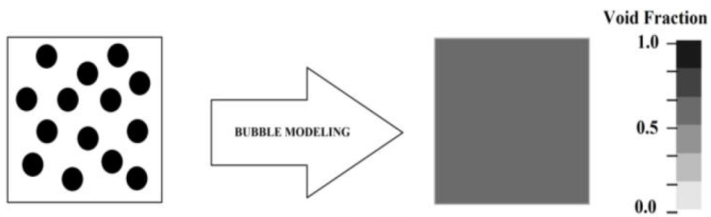


structure response

"Comparative Analysis of Occupant Responses between LS-DYNA® Arbitrary LaGrange in Euler and (ALE) and Structured–ALE (S-ALE) Methods", V. Babu *U.S. Army, Research Development & Engineering Command, (RDECOM), Tank Automotive Research* 15th International LS-DYNA® Users Conference

Phase Change EOS for ALE FSI

- In order to simulate fast transient phenomena such as Water Hammers or UNDEX, one must take into consideration phase change.
- Homogeneous Equilibrium Model (HEM) is one of the "one-fluid models" where only the average flow is considered by solving a unique set of governing equations and it can be based on a pure phase model.



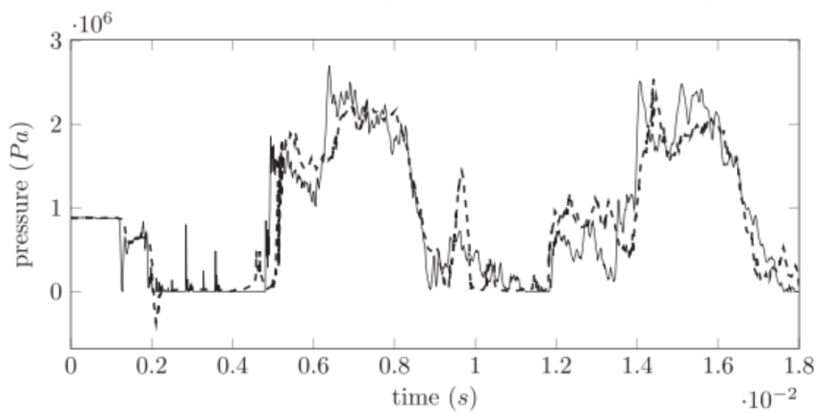
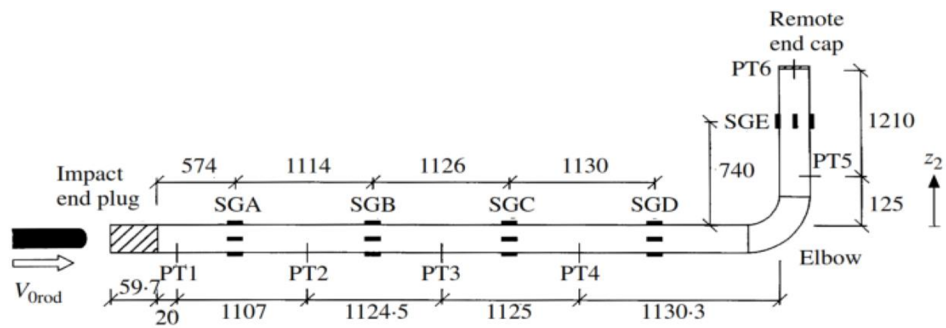
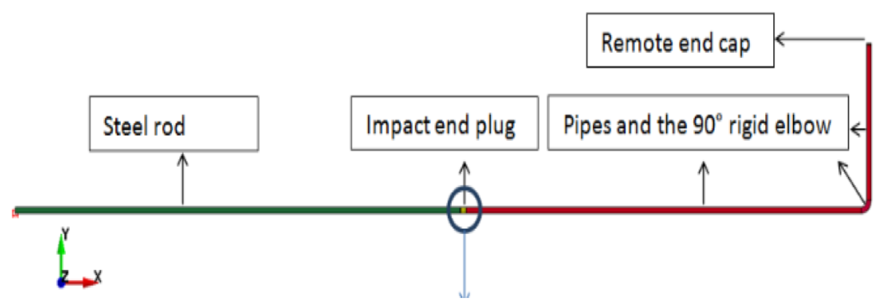


Figure 4: Absolute pressure at sensor PT6: Experimental results Tijsseling et al., [8], (--), numerical results with elastic pipes (—).

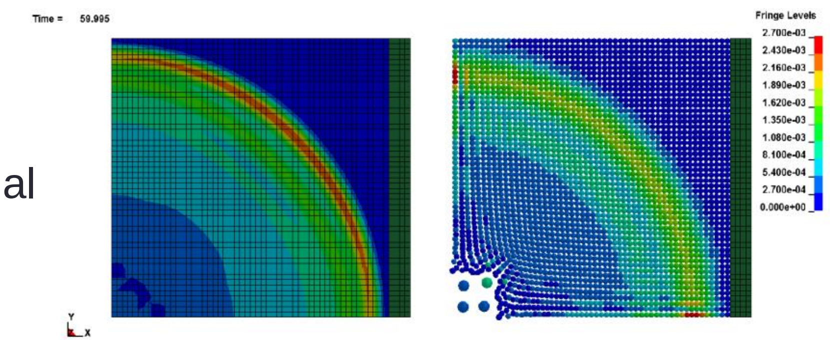


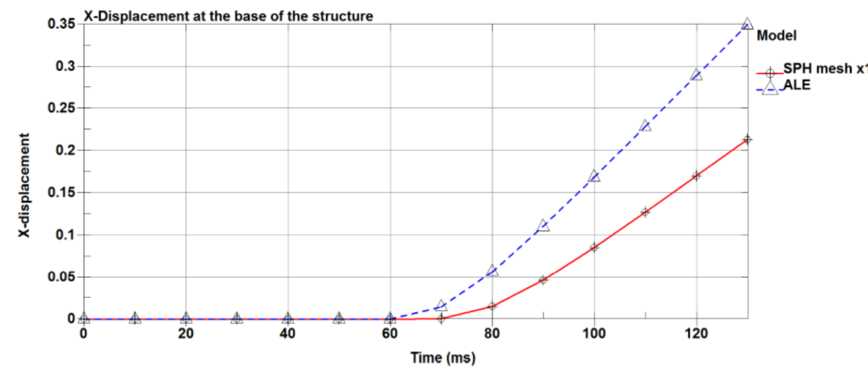


SPH

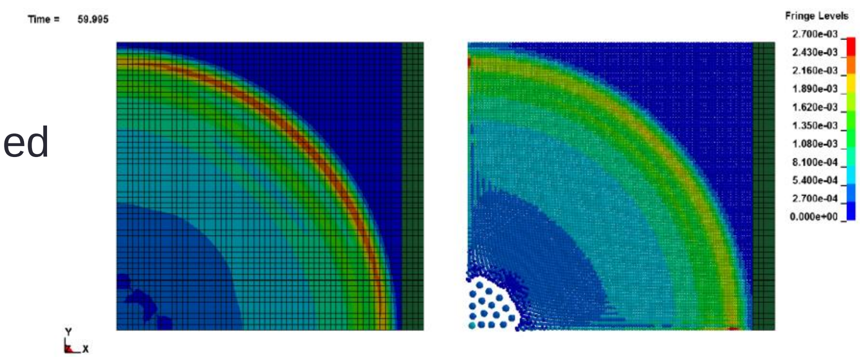
Comparing SPH & ALE for UNDEX

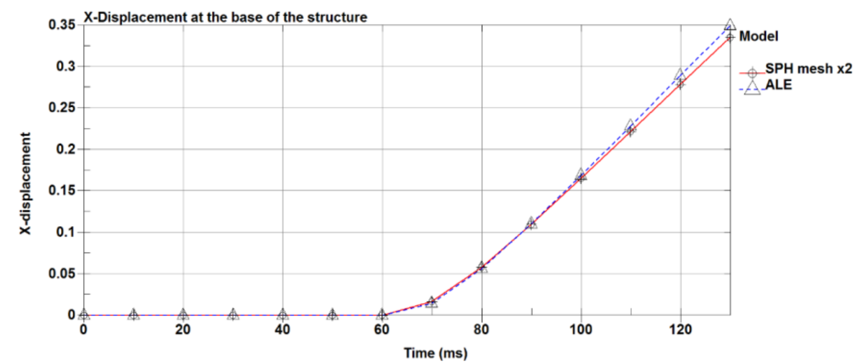
Original SPH





Refined SPH





Pressure contour

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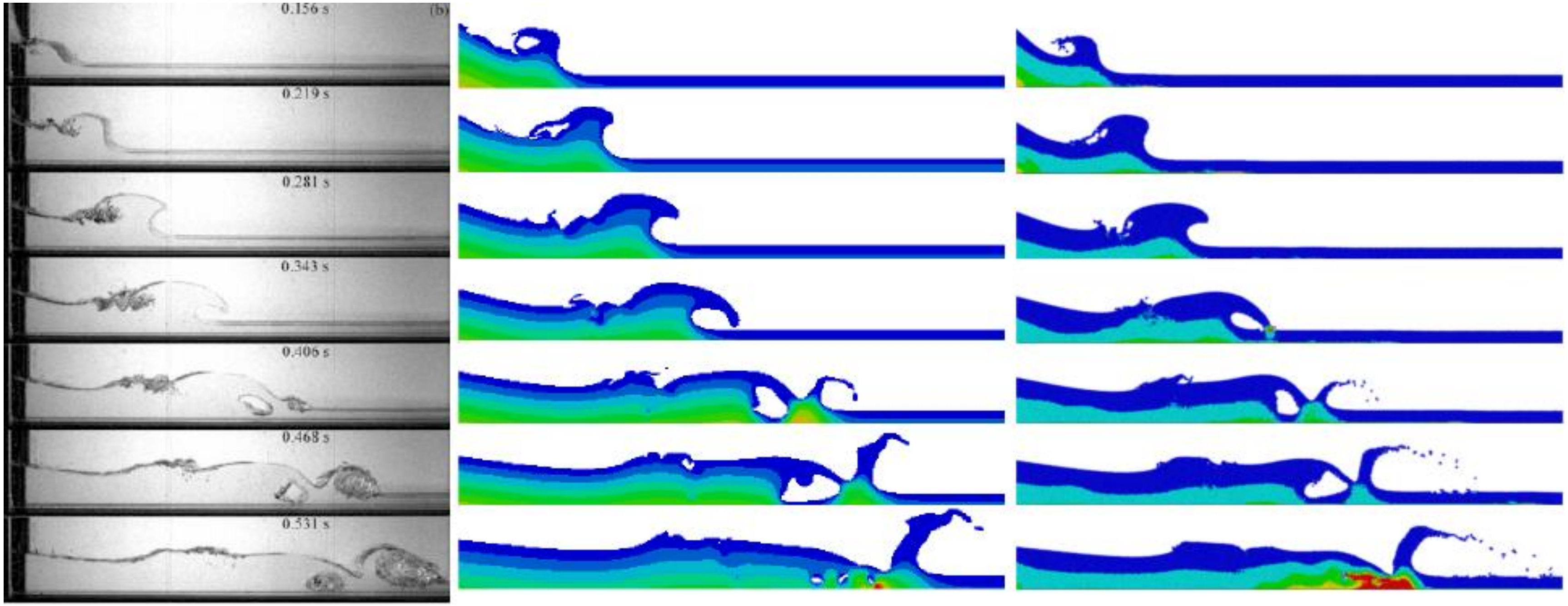
"ALE and SPH formulations for Fluid Structure Interaction: Shock waves impact", Ramzi MESSAHEL *Université de Lille 2016*

SPH: Murnaghan Equation of State, IFORM=15/16

- Model incompressible fluid with SPH elements
- Weakly compressible formulation to numerically reduce the sound speed, and consequently increase the time step size

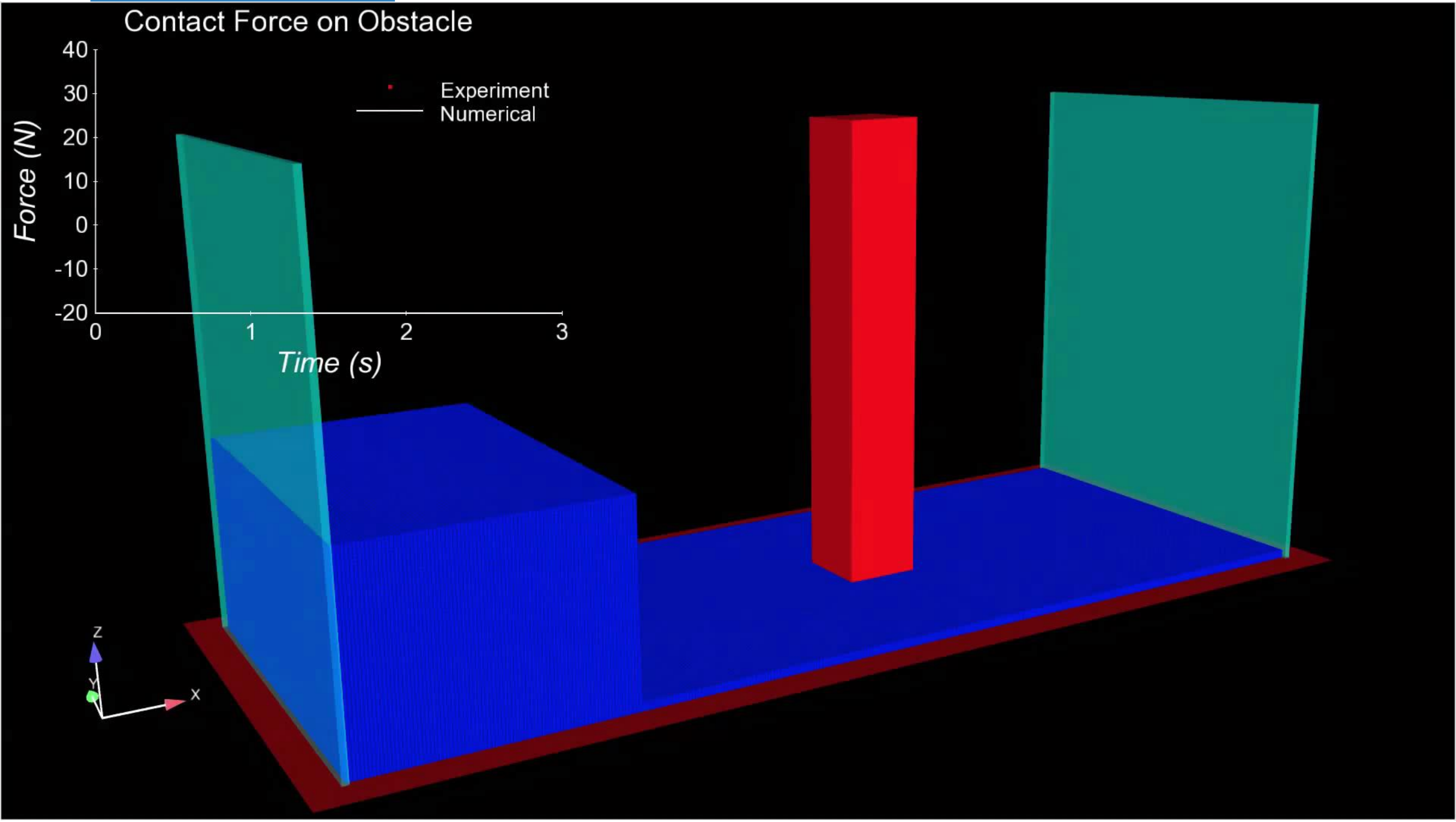
Validation: 2D dambreak, free surface flow



Experiment [1] ICFD SPH

[1] Janosi, I. M., Jan, D., Szabo, K. G. and Tel, Tamas. "Turbulent drag reduction in dam-break flows". Experiments in Fluids, 37: 219-229, (2004).

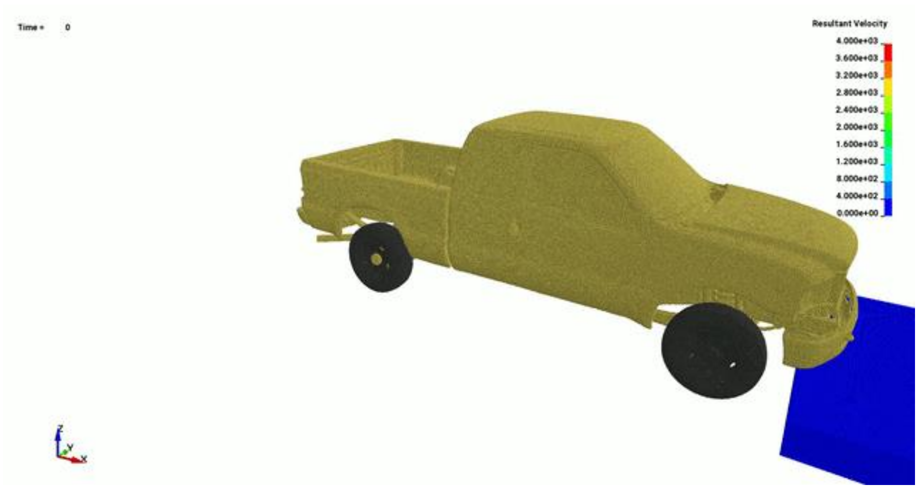
SPH: 3D Validation of Murnaghan Equation of State



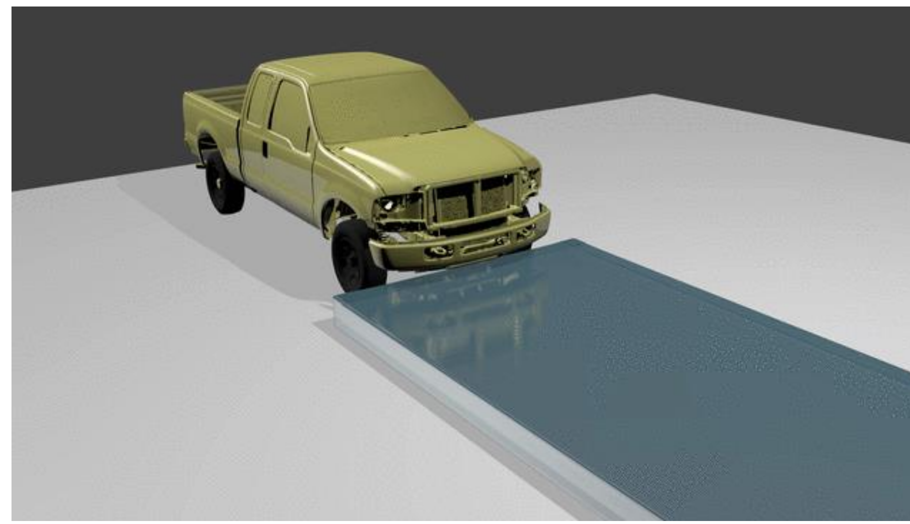
Validated in 2D and 3D formulations

Implicit SPH

- 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

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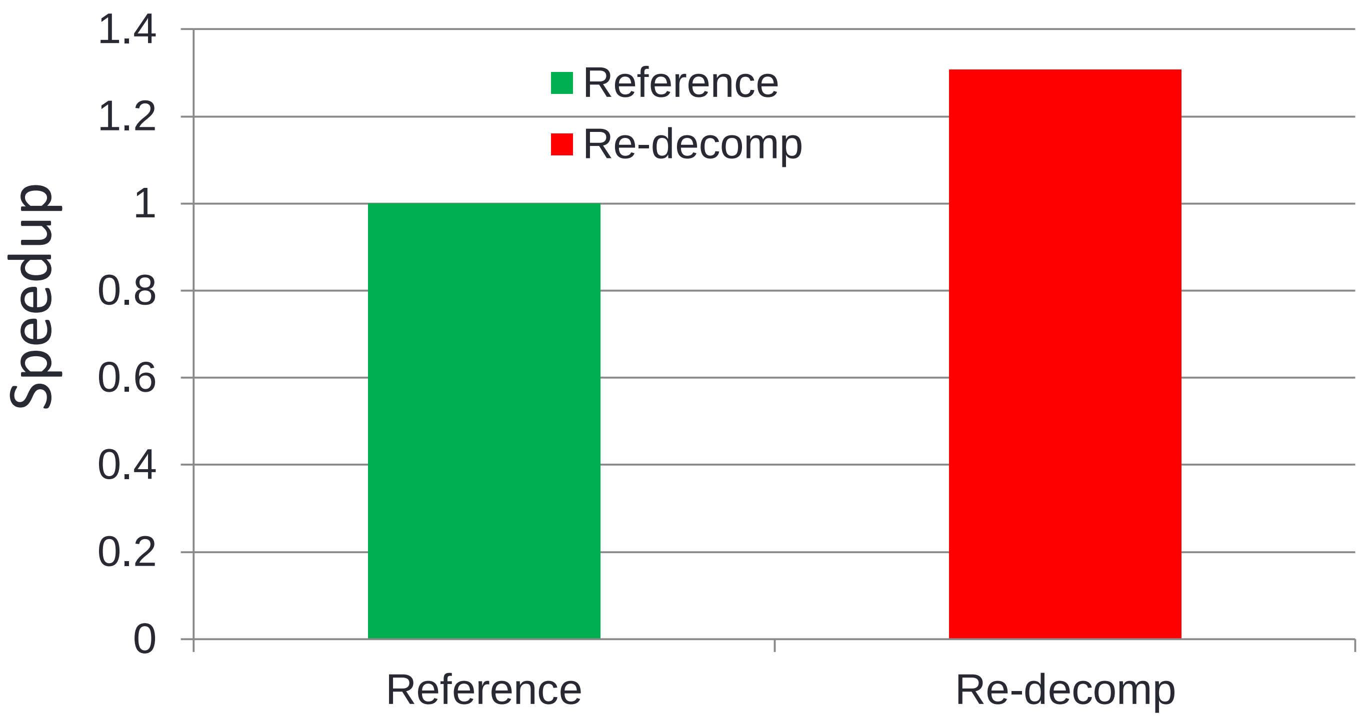
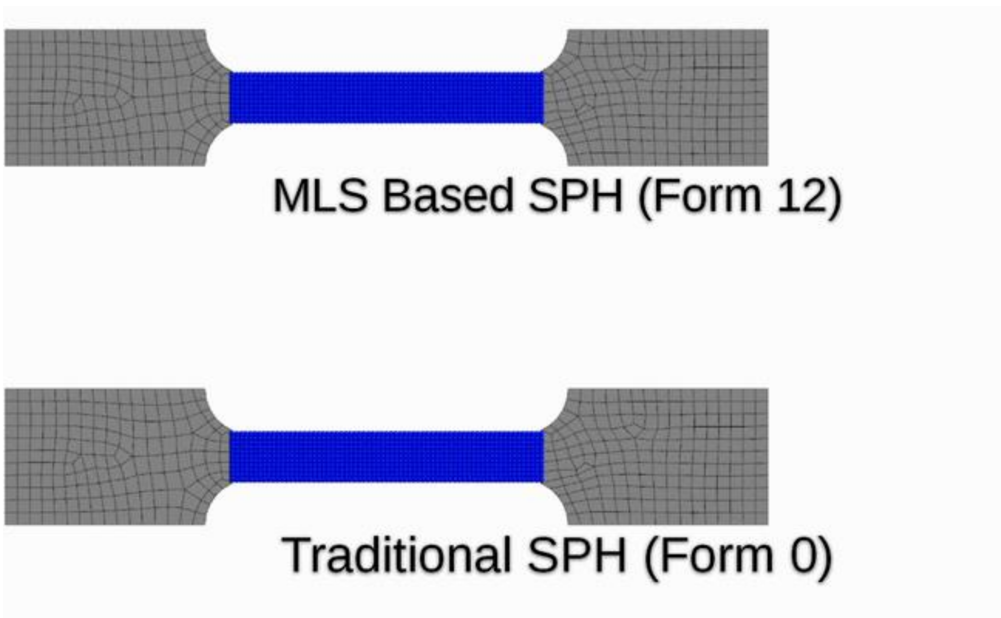
Dynamically Rebalanced SPH

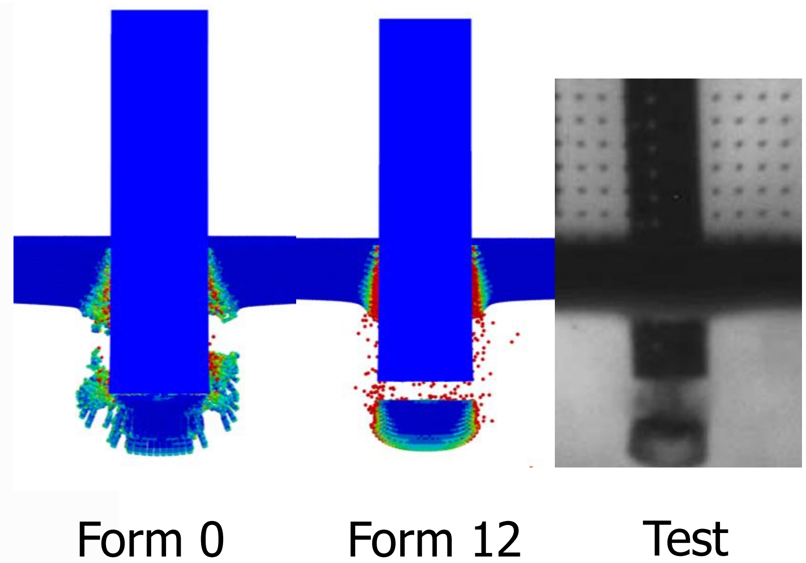
- Re-decomposed the model several times during simulation using a full deck restart
- 30% of cpu saving is observe in a typical bird strike simulation



MLS-based SPH

- A formulation based on moving least-squares (FORM = 12) is implemented to improve the major drawbacks associated with SPH: tensile instability and essential boundary condition enforcement. Moving Least Square formulaton.





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).

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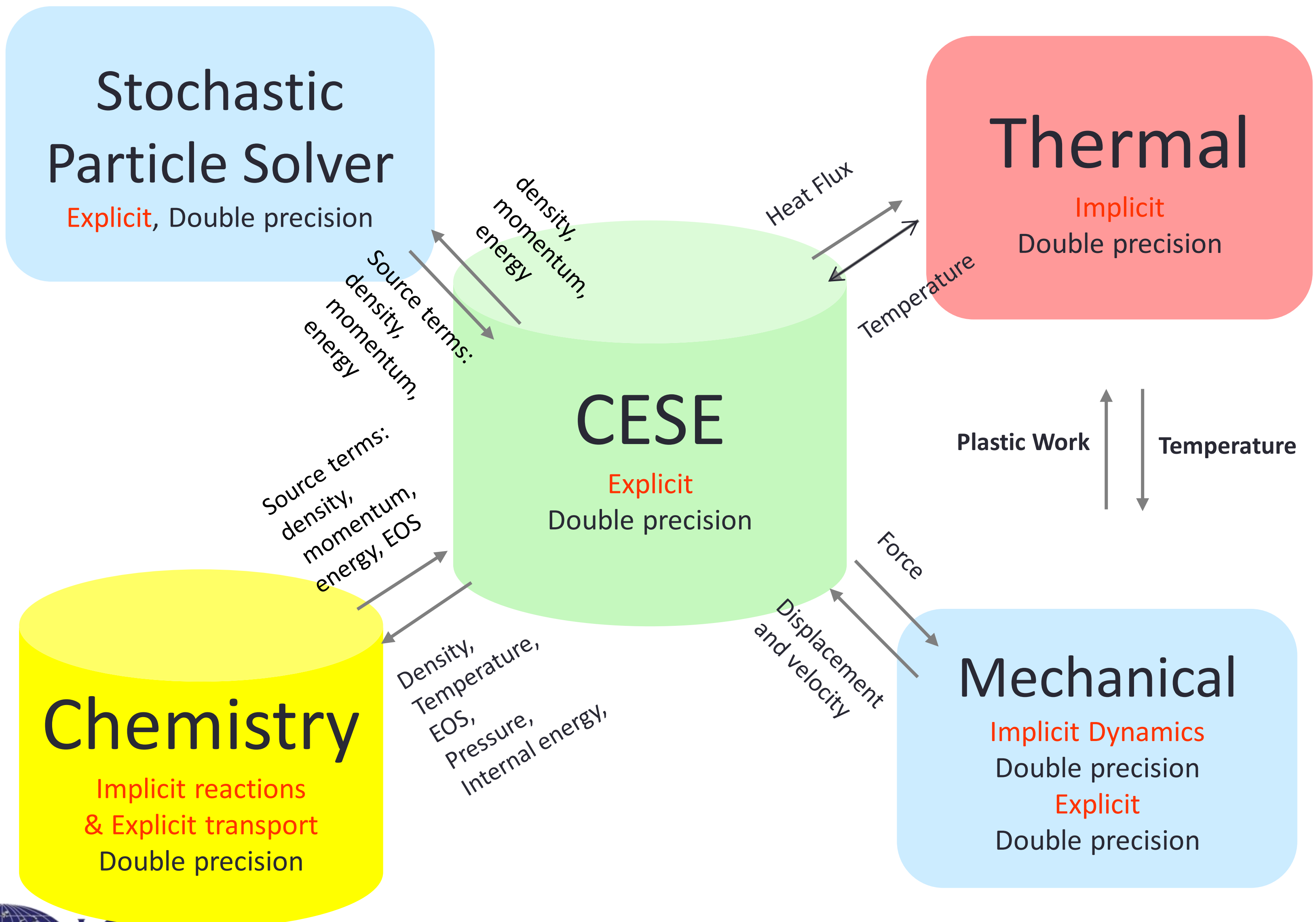
CESE and Chemistry Solvers

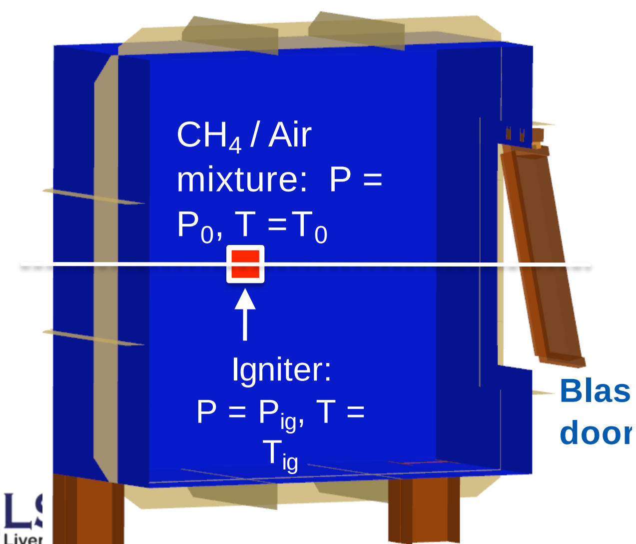
Zeng-chan Zhang, Kyoung-Su Im, and Grant Cook, Jr.

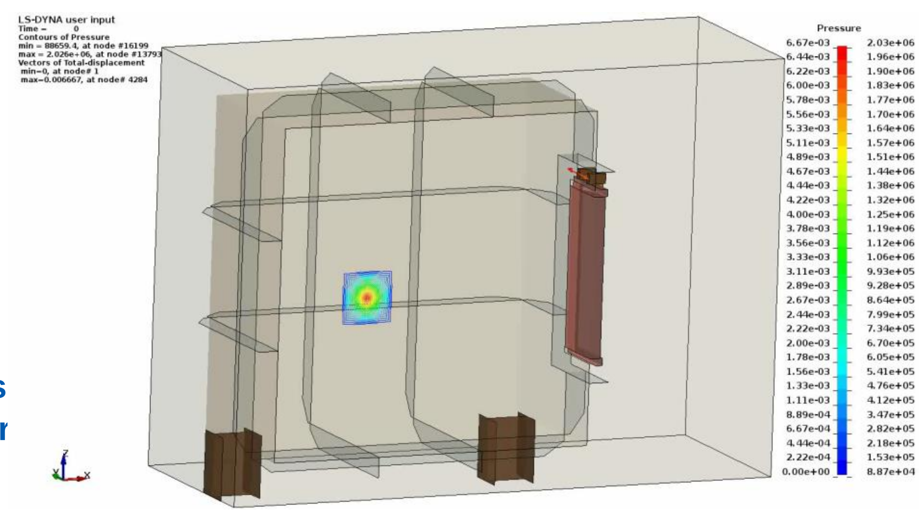
CESE coupling with other LS-DYNA solvers



CESE for blast relief valve

- The purpose of the blast relief wall is to vent the combustion gases and pressure resulting from a deflagration of an enclosure in offshore plant. Gas mixture consists of air and methane (CH4).



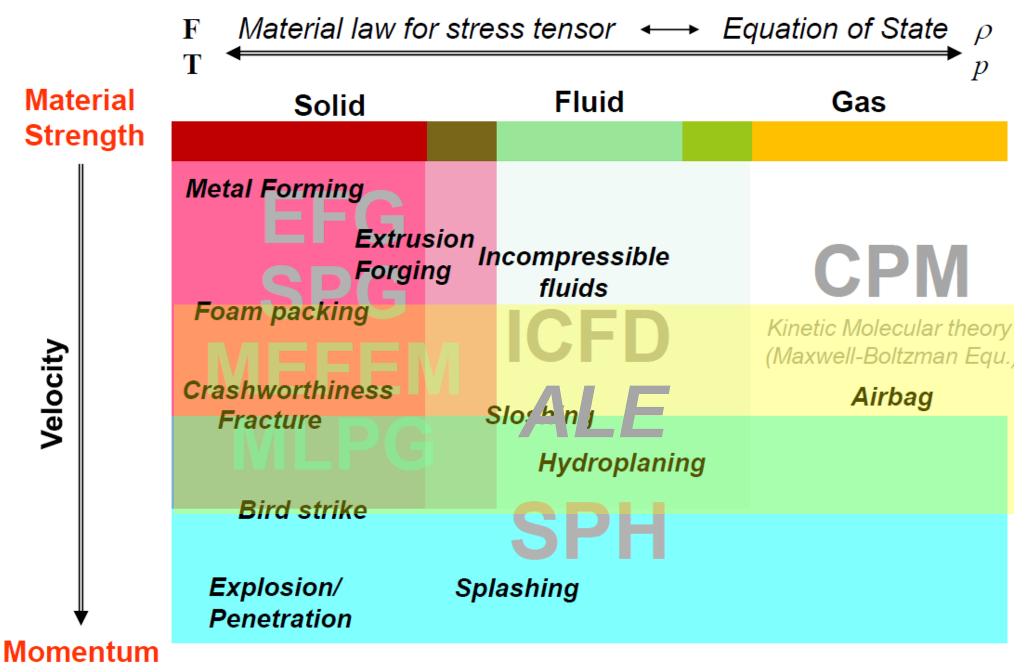


Meshless & particle methods

SPH	J. Xu
ALE	H. Chen
DEM	H. Tang, B. Zhang
SPG	Y. Wu, C.T. Wu
Peridynamics	W. Hu, B. Ren, C.T. Wu
XFEM	Y. Guo, C.T. Wu

Meshfree & Particle Methods in LS-DYNA

- Discrete
  - Explicit
    - DEM (Discrete Element Method)
    - CPM (Particle Gas)
    - PARTICLE_BLAST



- Continuum
  - Explicit Meshfree Collocation
    - SPH
  - Explicit Meshfree Galerkin
    - EFG, SOLID41&42, SHELL41~44
    - XFEM SHELL52&54
    - MEFEM for nearly incompressible material,SOLID43
    - SPG (Smooth Particle Galerkin), SOLID47 for ductile failure
    - Peridynamics (Discontinuous Galerkin) for brittle fracture, SOLID48&MAT_ELASTIC_PERI
  - Implicit Meshfree Galerkin
    - EFG, SOLID41&42, SHELL41~44
    - MEFEM, SOLID43

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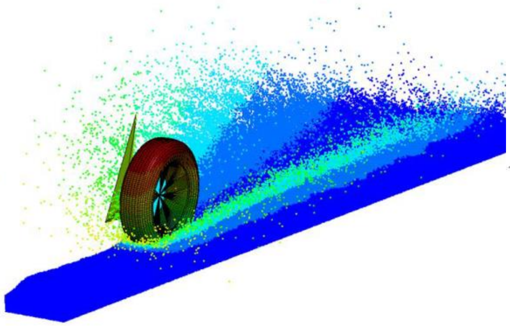
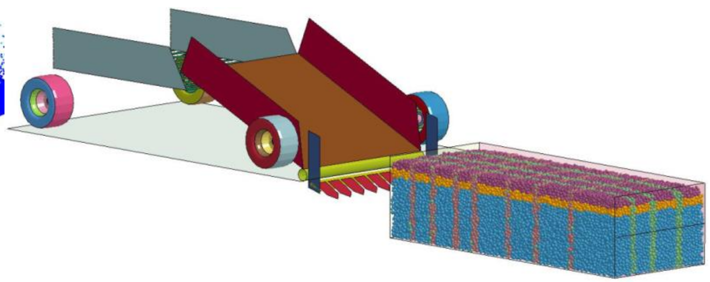
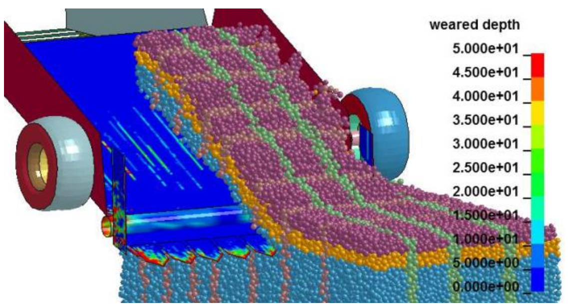
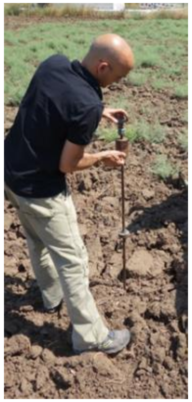
DEM

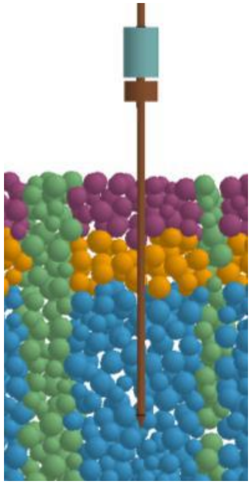
- for granular materials that consist of discrete particles like liquids and solutions, cereal, sand, toner,..

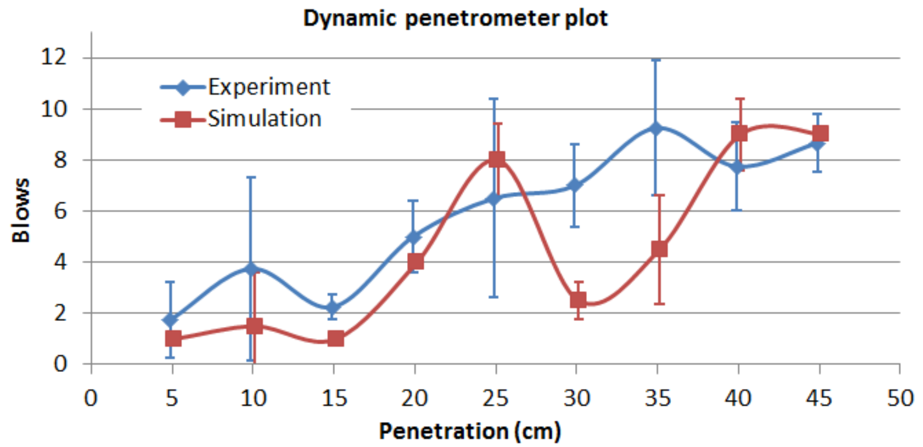








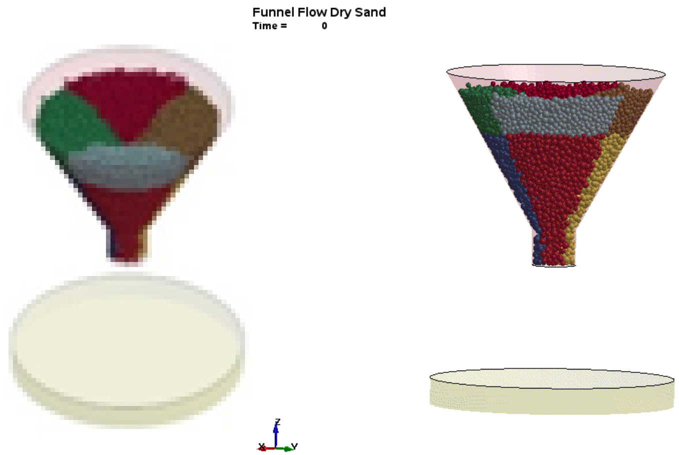




"Simulation of Agricultural Soil Tillage Machine using DEM", H. Mouradjalian, 11th European LS-DYNA Conference

DEM: DE-DE contact improvement

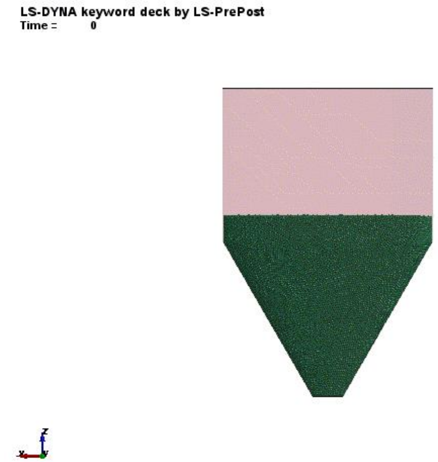
- MPP scalability could deteriorate due to load imbalance when particles undergo large motion

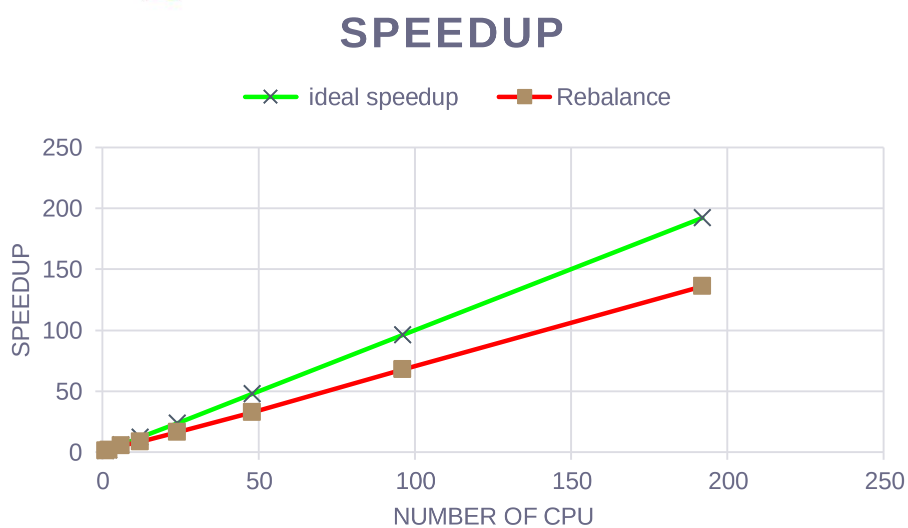


- re-decompose for every N time steps

Different particle color represent different core

- Performance improvement





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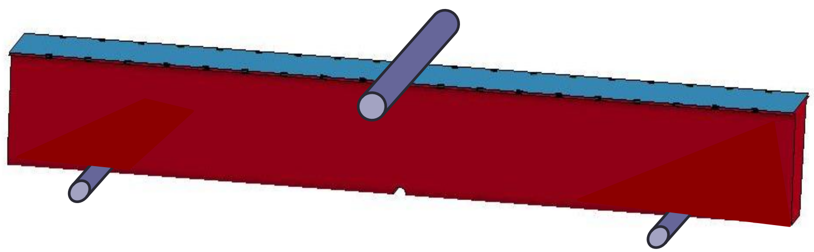
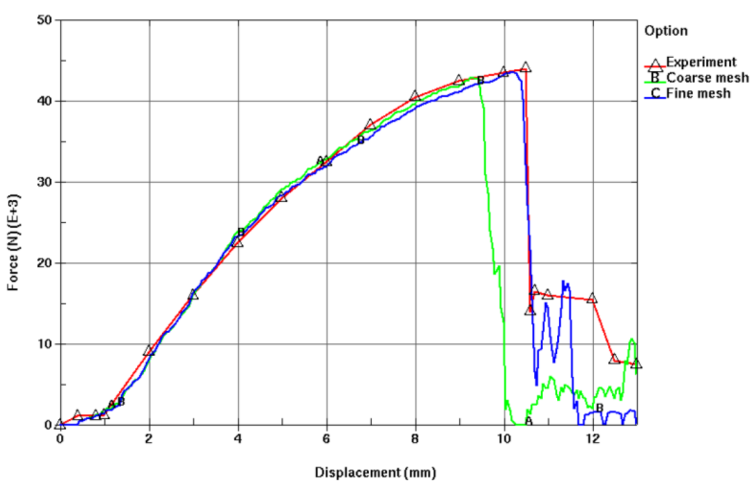
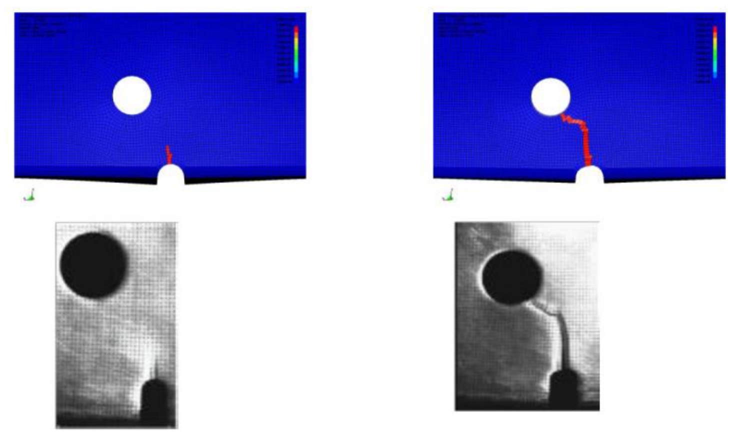
XFEM

- Most suitable for ductile materials in shell formulation, especially for pre-cracks
- A non-local algorithm is developed to minimize the mesh-size/orientation problems







(a) Initial crack

(b) Intermediate crack

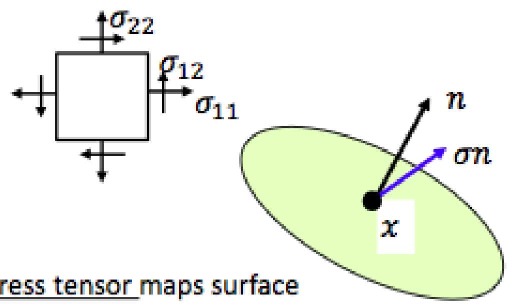
Courtesy of Honda, JSOL Japan

Peridynamics Method

- *Extension of classical pdf-based equation.*

Standard theory

Stress tensor field
(assumes continuity of forces)



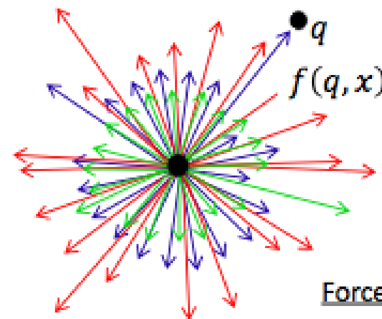
Stress tensor maps surface normal vectors onto surface forces

$$\rho \ddot{u}(x,t) = \nabla \cdot \sigma(x,t) + b(x,t)$$

Differentiation of surface forces

Peridynamics

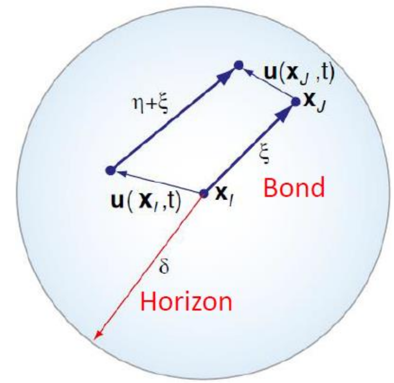
Bond forces between neighboring points
(allowing discontinuity)



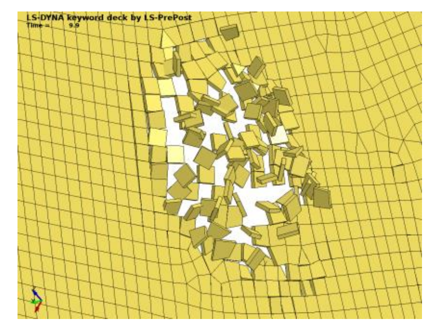
Force state maps bonds onto bond forces

$$\rho \ddot{u}(x,t) = \int_{H_x} f(q,x) dV_q + b(x,t)$$

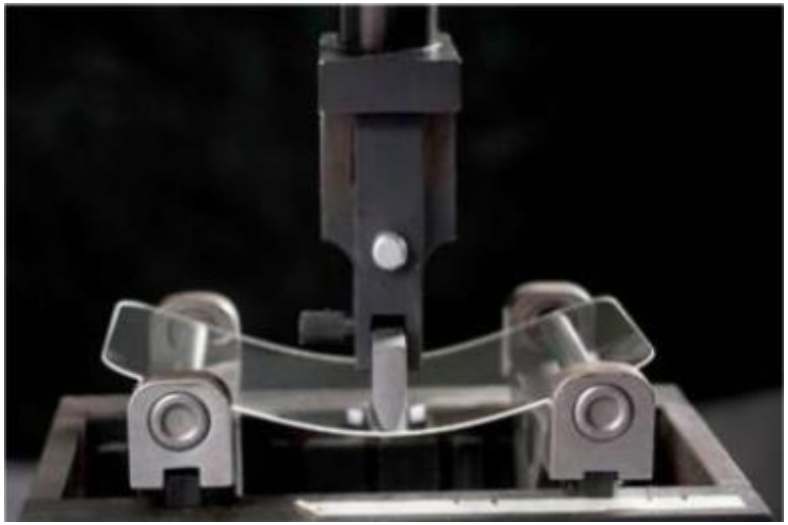
Summation over bond forces

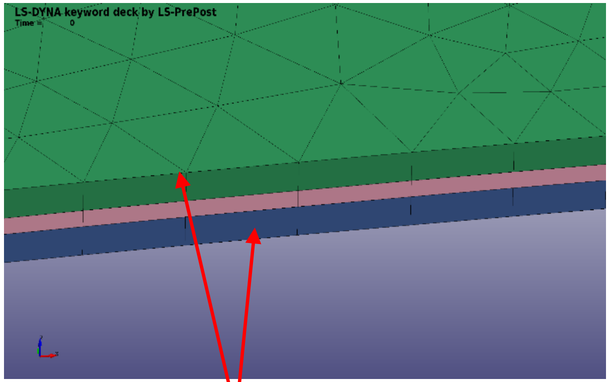


- *Most suitable for brittle materials in 3D solid formulation.*
- *Modified version formulated in Discontinuous Galerkin FEM*
- *Failure criteria is based on fracture energy released rate*

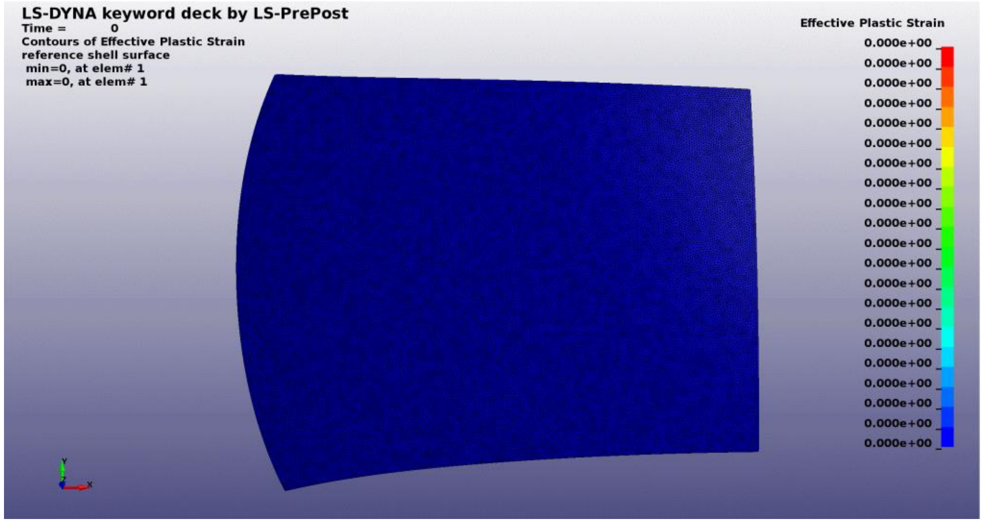


Peridynamics for windshield 3-point bending analysis





Glass layers, MAT_ELASTIC_PERI



Maximum Force (N)		Displacement (mm)	
Exp.	Num.	Exp.	Num.
2841	2860	24.6	26.0

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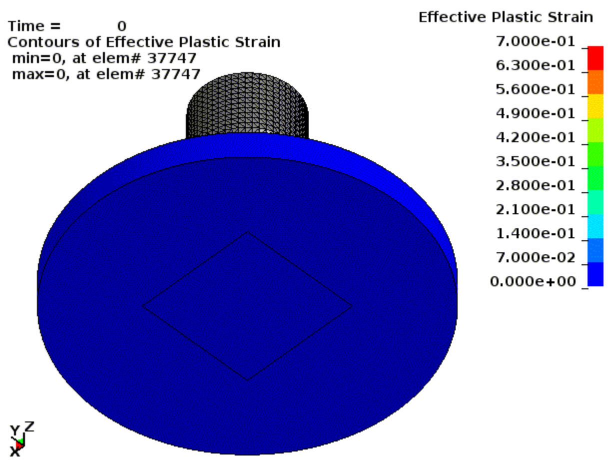
Courtesy of Tesla, USA

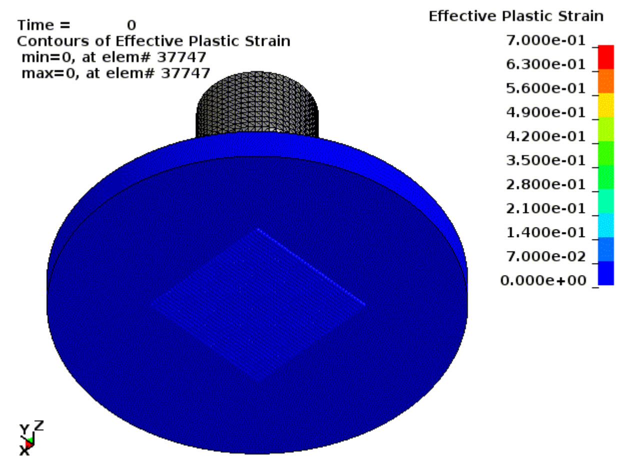
SPG

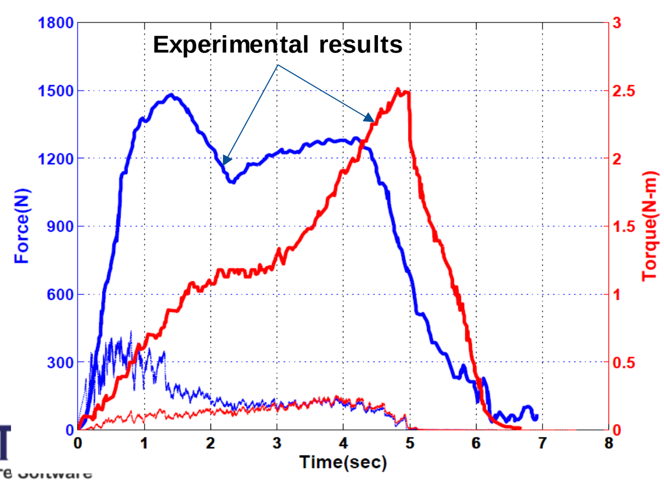
- Particle integration, able to handle severe deformation
- Most suitable for ductile materials in 3D solid formulation.
- Applications include machining, joining, cutting, riveting & drilling

FEA

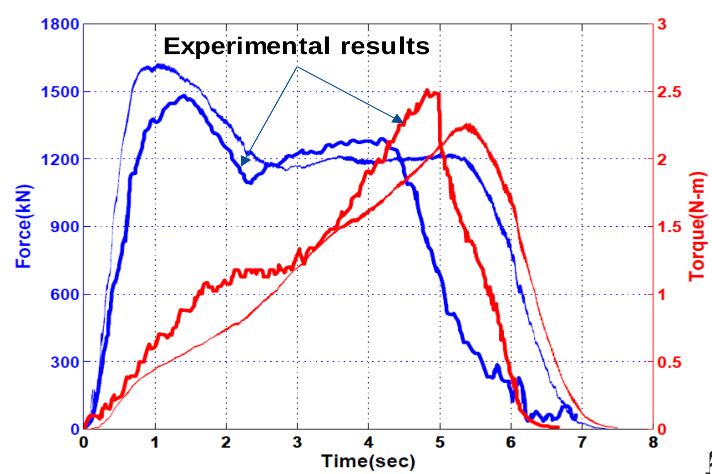


SPG





(b)



(a)

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Summary

- LSTC is working to be the leader in cost effective large scale numerical simulations
- LSTC is providing dummy, barrier, and head form models to reduce customer costs.
- LS-PrePost, LS-Opt, and LS-TaSC are continuously improving and gaining more usage within the LS-DYNA user community
- LSTC is actively working on seamless multistage simulations in automotive crashworthiness, manufacturing, and aerospace
- The scalable implicit solver is quickly gaining market acceptance for linear/nonlinear implicit calculations and simulations
- Robustness, speed, accuracy, and scalability have rapidly improved

Future

- New features and algorithms will be continuously implemented to handle new challenges and applications
  - Electromagnetics,
  - Acoustics,
  - Compressible and incompressible fluids
  - Isogeometric shell, solid elements and NURB contact algorithms
  - Discrete element methodology for modeling granular materials, failure, etc.
  - Peridynamics combined with EFG and DES
  - Composite material manufacturing
  - Modeling battery response in crashworthiness simulations
  - Sparse solver developments for scalability to huge # of cores, >10K

12th LS-DYNA European Conference

14 - 16 May 2019, Koblenz, Germany