2023 LS-DYNA Development Updates for Manufacturing and Multiscale Simulations

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Ansys

Background

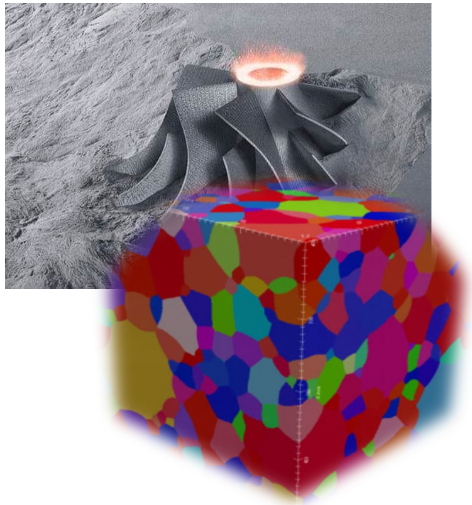
- Multiscale problems arise in material design, manufacturing, structural analysis, and optimization.
- With more new materials and modern manufacturing techniques, we need **more experiments**, **material calibrations and much refined mesh** for structure analysis, thus high cost in product development process.
- **Multiscale analysis** plays an important role in accelerating the virtual product development for industries (Digitalization, Digital Transformation, etc.).

A model-based simulation workflow for structure design and analysis

Structural analysis ← **Mechanical Tests** ← Manufacturing Simulation ← Materials design and optimization

https://www.carmagine.co.uk

- **Objective phenomenological materials model**
- **Heterogeneous and nonlinear**
- **Complexity in calibrations**



Goal

Develop advanced numerical methods including multiscale methods integrating structural analysis with manufacturing information to reduce experiments for digital prototyping

✓ Manufacturing information

- As-manufactured geometry/warpage, residual stress, defects, heterogeneous material properties, microstructures, etc.

✓ Numerical methods involved

Multi-disciplinary Manufacturing Solvers (1)
To perform material process simulation
Adaptive EFG/FEM, **Adaptive ISPG**, FEM, **SPG**, SPH, other LS-DYNA/Ansys solvers, third-party solvers, etc. (Material Science and Engineering)

Multi-physics Structure and FSI Solvers (2)
To improve accuracy
High-order FEMs, CESE, CPM, DEM, EM, FEM, ICFD, IGA, ISPH, S-ALE, SPG, SPH, etc.

Material Softening Methods (3)
To model material damage and failure
FEM/IGA/SPG + CDM & Dynamore-Gissmo

Strong Displacement Discontinuity Methods (4)
To model dynamic crack propagation
Peridynamics, XFEM

Material Multiscale Methods (5)
To minimize experiments
Deep Material Network (DMN), RVE Concurrent Multiscale Method

Geometric Multiscale Methods (6)
To deal with very fine mesh
Sub-cycling, Sub-modeling, **Two-scale Co-simulation**

Outline

1. Methods for Manufacturing Simulation
    1.1 **Incompressible Smoothed Particle Galerkin (ISPG) Method** for Adhesive Fluid Mechanics Analysis
    1.2 Smoothed Particle Galerkin (SPG) for Solid Mechanics Analysis

2. Methods for Multiscale Simulation
    2.1 **Deep Material Network (DMN)** for Component Material Characterization
    2.2 **Two-scale Co-simulation** for Assembly Structural Analysis

3. A Paradigm Integrating Structural Analysis with Manufacturing Information Using Multiscale Methods

PART 1 ISPG and SPG for Manufacturing Simulation

Adhesive Fluid Mechanics Solver

Solidification/Crystallization/Curing

Melting/Vaporizing

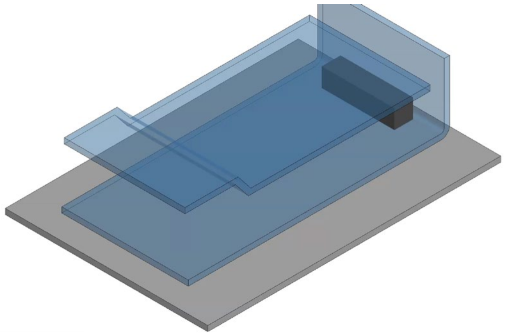
Solid Mechanics Solver

Adaptive ISPG

Model free-surface Non-Newtonian Lagrangian fluid with Surface tension

Implicit

Adhesive bonding, *Reflow soldering, Semi-solid fluid flow, Thin-film coating, etc.*

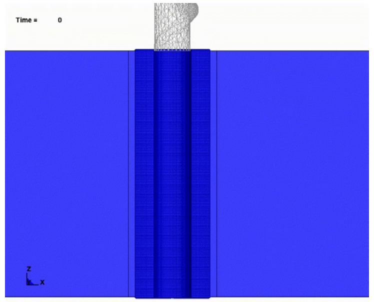


SPG

Model large deformation with material removal

Explicit

Threading, *Drilling, Screwing, Machining, Grinding, etc.*

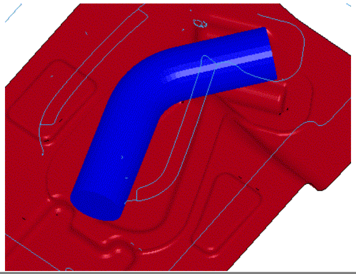


Adaptive FEM/EFG

Model large deformation w/o material removal

Both Implicit and Explicit

Forging, *Extrusion, Compression molding, Sintering*



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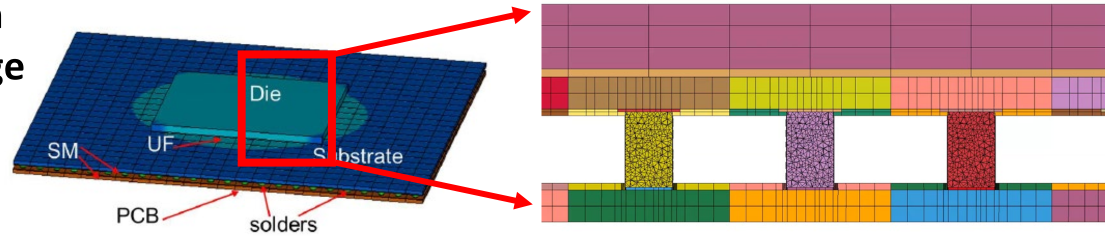
Incompressible Smoothed Particle Galerkin (ISPG) method[1,2]

- ISPG developed by LS-DYNA is a new Navier-Stokes solver for modeling free-surface Non-Newtonian adhesive fluid flow with surface tension and adhesion force (soldering, glue bonding, semi-solid alloy forming, etc.).
- ISPG approximates the Navier-Stokes equation using weak form discretized by Lagrangian particle approximations

$$\frac{D\boldsymbol{v}}{Dt} = -\frac{1}{\rho}\nabla p + \frac{\vartheta}{\rho}\nabla^2\boldsymbol{v} + \boldsymbol{g}, \quad \nabla\cdot\boldsymbol{v} = 0. \quad \boldsymbol{\sigma}\cdot\boldsymbol{n} = \gamma\kappa\boldsymbol{n} \text{ on } \Gamma_s \quad \boldsymbol{u}^h(\boldsymbol{x}) = \sum_{I\in Z_I}\Psi_I^a(\boldsymbol{x})\boldsymbol{u}_I \;\; \forall\boldsymbol{x}\in\Omega,$$

  - **A full-implicit method** with a second-order upwind scheme for time discretization.
  - Penalty method for fluid-solid wall interaction.
  - Alpha Shape algorithm for free surface detection and tracing.
  - A Momentum-Consistent (MC) smoothing scheme[2] is applied to the particle velocity field and position update.
  - Fluid particle inserting and merging for optimal efficiency and accuracy.

Ex 1: Reflow of 480 solder balls on PCB with thermal-induced warpage using R15 MPP version



~2.5 M elements, 64 cores
CPU 1.17 hours << Established numerical methods in weeks

(Courtesy of Ansys ACE, Arka Sengupta)

- MPP linear scalability was achieved in R15 Adaptive ISPG method.

CPU cost			
CPU cores:	8	32	64
Clock time[hours]:	8.4	2.1	1.17
Speed up:	1	4	7.6

[1.] IJNME, 121 (17), 3979-4002, 2020 ; [2.] Comp. Part. Mech., 7 (2), 177-191, 2020

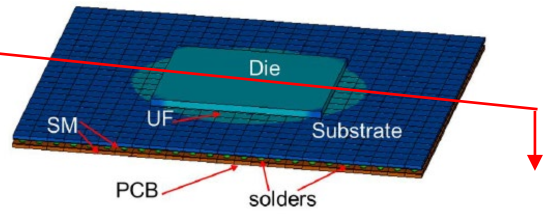
2023 R15 New Release - Adaptivity

- ✓ R15 ISPG introduces an **adaptivity ISPG method** to model complex reflow and severe contact angle.
- ✓ **Full-implicit** version based on MF2 solver was implemented for decomposition of solder balls on all CPUs for optimal scalability.
- ✓ The Beta version of **LS-Prepost (4.11)** supports the desired functions for Adaptive ISPG display.

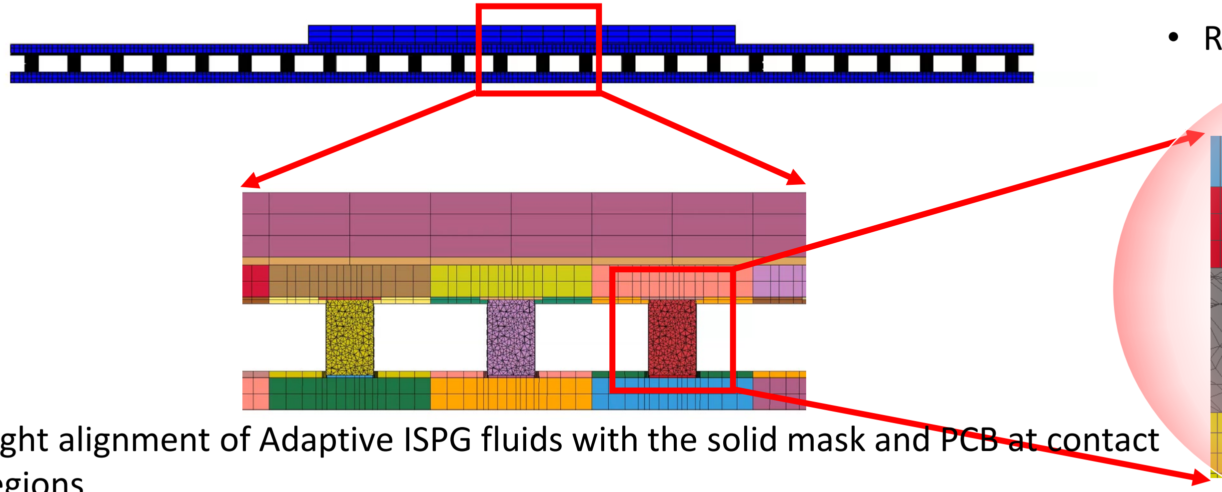
Ex2 : Large-scale Reflow Soldering Simulation using R15 Adaptive ISPG method

(Courtesy of Ansys ACE, Arka Sengupta)

480 solder balls, ~2.5 M elements, 64 cores, **1.17 hours** in R15



- Heterogeneous deformation of solders due to large PCB thermal warpage

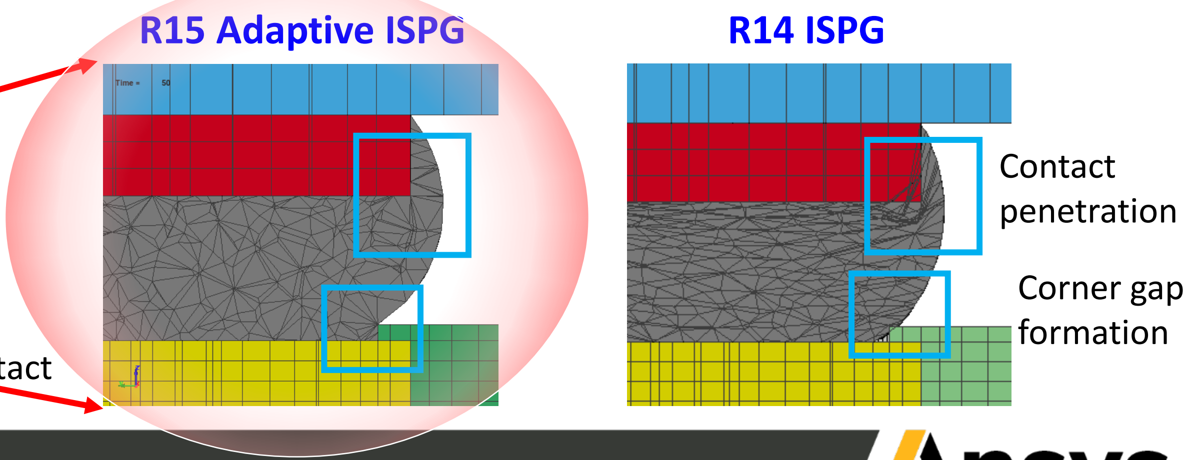


- Tight alignment of Adaptive ISPG fluids with the solid mask and PCB at contact regions

- Theoretical linear scalability was achieved in R15 Adaptive ISPG method.

Computation cost	R15	R15	R15	R14
CPU cores	8	32	64	80
Clock time[hours]	8.4	2.1	1.17	10.0
Speed up	1	4	7.6	

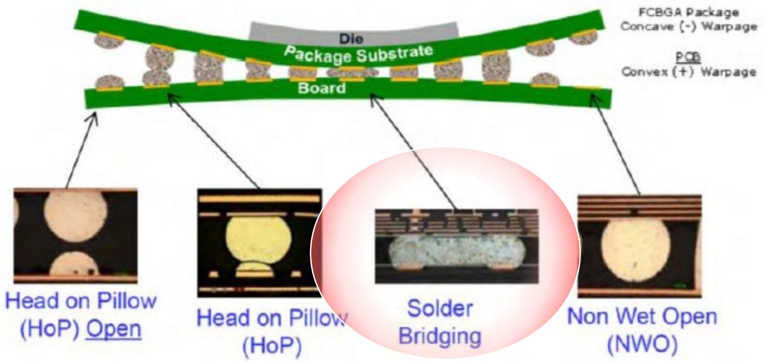
- R15 Adaptive ISPG resolves resolution issue in R14 non-adaptive ISPG



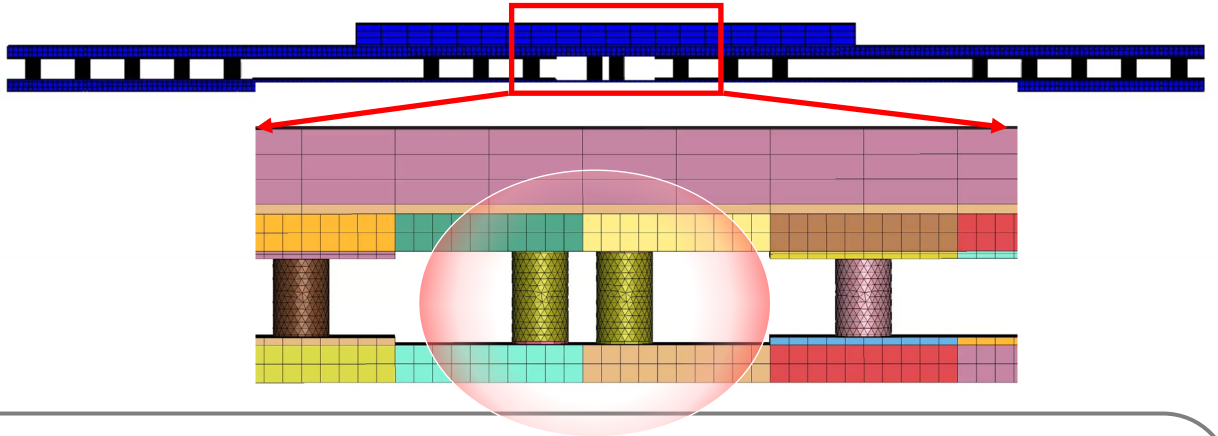
2023 R15 New Release – Solder bridging defects

- ✓ R15 Adaptive ISPG can model **solder bridging critical defects**
- ✓ A new full-implicit **sub-cycling scheme** for speed-up

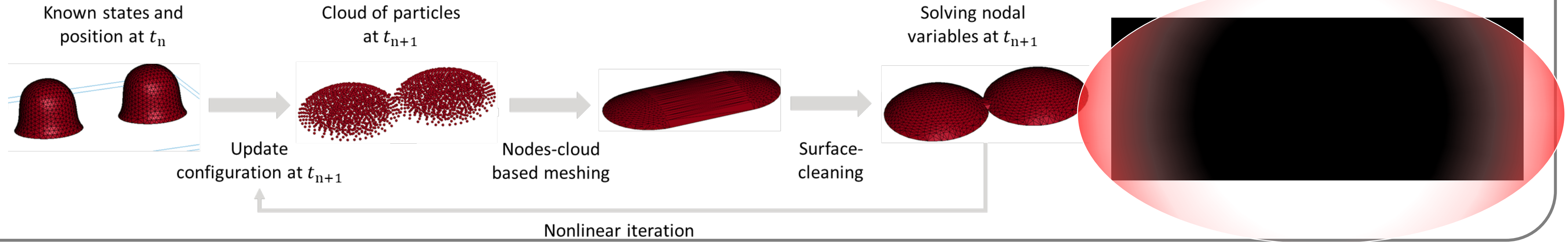
Ex3: Simulating solder bridging defects due to PCB warpage with wetting condition *(Courtesy of Ansys ACE, Arka Sengupta)*



Criticial Solder defects at SMT (Loh et al., 2016)



ISPG material fusion scheme for solder bridging under surface tension and wall adhesion force



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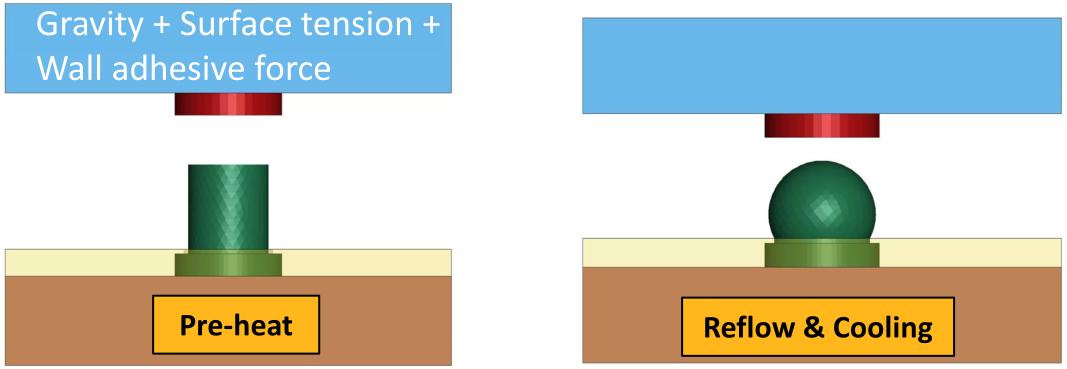
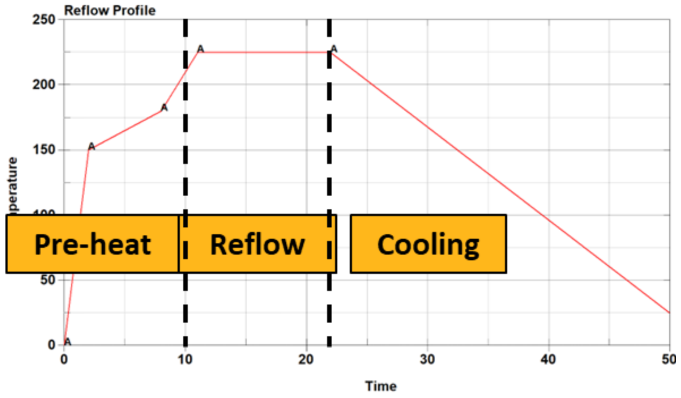
2023 R15 New Release – Temperature-dependent viscosity

✓ R15 features also consider **solder pre-heat and cooling** stages

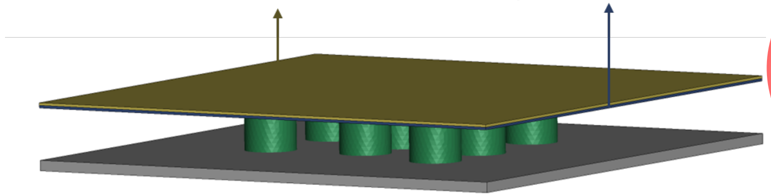
- Non-Newtonian fluids and temperature-dependent viscosity



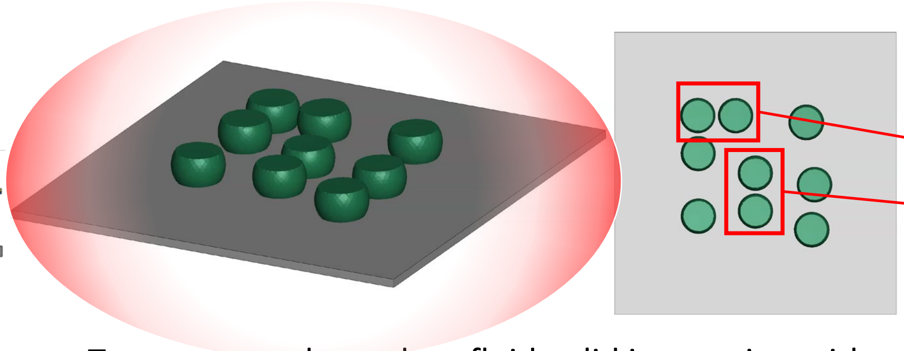
- Time history of thermal loading



Ex 4: Defect of reflow soldering with temperature-dependent viscosity in semiconductor application

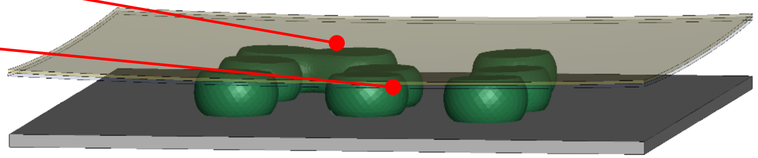


Ball-grid array (BGA) pattern



Temperature-dependent fluid-solid interaction with surface tension and wall adhesive force

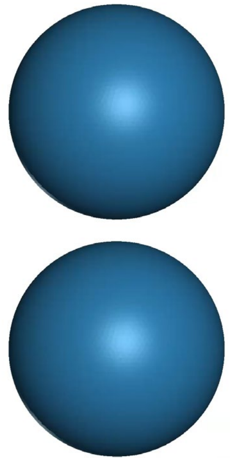
Identification of solder bridging defects

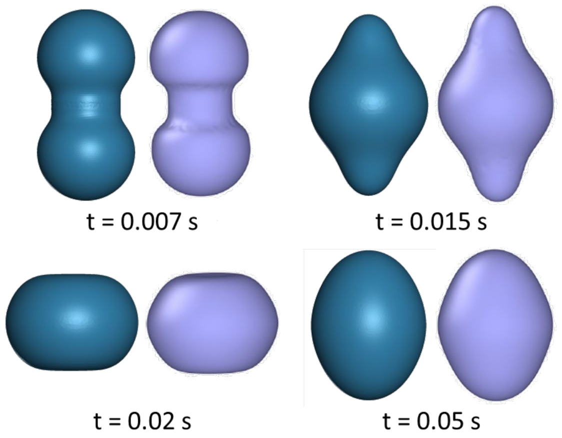


Application - 3D droplet-coalescence

Ex 5: 3D droplet-coalescence simulation in surface engineering application

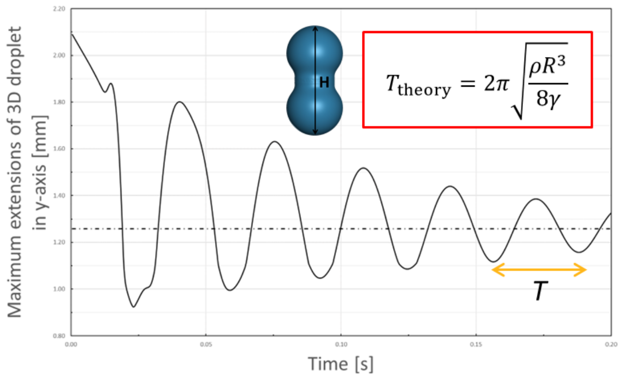
- UV-curing epoxy resins.
- For dotting, potting and filling in chip encapsulating applications.
- Other applications such as adhesive dispensing and thin film coating.





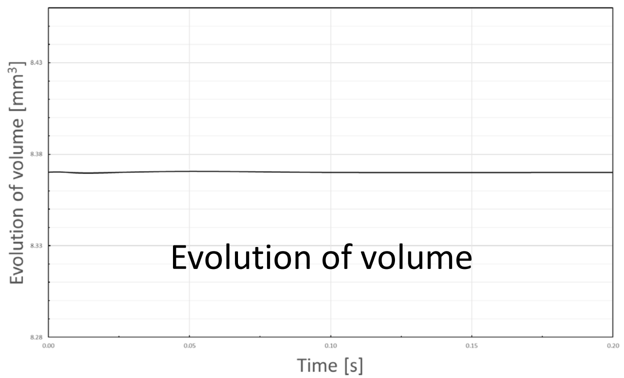
The droplet shapes at different times, comparing to the work of G. Duan (2022, CMAME)

Initial radius of each droplet, R	0.001 m
Initial approaching velocity	0.02 m/s
Density, ρ	1000 kg/m^3
Viscosity, μ	0.005 Pa s
Surface tension, γ	0.01 N/m
Ohnesorge number, $\frac{\mu}{\sqrt{2\rho\gamma R}}$	0.000997
Collision time	c.a. 0.2 s



Time dependence of the surface extension in y-direction

Simulated period, T [s]	Theoretical period, T_{theory} [s]	Relative error
0.0315	0.0314	0.317%

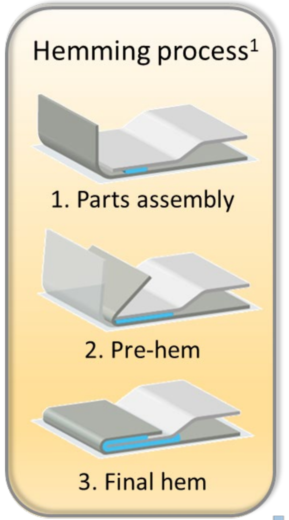


Initial volume	Volume at final time step	Relative volume error
8.37022	8.37004	0.00215%

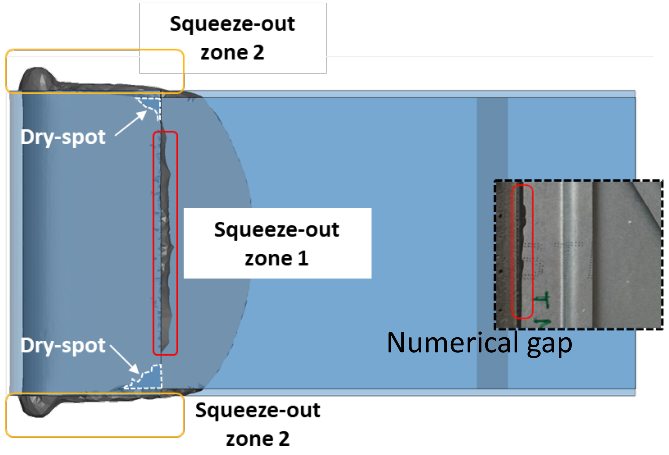
Application – Structural adhesive bonding

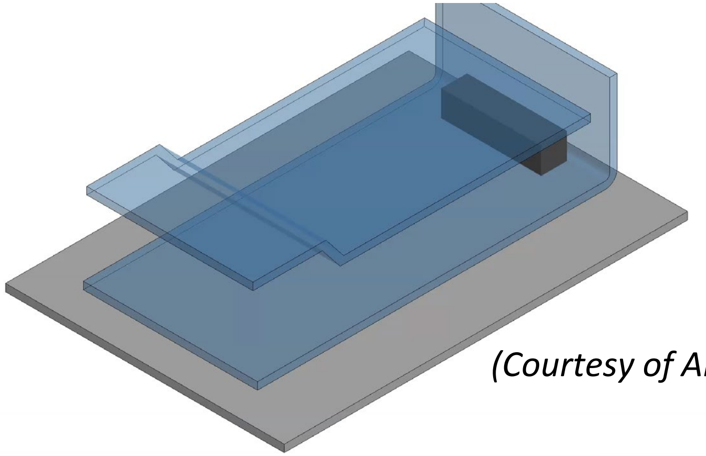
Ex 6: Simulating adhesive flow and bonding defects in automotive Hem Flange Bonding Process

- Adhesive bead position plays an important role on optimal filling inside the hemmed area: Squeeze outs or insufficient filling
- Resultant adhesive layer thickness and gap-filling affect the mechanical properties of bonded structure

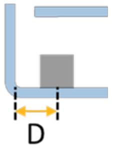


Needs to be removed by a pain-stacking process



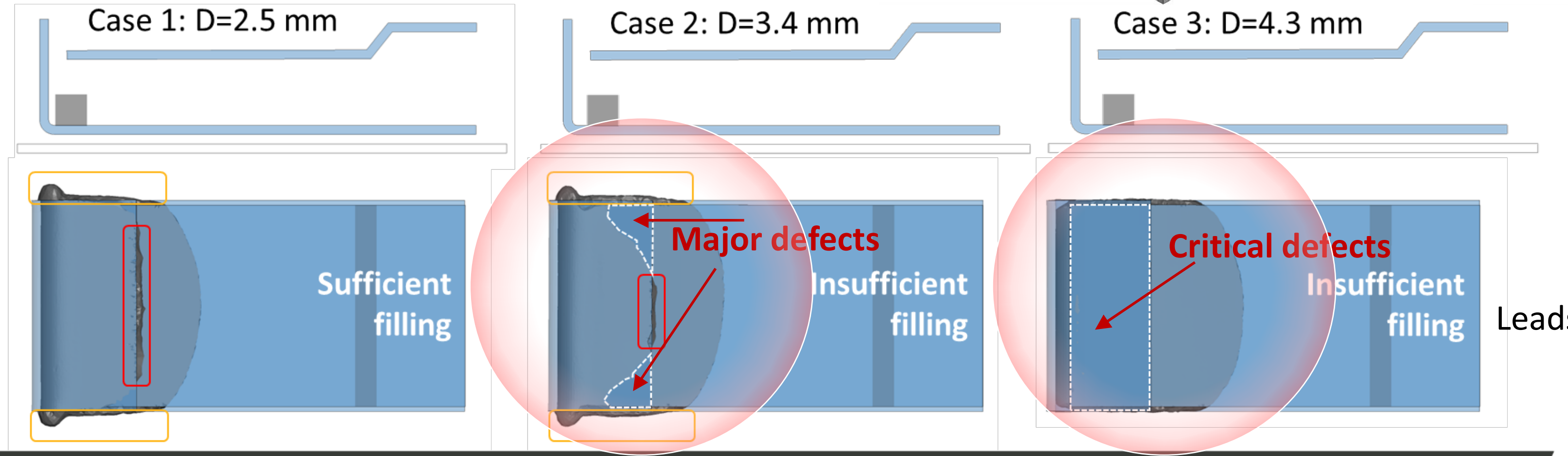


(Courtesy of Ansys ACE, Li Zhang)



Adhesive bead position, D

Top view



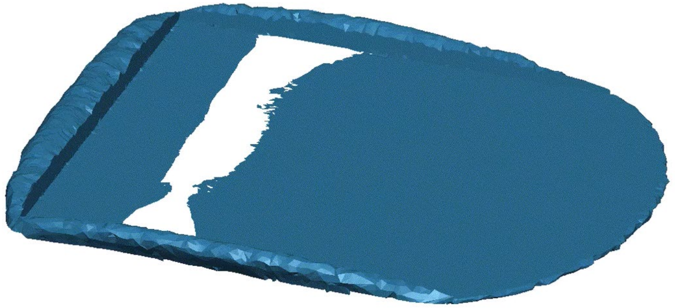
Leads to corrosion

Application – Structural adhesive bonding

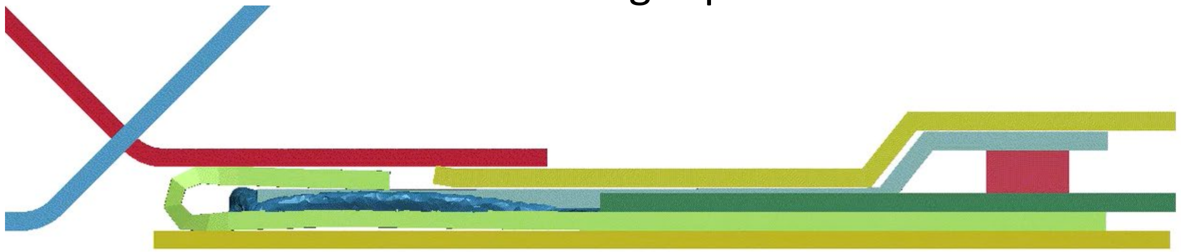
Ex 7: Study of critical defect - excessive glue squeeze-out

(Courtesy of Ansys ACE, Li Zhang)

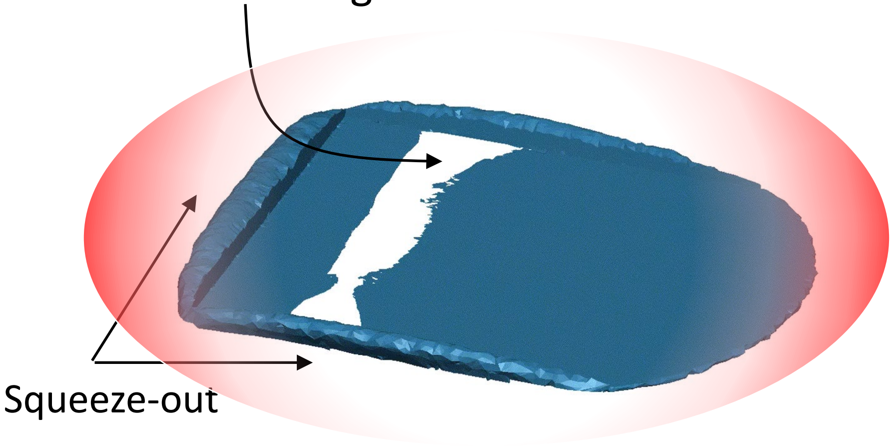
- Joining similar or dissimilar materials with structural adhesives



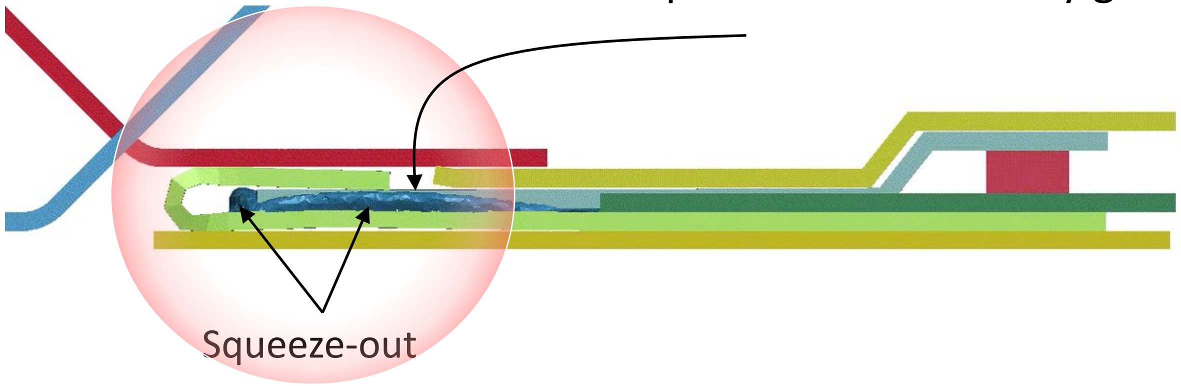
Straight position



Defect prediction: excessive glue squeeze-out that not enough is left in this zone



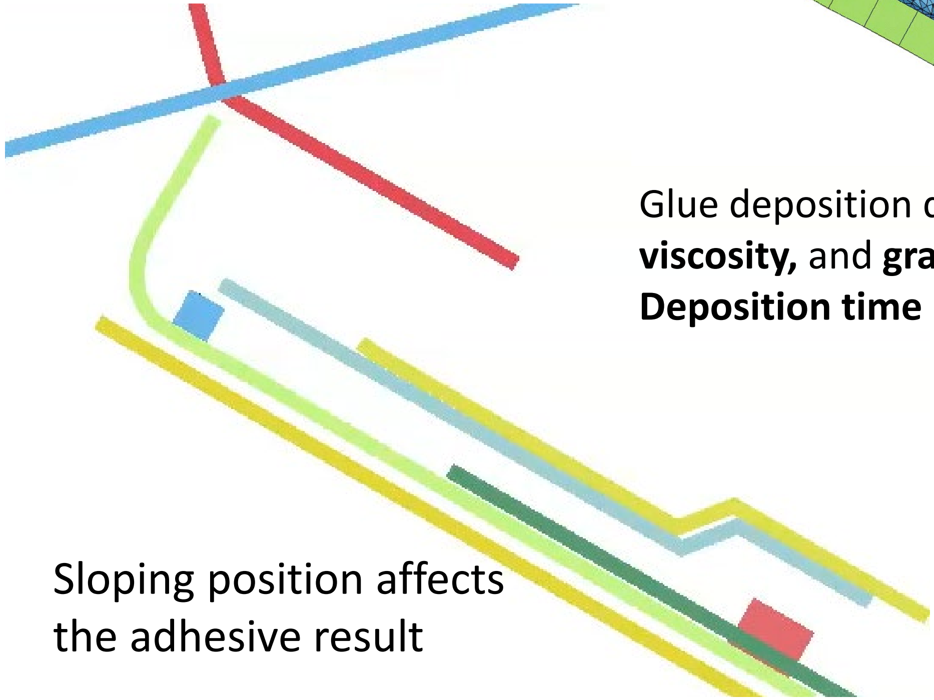
Three workpieces are bonded by glue

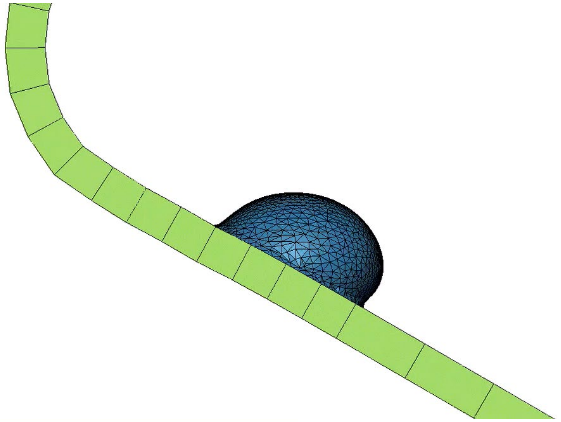


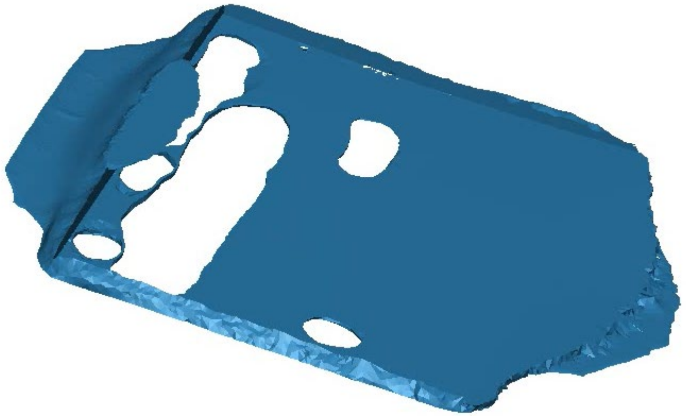
Application – Structural adhesive bonding

Ex 8: Study of critical defect under gravity effect

(Courtesy of Ansys ACE, Li Zhang)



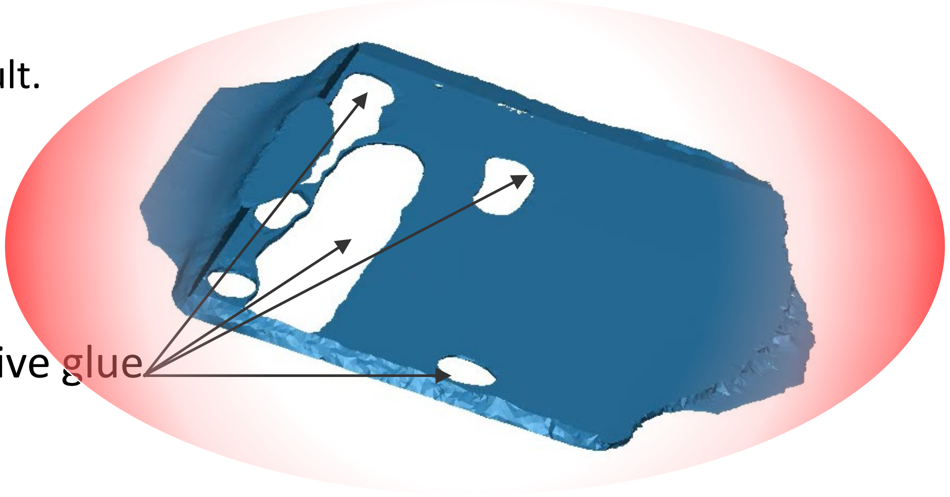




Glue deposition due to **surface tension, adhesive viscosity,** and **gravity**
Deposition time is also important to flow result.

Sloping position affects the adhesive result

More defects: excessive glue squeeze-out

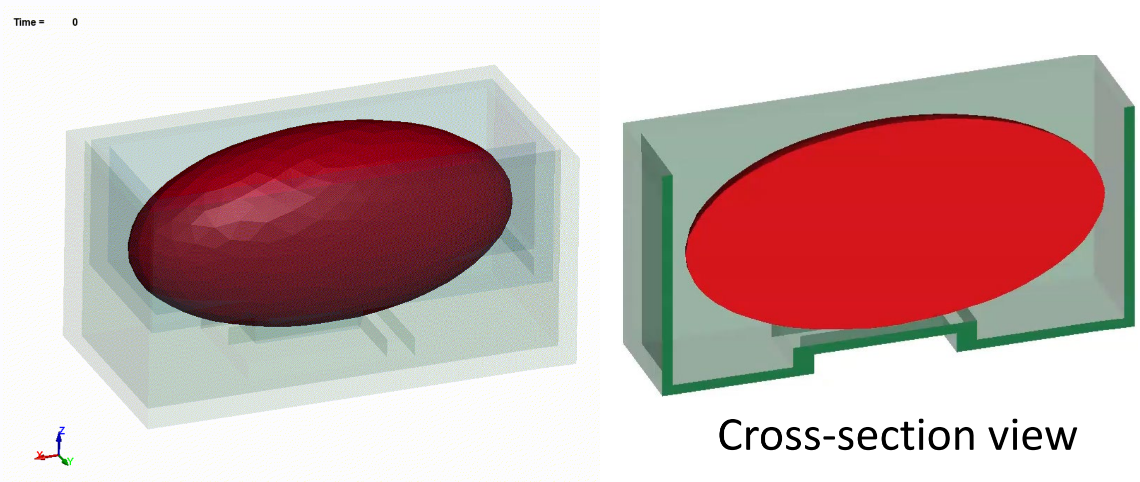


Application – Semi-solid material flow in metal processing

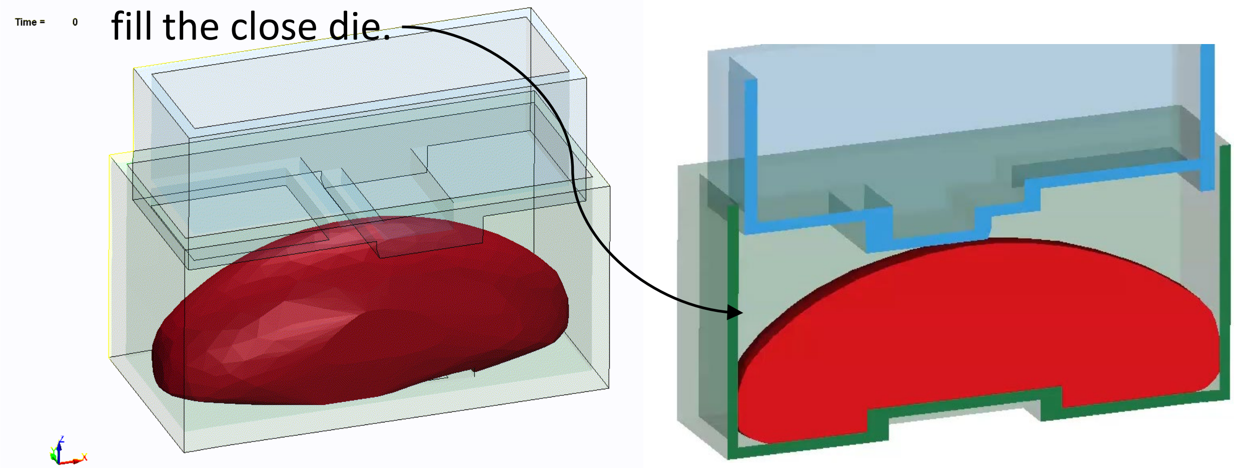
Ex 9 : Simulating aluminum semi-fluid flow in automotive semi-solid metal (SSM) die casting process

- Under different names such as Squeeze Casting, Thixoforging, and Thixocasting
- Combine the advantages of casting and forging for the high-end net shape products in auto, aero, high-tech, medical, etc.
- **Non-ferrous metals**, such as aluminum, magnesium, copper, … with **non-dendritic microstructure**.
- Complex parts, porosity-less, reduced shrinkage, thin walls, good surface finish, excellent mechanical performance..

(Courtesy of Ansys ACE, Li Zhang)



Open Die Casting



Close Die Forging in Casting (Squeeze Casting)

Current and Potential ISPG Applications

ISPG Applications

Semiconductor

Reflow Soldering

- Large-scale reflowing
- Bridging
- Tombstoning
- Poor wetting
- Head-in-pillow
- Beading
- Voiding
- Opening

Chip Encapsulating

- Compression Molding
- Transfer Molding
- Molded Underfill
- Capillary Underfill
- Dotting/Potting

High-Tech

Auto/Aero

- Metal hem flange bonding
- Semi-solid casting/forging
- Structural adhesive bonding
- Rivet bonding
- Laser welding

Electronics

- Adhesive forging
- Adhesive jointing
- Thin film coating
- Filling or potting a mold

EV Battery

- Cell-to-Module upper gap filling
- Module-to-Pack lower gap filling
- Cell-to-Cell bonding
- Battery tray bonding
- Crash box bonding

Other Battery Packing

- Potting
- Encapsulating

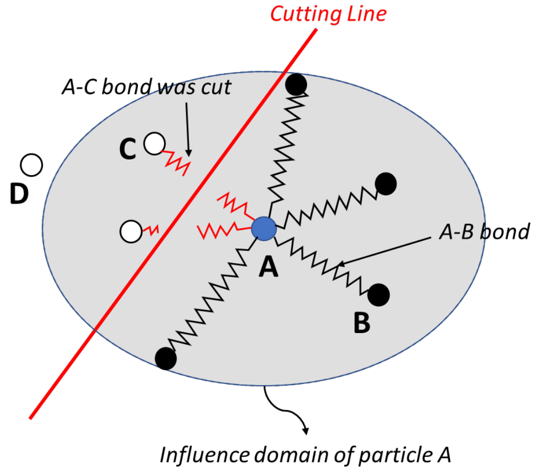
Smoothed Particle Galerkin (SPG) Method[1,2]

- SPG is a new particle method for simulating severe deformation and material removal processes.
- SPG approximates the dynamic equation of motion using weak form discretized by particle approximations.

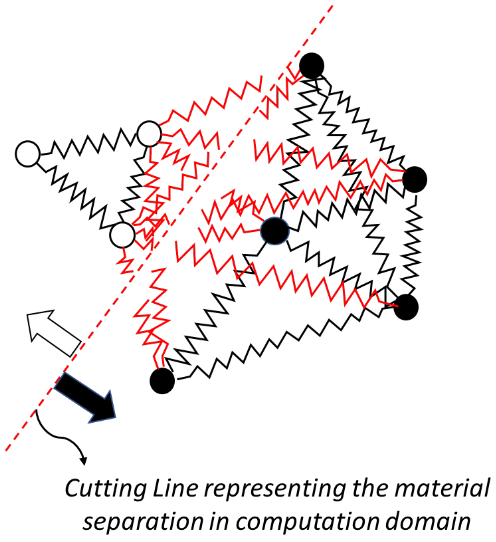
$$\int_{\Omega} \rho \ddot{\boldsymbol{u}}^h \cdot \delta \boldsymbol{u}^h \mathrm{d}\Omega + \int_{\Omega} \boldsymbol{\sigma} \cdot \nabla \delta \boldsymbol{u}^h \mathrm{d}\Omega - \int_{\Omega} \boldsymbol{b} \cdot \delta \boldsymbol{u}^h \mathrm{d}\Omega - \int_{\partial\Omega^h} \boldsymbol{h} \cdot \delta \boldsymbol{u}^h = 0 \quad \boldsymbol{u}^h(\boldsymbol{X},t) = \sum_{I \in Z_I} \phi_I^a(\boldsymbol{X}) \boldsymbol{u}_I(\boldsymbol{X},t) = \sum_{I \in Z_I} \phi_I^a(\boldsymbol{X}) \boldsymbol{u}_I \quad \boldsymbol{P}_I := \sum_{J \in Z_I} \hat{m}_J \phi_I^a(\boldsymbol{X}_J) \hat{\boldsymbol{u}}_J$$

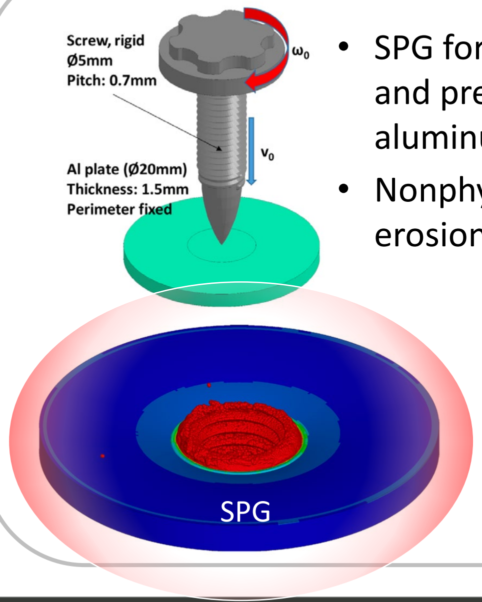
  - MC smoothing algorithm removes the low-energy modes and preserves linear/angular momentum.
  - **Bond-breaking scheme** avoids element/material erosion thus system mass is preserved in material removal simulation.
  - **Bond-breaking scheme** prevents non-physical material fusion in solid mechanics simulation.

Bond breaks permanently within the Influence domain of particle A

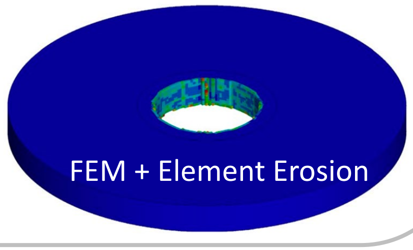


Collection of breaking bonds forms the cutting line





- SPG forms a desired thread pattern and preserves the mass in an aluminum plate screwing simulation.
- Nonphysical FEM result by element erosion.



1. Comp. Part. Mech., 7 (2), 177-191, 2020; 2. Comp. Mech., 64 (3), 625-644, 2019

2023 R15 New Release – Particle-to-Surface contact

- ✓ Main feature in R15 release: **a SPG particle-to-surface contact algorithm**
- ✓ Importance: new feature can improve the contact stability due to the complex geometry of drilling/machining tools.
- ✓ New Keyword: *DEFINE_SPG_TO_SURFACE_COUPLING .vs. *NODE_TO_SURFACE
  - Surface part can be rigid or deformable
  - Thermal-mechanical coupling
  - Include sliding and tied contact options
  - Released in SMP version; but MPP version is also available for trial use in R15

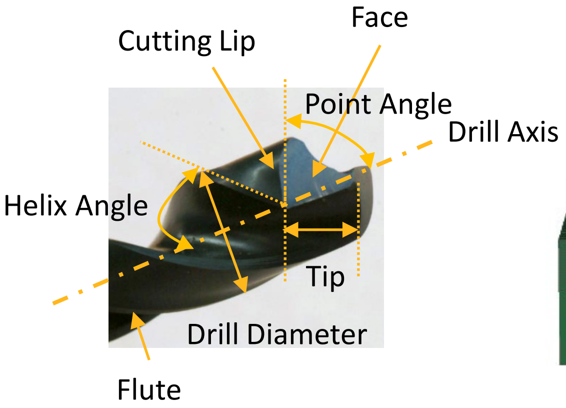
Ex1: A grooving tool design for a spiral chip formation in the metal dry drilling simulation *(Courtesy of Ansys ACE, Amit Nair)*

Types of drill bits

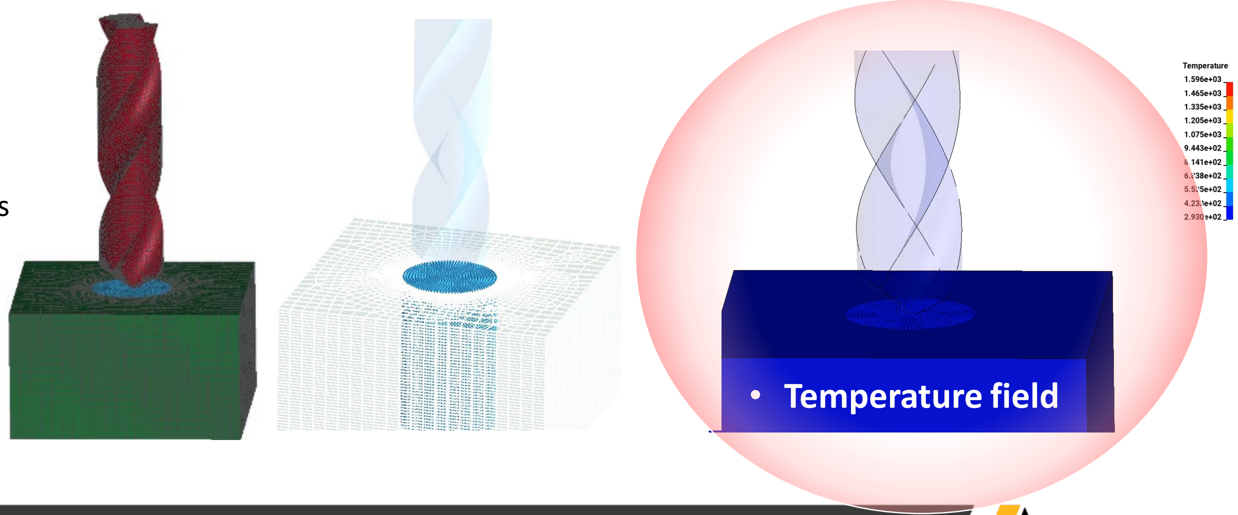
https://en.wikipedia.org/wiki/Drill_bit

https://www.123rf.com

Drill bit geometry



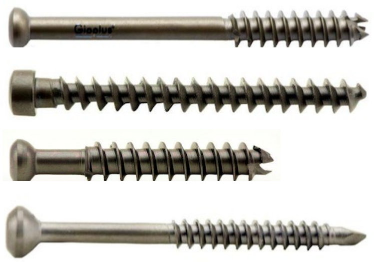
- Material is not eroded in simulation (thus mass/momentum conservation)
- Spiral-shaped chips can be reproduced



Application – Orthopedic Screw Mechanics

- Orthopedic screw design affects the bone fixation for fractures.
- The pull-out strength of orthopedic screws is used to measure the **screw fixation strength**.
- New feature can simulate the formation of bone threads and residual stress in insertion process determining the pull-out strength.
- SPG is an exclusive numerical method to perform this process simulation.

Types of bone screws

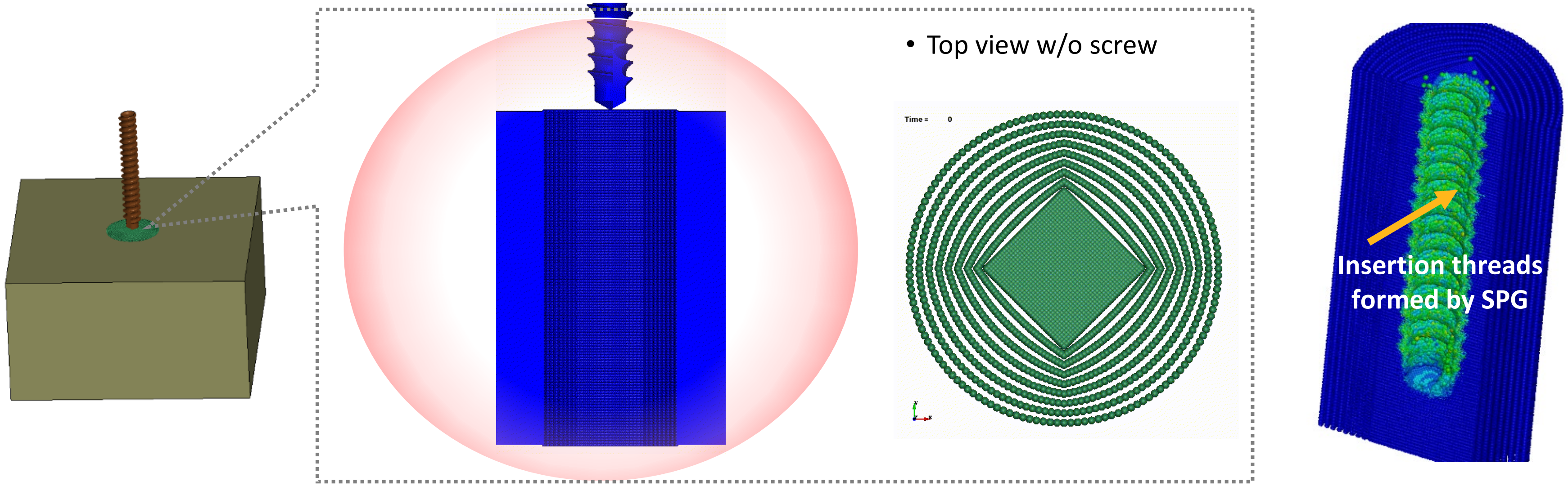


https://giaplus.com/orthopedic-screws

Front. Bioeng. Biotechnol. 10:816250, 2022

Ex2: Simulation of surgical screw insertion & pullout in sawbones

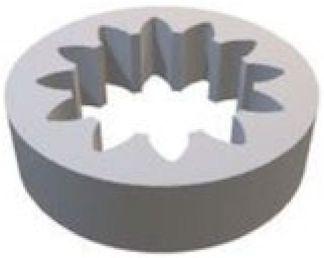
- Threads can be formed in sawbones during inserting
- Residual material is captured on screw affecting the pullout strength

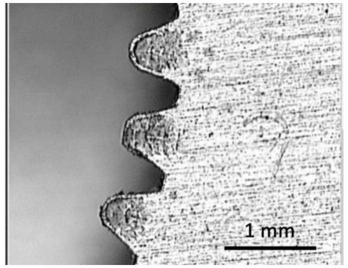


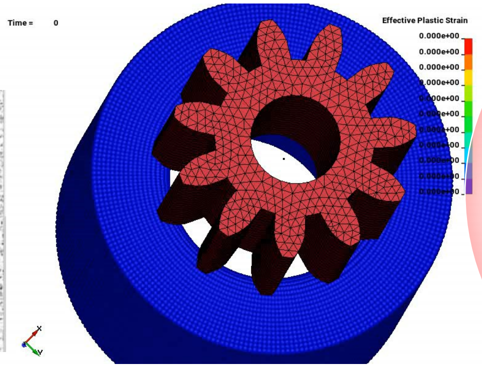
Application – Open-die Cold Extrusion

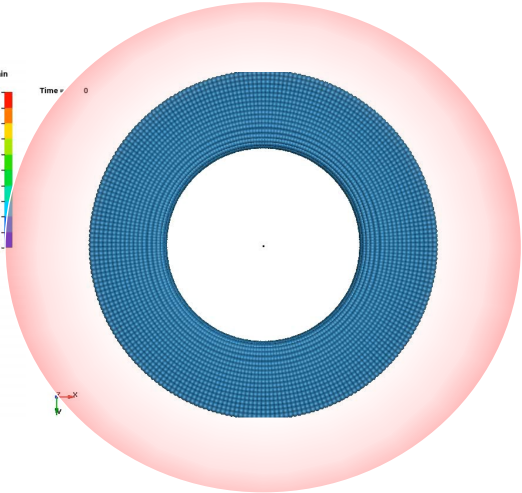
- Cold extrusion usually yields better mechanical properties than machining.
- But the forming quality and defects are difficult to control (lubricating condition, entrance angle, blank size, and extrusion speed).
- New SPG feature can prevent contact penetration and maintain the numerical stability in precision extrusion simulation.

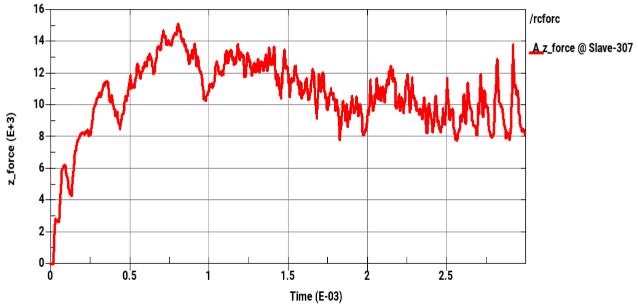
Ex3: Formability and defect cause analysis in Cup-shaped (Spur) Internal Gear manufacturing







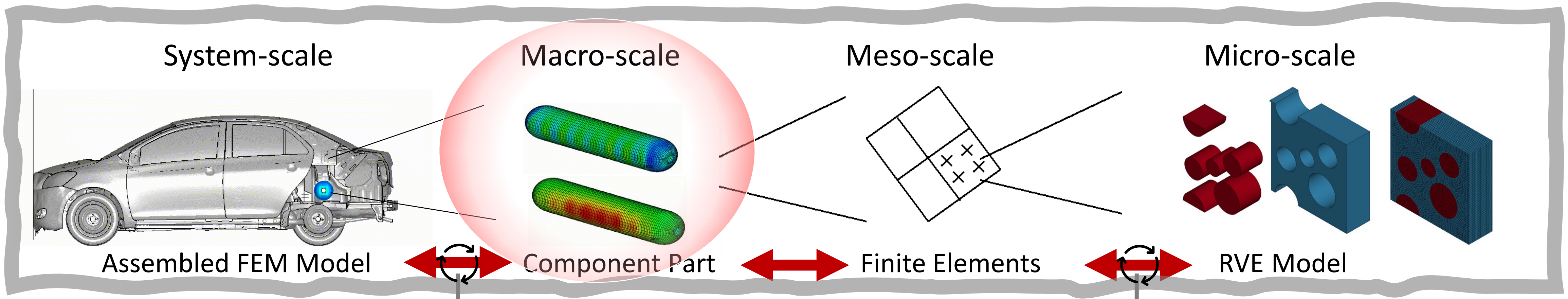




Metals 2022, *12*(5), 826; https://doi.org/10.3390/met12050826

PART 2 Multiscale Simulation Methods

Ex. Study of composite components in the system analysis



Geometric Multiscale Method

Speed up bridging macro – system scale for assembly analysis to deal with fine mesh

Two-scale Co-simulation

Modeling joints, components and adhesives in system analysis

Material Multiscale Method

Speed up bridging micro – meso scale for material characterization to minimize experiments

DMN

Heterogeneous microstructure

Short fiber reinforced composite

Polycrystalline metal, UD

RVE Concurrent Multiscale

Homogeneous microstructure

Weaved

Plain woven

Ansys

Material Multiscale Methods

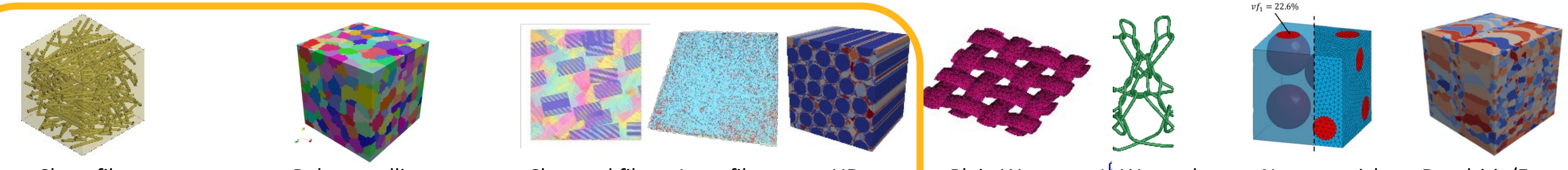
- Fill the gap between manufacturing simulation and structural Analysis
- Requires the **microstructure reconstruction, RVE technology and Material Multiscale method**

Classification of Microstructure Systems

	Short-Fiber Injection Molding	**Multi-stage Metal Fabrication**	**Bulk Compression Molding (CM)** (chopped fiber)	(glass fiber)	**Weaving**	**Unexplored**
Manufacturing Simulation and Solvers	Amorphous Thermoplastics PC/ABS/PS/PVC/PSU, …	Forging, Extrusion, Rolling, Machining, Grinding, Jointing, etc.	Thermoplastic epoxy /Carbon fiber	Polyamide Nylon6 /Glass fiber	Textile materials	Die-casting, Laser welding, Fiber-reinforced 3D Printing, Micro-injection Molding, Nanomaterials and Nano-manufacturing, etc.
Numerical Methods	CFD (Moldex3D, Moldflow) Third party software	ISPG, SPG, FEM, 3D adaptive FEM/EFG	3D adaptive FEM/EFG		Winding software	ISPG, ICFD, etc.
Physical Descriptors	Fiber Orientation/Volume Fraction Rheology model	Grain Density, Size, Orientation Dir/Rheology model	Forming indicators		Weaving methods	**Imagine-based methods** (Computed Tomography, CNN/Transfer Learning)

As-manufactured geometry/warpage, residual stress, microstructures, defects, etc.

Microstructure Reconstruction



Short fiber	Polycrystalline	Chopped fiber	Long fiber	UD	Plain Woven	Weaved	Nano-particle	Dendritic/Eutectic
✓ 2022 R14	R&D			R&D		✓ 2023 R15		R&D

Material Multiscale Methods

(a) Deep Material Network (DMN)
AI for Heterogeneous Microstructures

(b) RVE Concurrent Multiscale Method
FE^2 for Homogeneous Microstructures

(c) AI-EBSD + GNN/DMN

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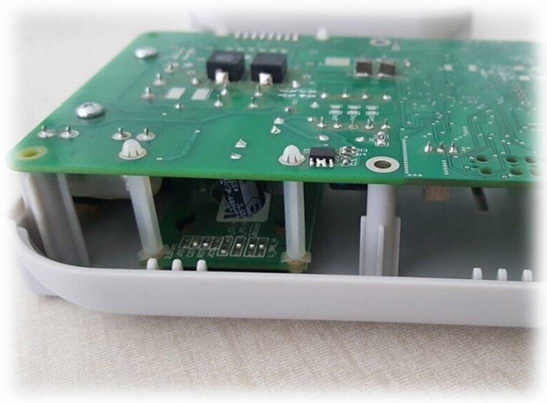
Short Fiber Composites

- Injection-molded short-fiber-reinforced composite (SFRC) is a high performance, low-cost, and environmental friendly material (light weigh, high productivity, chemical/corrosion resistant, recyclable, shock absorbing).
- They are widely used in Electronics, Auto, Consumer Goods, Protective equipment, Aerospace, Healthcare, Construction, etc.
- Modeling SFRC materials has been a challenging task for years.

PCBs

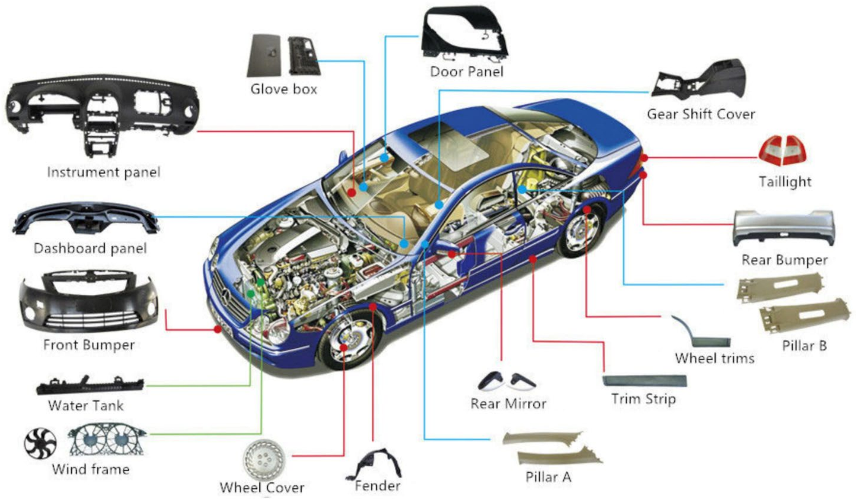


https://scorpiomfg.com/project/injection-molding-plastic-enclosure

Electronics Plastic Enclosures and Covers

https://app-nh.com/markets-electronics/

Automobile Parts



https://www.hollyplasticparts.com/solution/automotive-plastic-injection-molding/

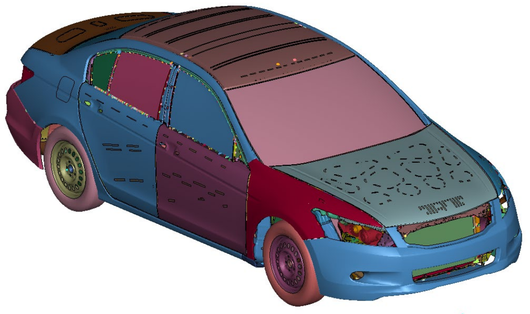
DMN for Modeling Short Fiber Composites

- Deep Material Network (DMN)[1,2,3] developed by LS-DYNA is a Machine Learning method.
- First version was released in 2022.
- DMN recognizes heterogeneous microstructure patterns in data to make efficient prediction of nonlinear material behavior in macroscale.

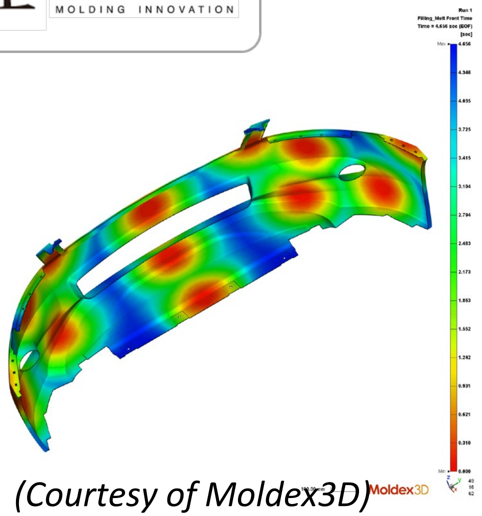
Ex. Multiscale Structural Analysis of Injection Molded Short Fiber Reinforced Bumper Cover by 2022 R14

Collaborators: HONDA, JSOL, Moldex3D MOLDING INNOVATION

Impact time	1.92ms
8 CPU time	33 min 25 sec

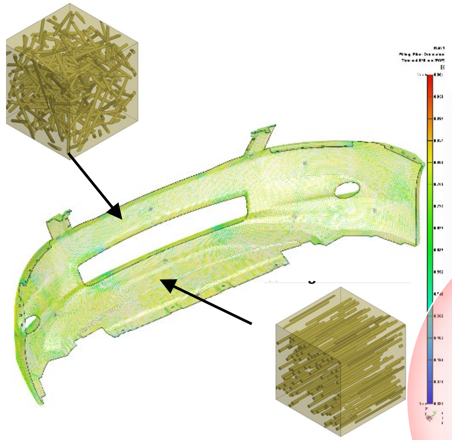


Honda 2017 Accord



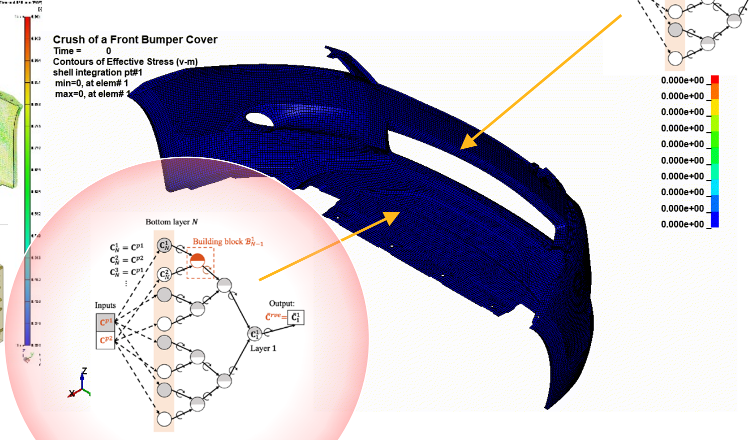
(Courtesy of Moldex3D)

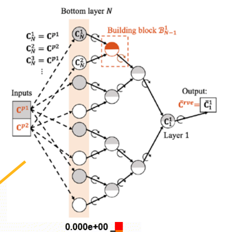
Moldex3D
Injection Molding Simulation



Moldex3D Predicted Fiber Orientation

LS-PrePost





25256 solid shell elements, 25600 nodes

LS-DYNA Online
Multiscale Structural Analysis

[1] CMAME, 345, 1138-1168, 2019; [2]. J. Mech. Phys. Solids, 127, 20-46, 2019; [3] Comp. Mech., 64(3), 625-644, 2020

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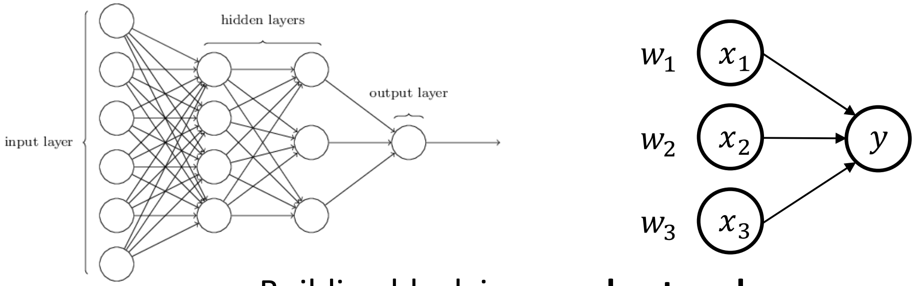
Difference between Deep Material Network (DMN) and Neural Network

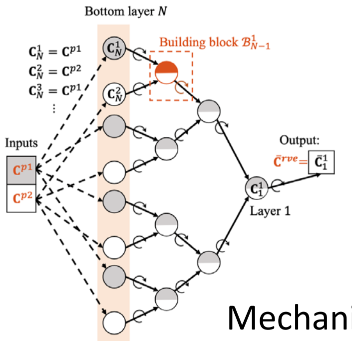
- **Artificial neural networks generally have the issues of loss of physics.** It leads to the problems in modeling material history dependency, keeping physical invariance and preserving conservation law.
- The Deep Material Network (DMN)[1] introduces a collection of connected **building blocks** with **analytical homogenization solutions** to resolve the issues.
- Targeted applications include arbitrary morphology, material nonlinearity (plasticity, damage, de-bonding), geometric nonlinearities (large deformations).

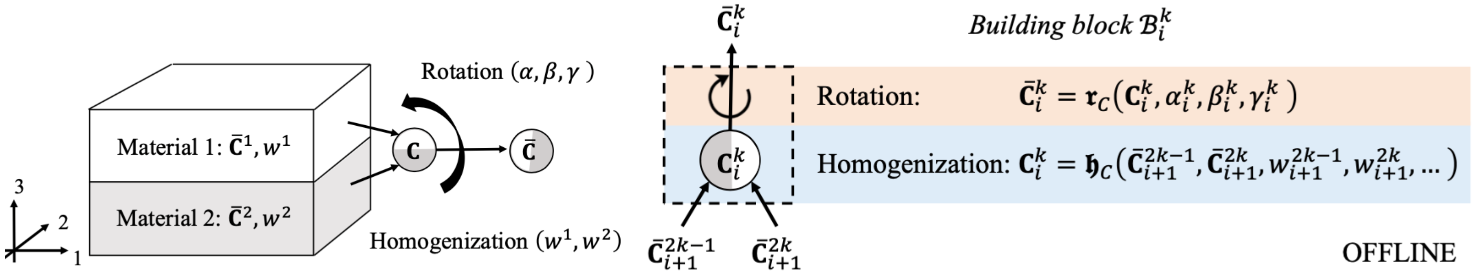


$$y = a\left(\sum_{i=1}^{n} w_i x_i\right)$$

w_i: fitting parameters
a: activation function

Building block in **neural network**





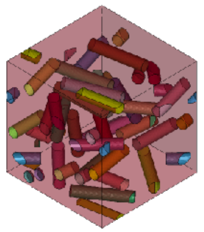
Mechanistic building block in **deep material network (DMN)**

[1] A deep material network for multiscale topological learning and nonlinear modeling of heterogeneous materials, CMAME, 345, 1138-1168, 2019.

Computational Procedure in Deep Material Network (DMN)[1]

Offline Training

3D RVE morphology



Data generation

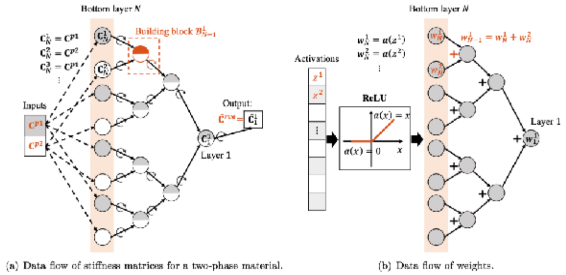
High-fidelity DNS or FFT

Generating orthotropic elastic samples

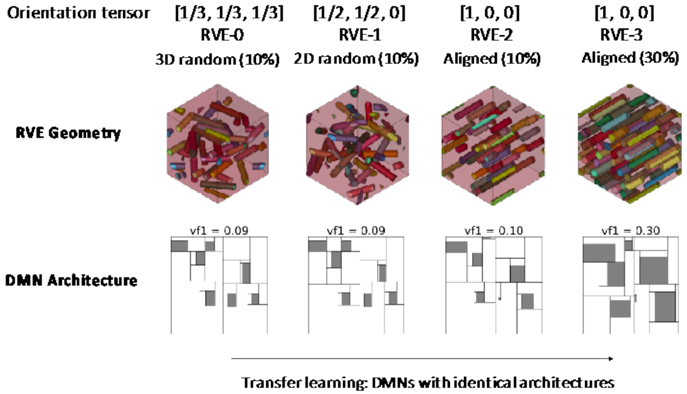
$$\underbrace{\bar{\mathbf{C}}^{rve}}_{\text{Output}} = \mathrm{f}_2(\underbrace{\mathbf{C}^{p1}, \mathbf{C}^{p2}}_{\text{Inputs}}, \overbrace{z^{j=1,2,\ldots,2^{N-1}}, \alpha^{k=1,2,\ldots,2^{i-1}}_{i=1,\ldots,N}, \beta^{k=1,2,\ldots,2^{i-1}}_{i=1,2,\ldots,N}, \gamma^{k=1,2,\ldots,2^{i-1}}_{i=1,2,\ldots,N}}^{\text{Fitting parameters}}).$$

$$Re'(z_N^j) = \begin{cases} 1 & \text{if } z_N^j > 0 \\ 0 & \text{otherwise} \end{cases}$$

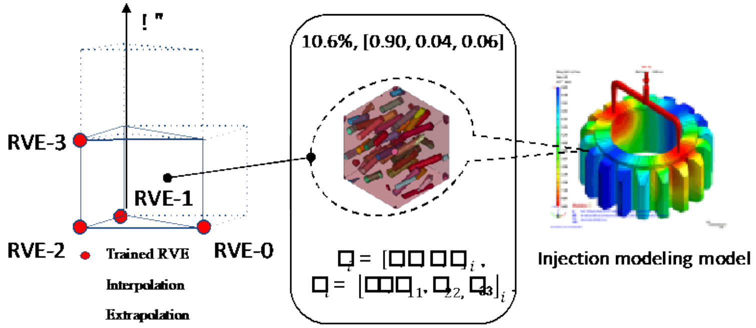
Network training



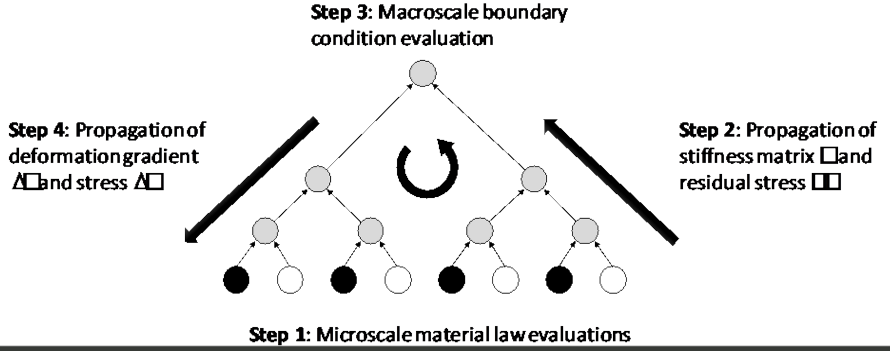
Transfer Learning
for Short-Fiber Reinforced Composites

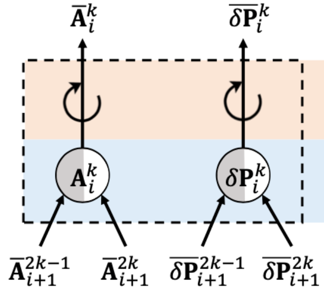


Design space



Online Extrapolation
Material Nonlinearity in the Network





Building block $\mathcal{B}_i^k$

Rotation: $\bar{\mathbf{A}}_i^k = \mathfrak{R}_A(\mathbf{A}_i^k, \alpha_i^k, \beta_i^k, \gamma_i^k)$, $\delta\bar{\mathbf{P}}_i^k = \mathfrak{R}_P(\delta\mathbf{P}_i^k, \alpha_i^k, \beta_i^k, \gamma_i^k)$

Homogenization: $\mathbf{A}_i^k = \mathcal{H}_A(\bar{\mathbf{A}}_{i+1}^{2k-1}, \bar{\mathbf{A}}_{i+1}^{2k}, w_{i+1}^{2k-1}, w_{i+1}^{2k}, \ldots)$, $\delta\mathbf{P}_i^k = \mathcal{H}_P(\delta\bar{\mathbf{P}}_{i+1}^{2k-1}, \delta\bar{\mathbf{P}}_{i+1}^{2k}, w_{i+1}^{2k-1}, w_{i+1}^{2k}, \ldots)$

ONLINE

[1] Exploring the 3D architectures of deep material network in data-driven multiscale mechanics, J. Mech. Phys. Solids, 127, 20-46, 2019.

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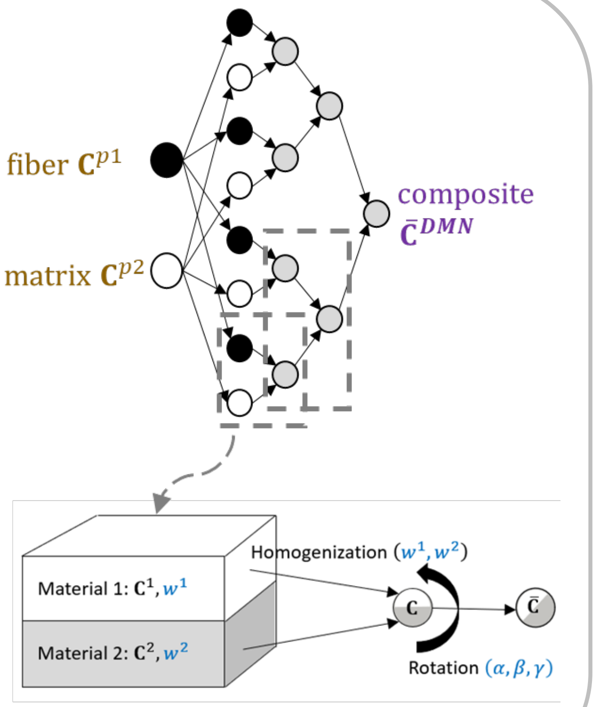
LS-DYNA DMN Performance

- $10^3 \sim 10^5$ times faster than model-based (RVE) concurrent multiscale methods in explicit dynamic analysis.
- Compared to Mori-Tanaka method, DMN can predict the complex micro-morphology and material nonlinearity.
- Six hidden layers for optimal efficiency and accuracy.

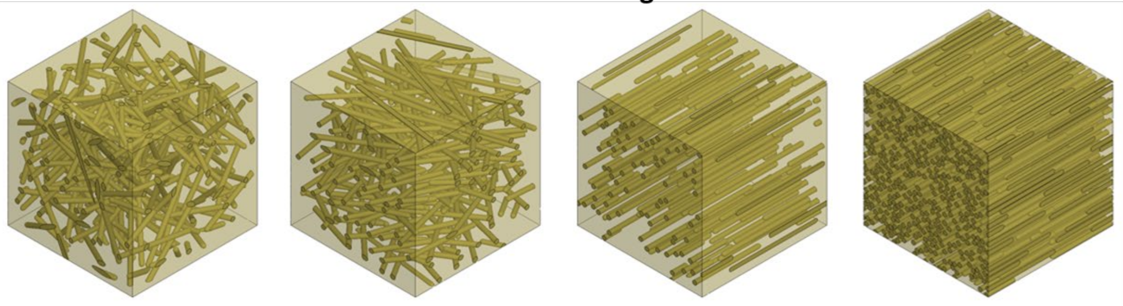


Physics-embedded Building Block

Offline Training

Online Prediction

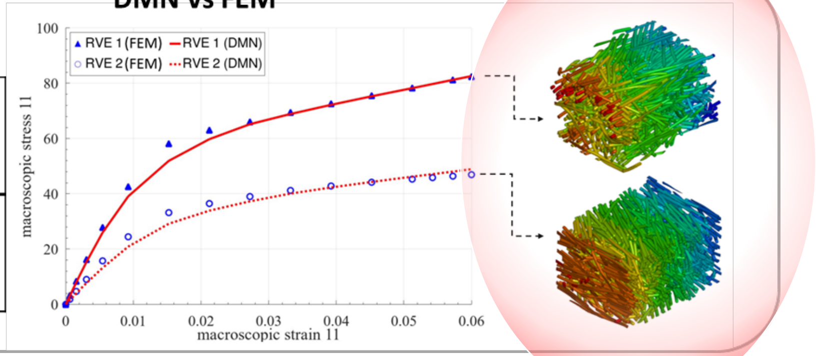
Transfer Learning



Computational time

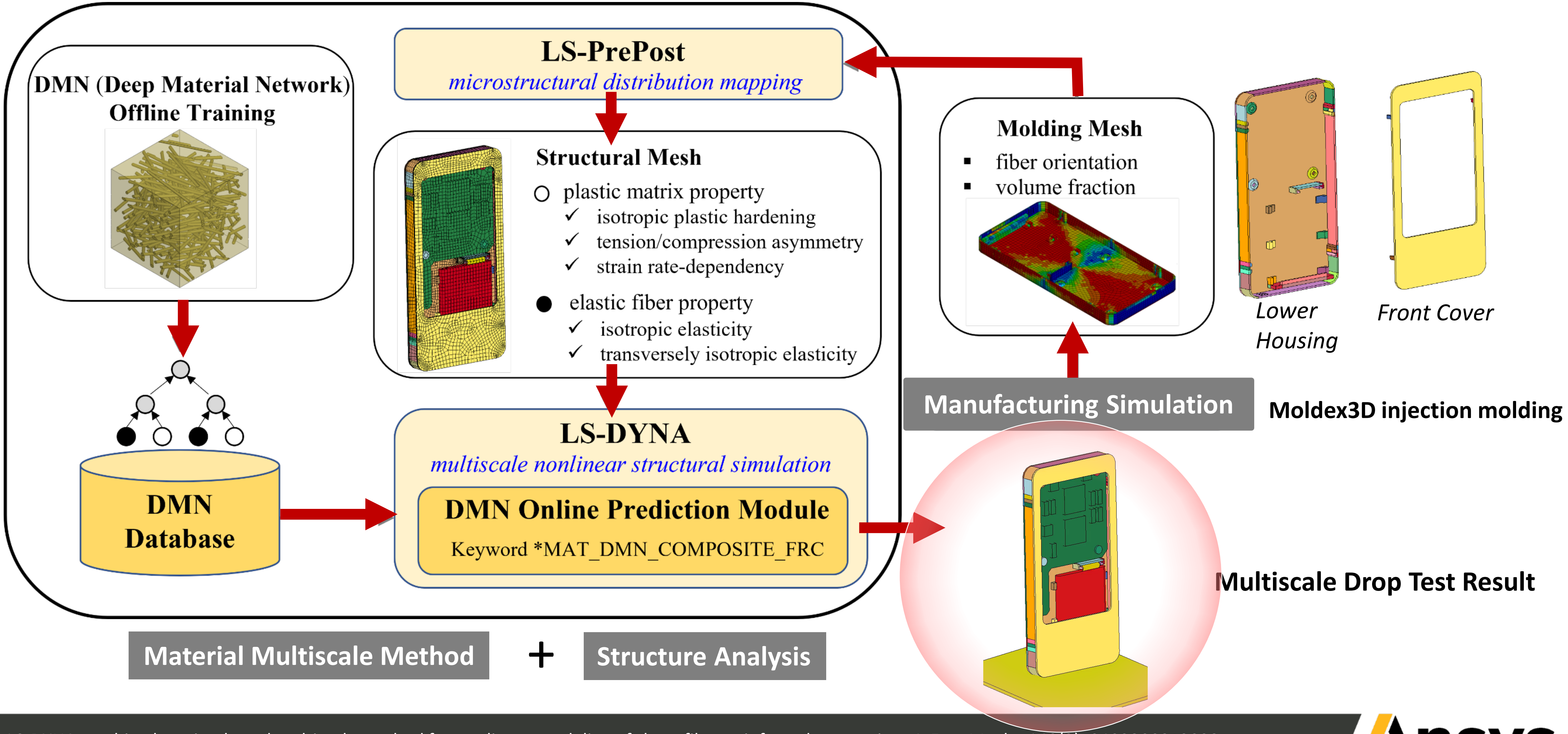
FEM	30-40 hours on 8 CPUs
DMN	1 second on 1 CPU

DMN vs FEM



2023 R15 Deep Material Network Workflow in LS-DYNA

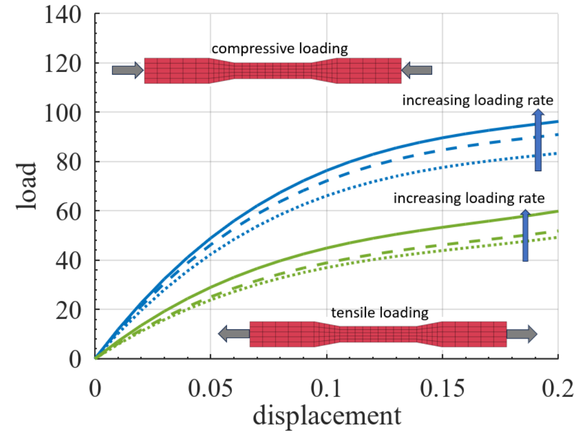
Workflow for LS-DYNA DMN Multiscale Analysis of Injection Molded Short Fiber Composites[1]



[1] LS-DYNA machine learning-based multiscale method for nonlinear modeling of short-fiber-reinforced composites, J. Eng. Mech., 149(3), 04023003, 2023.

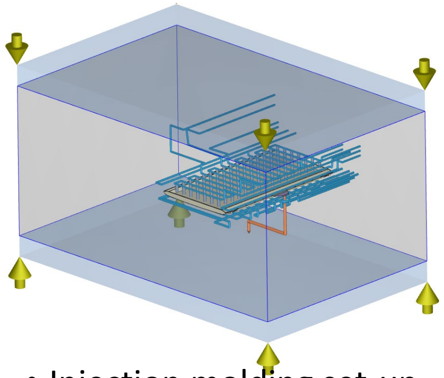
2023 R15 New Release – Strain Rate-dependence and Residual Stress

- ✓ Strain rate-dependency of the plastic matrix (resin)
- ✓ Tension/compression asymmetric properties of the plastic matrix
- ✓ Residual stress in Deep Neural Network
- ✓ New LS-PrePost interface for Solid-to-Solid/shell mapping, warpage, etc.

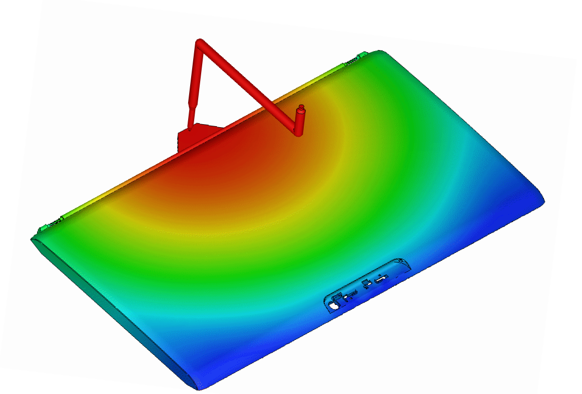


Ex: Drop Test of Laptop Plastic Cover

- DMN prediction of heterogeneous microstructures (position-dependent anisotropy)
- Plastic cover is a shock absorber to protect the solder balls inside chips



- Injection molding set-up

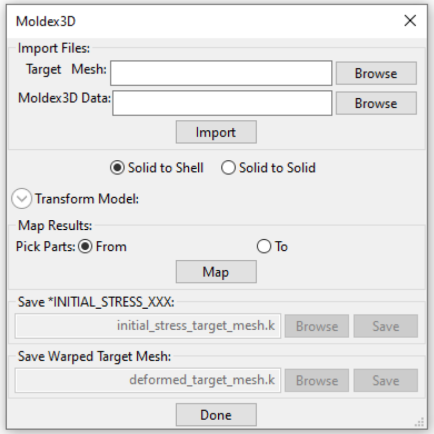


(Courtesy of Moldex3D)

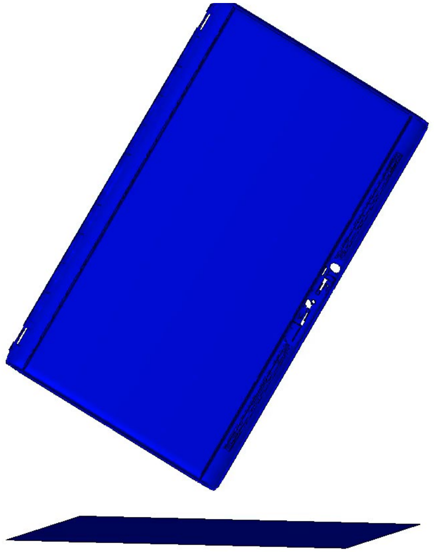
- Fluid flow in the molding process

Moldex3D

Injection Molding Simulation



LS-PrePost



LS-DYNA

Multiscale Drop Test

R15 Application - Structure Strength in Auto Composites Parts

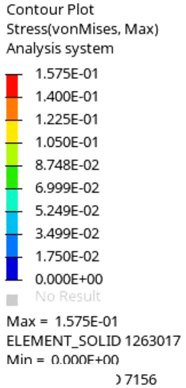
Ex. Multi-scale analysis of airbag housing

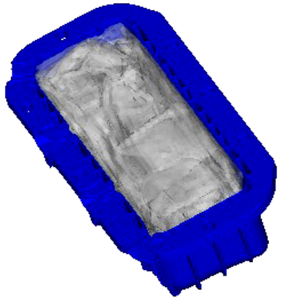
- Next goal: Anisotropic material failure of composites at different temperatures

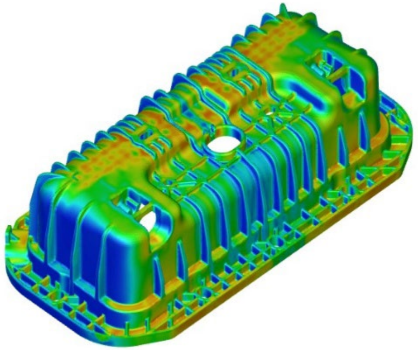
- Airbag deployment by Control Volume
- Airbag housing modeled DMN

https://www.autoliv.com

- **Simulation results are validated** *under various strain rates and temperatures*
- **Critical regions are identified** *for better product design that saves lives and reduces injuries*





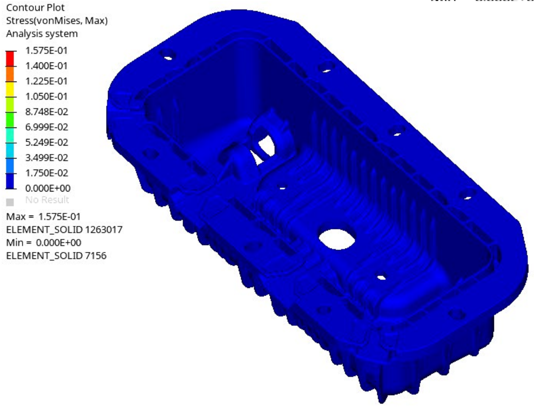


Moldex3D Predicted Fiber Orientation of Airbag Housing

Moldex3D

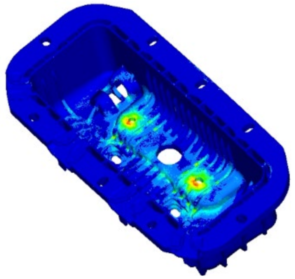
Injection Molding Simulation

LS-PrePost



LS-DYNA

Structure Simulation



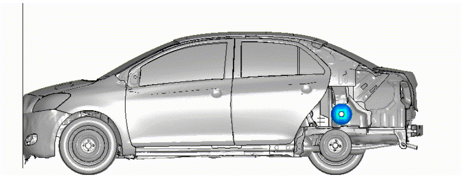
Stress Prediction

(Courtesy of Autoliv)

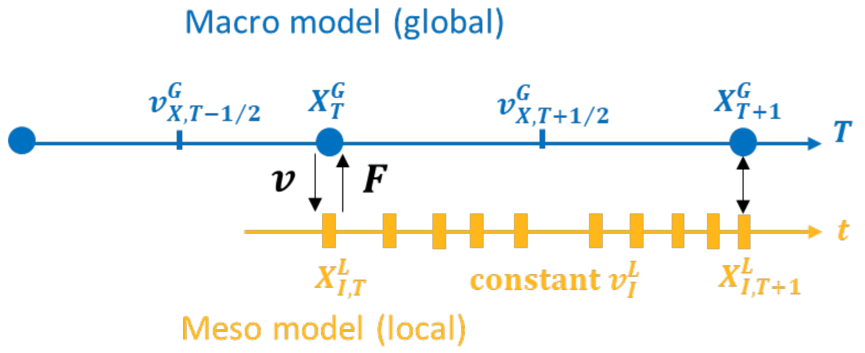
Two-scale Co-simulation[1]

- Assemble the components to the system for structural analysis.
- Two-scale Co-simulation is a joint simulation of two coupled standalone solvers for component analysis.
- It improves the efficiency of explicit dynamic analysis when local-scale mesh size (component) is much smaller than global-scale mesh size (assembly) in a local-global system.

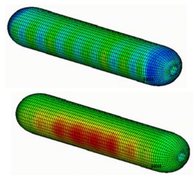
Global model



- Synchronized time steps



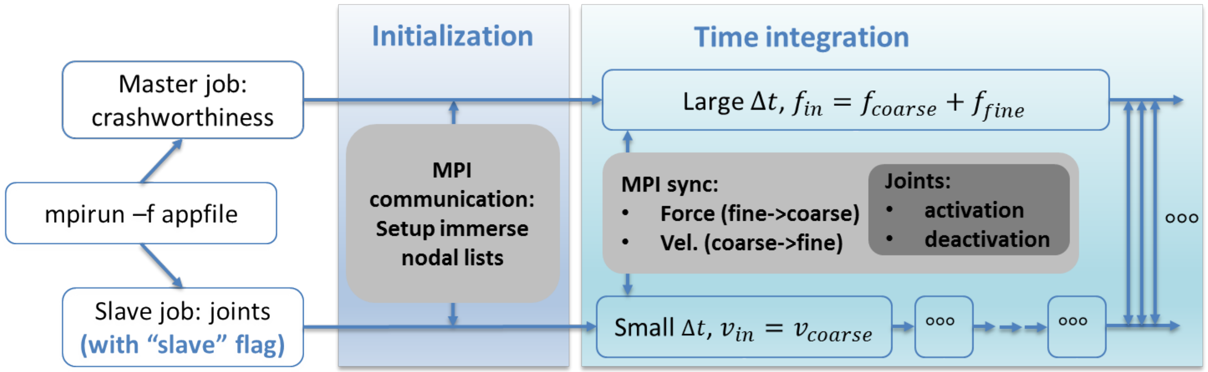
$\Delta t_{local} \ll \Delta t_{global}$



Local model

- MPI communication

  Tie contact, immersion, etc.



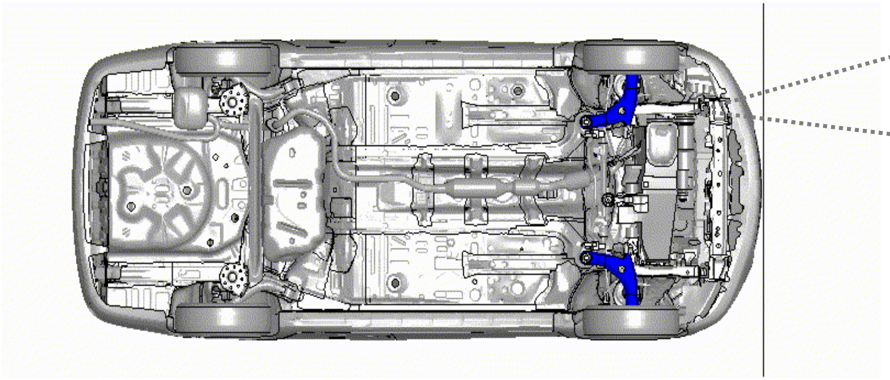
[1] Int. J. Multiscale Comp. Engrg., 18 (4), 455-476, 2020.

2023 R15 New Release – Two-way Co-simulation

- ✓ Main feature in R15 release: **a two-way co-simulation (*INCLUDE_COSIM)** based on tie constraint
- ✓ Easy setup two-scale co-simulation using new command line flag *nmsp* (number of MPI processes for local model)

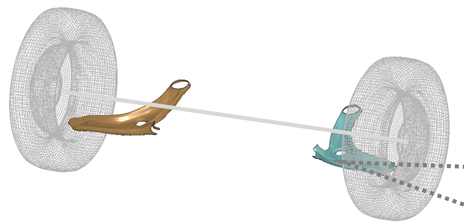
Ex1. Simulate failure of two local casting parts in a global car crash model

Toyota Yaris Model



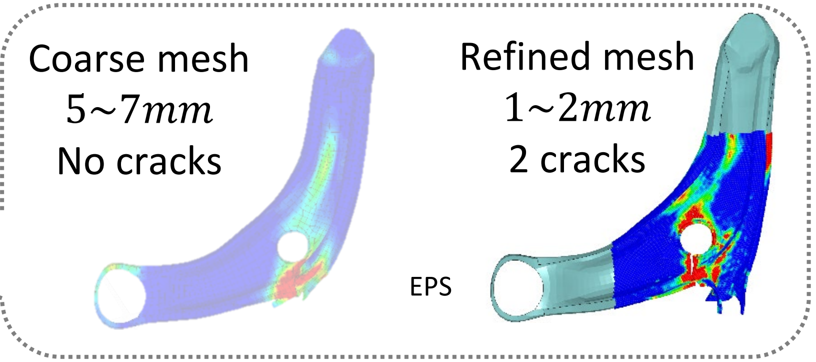
~ 1.5 *million elements in global model*

Two suspension control arms



$\sim 100{,}000$ *elements in local model*

Die casting arm cracking



- Casting arm failure by FEM element erosion.
- Refined elements to capture cracks.

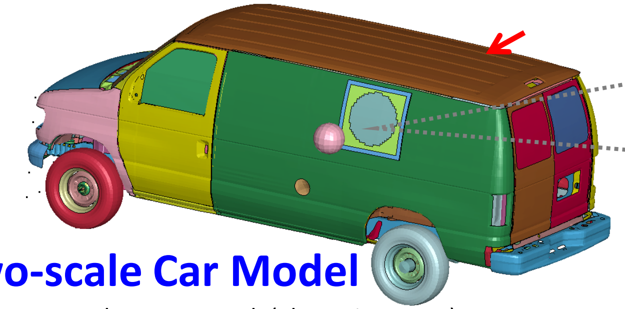
A full car with two coarsen casting parts	A full car with two refined casting parts	A full car in global with two refined casting parts in local
$dt = 1.0 \times 10^{-6}$	$dt = 1.0 \times 10^{-7}$ (mass scaling)	$dt^G = 1.0 \times 10^{-6}$; $dt^L = 1.0 \times 10^{-7}$ (mass scaling)
2.3 hours (24 CPUs) Single scale simulation	**26 hours** (24 CPUs) Single scale simulation	**4 hours** (global 24 CPUs dt^G + local 8 CPUs dt^L) **Two-scale Co-simulation**

Ansys

Application – Armor plating analysis

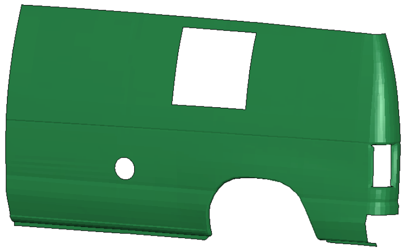
- ✓ A solid-in-shell immersion technique was implemented for easy component modeling in an assembled system.
- ✓ Ex2: Component study – failure of metal armor plating (modeled by SPG with $\Delta t = 1 \times 10^{-7}$) in a full-car model (with $\Delta t = 5 \times 10^{-7}$).

Ex2. Armor plating design: High speed rigid ball penetrating through a car



Two-scale Car Model

- Elements ~300k (elem. size ~1cm)
- $dt^G = 5.0 \times 10^{-7}$
- Penetration speed, 600m/s

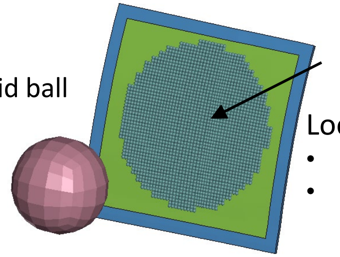


Coupling part in global model

- Non-conforming interface
- Global/local subcycling

+

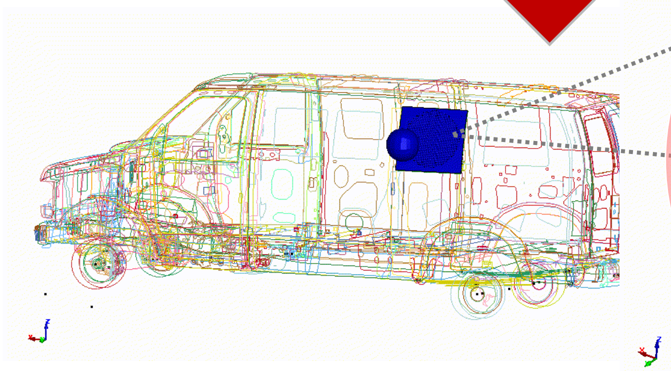
Rigid ball

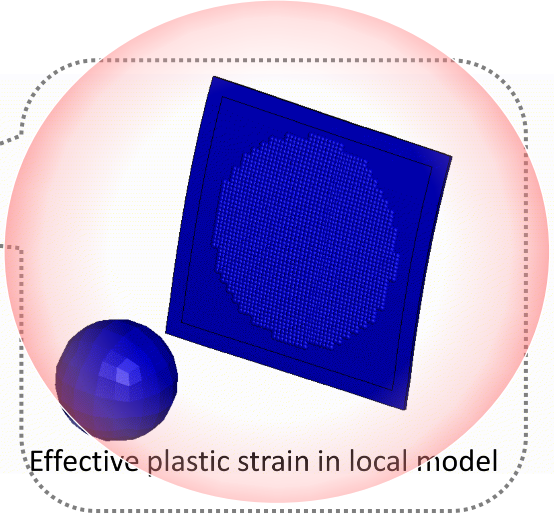


MC-SPG particles

Local model

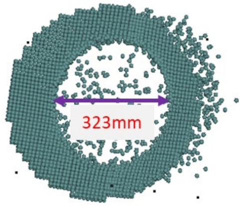
- SPG particles for failure analysis
- Coupled with FEM $dt^L = 1.0 \times 10^{-7}$



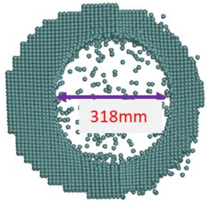


Effective plastic strain in local model

SPG + Two-scale Co-simulation

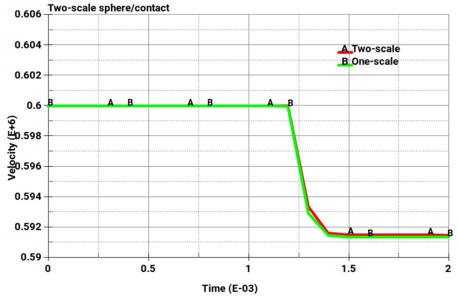


One-scale simulation



Two-scale Co-simulation

Velocity of rigid ball in the penetration process



Two-scale (14 cpus for global, 2 for local)	One-scale (16 cpus)
0.44	1.0

CPU time comparison (normalized)

Ansys

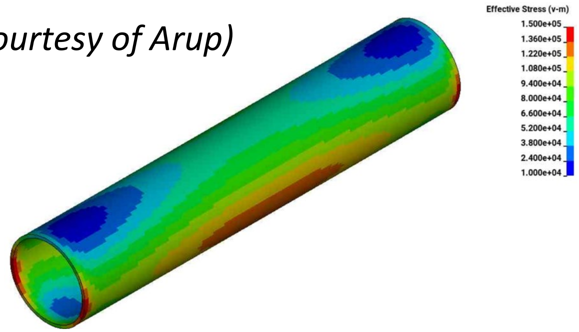
Application – Soil-Tunnel Interaction

- ✓ Soil-tunnel interaction under gravity
- ✓ Applied to Sewer, Metro, Rail/Road tunnels

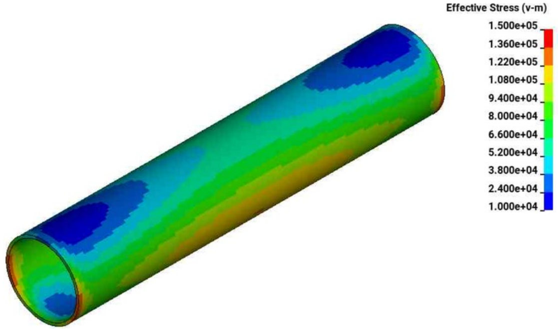
https://www.robbinstbm.com/

- Time step ratio 1:16 for local and global model

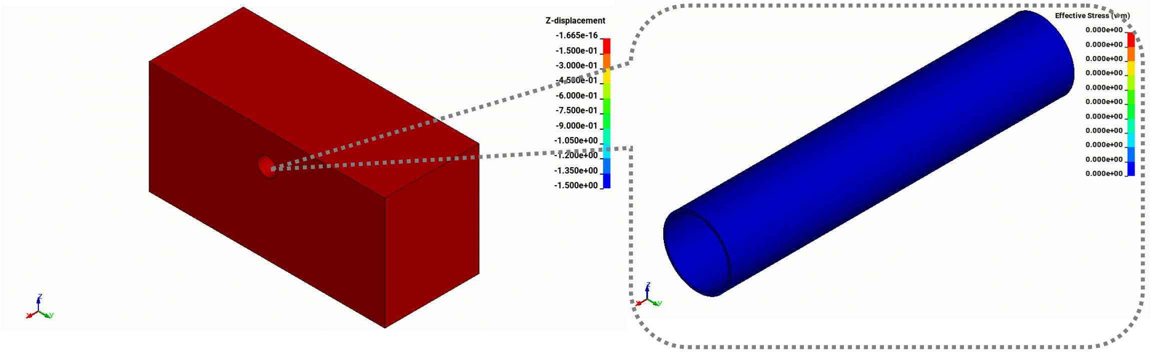
(Courtesy of Arup)



One-scale, von-Mises stress in tunnel

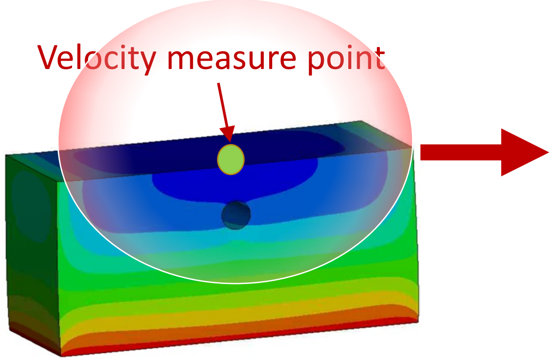


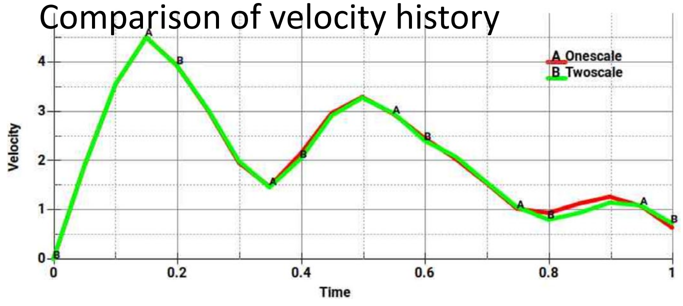
Two-scale, von-mises stress in tunnel



Displacement in global model
(~ 2M elements)

Von-Mises stress in local model
(~ 10k elements)





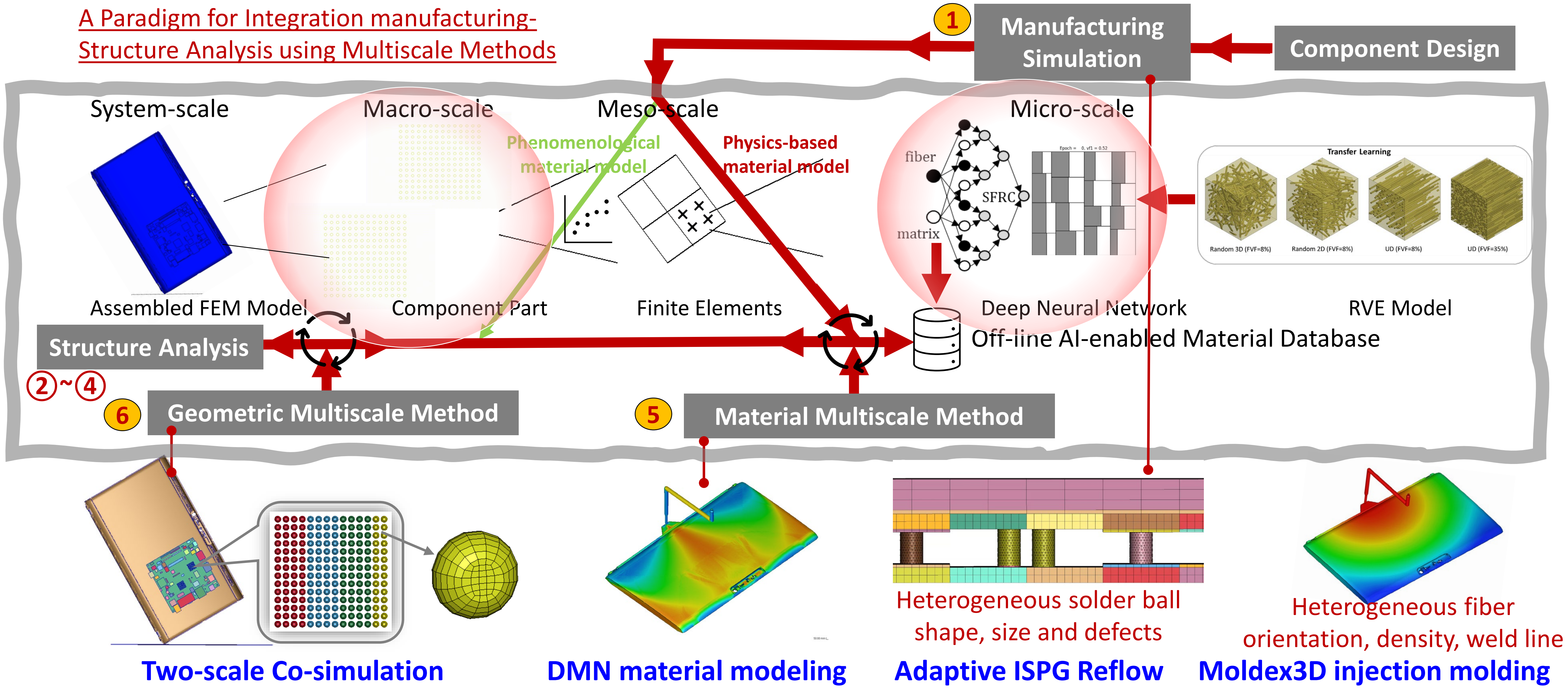
Two-scale (14 cpus for global, 2 for local)	**One-scale** (16 cpus)
Normalized 0.1 (39 mins)	**1.0 (6 hrs 23 mins)**

1. Methods for Manufacturing Simulation
    1.1 **Incompressible Smoothed Particle Galerkin (ISPG) Method** for Adhesive Fluid Mechanics Analysis
    1.2 Smoothed Particle Galerkin (SPG) Method for Solid Mechanics Analysis

2. Methods for Multiscale Simulation
    2.1 **Deep Material Network (DMN)** for Component Material Characterization
    2.2 **Two-scale Co-simulation** for Assembly Structural Analysis

3. A Paradigm Integrating Structural Analysis with Manufacturing Information Using Multiscale Methods

Ex. 1 – Solder balls reliability in a laptop drop test simulation using LS-DYNA R15



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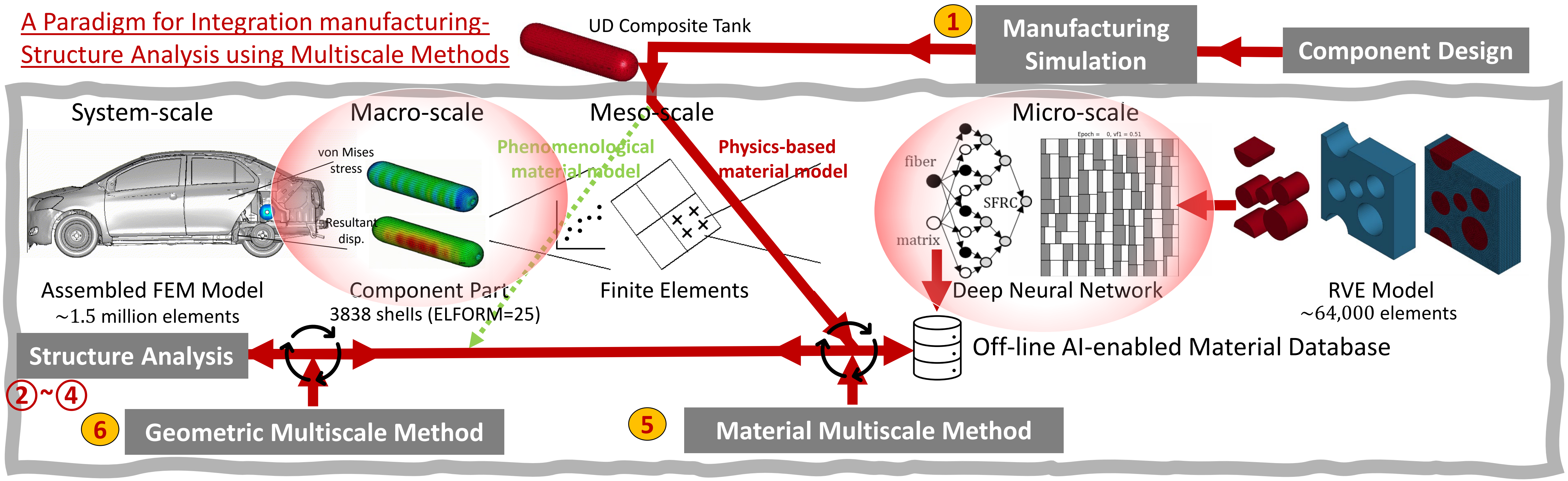
Ex. 2 - A composite component analysis in a full-vehicle crash test using LS-DYNA R15



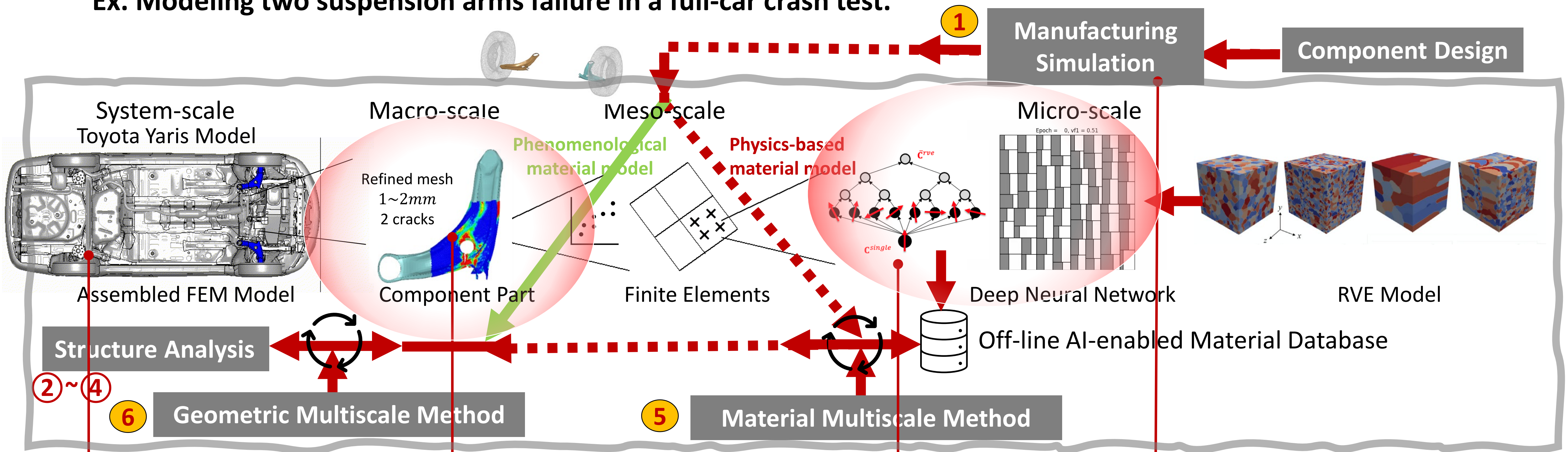
CPU time (single precision explicit dynamics MPP)

*Original crash model	*Concurrent for RVE-composite tank	*AI for RVE-composite tank	*AI + Two-scale Co-simulation ($dt^G = 1.0 \times 10^{-6}$)
2.3 hours (24 CPUs) ($dt = 1.0 \times 10^{-6}$)	**~1.5 years** (24 CPUs)	**~10 hours** (24 CPUs)($dt = 3.3 \times 10^{-7}$)	**3.4 hours (global 24 + local 8 CPUs)** ($dt^L = 3.3 \times 10^{-7}$)

Goal: 2.6 hours (global 24 + local 8 CPUs)

On-going Development for Polycrystalline Metals

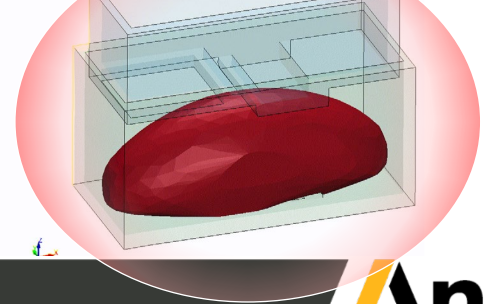
Ex. Modeling two suspension arms failure in a full-car crash test.



- Casting arm fails by FEM element erosion technique.
- Local area modeled by refined elements to improve accuracy.
- Need develop a **3D dynamic crack propagation method**.
- Need to develop **Multi-scale Co-simulation** for multiple local parts.

- Need to develop **DMN for Polycrystalline Metals** including micro-porosity

- Need to develop **ISPG Thermal-Fluid**, **Solidification** and **Thermal-Fluid-Mechanical** simulations.



Global: full car
~1.5 million elements
$dt^G = 1.0 \times 10^{-6}$
2.3 hours (24 CPUs) Single scale

Local: two suspension arms
~100,000 elements
$dt^L = 1.0 \times 10^{-7}$ (mass scaling)
26 hours (24 CPUs) Single scale

✓ **Two-scale Co-simulation**
4 hours (global 24 CPUs dt^G + local 8 CPUs dt^L)

Ansys

Conclusion

1. 2023 LS-DYNA developments of several manufacturing simulation methods and multiscale methods were updated.
2. We demonstrated how to predict manufacturing, assembly, and system performance using those methods.
3. The ultimate goal is to accelerate structure design and analysis driving product innovation and digitization for your industry.

Thank you!