Recent Advances in Isogeometric Analysis

David Benson

Isogeometric Analysis Development Teams

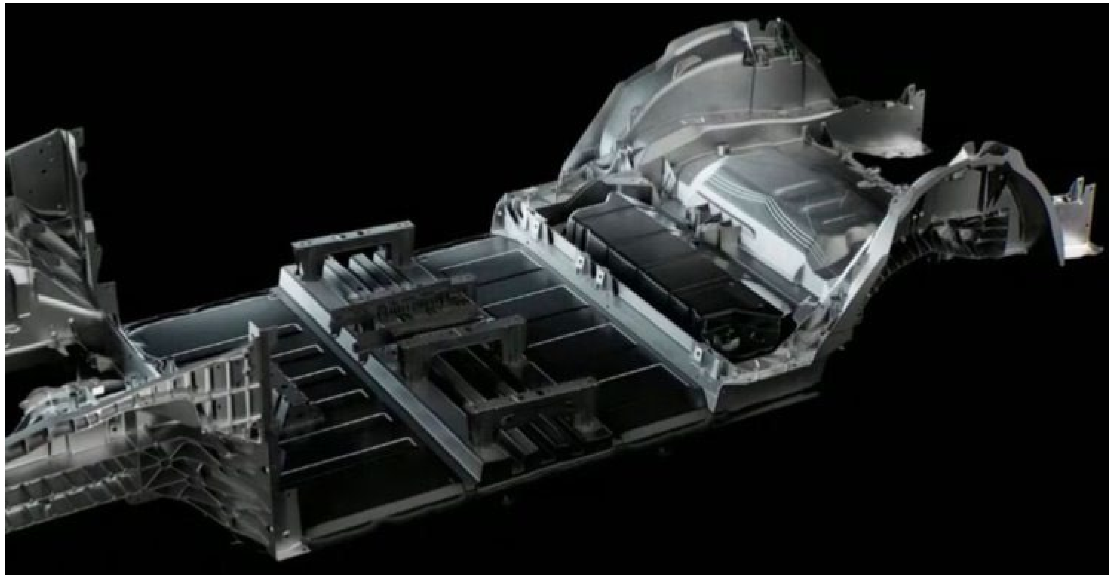
- LS-DYNA Solver
  - David Benson
  - Attila Nagy
  - Stefan Hartmann
  - Liping Li
  - Marco Pigazzini
  - Lam Nguyen
  - Gunther Blankenhorn

Most don't work on IGA 100% of the time, but the people listed have made significant contributions to IGA in LS-DYNA.

- Prime Mesh Generator
  - Harsh Vardhan
  - Jan Frykestig
  - Wenyan Wang
  - Mukul Kanitkar
  - Aditya Mukane
- ACE Team
  - Sourabh Chadha
  - Amit Nair
  - Lukas Leidinger

Modeling Large Castings

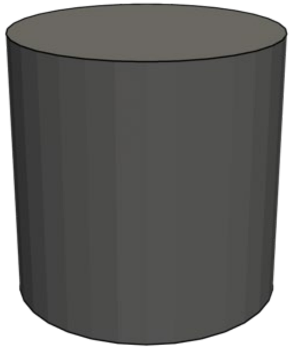
Aluminum Castings for Large Structural Components

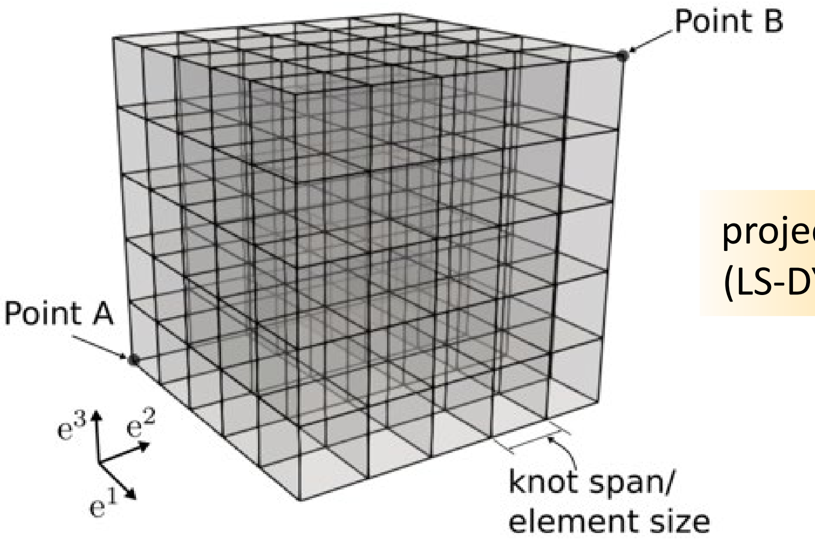


GW Celebrates... the Tesla Giga Casting (gwcast.com)

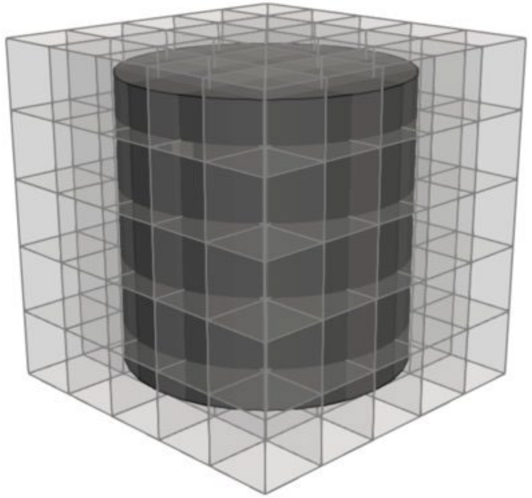
- Large castings eliminate hundreds of parts.
- Challenges include control of porosity and other defects that can reduce structural integrity.
- Solids are required to model complicated three-dimensional stress states accurately.
- FEA tet elements: small time step versus solution accuracy.
- FEA hex elements: difficult to mesh.

Trimmed Solids: The Basic Concept





projection
(LS-DYNA)



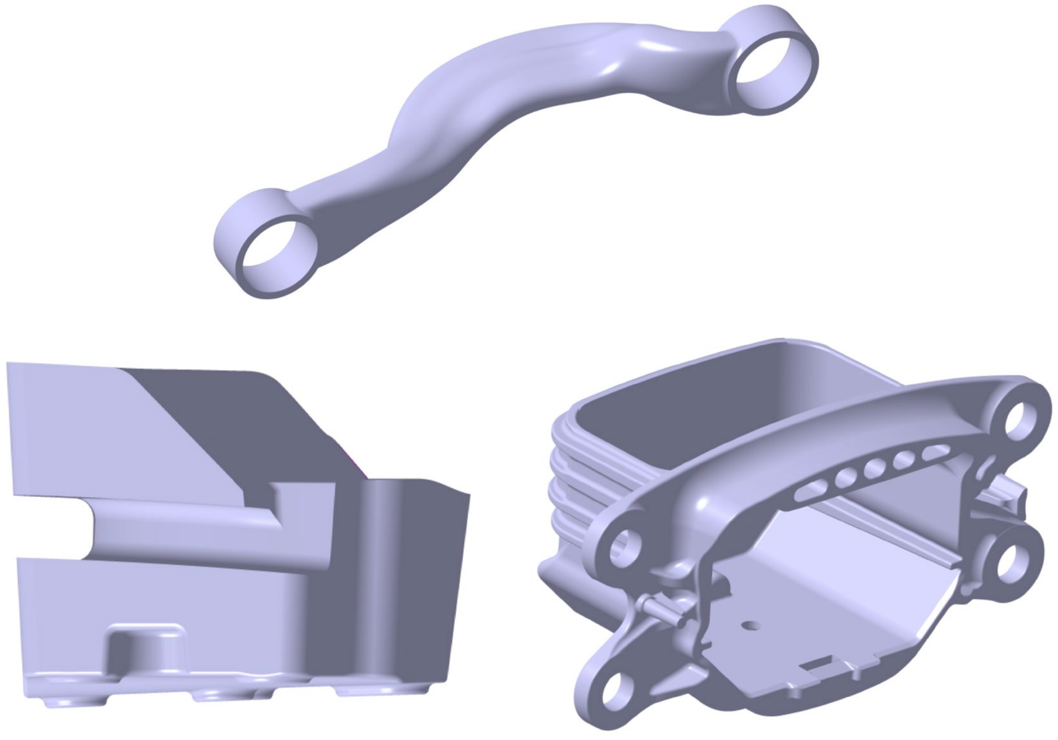
MESSMER ET AL. (2022)

Boundary representation (CAD)
cleaned up during preprocessing

Structured trivariate B-spline
`*IGA_3D_NURBS_XYZ`
(quadratics are sufficient)

Isogeometric model
`*IGA_2D_BREP`
`*IGA_VOLUME_XYZ`
`*IGA_SOLID`
`*SECTION_IGA_SOLID`

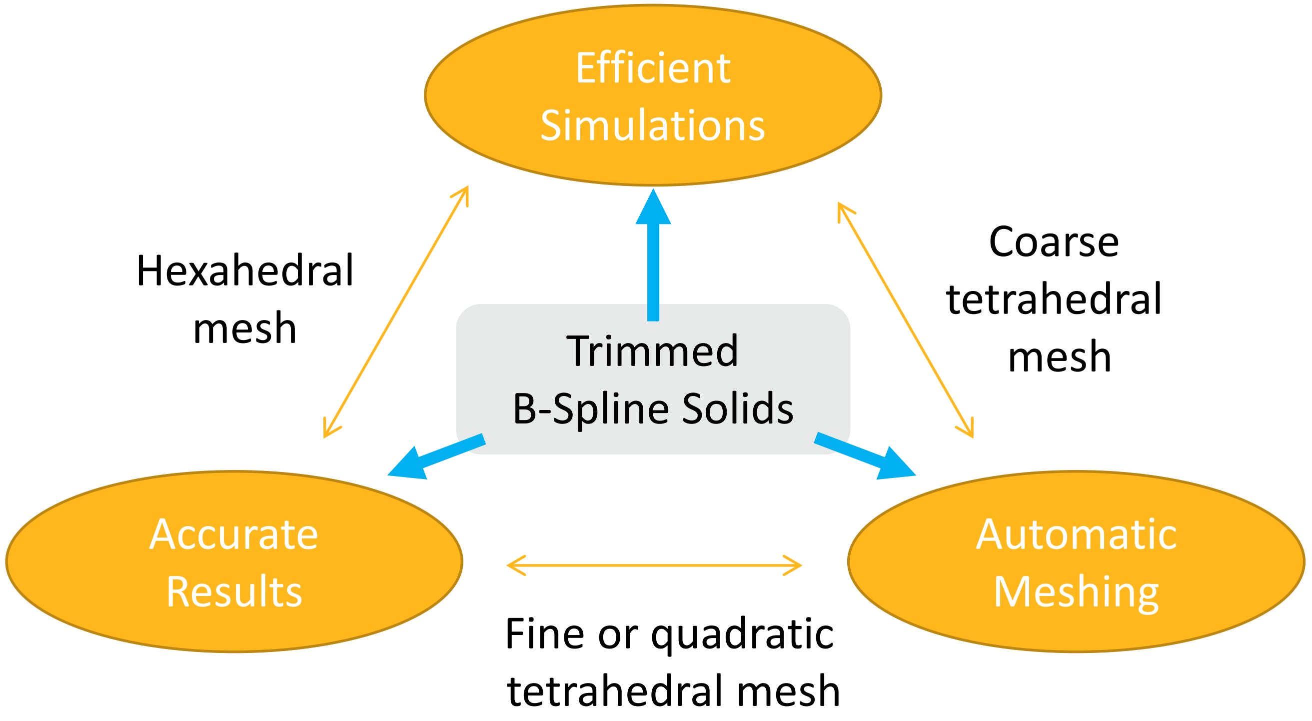
Trimmed IGA Solids for Crash



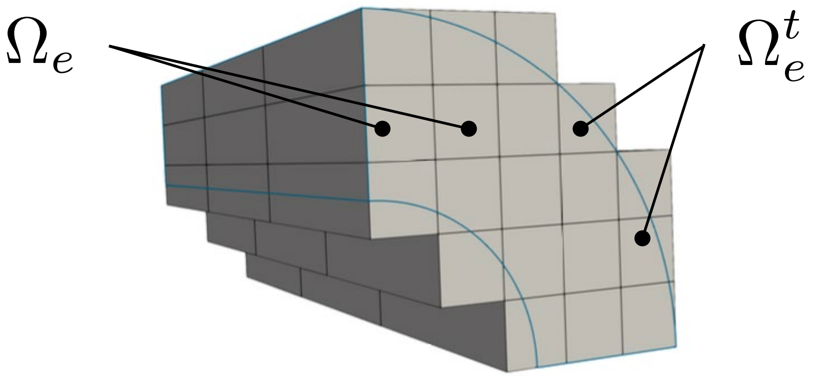
Courtesy of BMW Group

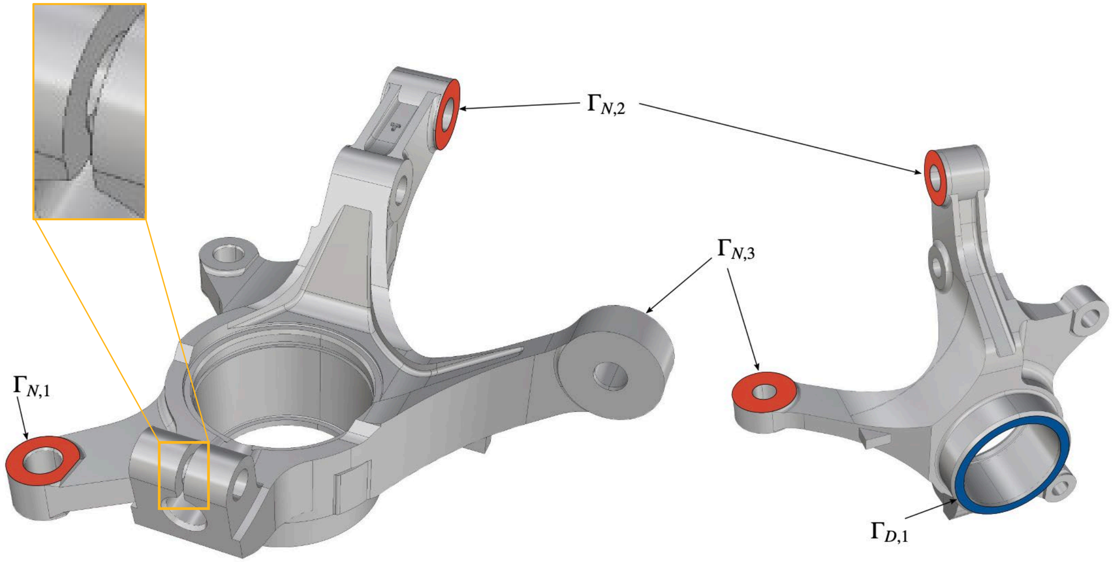
Conflicting goals:

Each FEA option
satisfies 2 out of 3.



Highlights of Trimmed Solid-Based IGA





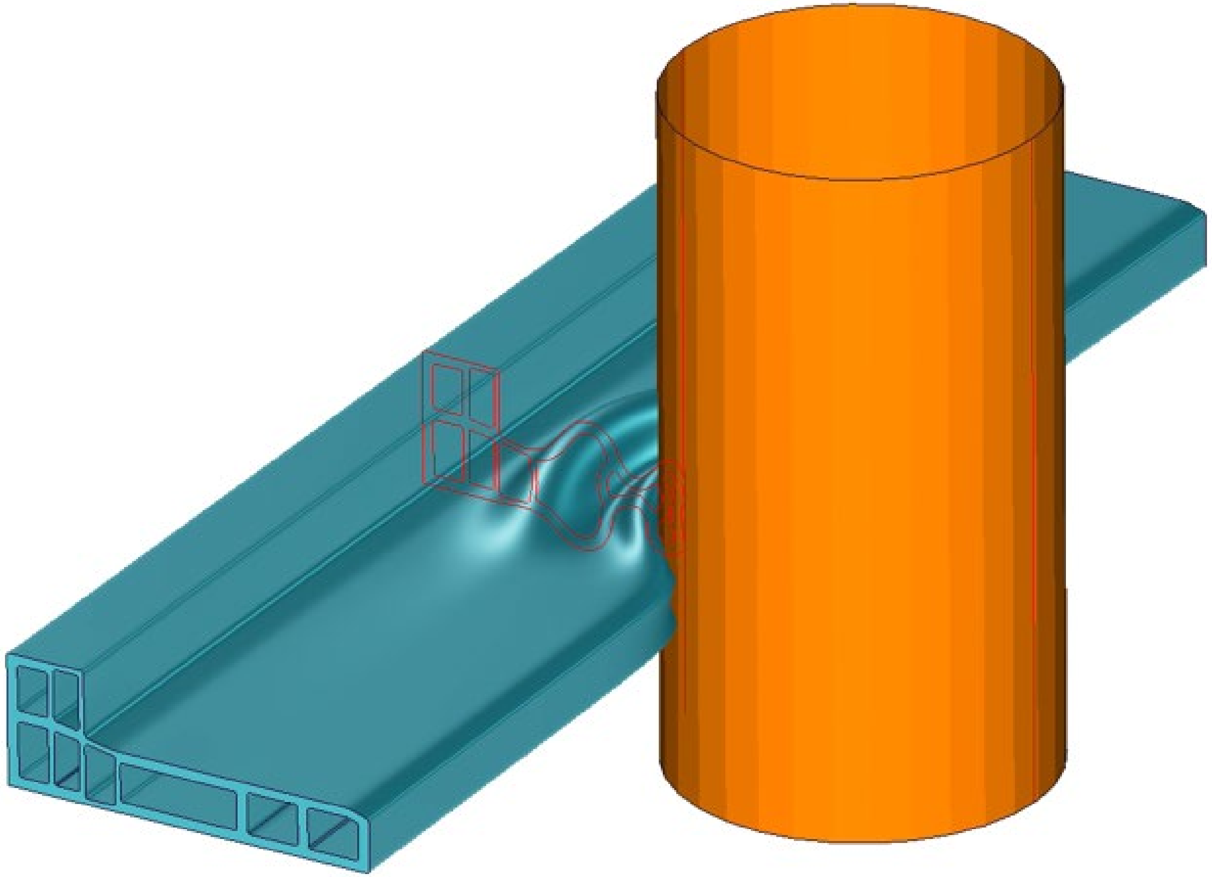
MESSMER ET AL. (2022)

- Simplified discretization (PDE)
- Element-wise specific quadrature rules for trimmed elements
  - Meshing (element quality is less important)
- Not boundary-fitted
- Feature preserving (BC)
- Stability (control points associated with trimmed basis)
- Local initial and geometry driven refinement may be necessary
- Accurate enough and very efficient

Trimmed B-Spline Solids: Examples

Extruded profile

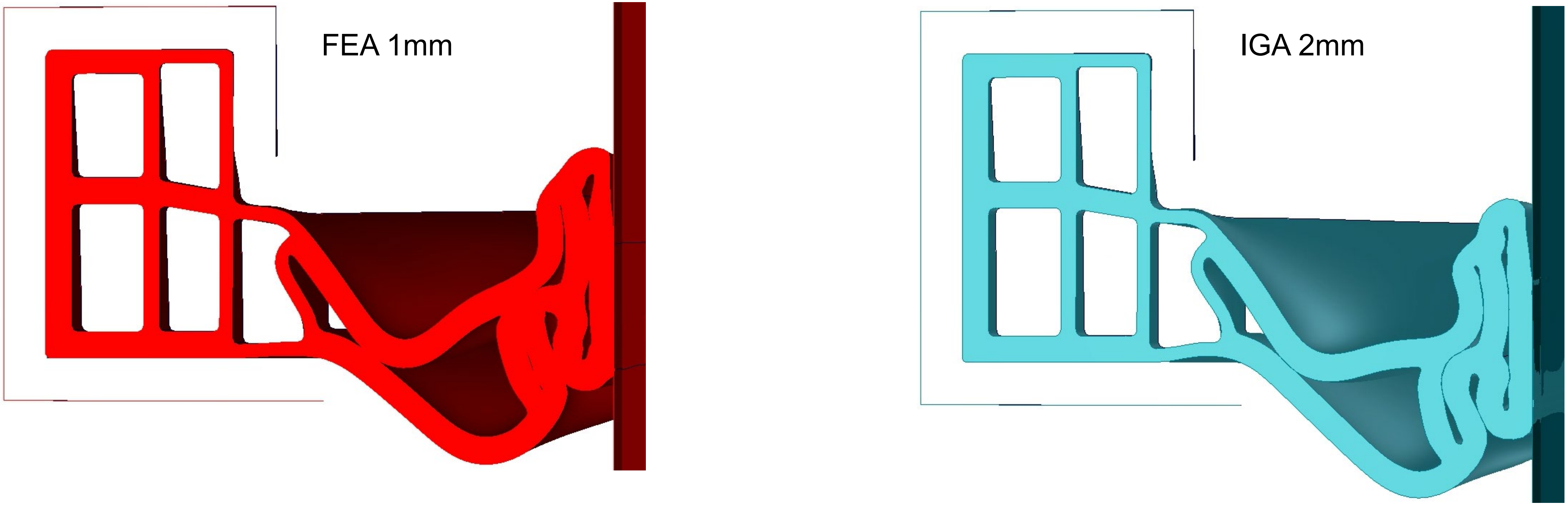
- length: 800mm
- cross-section: 200x72mm
- elasto-plastic material (without failure)
- impactor: rigid cylinder



Courtesy of BMW Group

Trimmed B-Spline Solids: Examples

- Local buckling pattern of the cross-section in the center of the profile

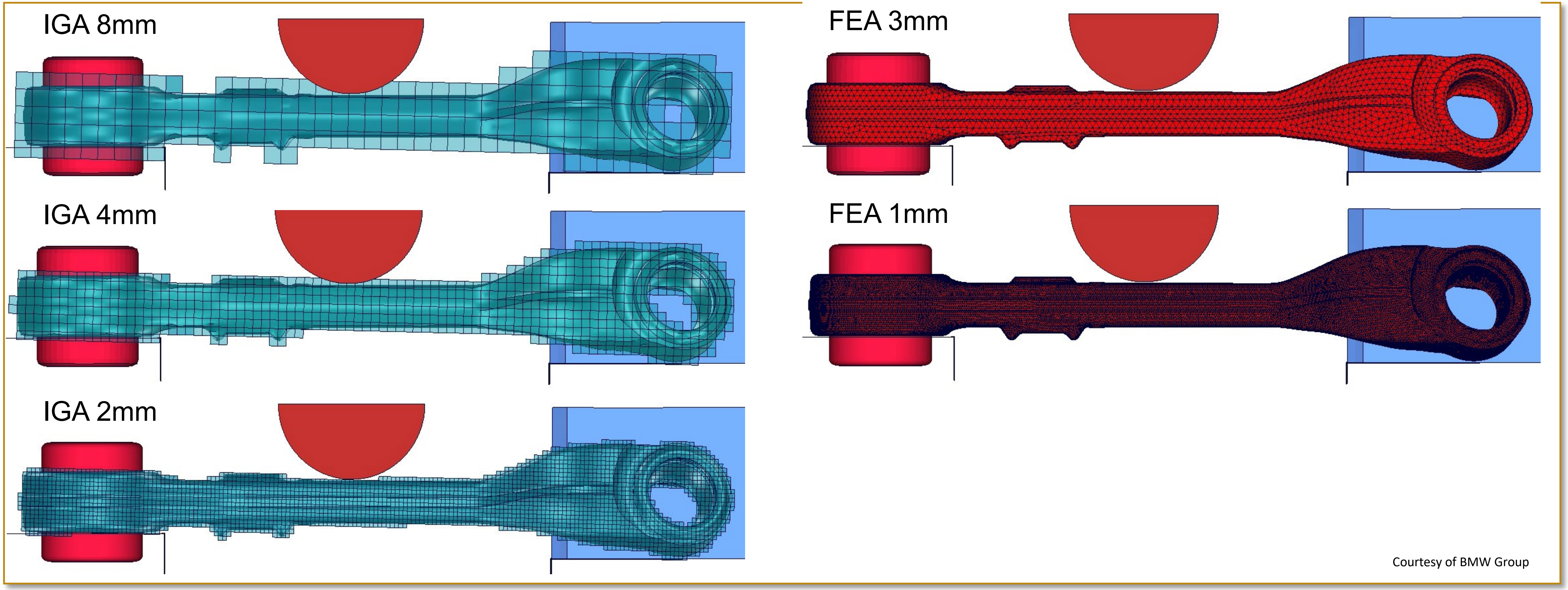


Courtesy of BMW Group

Trimmed B-Spline Solids: Examples

Wishbone (3-point-bending test)

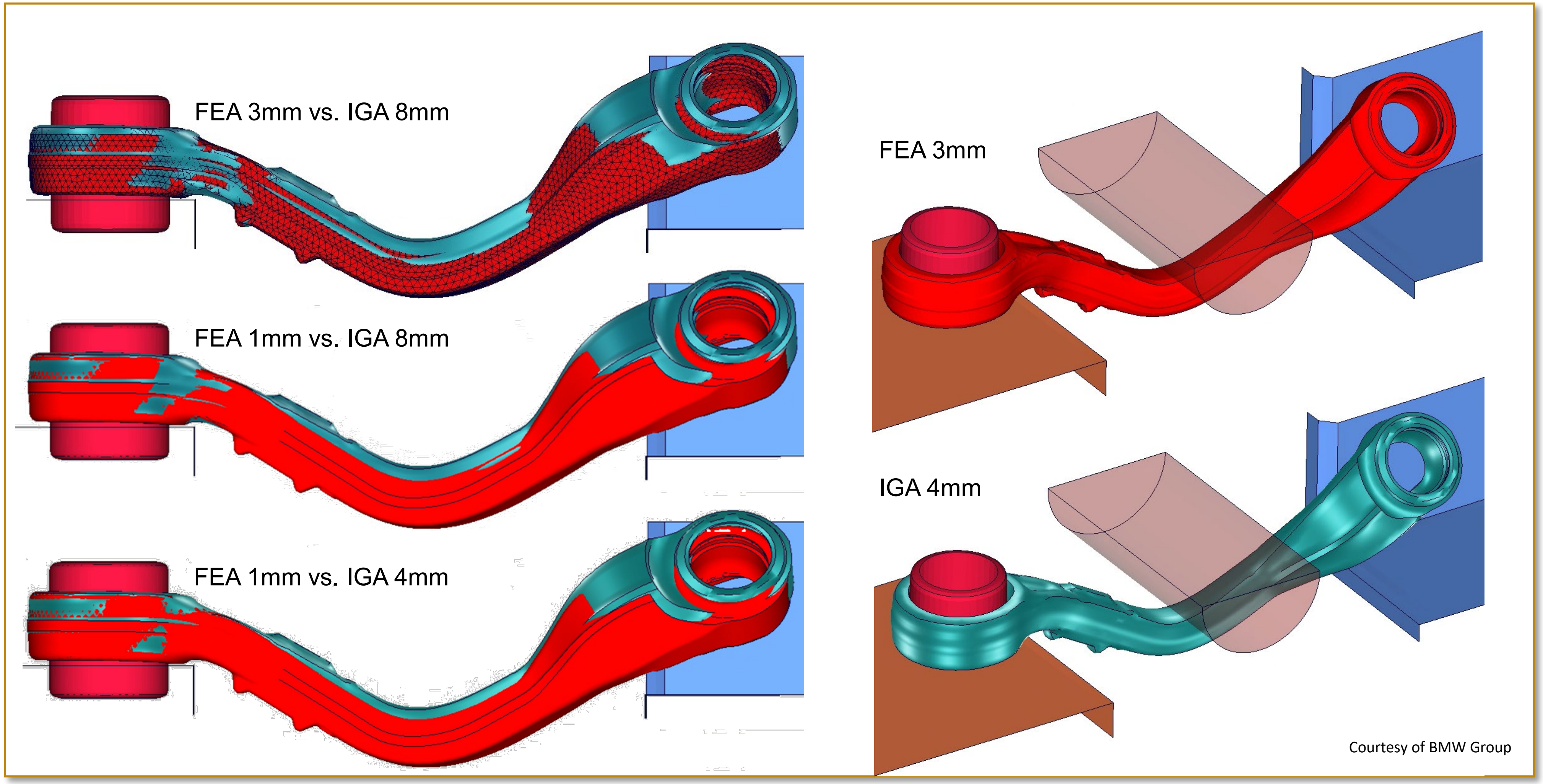
- elasto-plastic material – rigid impactor – 5 discretizations



Trimmed B-Spline Solids: Examples

Wishbone (3-point-bending test)

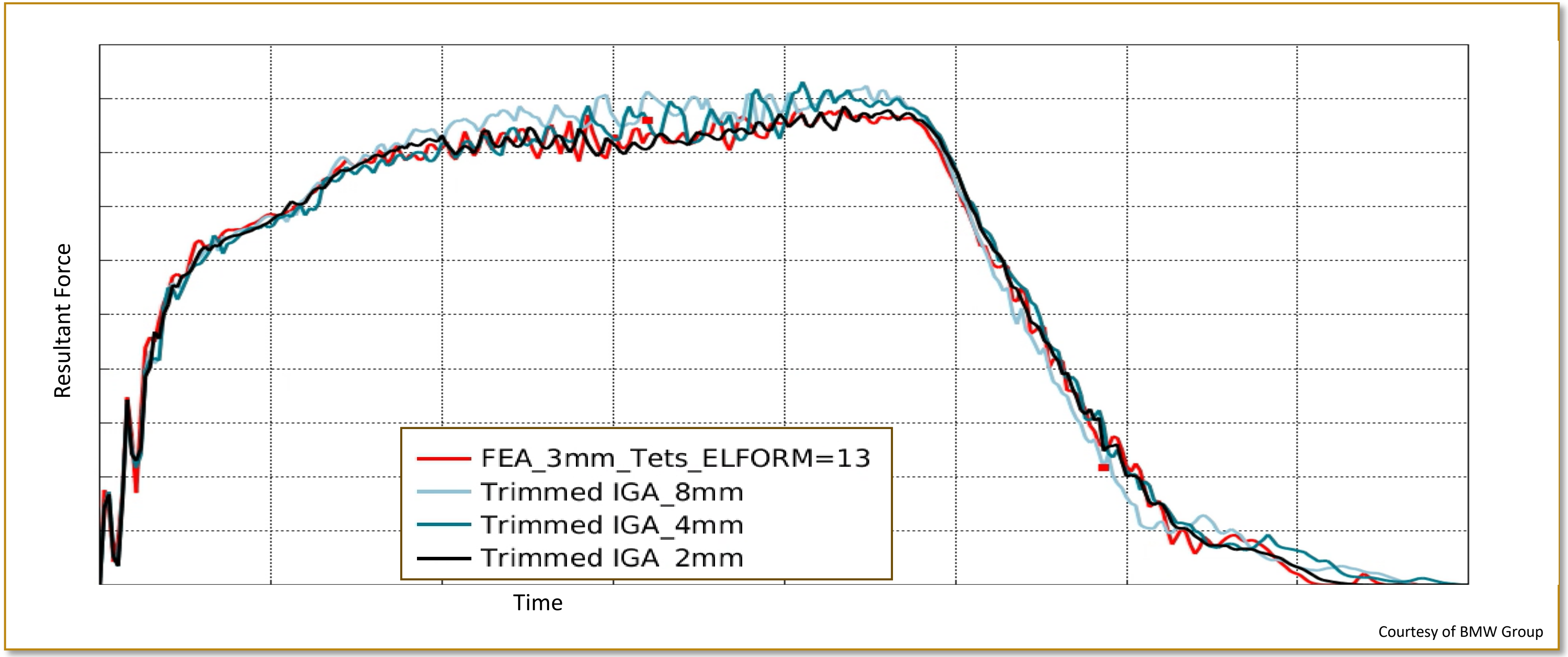
- good agreement



Trimmed B-Spline Solids: Examples

Wishbone (3-point-bending test)

- Resultant force vs. time – all very similar



Trimmed B-Spline Solids: Examples

Wishbone (3-point-bending test)

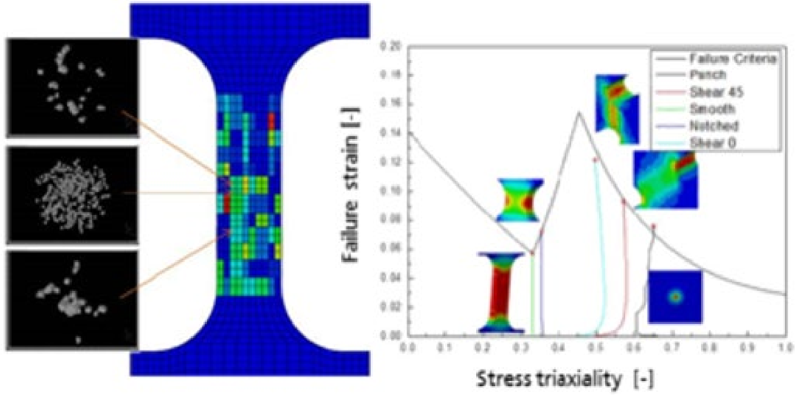
- some statistics:
  - larger time step / no mass scaling / faster computation

Model	time step (dt0, used)	added mass	added mass ratio	solved on	CPU time
FEA 3mm (ELFORM=13)	1.80E-07	1.0433E-05	2.05%	12 CPUs, local	54 min 19 seconds
FEA 1mm (ELFORM=13)	1.80E-07	2.3102E-03	**455%**	48 CPUs, cluster	2 hours 46 minutes 57 seconds
IGA 8mm	1.29E-06	0	0	12 CPUs, local	0 hour 6 minutes 12 seconds
IGA 4mm	6.47E-07	0	0	12 CPUs, local	0 hour 16 minutes 51 seconds
IGA 2mm	3.18E-07	0	0	48 CPUs, cluster	1 hour 15 minutes 40 seconds

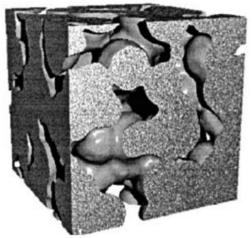
Courtesy of BMW Group

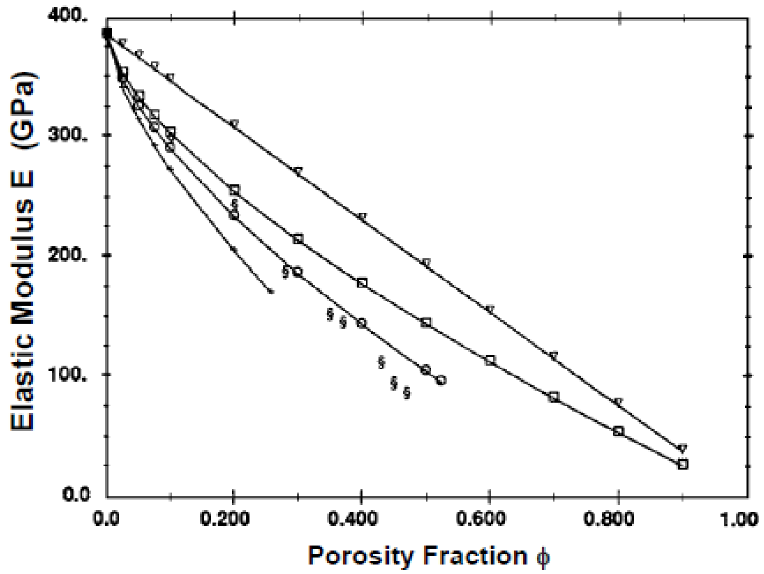
Material Model for Castings in Crash

- Spatial variation of properties with ***MAT_TAILORED_PROPERTIES (251)**
  - J2 plasticity with history-dependent yield stress using TABLE_3D/4D
  - New in R15: history dependent stiffness (Young's modulus), too
  - can be defined via *INITIAL_STRESS_SHELL/SOLID
  - that "history" could be porosity from a preceding flow process



Courtesy of Tobias Erhart, Ansys Germany



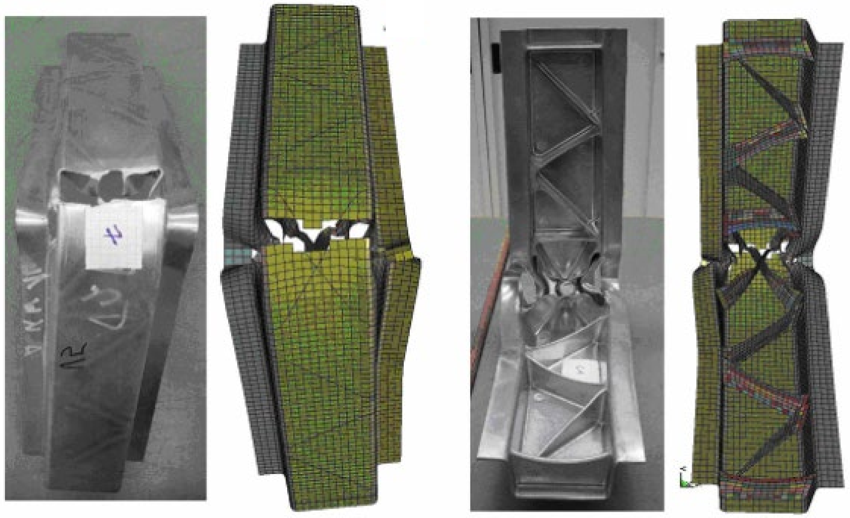


e.g. Hardin & Beckermann (2012): "Integrated design of castings: effect of porosity on mechanical performance"

Damage/Failure for Castings in Crash

- Spatial variation in ***MAT_ADD_DAMAGE_DIEM/GISSMO**
  - Locally altered failure properties, e.g., porosity from manufacturing process
  - initial conditions as history variables on *INTIAL_STRESS_SOLID/SHELL
  - alternatively, via node sets: new keyword *INITIAL_HISTORY_NODE_SET
  - or as stochastic distribution: *MAT_ADD_DAMAGE_GISSMO_STOCHASTIC
  - Failure strain as function of stress state and history variable(s)
  - multi-dimensional functions needed: keywords *DEFINE_TABLE_XD or *DEFINE_TABLE_COMPACT

Courtesy of Tobias Erhart, Ansys Germany



Mapping Data to Meshes: Two Methods

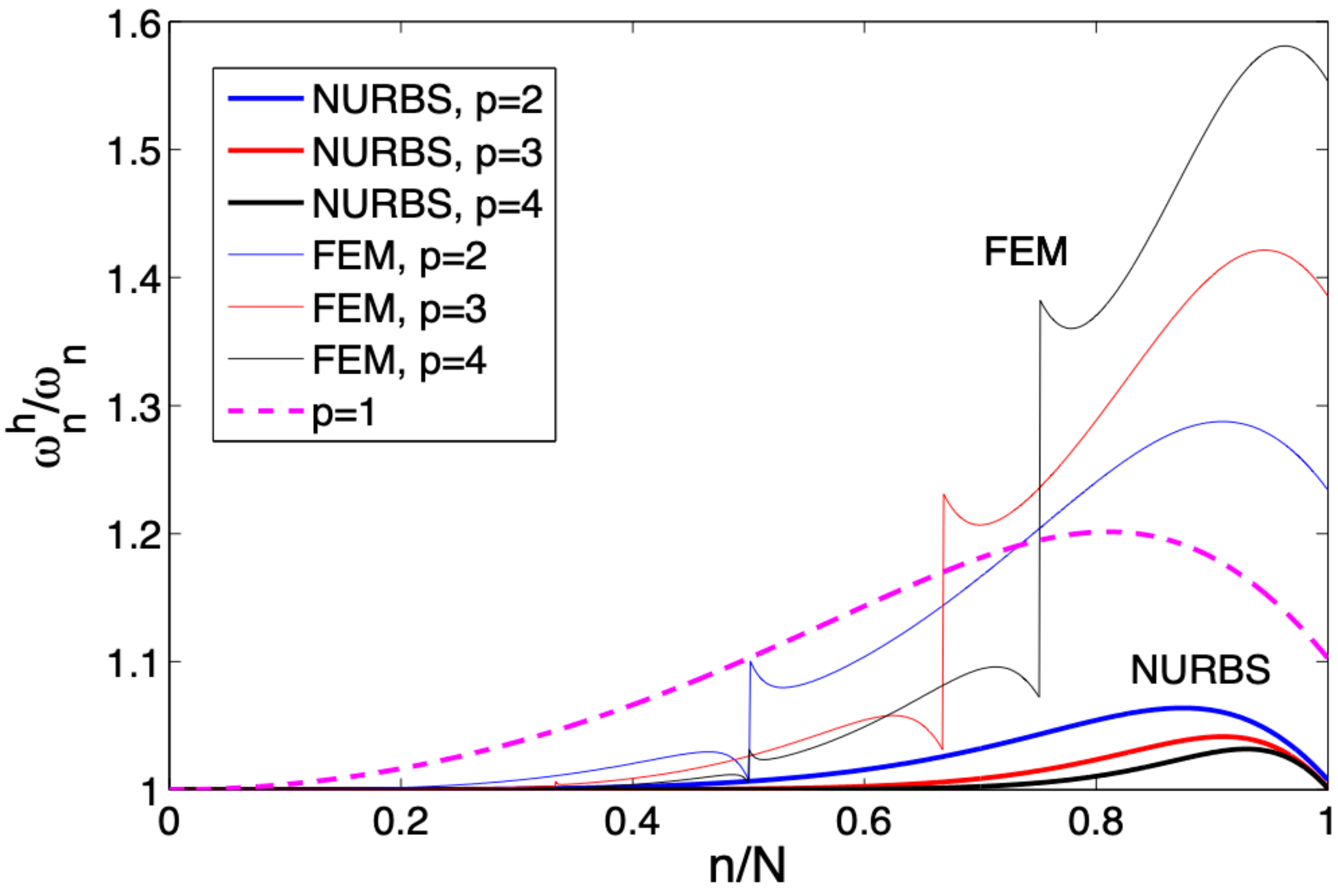
- Both methods only work for initializing existing history variables. They do not, for example, allow spatially varying elastic modulus for arbitrary materials.
- ENVYO
  - Product for mapping originally from Dynamore, now an Ansys product.
  - Generates a full deck restart file with mapped data.
- *PART_FIELDS
  - Define a point cloud in LS-DYNA input that is mapped to the mesh.
  - Material data and the mesh are independent, allowing
    - Mesh refinement without remapping material data externally.
    - Changing the material processing (the point cloud data) without the extra step of generating a restart file.

IGA & FEA Time Step Size

Time Step Size and Stability: Basic Relationships

$$\Delta t \leq 1/\Lambda_{max} = \ell/c$$

"ISOGEOMETRIC DISCRETIZATIONS IN STRUCTURAL DYNAMICS AND WAVE PROPAGATION"
J. Austin Cottrell, Thomas J.R. Hughes, Alessandro Reali and Giancarlo Sangalli
ECCOMAS Crete, Greece, 13-16 June 2007



Why higher order FEA time step sizes decrease: error in the maximum eigenvalue.

Why higher order NURBS time step sizes don't decrease with degree.

Time Step Size and Stability: Useful Heuristics

- For logically regular trimmed and untrimmed IGA meshes, the time step is approximately the same as for linear FEA.
- For IGA meshes containing extraordinary points, the stable time step size depends on the method used to treat the extraordinary points.
  - No treatment (C0 continuity): no impact on the time step.
  - Special treatment to improve continuity:
    - Depends on the method, which depends on the mesh generator.
    - The time step size may be reduced.
    - Set ISDO=3 on *CONTROL_TIMESTEP and make a short test run to obtain the maximum possible time step size. ISDO=3 calculates the maximum eigenvalue by power iteration.

Frequency Response Function Analysis with IGA

Slides courtesy of Yun Huang.

Ansys

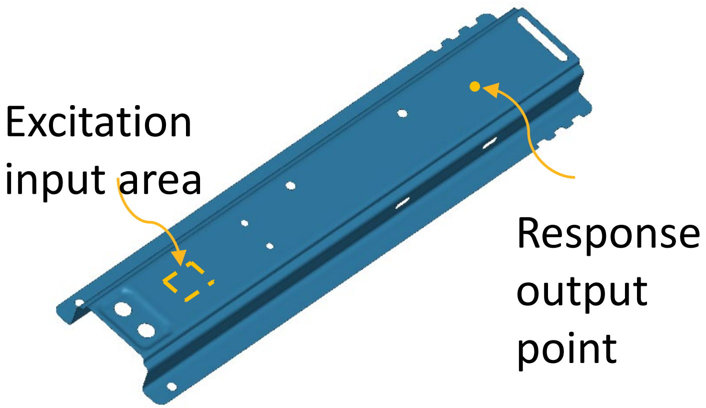
Towards One IGA Model for Crashworthiness and NVH

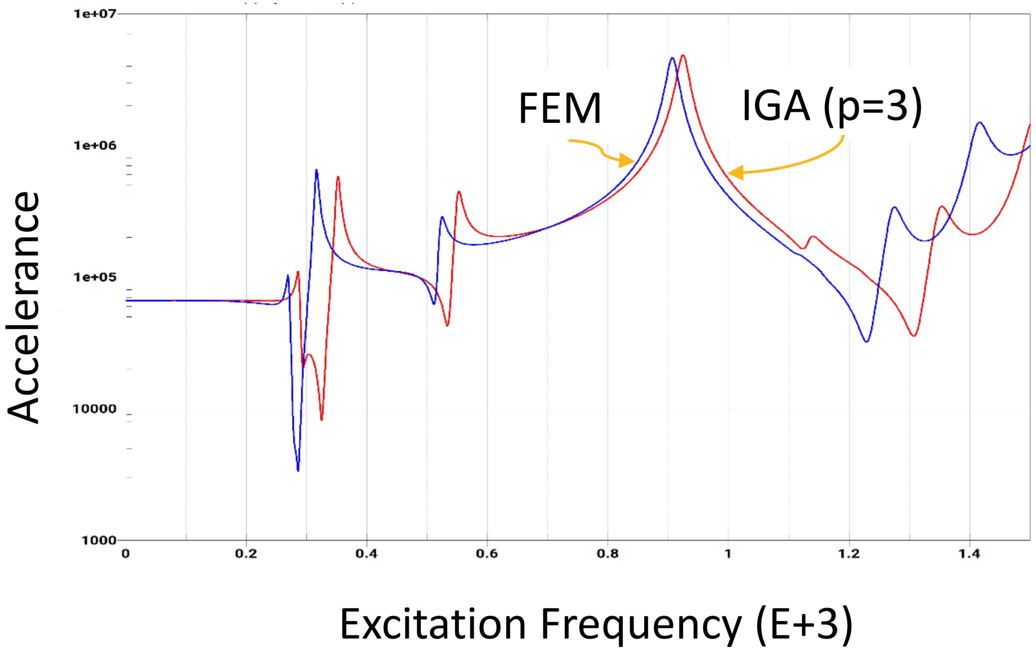
- Modal analysis is performed on the IGA *not* on the FE discretization.
- Compatible with concepts and features developed for the **`*IGA`** keywords.
- Steady state dynamics and random vibration fatigue currently use the IGA interpolation finite elements but will be migrated to direct IGA analysis in the future like the modal analysis.

Isogeometric Eigenvalue and Modal Analysis

↓

Frequency Domain Analysis Output





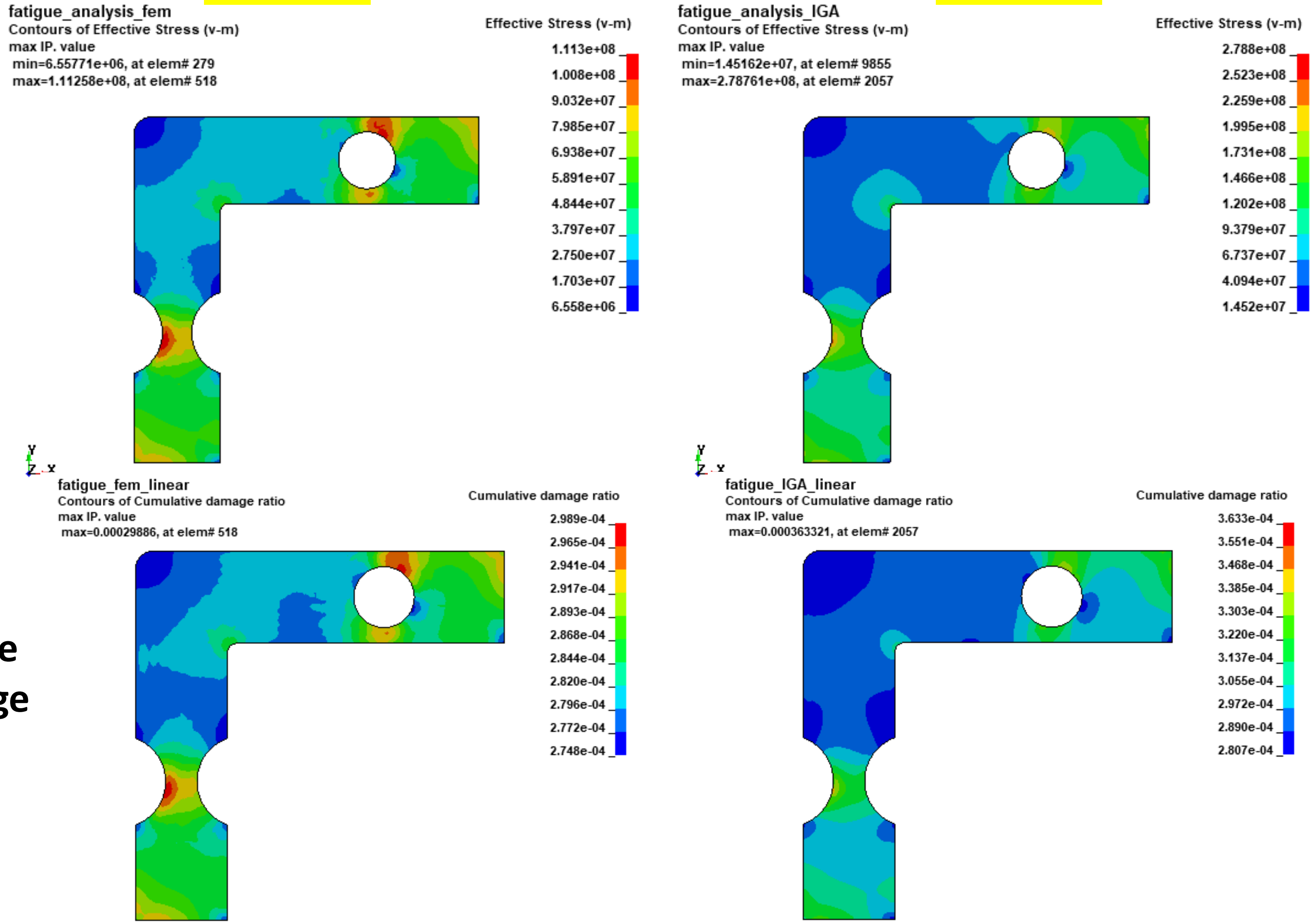
Random Vibration Fatigue Analysis (compare with FEM)

- Good match for both stresses and fatigue damage ratios.
- IGA provides more accurate stress values (stress concentration), thus more accurate fatigue damage.
- IGA takes less CPU time.

FEM | IGA

Stress

Fatigue damage



Commitment to New Technology

- We have ongoing contact and collaborations with the leaders in IGA technology including:
  - Thomas J. R. Hughes, inventor of IGA.
  - Yuri Bazilevs, co-author on the first IGA paper.
  - Jessica Zhang, first post-doc of T. J. R. Hughes devoted to meshing.
  - Hugo Casquero, U. of Mich. Assistant Professor, meshing and element technology. Post-doc of Jessica Zhang.
- Our element implementations permit immediate use of any basis functions that can be expressed through Bezier extraction operators and NURBS.