Isogeometric Shell Components in Full Vehicle Crash Simulations: Hybrid Modeling

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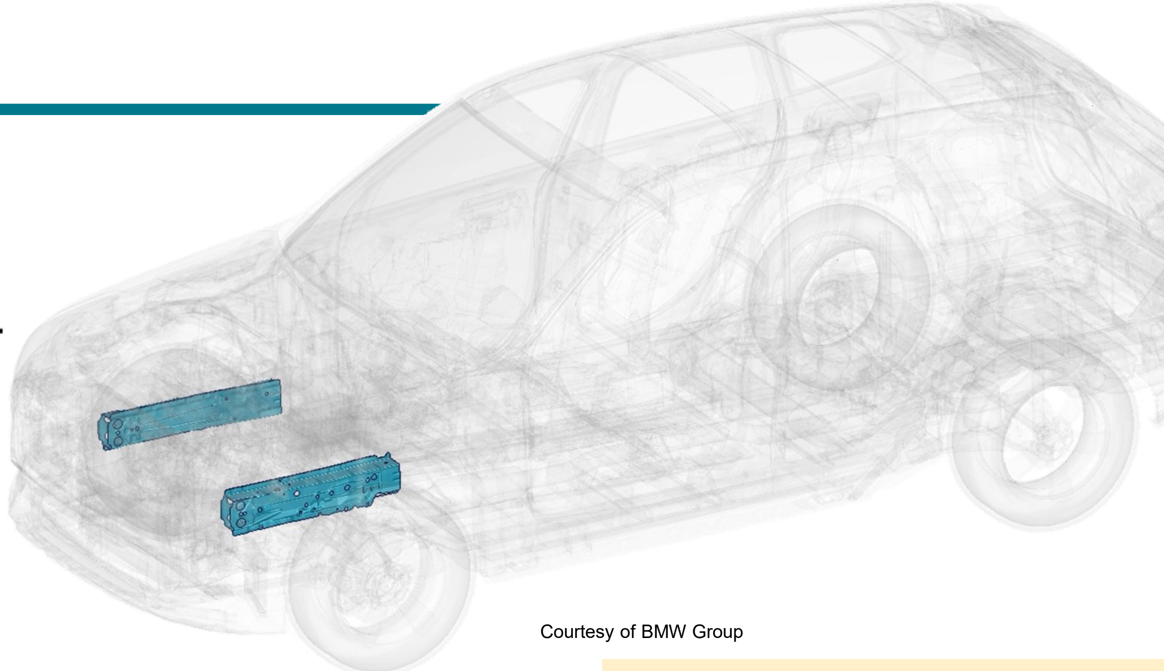

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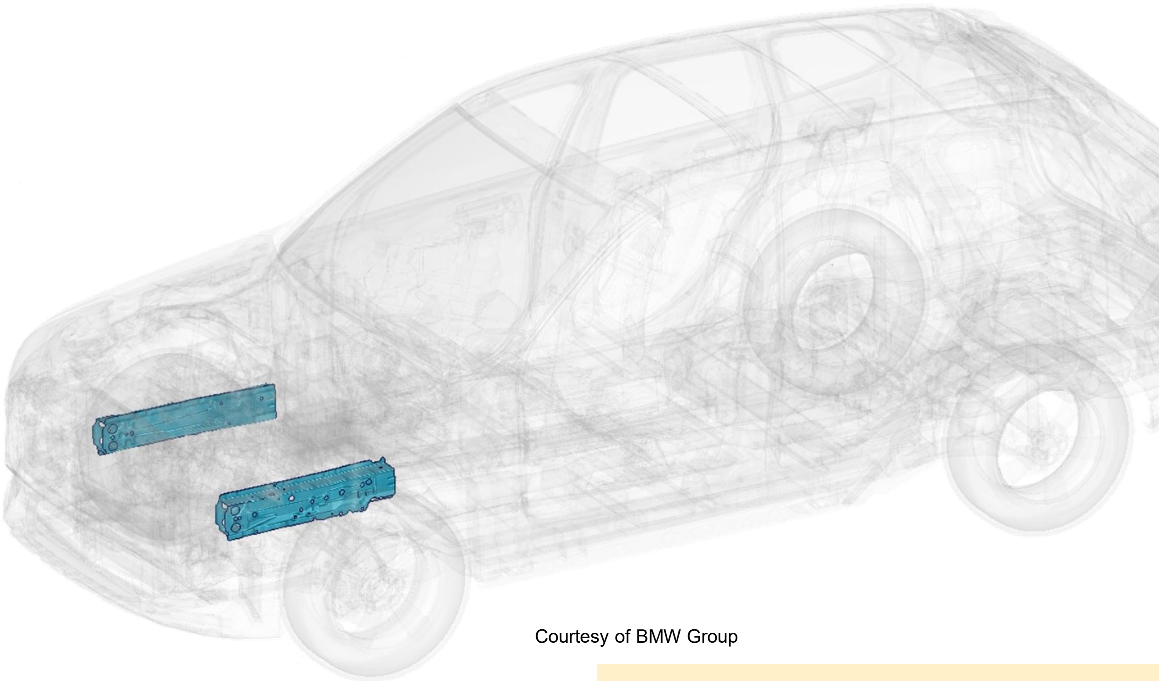
Outline



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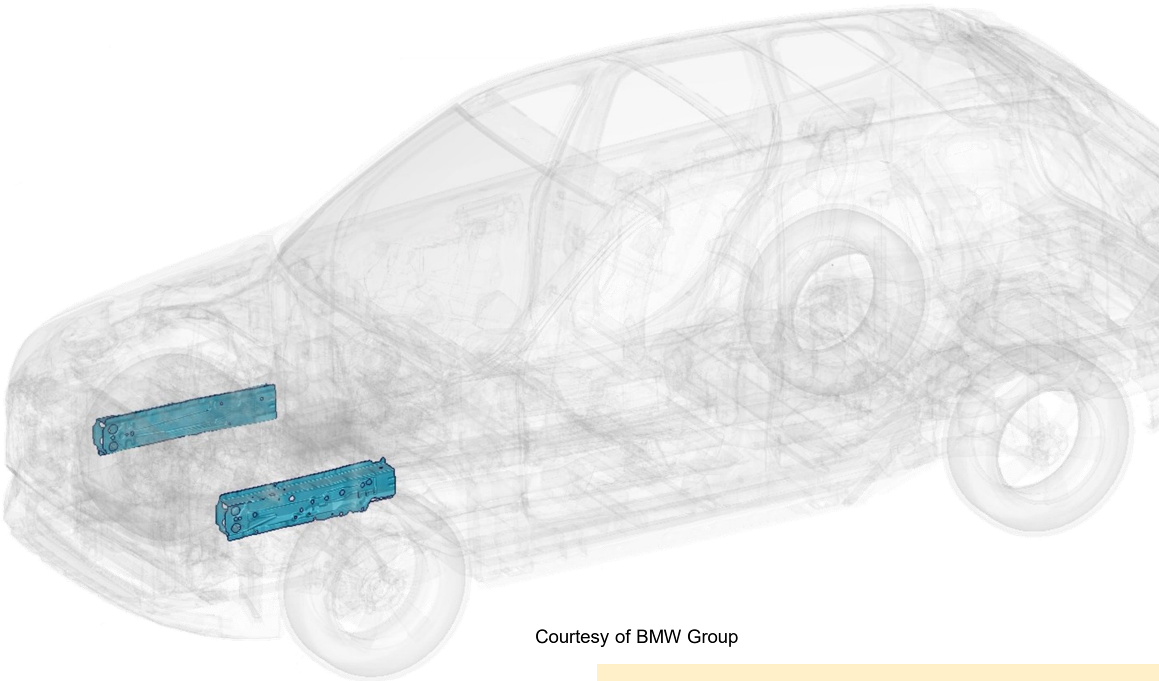

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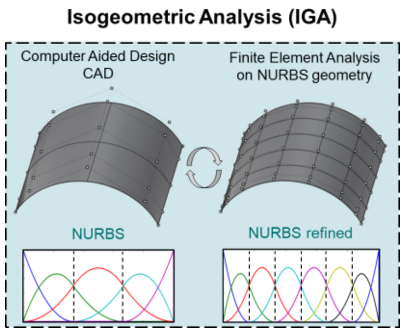
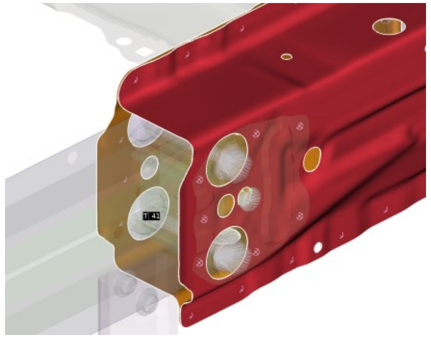
Why Isogeometric Analysis?

Potential benefits

- **Faster development process** by integrating design and analysis
  - Same NURBS-based geometry description, consistent data structure
  - Mesh-independent modeling (spotwelds, connections, etc.)





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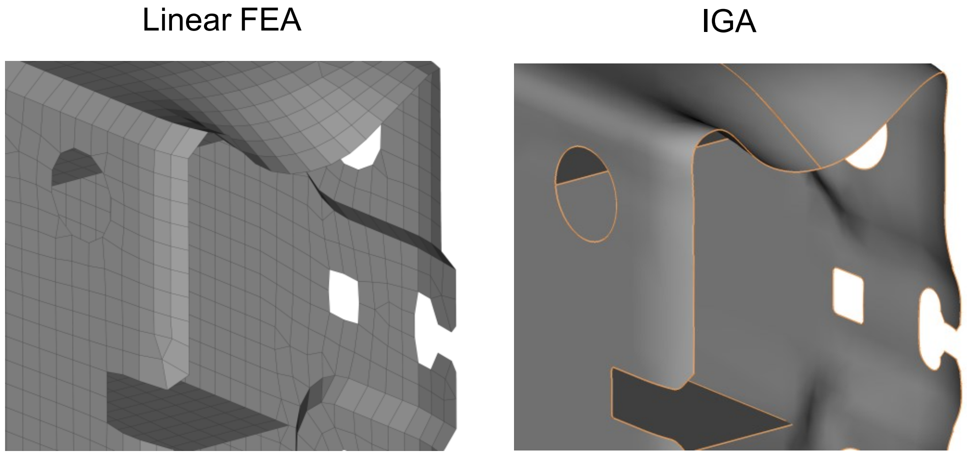
- **Higher predictive accuracy** (for similar element size)
  - More accurate geometry description: Consider details neglected with standard FEA
  - Higher-order AND higher-continuity basis
    - Smooth solution field
    - Capture deformation modes correctly

- **Increased efficiency**
  - Larger element size and fewer DOFs (for similar accuracy)
  - Larger time step size in explicit dynamics
    (for similar element size, C^{p-1} continuity and interior elements)



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Why Hybrid IGA/FEA Models?

- Long-established and optimized development processes for FEA
- All-encompassing IGA process: Requires fundamental changes and mind shift

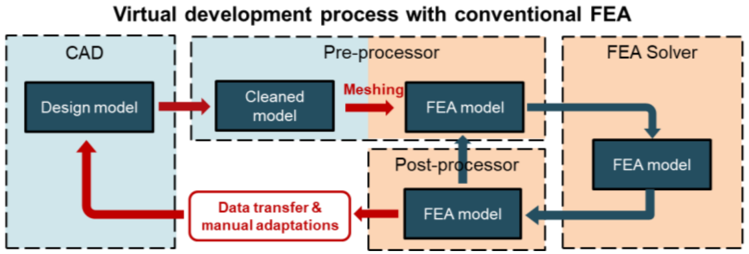
1. Impossible to change entire process at once
2. Pure isogeometric vehicle model not yet possible

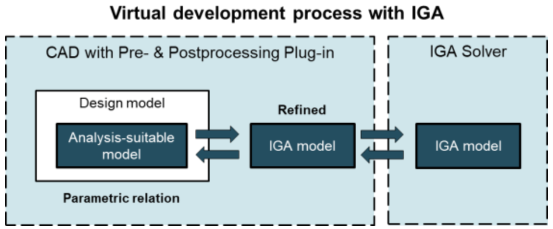
→ Start with small changes: Replace certain components

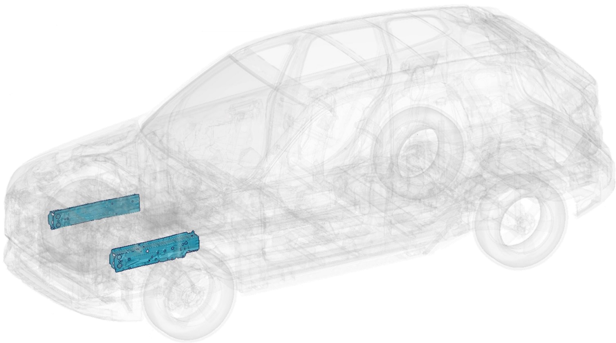
→ Make changing to IGA as simple as changing the element formulation

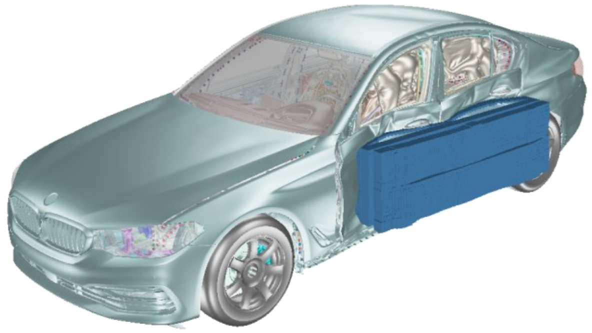
→ Build trust in the technology

→ Demonstrate specific benefits









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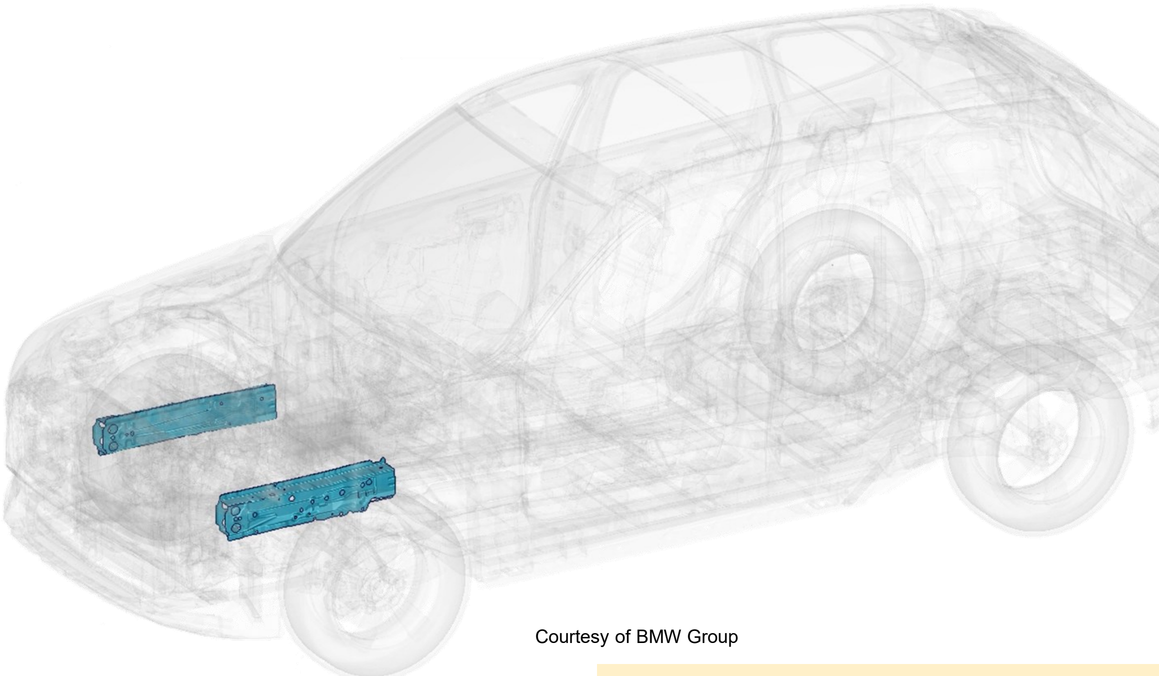

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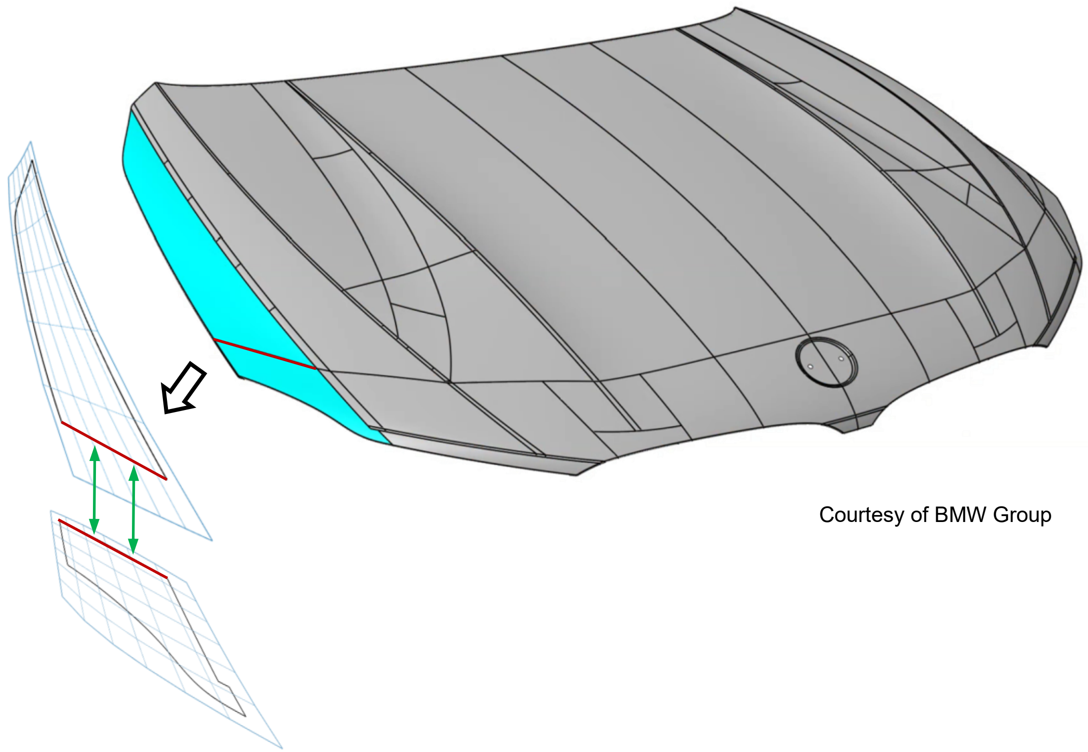
Handling of Trimmed Multi-Patch NURBS Shells

LS-DYNA Capabilities

1. Processing of CAD data: Geometry + Topology + Analysis information

   → CAD-inspired ***IGA** keyword family

*IGA Keywords for Geometry and Topology	
*IGA_1D_NURBS_UVW	NID NR PR RKi U V W WGT
*IGA_EDGE_UVW	EID EXYZID NID
*IGA_EDGE_XYZ	EID NID PSID
*IGA_1D_BREP	BRID EIDi
*IGA_2D_NURBS_XYZ	NID NR NS PR PS RKi SKi X Y Z WGT
*IGA_FACE_XYZ	FID NID ORI PSID ESID BRIDi
*IGA_SHELL	SID PID NISR NISS
*PART	PID SECID MID
*SECTION_IGA_SHELL	SECID ELFORM SHRF NIP IRL
*MAT_ELASTIC	MID RO E PR



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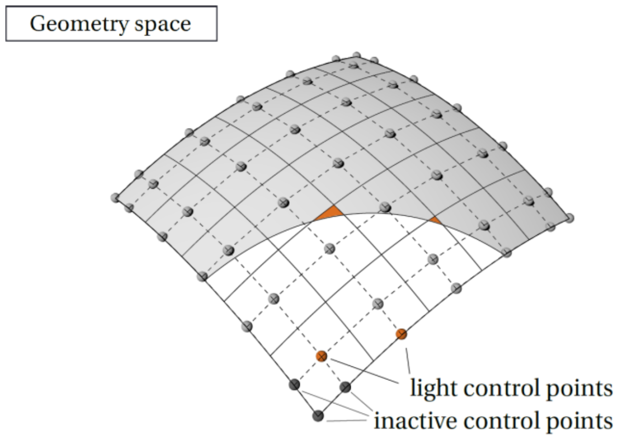
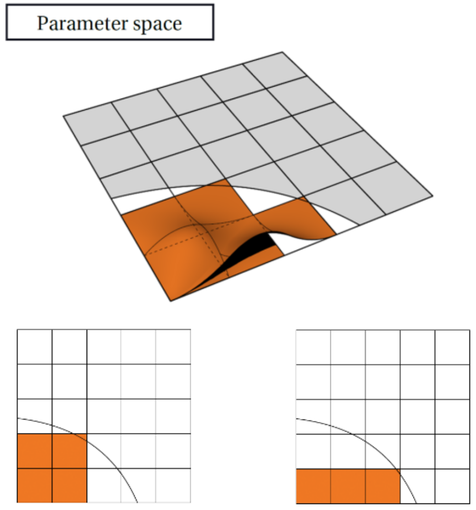
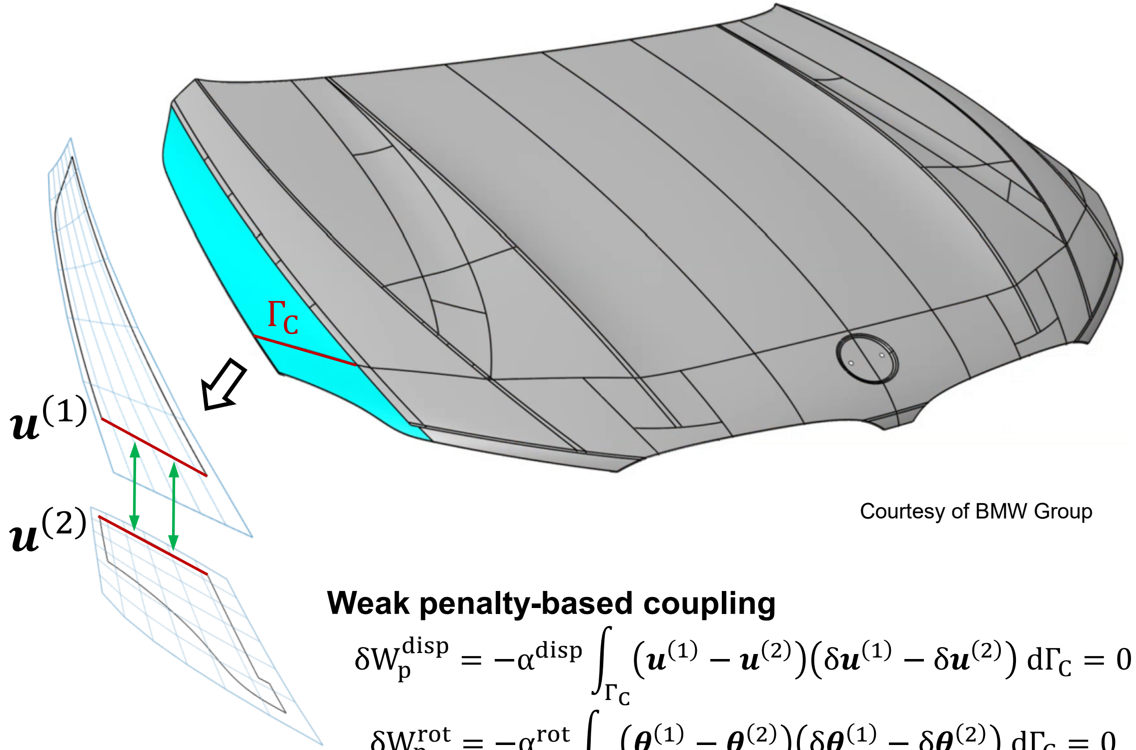
Handling of Trimmed Multi-Patch NURBS Shells

LS-DYNA Capabilities

1. Processing of CAD data: Geometry + Topology + Analysis information
2. Numerical integration of trimmed NURBS elements [1]
3. Application of coupling and boundary conditions [2,3,4]
4. Stabilization of small trimmed elements [4]







[4]

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Weak penalty-based coupling

$$\delta W_p^{disp} = -\alpha^{disp} \int_{\Gamma_C} \left(\boldsymbol{u}^{(1)} - \boldsymbol{u}^{(2)}\right)\left(\delta\boldsymbol{u}^{(1)} - \delta\boldsymbol{u}^{(2)}\right) d\Gamma_C = 0$$

$$\delta W_p^{rot} = -\alpha^{rot} \int_{\Gamma_C} \left(\boldsymbol{\theta}^{(1)} - \boldsymbol{\theta}^{(2)}\right)\left(\delta\boldsymbol{\theta}^{(1)} - \delta\boldsymbol{\theta}^{(2)}\right) d\Gamma_C = 0$$

[1] A.P. Nagy & D.J. Benson, On the numerical integration of trimmed isogeometric elements. Comput. Methods Appl. Mech. Eng. 284 (2015), 165–185.
[2] M. Breitenberger, A. Apostolatos, B. Philipp, R. Wüchner, K.-U. Bletzinger, Analysis in computer aided design: Nonlinear isogeometric B-Rep analysis of shell structures, Comput. Methods Appl. Mech. Eng. 284 (2015) 401–457.
[3] L.F. Leidinger, M. Breitenberger, A.M. Bauer, S. Hartmann, R. Wüchner, K.-U. Bletzinger, F. Duddeck, L. Song, Explicit dynamic isogeometric B-Rep analysis of penalty-coupled trimmed NURBS shells, Comput. Methods Appl. Mech. Eng. 351 (2019) 891–927.
[4] L.F. Leidinger, Explicit Isogeometric B-Rep Analysis for Nonlinear Dynamic Crash Simulations: Integrating Design and Analysis by Means of Trimmed Multi-Patch Shell Structures, PhD thesis, Technical University of Munich, Germany (2020).

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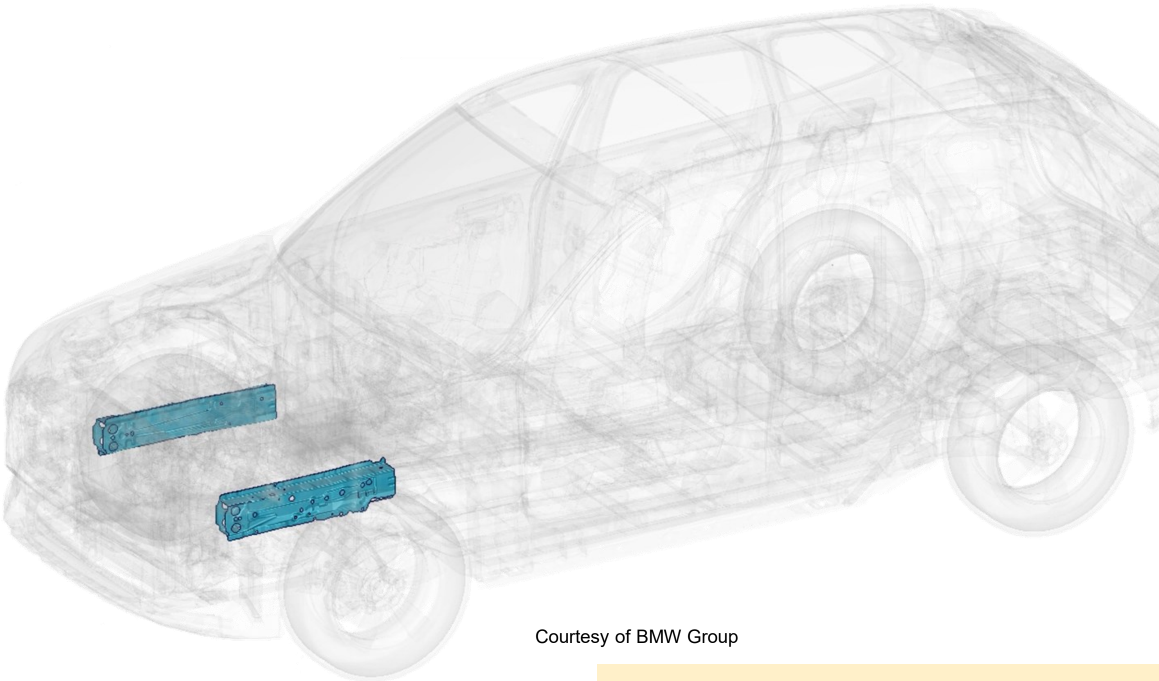

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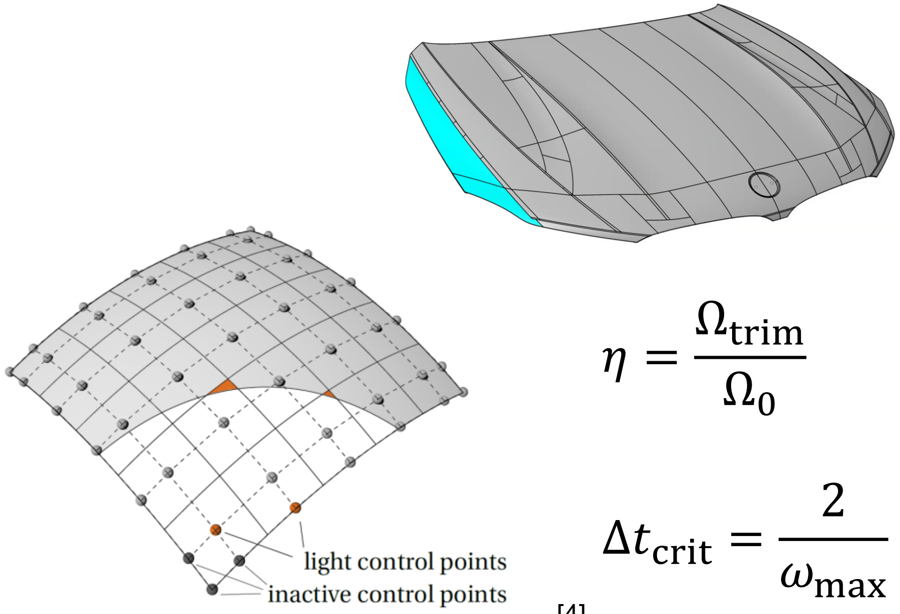
Analysis Capabilities for Explicit Dynamic Crash

Time Step Size, Time Step Estimation, Mass Scaling

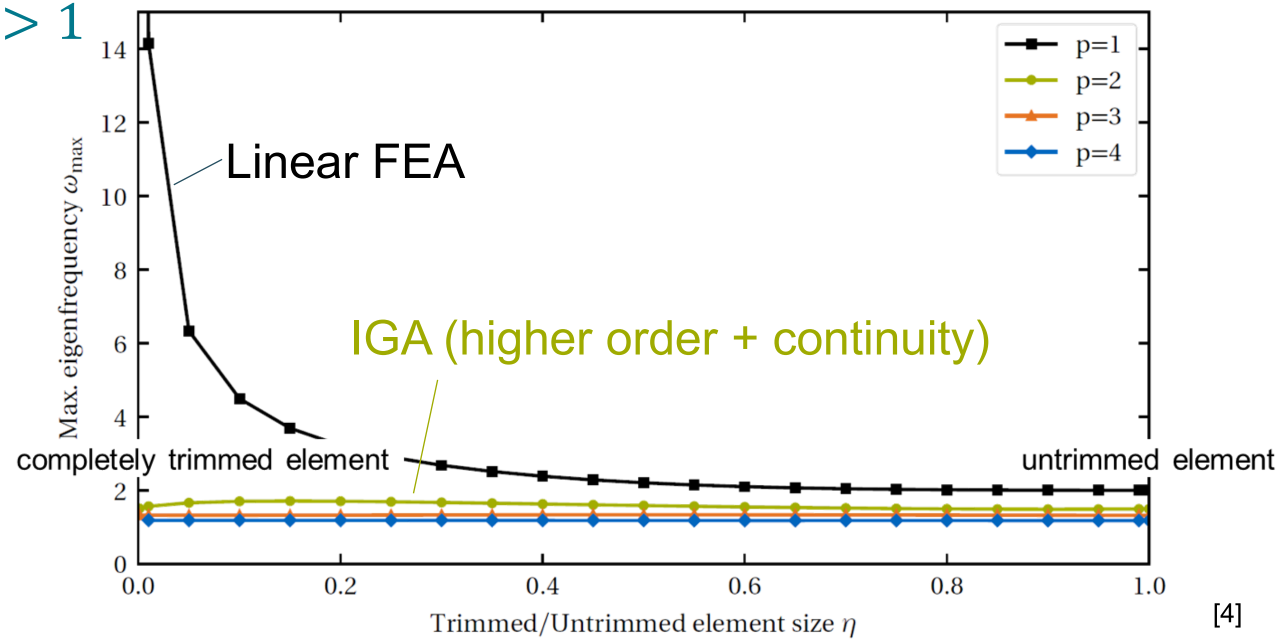
- Effect of trimmed element size on time step size?
  → Practically, no effect for IGA with C^{p-1} and $p > 1$



[4]

$$\eta = \frac{\Omega_{\text{trim}}}{\Omega_0}$$

$$\Delta t_{\text{crit}} = \frac{2}{\omega_{\max}}$$



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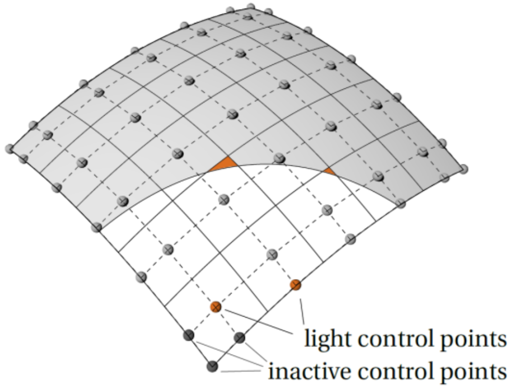
  → $\Delta t_{\text{Interior}} > \Delta t_{\text{Boundary}}$ → Cut-off boundaries



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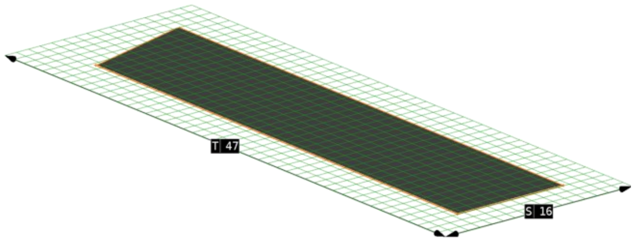
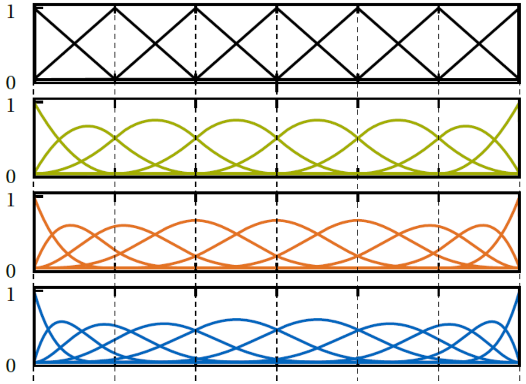
"Extend" option in ANSA

Mode	Create
Distortion di...	0.05
Subinterval par...	
Min span	6.
Max span	20.
Uniform	✓
Extend	✓
Join	✓



Bar models
Basis functions

Linear FEA
NURBS p=2
NURBS p=3
NURBS p=4



$\omega^e_{\max}$

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- Accurate time step estimation
  → IGADO=1 in `*CONTROL_TIMESTEP`
  → Account for continuity

$$\eta = \frac{\Omega_{\text{trim}}}{\Omega_0}$$

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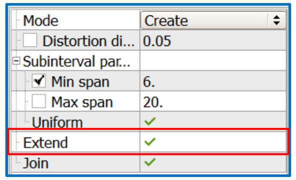
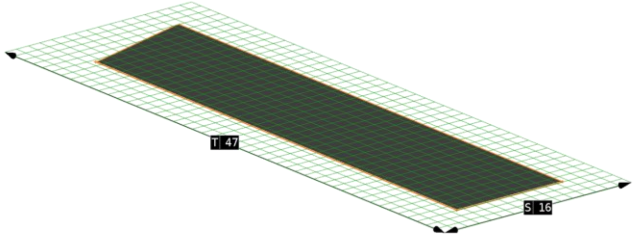
"Extend" option in ANSA





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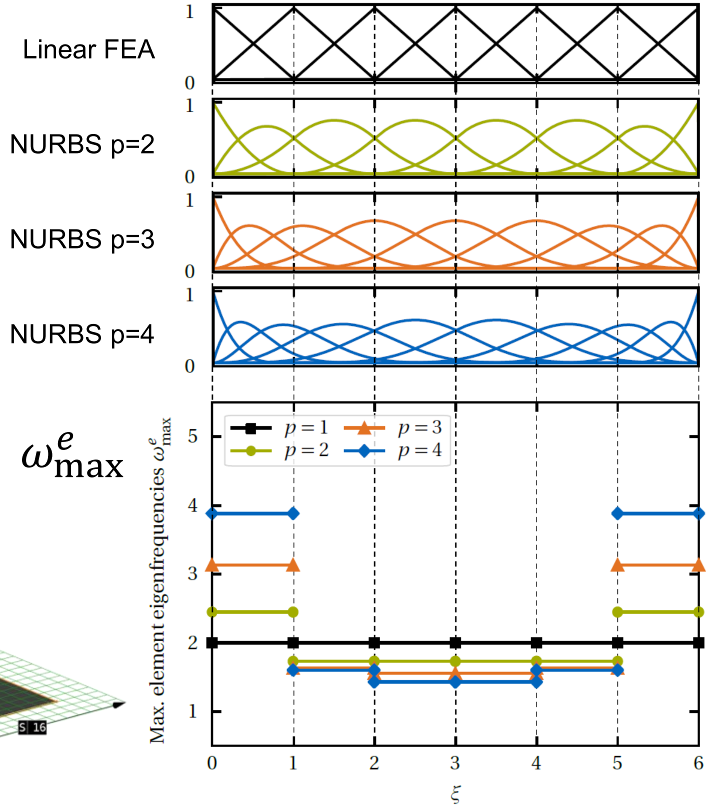

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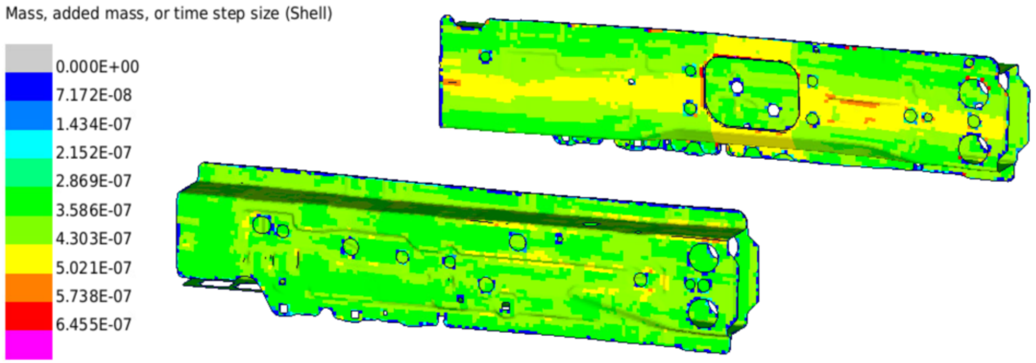
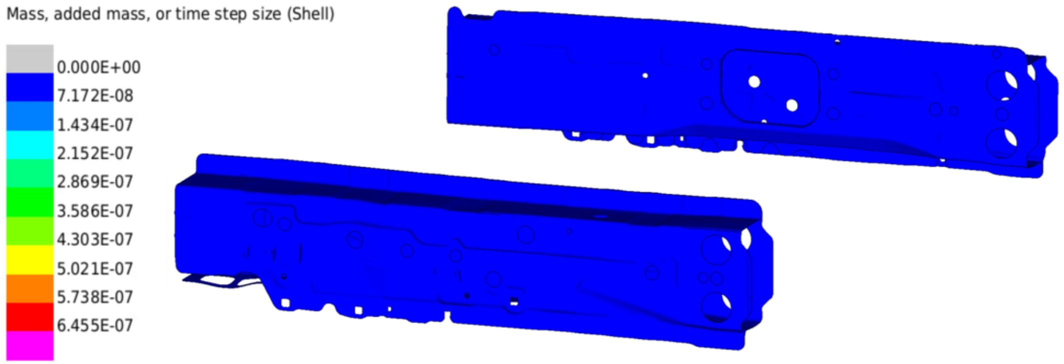
- Accurate time step estimation
  → IGADO=1 in `*CONTROL_TIMESTEP`
  → Account for continuity
- Mass scaling for predefined time step
  → Significant scaling for FEA with same mesh size

IGA time step estimate **not accounting** for continuity:
→ Significant mass scaling



IGA time step **accounting** for continuity:
→ No mass scaling



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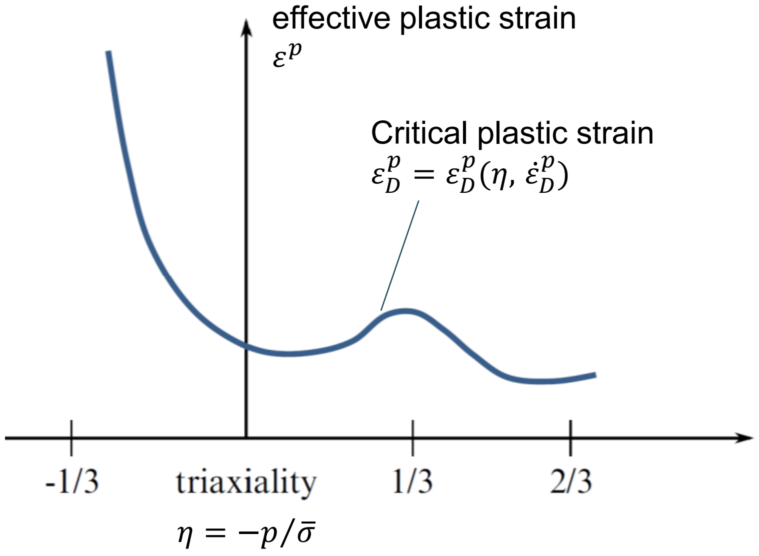
Analysis Capabilities for Explicit Dynamic Crash

Plasticity, Damage and Failure

Goal: No modification of existing material data

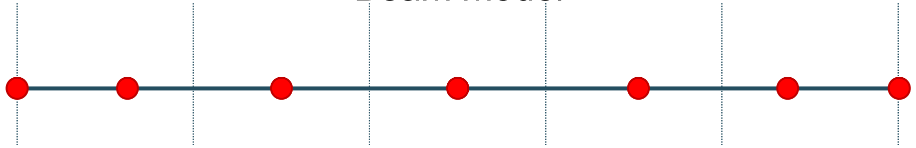
- Plasticity: Use existing elasto-plastic material models with $E, \nu, \sigma(\varepsilon^p, \dot{\varepsilon})$
- Damage and Failure modeling (e.g. DIEM)
  - Continuum Damage Mechanics approach $\sigma = (1 - D)\,\tilde{\sigma}$ Damage variable
    1. Damage initiation $D > 0$ determined by Forming Limit Curve
    2. Damage evolution $\dot{D} = \dot{D}(\dot{\varepsilon}^p, \eta, D, l)$ char. element length
    3. Integration point failure if $D = 1$
    4. Element failure: If n in-plane IPs and m layers failed

Forming Limit Curve (FLC)



Control points

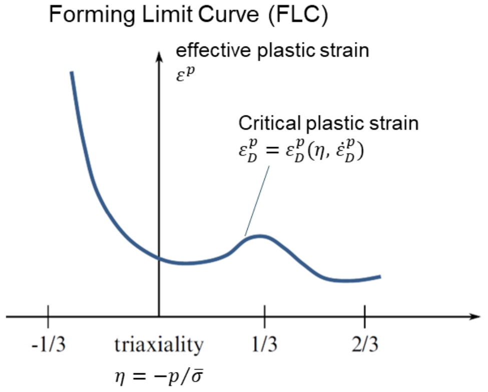
Beam model



`*MAT_ADD_DAMAGE_DIEM`
DIEM = Damage Initiation and Evolution Model

Analysis Capabilities for Explicit Dynamic Crash

Plasticity, Damage and Failure



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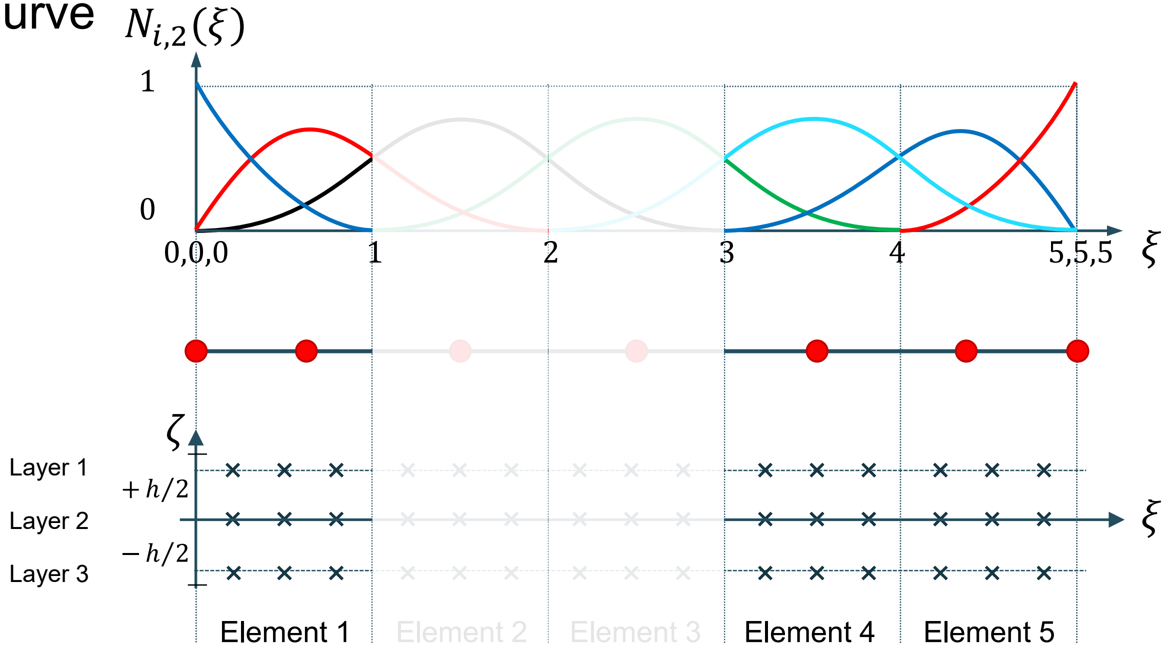
    3. Integration point failure if $D = 1$ — char. element length
    4. Element failure: If n in-plane IPs and m layers failed
  - Crack modeling
    - So far: simple element deletion
      → Discontinuity? → “Cross-talk”!
      → Delete p elements for discontinuity
    - More sophisticated crack modeling to be developed



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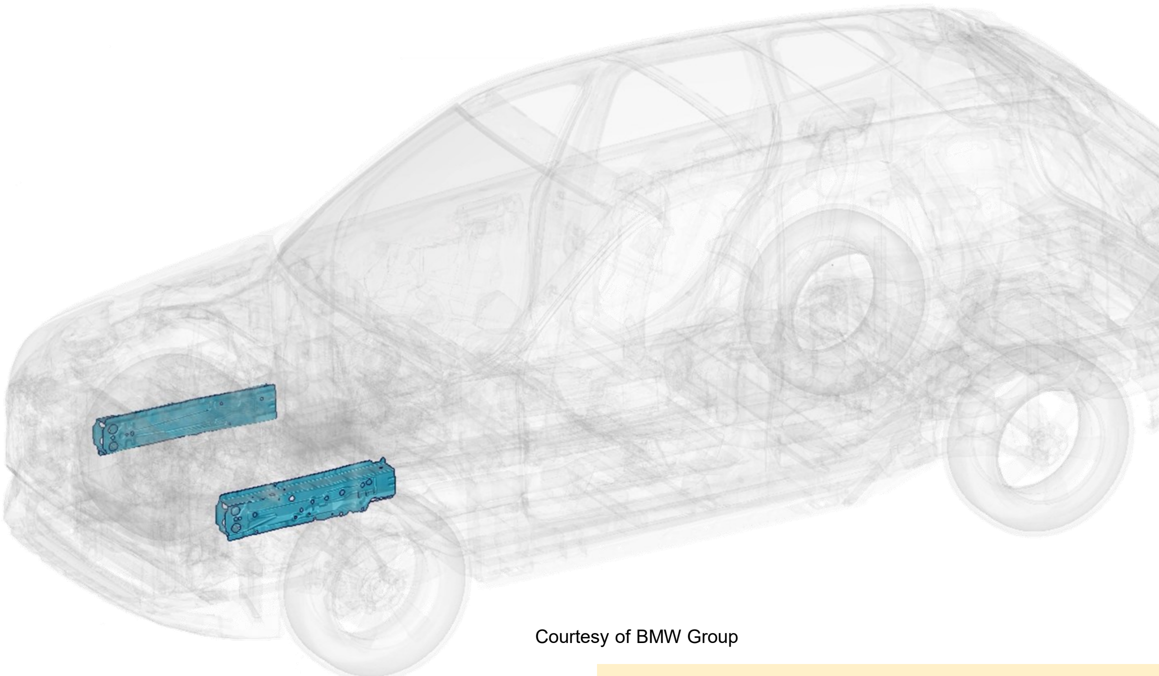

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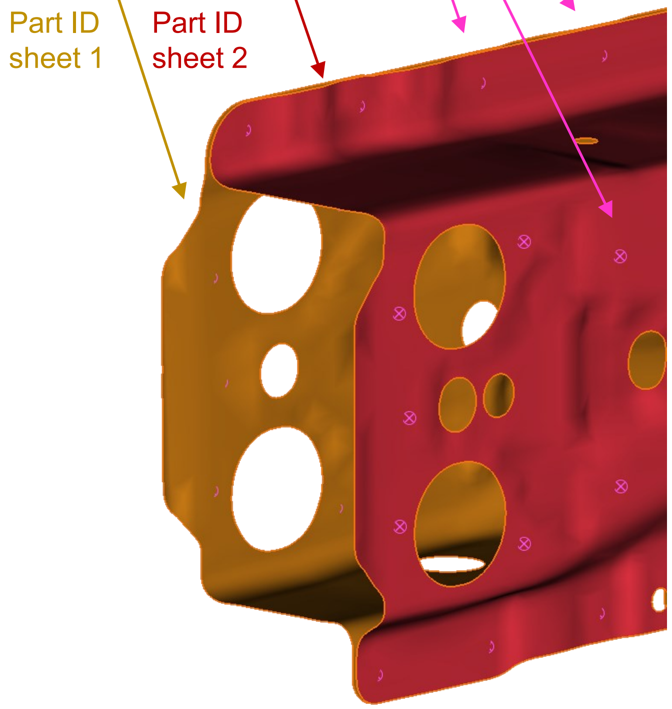
Connection Modeling

For One-To-One Component Exchange (FEA→IGA)

- Spotwelds: PID-based and mesh-independent
  - ***CONSTRAINED_INTERPOLATION_SPOTWELD**

```
*CONSTRAINED_INTERPOLATION_SPOTWELD
$      MID       SID      NSID     THICK         R
       101       102       200       3.0         7
$       RN        RS     BETA1       LCF     LCUPF
       xxx       xxx       xxx       xxx       xxx
$       ES        EB        ET    LCDEXP     GAMMA
       xxx       xxx       xxx       xxx       xxx
```



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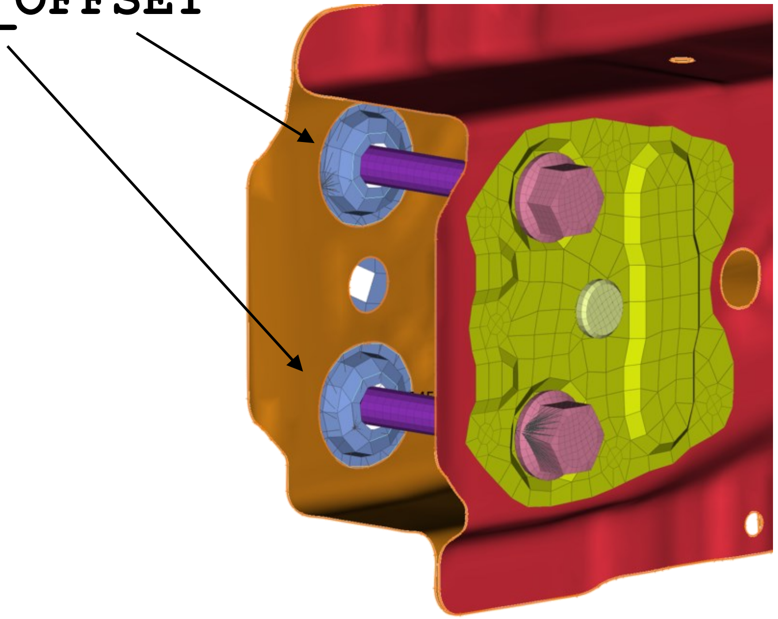
- Spotwelds: PID-based and mesh-independent
  - **`*CONSTRAINED_INTERPOLATION_SPOTWELD`**
- Tied contact between bolts and IGA shells (PID-based)
  - **`*CONTACT_TIED_SHELL_EDGE_TO_SURFACE_BEAM_OFFSET`**

```
*CONSTRAINED_INTERPOLATION_SPOTWELD
$       MID       SID      NSID     THICK         R
        101       102       200       3.0         7
$        RN        RS     BETA1       LCF     LCUPF
        xxx       xxx       xxx       xxx       xxx
$        ES        EB        ET    LCDEXP     GAMMA
        xxx       xxx       xxx       xxx       xxx
```



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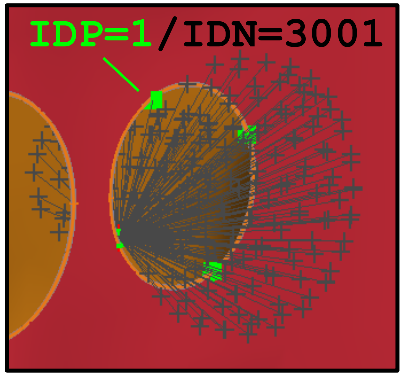
Connection Modeling

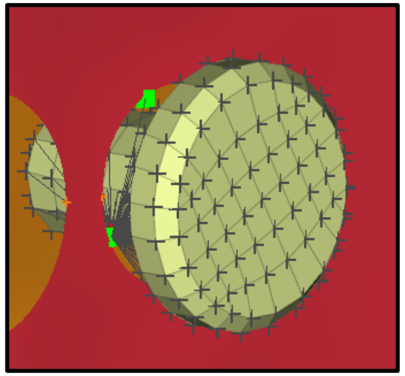
For One-To-One Component Exchange (FEA→IGA)

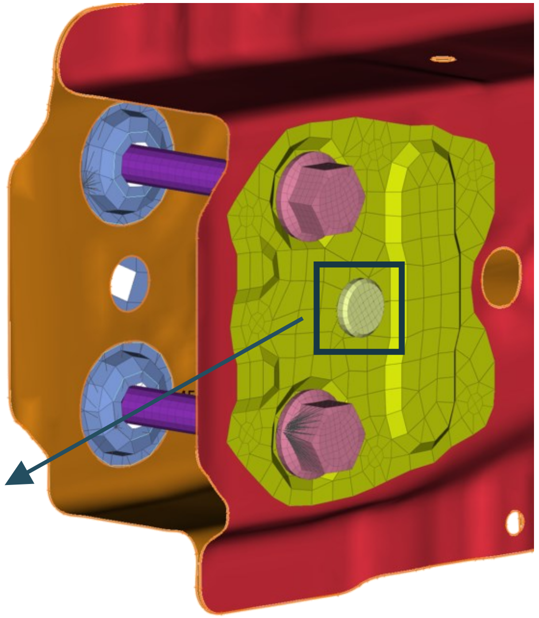
- Spotwelds: PID-based and mesh-independent
  - **`*CONSTRAINED_INTERPOLATION_SPOTWELD`**
- Tied contact between bolts and IGA shells (PID-based)
  - **`*CONTACT_TIED_SHELL_EDGE_TO_SURFACE_BEAM_OFFSET`**
- Attach existing rigid bodies (pins and bolts)
  - "Glue" FE nodes of **`*CNRB`** to IGA shells using
  - **`*IGA_POINT_UVW`**

```
*CONSTRAINED_INTERPOLATION_SPOTWELD
$        MID       SID      NSID     THICK         R
         101       102       200       3.0         7
$         RN        RS     BETA1       LCF     LCUPF
         xxx       xxx       xxx       xxx       xxx
$         ES        EB        ET    LCDEXP     GAMMA
         xxx       xxx       xxx       xxx       xxx
```

```
*IGA_POINT_UVW
$      IDP|      IDN|        U|        V|
         1      3001      0.78      0.15
```







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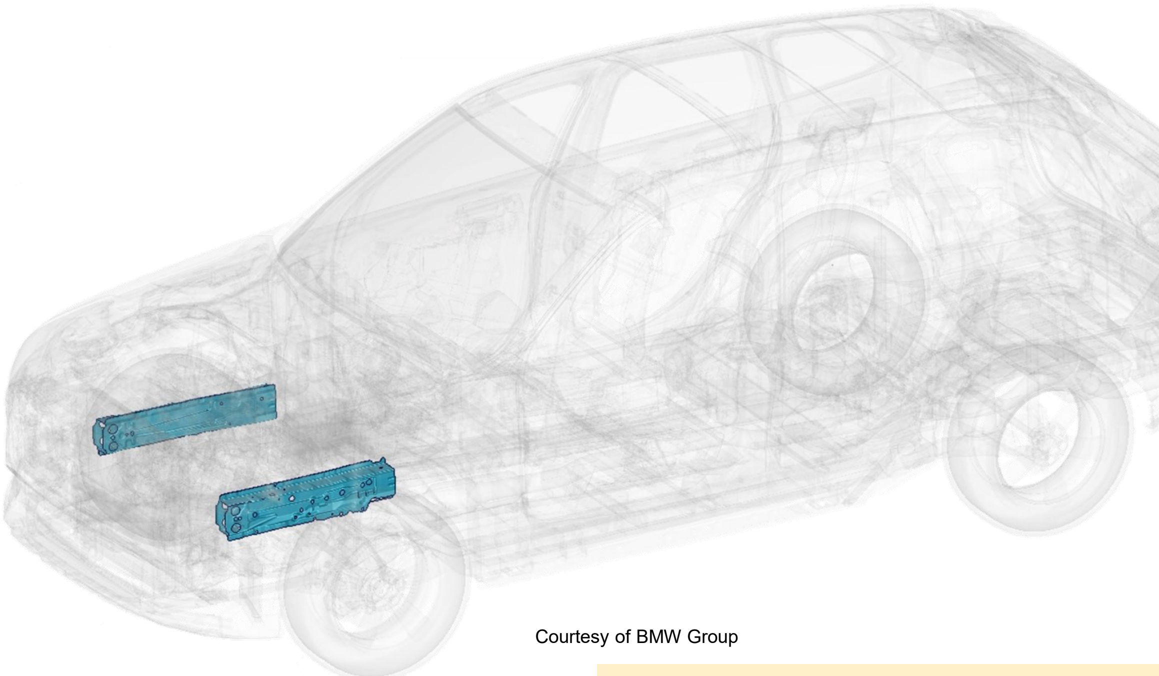

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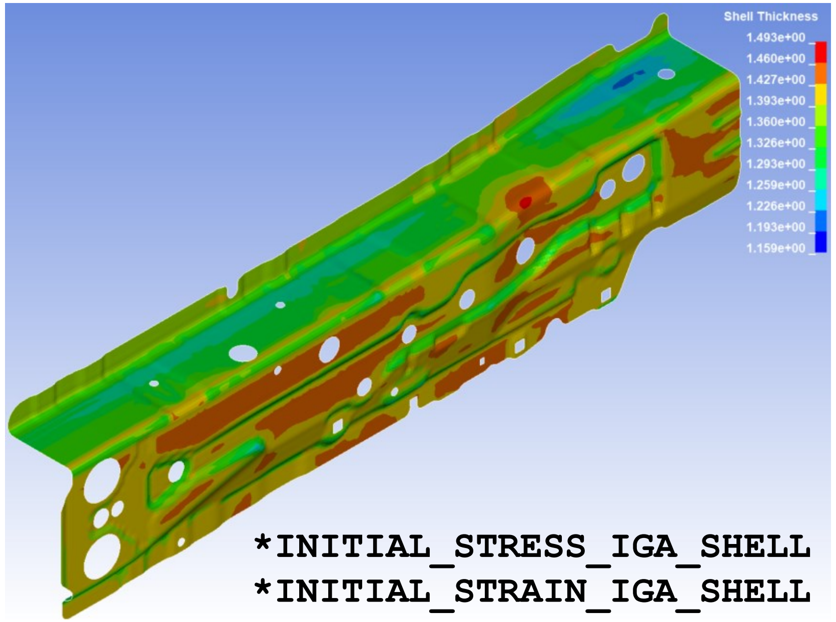
Process-Specific Capabilities

For One-To-One Component Exchange (FEA→IGA)

- Initialization with material history data (e.g. from forming simulations)
  - **Current approach**
    - External mapping from dynain file using DYNAmore ENVYO
    - Difficulty: IGA integration point location for trimmed elements
    - **`*INITIAL_STRESS/STRAIN_IGA_SHELL`**
  - **Possible future approach**
    - Internal mapping in LS-DYNA
    - Spatial point cloud + field data for history variables



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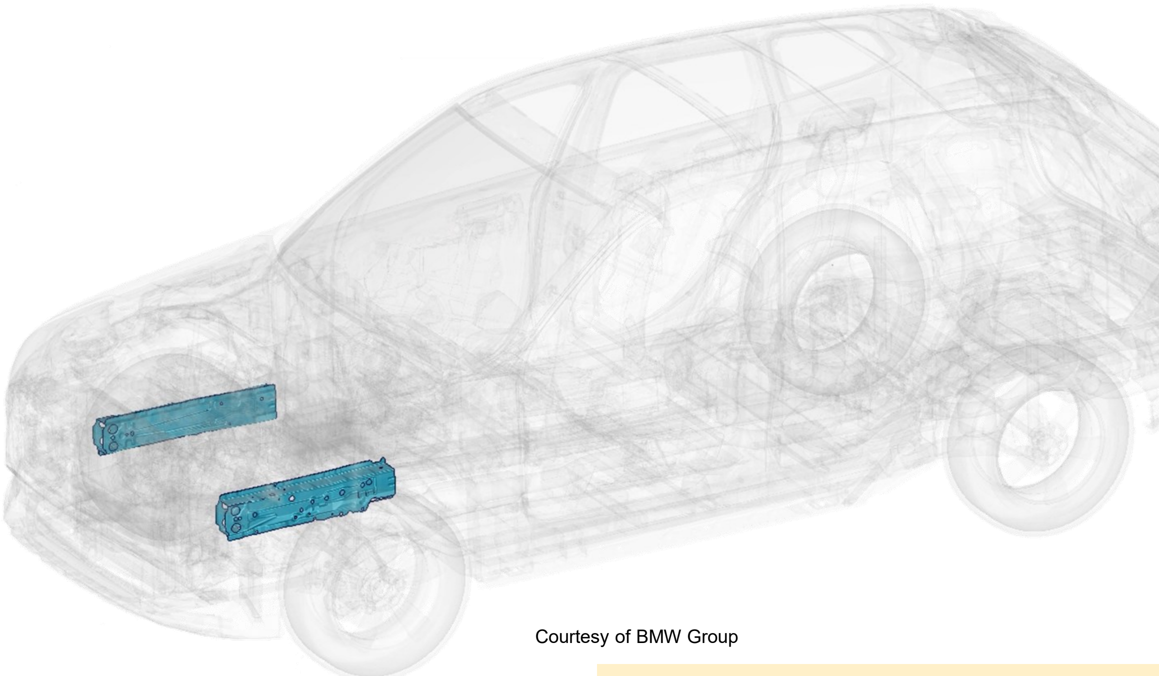


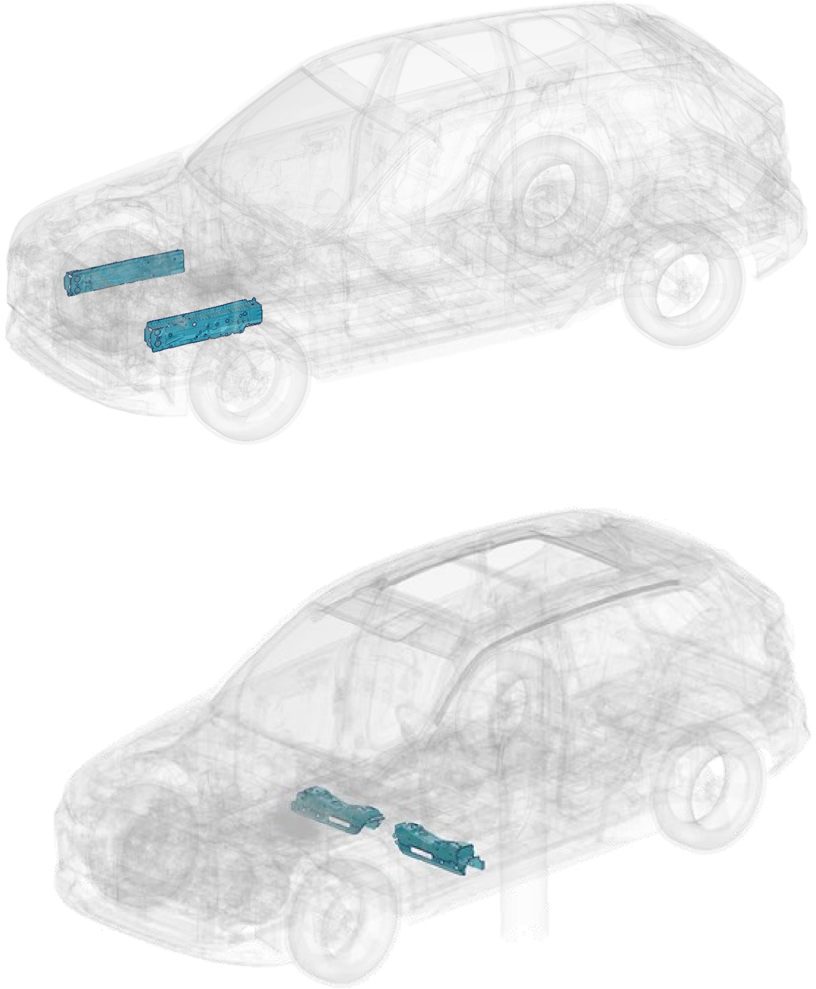
Courtesy of BMW Group

Examples: Hybrid Vehicle Crash Simulations

Overview

- Conventional FEA vehicle model

  → Replace certain components with IGA shells
- One-to-one component exchange without further modifications
- Semi-automatic IGA model generation with ANSA
- IGA settings:
  - Cubic NURBS-based Reissner-Mindlin shell
  - 4mm average element length
  - Reduced Gauss integration (3x3 integration points)
  - New time step estimate → practically no mass scaling for IGA shells
  - Plasticity, damage and failure considered



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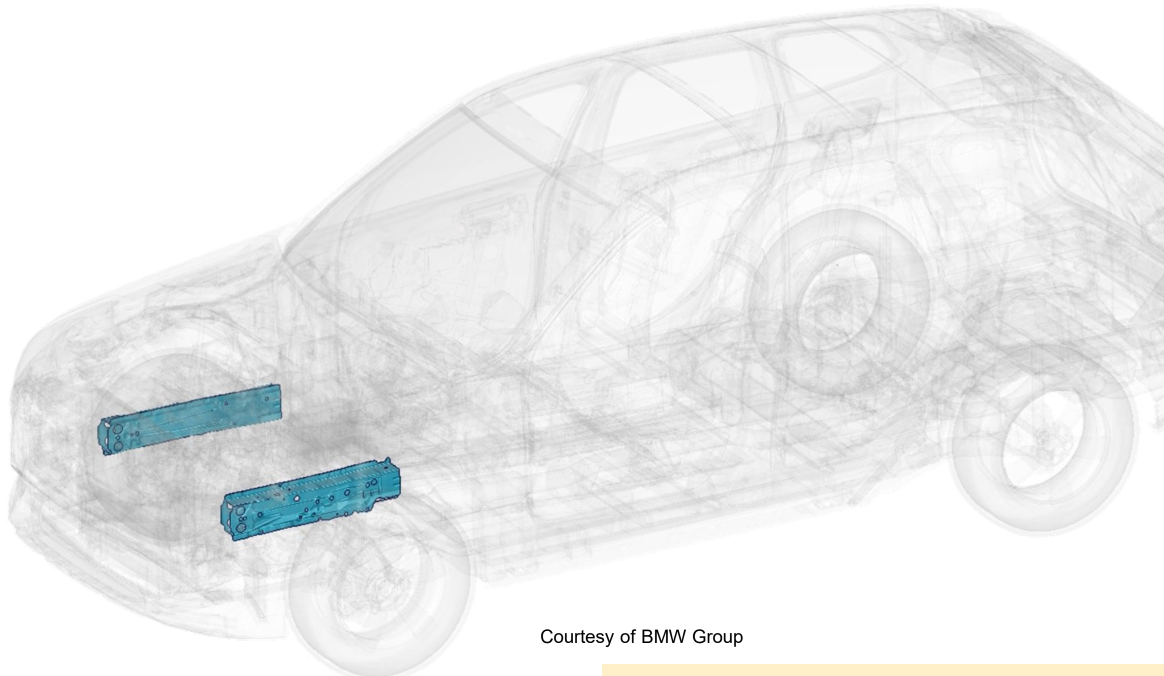
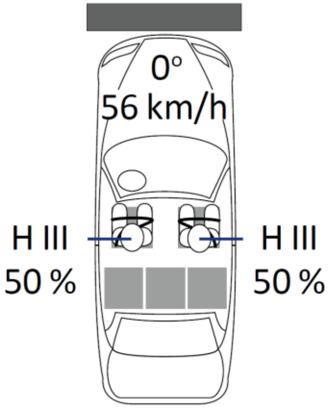


Courtesy of BMW Group

Examples: Hybrid Vehicle Crash Simulations

Front Crash: Car Against Rigid Wall

- Hybrid model with IGA longitudinal members
  - Two trimmed single-patch shells each side
  - Connected via spotwelds + bolts
  - ~5.5M elements
- Full width frontal impact



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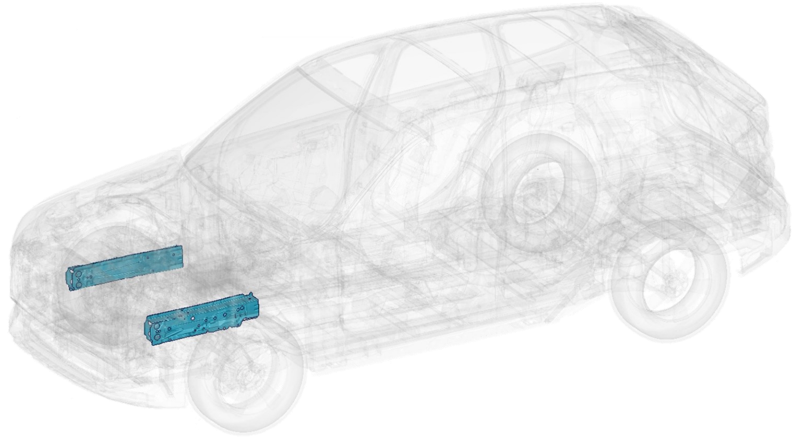

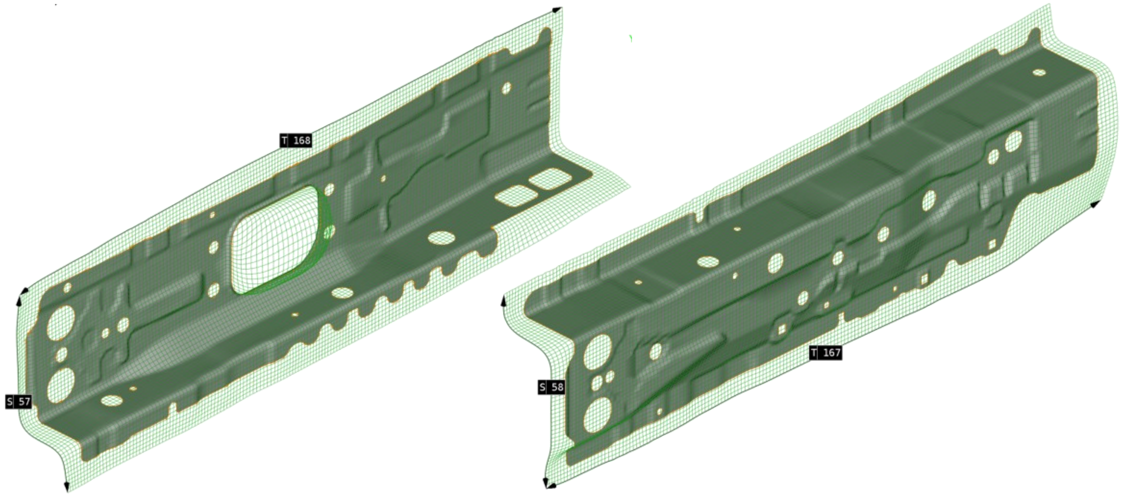

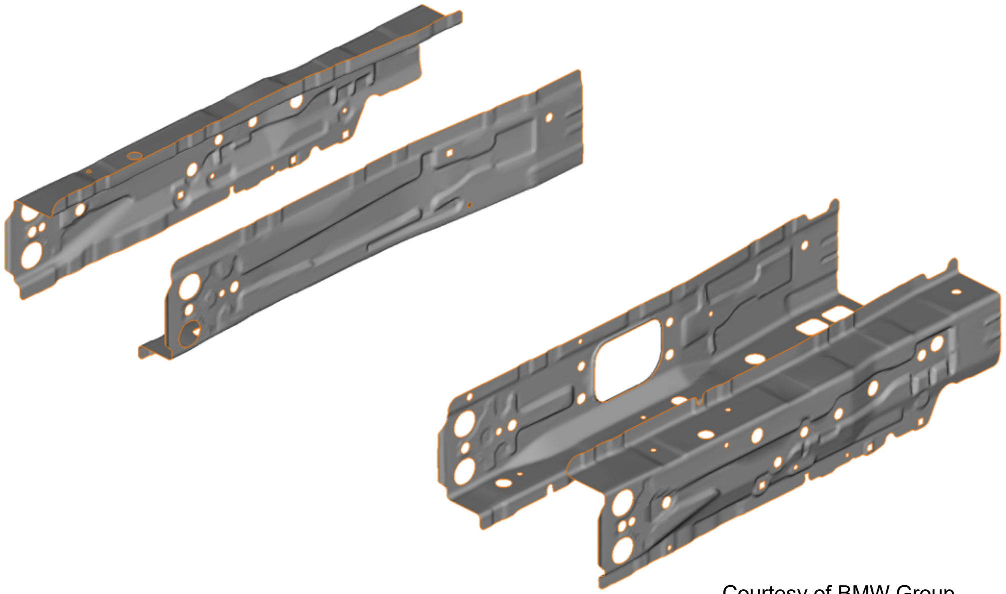

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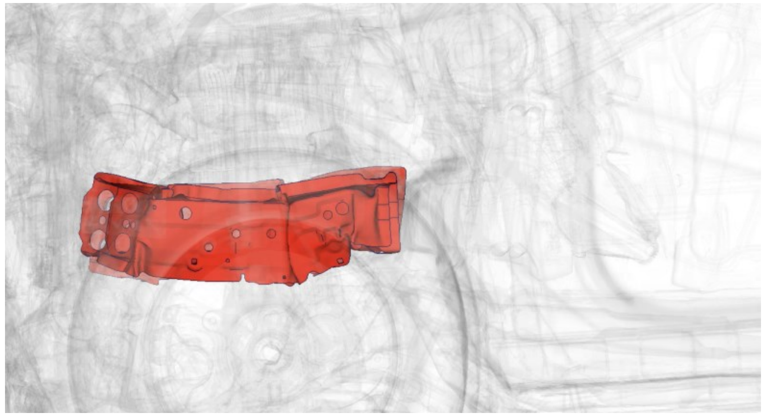
Examples: Hybrid Vehicle Crash Simulations

Front Crash: Car Against Rigid Wall

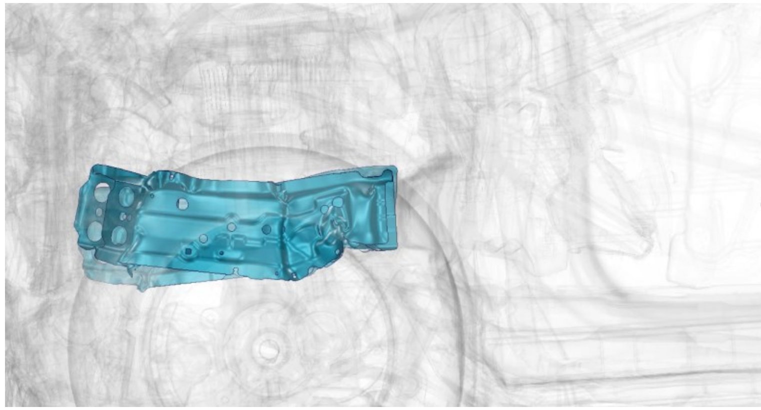
- Pure FEA vs. Hybrid IGA/FEA model

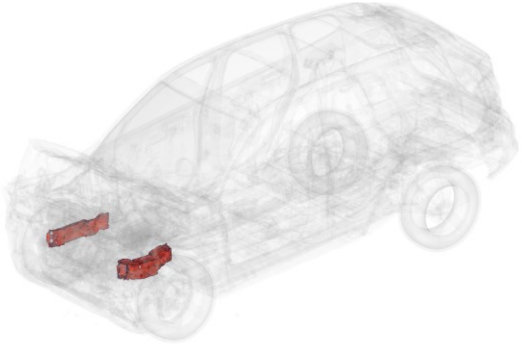
Side view

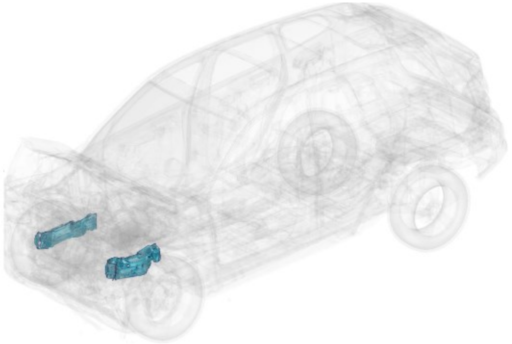
FEA

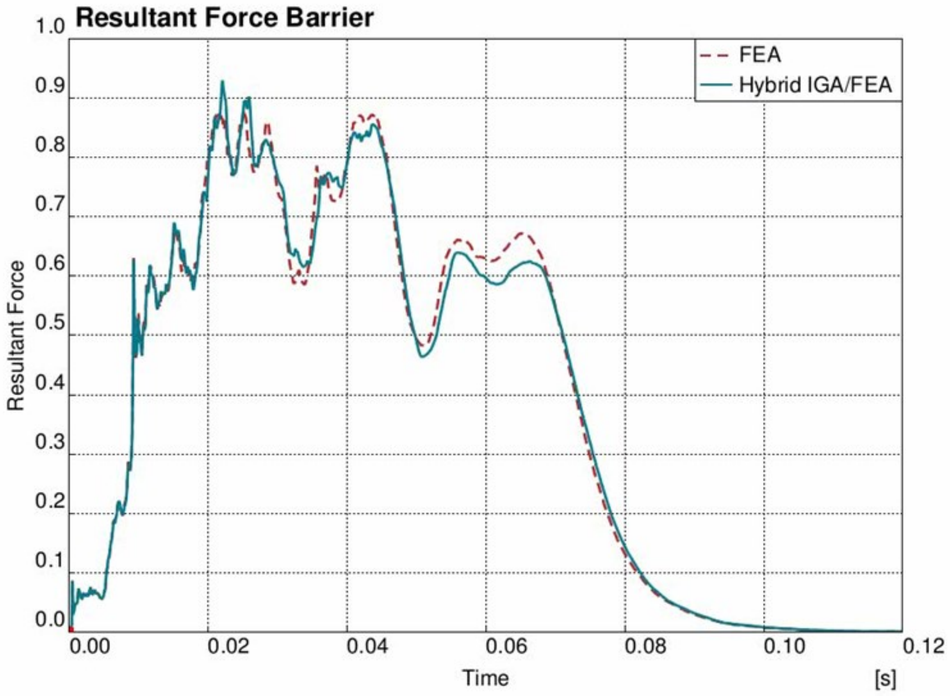


Hybrid IGA/FEA









Courtesy of BMW Group

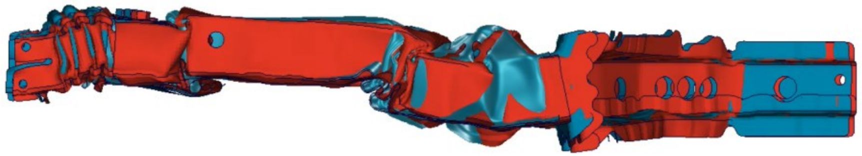
Examples: Hybrid Vehicle Crash Simulations

Front Crash: Car Against Rigid Wall

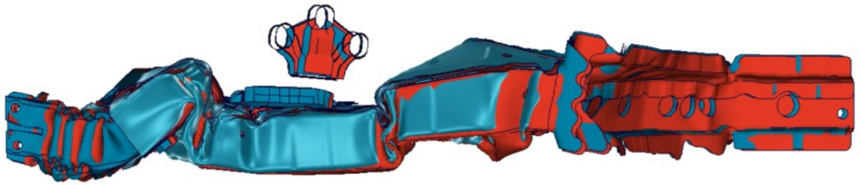
- Pure FEA vs. Hybrid IGA/FEA model

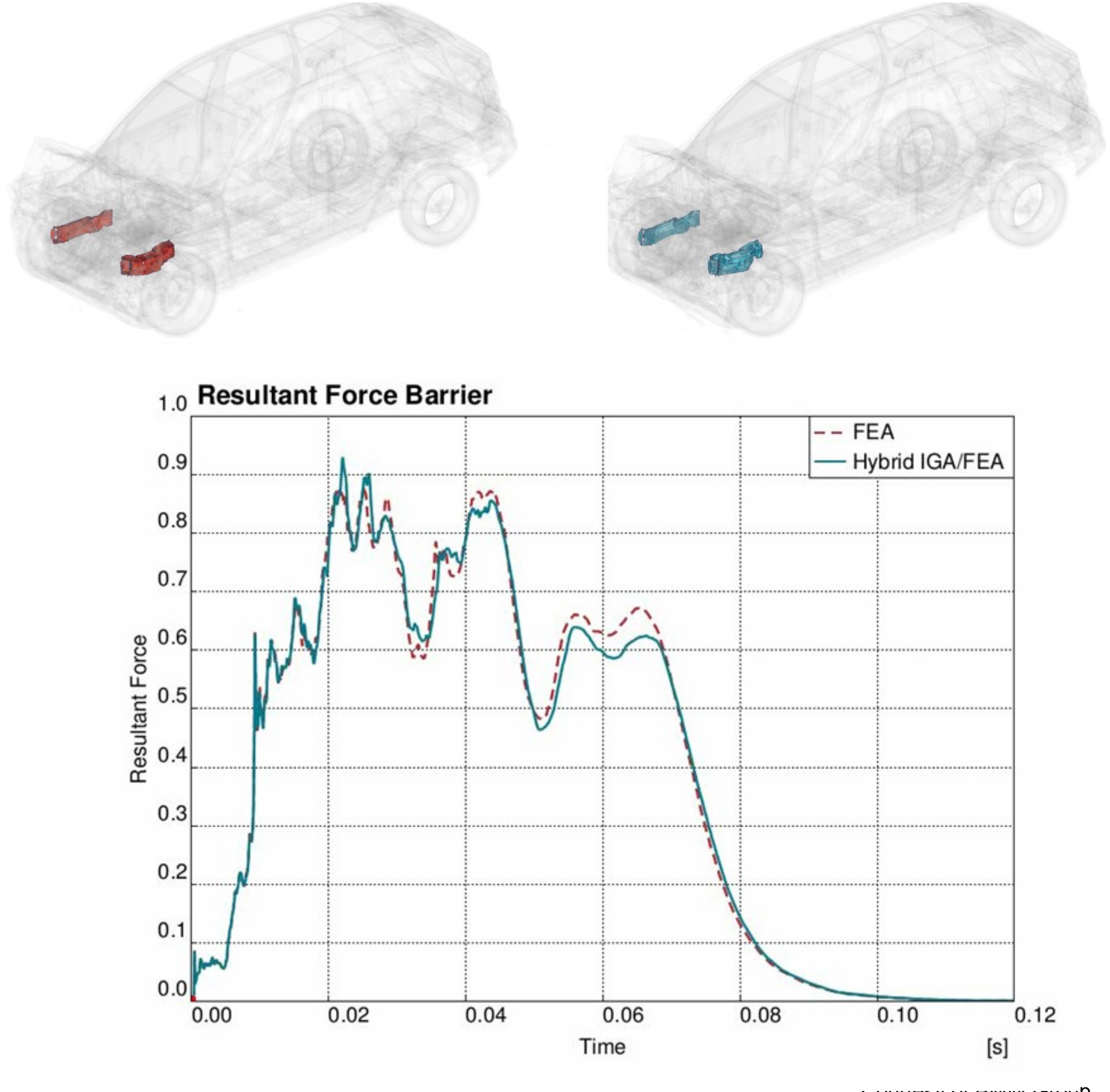
Top view (overlay)

Right load path



Left load path





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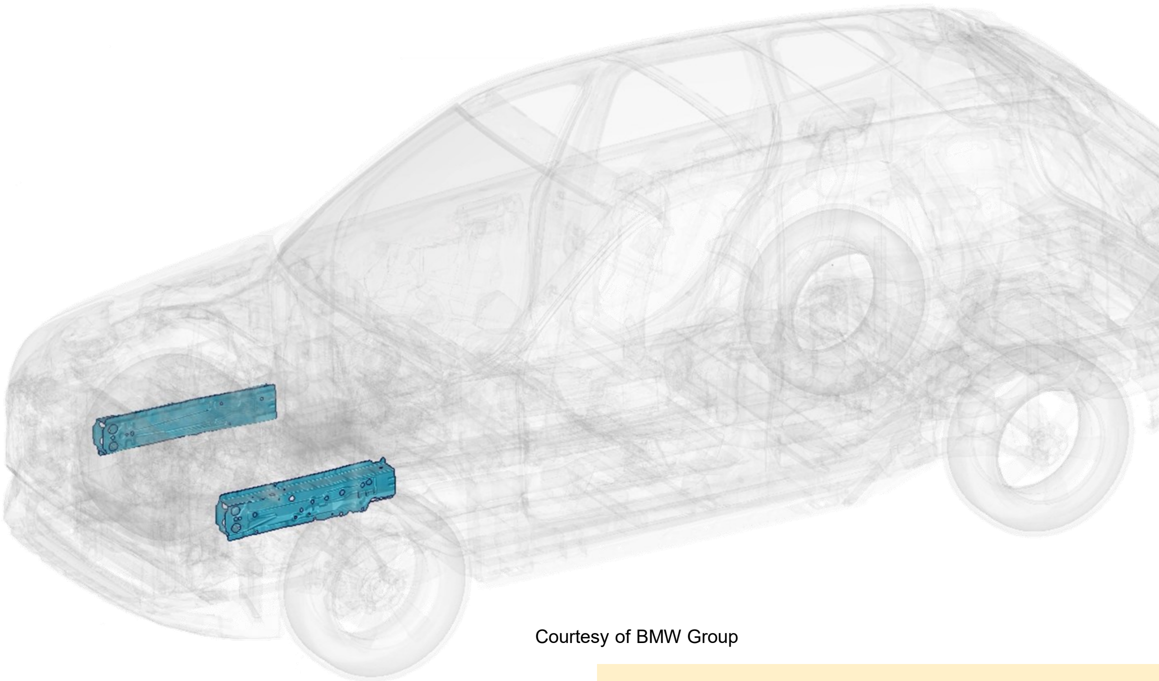
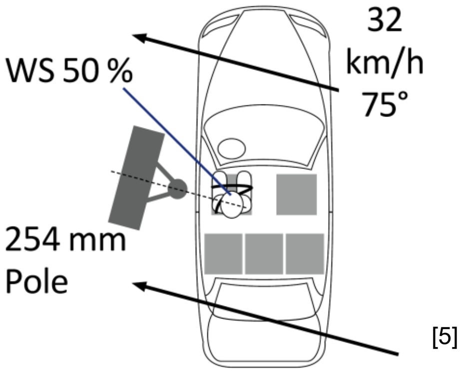


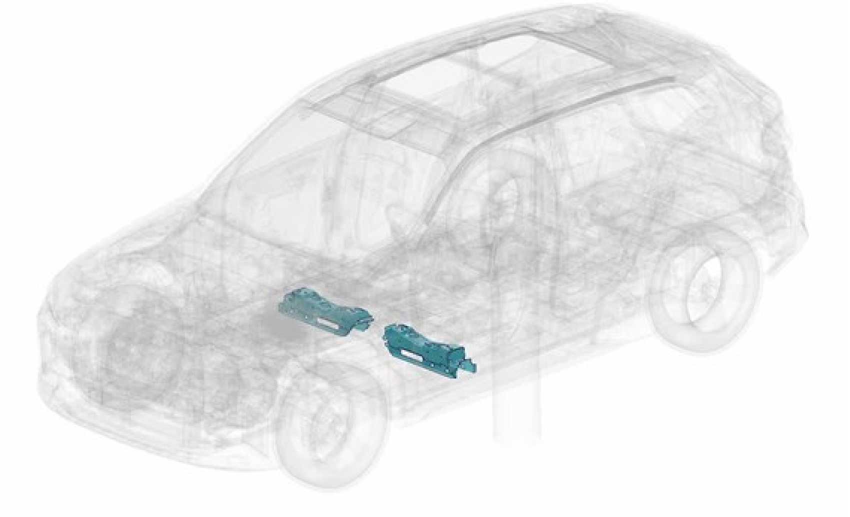
Courtesy of BMW Group

Examples: Hybrid Vehicle Crash Simulations

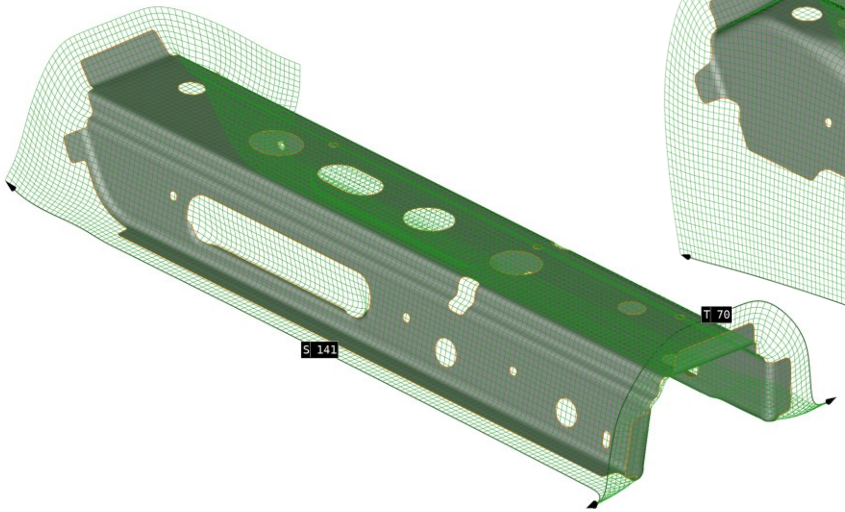
Side Crash: Car Against Rigid Pole

- Hybrid model with IGA seat cross-members
  - Basis + top component
  - Spotweld and bolt connections
  - Including dummy + airbags (~9M elements)

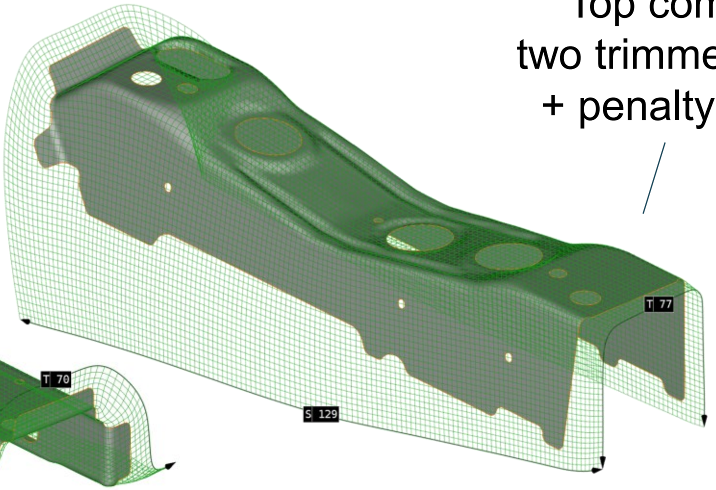


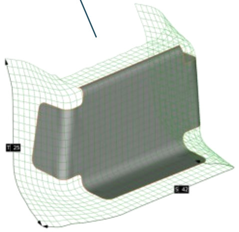


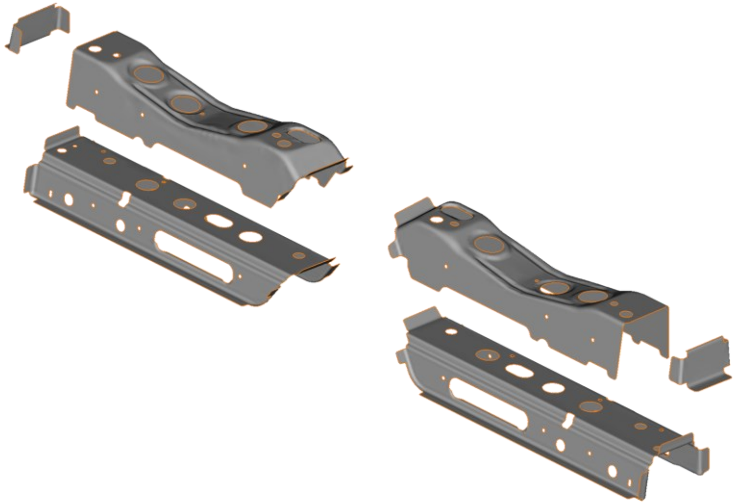
Basis component
single trimmed patch



Top component
two trimmed patches
+ penalty coupling







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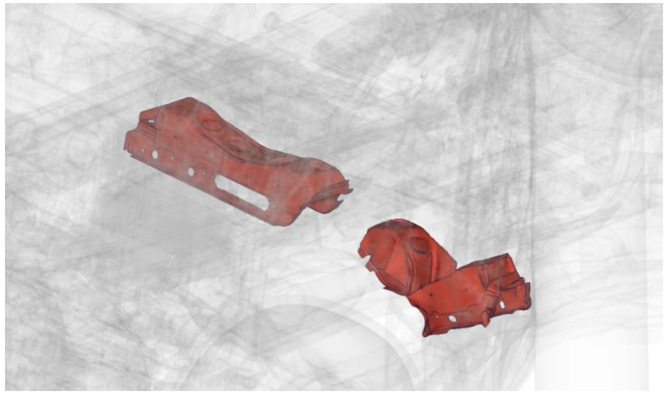
Examples: Hybrid Vehicle Crash Simulations

Side Crash: Car Against Rigid Pole

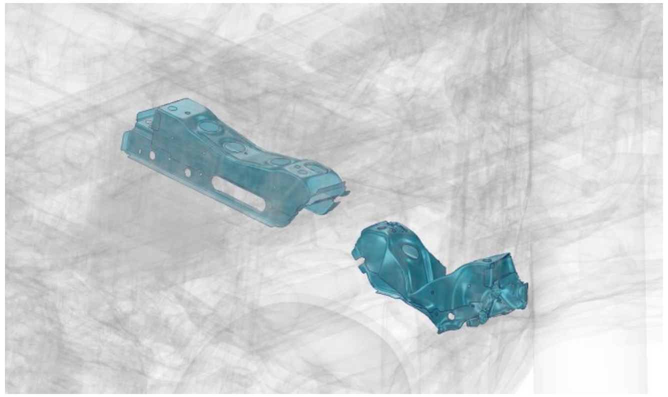
- Pure FEA vs. Hybrid IGA/FEA model

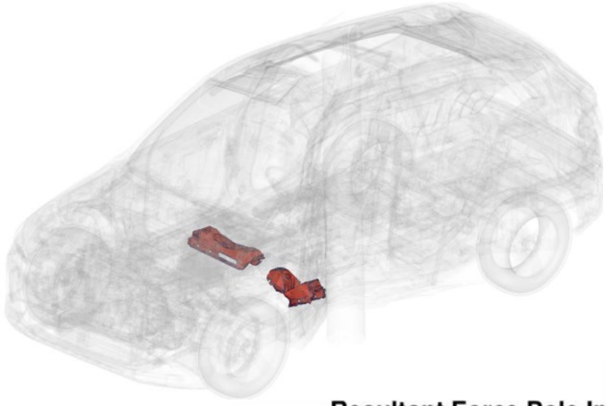
Oblique view

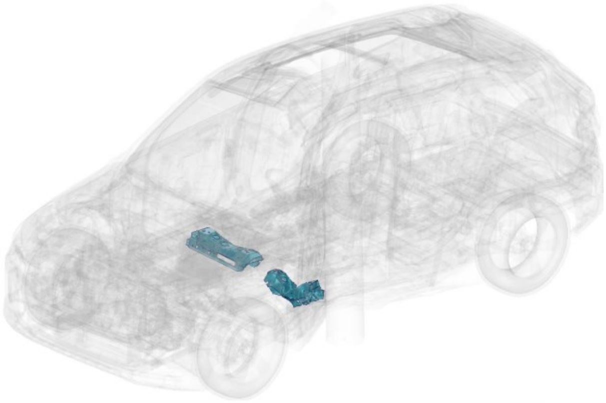
FEA

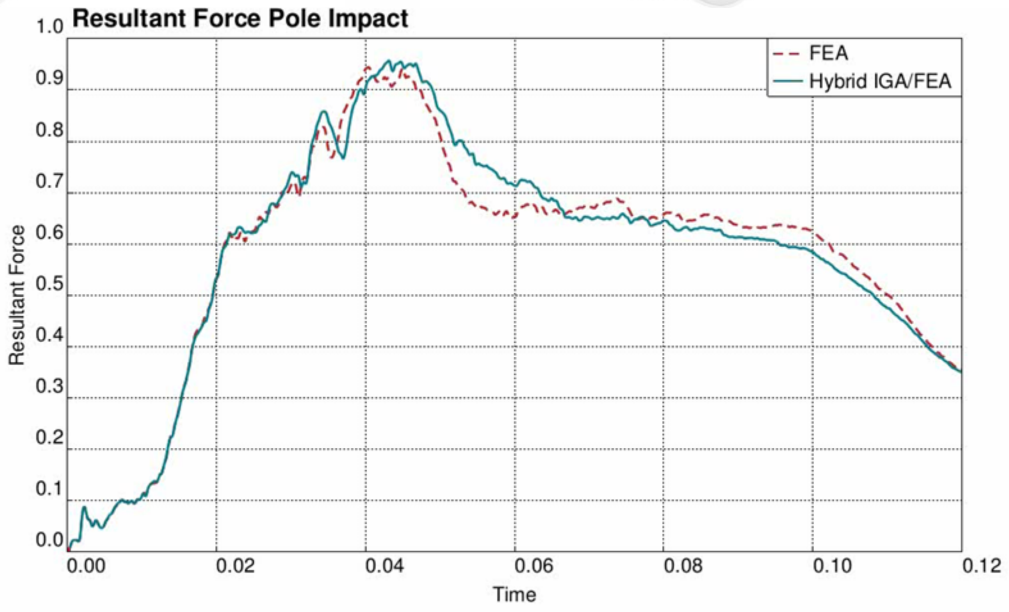


Hybrid IGA/FEA









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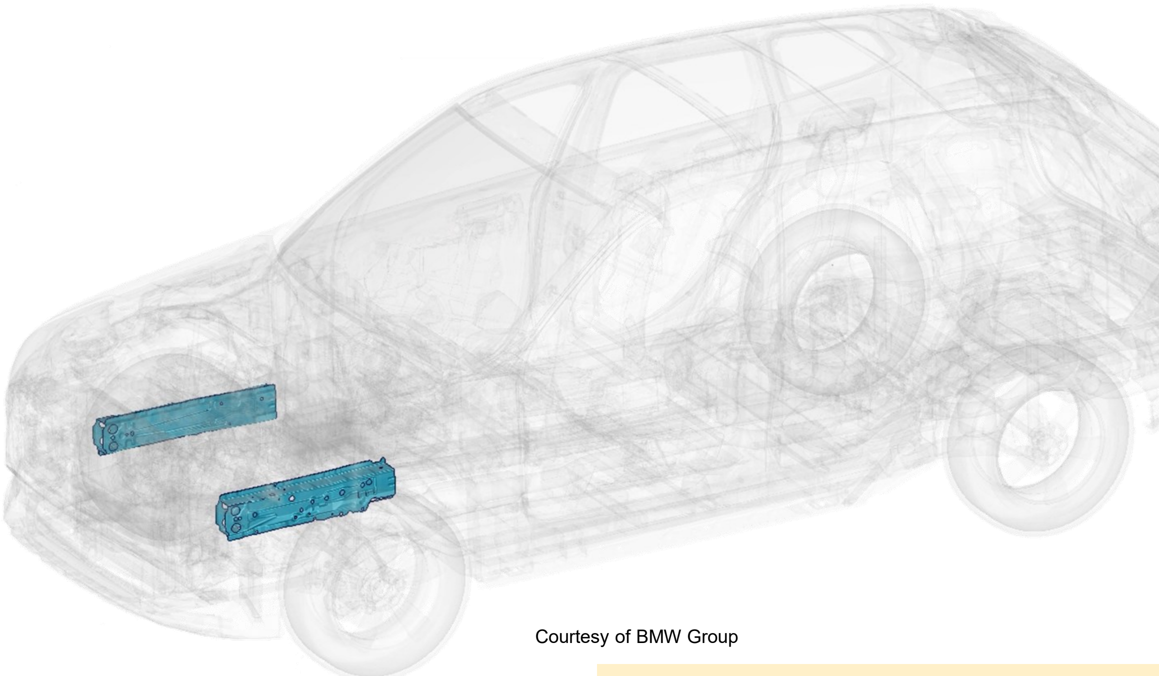

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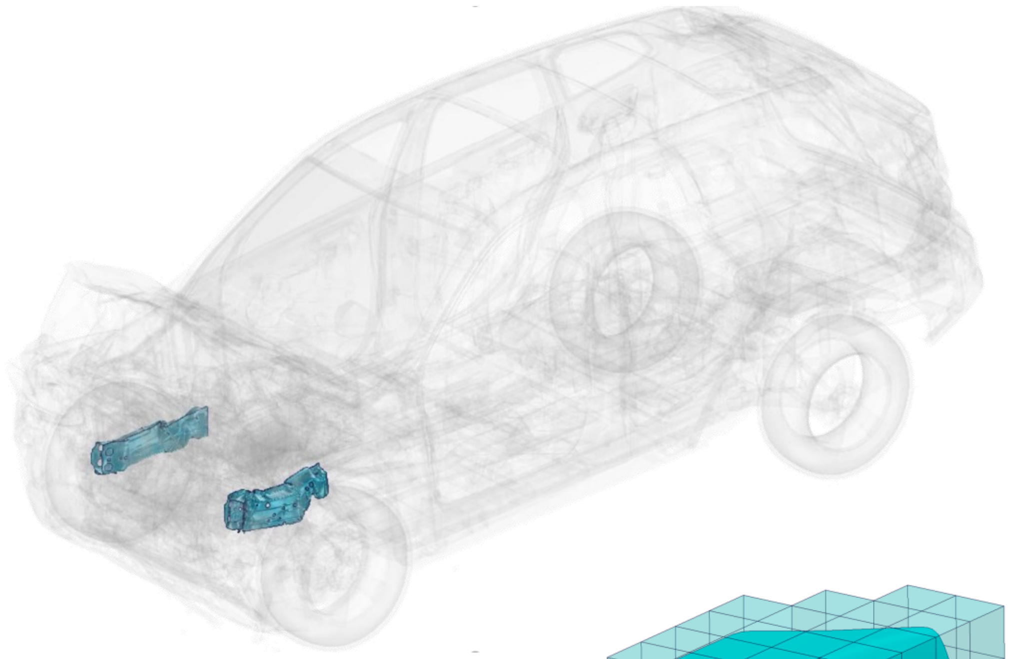
Conclusion

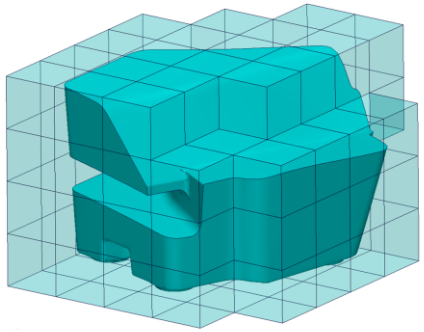
Hybrid Modeling

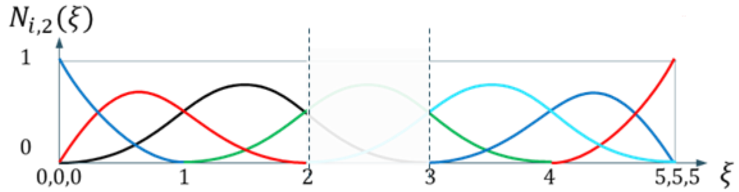
- Industrial workflow ANSA – LS-DYNA enables
  - Hybrid IGA/FEA full vehicle crash simulations
  - Simple 1:1 exchange of shell components

  → Ready for productive tests

- Next Steps
  - Increase numerical efficiency + robustness
  - Validation of damage and failure, connection technology
- Ongoing R&D topics
  - Improved modeling of cracks and discontinuities
  - Feature-based modeling
  - Trimmed IGA solids







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Thank You

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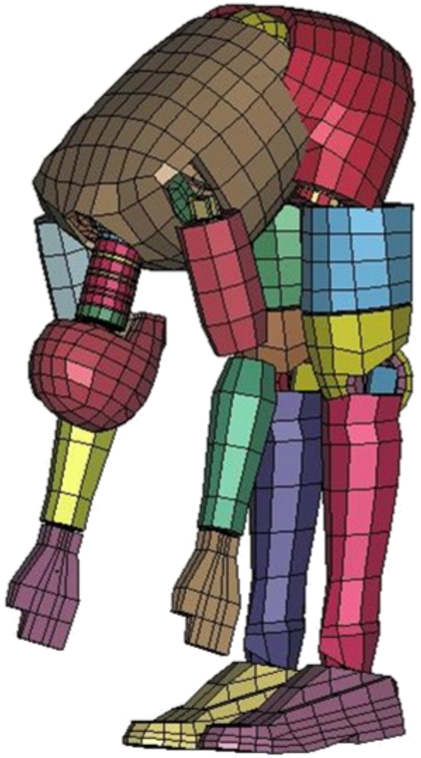

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