Powering Innovation That Drives Human Advancement

LS-DYNA中的等几何分析（IGA）简介

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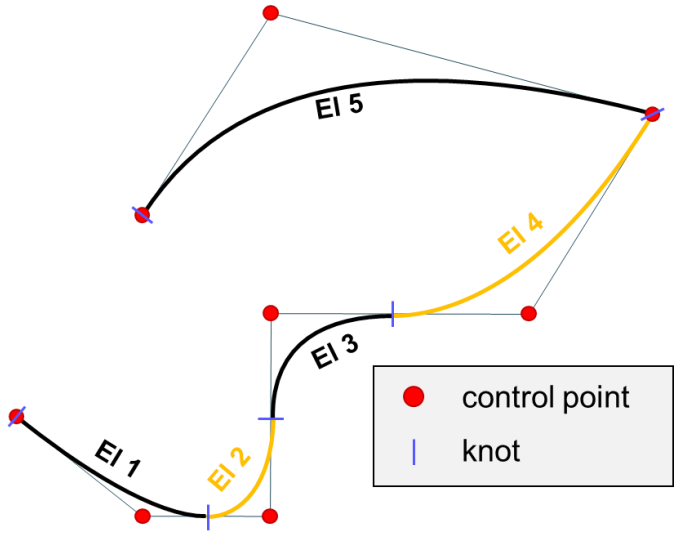
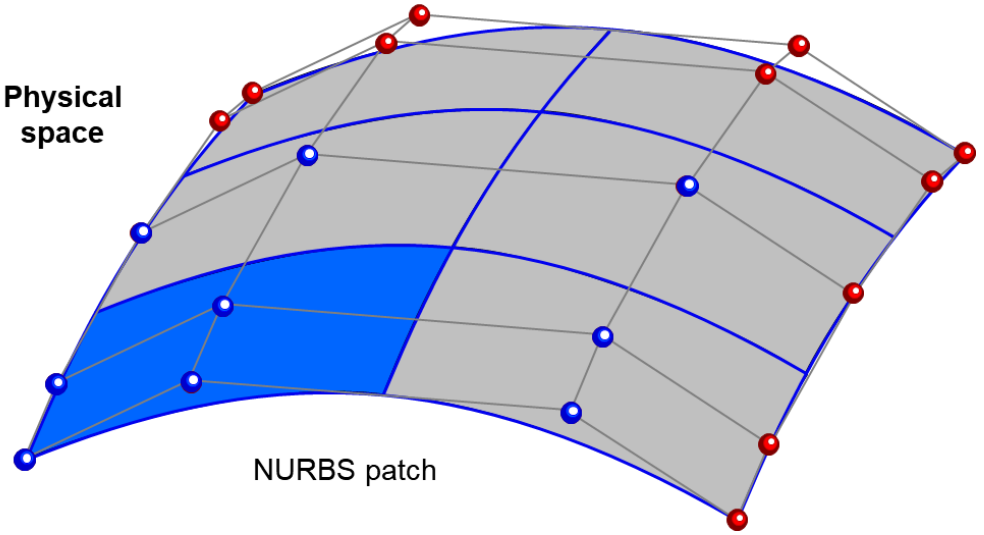
演讲者：董骁

什么是等几何分析（IGA）？

- Isogeometric Analysis
  - 使用B-spline作为形函数的FEA
  - 直接基于几何数据（NURBS）进行有限元分析

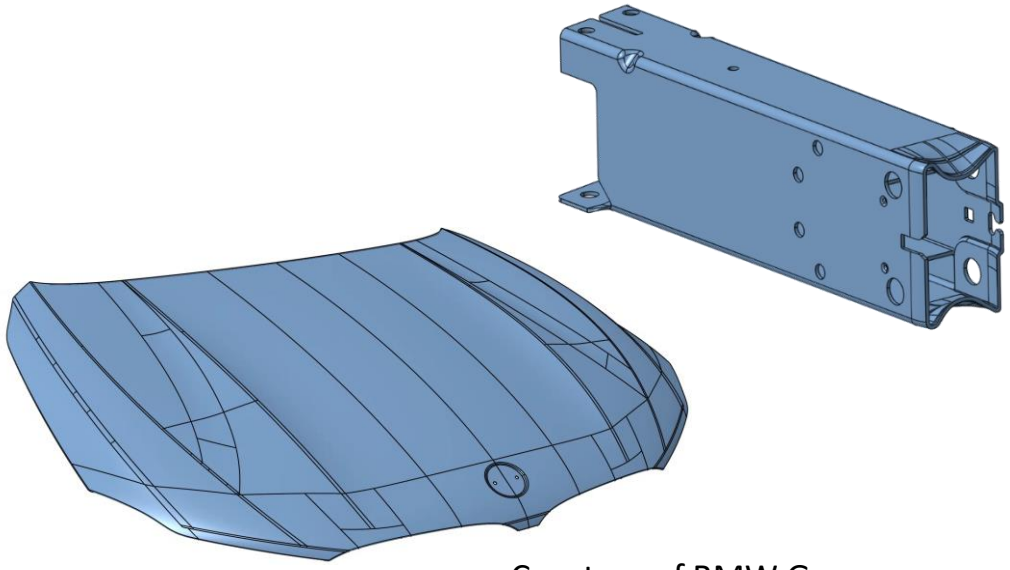


- NURBS（Non-Uniform Rational B-Splines）
  - 能够定义复杂的曲面
  - CAD软件常用的几何描述方式



CAD模型数据结构

- B-Rep
  - 目前业内最常使用的建模方法： Boundary Representation(B-rep)
    - 3D物体通过其外部表面来表征
    - 多个裁切的NURBS曲面
    - 定义拓扑关系



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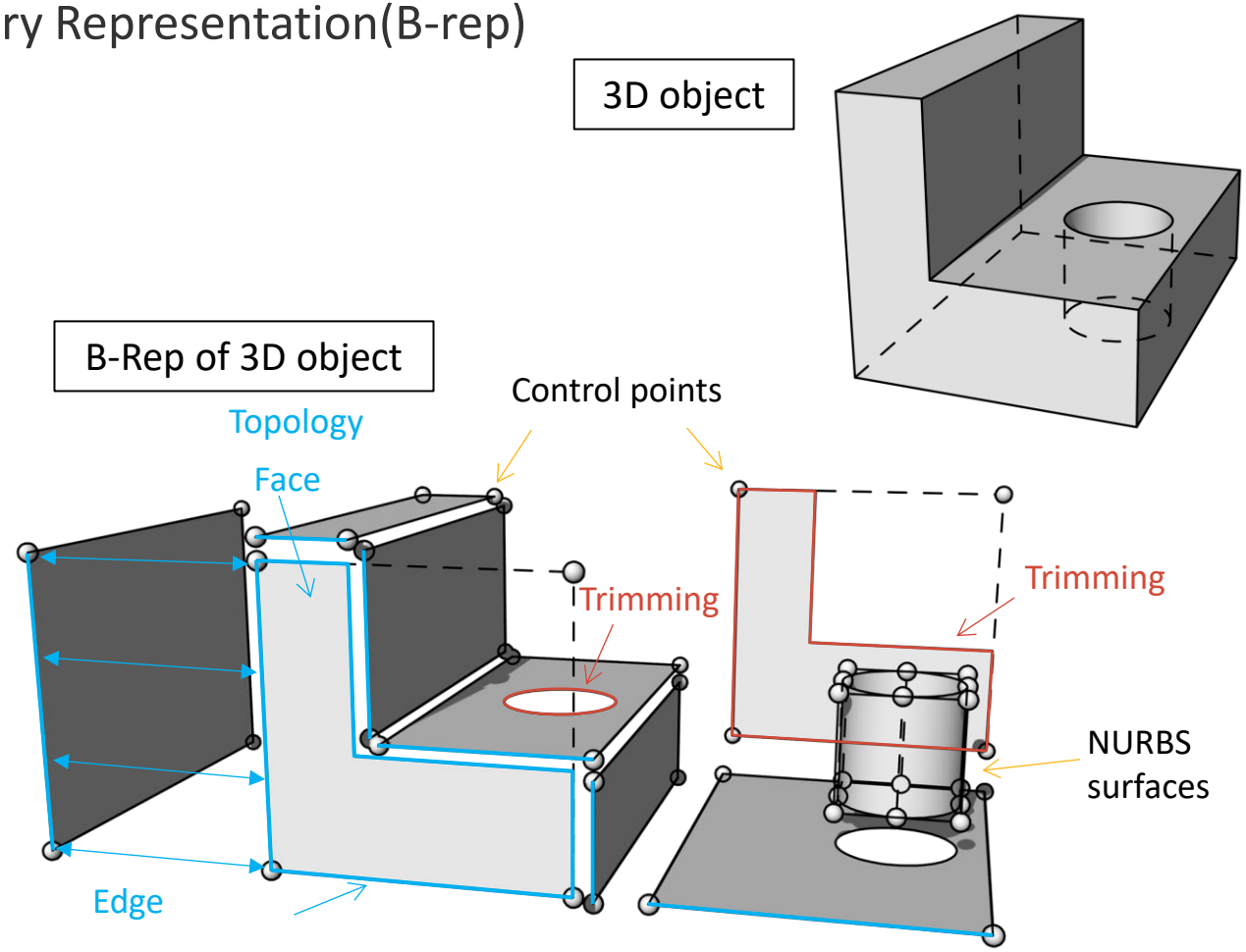
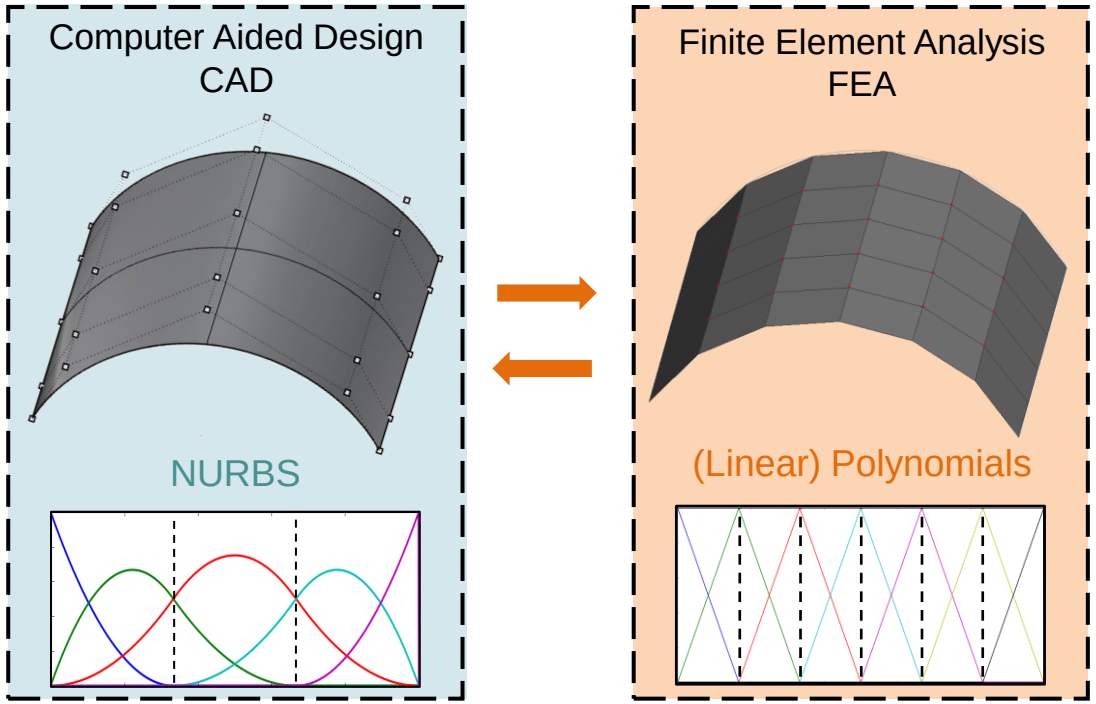


[1] M. Breitenberger, PhD Thesis, TUM, 2016

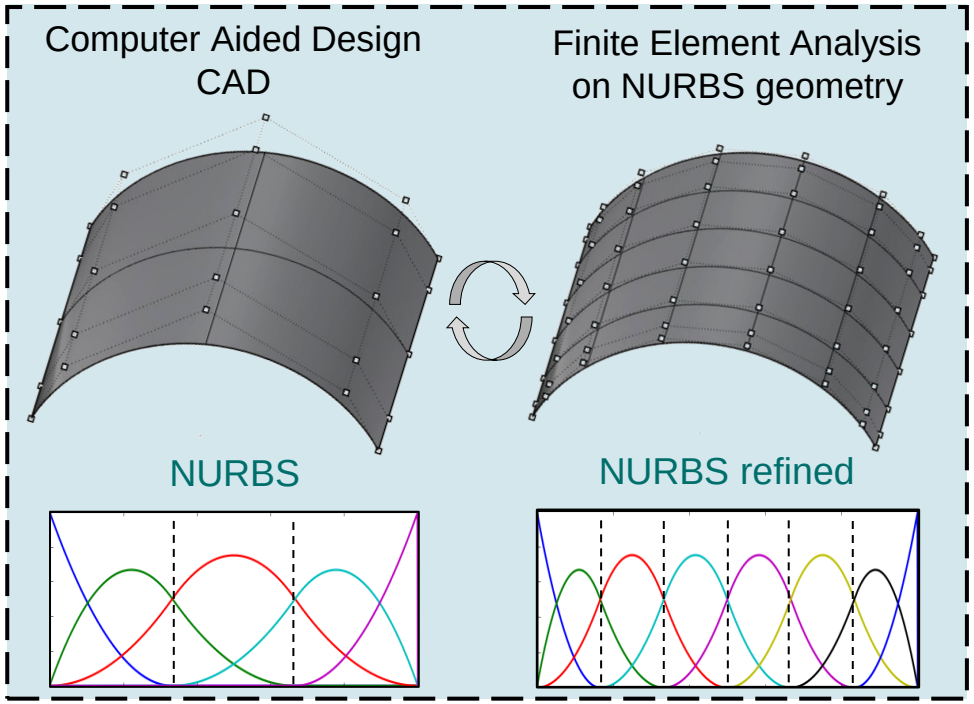
IGA和传统FEA方法的差异

Conventional Finite Element Analysis (FEA)



- 几何描述的改变（网格划分）
- 近似表征几何形状
- 花费时间成本和人力成本进行数据转换

Isogeometric Analysis (IGA)



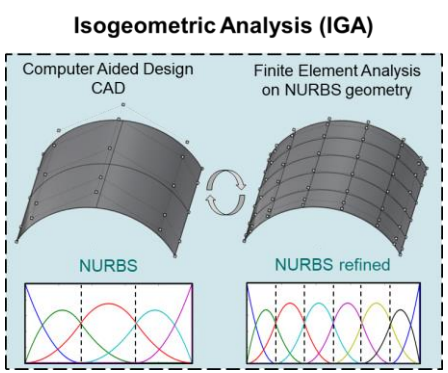
- 直接基于几何数据进行分析
- 精确表征几何形状
- 设计和分析数据协同

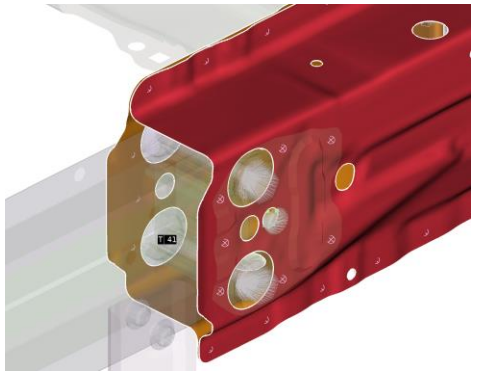
IGA方法的优势

- 加快研发流程，设计和分析一体化
  - 设计数据和分析数据**拥有统一的数据结构**（基于NURBS）
  - 不依赖网格的建模方法（焊点、连接等）

- 更高的预测精度（相同网格尺寸）
  - IGA模型更贴近原始几何特征
  - 使用**更高阶**、**更连续**的基函数
    - 更平滑的的分析结果，更精确的捕捉变形

- 提高分析效率
  - 相同精度等级下，IGA可以有更大的网格尺寸
  - 显式分析**更大的timestep**





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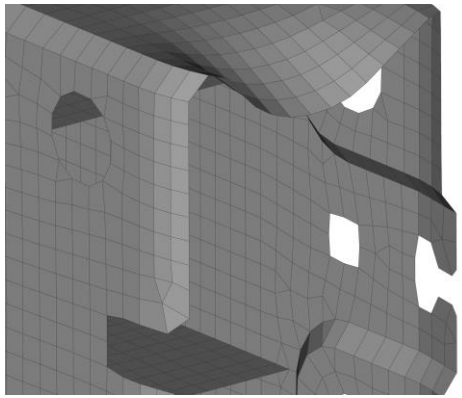
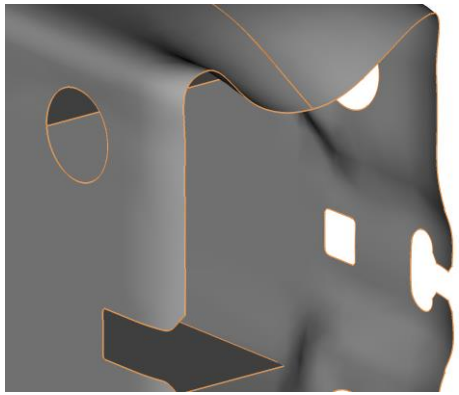
Linear FEA



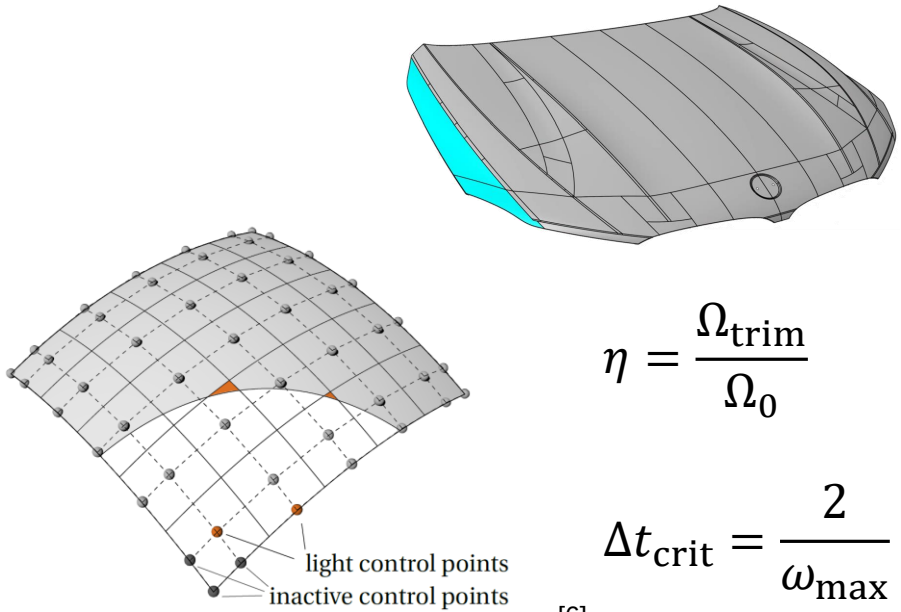
IGA



Courtesy of BMW Group

IGA方法的优势

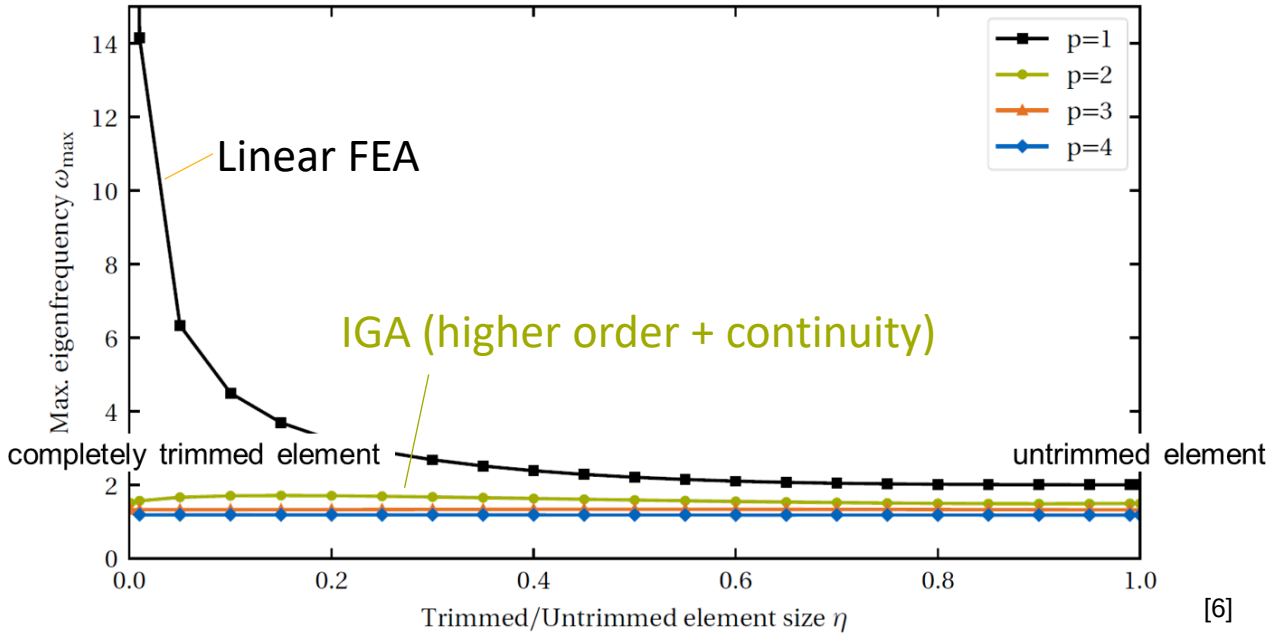
- 时间步长
  - 裁切NURBS单元对于时间步长没有影响(C^{p-1} and $p > 1$)



[6]

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

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

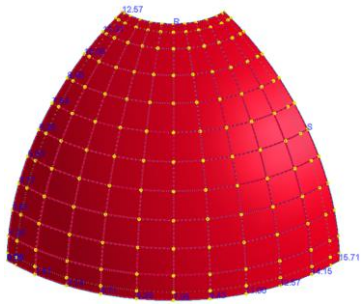


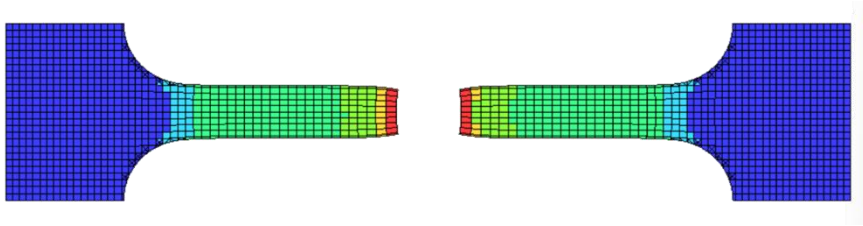
[6]

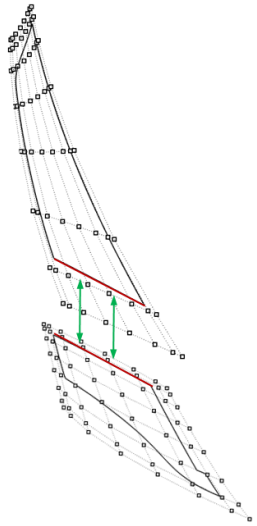
[6] L. F. Leidinger, Explicit Isogeometric B-Rep Analysis for Nonlinear Dynamic Crash Simulations: Integrating Design and Analysis by Means of Trimmed Multi-Patch Shell Structures, PhD thesis, Technical University of Munich, Germany (2020).

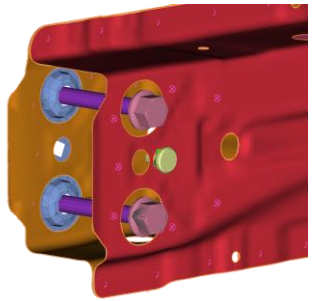
LS-DYNA中的IGA方法

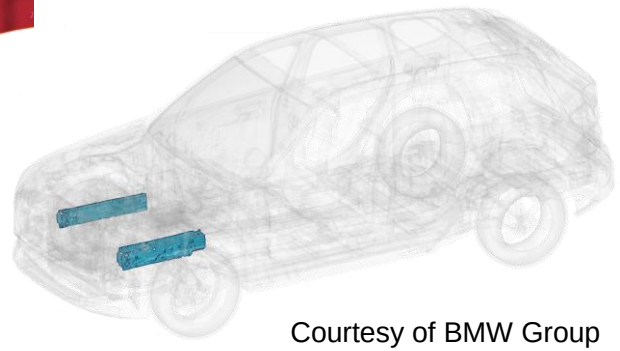
- 支持的功能特性
  - Shell和Solid，包括trimmed和untrimmed
  - 显式和隐式分析
  - SMP和MPP
  - 几乎所有的材料本构模型
  - 材料损伤和失效，包括单元删除
  - 边界条件和载荷
  - 接触
  - 模型连接（焊点、tied接触等）
  - 网格插值（用于后处理以及接触）
  - 裁剪和连接NURBS patch
  - FEA和IGA混合建模
  - 时间步长估算和质量缩放（显式）











Courtesy of BMW Group

LS-DYNA中的IGA方法

- 关键字结构

传统有限元分析关键字结构

```
*NODE                   NID X Y Z
*ELEMENT_SHELL          EID PID N1 N2 N3 N4
*PART                   PID SECID MID
*SECTION_SHELL          SECID ELFORM SHRF NIP
*MAT_ELASTIC            MID RO E PR
```

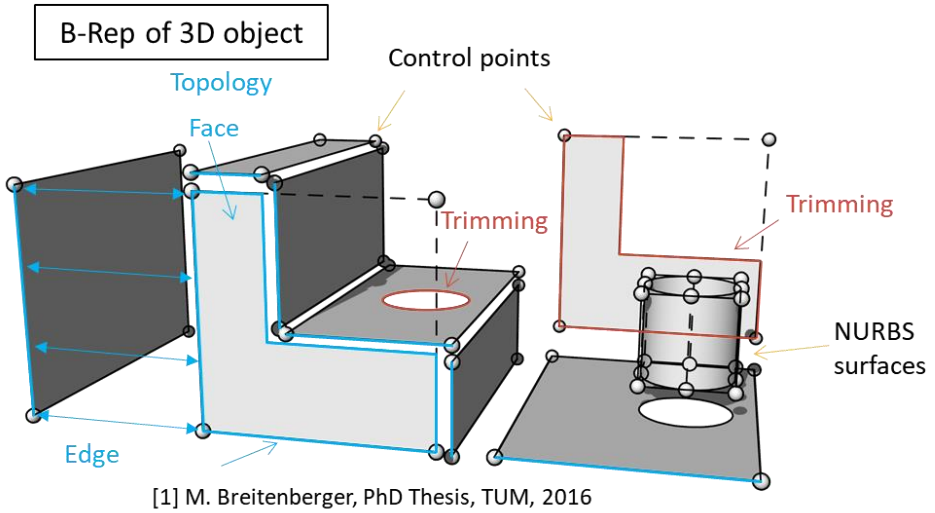
IGA分析关键字结构

```
*IGA-KWs for Geometry and Topology
*IGA_SHELL              SID PID NISR NISS
*PART                   PID SECID MID
*SECTION_IGA_SHELL      SECID ELFORM SHRF NIP IRL
*MAT_ELASTIC            MID RO E PR
```

LS-DYNA中的IGA方法

- 关键字结构

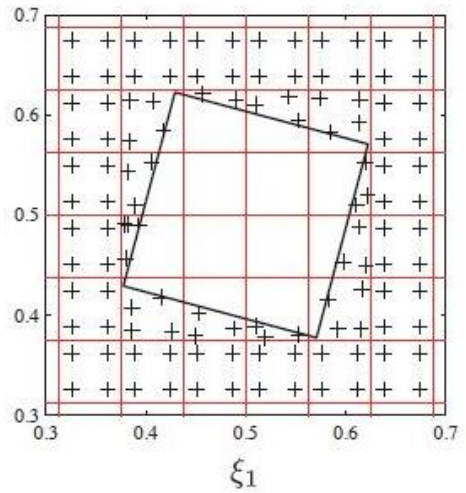
*IGA-KWs for Geometry and Topology	
*IGA_1D_NURBS_UVW	NID NR PR RKi U V W WGT
*IGA_EDGE_UVW	EID EXYZID NID
*IGA_EDGE_XYZ	EID NID ... PSID
*IGA_1D_BREP	BRID EIDi
*IGA_2D_NURBS_XYZ	NID NR NS PR PS RKi SKi X Y Z WGT
*IGA_FACE_XYZ	FID NID ORI PSID ESID BRIDi
*IGA_SHELL	SID PID NISR NISS
*PART	PID SECID MID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



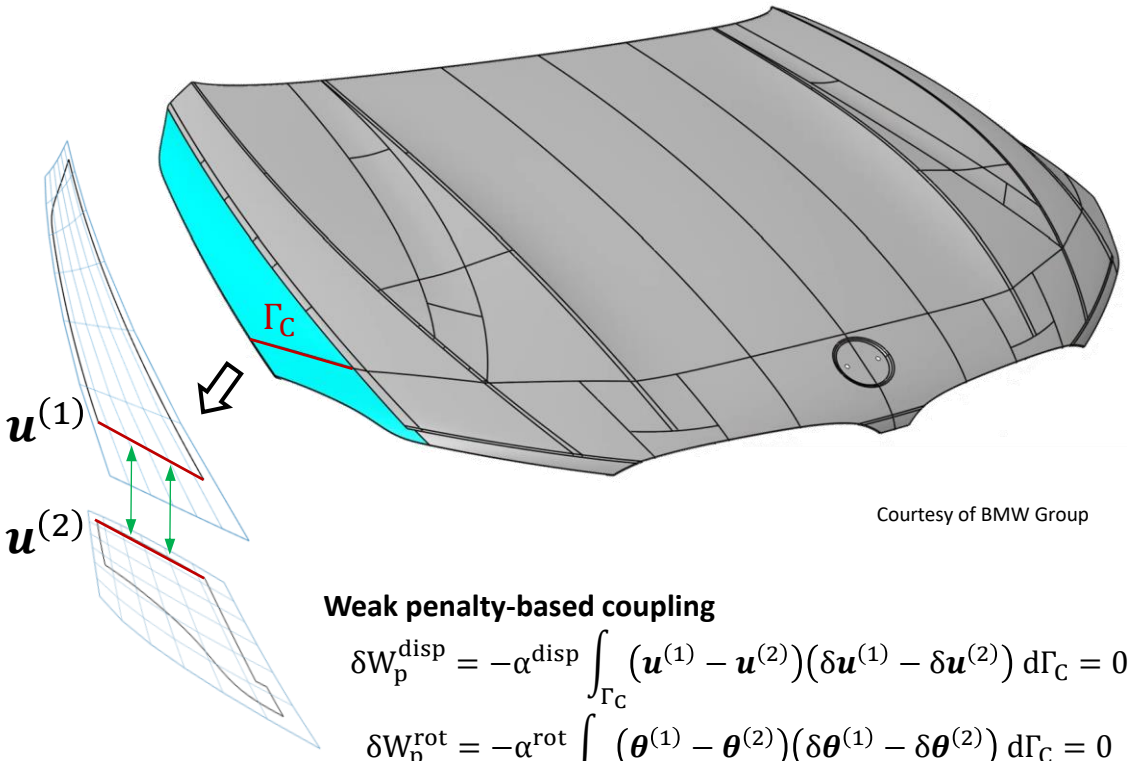
[1] M. Breitenberger, PhD Thesis, TUM, 2016

Trimmed IGA Shells

- 前处理
  - 处理几何数据（B-Rep），生成*IGA关键字
  - NUBRS单元的数值积分点[3]
  - 曲面之间耦合（连接），边界条件施加[3,4,5]



[2]



Courtesy of BMW Group

Weak penalty-based coupling

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

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

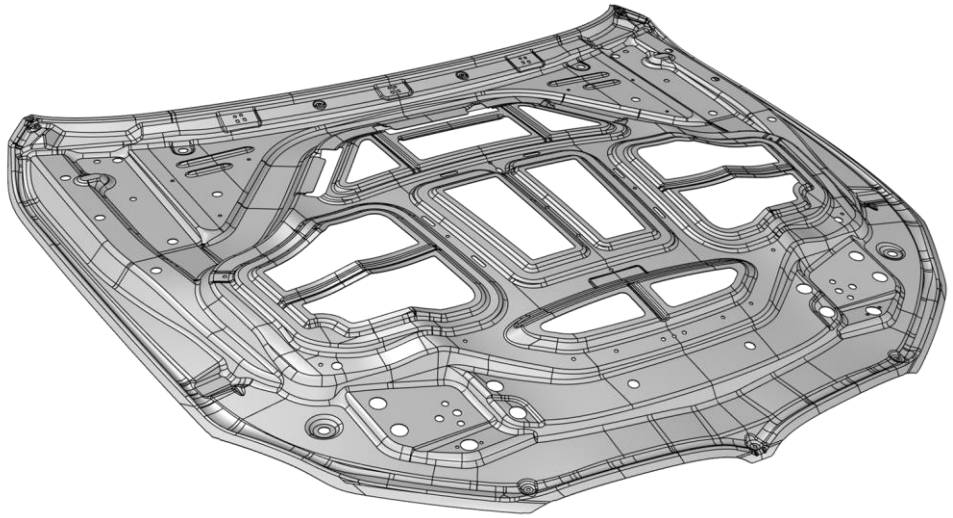
[2] A.P. Nagy & D.J. Benson, On the numerical integration of trimmed isogeometric elements. Comput. Methods Appl. Mech. Eng. 284 (2015), 165–185.
[3] M. Breitenberger, A. Apostolatos, B. Philipp, R. Wüchner, K.-U. Bletzinger, Analysis in computer aided design: Nonlinear isogeometric B-Rep analysis of shell structures, Comput. Methods Appl. Mech. Eng. 284 (2015) 401–457.
[4] 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.
[5] 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).

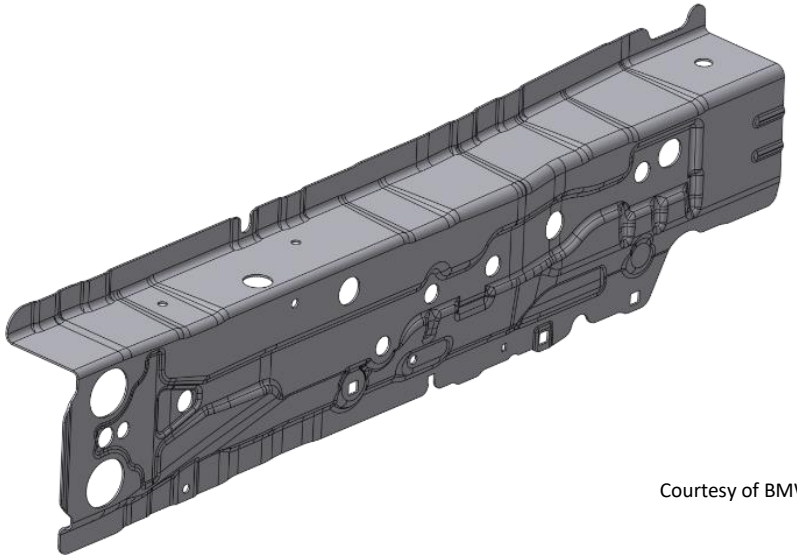
Trimmed IGA Shells

- 当前的CAD模型
  - 在设计时并未考虑适用于IGA分析
    - 窄小的面 -> 小的NURBS单元
    - 使用更高阶的NURBS曲面
    - 不包含中面数据
  - 几何处理
    - 生成中面
    - 降低阶次，合并/切割NURBS曲面
    - 定义单元最大/最小尺寸，生成均匀的NURBS单元

ANSA PRE PROCESSOR

- 未来的CAD模型
  - 考虑分析的适用性，基于模型规范
    - 提供中面数据
    - 规定最小的网格尺寸、最大的阶次等





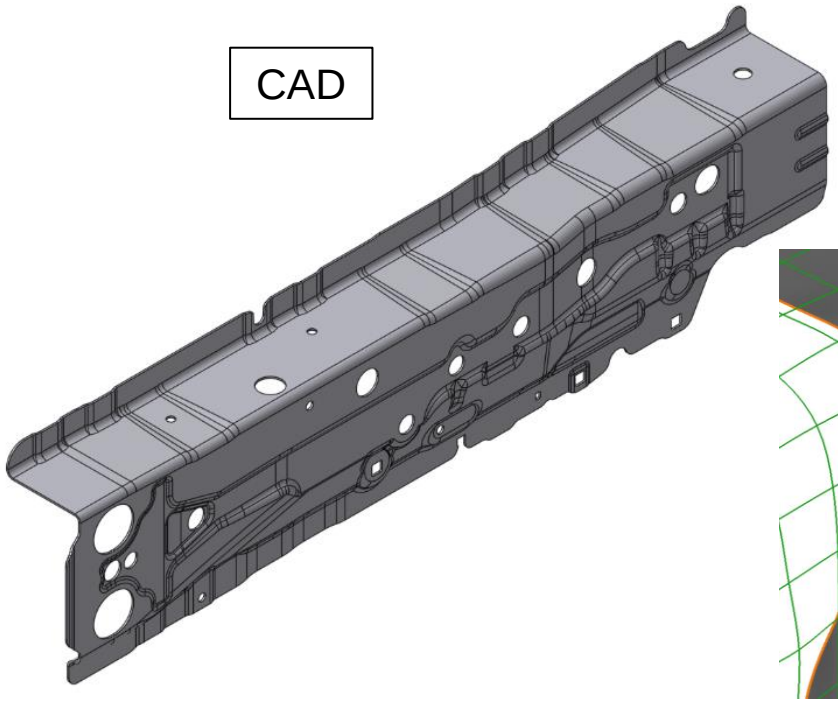
Courtesy of BMW Group

Trimmed IGA Shells

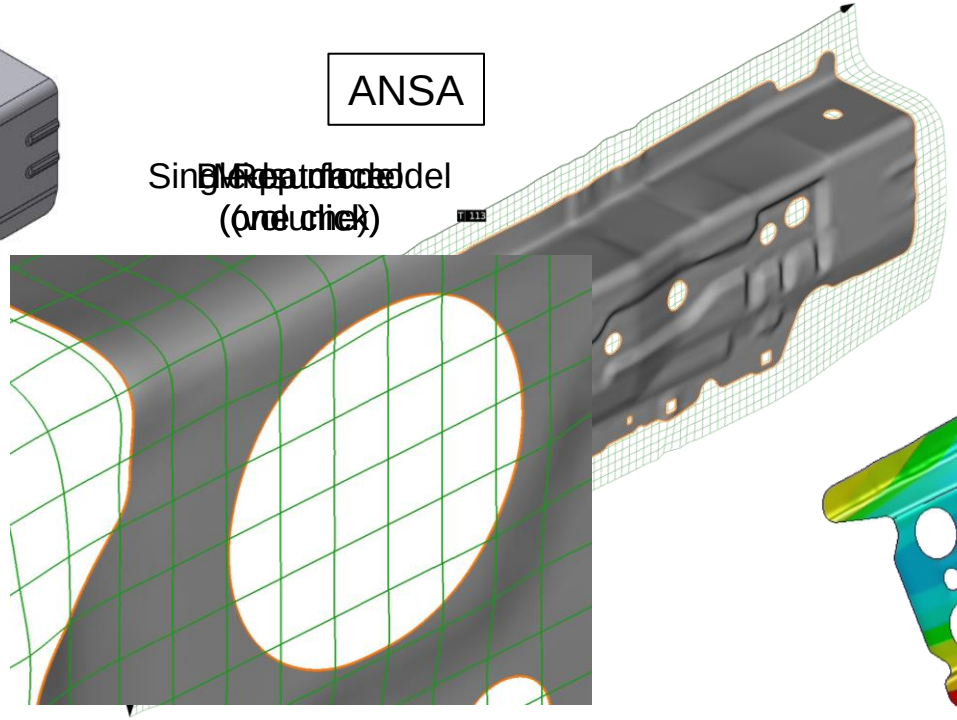
- 使用ANSA处理适用于分析的模型
  - 导入B-rep模型
  - 生成中面
  - 生成均匀的NURBS单元（定义单元最大/最小尺寸，合并patch）

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

CAD

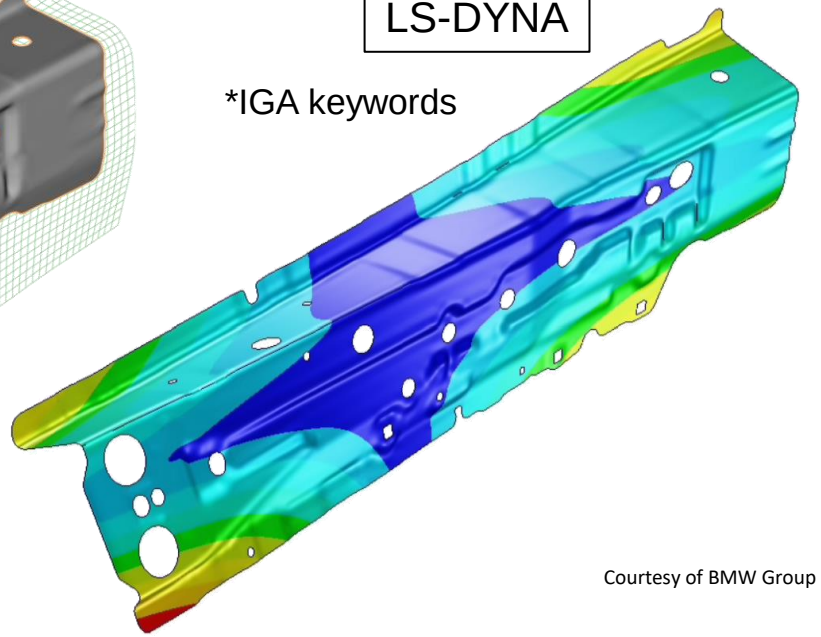


ANSA



LS-DYNA

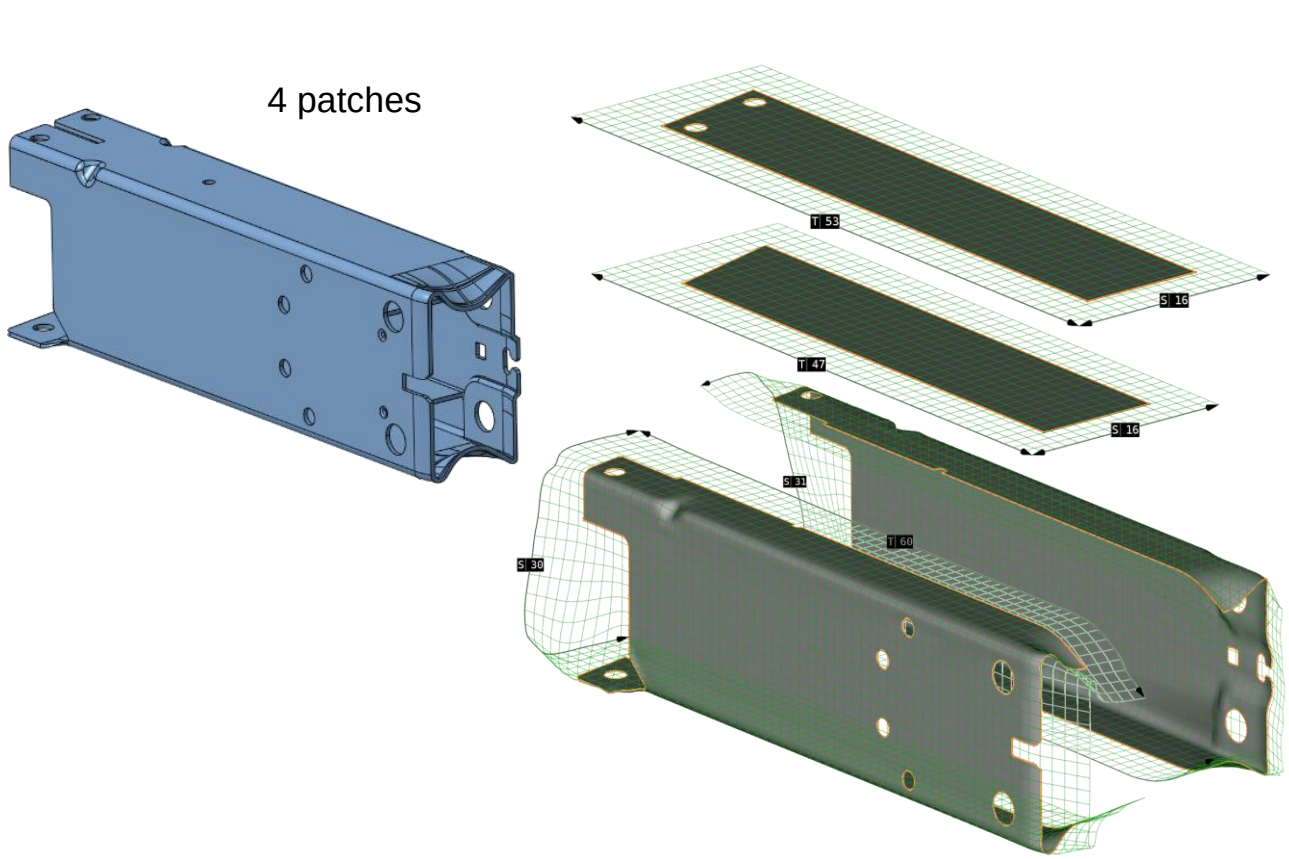
*IGA keywords

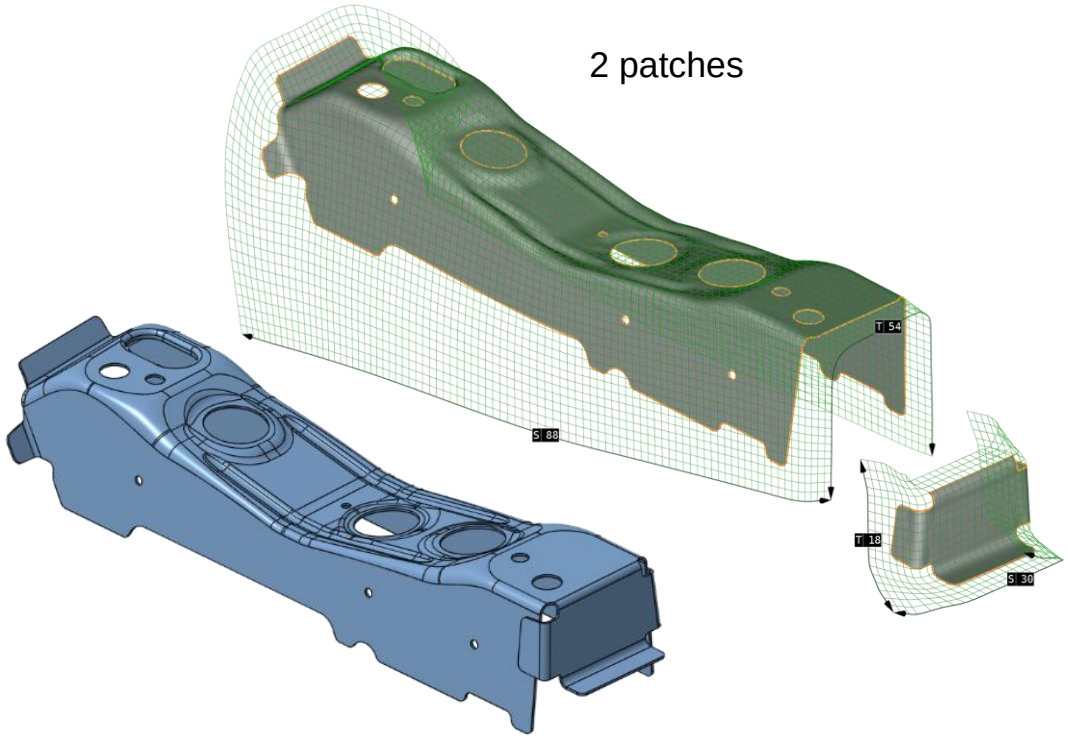


Courtesy of BMW Group

Trimmed IGA Shells

- 某些情况下，单个的NURBS patch并不足够
  - 封闭的截面，T-joint，重叠等
- 使用多个NURBS patch，多个patch之间进行耦合





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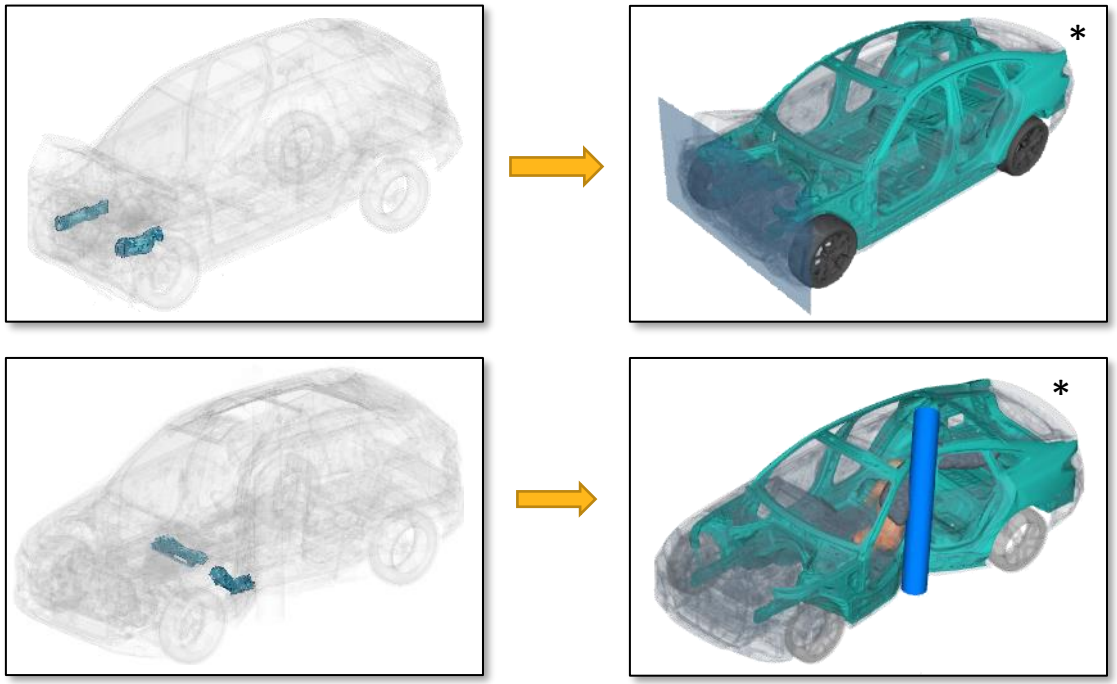
Trimmed IGA Shells | 应用案例

- 混合IGA/FEA车辆模型

LS-DYNA
Forum 2022

LS-DYNA
Conference 2023



Up to 4 IGA components

288 IGA components

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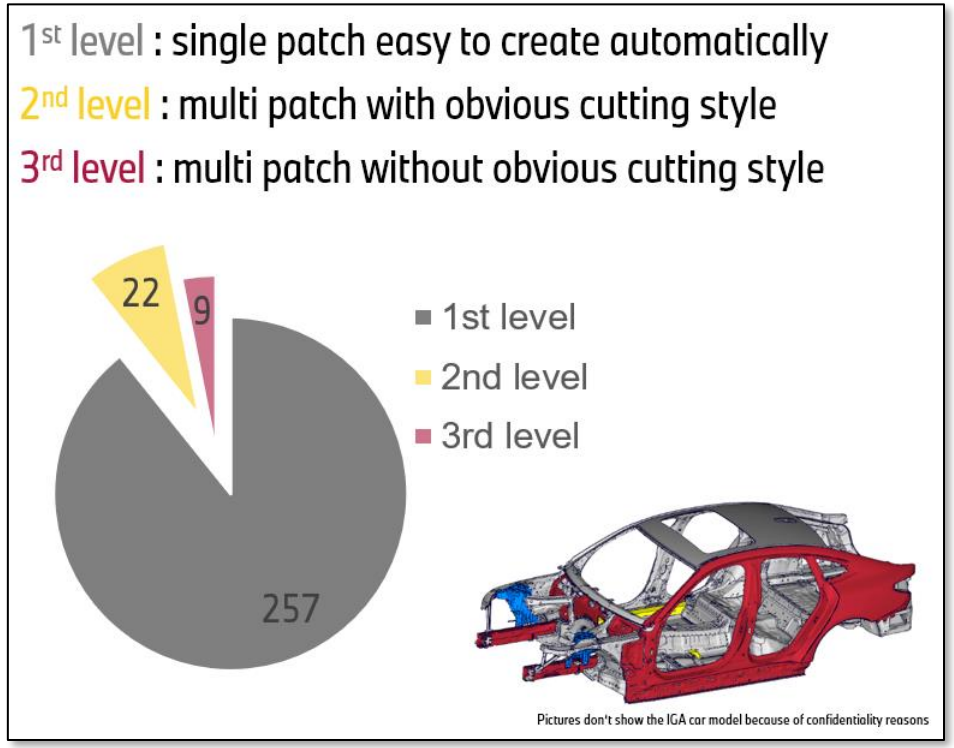
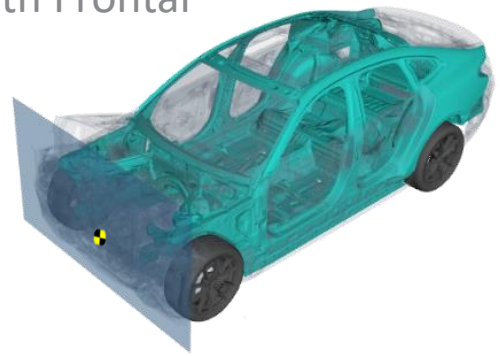


[7] F. Bauer, T. Yugeng, L. Leidinger, S. Hartmann, Experience with Crash Simulations using an IGA Body in White. 14th European LS-DYNA Conference 2023, Baden-Baden, Germany.

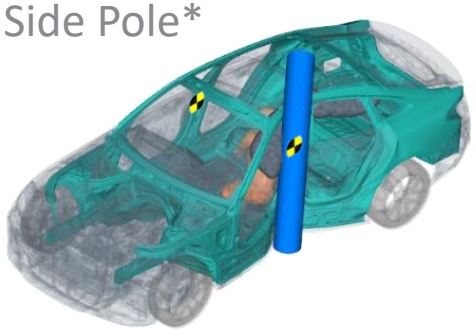
Trimmed IGA Shells | 应用案例

- 混合IGA/FEA车辆模型
  - 与传统FEA模型结果接近

Full Width Frontal*



Side Pole*



Courtesy of BMW Group

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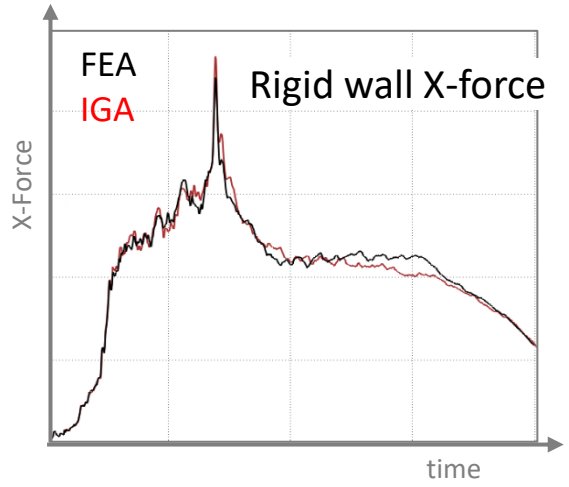
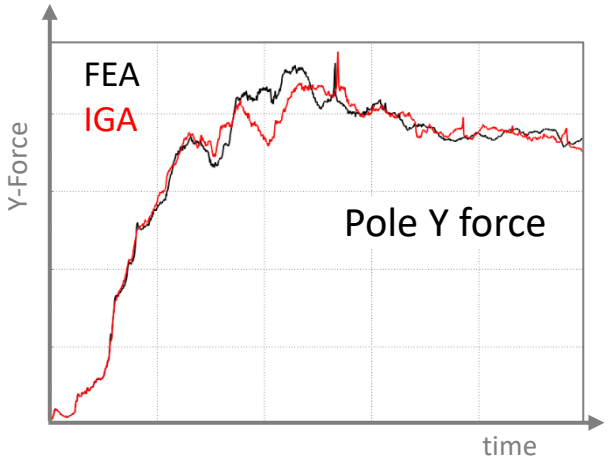


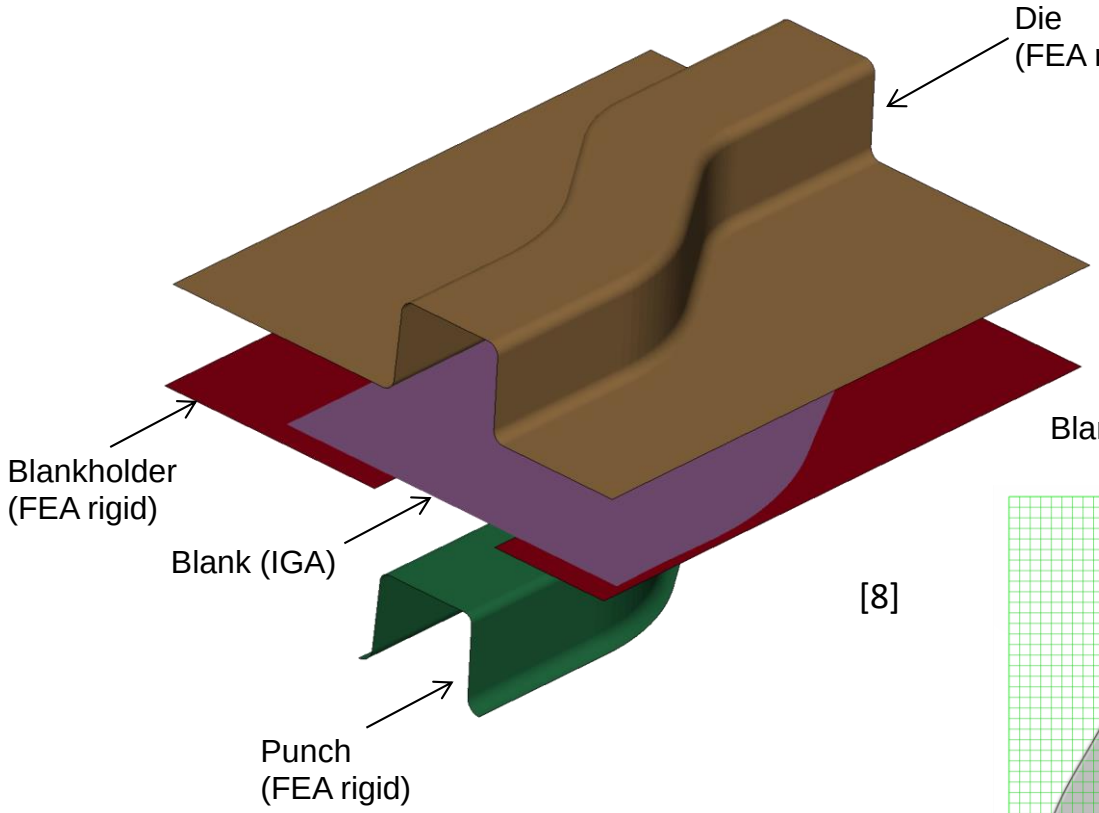


[7] F. Bauer, T. Yugeng, L. Leidinger, S. Hartmann, Experience with Crash Simulations using an IGA Body in White. 14th European LS-DYNA Conference 2023, Baden-Baden, Germany.

Trimmed IGA Shells |应用案例

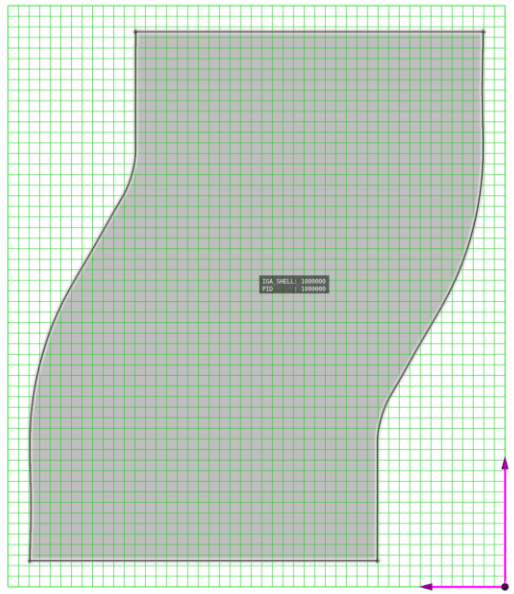
- S-RAIL钣金冲压模型
  - Numisheet benchmark
  - 模具：刚体的FEA shell单元
  - 坯料：
    - Trimmed IGA shell, ELFORM=3
    - FEA shell, ELFORM=2/16

- 目的：比较IGA模型和FEA模型的精度和效率



[8]

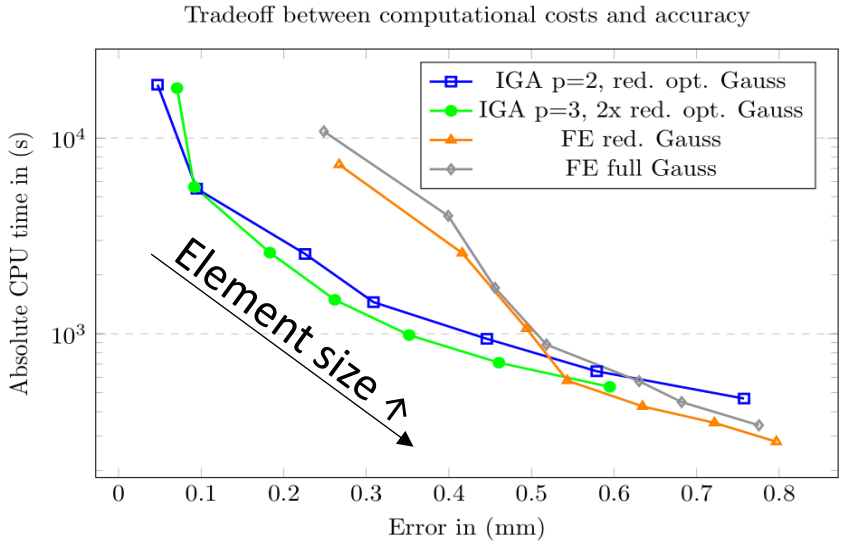
Blank modelled with trimmed IGA shells

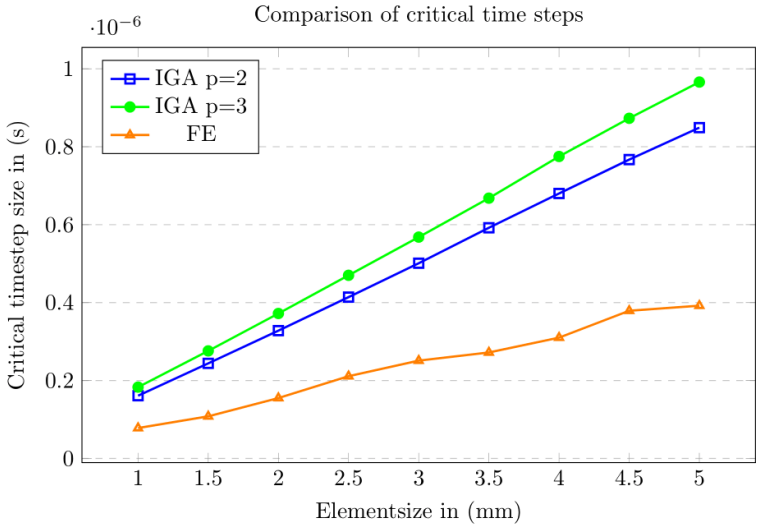


[8] C. Hollweck, L. Leidinger, S. Hartmann, L. Liping, M. Wagner, R. Wüchner. Systematic assessment of isogeometric sheet metal forming simulations based on trimmed, multi-patch NURBS models in LS-DYNA. 14th European LS-DYNA Conference 2023, Baden-Baden, Germany.

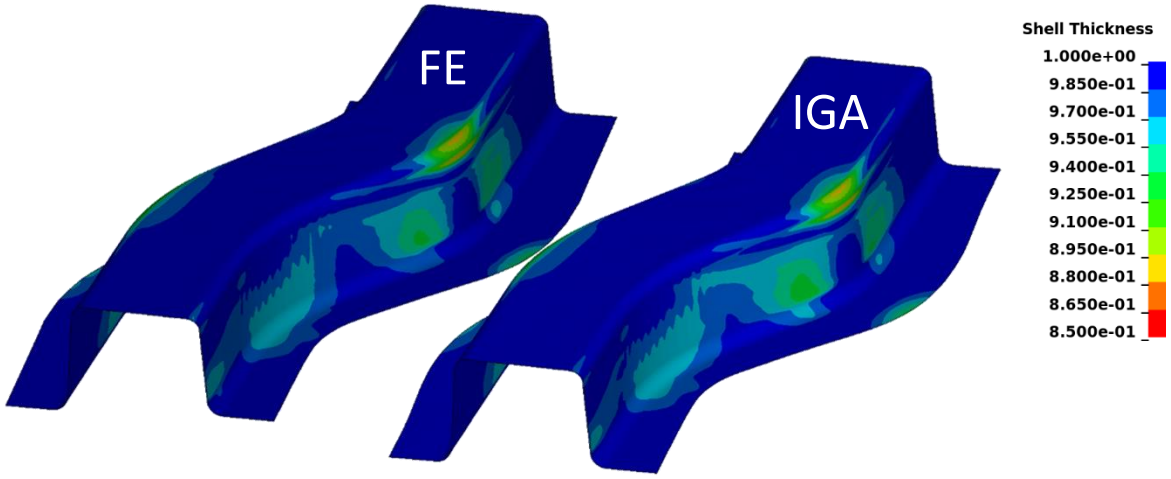
Trimmed IGA Shells | 应用案例

- S-RAIL钣金冲压模型
  - 更大的Timestep
  - 相同的计算时间时，IGA有更高的精度
  - 相同的精度时，IGA有更短的计算时间





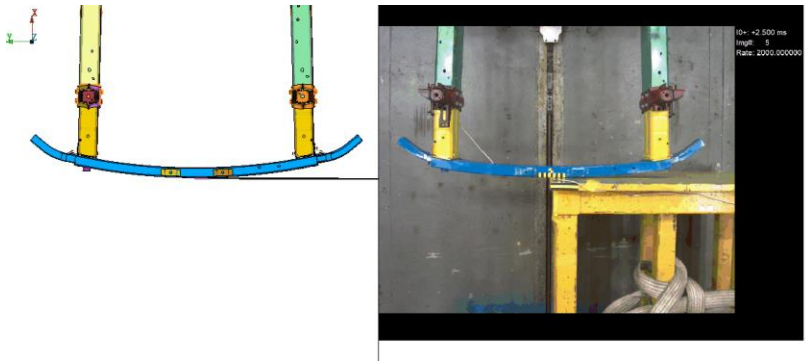
[8]



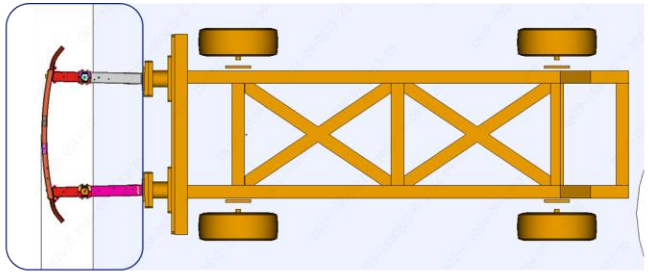
[8] C. Hollweck, L. Leidinger, S. Hartmann, L. Liping, M. Wagner, R. Wüchner. Systematic assessment of isogeometric sheet metal forming simulations based on trimmed, multi-patch NURBS models in LS-DYNA. 14th European LS-DYNA Conference 2023, Baden-Baden, Germany.

Trimmed IGA Solids | 应用案例

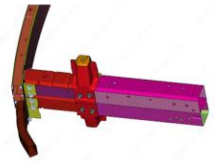
- 前防撞梁子系统耐撞性分析
  - 计算速度提升约40%(64核 5h->3h)
  - 在同样设置的情况下IGA与FEA的变形模式接近
  - 在变形的褶皱部位IGA变形更光滑，与试验的褶皱部位更接近

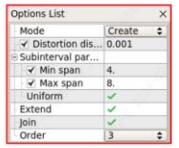


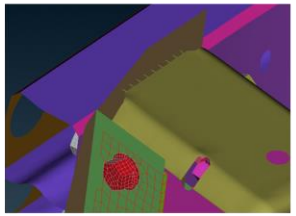
IGA(Correlation)&Test



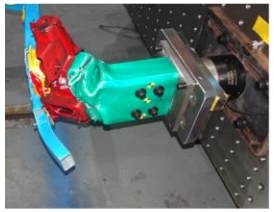
IGA Model:
1. Crash box
2. Bump beam
3. Longitude rail

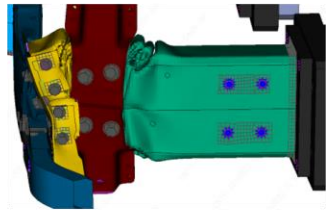


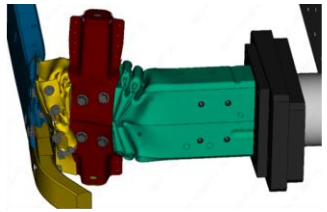




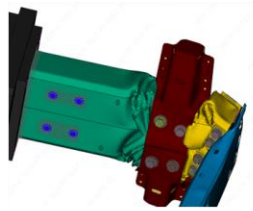
Connection（同FEA）:
1. Spot line
2. Bolt
3. Glue
4. Weld point



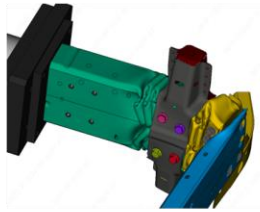




Test



FEA



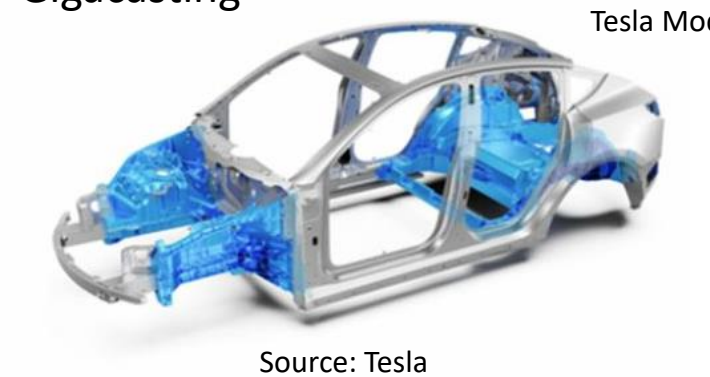
IGA

Trimmed IGA Solids

- 基于实体网格的碰撞模型
  - 求解效率、结构精度、前处理效率不可能三角

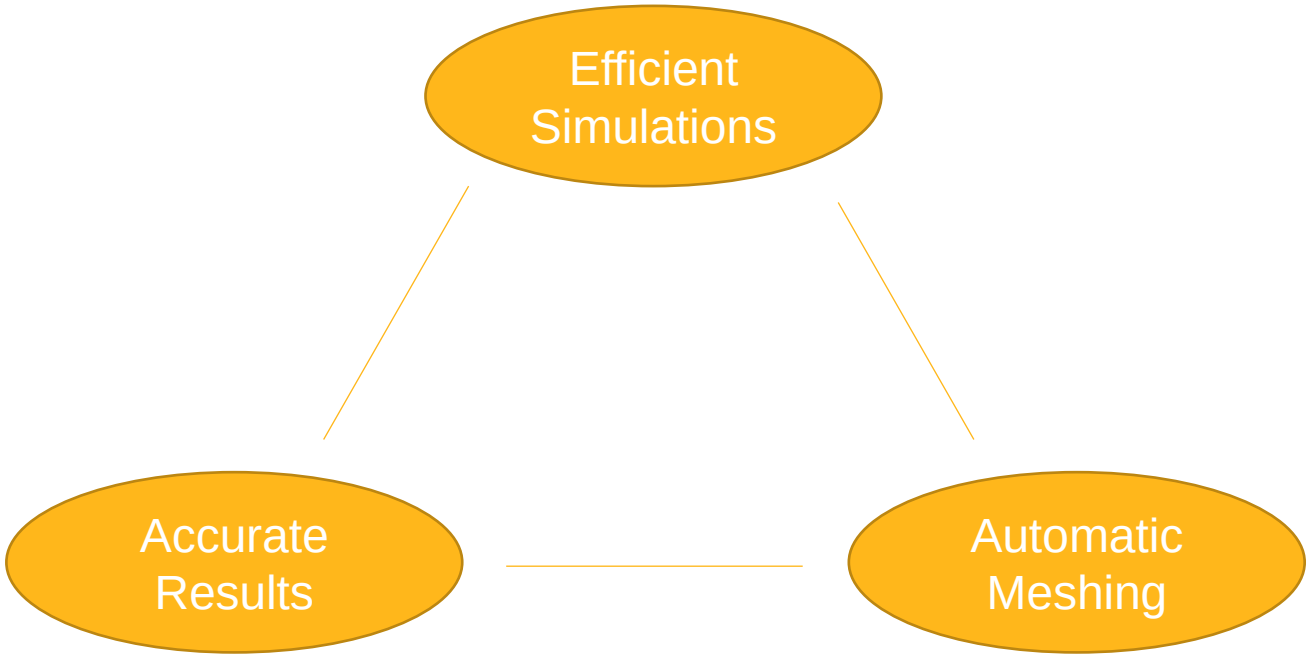
Gigacasting

Tesla Model Y



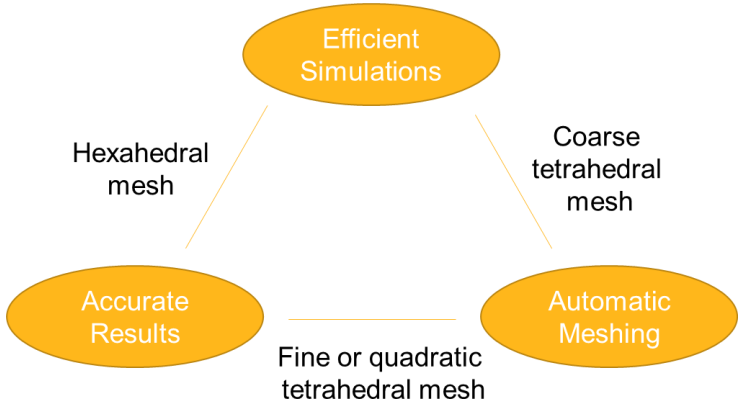
Source: Tesla

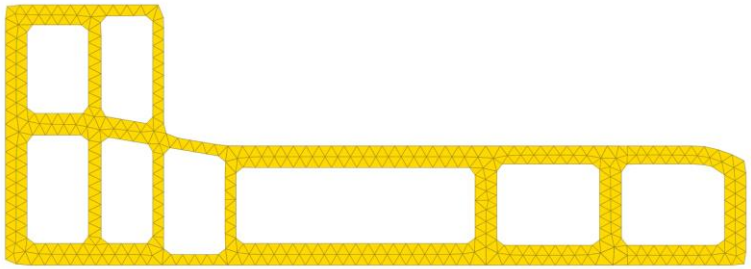
Few big casting parts
→ Solid elements

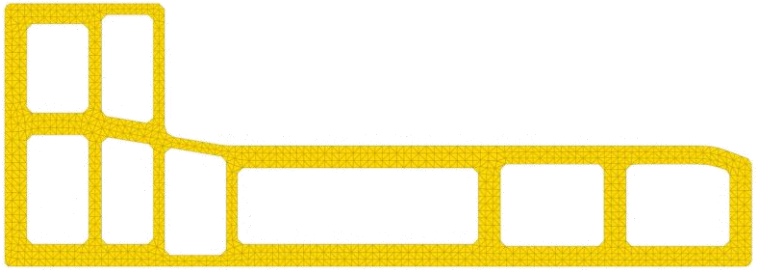


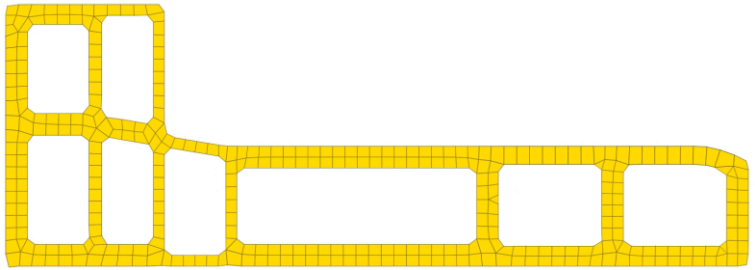
Trimmed IGA Solids

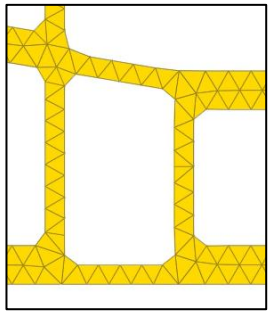
- 基于实体网格的碰撞模型

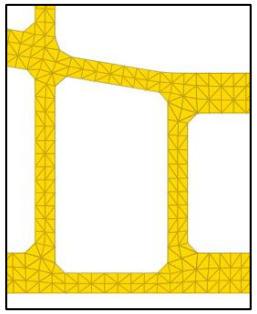


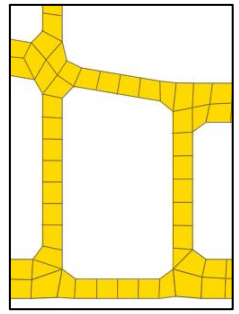












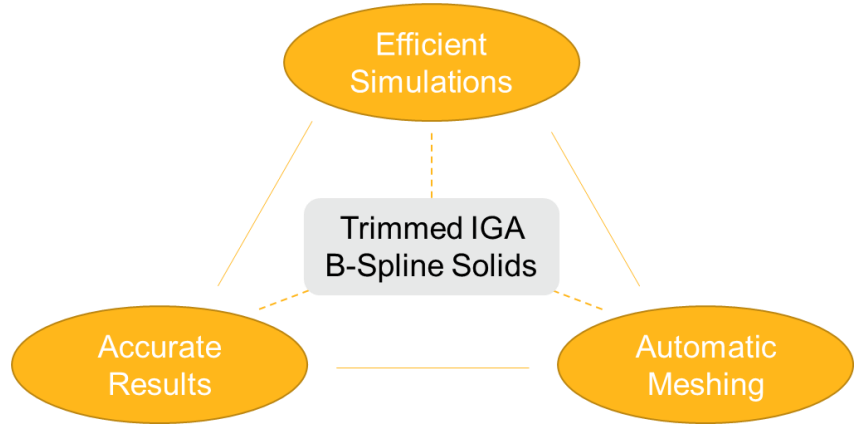
粗糙的四面体网格

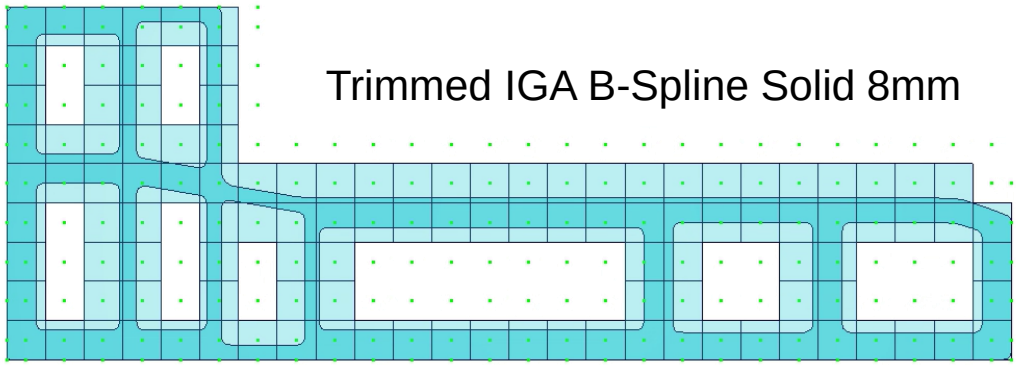
细化的四面体网格

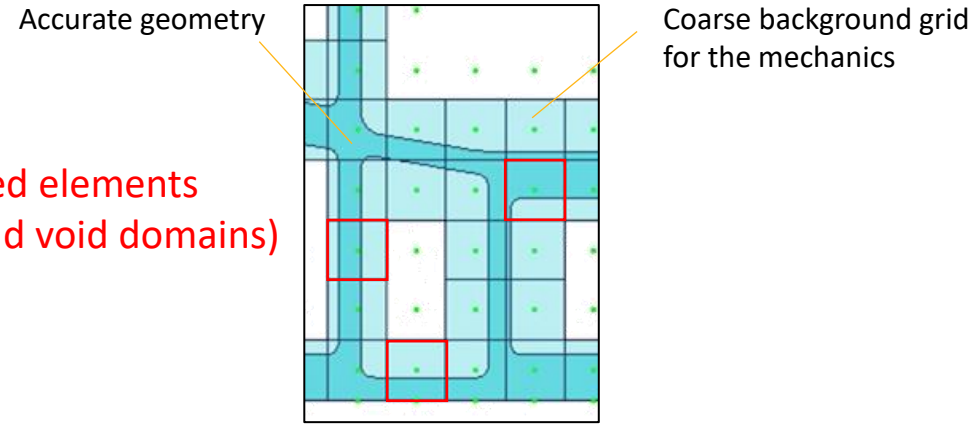
六面体网格

Trimmed IGA Solids

- IGA实体模型，将精确的CAD几何嵌入到相对粗糙的背景网格中
  - 计算几何和背景网格之间的交集
  - 确定网格中裁切的部分
- 优势
  - 单元尺寸不被壁厚限制
  - 背景网格使用B-spline作为形函数，有利于计算时间步长
  - 更容易进行网格细化

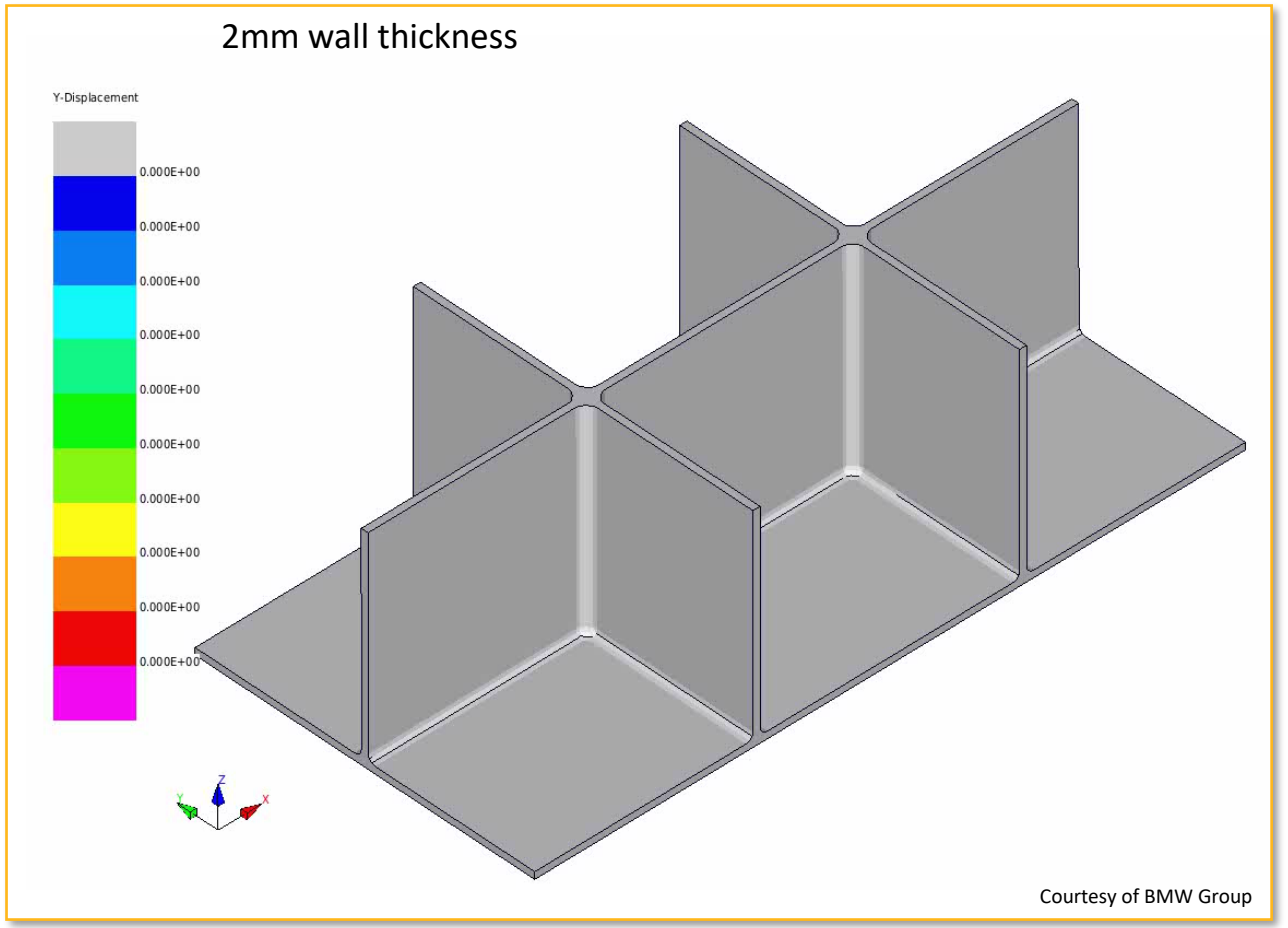






Trimmed IGA Solids

- 测试案例
  - FEA
    - 一阶四面体单元，ELFORM=13
    - 单元尺寸：0.5mm/1mm/2mm
  - IGA
    - Trimmed tri-quadratic B-spline solid
    - 单元尺寸： 2mm/4mm/8mm

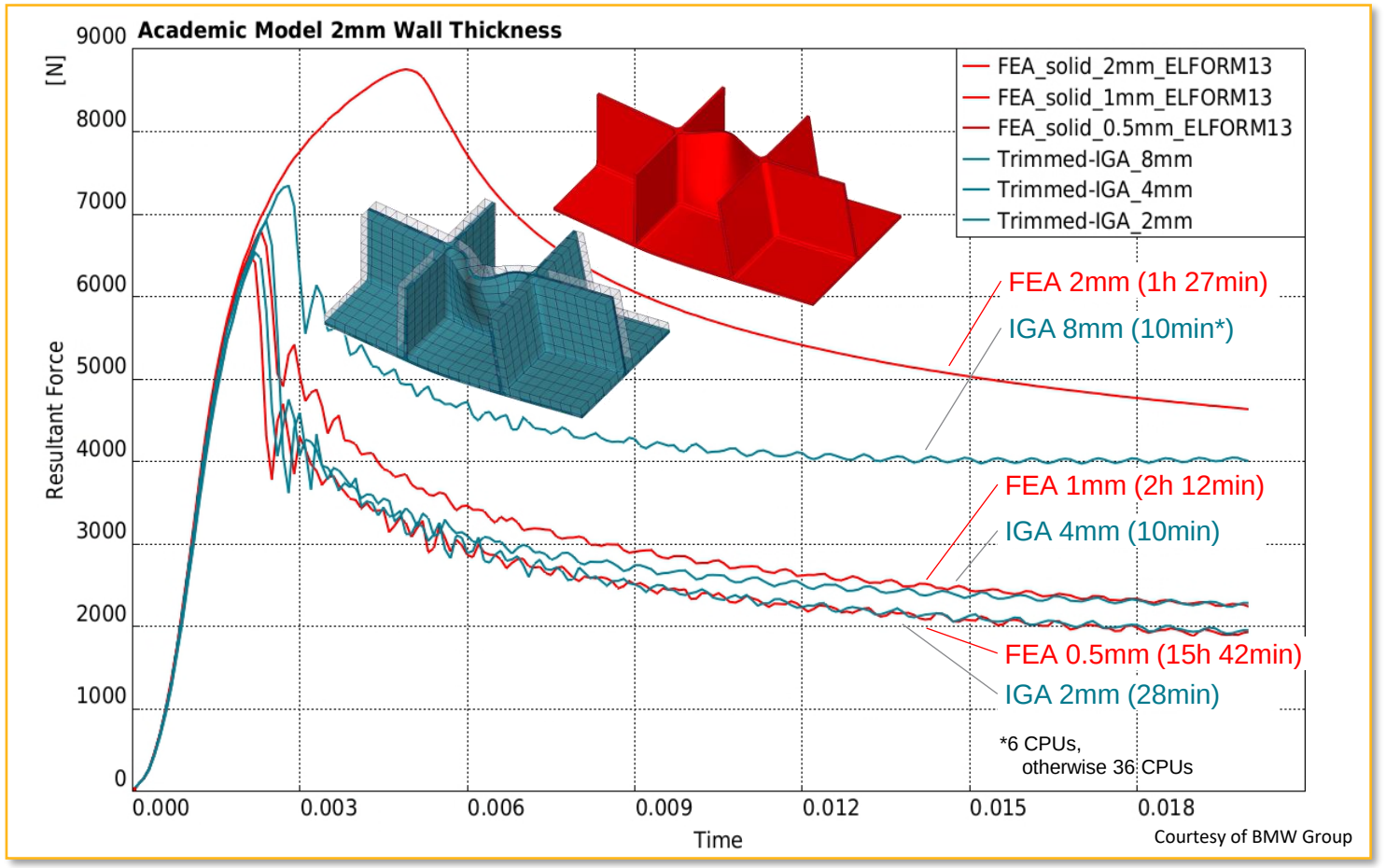


In cooperation with BMW GROUP TUM

Trimmed IGA Solids

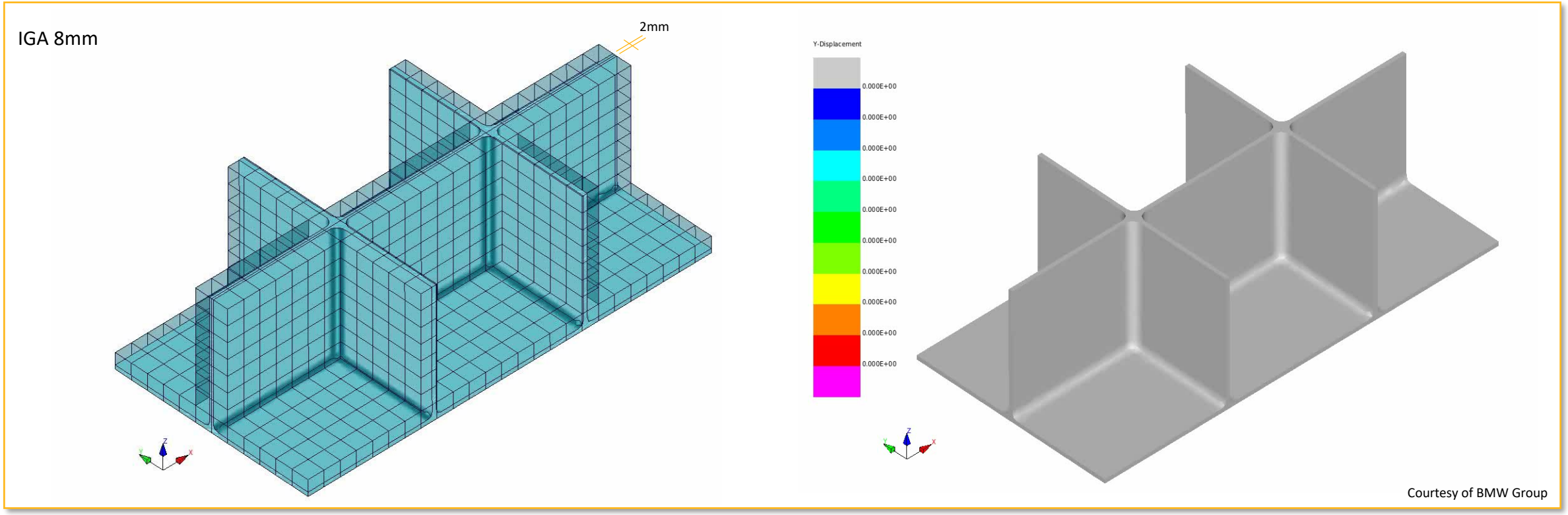
- 相同等级的精度
  - FEA_1mm – IGA_4mm
  - FEA_0.5mm – IGA_2mm
- 单元尺寸同为2mm时
  - IGA模型的计算效率约为FEA模型的3倍
- IGA模型有更大的时间步长

In cooperation with BMW GROUP TUM



Trimmed IGA Solids

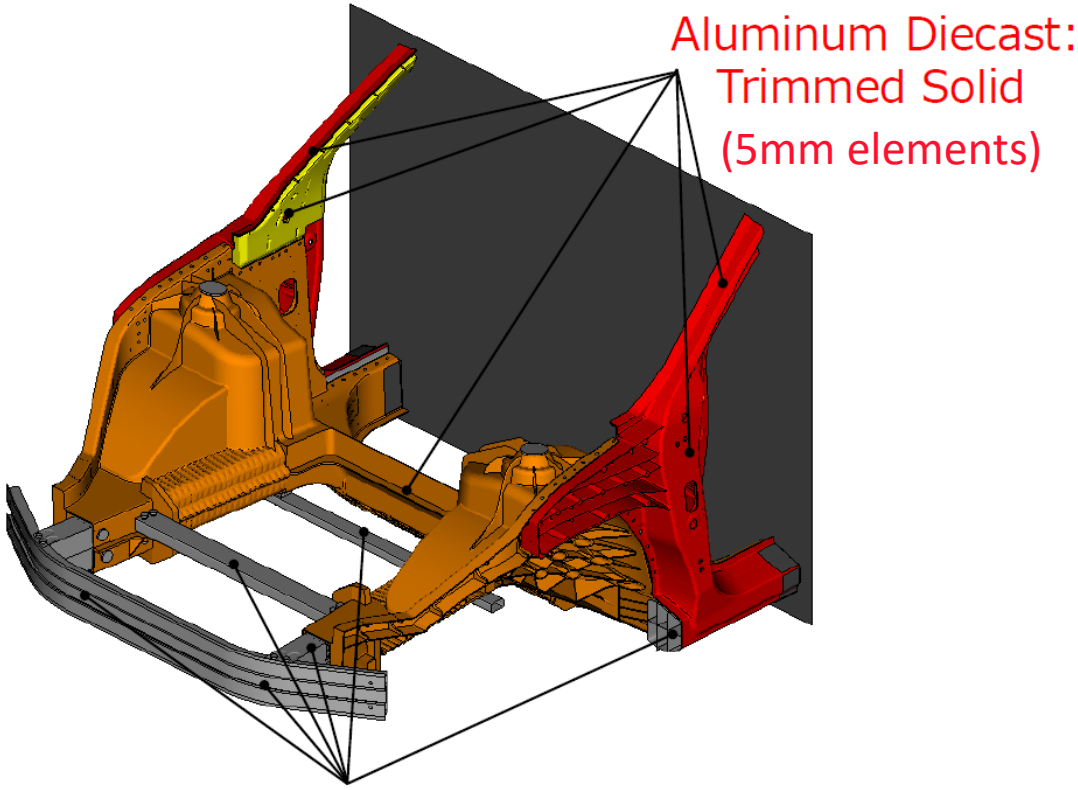
- 8mm单元尺寸的IGA模型
  - 已经能捕捉正确的屈曲变形
  - 壁厚2mm

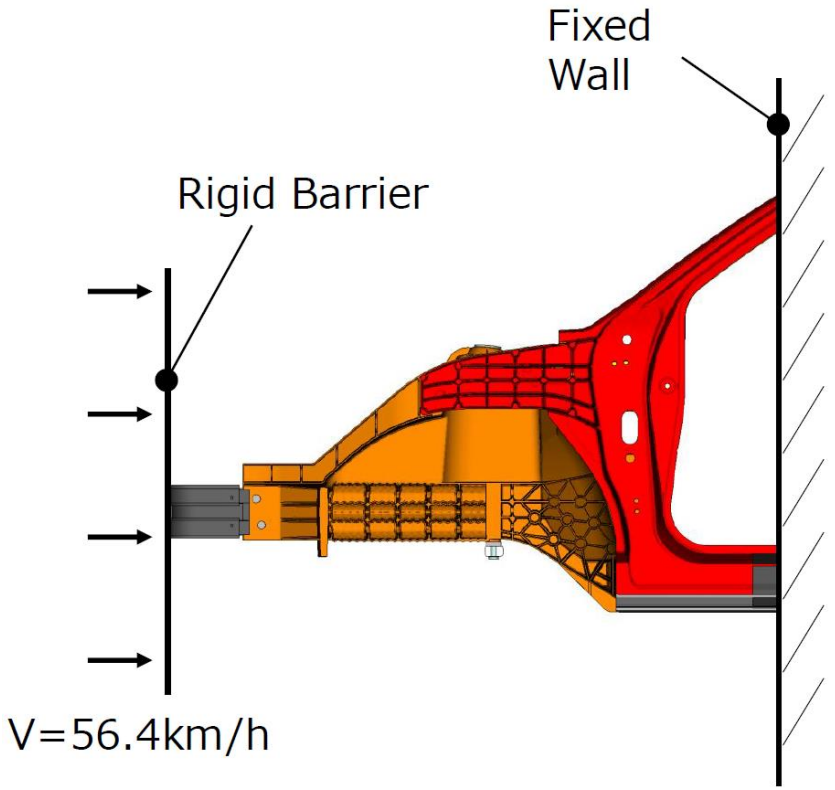


Trimmed IGA Solids | 应用案例

- 车身前部结构前碰分析

HONDA
The Power of Dreams

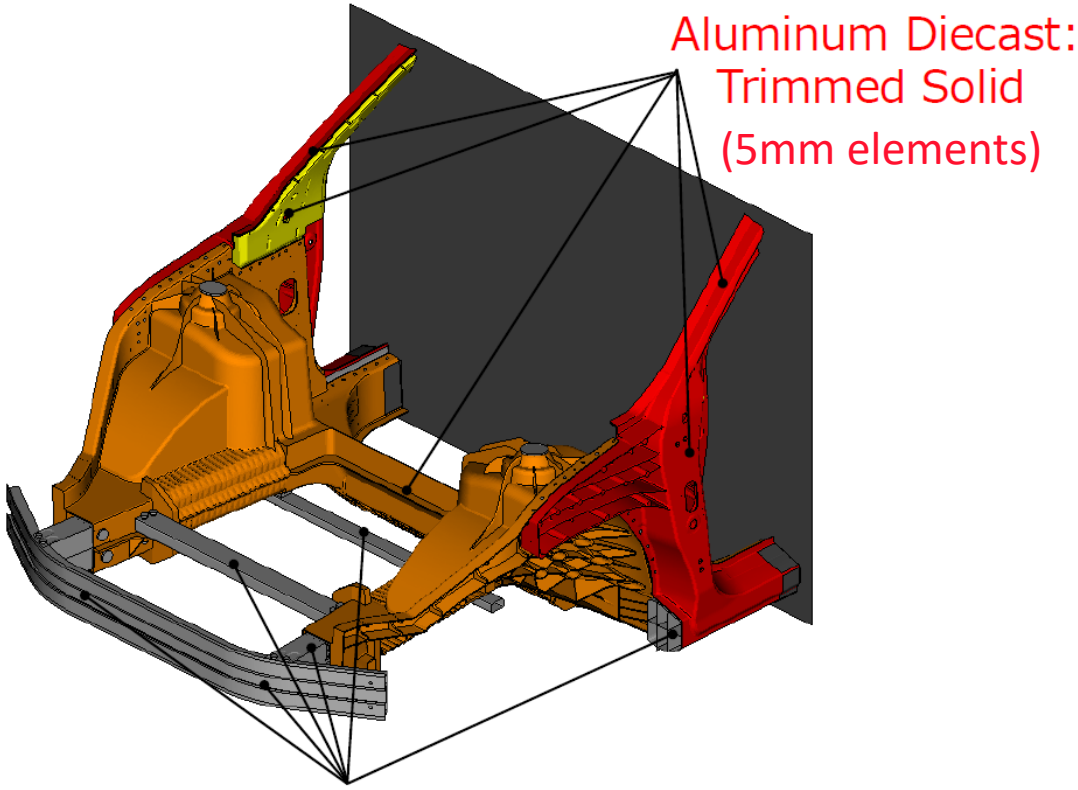




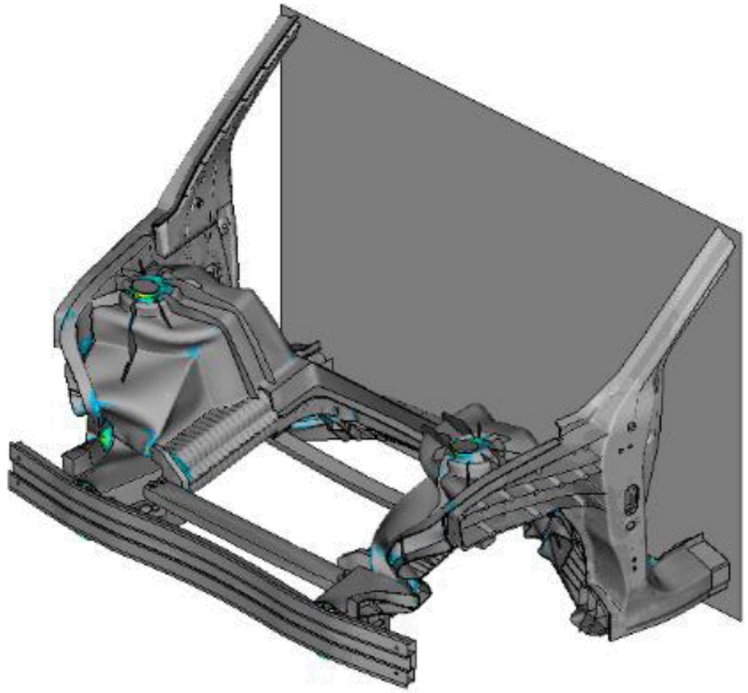
[9] Tadashi, N., Shinnosuke, N., Takafumi, O.: “Application of Trimmed Solid in Isogeometric Analysis to Aluminum Diecast Part”, International LS-DYNA Conference 2024, Metro Detroit, Michigan, USA.

Trimmed IGA Solids | 应用案例

- 车身前部结构前碰分析



Crash simulation in LS-DYNA



- 与5mm的四面体单元模型相比，计算时长缩短59%

[9] Tadashi, N., Shinnosuke, N., Takafumi, O.: “Application of Trimmed Solid in Isogeometric Analysis to Aluminum Diecast Part”, International LS-DYNA Conference 2024, Metro Detroit, Michigan, USA.

总结

- IGA方法的优势
  - 设计和分析模型的数据协同，加速研发流程
  - 基于NURBS的形函数，更高精度、更高效率

- 距离大规模应用
  - 更方便、自动化的几何前处理
  - 尽管相同单元尺寸下，IGA允许更大的Timestep，但某些时候总的计算时间反而更长
  - 支持更多的分析特性


Ansys