



汽车被动安全与轻量化设计

大连理工大学 亓 昌



汇报提纲

- 个人情况
- 研究方向、研究目标与关键技术
- 研究成果与承担项目
 - 汽车碰撞安全设计
 - 车身耐撞性
 - 乘员约束系统
 - 新能源汽车车身拓扑优化与电池碰撞防护
 - 特种汽车防爆、防弹设计
 - 军车防雷装甲
 - 新型车用防弹结构



学习经历

- 2000-09

清华大学

汽车工程

学士

- 2002-07

清华大学

车辆工程

硕士

- 2008-04

密歇根大学

机械工程

博士

仅供学习交流。未经DUTchina许可，谢绝转载和其它用途。



工作经历

- 2002-08 至 2006-04
美国密歇根大学 汽车研究中心 研究助理
- 2006-05 至 2009-02
美国福特汽车公司 产品开发中心 研发工程师
- 2009-03 至 2009-10
意大利ESTECO 北美分公司 技术经理
- 2009-10 至今
大连理工大学 汽车工程学院 教授、博导
副院长
辽宁省节能与新能源汽车重点实验室 常务副主任



个人介绍

• 获奖情况

- 大连市首批领军后备人才 大连市政府
- 重大技术贡献奖 3次 美国汽车工程师学会 (SAE)
- 北美CAE技术创新最高奖“总裁奖” 福特汽车公司

• 学术兼职

- 评审专家 ★国家自然科学基金委 ★大连市高新园区 ★10余项冲击领域国际知名SCI期刊
 审稿人



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个人介绍

- 福特技术最高奖——总裁奖 2007

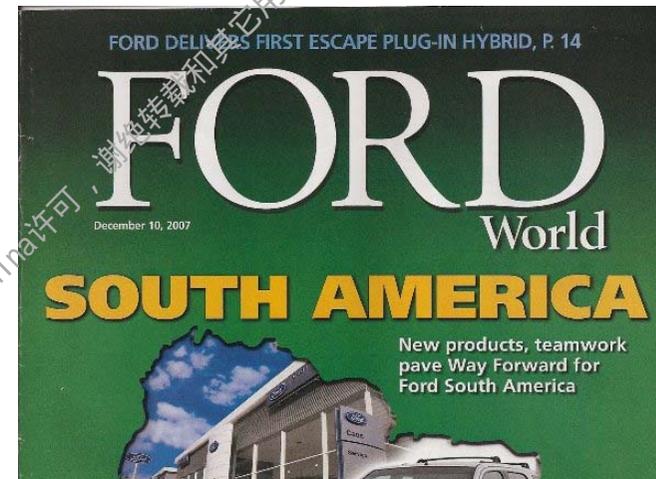




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个人介绍

- 福特总裁奖 2007



Interior safety project takes engineering Innovation Award

"Optimization and Robustness for an Occupant Restraint System Design," a project developed to increase interior safety in Ford vehicles while reducing development time and costs, received the 2007 Technical Innovation Award recently at the first North American CAE (Computer Aided Engineering) Technical Innovation Awards. The project developed a new methodology to drive the upfront design optimization of interior safety systems to meet NHTSA five-star requirements for occupant safety, while simultaneously reducing engineering development time and costs.



From left: award panel judge Randy Visintainer, executive director; Body and Chassis Engineering; winning team members Yan Fu, Ed Abramoski, Brian Kachnowski, Chang Qi and Guosong Li; and Rand Kochhar, executive technical leader, CAE.



研究方向与目标

研究方向

- 车辆防撞性与乘员保护
- 结构力学分析与轻量化设计
- 车用轻质装甲结构设计

研究目标

设计开发先进的轻质防护结构与材料，避免和减小（碰撞、爆炸等）冲击载荷下的车辆乘员及行人伤害。



关键技术

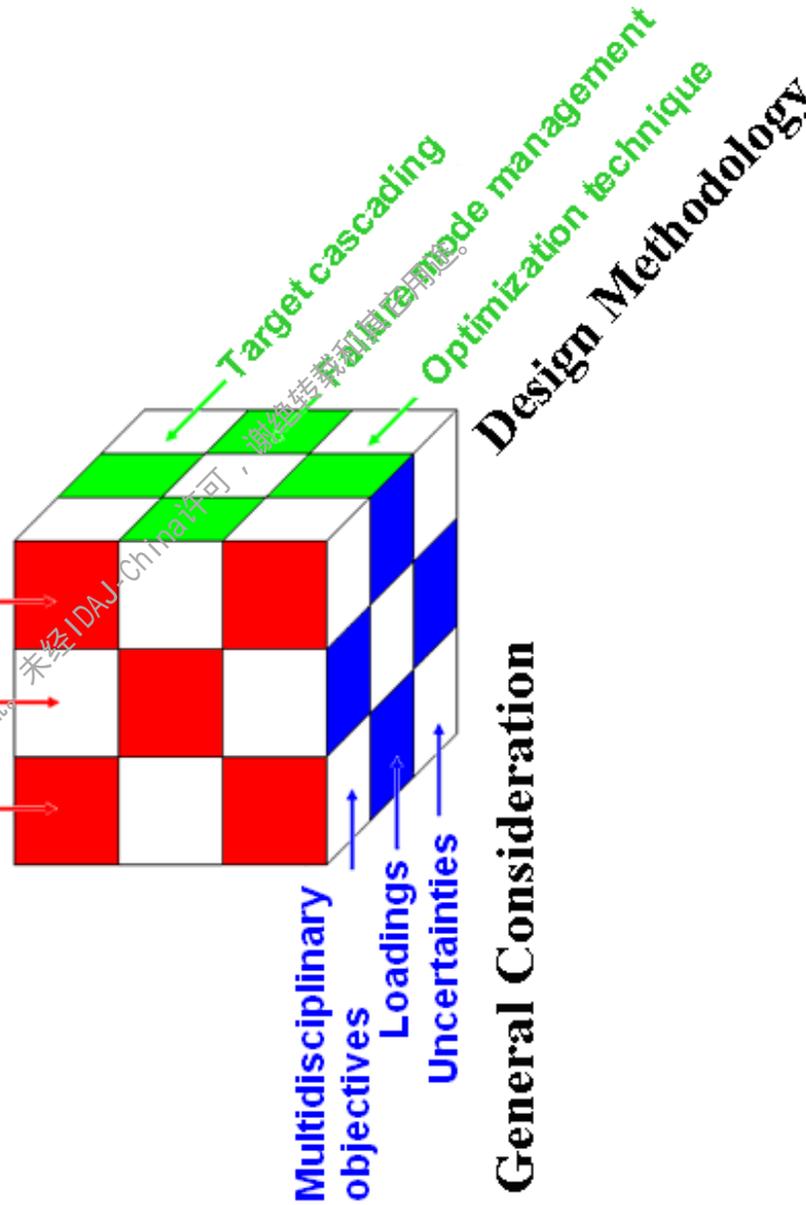
- 设计目标的时域、空间域分解方法
- 结构与材料一体化设计技术
- 先进的轻量化设计技术 —— 拓扑优化
- 多学科协同设计与优化流程开发
- 多载荷工况（碰撞、爆炸、侵彻）力学分析与设计
- 高可靠性设计与评估技术等



关键技术

-
-
-
-
-
-
-
-

Time decomposition
 Space decomposition
 Scale decomposition
Decomposition



+



车身耐撞性研究项目：

- 整车耐撞性设计目标分解
- 关键吸能件可靠性与轻量化设计
- 车身轻量化与多学科优化
- 异质材料车身接头碰撞失效机理研究



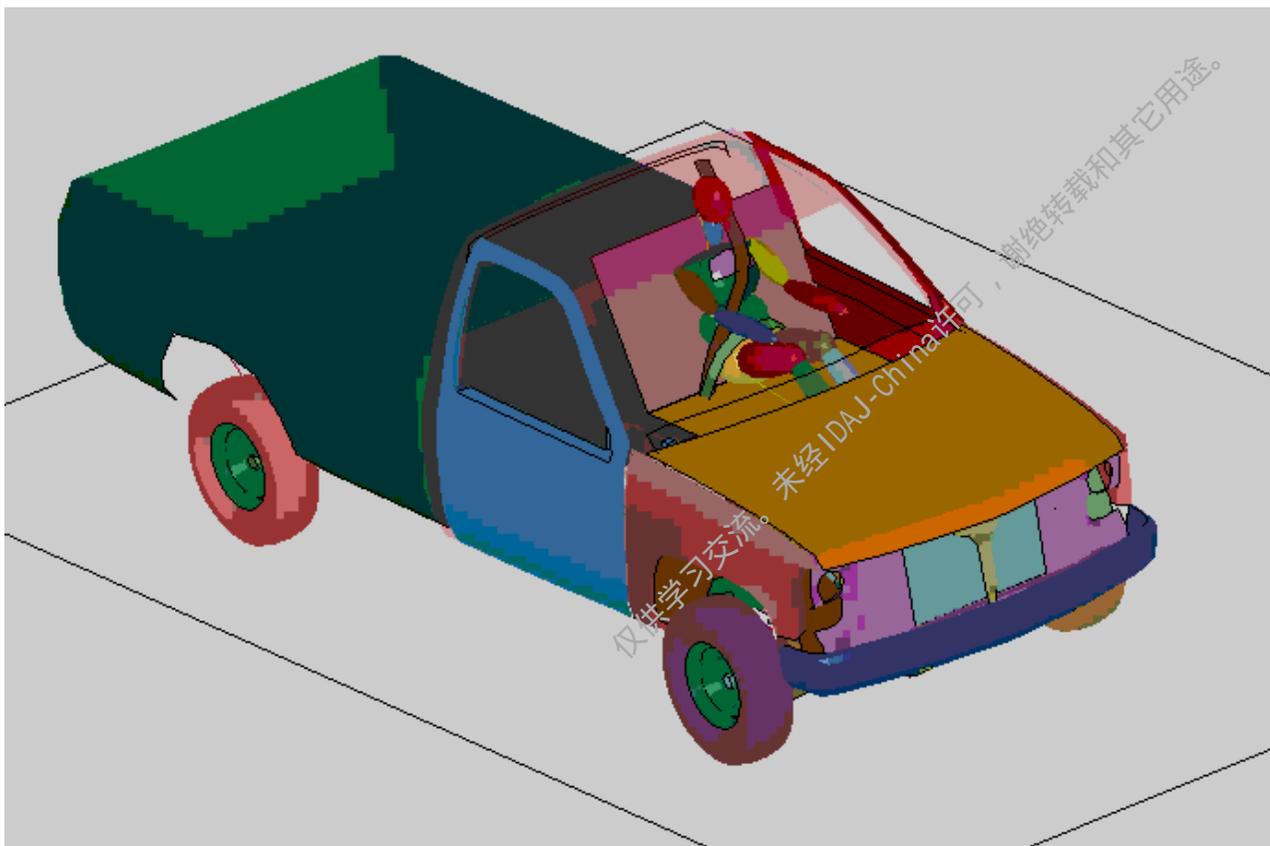
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整车耐撞性设计

- 时域与空域的设计目标分解

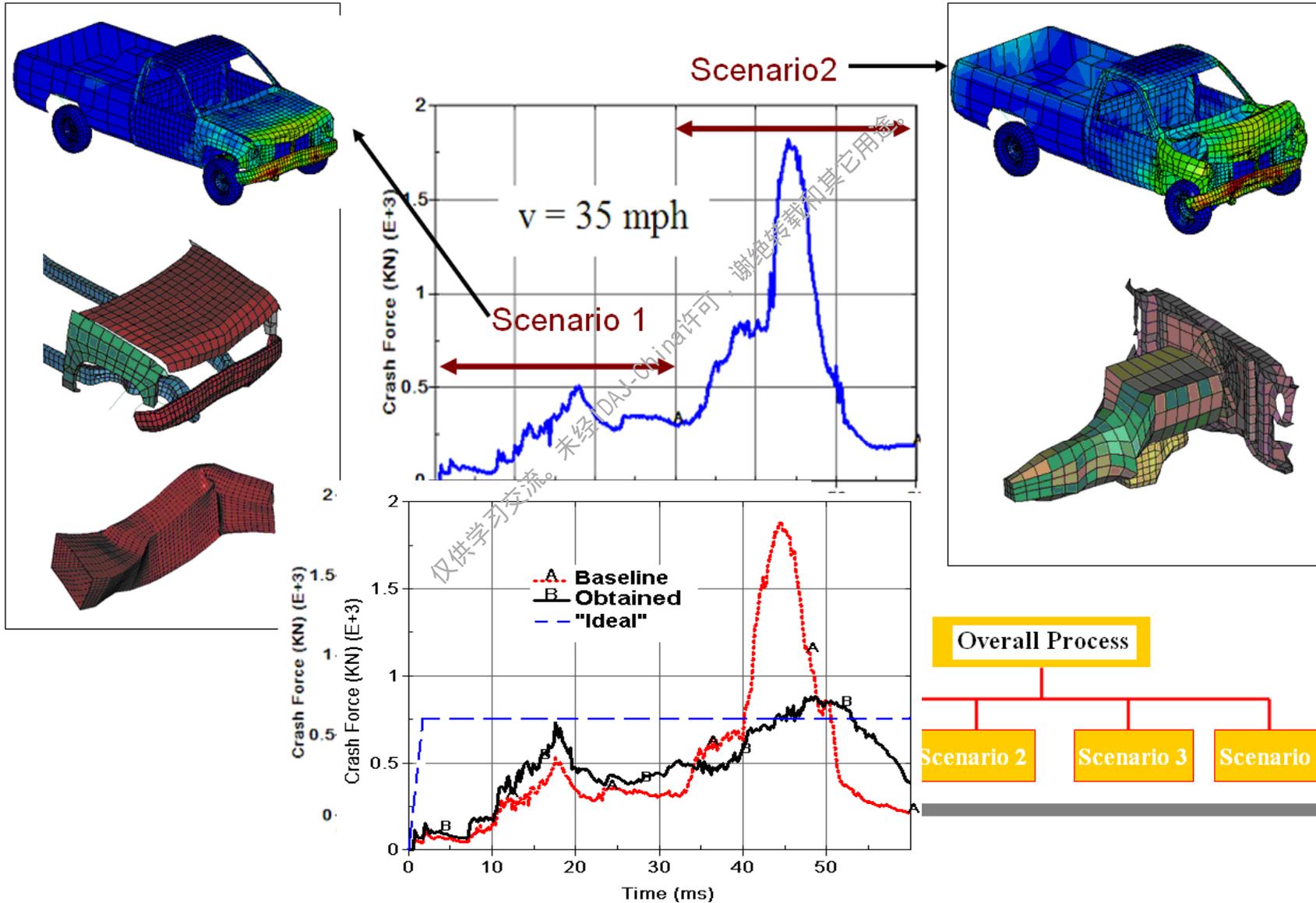


- 非线性大变形
- 惯性效应
- 应变率效应
- 复杂接触
- ...



整车耐撞性设计

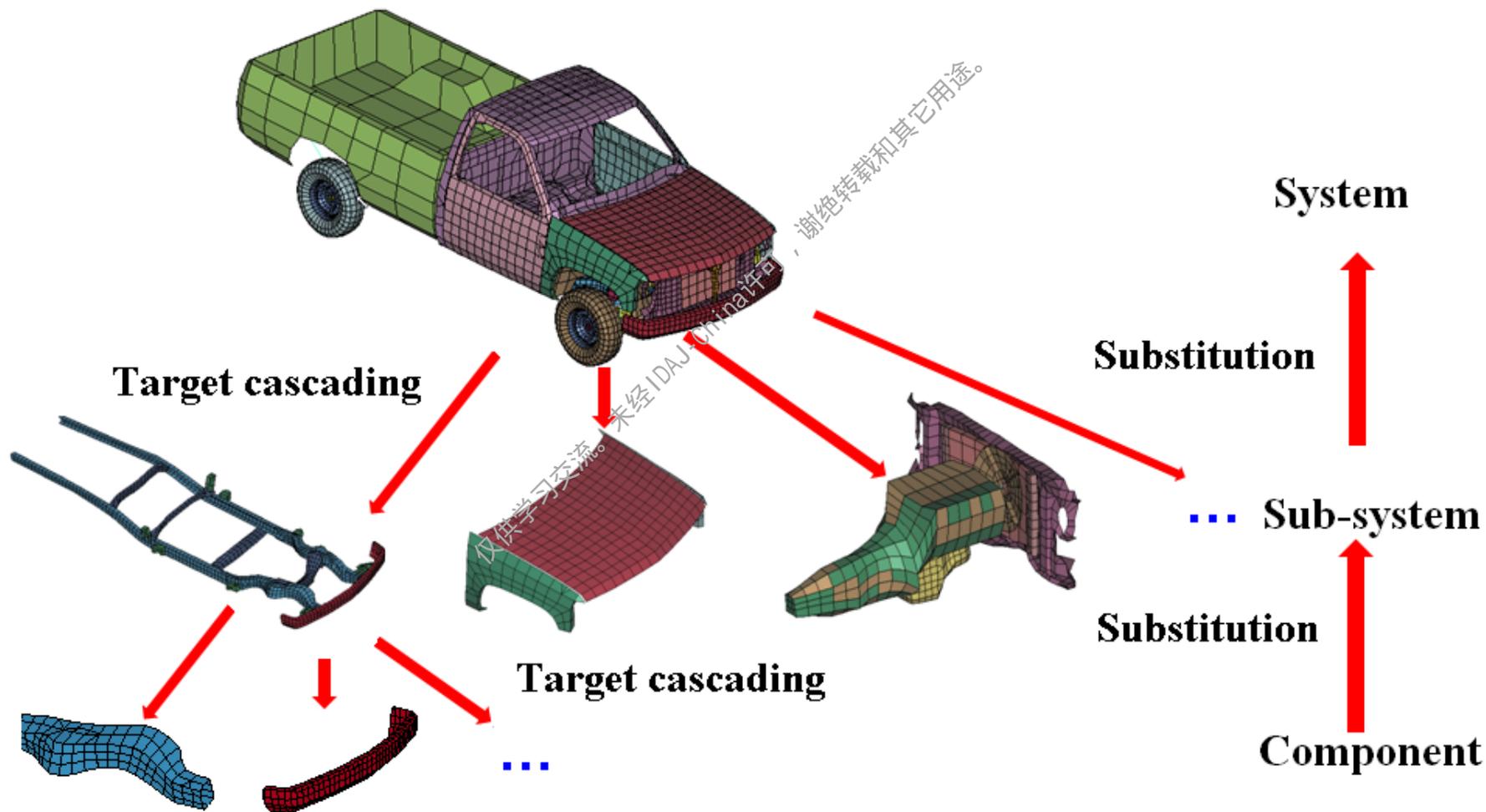
• 设计目标时域分解方法





整车耐撞性设计

- 设计目标空域分解方法



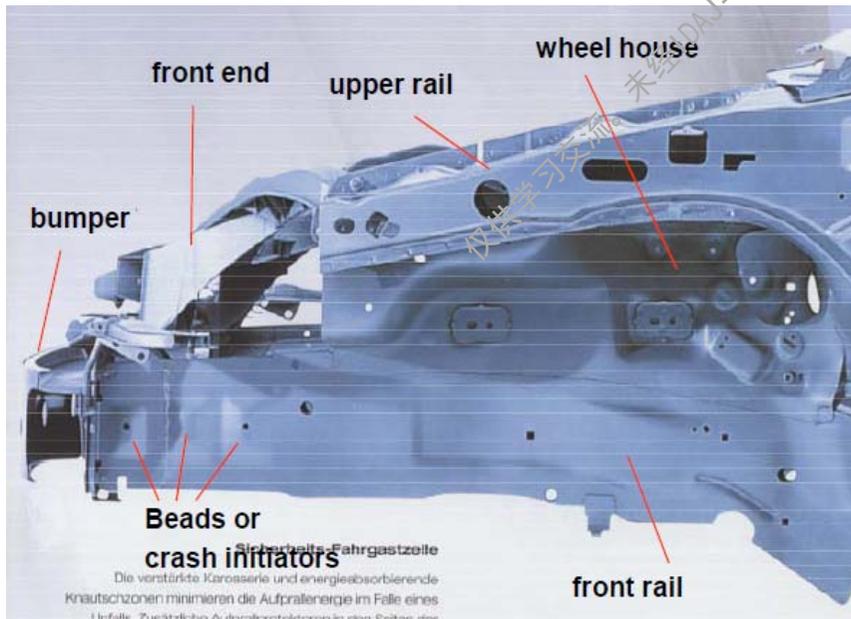
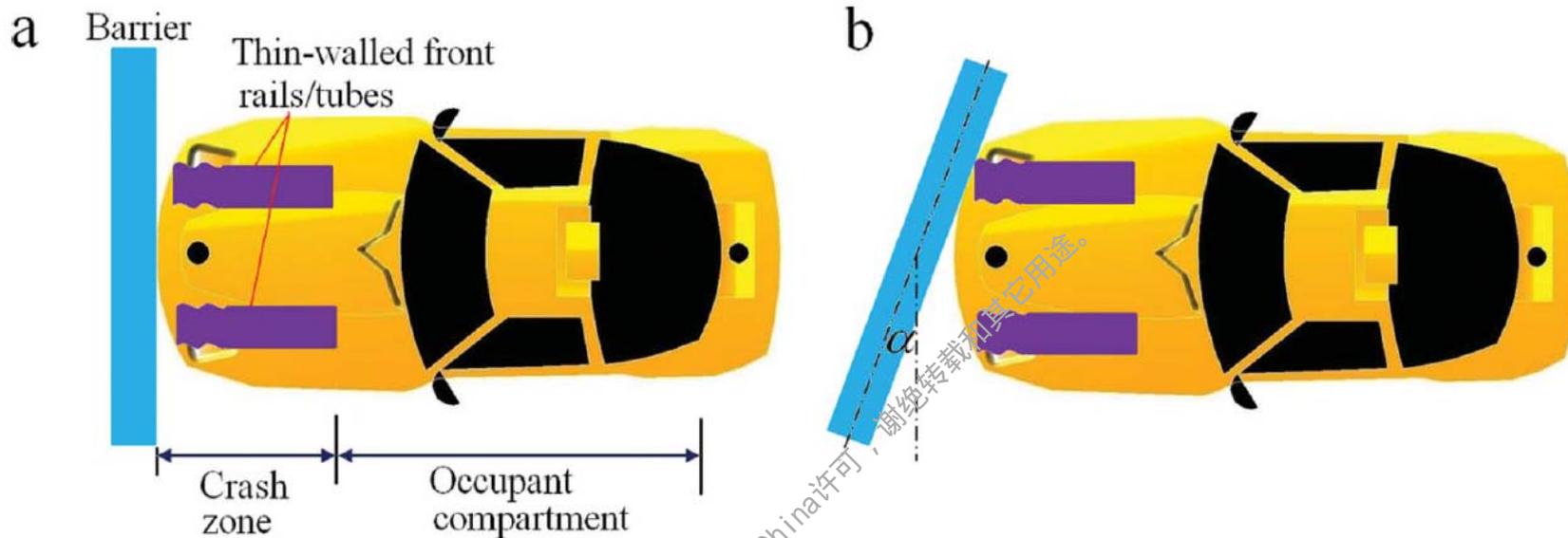


车身耐撞性研究项目：

- 整车耐撞性设计目标分解
- **关键吸能件可靠性与轻量化设计**
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DUT 关键吸能件可靠性与轻量化设计



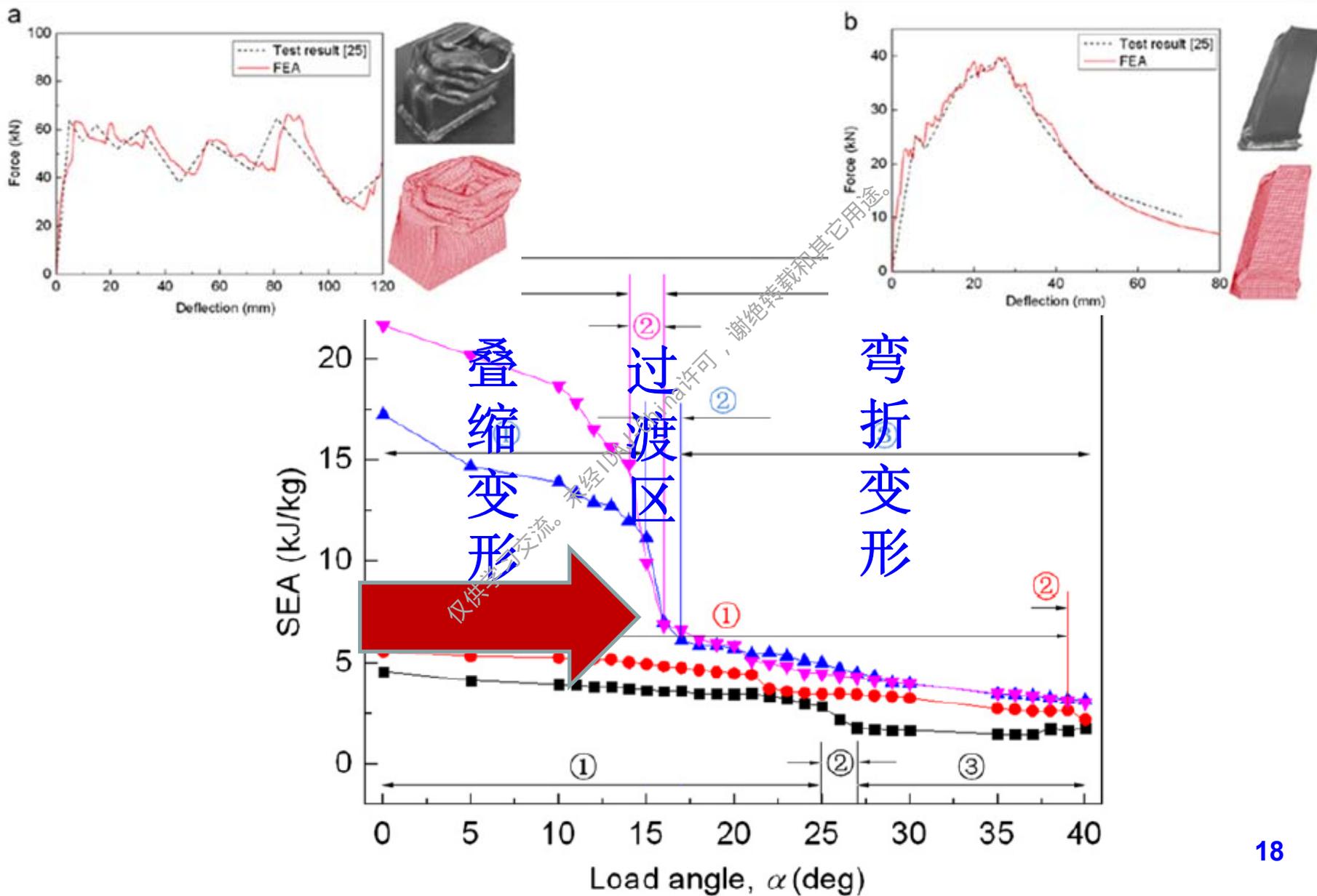
设计目标:

- 降低小角度下的冲击峰值力
- 提高大角度下的吸能能力
- 满足轻量化要求。



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关键吸能件可靠性与轻量化设计





DUT 锥胞管斜向冲击分析与优化

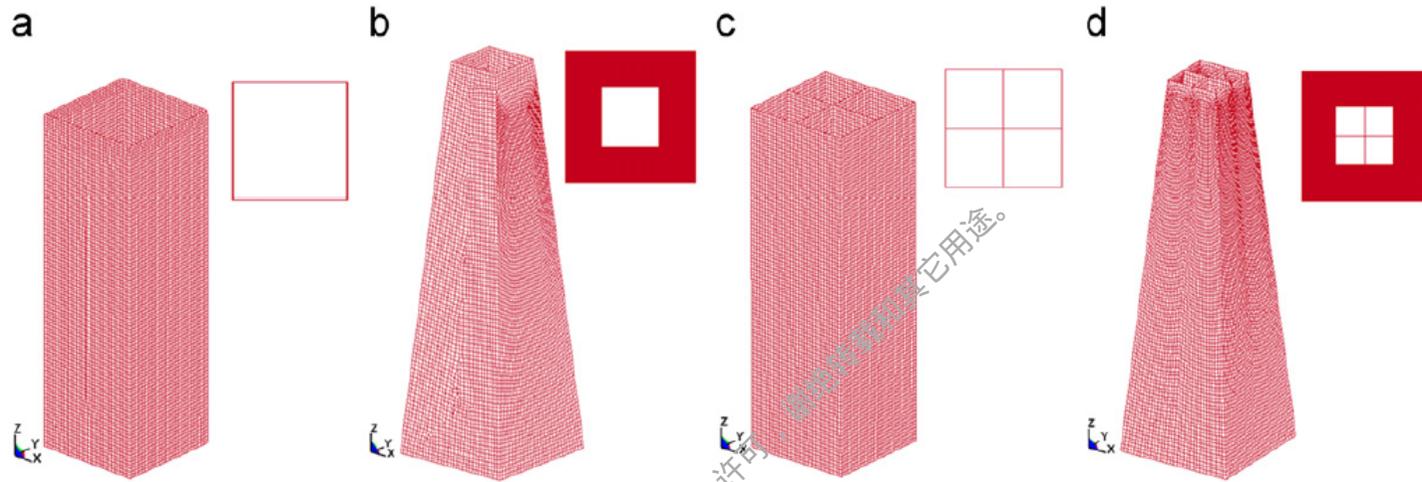
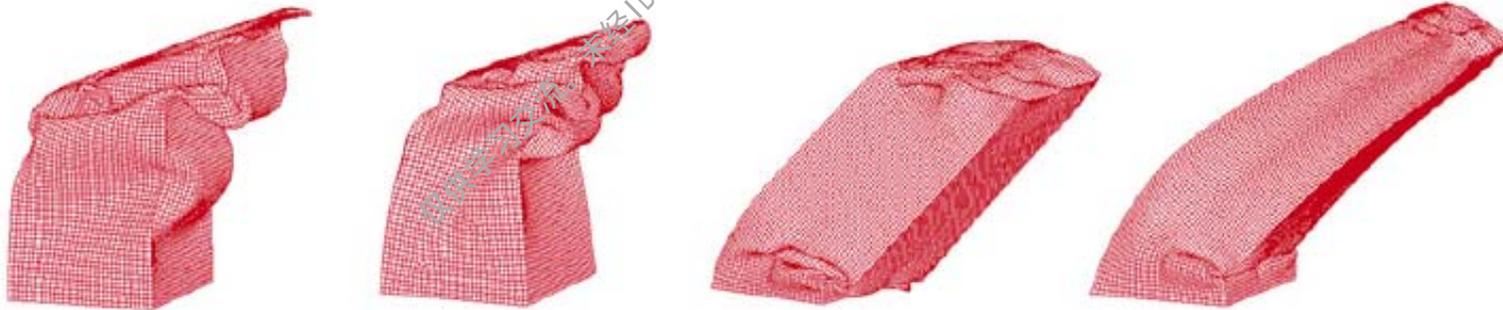


Fig. 4. FE models of the ATS tubes (Overall view and top view): (a) SCS, (b) SCT, (c) MCS and (d) MCT.

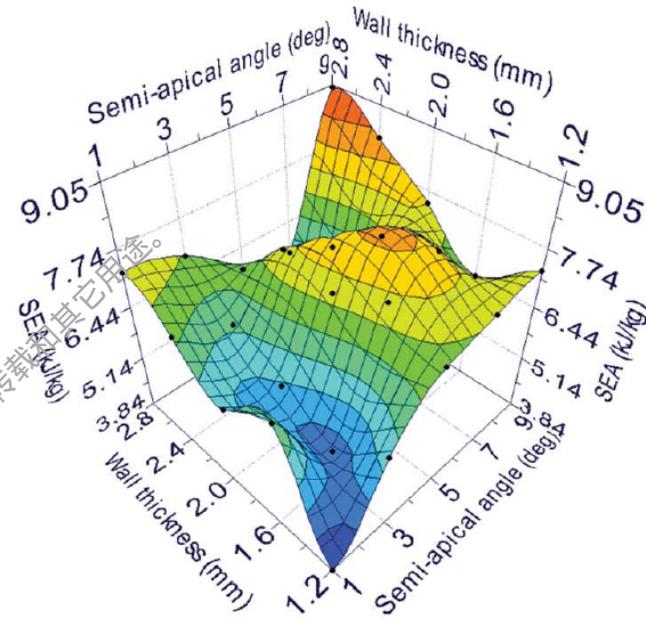
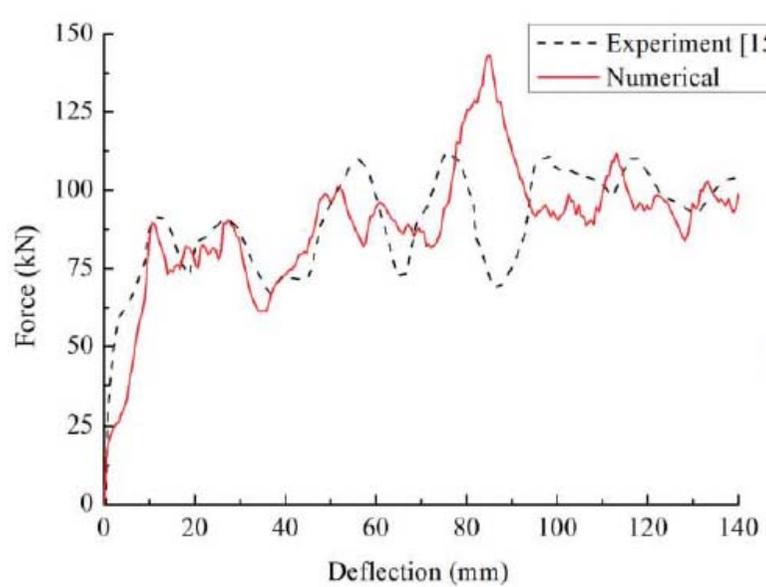


$\alpha = 20^\circ$

Chang Qi, Shu Yang*, Fangliang Dong. *Thin-Walled Structures*, 2012. SCI/EI, IF:1.231.



DUT | 圆锥管斜向冲击分析与优化



(a) Load angle $\alpha = 10^\circ$ (crush distance $d = 140$ mm)



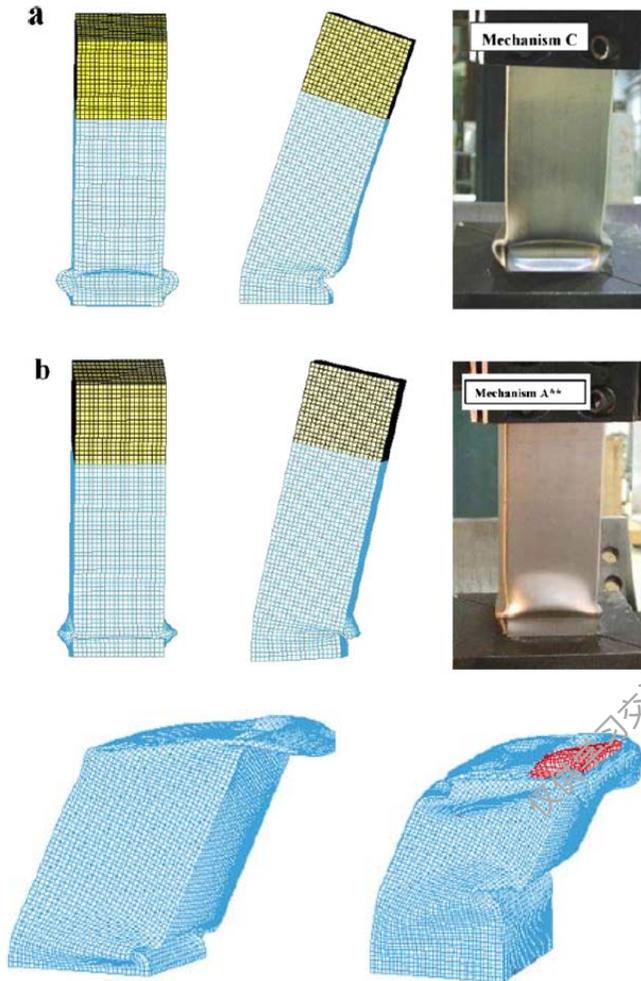
$\alpha = 20^\circ$

Chang Qi, Shu Yang*. *International Journal of Crashworthiness*, 2014. SCI/EI, IF:0.789.

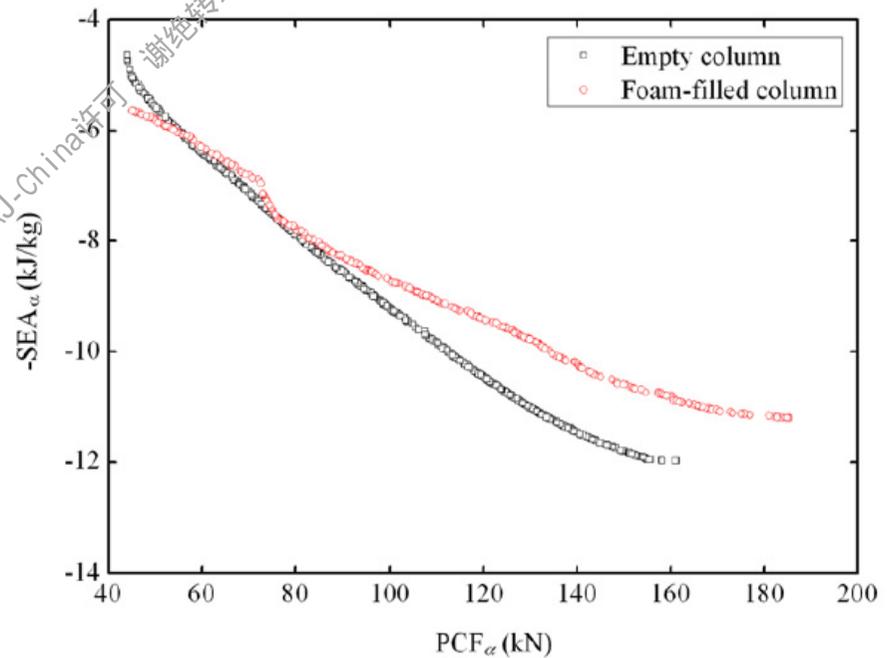


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铝泡沫填充管斜向冲击分析与优化



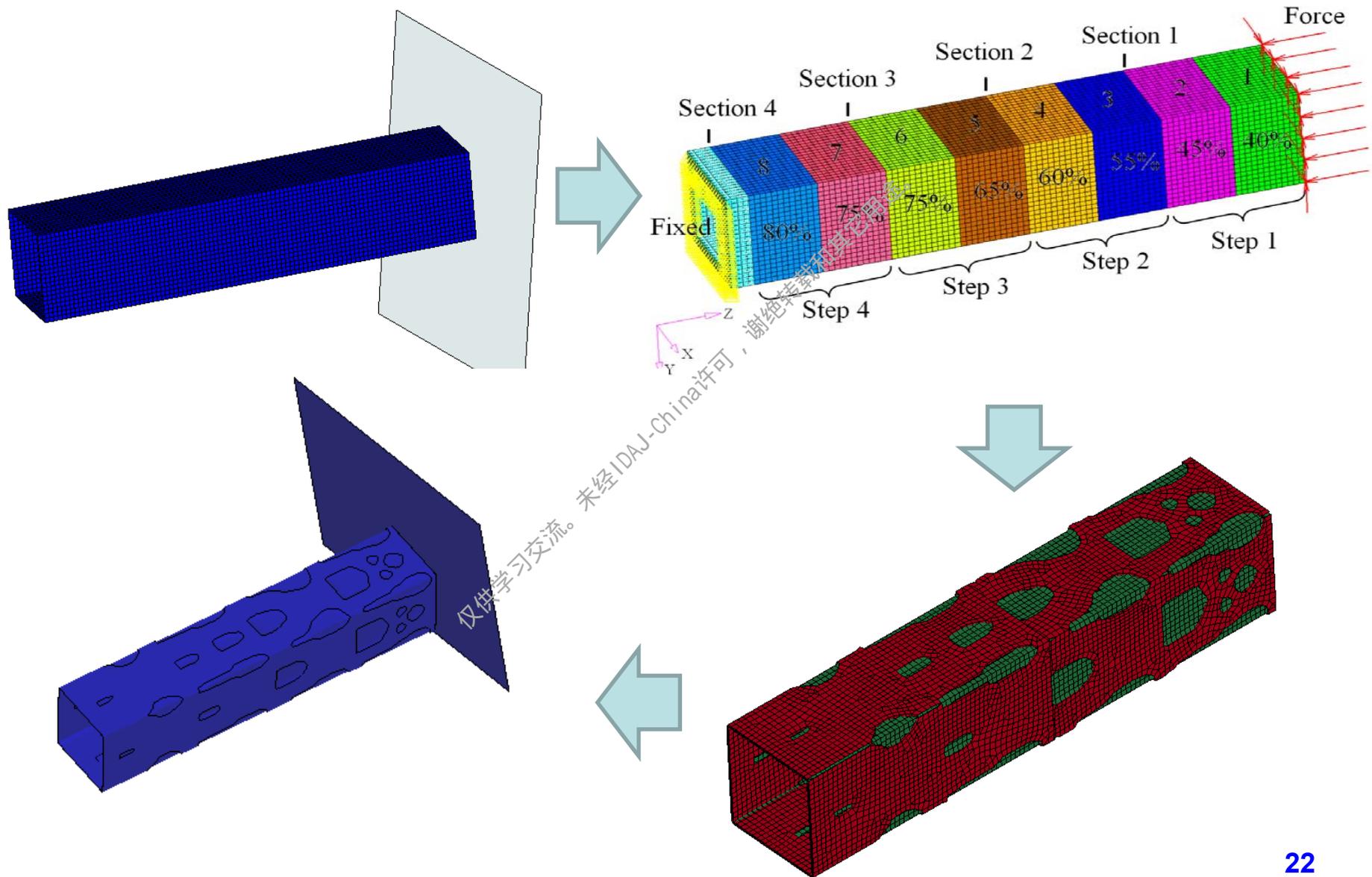
$$\left\{ \begin{array}{l} \text{Min } \left\{ -SEA^{\alpha_i}(a, t, \sigma_y, \rho_f), PCF^{\alpha_i}(a, t, \sigma_y, \rho_f) \right\} \\ \text{s.t. } \sigma \leq \sigma_u \\ 60 \text{ mm} \leq a \leq 100 \text{ mm} \\ 1.4 \text{ mm} \leq t \leq 3.0 \text{ mm} \\ 140 \text{ MPa} \leq \sigma_y \leq 230 \text{ MPa} \\ 27 \text{ kg/m}^3 \leq \rho_f \leq 270 \text{ kg/m}^3 \end{array} \right.$$



Shu Yang, Chang Qi*. *International Journal of Impact Engineering*, 2013. SCI/EI, IF:1.681.

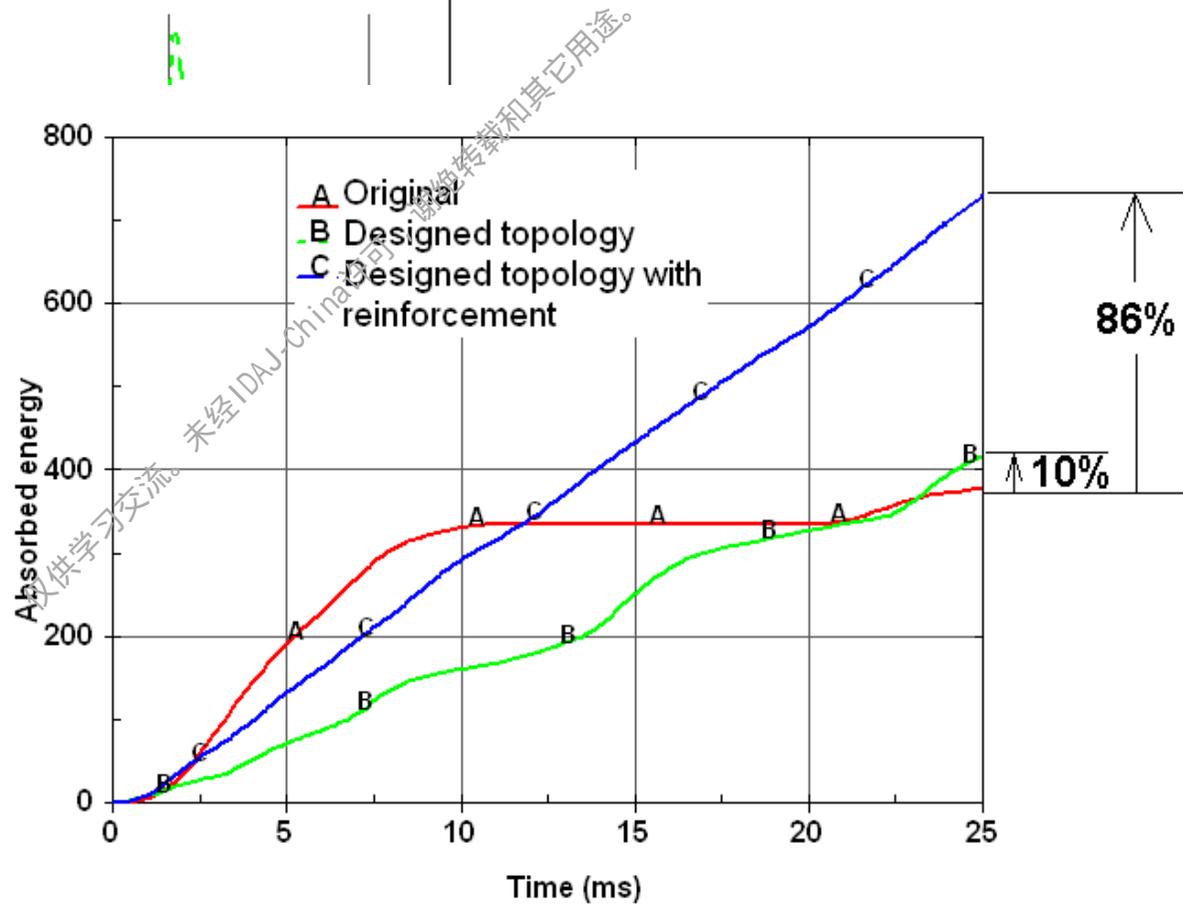
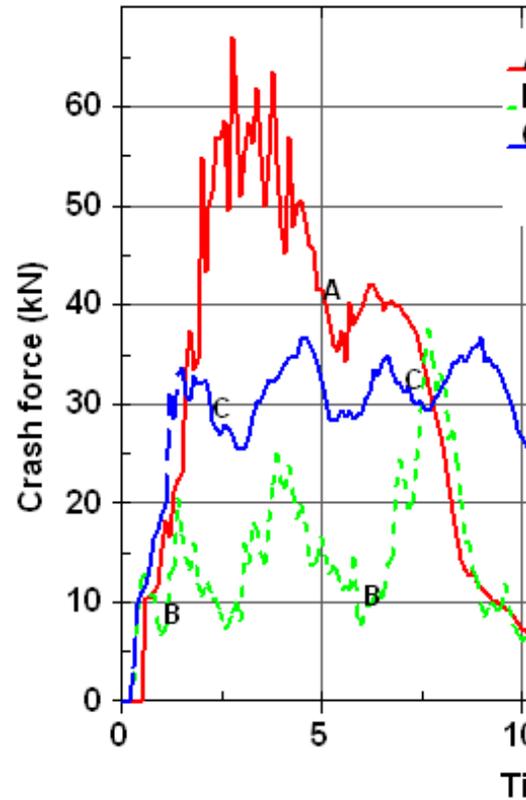


前纵梁拓扑优化设计



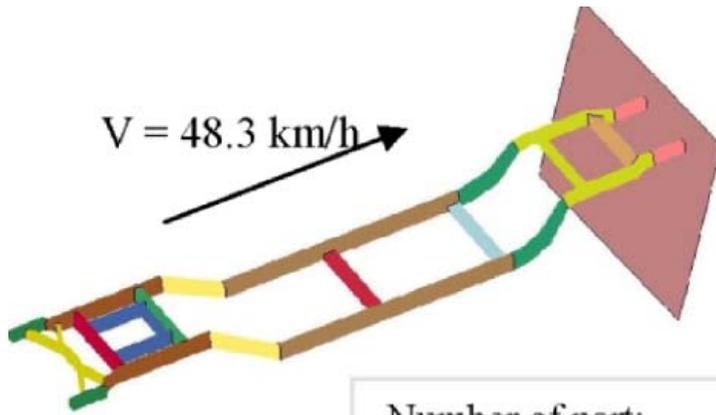


前纵梁拓扑优化设计

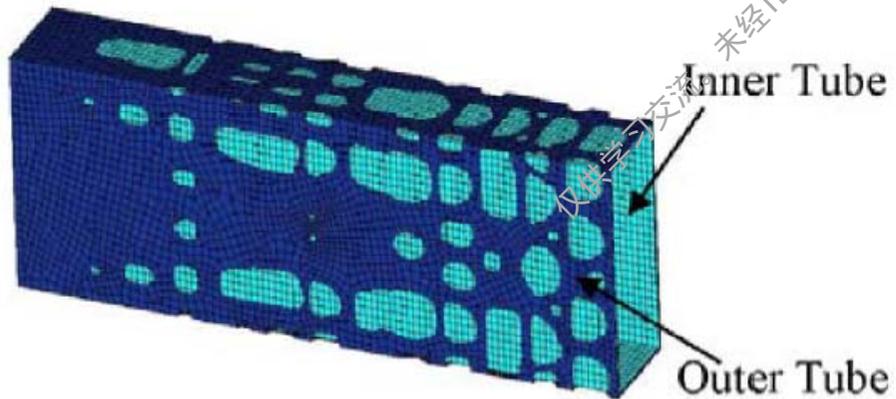




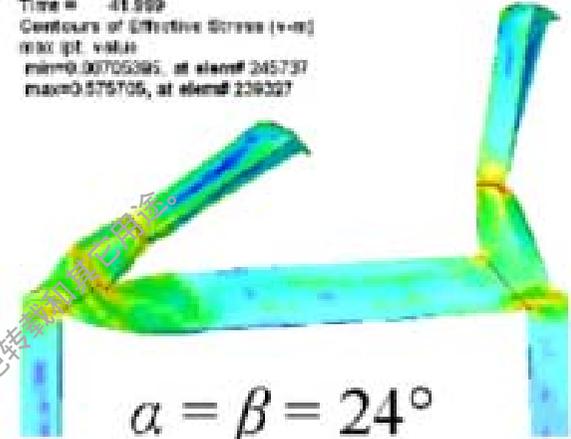
前纵梁拓扑优化设计



Number of part:	14
Number of node:	60712
Number of element:	66150

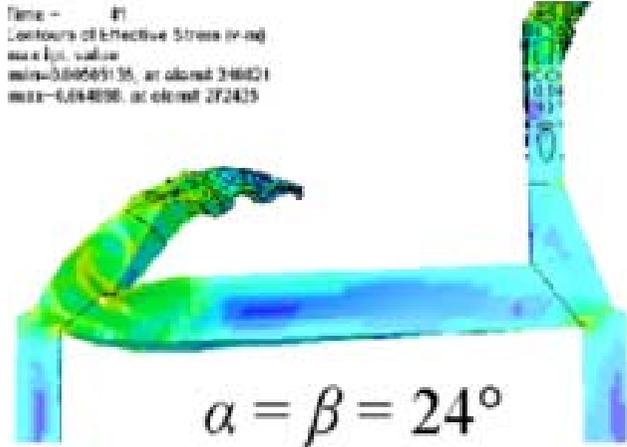


Time = 48.889
Contours of Effective Stress (v-m)
max (pt. value)
min=0.00705385, at elem# 245737
max=0.575705, at elem# 236327



$\alpha = \beta = 24^\circ$

Time = 47
Contours of Effective Stress (v-m)
max (pt. value)
min=0.00569135, at elem# 346021
max=0.614488, at elem# 272425

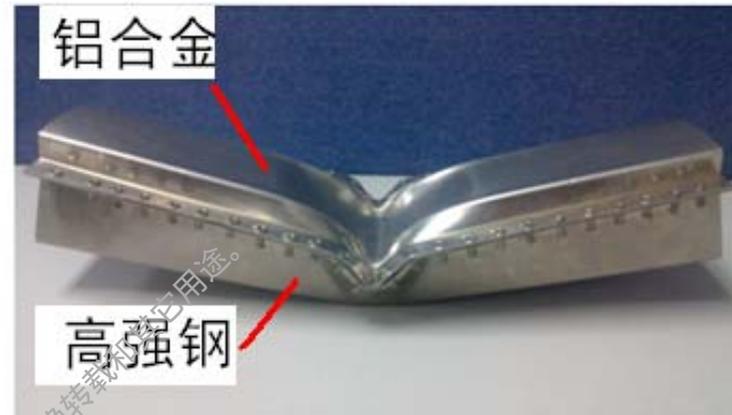
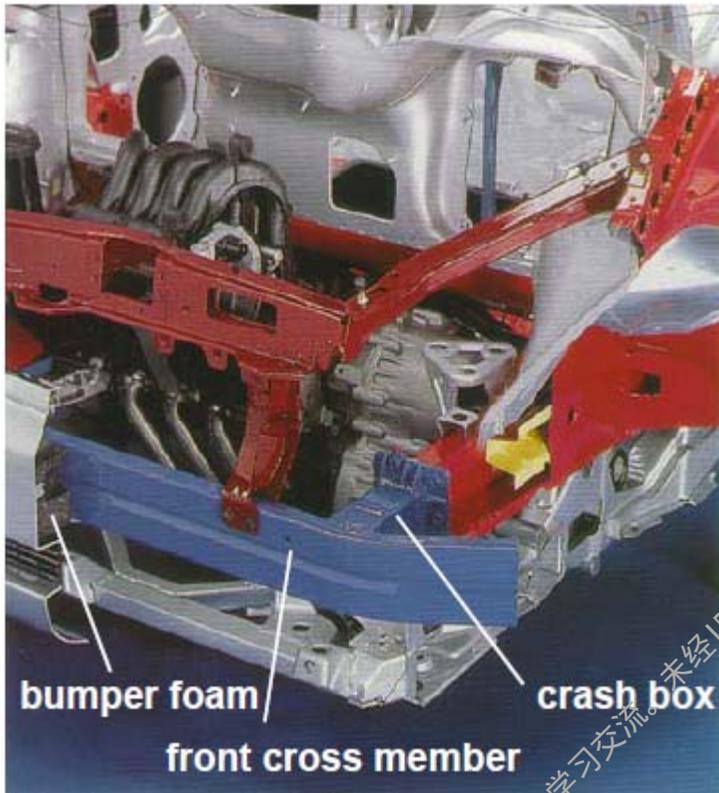


$\alpha = \beta = 24^\circ$

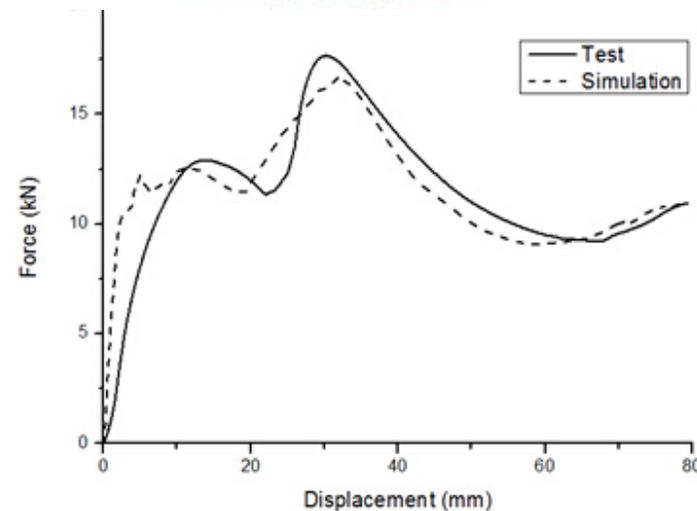


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钢铝混合轻量化保险杠设计

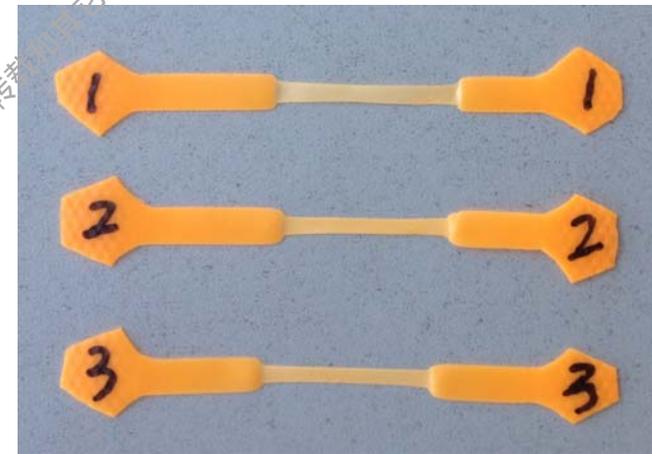
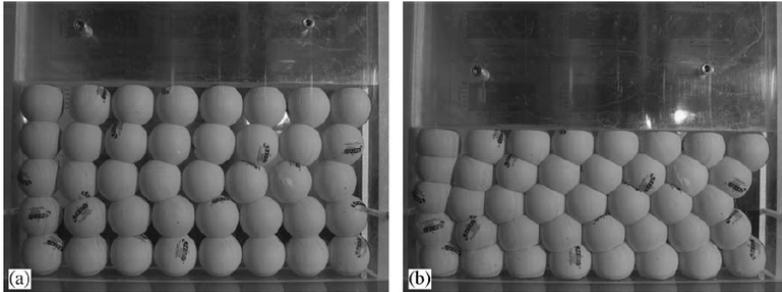


- 低速碰撞时，铝合金能减小碰撞峰值，有利于行人保护；
- 高速碰撞时，高强钢能有效传力，减小变形侵入，提高车身吸能。

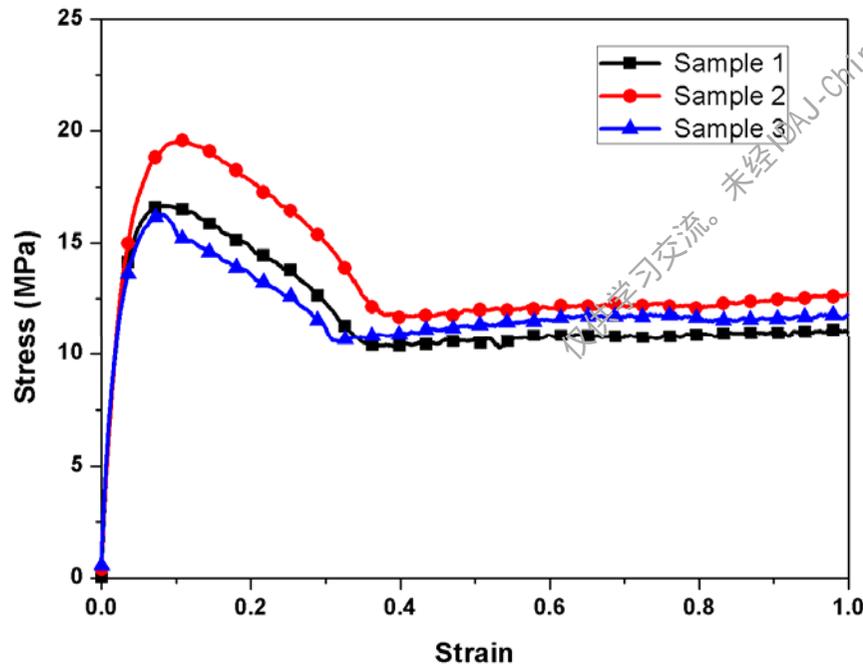




轻质吸能材料 (MHS) 设计



Experiment by Ruan, Gao & Yu (2006)



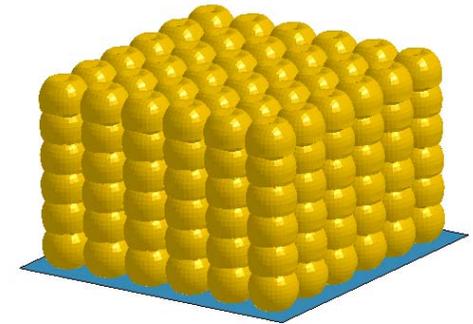
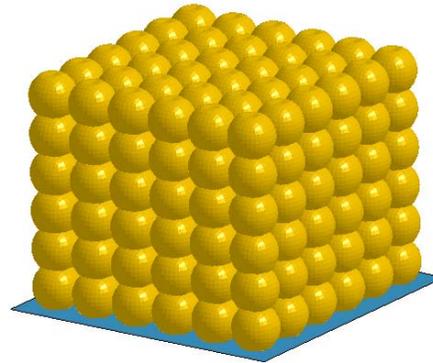
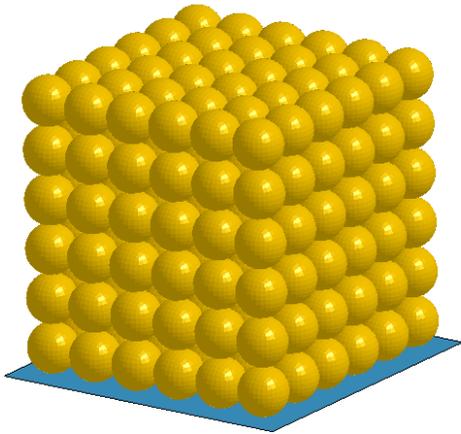
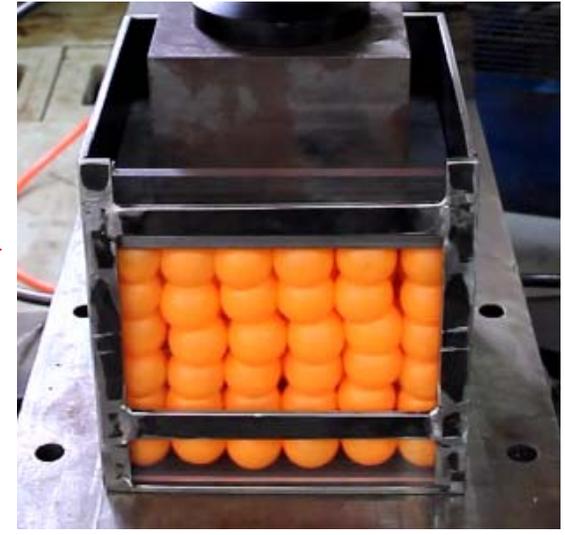
应力应变曲线通过数据处理：

- 屈服强度：16MPa
- 杨氏模量：2GPa



DUT

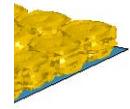
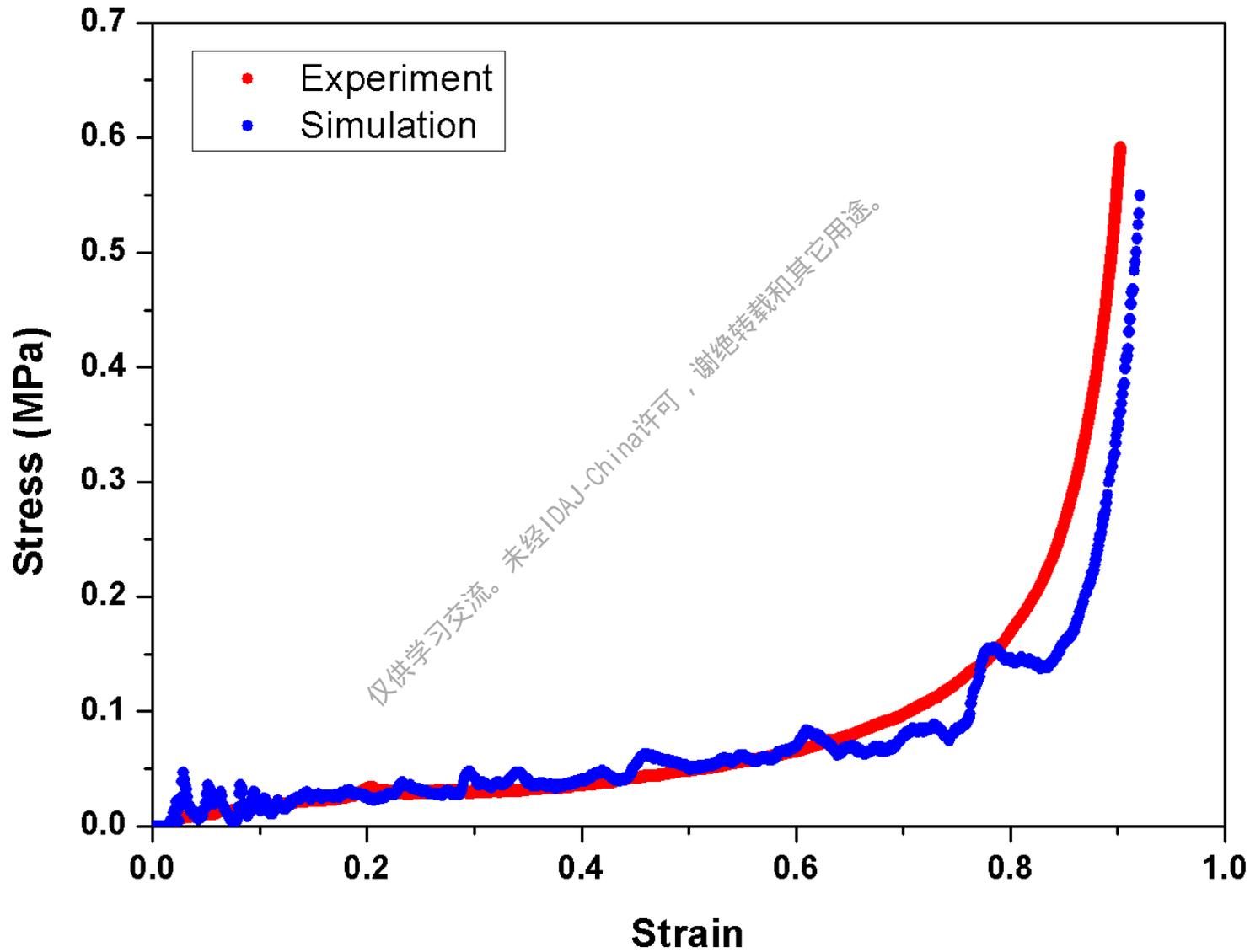
轻质吸能材料 (MHS) 设计



仅供学习交流。未经IDAJ-China许可，谢绝转载和其它用途。

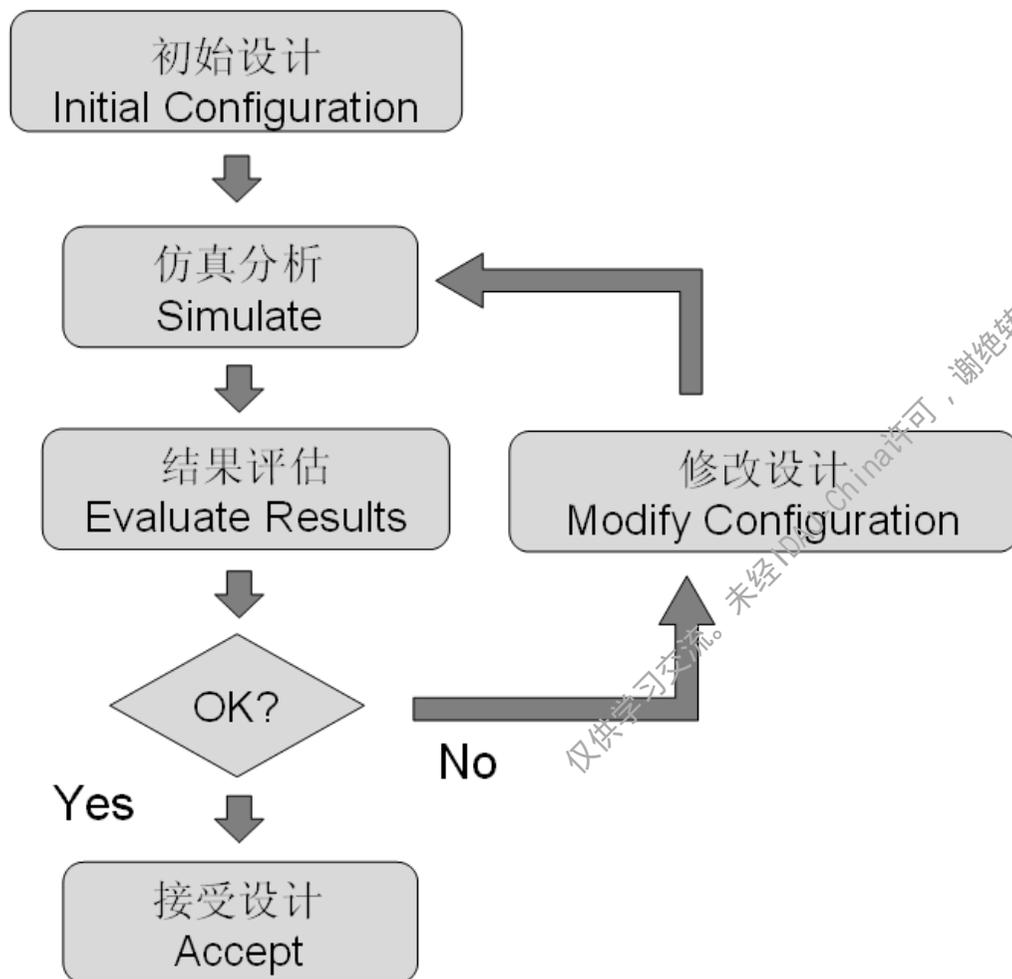


轻质吸能材料 (MHS) 设计





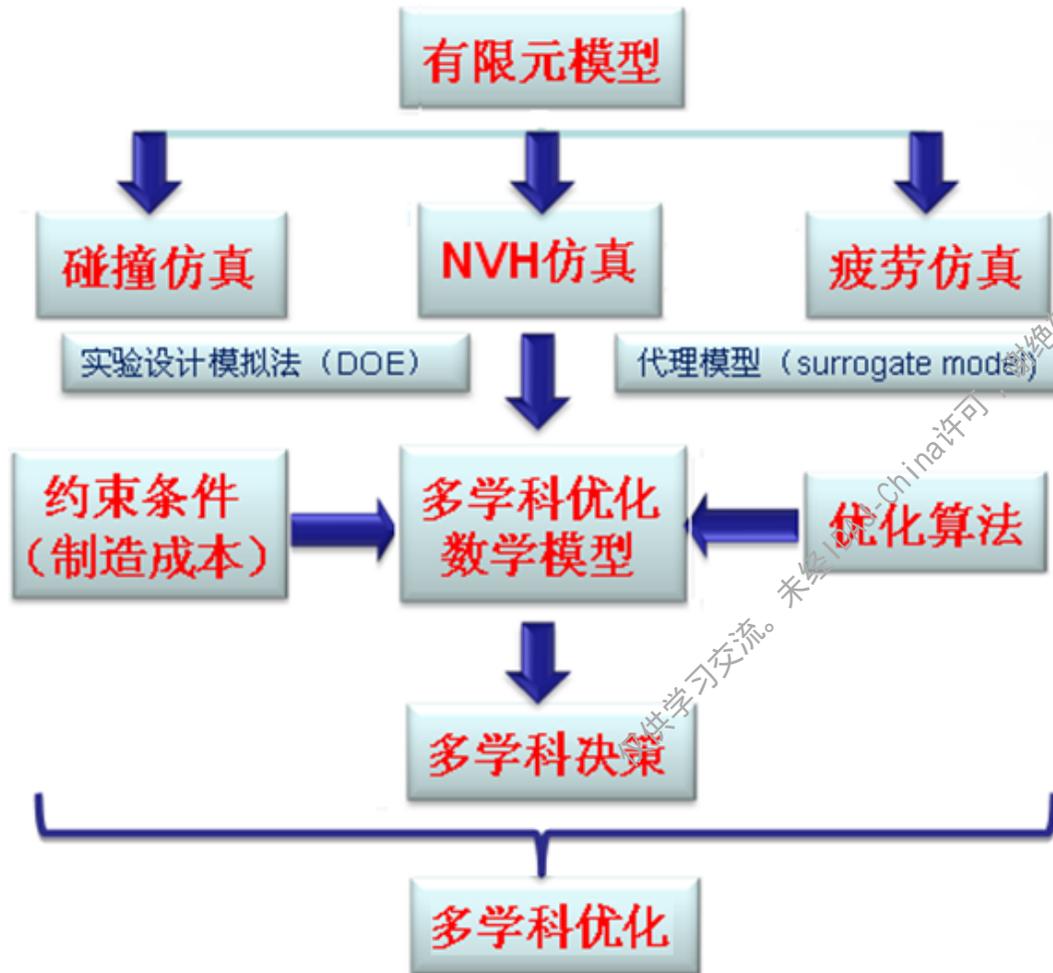
传统解决方案



- 手动修改设计，工作量大，效率很低；
- 设计方案评估数量有限（一般情况下 < 10）
- 基于经验，很难找到最优设计
- 难以实现多学科协同优化



基于软件集成平台的MDO

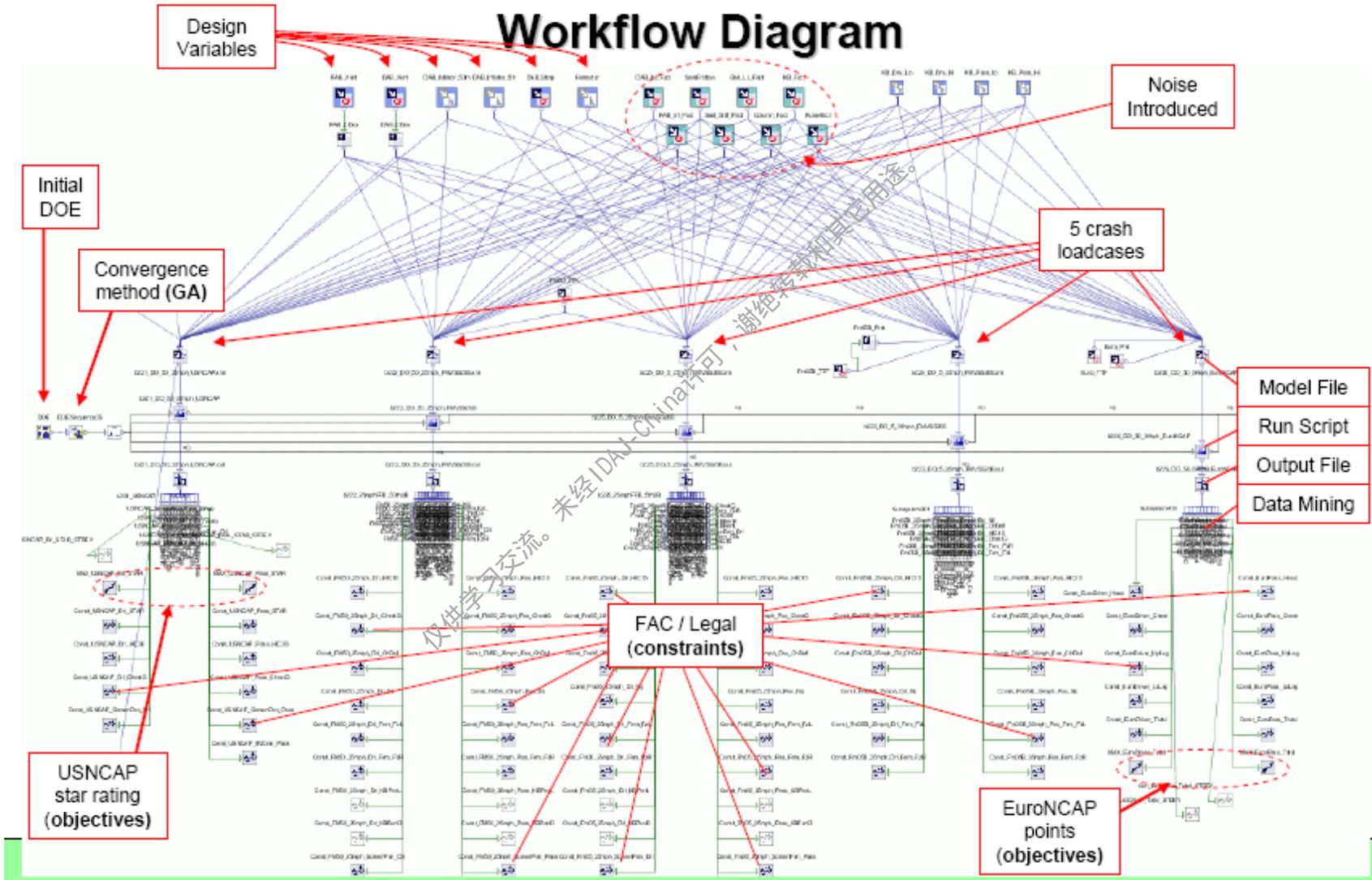


- 模型建立后可对方案自动评估（以千计）
- 设计过程标准化，具有可重复性
- 先进的优化算法保证高效寻优
- 多学科目标协同考虑
- 可以根据设计者意愿最终决策



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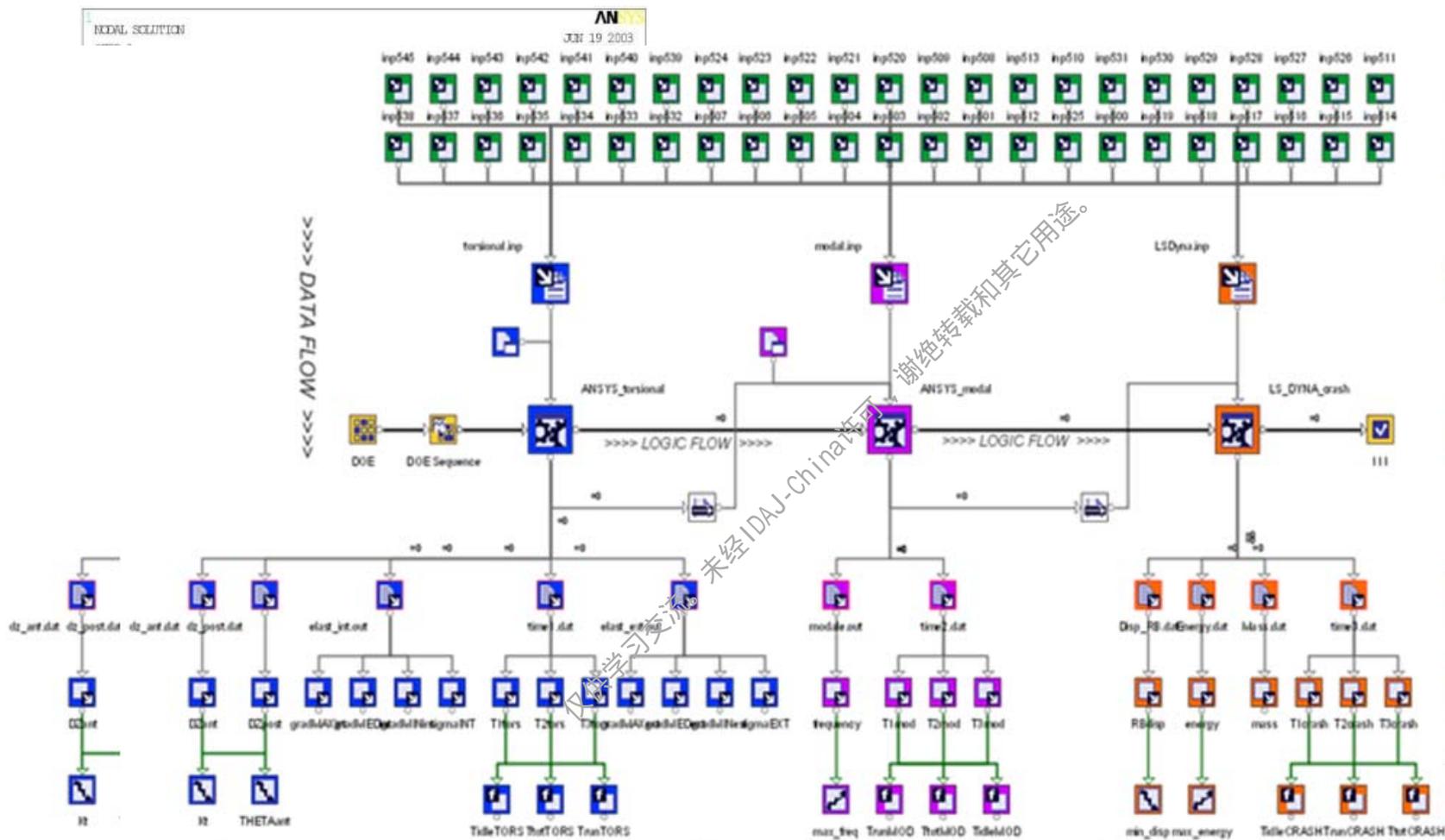
白车身耐撞性优化设计





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白车身多学科优化



设计变量选择

输入文件

仿真分析

输出文件

输出变量

设计目标设定

疲劳寿命优化

模态 (NVH)优化

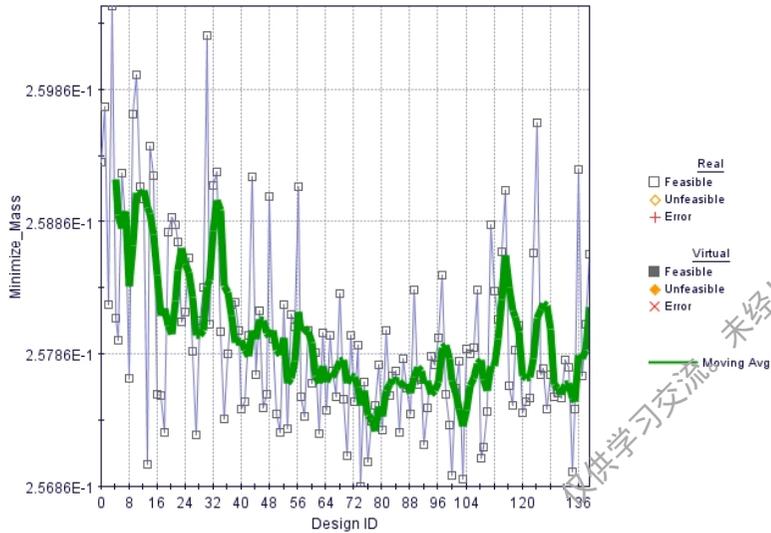
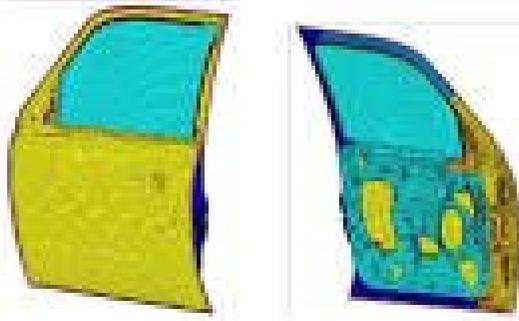
碰撞优化

(LS-DYNA)

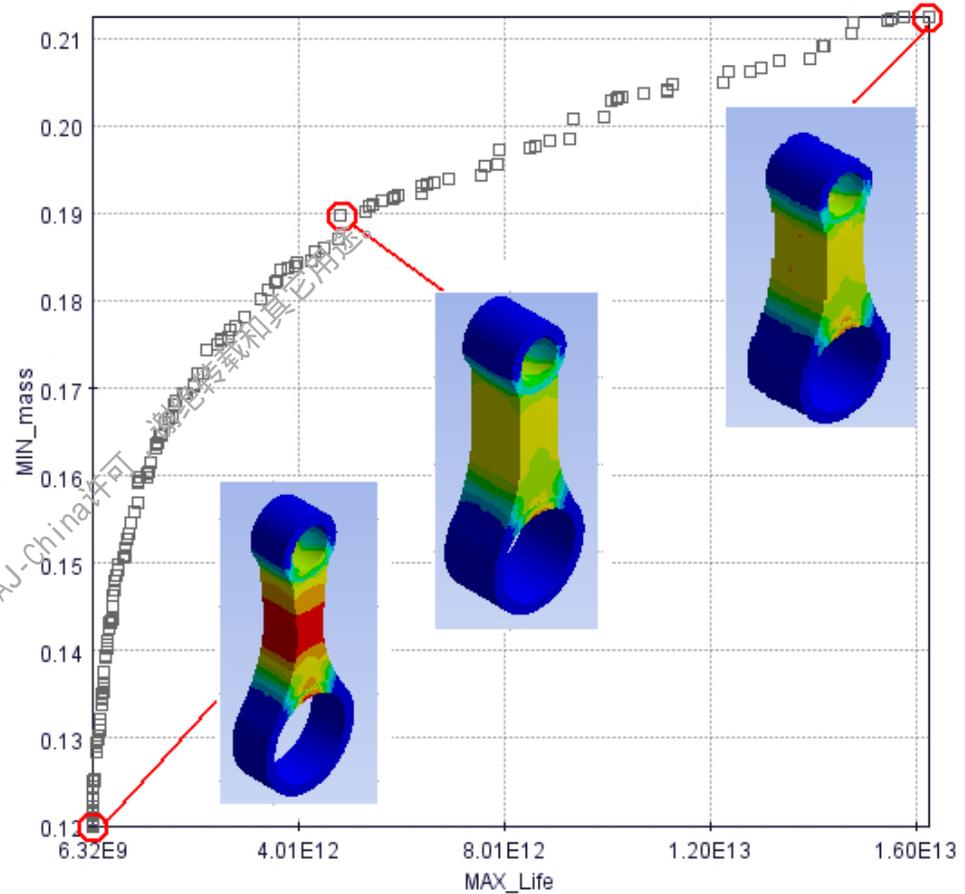


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零部件力学分析与轻量化



卡车车门轻量化设计
 模态分析 (NASTRAN)
 变形分析 (ABAQUS)

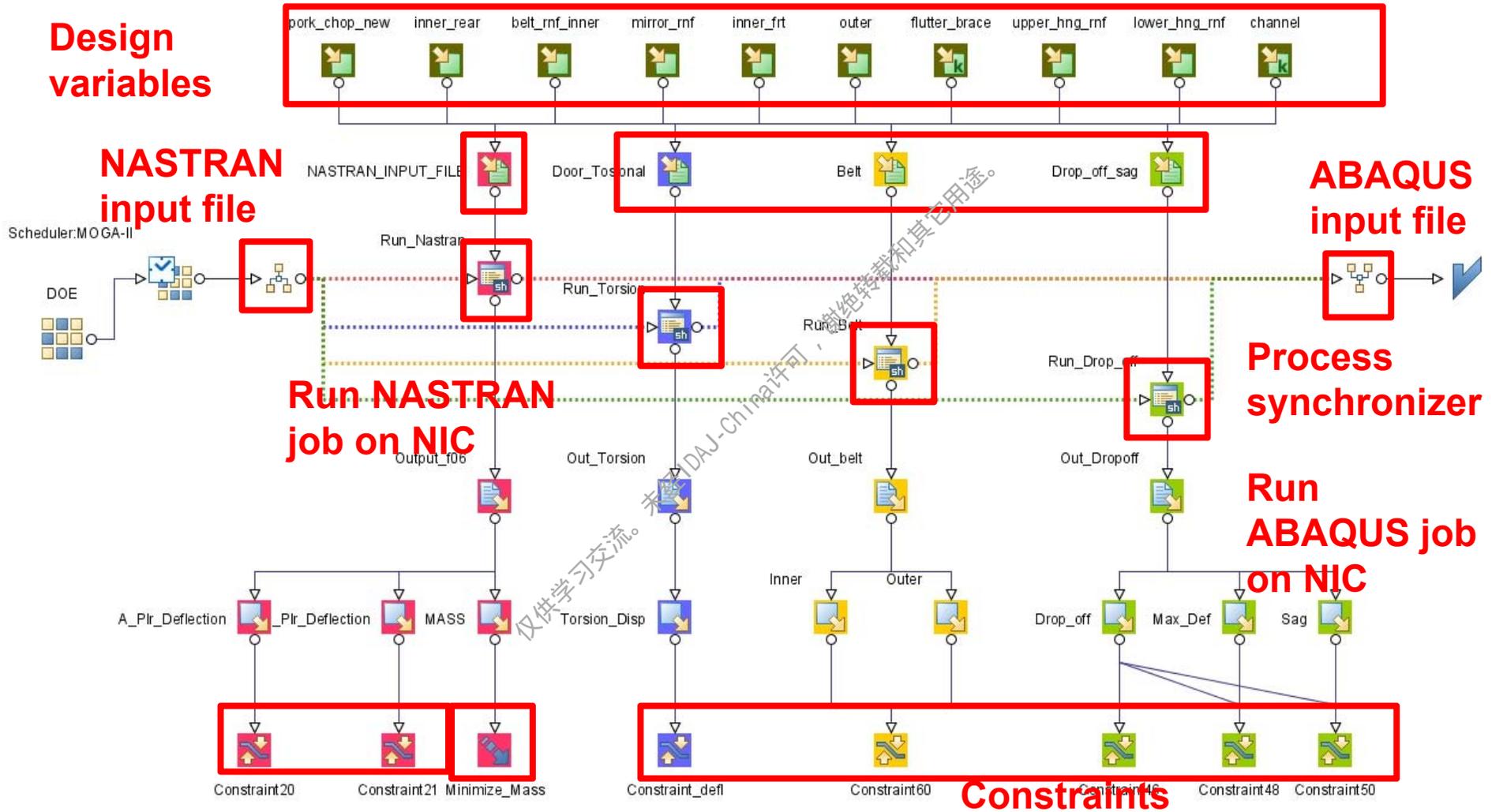


活塞连杆轻量化设计
 应力分析 (ANSYS)
 疲劳分析 (nCode)



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零部件轻量化设计

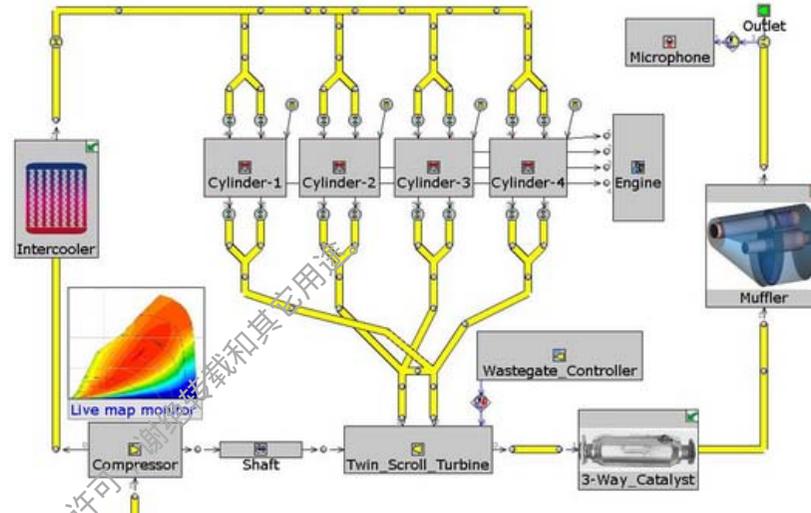


优化设计流程

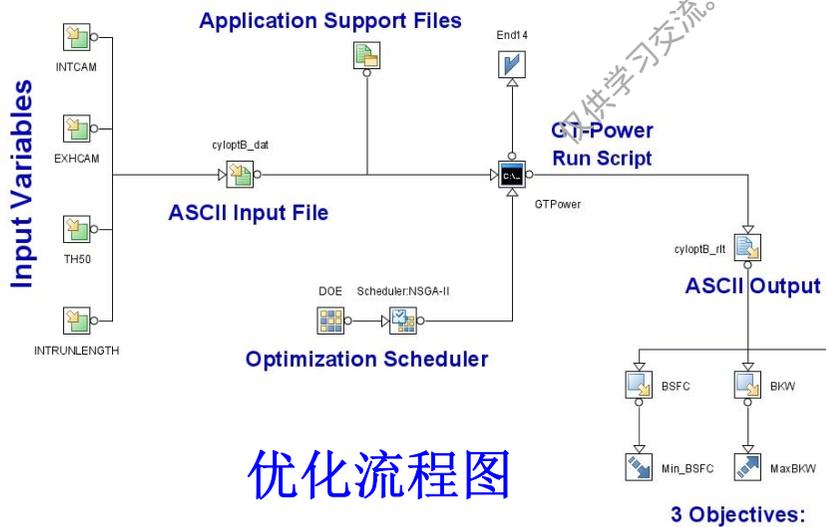


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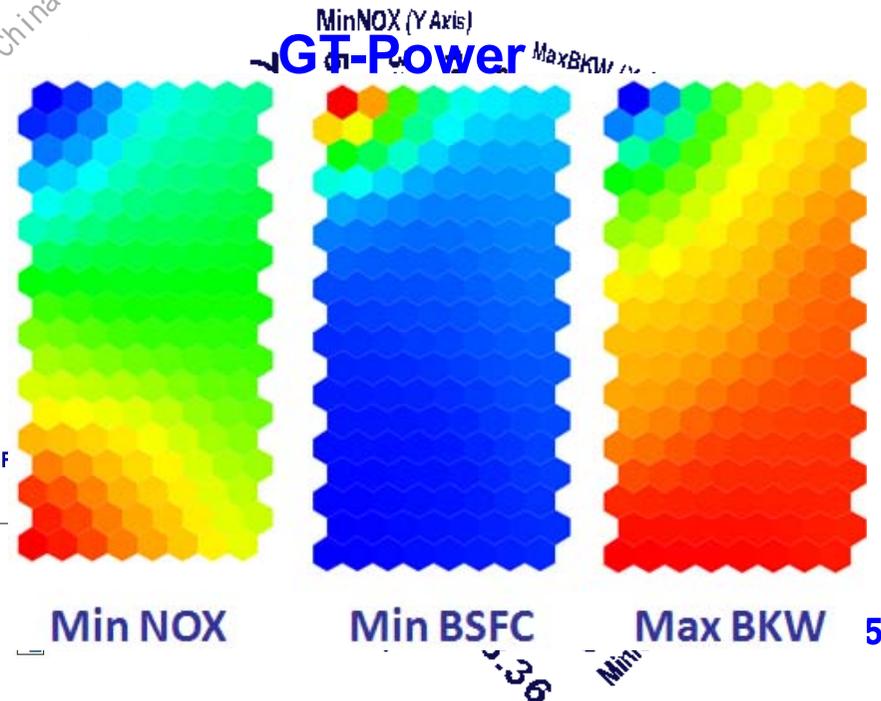
内燃机性能优化



Find : INTCAM , EXHCAM , INTRUN , TH50
To Max: Power; Min: Fuel consumption; Nox



优化流程图



Min NOX

Min BSFC

Max BkW



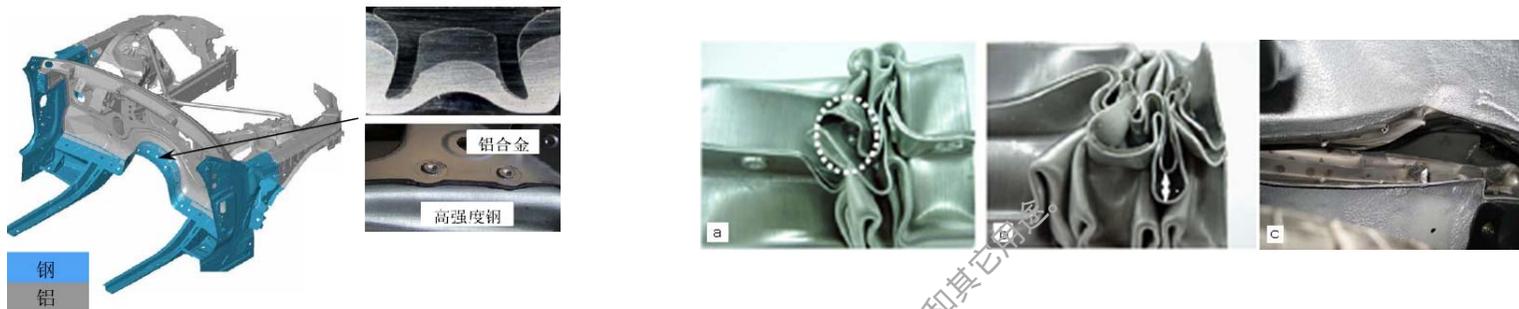
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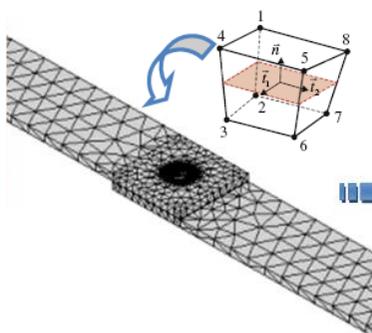
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异质金属车身耐撞性研究

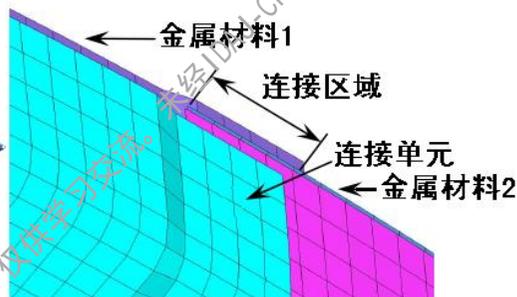


异质金属混合车身需采用新的连接方式

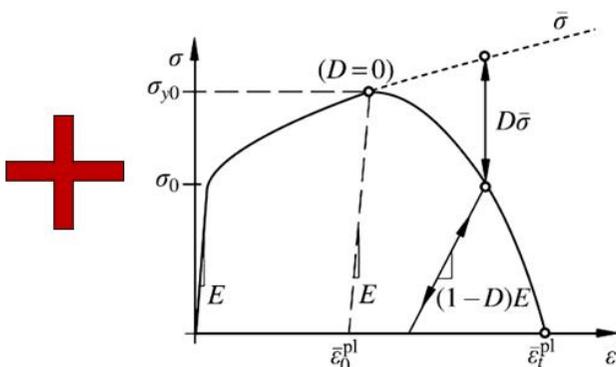
新方式连接的车身耐撞性亟需研究



精细接头模型



适用于碰撞仿真的等效接头模型

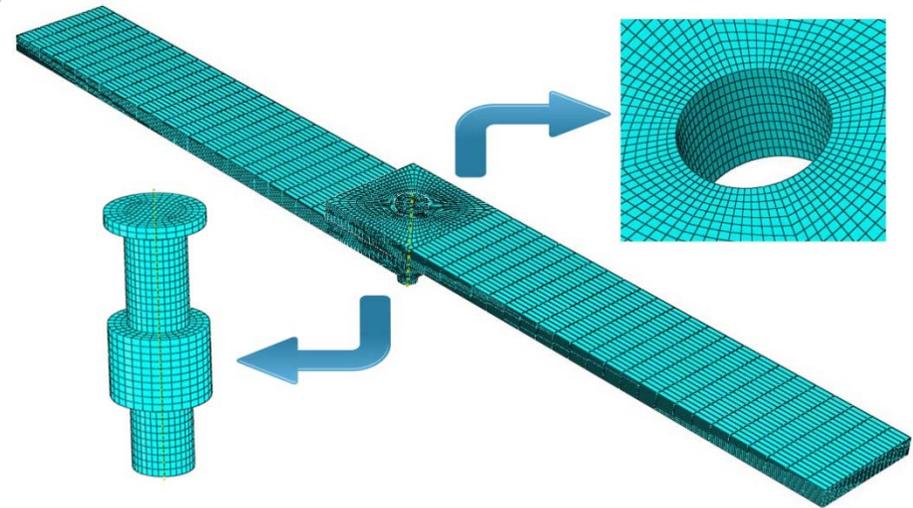
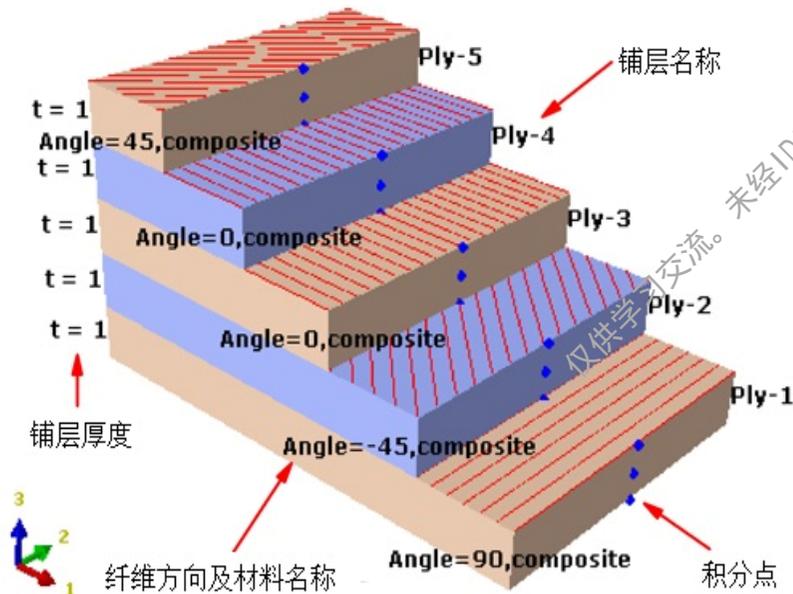
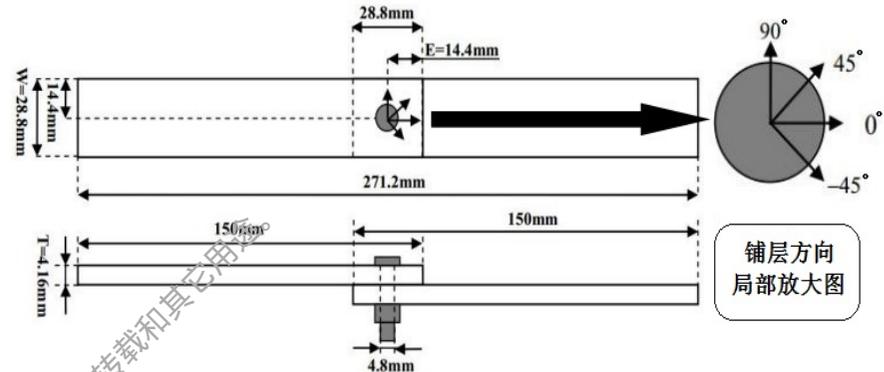


高应变率下材料失效关系

精细接头模型不适用碰撞分析——> 需要建立碰撞等效模型



DUT | 复合材料层合板机械连接研究

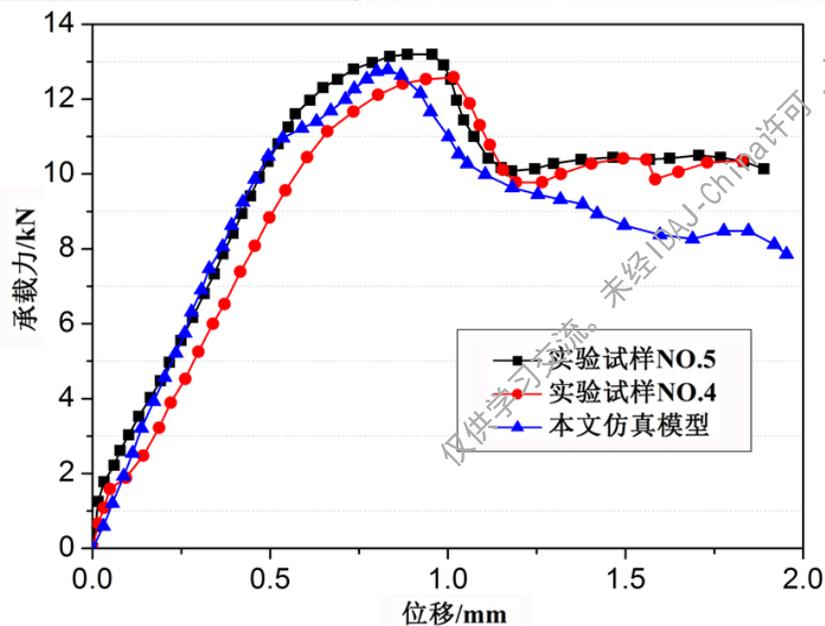
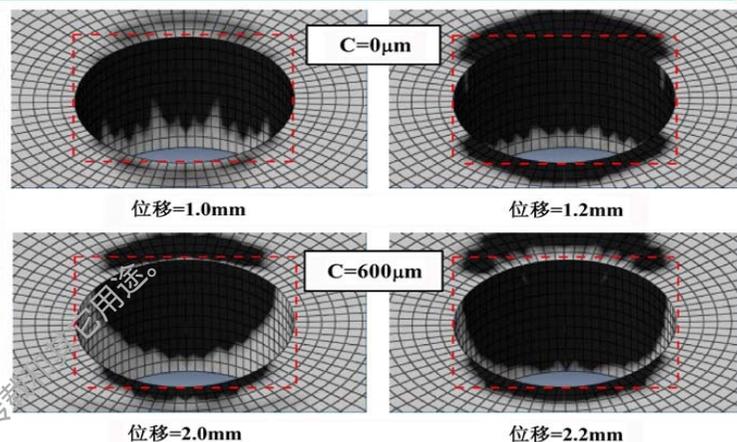
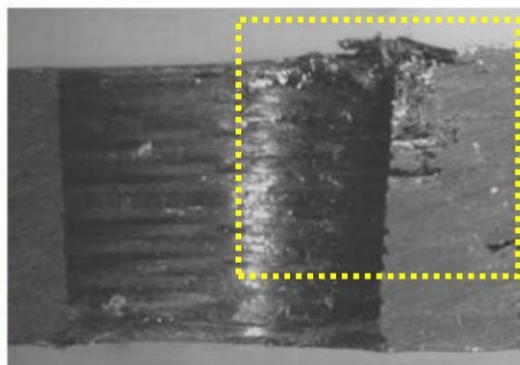
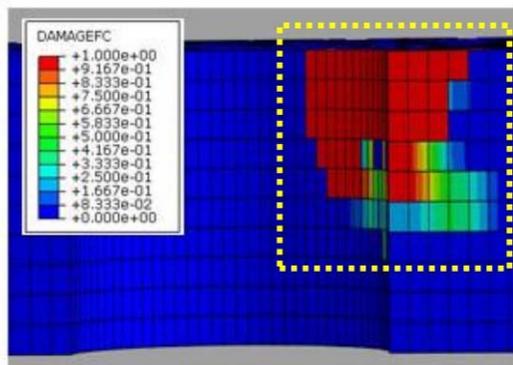


碳纤维层合板机械连接损伤机理仿真分析

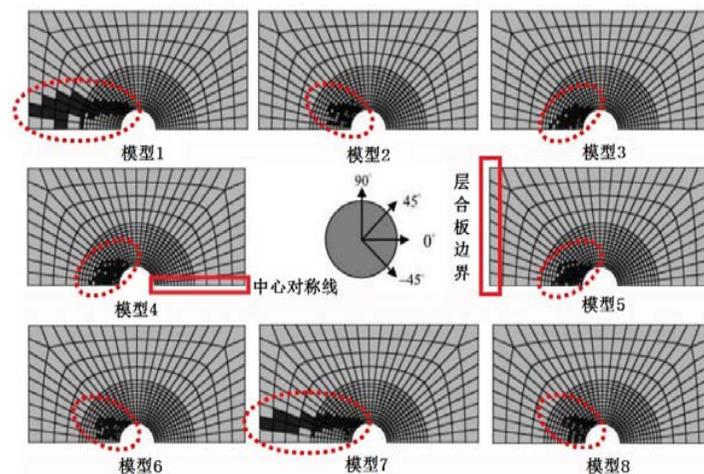


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复合材料层合板机械连接研究



不同连接孔间隙模型的失效形式



挤压失效预测 (仿真 vs 实验)

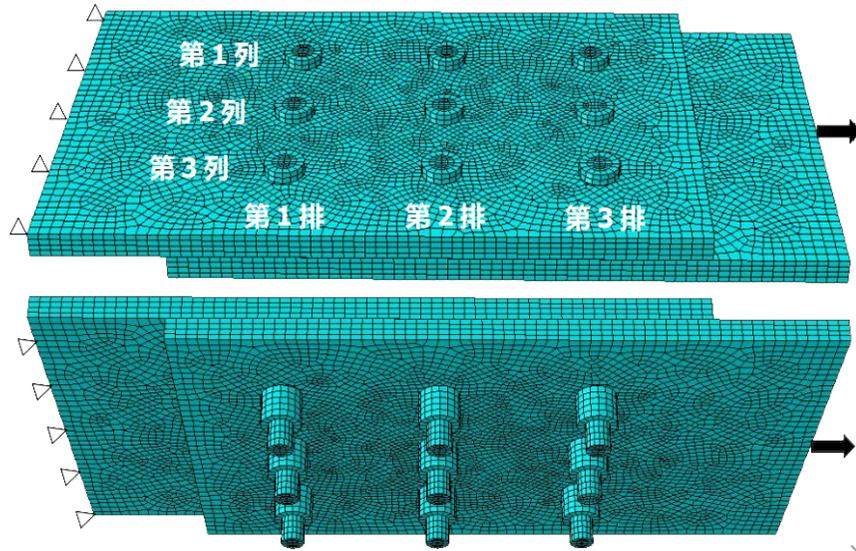
不同铺层比例模型失效形式

碳纤维层合板机械连接损伤机理仿真分析



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复合材料层合板机械连接研究



多钉连接层合板仿真模型

$$\begin{cases} \max & F_{max}, -S_{均} \\ s.t. & 15\text{mm} \leq P \leq 35\text{mm} \\ & 15\text{mm} \leq S \leq 35\text{mm} \\ & L \in \{L_1, L_2, L_3, L_4, L_5\} \end{cases}$$

优化模型

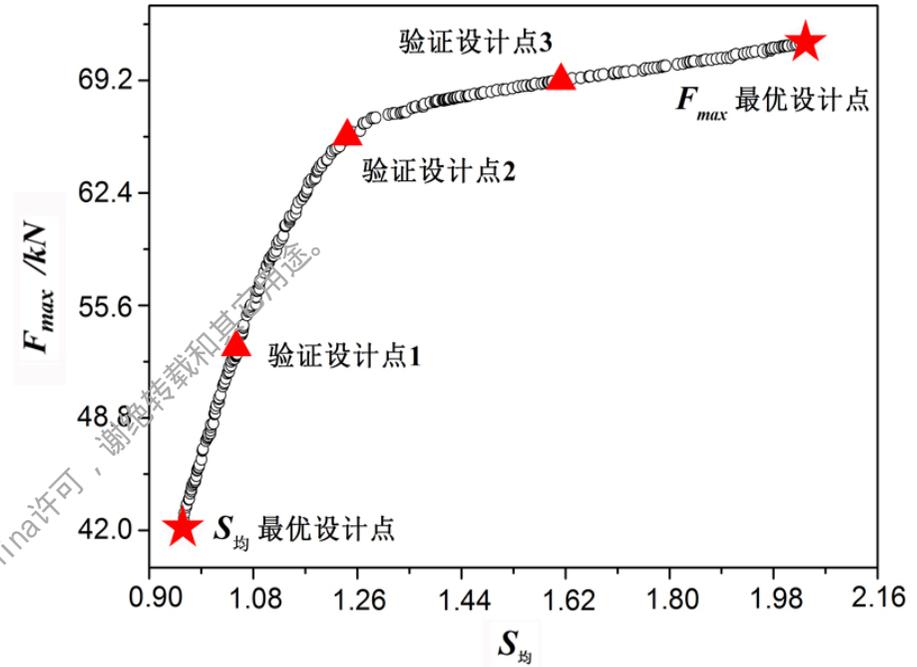


表 5.17 帕累托前沿最优设计点验证

Tab. 5.17 Verification of pareto curve

	F_{max}			$S_{均}$		
	前沿预测	有限元分析	误差/%	前沿预测	有限元分析	误差/%
$S_{均}$ 最优点	40.385	41.894	3.602	0.927	0.939	1.278
F_{max} 最优点	68.598	71.981	4.610	1.947	2.033	4.230
验证点 1	53.793	52.394	2.670	1.052	1.101	4.450
验证点 2	66.012	68.266	3.302	1.249	1.210	3.223
验证点 3	69.184	71.976	3.879	1.609	1.543	4.277

优化设计结果

层合板机械连接优化设计



乘员约束系统研究项目：

- 乘员约束系统鲁棒性设计
- 新概念安全带织带研究

仅供学习交流。未经许可，不得转载和其它用途。



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乘员约束系统研究项目：

- 乘员约束系统鲁棒性设计
- 新概念安全带织带研究

仅供学习交流。未经DUT-China许可，谢绝转载和其它用途。



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乘员约束系统鲁棒性设计

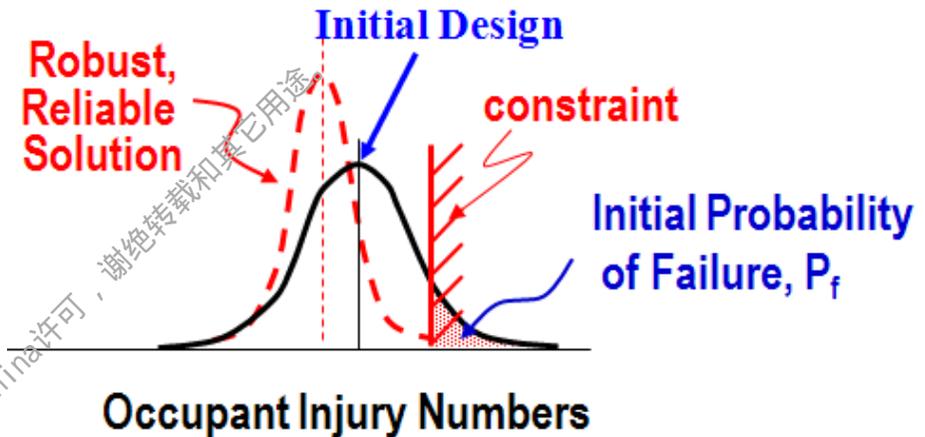
项目背景



SDG FAC

FMVSS/CMVSS

Real-world Safety



- 创新性：针对碰撞安全的鲁棒性设计方法和通用CAE流程
- 价值：有效提高碰撞星级并显著降低/避免成本，仅Edge/MKX一个平台每年节约开发成本7,000,000美元。
- 影响：减小实车碰撞测试不达标概率
- 应用：已应用于众多项目及整车平台



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乘员约束系统鲁棒性设计

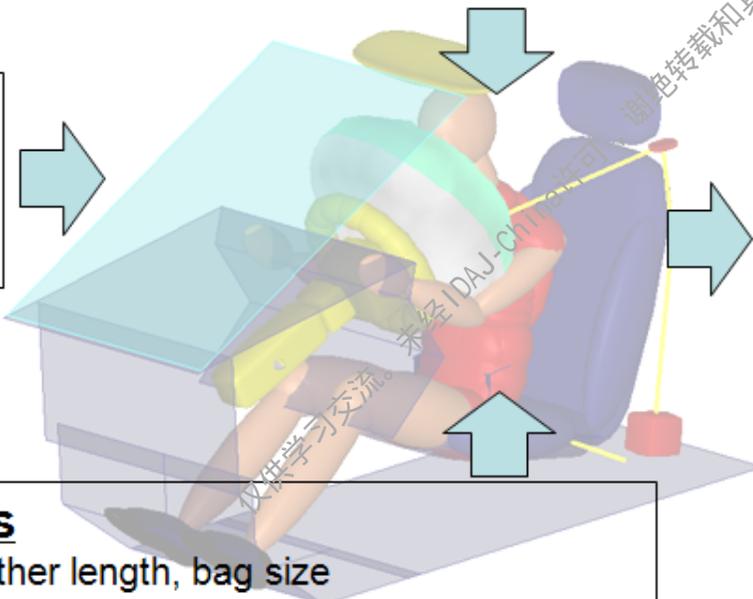
Occupant Dynamic Response: P-Diagram

Noise Factors

Airbag (vent size, tether length, bag geometry, material), Inflator (gas mass, temperature), Retractor load, Pretensioning, Belt webbing, Column (load, stroke, and intrusion), Seat stiffness, Bolster stiffness, dummy positioning

Inputs

Crash Modes:
barrier type, impact
speed, impact angle



Control Factors

Airbag: vent size, tether length, bag size
Inflator: gas mass, temperature
Seat Belt: retractor load, pretensioning, webbing
Column: stroke load, stroke length
Seat: stiffness
Knee Bolster: stiffness, position
Crash Pulse: crush space, pulse shape

Outputs:

Dummy Responses
• HIC (36)
• HIC (15)
• Chest G
• Chest defl.
• Nij
• Femur Fz
• Tibia Index



FMVSS208

FAC & Real-world Safety

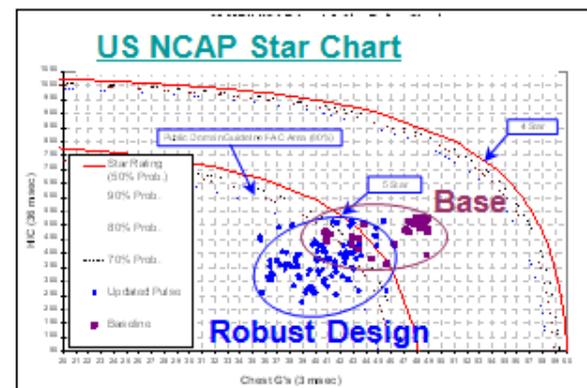
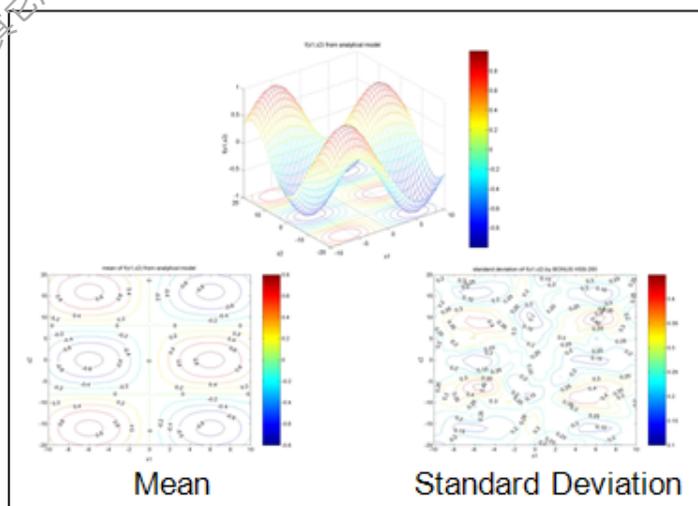
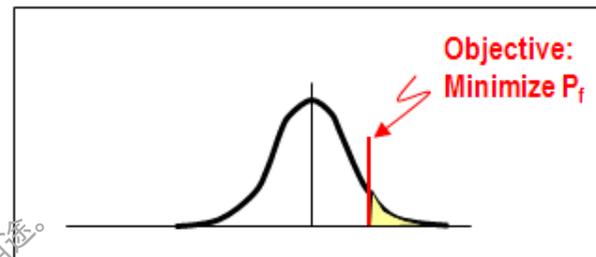
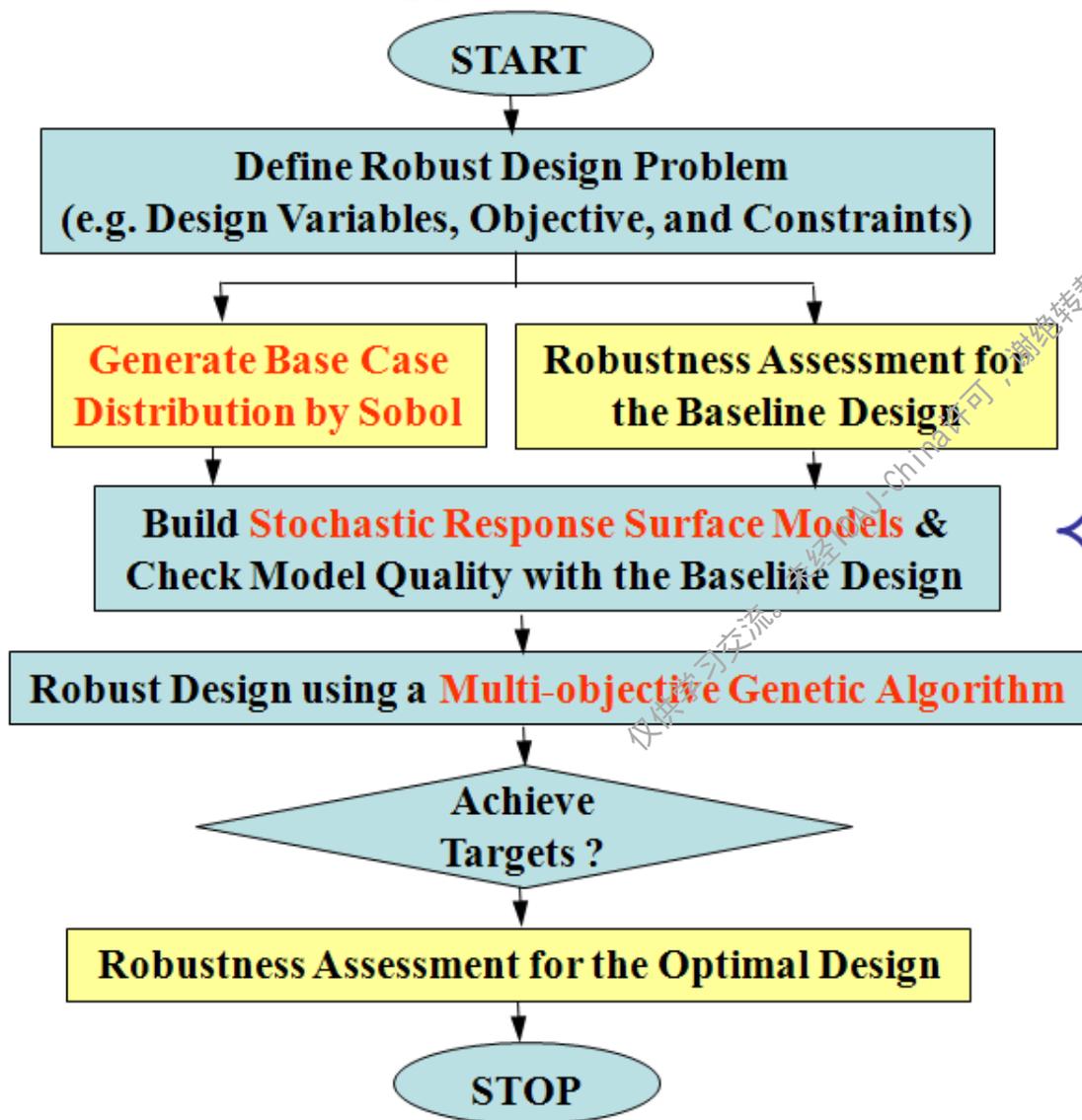
Error State:

Dummy metric exceeds public domain target or FAC



DUT 乘员约束系统鲁棒性设计

Methodology

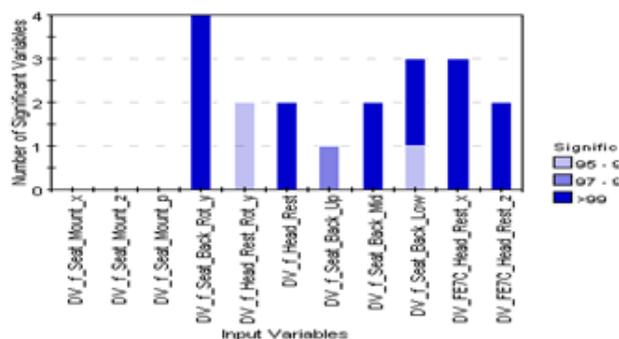




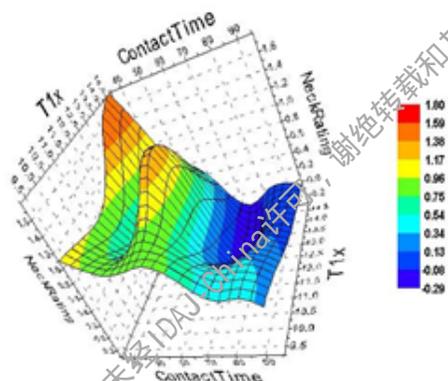
DUT | 乘员约束系统鲁棒性设计

Edge Rear Impact Example

Significant Variables

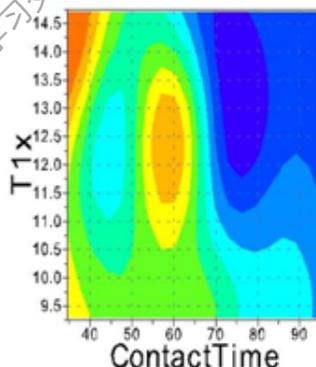


Robust Design Optimization



Correlation Matrix

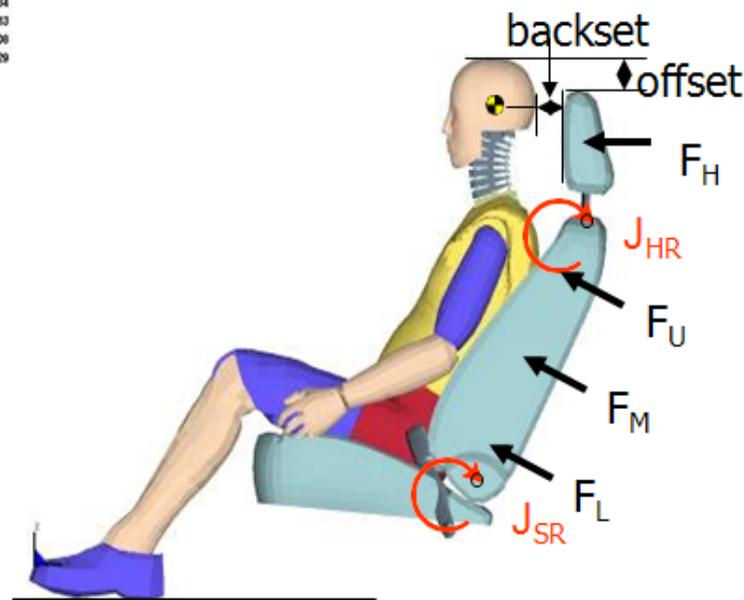
	Contact Time	T1x	Fx	Fz
DV_f_Seat_Mount_x	-0.02	0.03	0.04	0.01
DV_f_Seat_Mount_z	-0.02	0.01	0.02	0
DV_f_Seat_Mount_p	0.05	0.01	0.01	-0.01
DV_f_Seat_Back_Rot_y	-0.58	0.79	0.58	0.16
DV_f_Head_Rest_Rot_y	0.13	-0.08	-0.11	0
DV_f_Head_Rest	0.04	0.01	-0.23	0.47
DV_f_Seat_Back_Up	0.03	0.02	-0.11	0.03
DV_f_Seat_Back_Mid	0.03	0.25	0.13	0.29
DV_f_Seat_Back_Low	0.07	0.2	0.13	0.17
DV_FE7C_Head_Rest_x	0.77	-0.1	-0.08	0.3
DV_FE7C_Head_Rest_z	-0.09	0.03	-0.51	0.5



3 Objective Functions:

- ✓ Min. 90 percentile Neck Rating
- ✓ Min. 90 percentile Contact Time
- ✓ Min. 90 percentile T1x Acceleration

11 Design Variables:

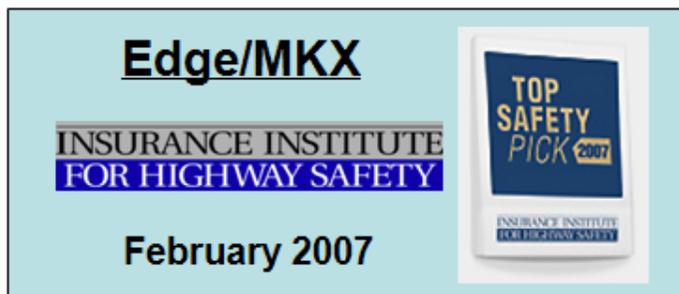




DUT

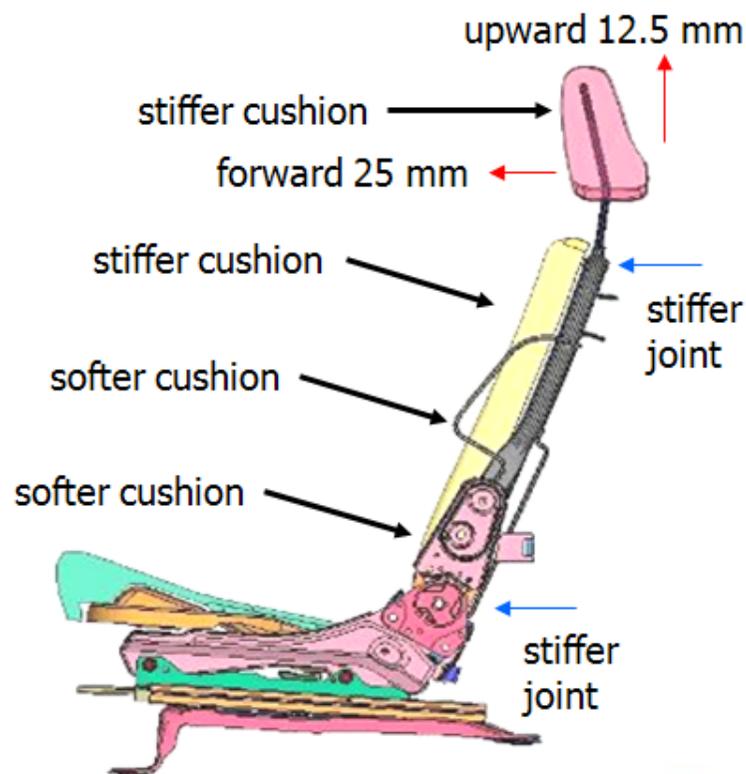
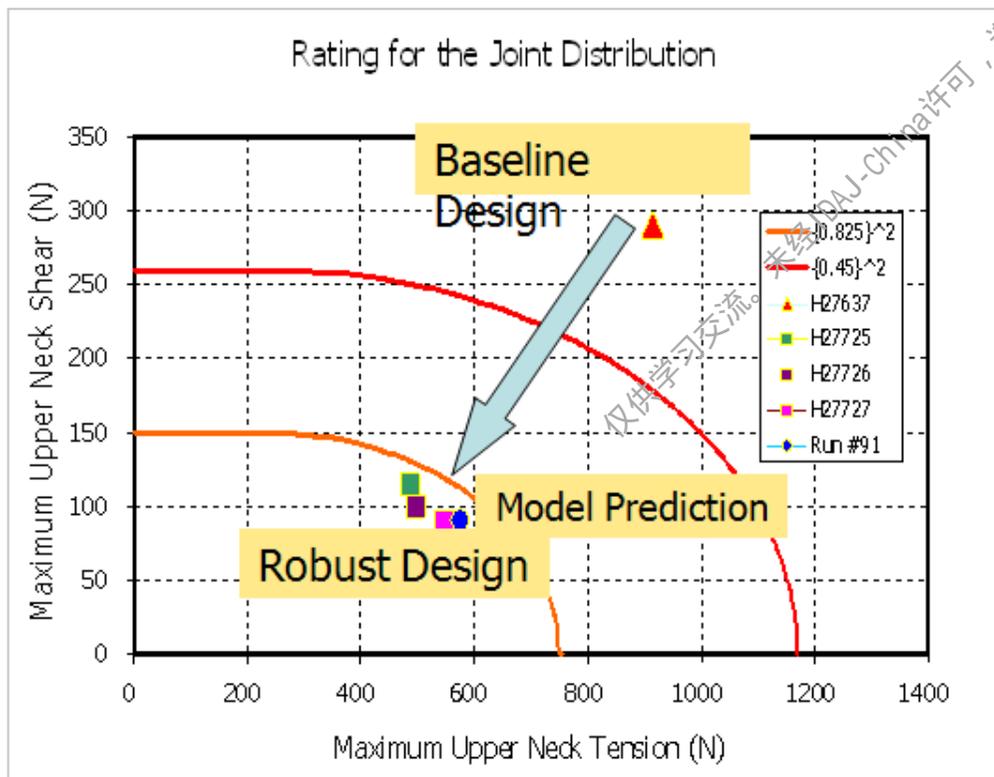
乘员约束系统鲁棒性设计

Edge Rear Impact Example



Provided a **\$35/vehicle**
(or **\$7 million/year**) cost avoidance

Recommended modifications:





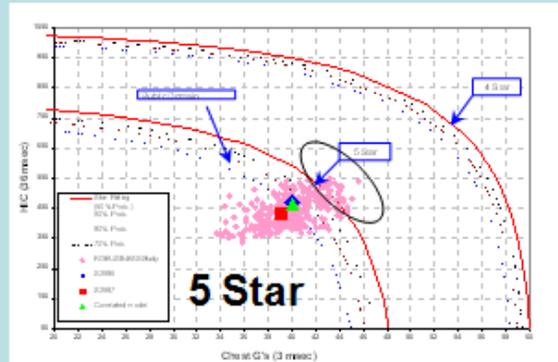
DUT

乘员约束系统鲁棒性设计

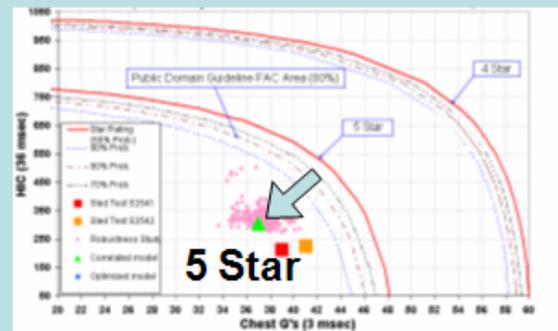
Front Impact Examples

D-Car Restraint Optimization

Base



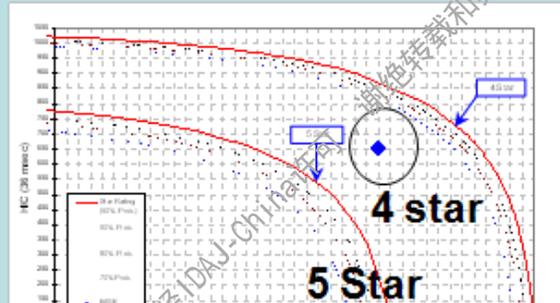
Optimized



More Robust 5 Star

B-Car Restraint Optimization

Base



Optimized



4 Star to 90% Confidence 5 Star

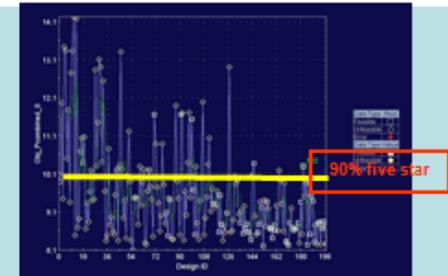
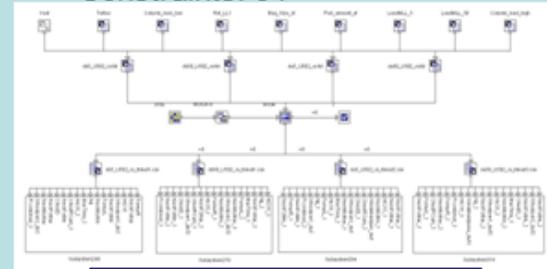
U502 Restraint Optimization

Multi-Objective Optimization

4 Crash Modes

- 50th% 35mph Belted
- 50th% 25mph Unbelted
- 5th% 35mph Belted
- 5th% 25mph Unbelted

Objective: CPI (5 Star NCAP)
Constraints: 64



> 90% Confidence 5 Star



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乘员约束系统鲁棒性设计

Impact on Ford's Business Objectives

Innovation

- **Industry First Robust Optimization Design Framework & Tools** for Occupant Crash Safety;
- **Industry First CAE Common Process** for Occupant Crash Safety

Value to Ford

- Improve occupant safety & increased confidence level for achieving **top safety ratings**
- Improved PD efficiency through **reducing product cost, reducing prototype build/test, and improving quality by robust design**
 - e.g. Method provided a **\$35/vehicle (or \$7 million/year for Edge/MKX alone) cost avoidance** over OEMs that use "active" seat/head restraint system
- **Reduce development time**, e.g. the application of this tool was the only way to get Ford Edge/Lincoln MKX to achieve "Good" rating within 6 months before Job 1
 - e.g. reduced turn-around time by 90%

Impact

Technology Validated



Implementation

Cross-Carline Deployment

U387 – 2007MY
D219 – 2008MY
D258 – 2008MY
C170 – 2008MY
D385 – 2009MY
D471 – 2009MY
D472 – 2009MY
B299 – 2010MY
C3XX – 2011MY

- **Management direction is to apply this method to all future programs**
- **15 NAE Engineers Trained**
- **CAE Best Practice**

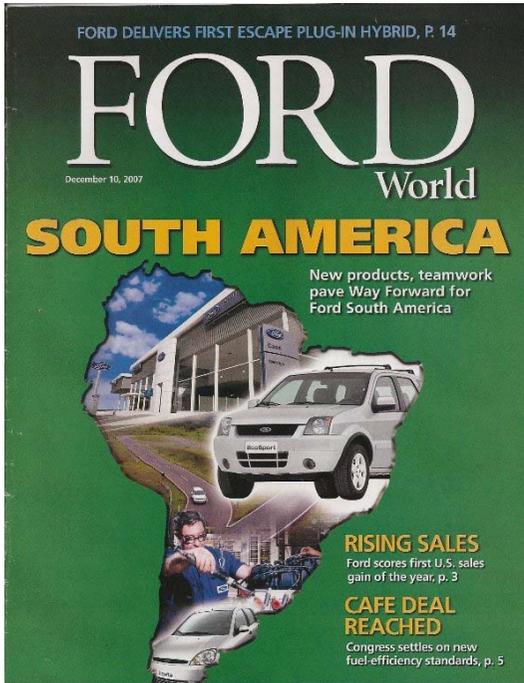
Global Product Development

Technology transferred to Mazda, Jaguar, Volvo, Ford of Europe for applications



DUT

福特“总裁奖”



“福特世界” 专题报道



乘员约束系统研究项目：

- 乘员约束系统鲁棒性设计
- **新概念安全带织带研究**

仅供学习交流。未经China许可，谢绝转载和其它用途。

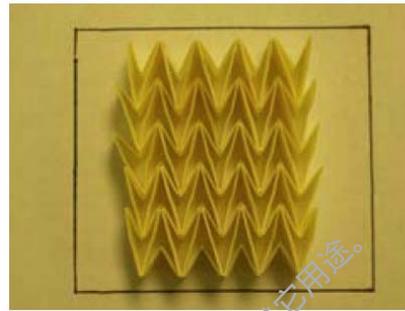


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新概念安全带织带

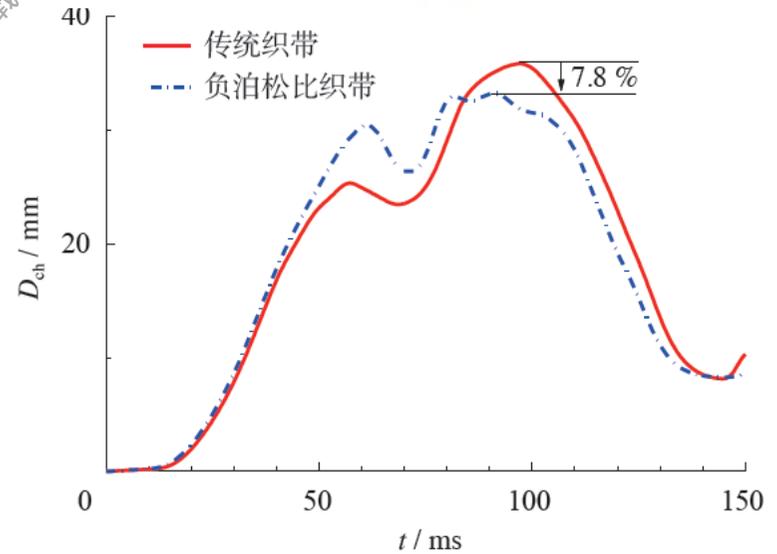


福特充气式安全带

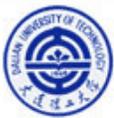


拉伸前

拉伸后



- 教育部博士点基金项目“基于负泊松比材料的新型汽车安全带织带设计优化研究”
- 获批专利 1 项



新能源汽车相关研究项目：

- 新能源汽车车身拓扑优化
- 电池碰撞防护

仅供学习交流。未经IDAJ-China许可，谢绝转载和其它用途。



新能源汽车相关研究项目：

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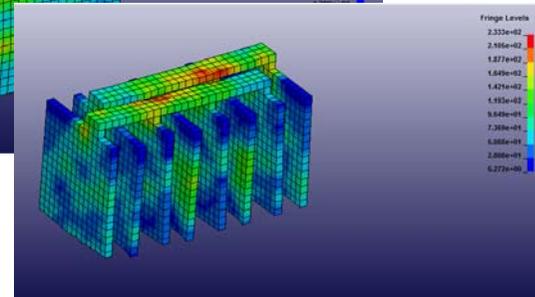
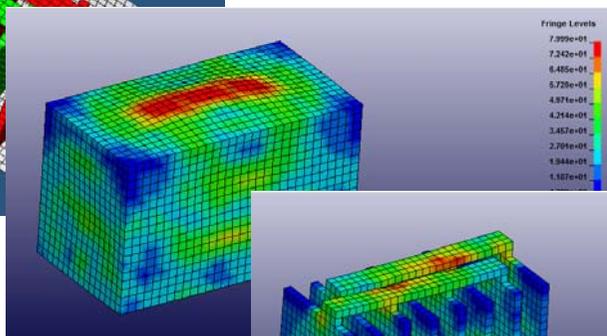
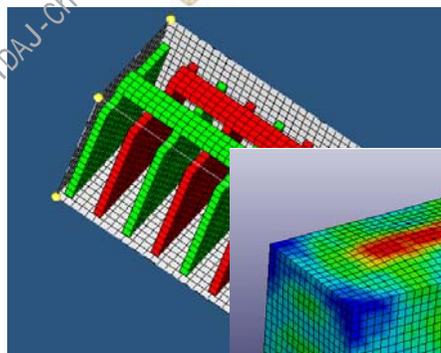
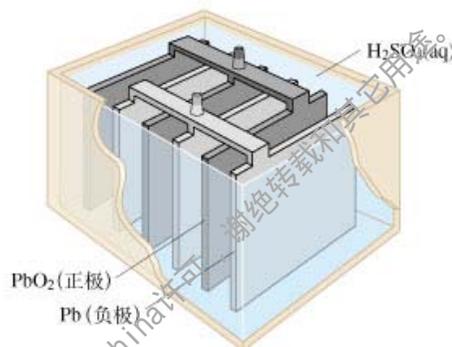
仅供学习交流。未经IDAJ-China许可，谢绝转载和其它用途。



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电池冲击破坏机理研究

- 国家自然科学基金“基于负泊松比材料的电动汽车电池碰撞安全防护结构设计优化研究”





DUT

动力电池新型防护结构设计

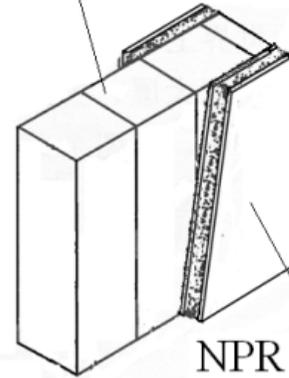


(a) 单体电池;

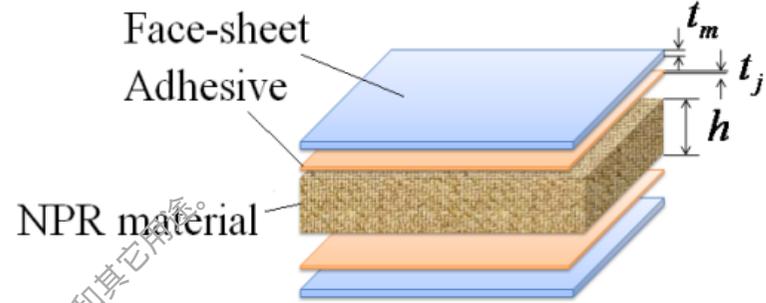


(b) 电池箱

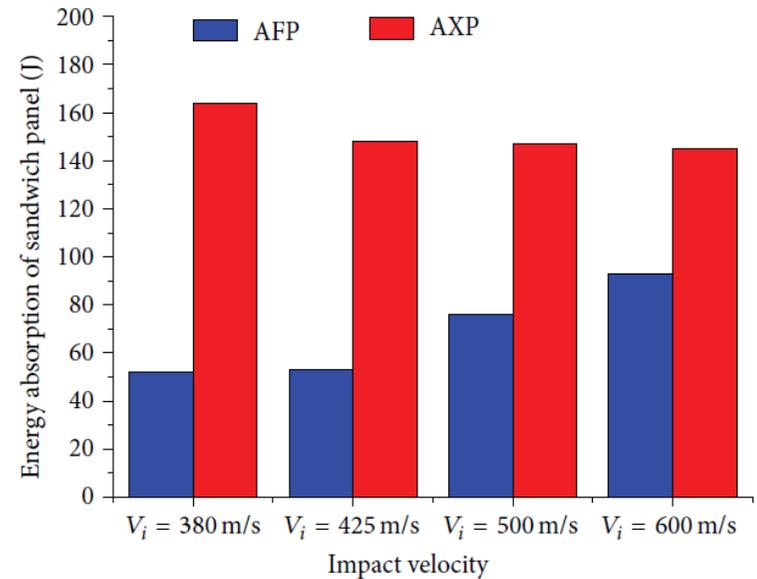
Battery pack



NPR material-cored sandwich structure



电池防护结构抗穿刺实验与仿真



Shu Yang, Chang Qi* et al. *Advances in Mechanical Engineering*, 2013. SCI, IF:1.062.



特种汽车防爆防弹研究项目：

- 军车防雷装甲设计
- 新型车用防弹结构研究

仅供学习交流。不得转载和其它用途。
IDAJ-China 许可，谢绝转载和其它用途。



特种汽车防爆防弹研究项目：

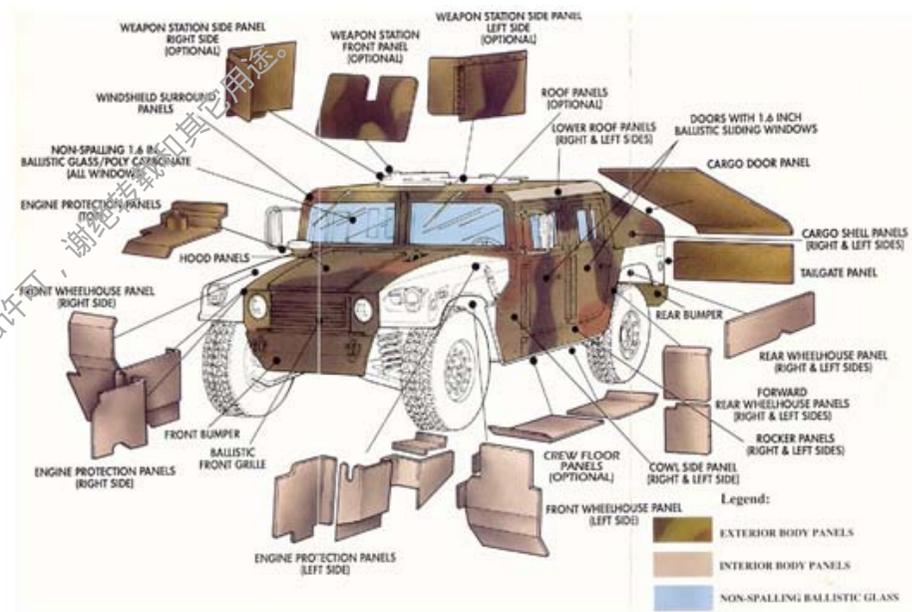
- 军车防雷装甲设计
- 新型车用防弹结构研究

仅供学习交流。未经许可，谢绝转载和其它用途。



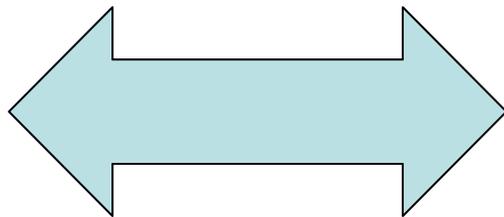
军车防雷问题

- 美国国防重点项目“军用悍马防雷装甲研究”



被地雷摧毁的美军多用途轮式战术车 HMMWV 及其附加装甲

安全性



轻量化



DUT

某型军车改款设计与仿真



长头软顶、两门驾驶室



长头软顶、四门驾驶室



长头硬顶、四门驾驶室



短头软顶、两门驾驶室⁶⁰

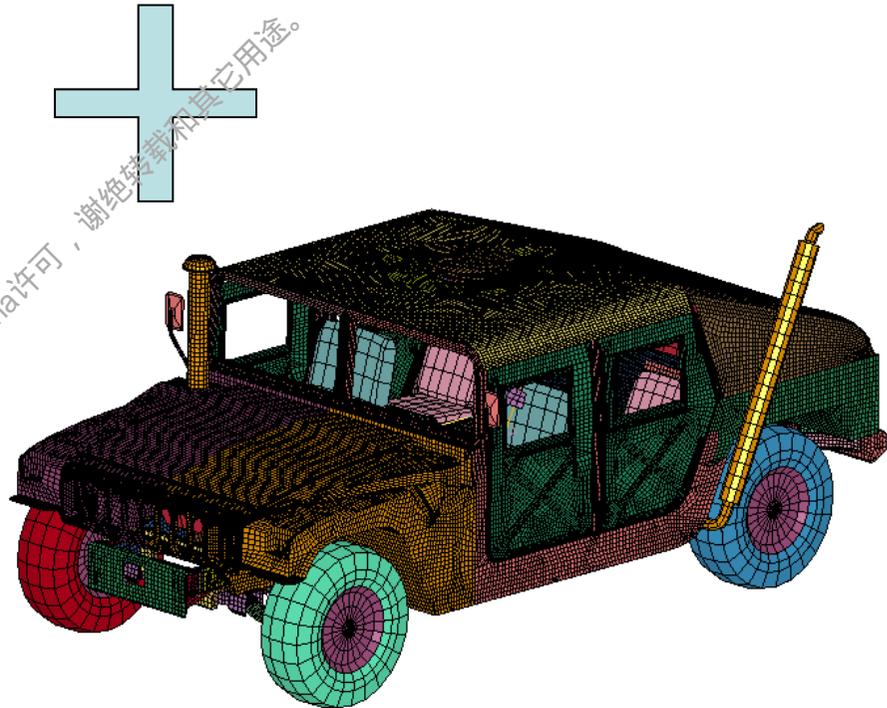
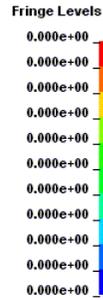
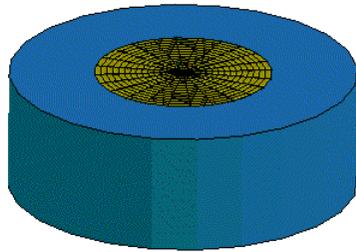


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军车防雷问题

LANDMINE EXPLOSION
Time = 0

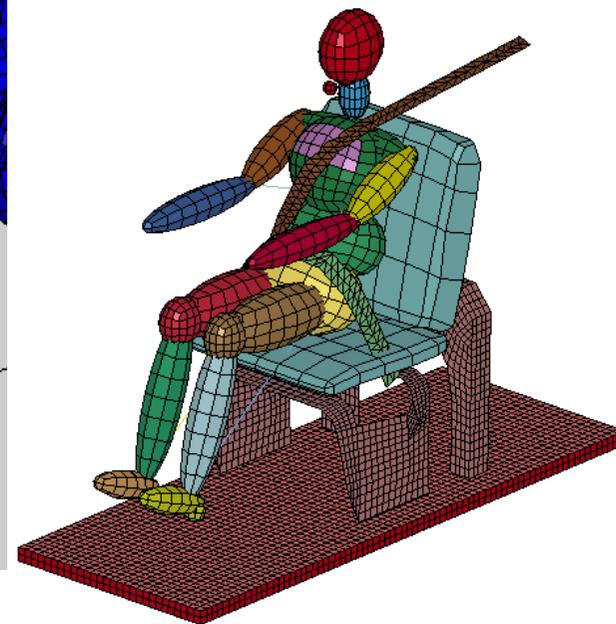
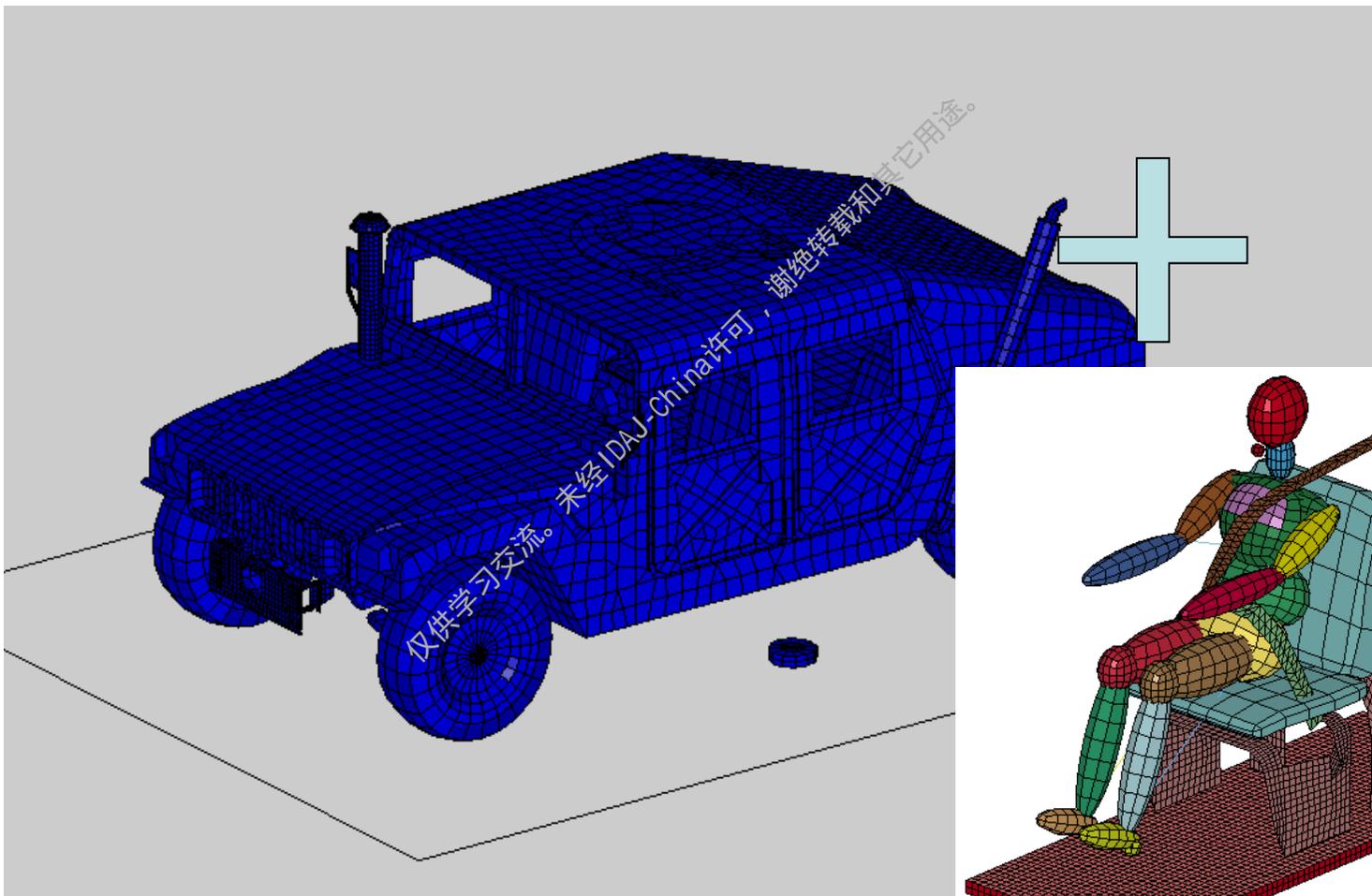
LANDMINE EXPLOSION
Time = 0
Vector of Total-velocity
min=0, at node# 2142
max=0, at node# 2142





DUT

军车防雷问题



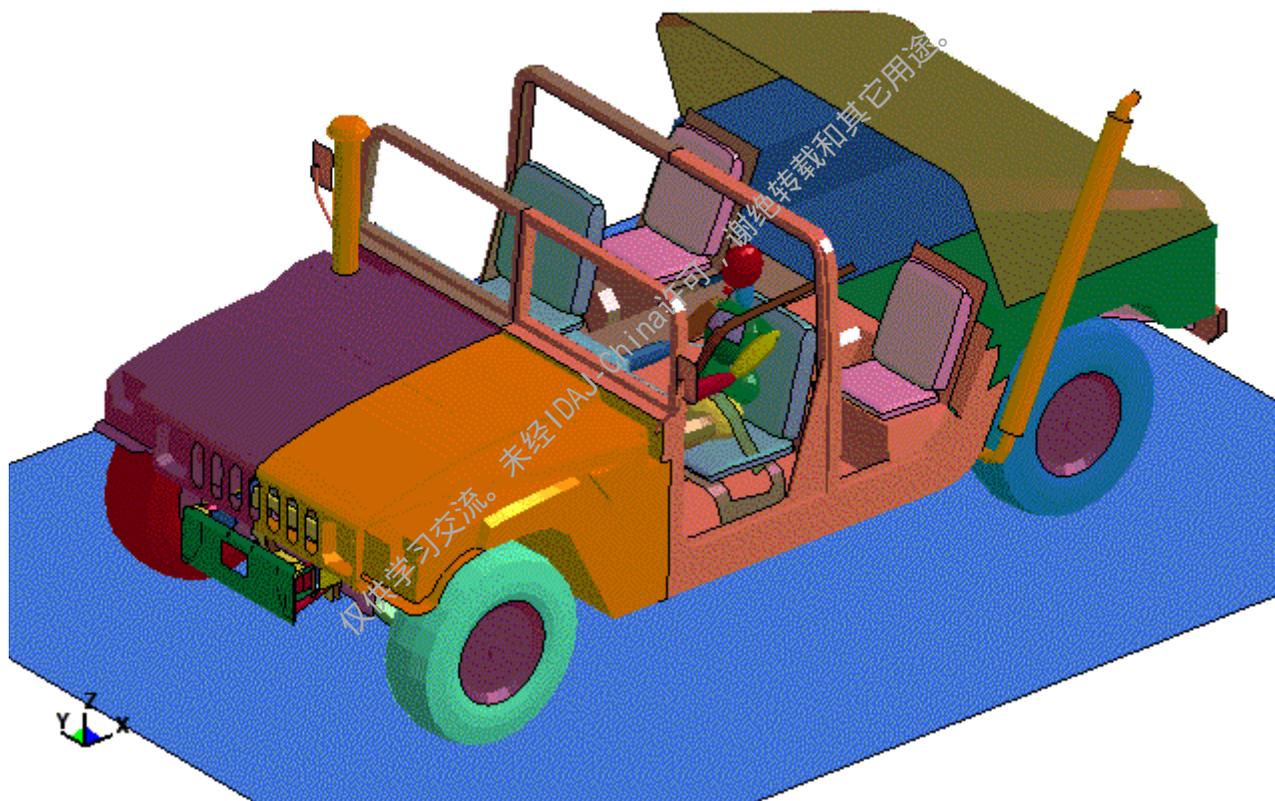


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军车防雷问题

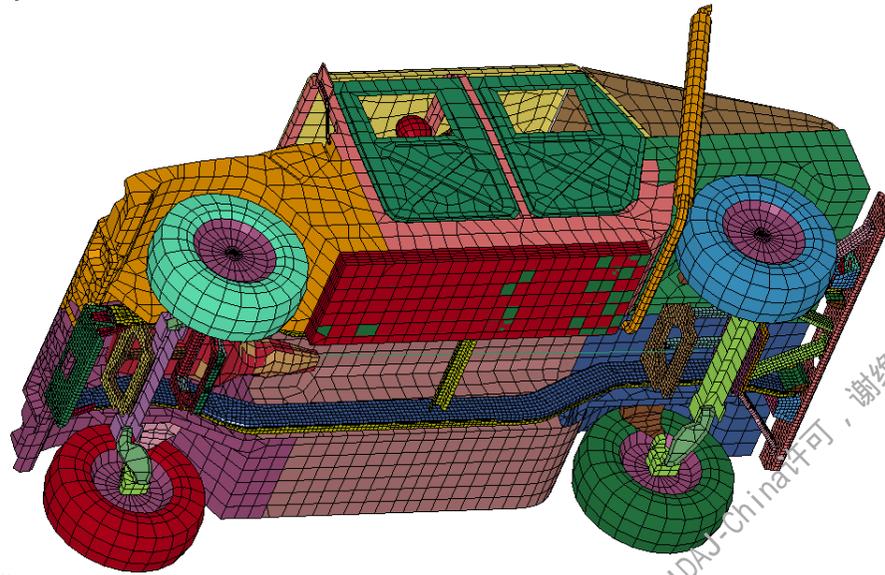
HMMWV FRONTAL IMPACT TEST

Time = 0

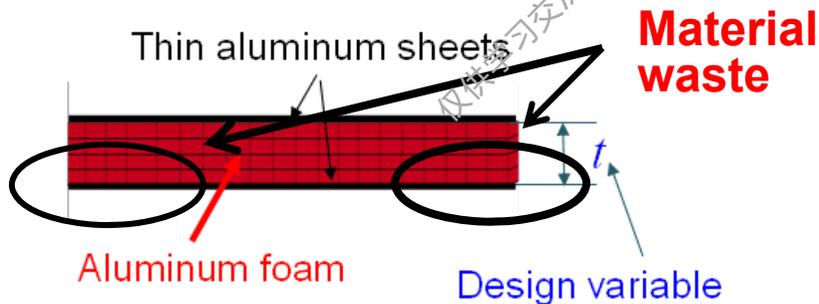




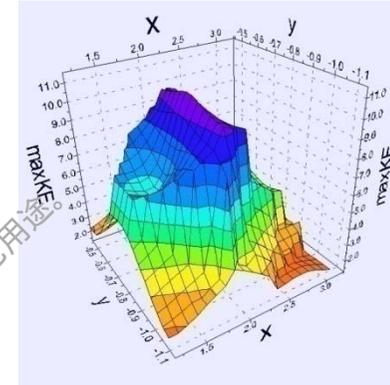
DUT | 轻质装甲设计



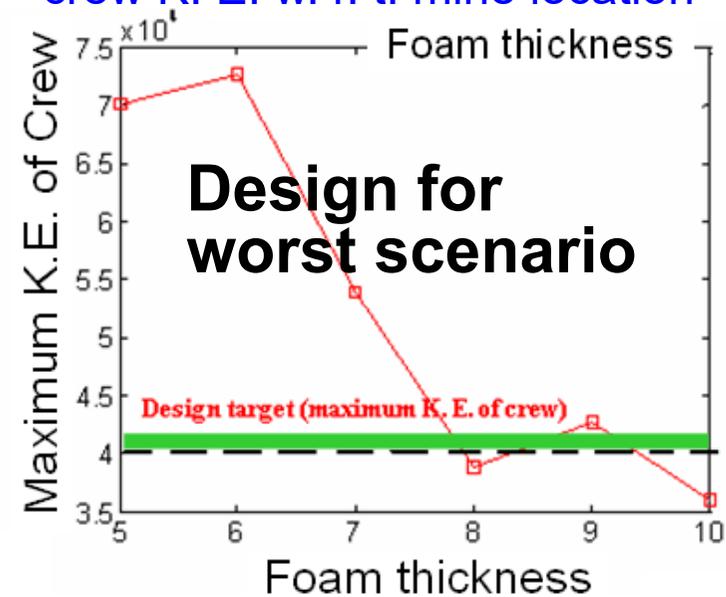
Land mine blast location uncertainty



Design variable is the metal foam thickness

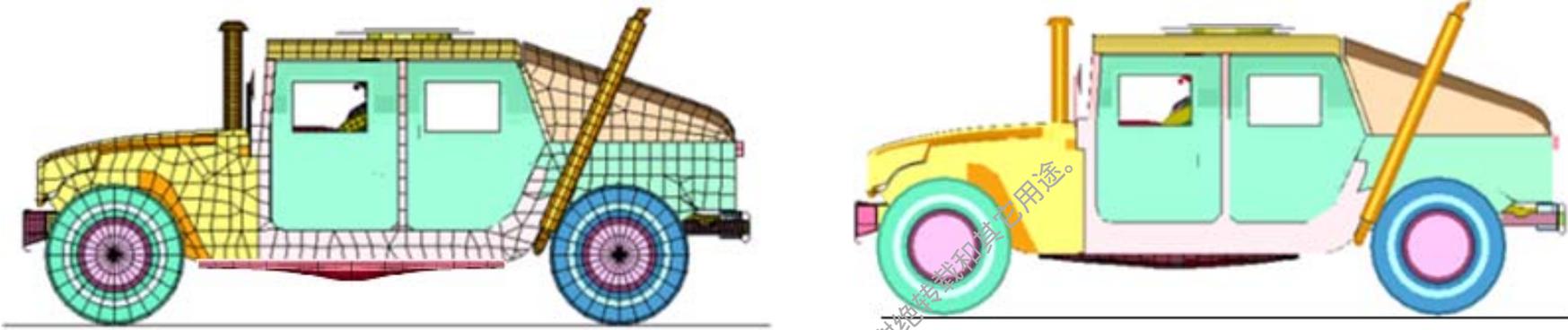


Response surface of maximum crew K. E. w. r. t. mine location





DUT | 轻质装甲设计



Systems	(Added) mass (kg)	(Added) mass ratio (%)
Vehicle	3,397	100
Steel armor	1,797	53
Uniform aluminum foam armor	116	3.4
Designed aluminum foam armor	66	1.9



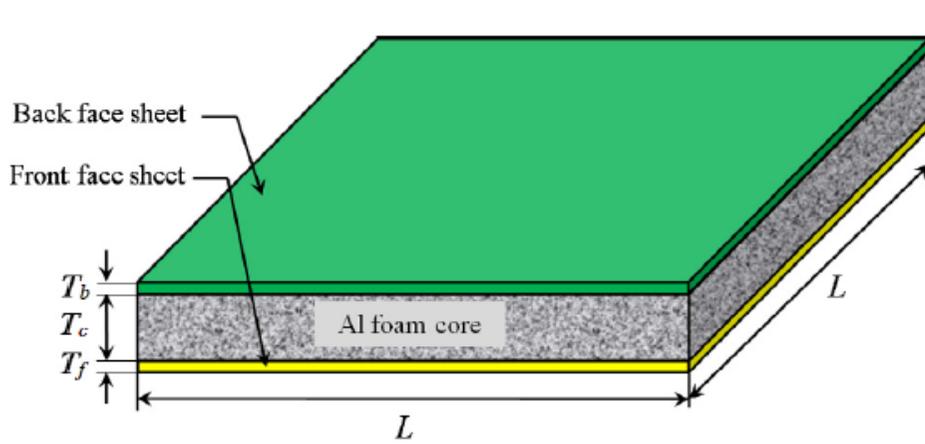
DUT | 学术成果评价

- 悍马军车的底盘装甲结构减重超过50%，受到**美国坦克与机动车司令部（TANCOM）**的认可。
- 获得国际汽车工程师学会（SAE）“重要技术贡献奖”

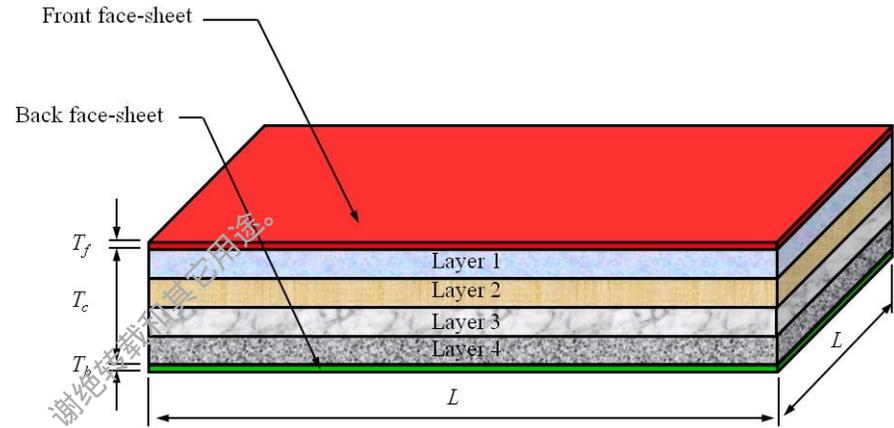




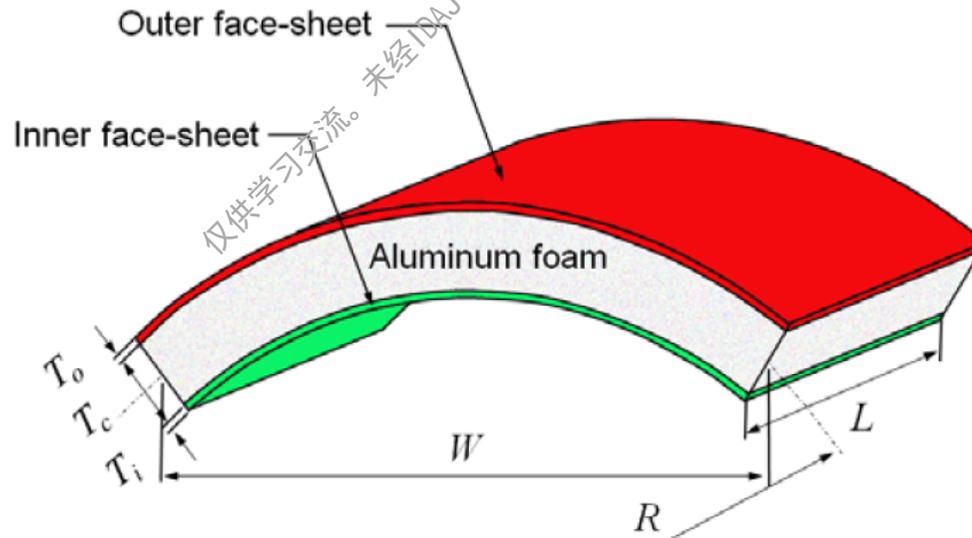
铝泡沫夹层防爆装甲设计



铝泡沫夹层平板装甲



梯度铝泡沫夹层平板装甲

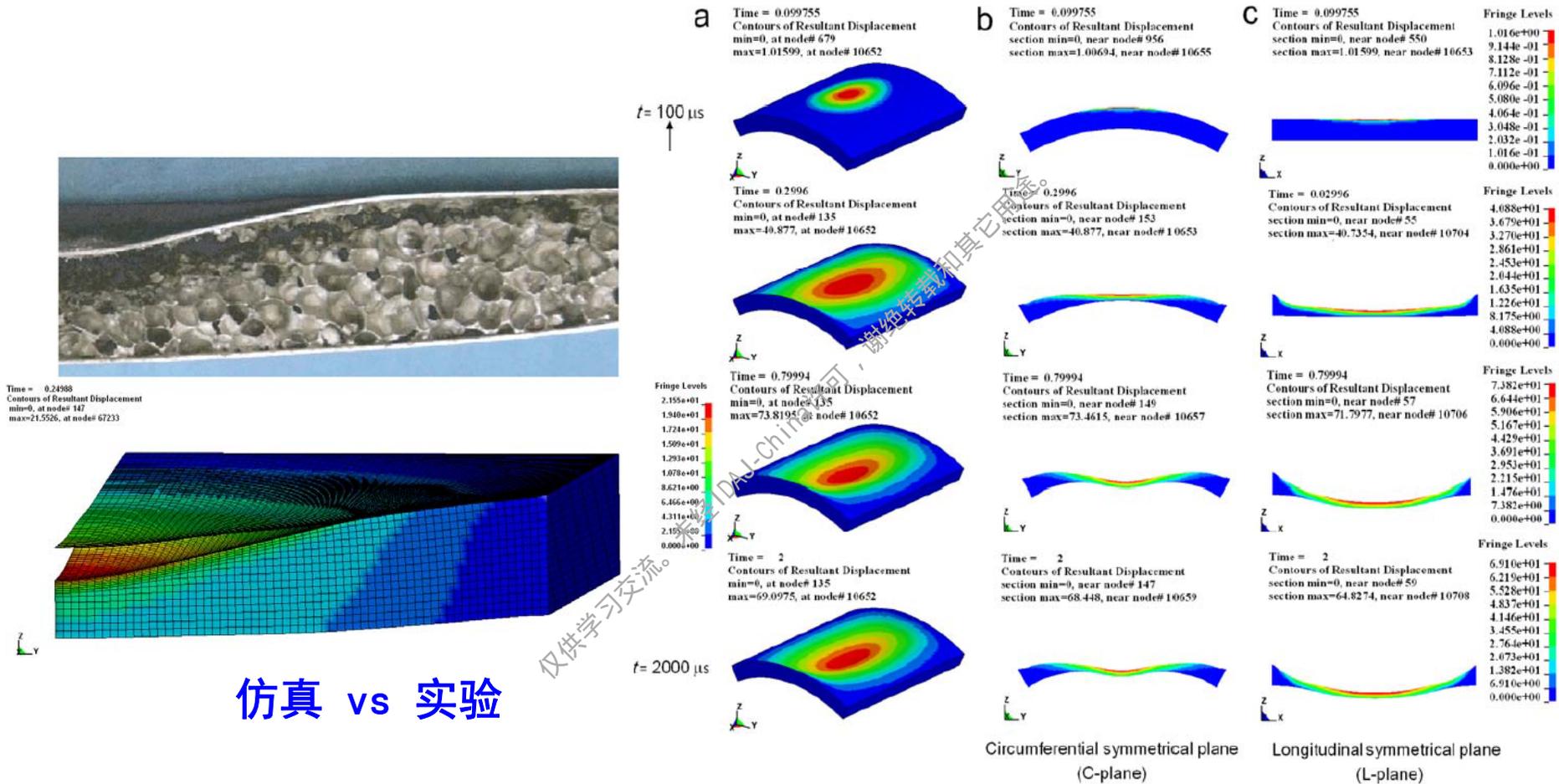


铝泡沫夹层弧形板装甲



DUT

铝泡沫夹层防爆装甲设计



爆炸载荷下的装甲动态响应

Chang Qi, Shu Yang*, et al. *Composite Structures*, 2013. IF: 2.231.

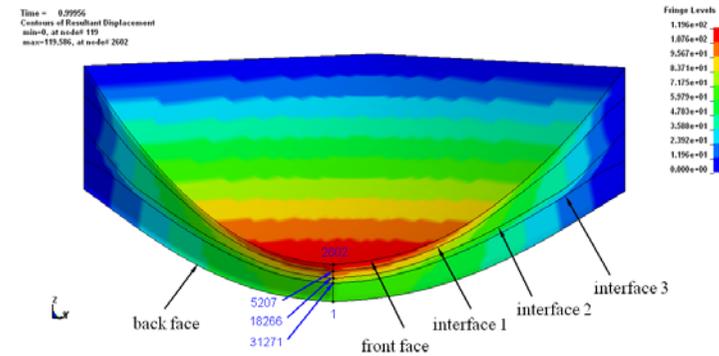
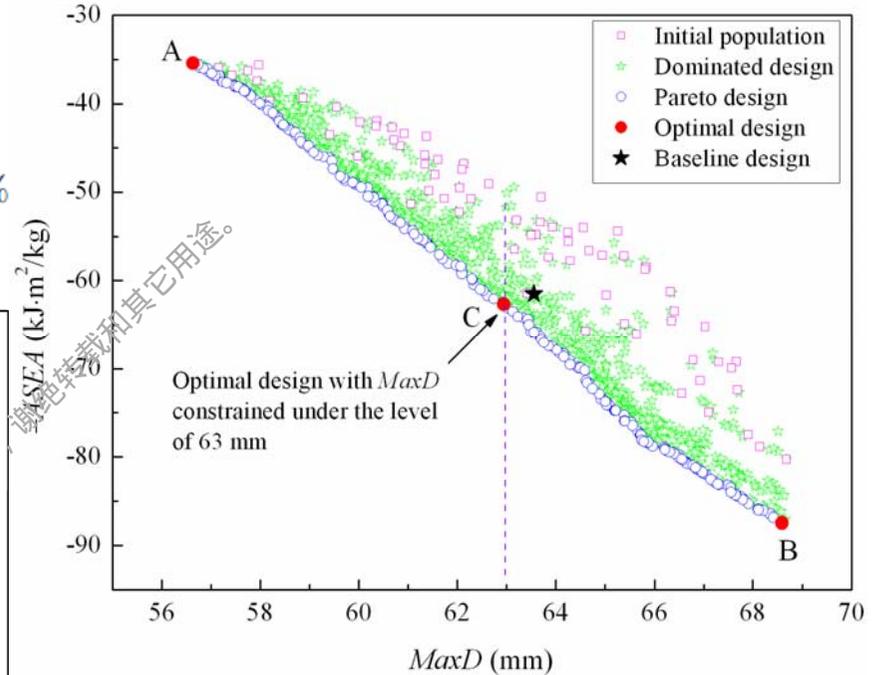
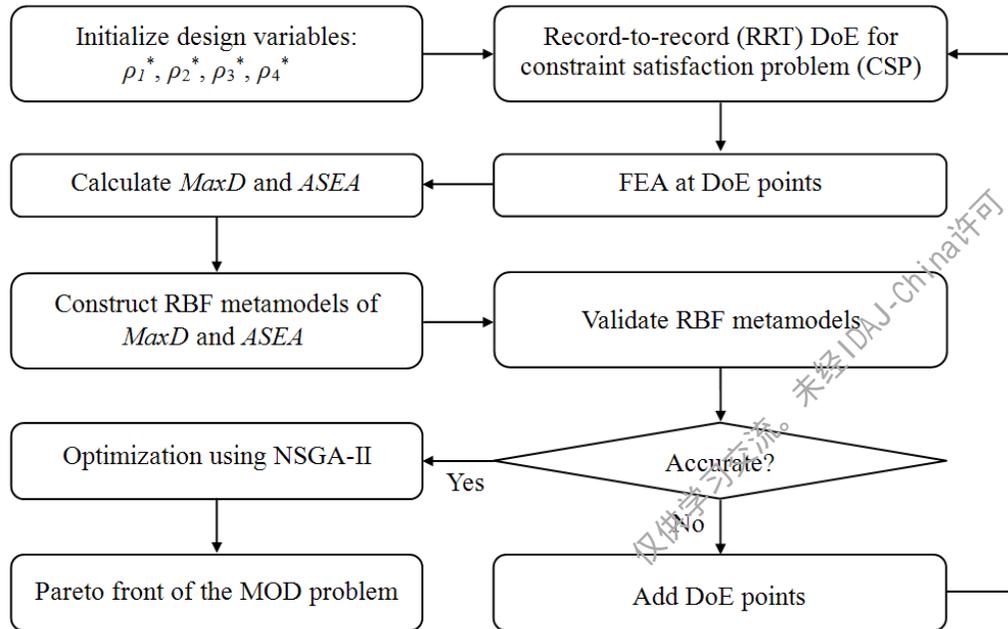
Chang Qi, Shu Yang*, et al. *The Scientific World Journal*, 2014. IF: 1.730.



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铝泡沫夹层防爆装甲设计

$$\begin{cases} \text{Minimize } \{MaxD_c(T_f, T_b, T_c, \rho_f), -ASEA_c(T_f, T_b, T_c, \rho_f)\} \\ \text{subject to } 2 \text{ mm} \leq T_f, T_b \leq 4 \text{ mm} \\ 40 \text{ mm} \leq T_c \leq 60 \text{ mm} \\ 135 \text{ kg/m}^3 \leq \rho_f \leq 540 \text{ kg/m}^3 (\text{i.e. } 5\% \leq \rho^* \leq 20\%) \end{cases}$$



装甲优化模型与设计流程

优化设计结果



军车及特种车辆防爆防弹设计 案例：

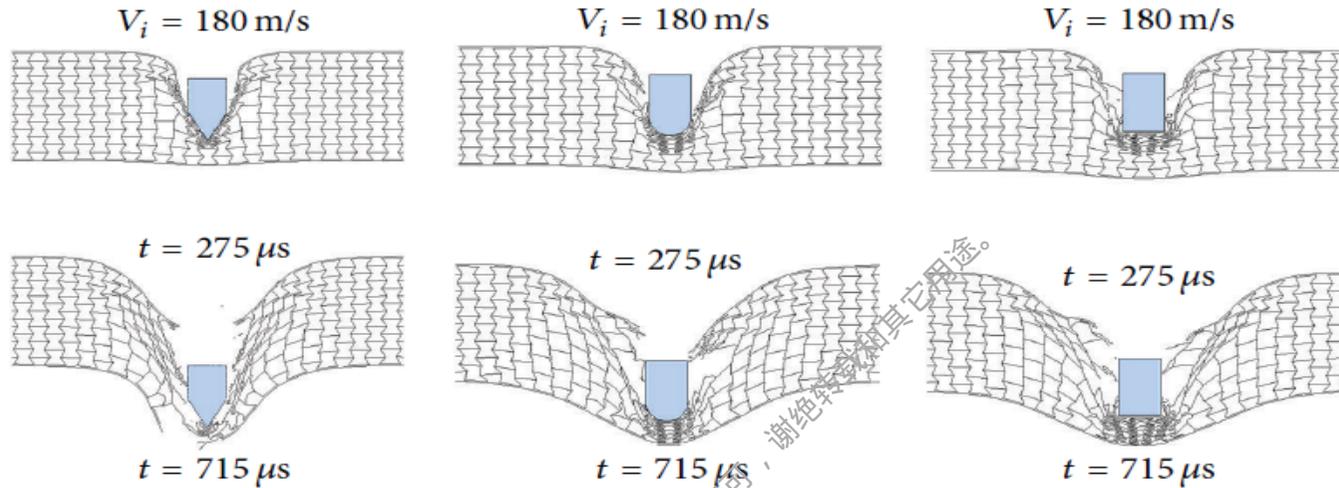
- 军车轻质防雷装甲设计
- 车用新型轻质防弹结构设计

仅供学习交流，谢绝转载和其它用途。

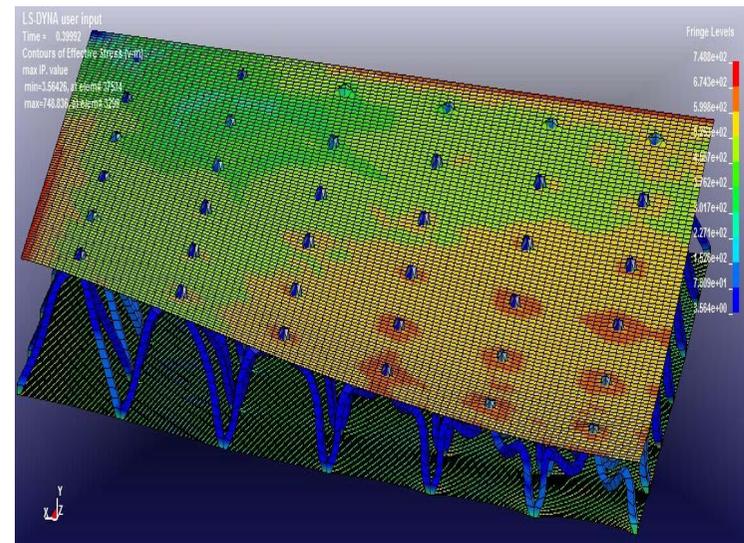
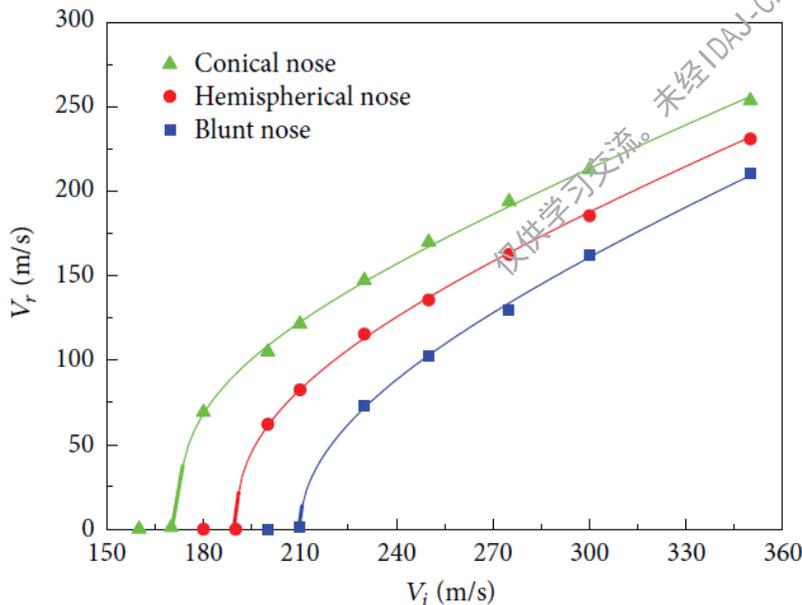


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车用新型轻质防弹结构设计

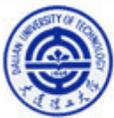


NPR夹层轻质防弹结构 (获批专利 1项)



金属点阵夹层轻质装甲结构 71

Chang Qi, Shu Yang*, et al. *The Scientific World Journal*, 2013. SCI, IF:1.730.



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谢谢！

仅供学习交流。未经IDAS Group许可，谢绝转载和其它用途。