

第三届LS-DYNA中国论坛

2018年10月26日 上海



Livermore Software Technology Corporation



上海仿坤软件科技有限公司 (LS-DYNA 中国)



LS-DYNA应用于制造过程和材料失效的 先进有限元和无网格方法

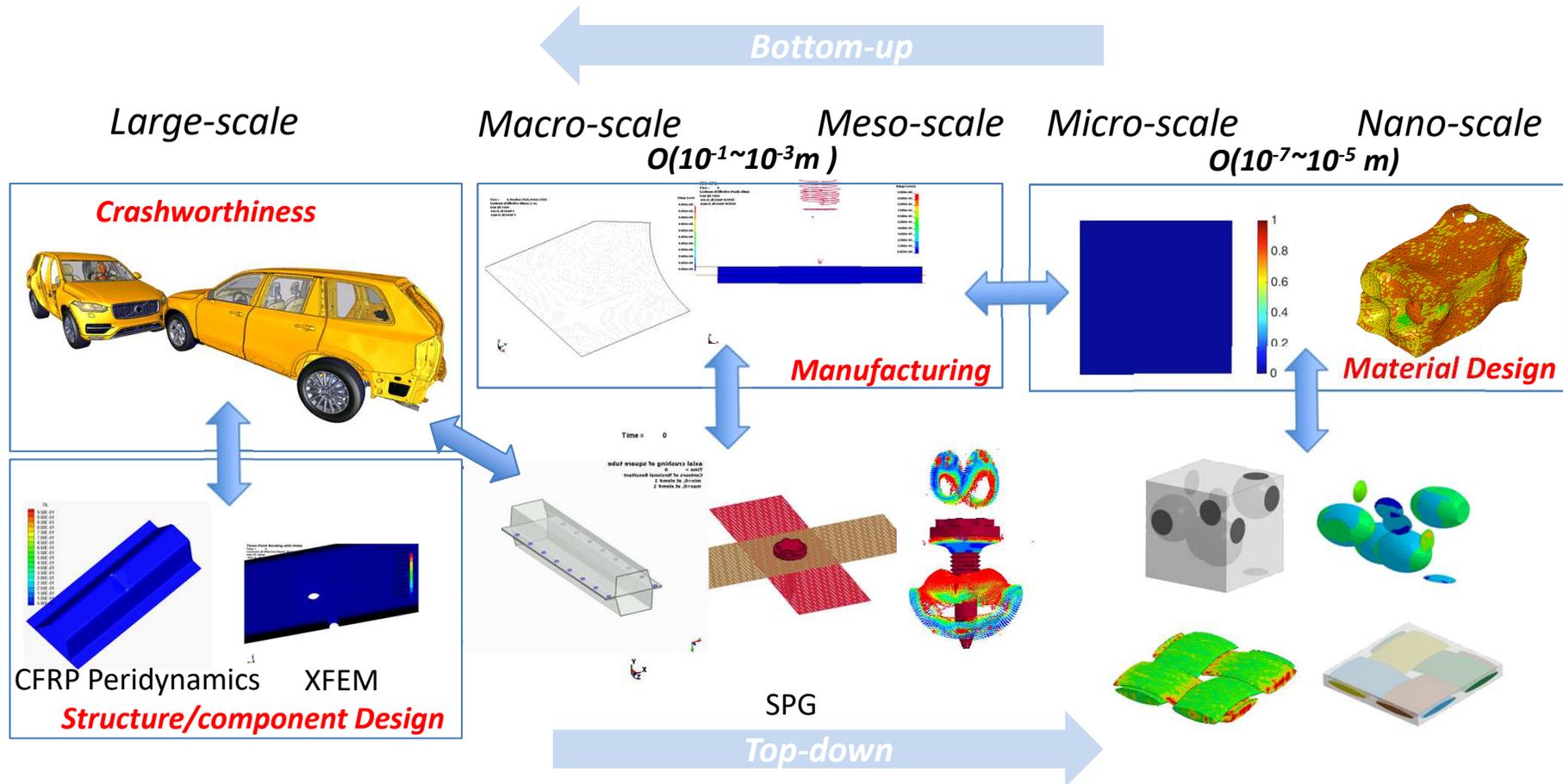
Wei Hu*, C.T. Wu, Bo Ren, Youcai Wu
Yong Guo, Xiaofei Pan, Zeliang Liu, Dandan Lyu

Computational and Multi-scale Mechanics Group (CMMG)
Livermore Software Technology Corporation (LSTC)
<https://www.lstc-cmmg.org>

2018 第三届LS-DYNA中国论坛 上海

目前的挑战与问题

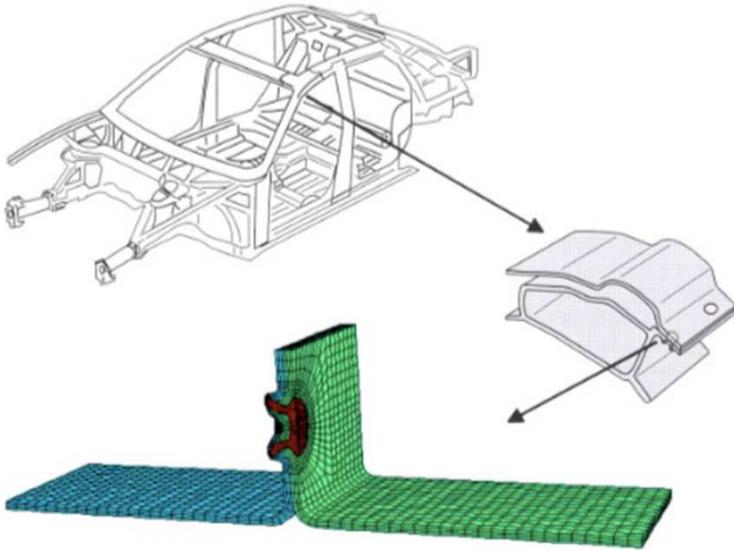
- ❑ 在碰撞模拟中，多种材料和连接的力学特性及破坏行为在预测变形模态和成员保护方面有关键影响
- ❑ 在零部件加工模拟中，材料和连接的类型及加工过程对结构强度和破坏行为的影响起至关重要的作用



计算多尺度分析

Two-scale simulation aims to enhance the geometrical information between meso and macro scales.

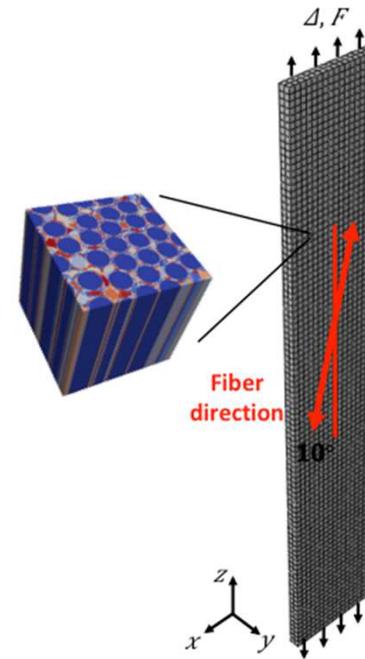
跨尺度数值模型问题



It is computationally infeasible to model the joints in body-in-white using solid elements with 0.1 mm mesh.

Multiscale concurrent simulation aims to enhance material information between micro and meso scales.

跨尺度物理问题



The phenomenological-based material law is not good enough to capture the detailed physics of failure induced by microstructure.

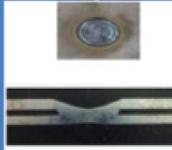
现代汽车结构中的连接

- ❑ 电阻点焊Resistance spot welding (RSW): 应用在焊接钢板, 车体通常有2000~5000 RSW
- ❑ 汽车轻量化带来连接方式的变革: 铝合金, 高强度钢HSS/UHSS和碳纤维复材CFRP
 - 连接的加工过程: 材料破坏和残余应力
 - 数值模拟: 基于传统有限元FEM的方法非常困难

Joining technology

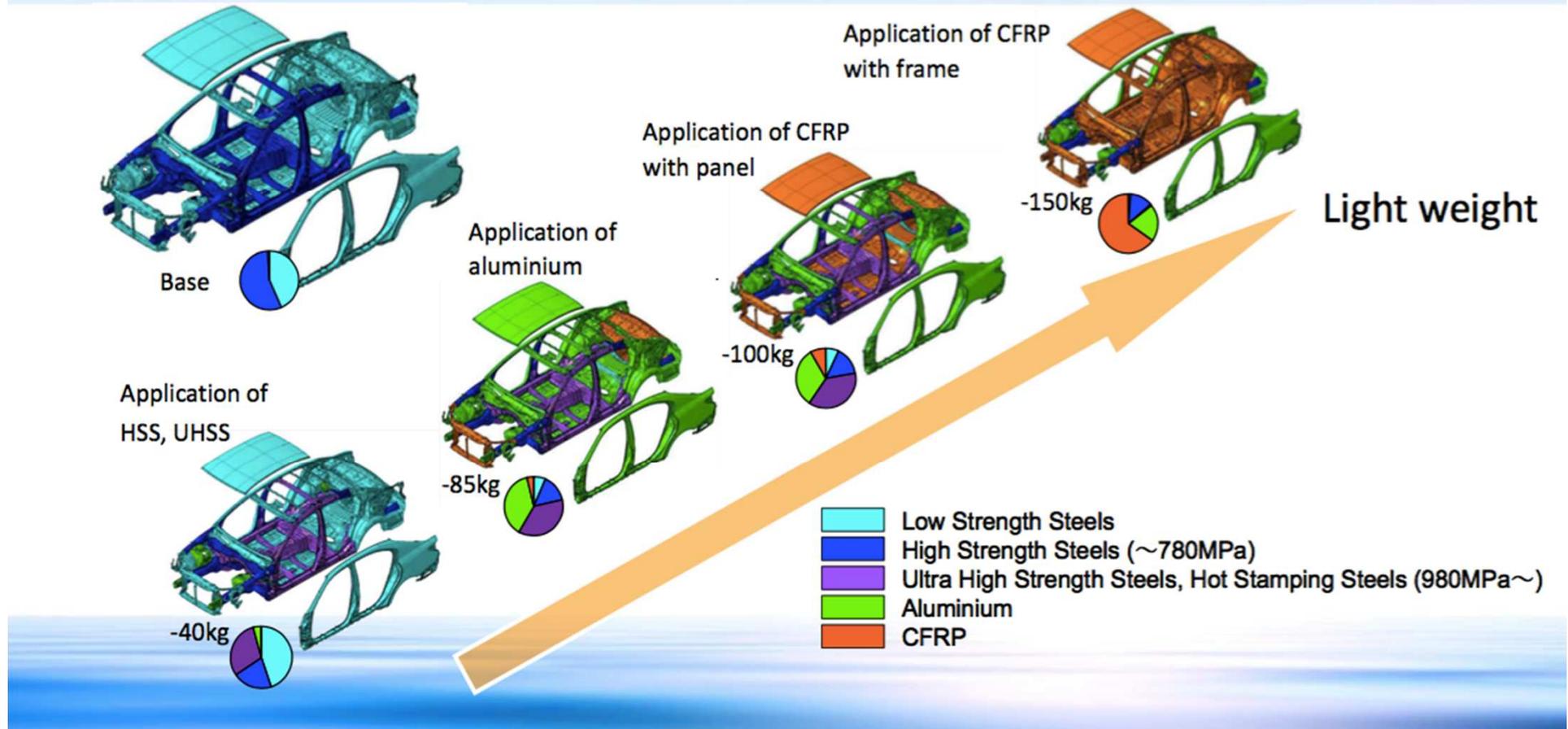
○=Candidates to use/develop in Toyota

LSS: Low Strength Steels
 HSS: High Strength Steels (~780MPa)
 USS: Ultra High Strength Steels , Hot Stamping Steels (980MPa~)
 AL : Aluminum

Combination of materials	SPR Self Piercing Rivet 	FDS Flow Drill Screw 	FSW Friction Stir Welding	FSJ Friction Spot Joining 	LSW Laser Screw Welding 	adhesive	...
Steel x Steel					○	○	
AL x AL	○	○	○		○	○	
Steel (LSS,HSS) x AL	○	○	○	○		○	
Steel(UHSS) x AL			○	○		○	
AL x CFRP(Random)	○	?	?	○		○	
Steel (UHSS) xCFRP(Random)	○	?		○		○	
CFRP x CFRP	○	?		○		○	
:							

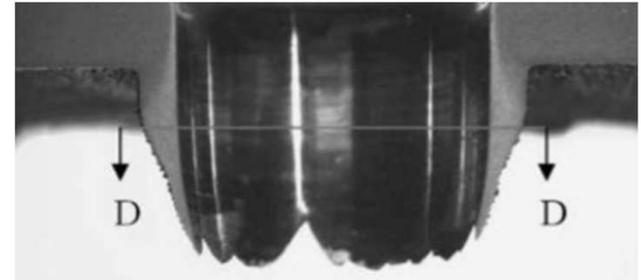
汽车轻量化使用的新材料

Estimation of light weight

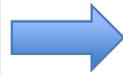


□ 汽车轻量化的设计和仿真过程中的关键难题：新材料，新连接方式以及相关的破坏

摩擦钻孔和螺钉连接



打孔

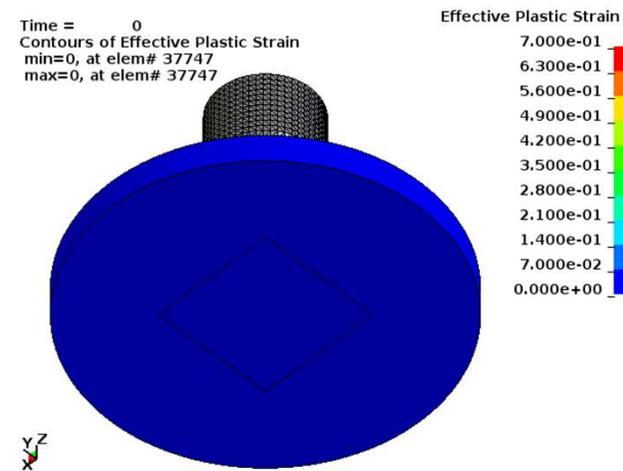
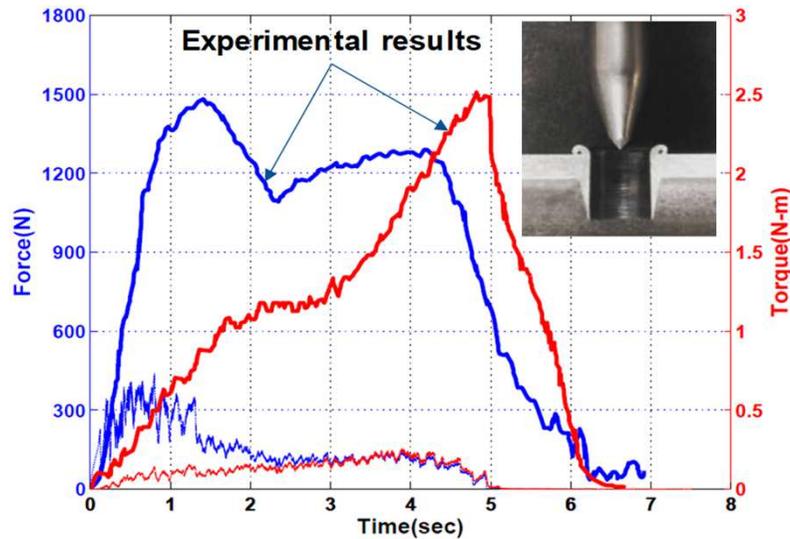
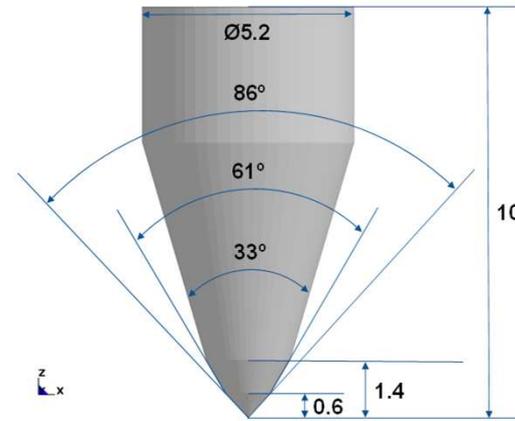
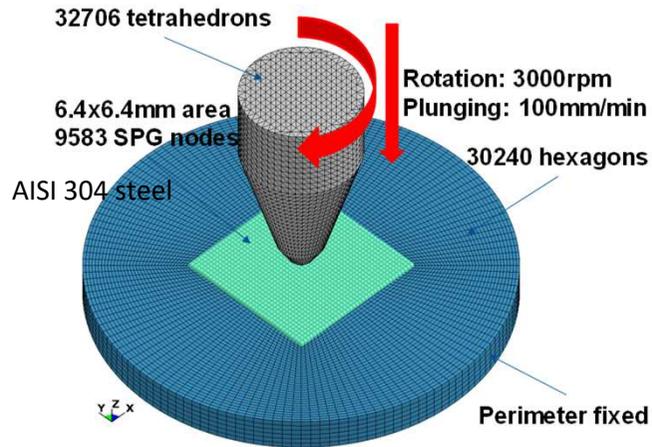


攻丝



螺钉连接

传统有限元分析：单元删除



- ❑ 没有产生thick bushing shape
- ❑ 采用单元删除的传统FEM完全低估作用力的量级

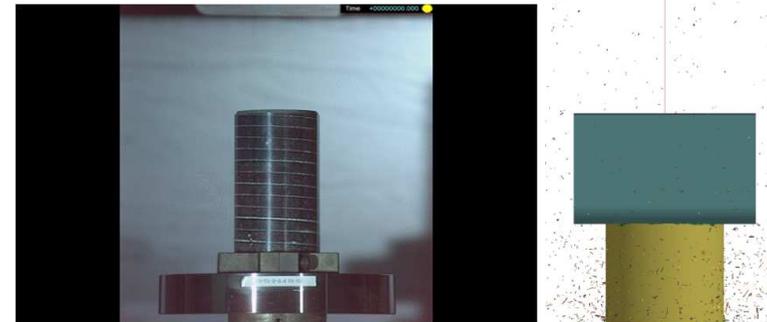
宏观材料模型和参数拟合的问题

- ❑ “In numerical simulation, the material properties directly obtained by conventional coupon tests do not predict the crash im **材料参数从实验测量到碰撞测试的不同**
- ❑ “Some material parameters need to be modified through the results of component tests, which are different from the coupon **材料参数在加工过程中产生变化**
- ❑ “For uni-directional CF composite, the crash simulation shows instability (material fails in the very early stage of the crash i **复合材料碰撞模拟的困难** in the mechanical experiments.” **- Scientific Research Laboratories, Ford Motor Company, USA**



LS-DYNA
*MAT_54

碳纤维复材(CFRP)
碰撞安全测试



*Courtesy of Ford Motor, USA

*Mat_ENHANCED_COMPOSITE_DAMAGE (054)

1	<u>MID</u>	<u>RO</u>	<u>EA</u>	<u>EB</u>	<u>(EC)</u>	<u>PRBA</u>	<u>(PRCA)</u>	<u>(PRCB)</u>
	30001	1.500e-006	146.53000	9.9569998	9.9569998	0.0224000	0.0224000	0.0224000
2	<u>GAB</u>	<u>GBC</u>	<u>GCA</u>	<u>(KF)</u>	<u>AOPT</u> <input type="checkbox"/>	<u>2WAY</u>		
	5.462	5.462	5.462	0.0	0.0	0.0		

Stiffness

Ultimate strain

4	<u>V1</u>	<u>V2</u>	<u>V3</u>	<u>D1</u>	<u>D2</u>	<u>D3</u>	<u>DFAILM</u>	<u>DFAILS</u>
	0.0	0.0	0.0	0.0	0.0	0.0	0.01999500	0.0300000
5	<u>TFAIL</u>	<u>ALPH</u>	<u>SOFT</u>	<u>FBRT</u>	<u>YCFAC</u>	<u>DFAILT</u>	<u>DFAILC</u>	<u>EFS</u>
	1.153e-009	0.1000000	1.0000000	0.5000000	1.2000000	0.0198000	-0.0076200	0.0
6	<u>XC</u>	<u>XT</u>	<u>YC</u>	<u>YT</u>	<u>SC</u>	<u>CRIT</u>	<u>BETA</u>	
	1.1170000	2.9030001	0.1990000	0.0652000	0.1540000	54.0	0.0	

Max strength

$YC = 5YC_0 \Rightarrow$ Stable

单元删除条件

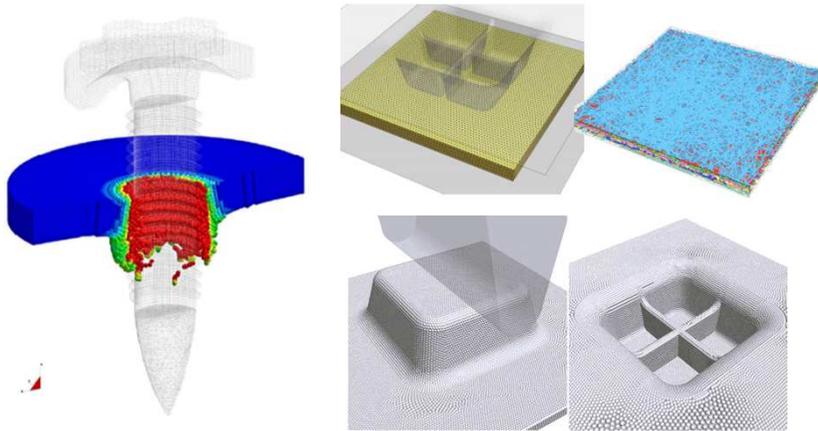
Element "damage"

- ❑ 材料输入参数的确定依赖工程师的经验和对于不同工况和预期结果来进行的试探性调整
- ❑ 传统的宏观材料模型和数值模拟方法在应对复杂问题(破坏, 复合材料, ...)时有很强的局限性

针对材料破坏分析的先进有限元和无网格方法

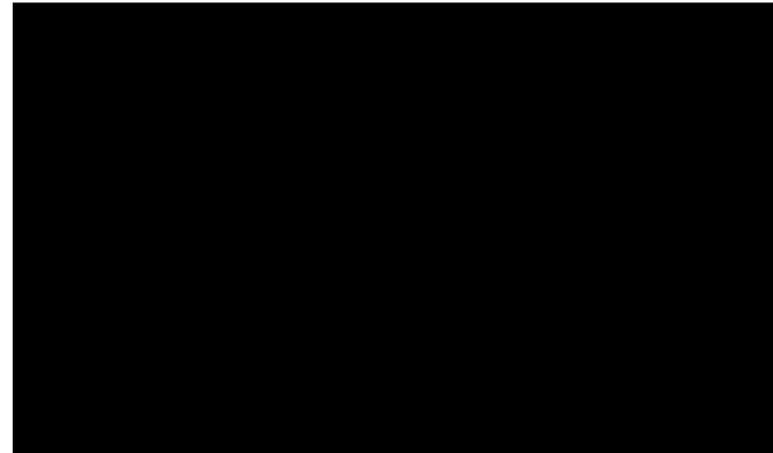
- 根据材料破坏分析的不同情况应用不同的数值方法：体结构，壳结构
- 数值方法应考虑不同材料的物理模型：延展性，脆性，复合分层

金属延展性材料：光滑粒子伽辽金法SPG
纤维增强塑胶GFRP：浸入Immerse SPG



大塑性变形，材料分离

碳纤维复材CFRP：脆性，层结构
数值方法：近场动力学Peridynamics
结合Laminate理论

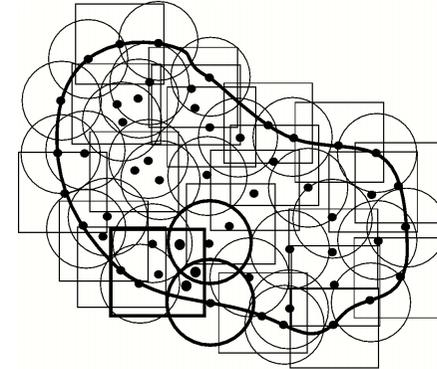


层内裂纹，层间分离

光滑粒子伽辽金法SPG

□ 数值稳定的粒子法

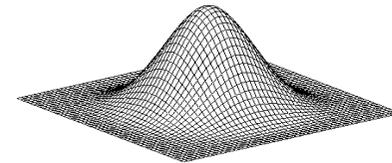
- 基于节点：构建近似函数，进行数值积分
- 引入**基于键断裂的数值模型**处理材料破坏分离
- 优点
 - ✓ 无需数值稳定参数
 - ✓ 便于和FEM模型耦合：共节点，接触
 - ✓ 时间步长不随材料变形而降低
 - ✓ 键断裂模型无需删除节点/单元



□ 关键字： *SECTION_SOLID_SPG (ELFORM=47)

□ 目前的功能

- 输入模型： FEM网格(TET/PENT/HEX固体单元)
- 延展性或半脆性材料
- 接触算法
 - ✓ 可以使用大部分LS-DYNA已有的接触算法
 - ✓ 基于粒子的接触(*CONTACT_SPG, *CONTACT_SPG_SPH)
- **浸入Immerse方法**： GFRP复合材料，壳体-连接件耦合(多尺度分析)
- 热固耦合，显式分析

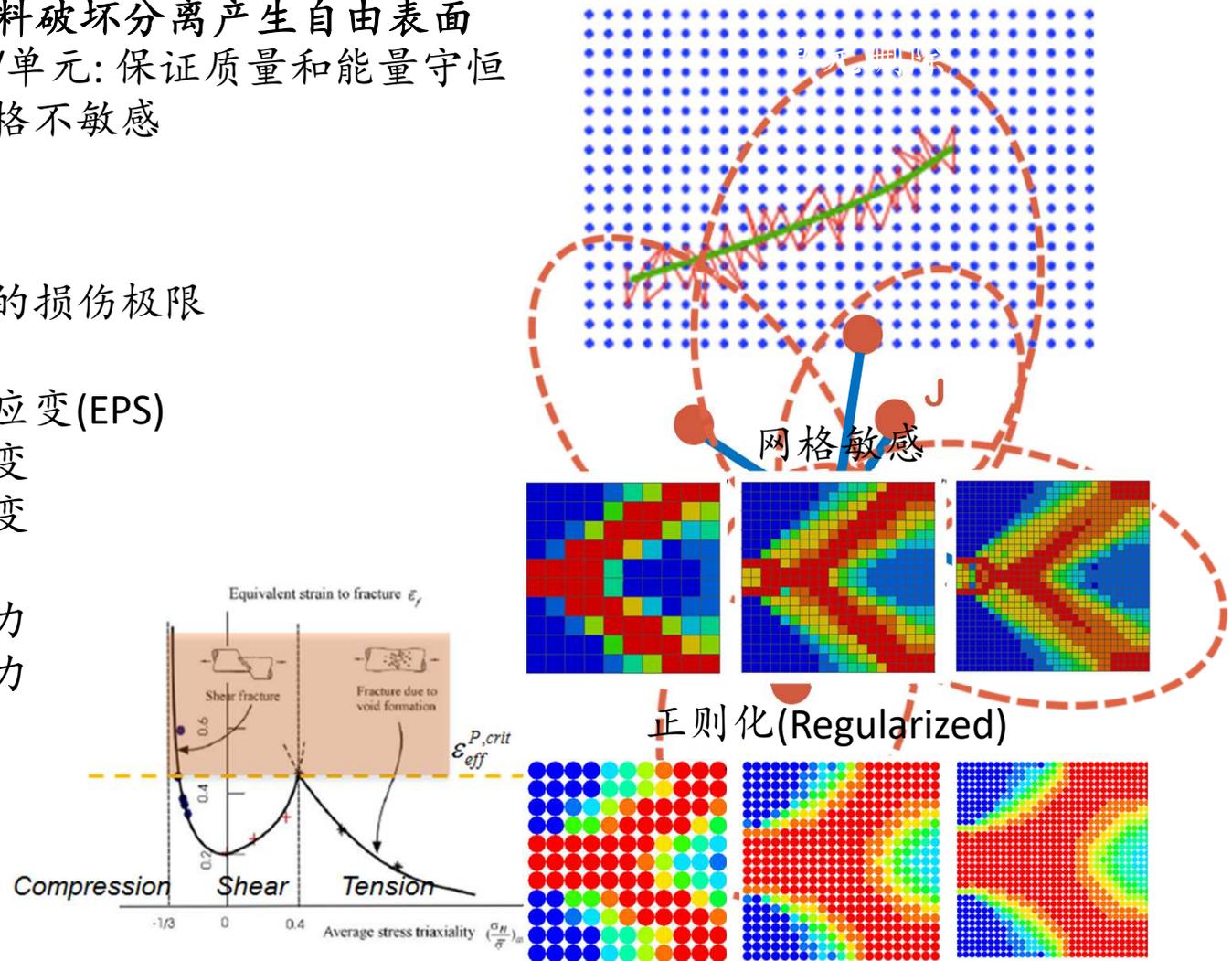


□ R10.0版本开始研发(MPP/SMP/Hybrid)

SPG基于键断裂的数值模型

- 键断裂区域模拟材料破坏分离产生自由表面
 - 无需删除节点/单元: 保证质量和能量守恒
 - 分析结果对网格不敏感
 - 计算效率高

- 键断裂准则
 - 材料模型给出的损伤极限
 - 延展性材料
 - ✓ 等效塑性应变(EPS)
 - ✓ 第一主应变
 - ✓ 最大剪应变
 - 半脆性材料
 - ✓ 第一主应力
 - ✓ 最大剪应力

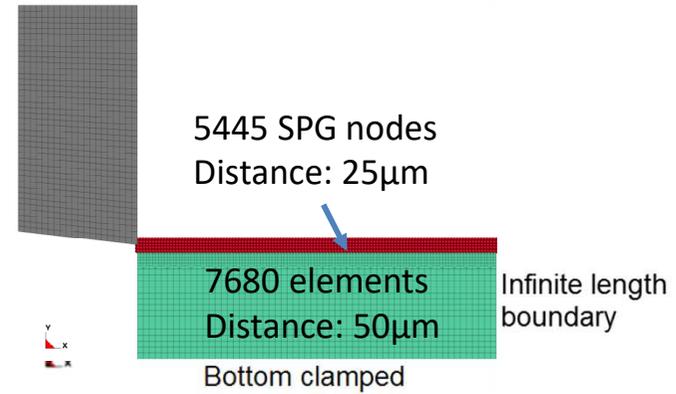
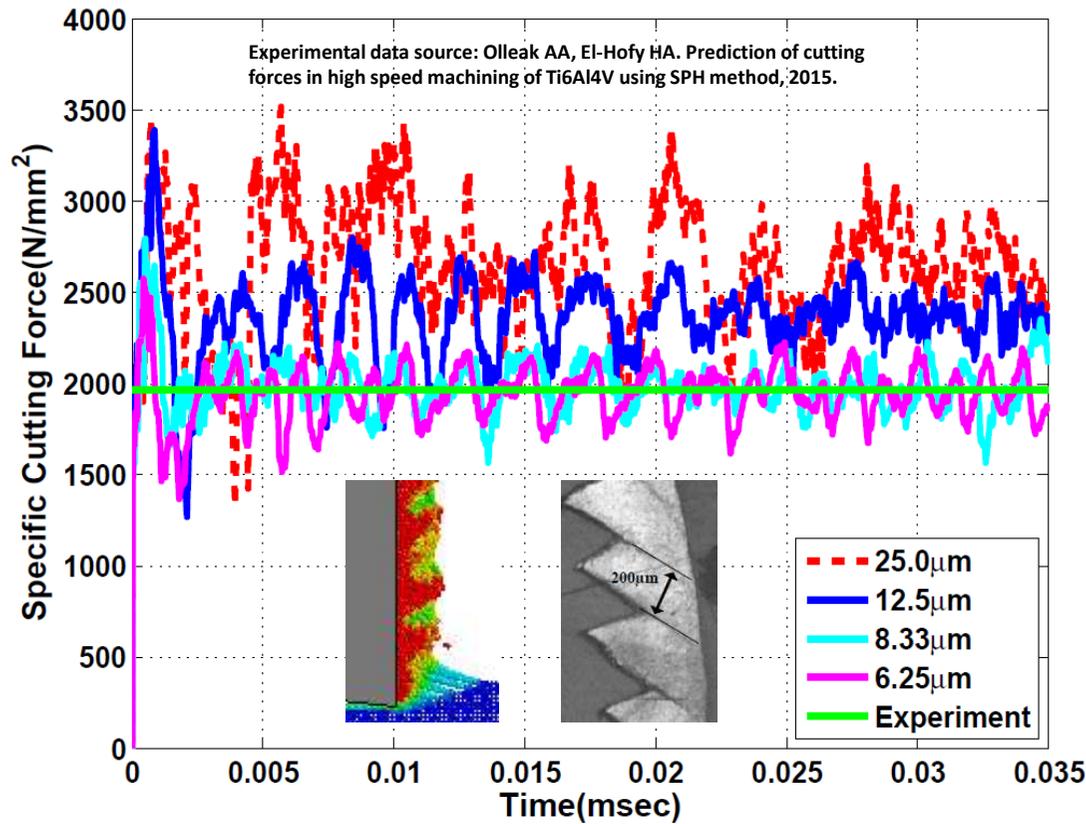


*CT Wu, Y Wu, M Koishi, A strain-morphed nonlocal meshfree method for the regularized particle simulation of elastic-damage induced strain localization problems, Computational Mechanics, 56 (2015) 1039-1054

SPG应用实例1：金属切削

□ 钛合金Ti6Al4V

- 材料模型：Johnson-Cook model
- 材料破坏：SPG键断裂模型(EPS=0.2)
- FEM&SPG耦合计算提高效率

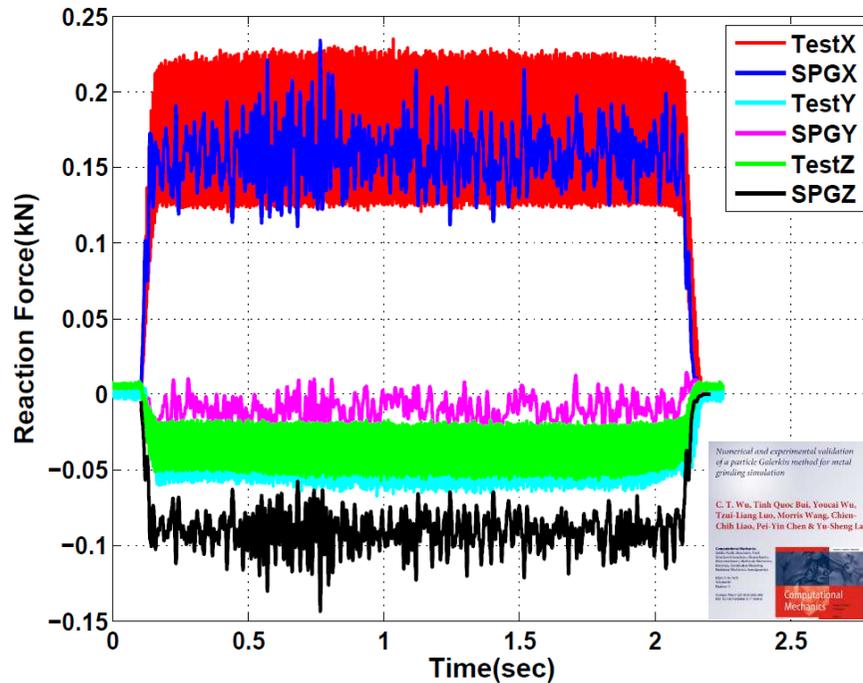
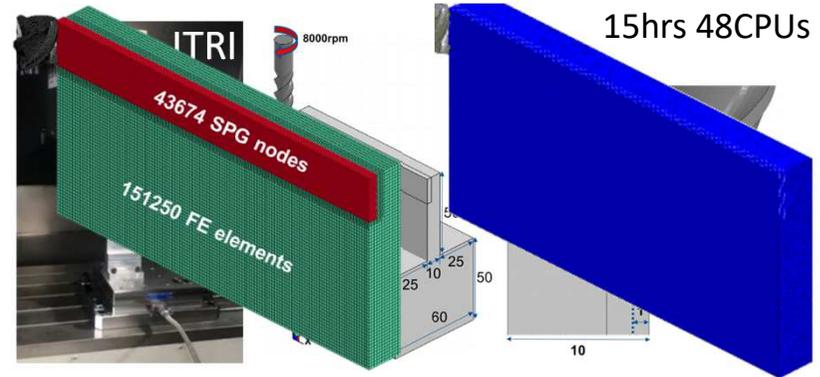


EPS云图

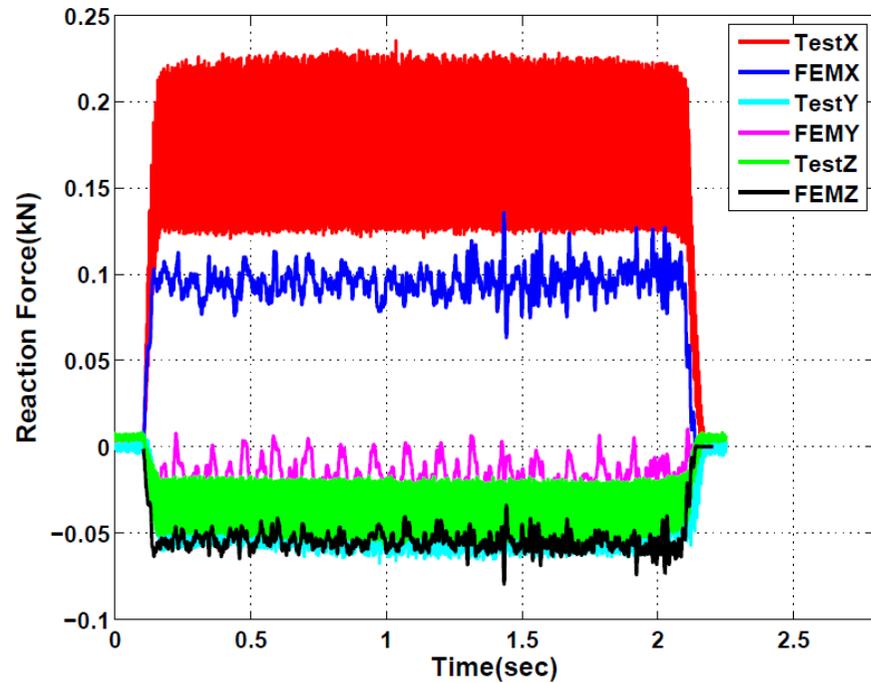
SPG应用实例2：金属表面高速研磨

□ 铝合金6061-T6

- 材料模型：Johnson-Cook model
- 材料破坏：SPG键断裂模型(EPS=0.2)
- FEM&SPG耦合计算提高效率
- 中国台湾工研院(ITRI)提供测试数据



SPG

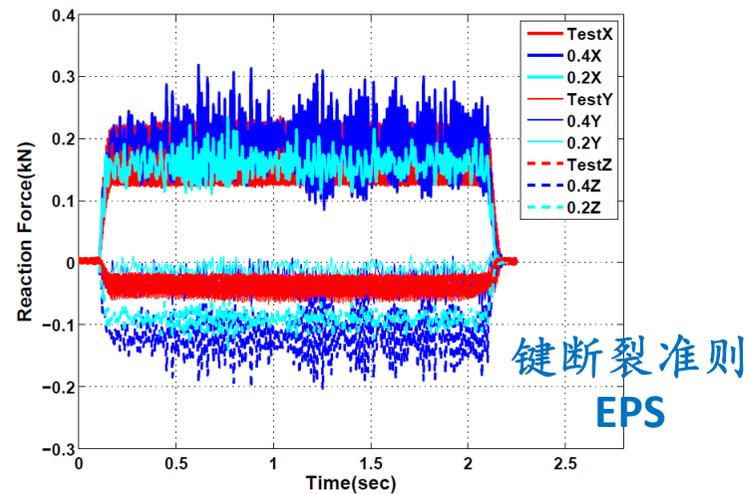
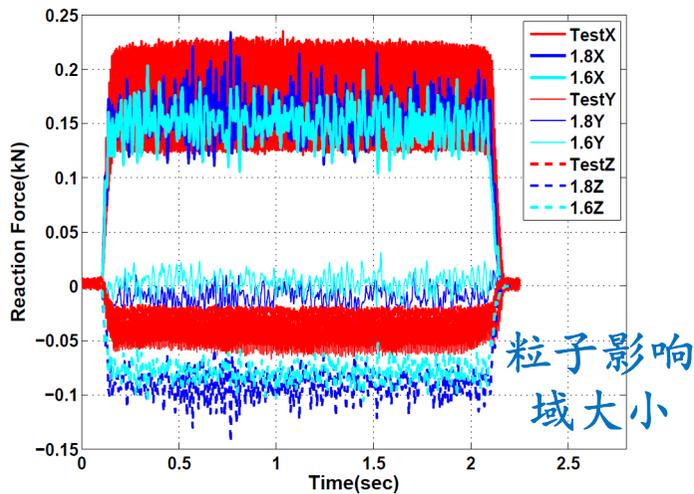
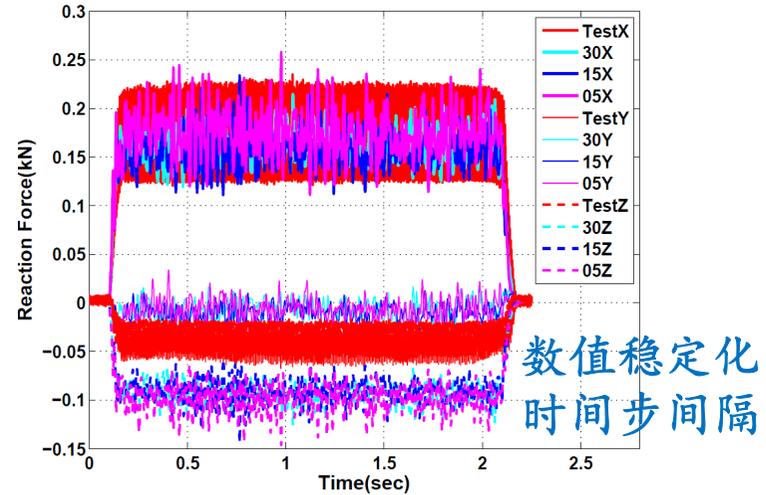
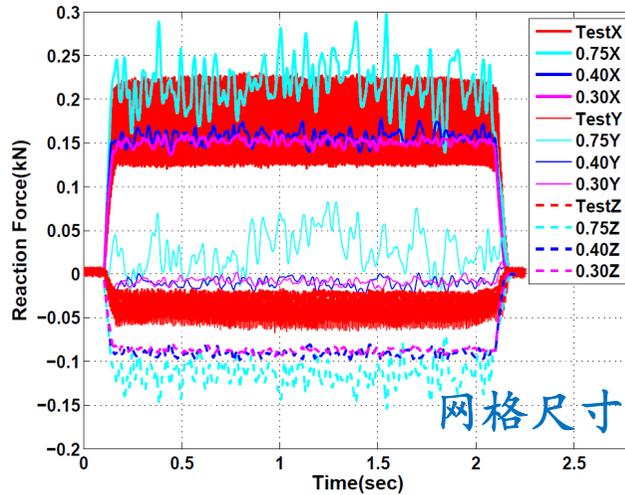


FEM 结合单元删除

SPG应用实例2：金属表面高速研磨

□ 铝合金6061-T6

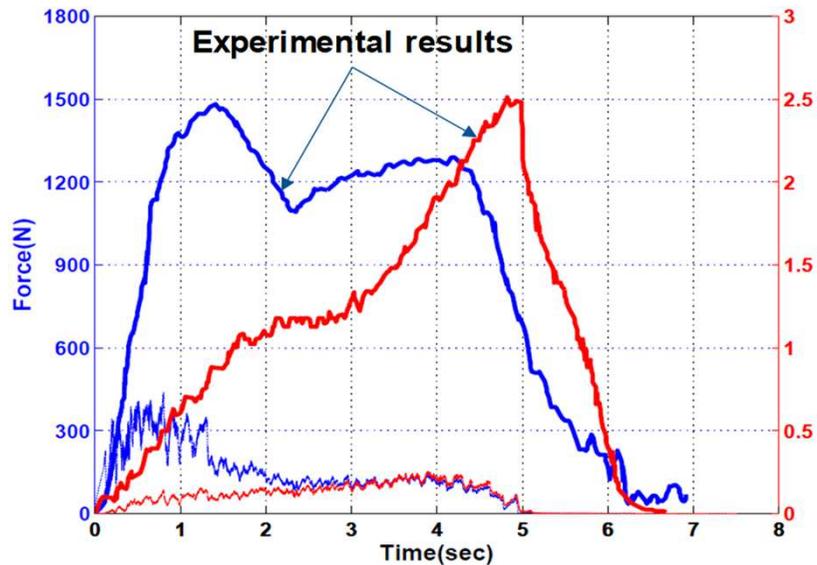
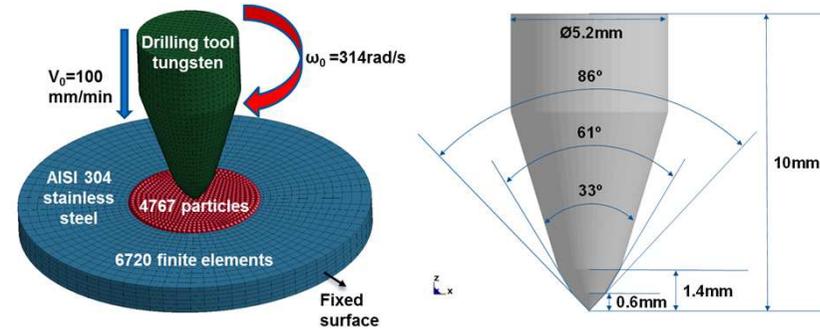
- SPG数值方法参数敏感度测试



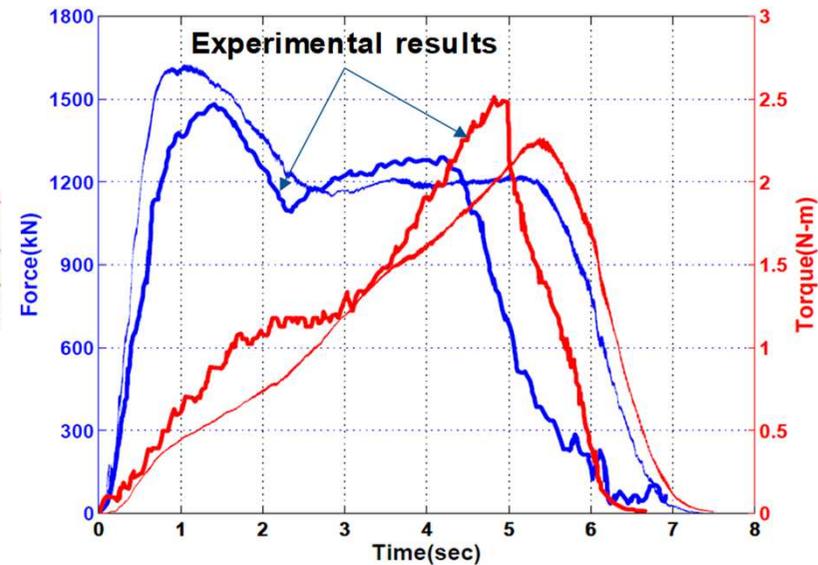
SPG应用实例3：摩擦钻孔

□ 不锈钢 AISI 304

- 材料模型：Johnson-Cook model
- 材料破坏：SPG键断裂模型($EPS=0.4$)
- 热固耦合显式分析
- FEM&SPG耦合计算提高效率



FEM 结合单元删除



SPG

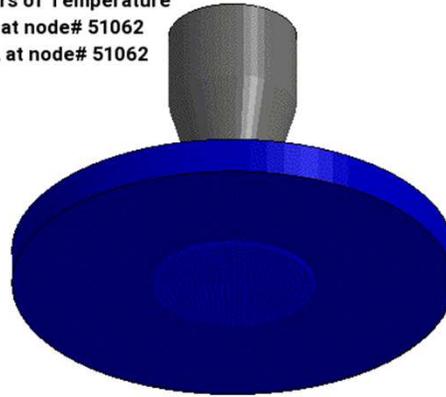
*Krasauskas P, Kilikevičius S, Česnavičius R, Pačenga D. Experimental analysis and numerical simulation of the stainless AISI 304 steel friction drilling process. Mechanika 2014;20(6):590-595

SPG应用实例3：摩擦钻孔

□ 不锈钢 AISI 304

温度

Time = 0
Contours of Temperature
min=0, at node# 51062
max=0, at node# 51062



Temperature



Time = 0
Contours of Temperature
min=0, at node# 51062
max=0, at node# 51062

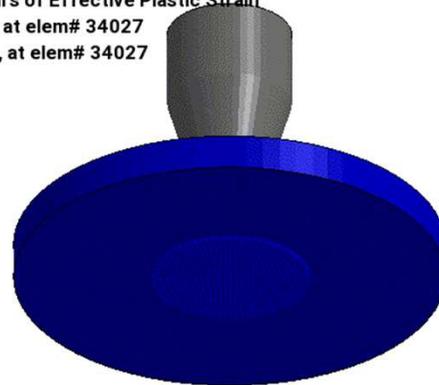


Temperature



等效塑性应变
EPS

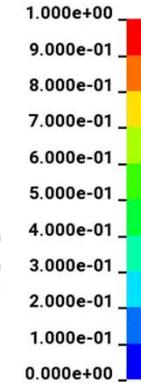
Time = 0
Contours of Effective Plastic Strain
min=0, at elem# 34027
max=0, at elem# 34027



Time = 0
Contours of Effective Plastic Strain
min=0, at elem# 34027
max=0, at elem# 34027

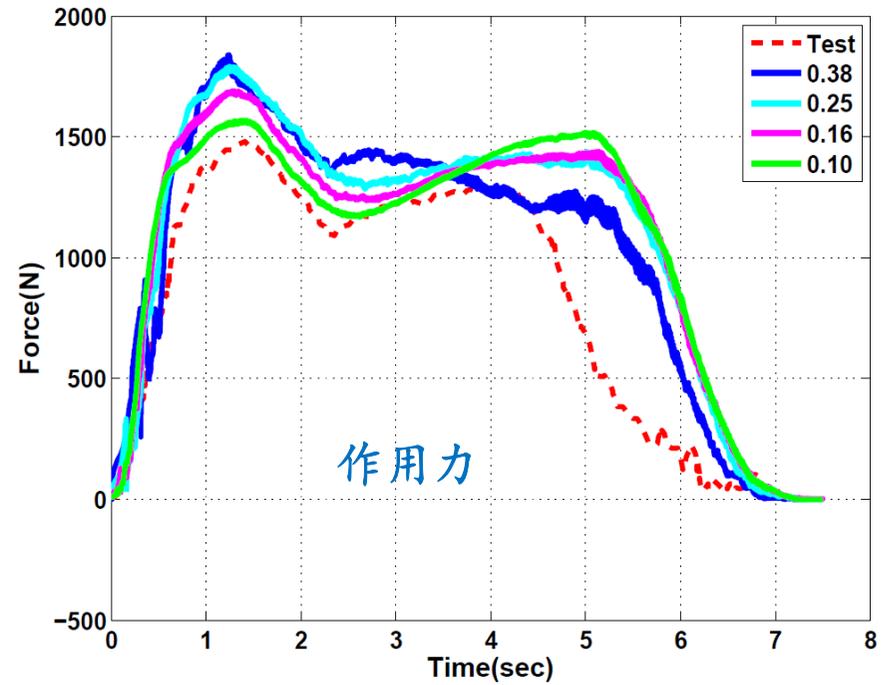
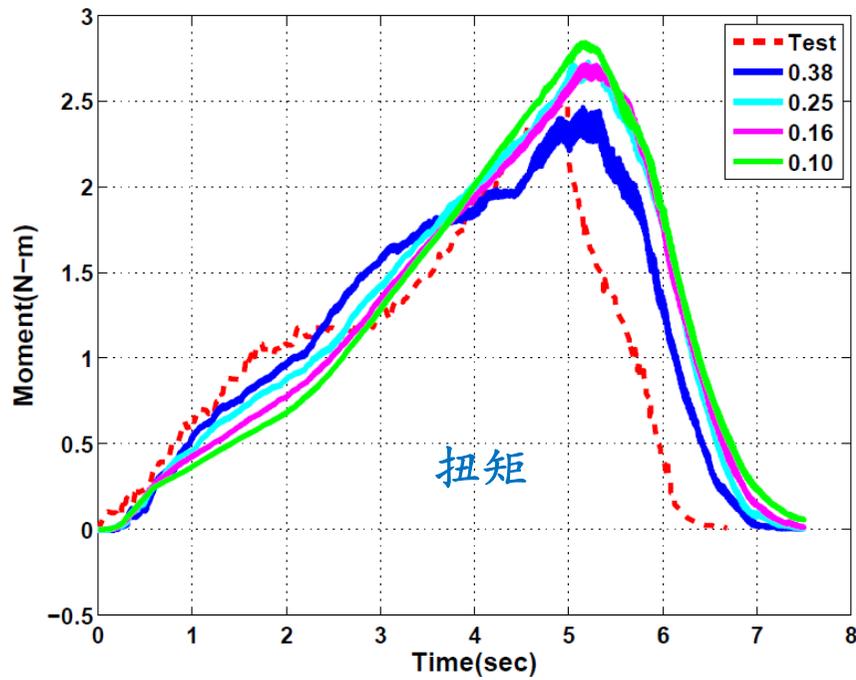


Effective Plastic Strain



SPG应用实例3：摩擦钻孔

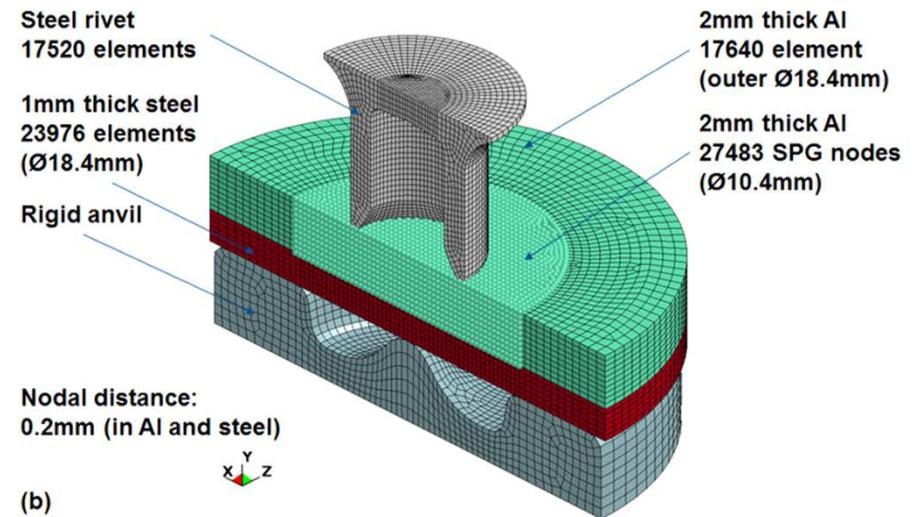
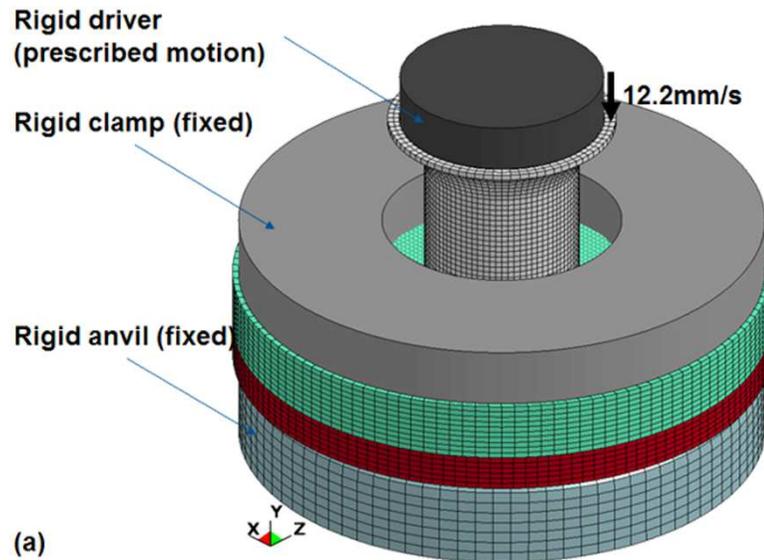
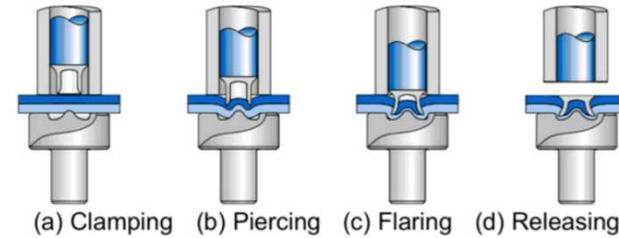
- 不锈钢 AISI 304
 - 网格收敛性测试



SPG应用实例4：自冲铆(SPR)

□ 铝合金 AA6111-T4

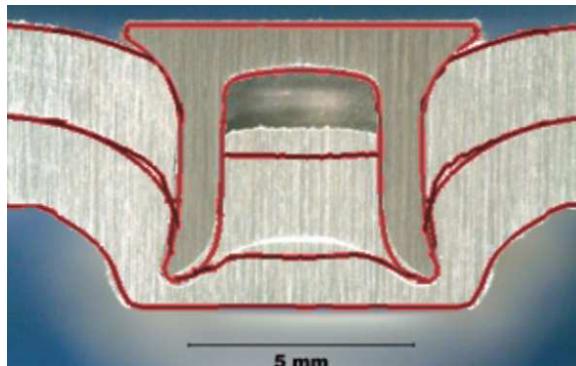
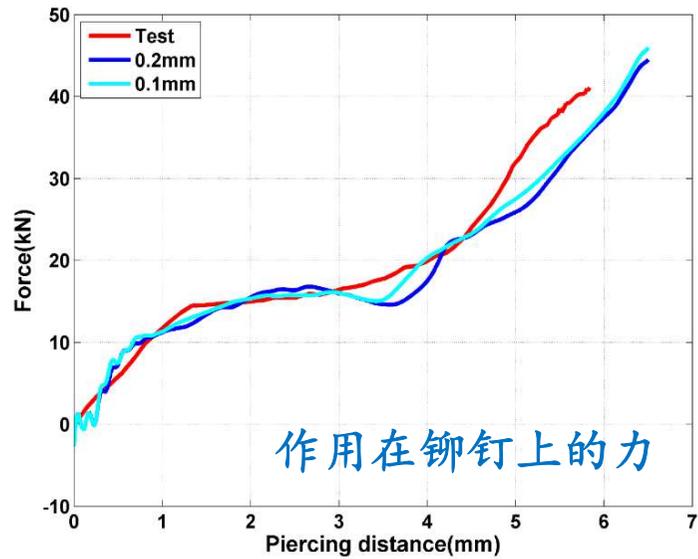
- 材料模型：*MAT_PLASTIC_KINEMATIC
- 材料破坏：SPG键断裂模型(EPS=0.2)
- FEM&SPG耦合计算提高效率
- 南京福特提供测试和实验数据



SPG应用实例4：自冲铆(SPR)

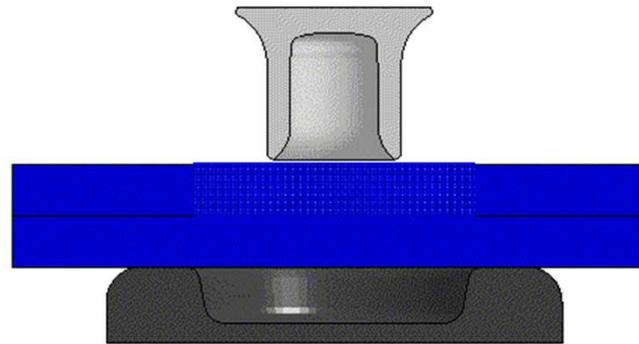
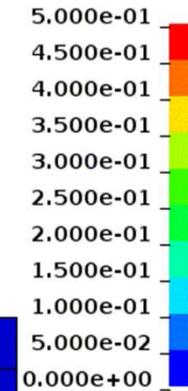
□ 铝合金 AA6111-T4

- 南京福特提供数据

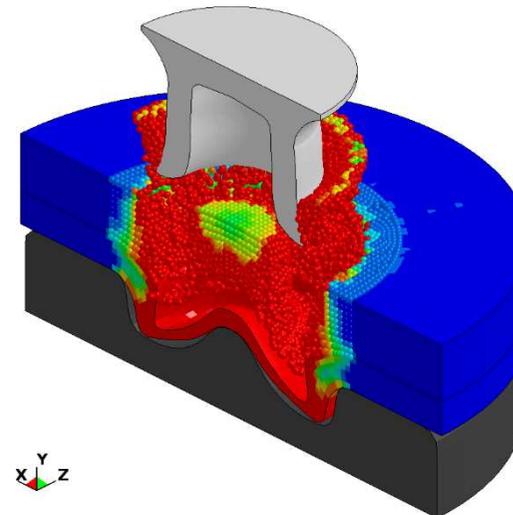


Time = 0
Contours of Effective Plastic Strain
min=0, at elem# 761661
max=0, at elem# 761661

Effective Plastic Strain



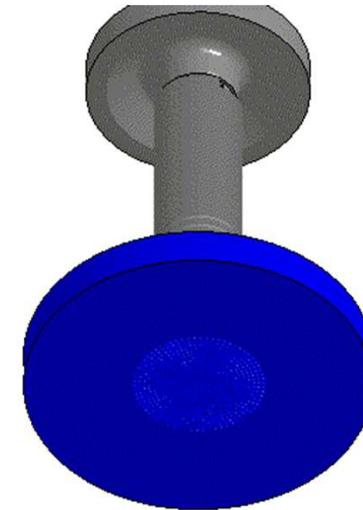
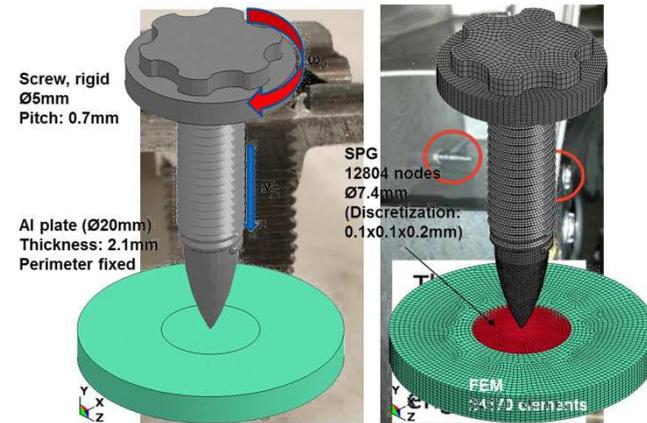
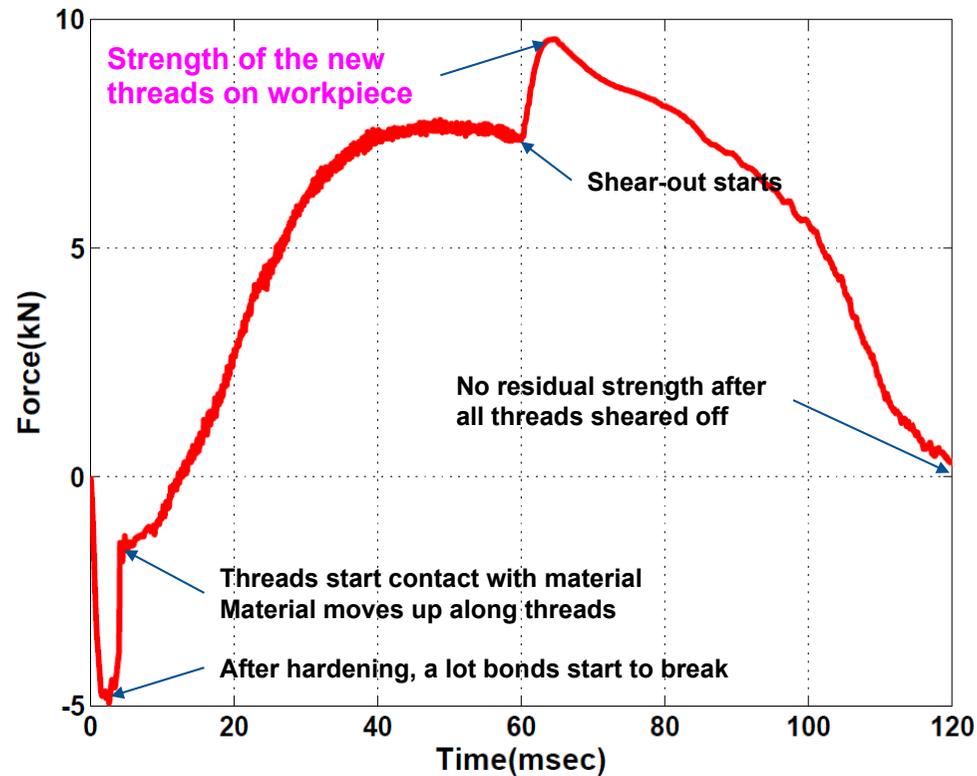
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SPG应用实例5：流钻螺丝(FDS)

□ 铝合金板材连接

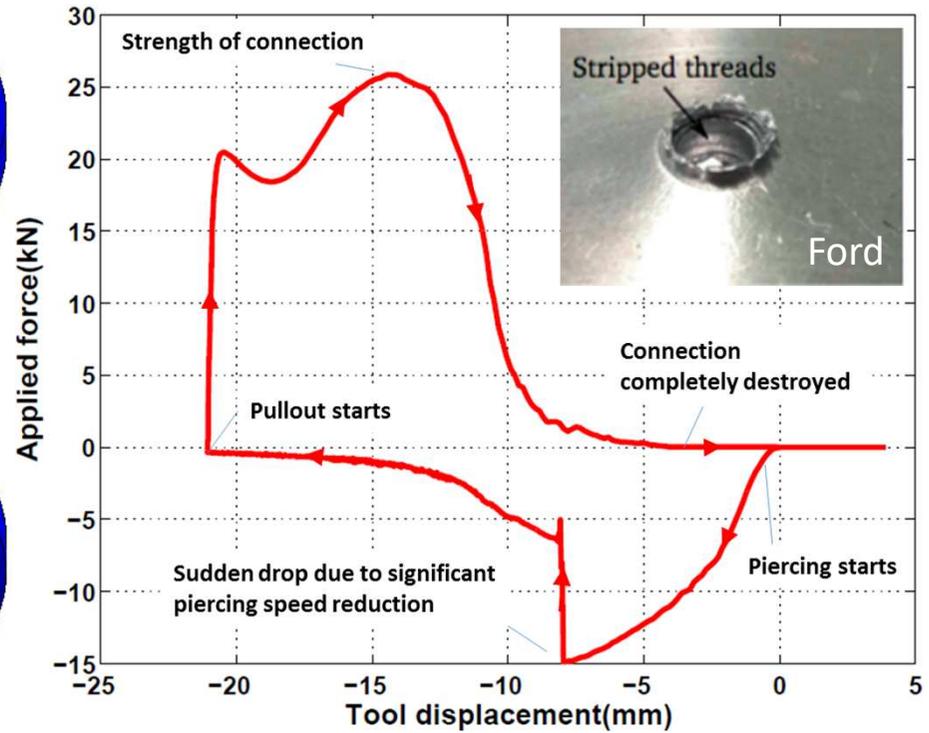
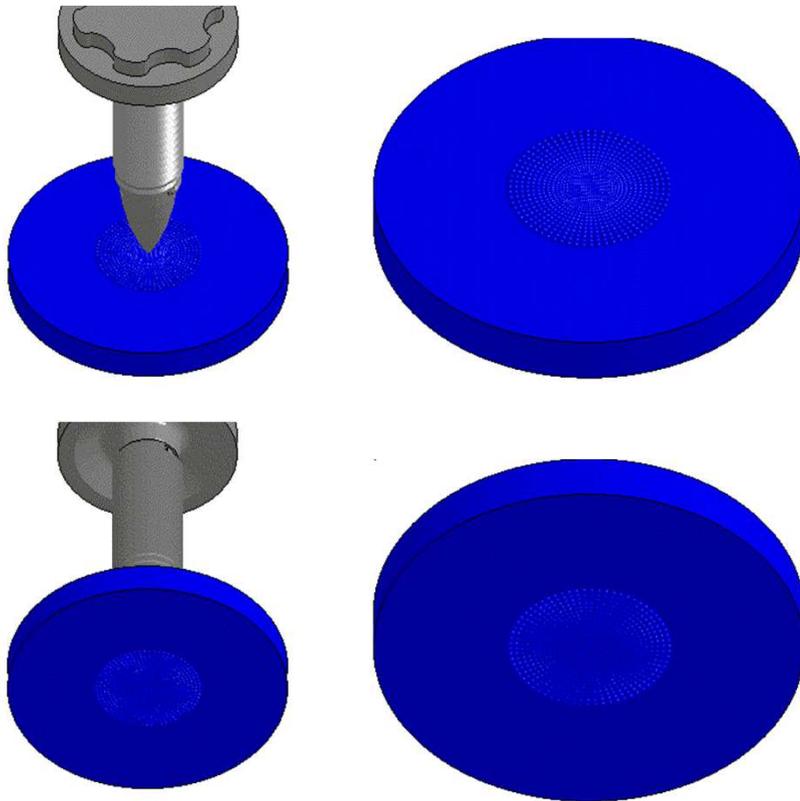
- 材料模型：Johnson-Cook model
- 材料破坏：SPG键断裂模型($EPS=0.4$)
- FEM&SPG耦合计算提高效率
- 连接加工及回旋测试



FDS加工及回旋测试过程

SPG应用实例5：流钻螺丝(FDS)

- 铝合金板材连接
 - 连接加工及拉力强度测试

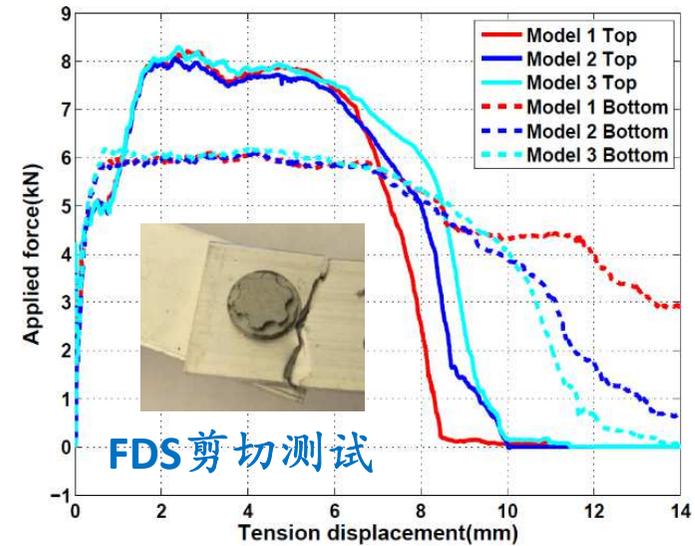
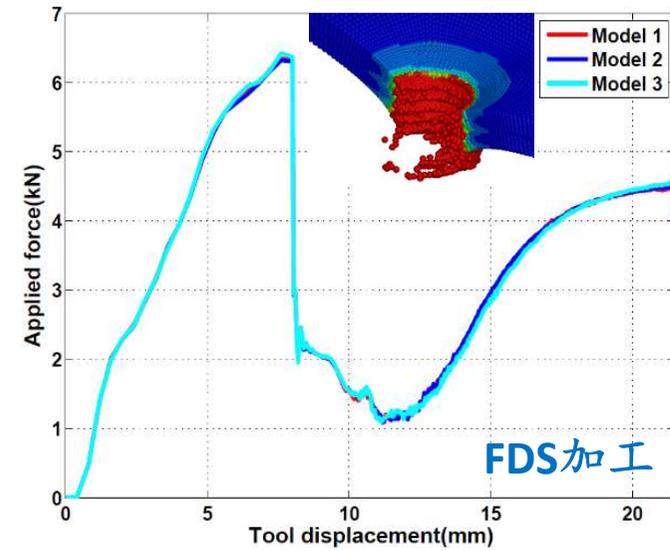
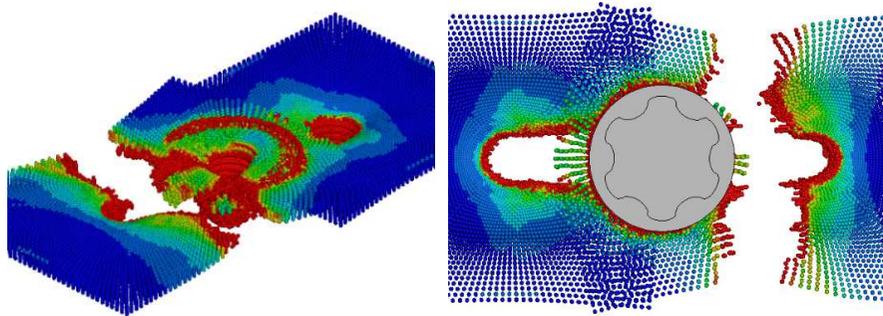
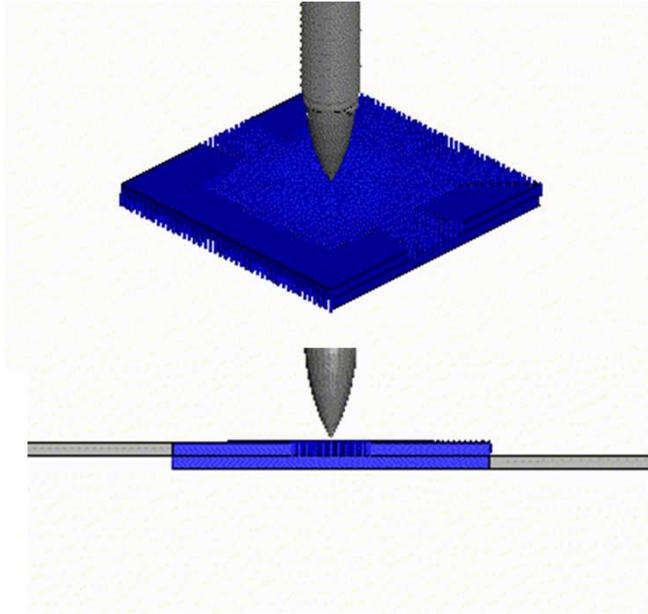


FDS加工及回拉测试过程

SPG应用实例5：流钻螺丝(FDS)

□ 不锈钢板材连接

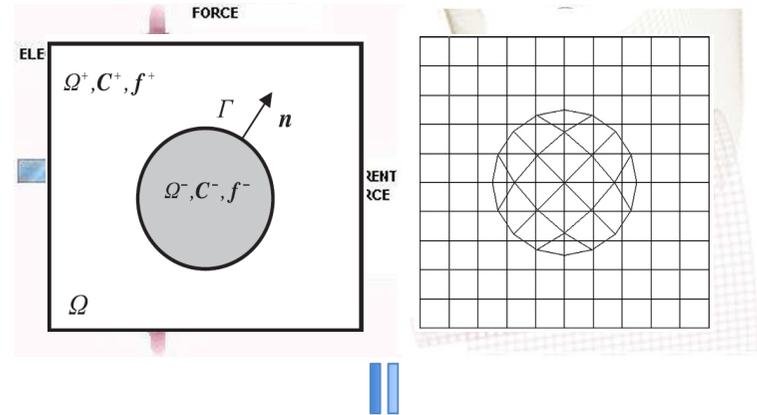
- 连接加工及横向剪切强度测试



SPG浸入式Immerse算法

❑ Non-conforming网格

- 复合材料建模
 - ✓ 基底材料(实体)
 - ✓ 掺杂材料(实体/纤维/孔洞/界面层)
- 多尺度耦合分析
 - ✓ 连接件(固体单元模型)
 - ✓ 车体结构件(壳单元)



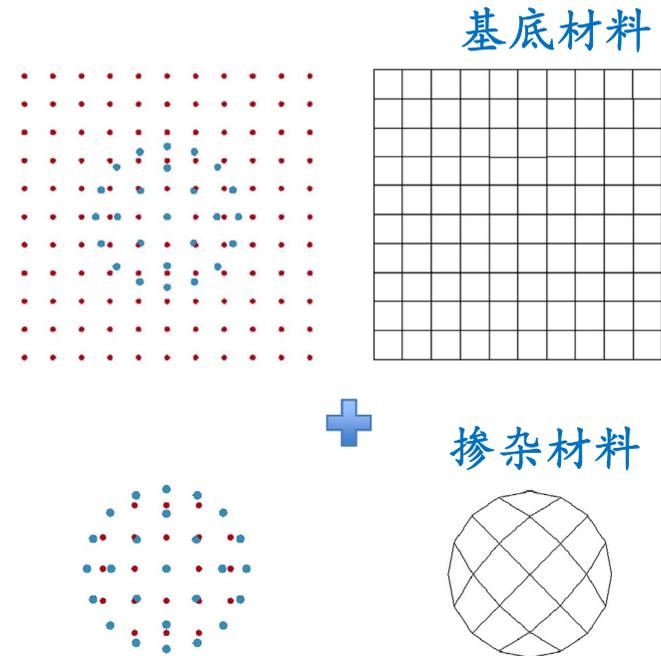
❑ 浸入Immerse算法

- 利用不同网格处理“重复”区域
- 正确处理界面边界条件

❑ 关键字: *CONSTRAINED_IMMERSSED_IN_SPG

❑ 目前的功能

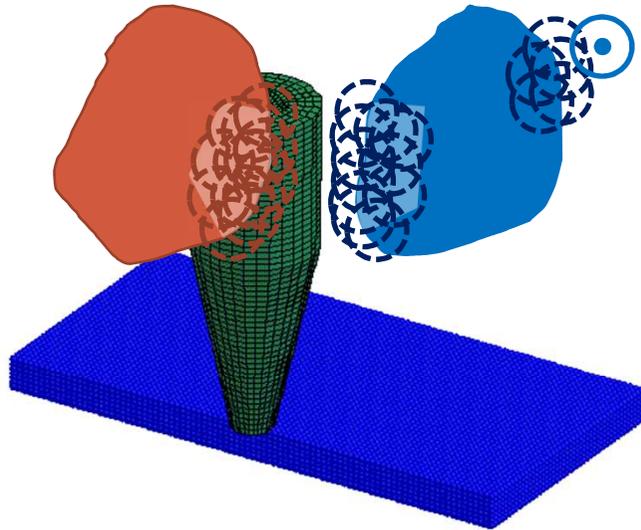
- 掺杂模型支持: 实体, 壳和杆梁单元
- 支持基于键破坏模型



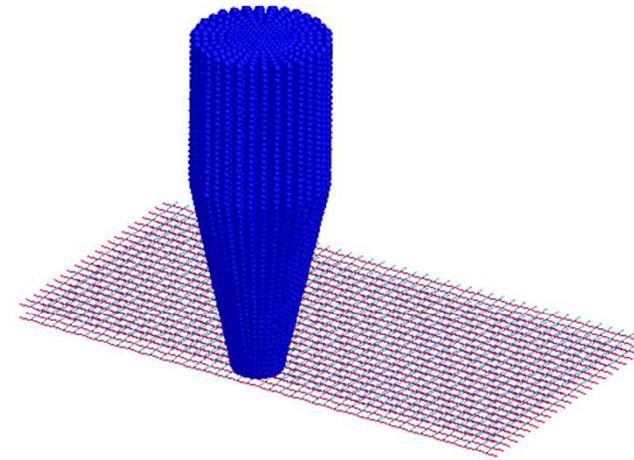
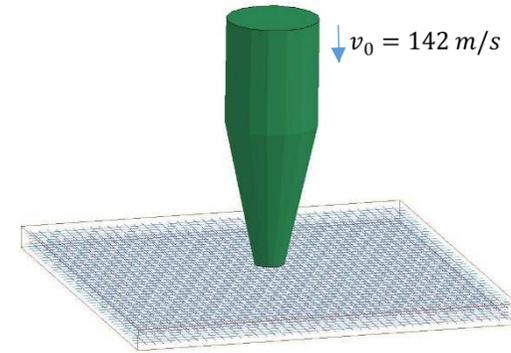
SPG浸入式算法实例1：弹丸冲击

□ 钢筋混凝土

- 钢筋：FEM梁单元
- 混凝土：SPG(半脆性材料键破坏模型)
- 金属弹丸：SPG(延展性材料键破坏模型)
- 粒子接触模型：*CONTACT_SPG



9.18 frame/sec

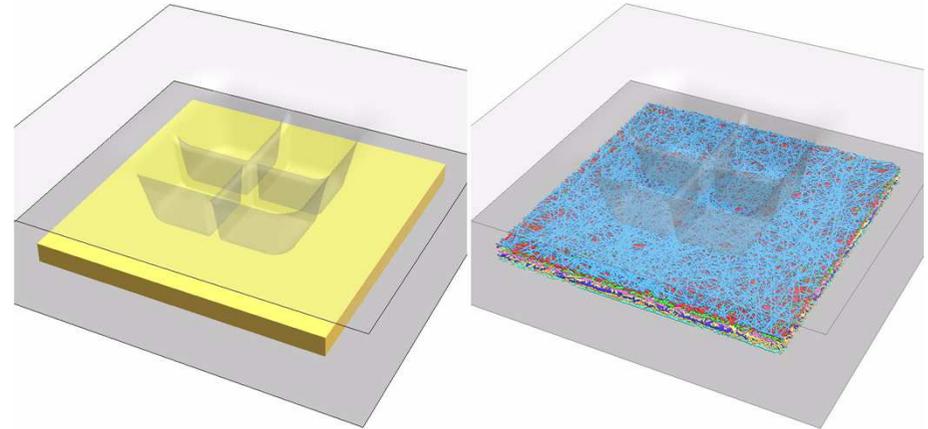


14.67 frame/sec

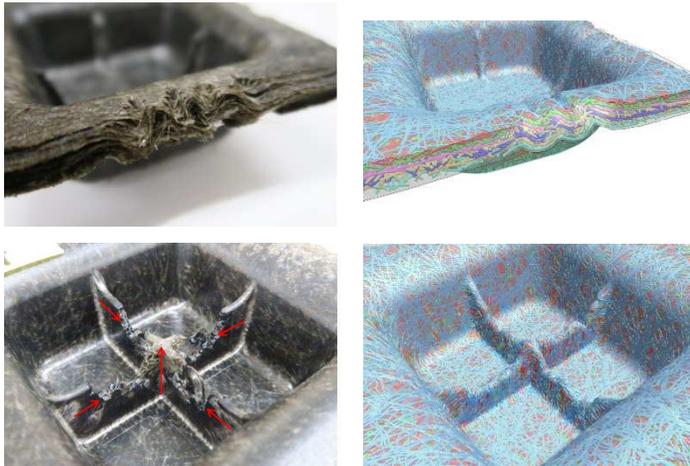
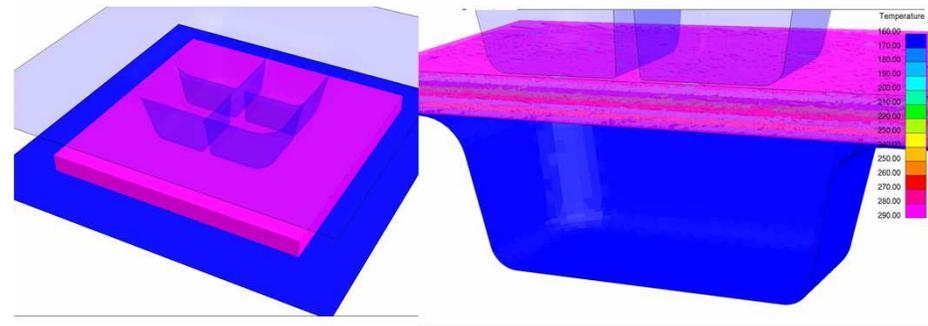
浸入式算法实例2：纤维增强塑胶

□ 压缩成型

- 玻璃纤维
 - ✓ 30-50mm
 - ✓ 2D无序纤维网络
 - ✓ 体积比47%
 - ✓ 弹性材料模型(FEM梁单元)
- 塑胶
 - ✓ Polyamide Nylon6 (PA6)
 - ✓ 温度相关塑性材料模型
 - ✓ 自适应无网格法



Courtesy of JSOL



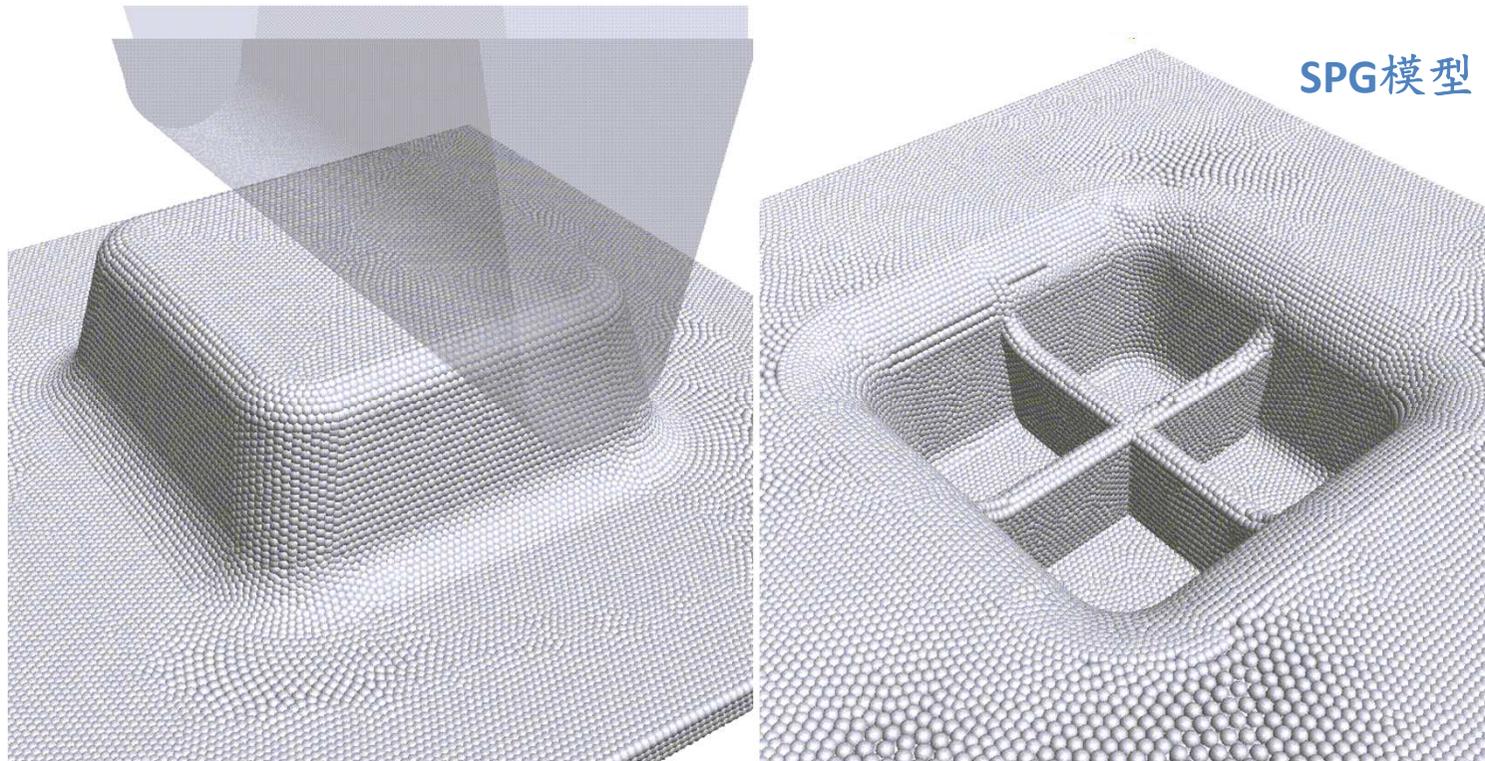
浸入式算法实例2：纤维增强塑胶

□ 冲击测试

- 玻璃纤维：FEM梁单元(单元删除)
- 塑胶：SPG键破坏模型



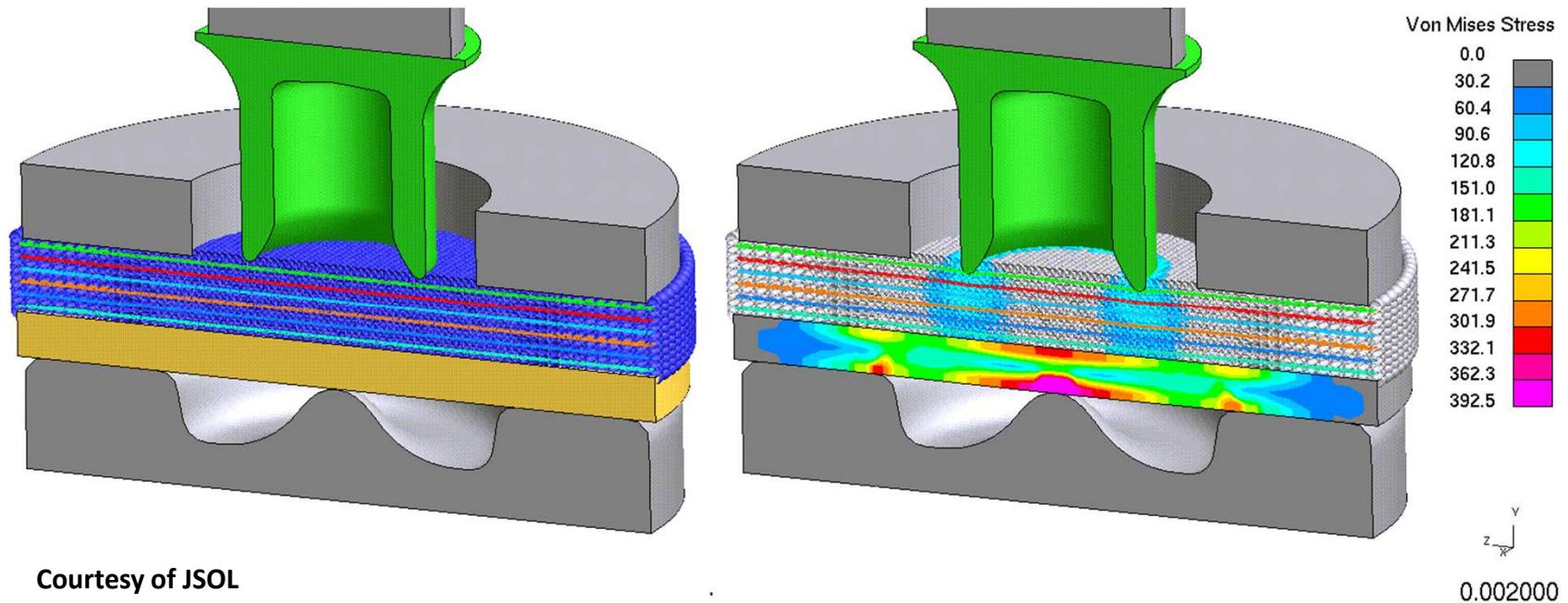
Courtesy of JSOL



浸入式算法实例2：纤维增强塑胶

□ 自冲铆接过程

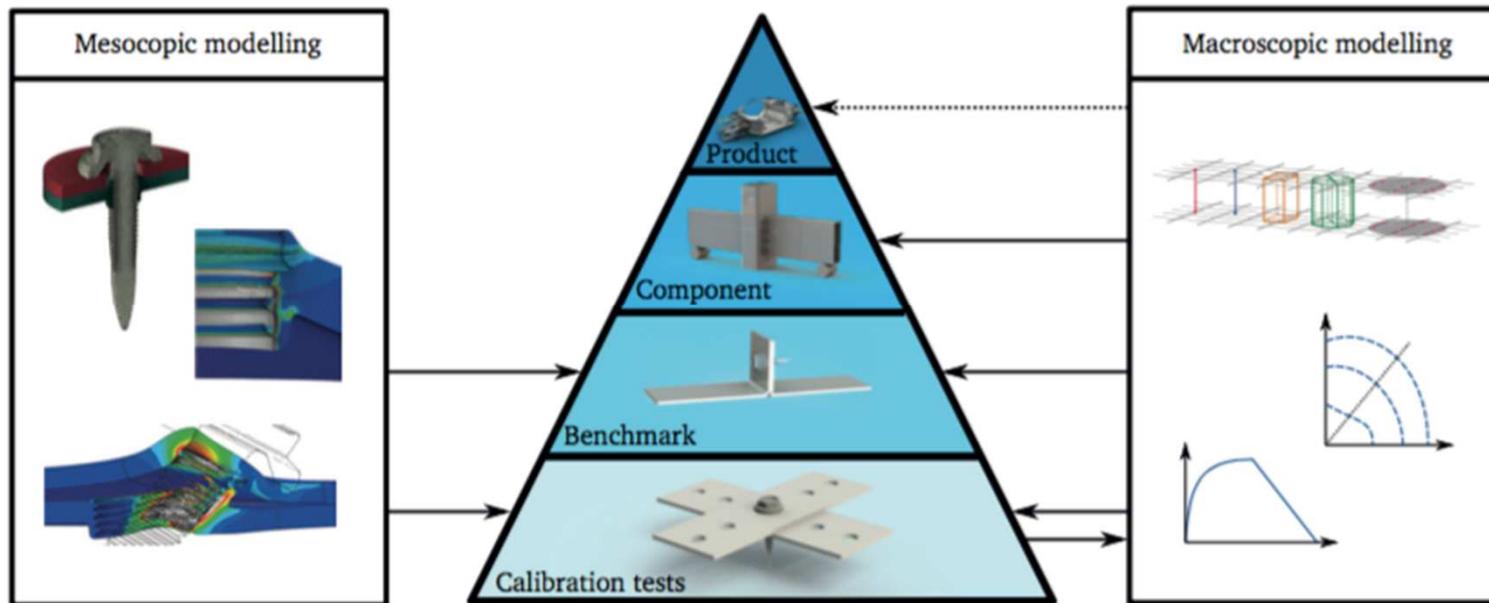
- 上层玻璃纤维增强塑胶：浸入模型(SPG&FEM梁单元) + 键破坏模型
- 下层金属板：FEM模型



全车碰撞模拟中的连接件破坏

□ 连接件简化模型

- 等效材料模型：现阶段的Meso-scale数值测试分析仅用来部分取代实验测试，来获得连接件等效材料参数
- 连接件通常简化为梁，杆或实体单元，并通过定义TIE接触作用于车体壳结构
- 计算效率高
- 无法将连接件加工过程的影响带入碰撞分析
- 无法模拟复杂载荷情况下连接件及其周边板壳的破坏行为

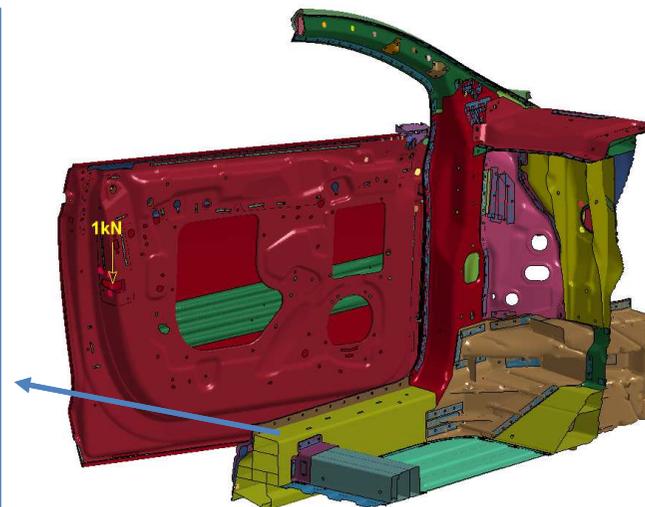
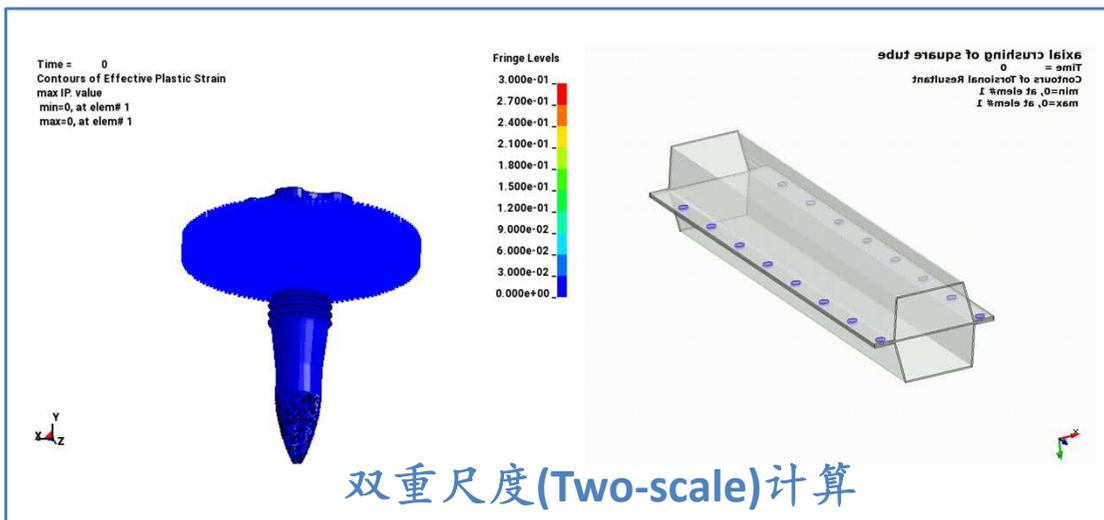
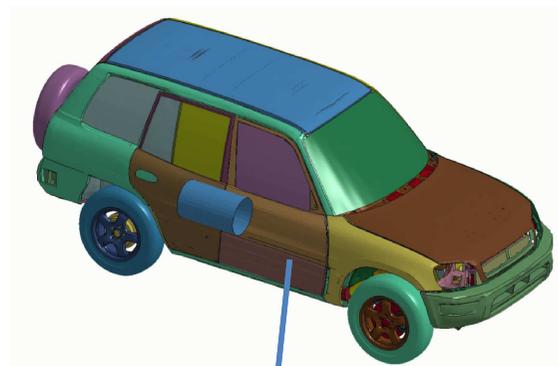


S. Sommer et al. 8th European LS-DYNA Users' Conference, 2011; J.K. Sonstabo, et al. Thin-Walled Structures 2016

全车碰撞模拟中的连接件破坏

- ❑ 子循环(Sub-cycling)算法：计算量大
- ❑ 多重尺度协同(Concurrent Multi-scale)算法：不成熟
- ❑ 双重尺度(Two-scale)算法：研发重点

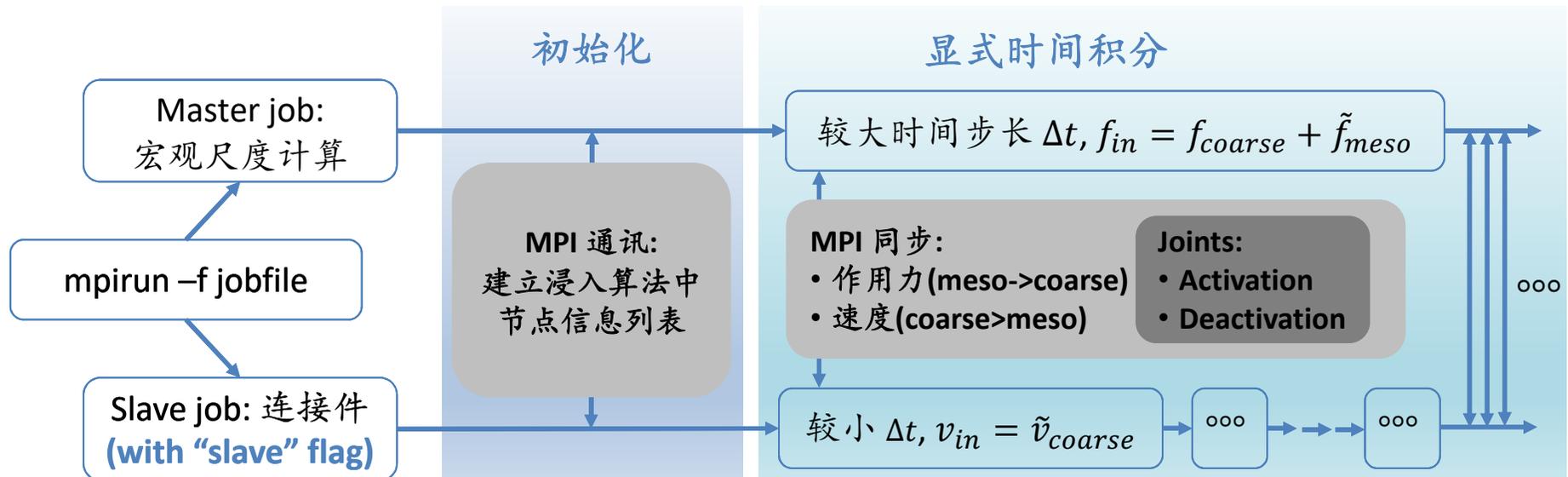
$$\Pi^{two}(\mathbf{u}, \theta) = \underbrace{\Pi^{\Omega_{Macro}/\Omega_I}(\mathbf{u}, \theta)}_{macro-scale} + \underbrace{\Pi^{\Omega_M}(\mathbf{u})}_{meso-scale} + \underbrace{\tilde{\Pi}^{\Omega_I}(\mathbf{u})}_{multiple\ constraint} + \underbrace{\Pi^{\Omega_I}(\mathbf{u})}_{immersed}$$



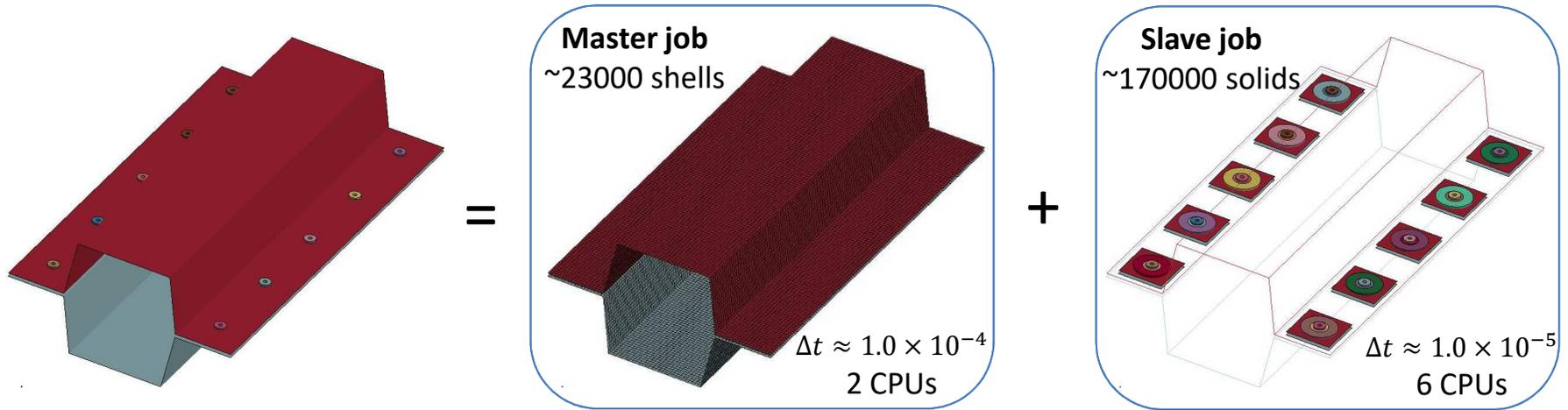
Courtesy of Ford

碰撞模拟中的连接件破坏：双重尺度算法

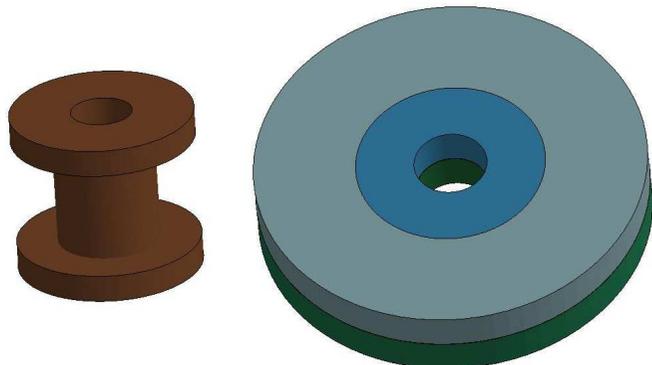
- ❑ 宏观尺度(coarse scale): 壳结构
- ❑ 中间尺度(meso scale): 实体单元构成的连接件结构 (FEM&SPG)
- ❑ 跨尺度
 - 浸入Immerse算法
 - 壳结构通过运动学参量(速度)驱动连接件变形
 - 连接件变形产生的反作用力提供壳结构的连接约束
 - 连接件模型的启动和删除
- ❑ 两个尺度的计算为分布式独立运行的LS-DYNA作业：数据传输通过MPI实现



双重尺度算法实例：管结构冲击测试

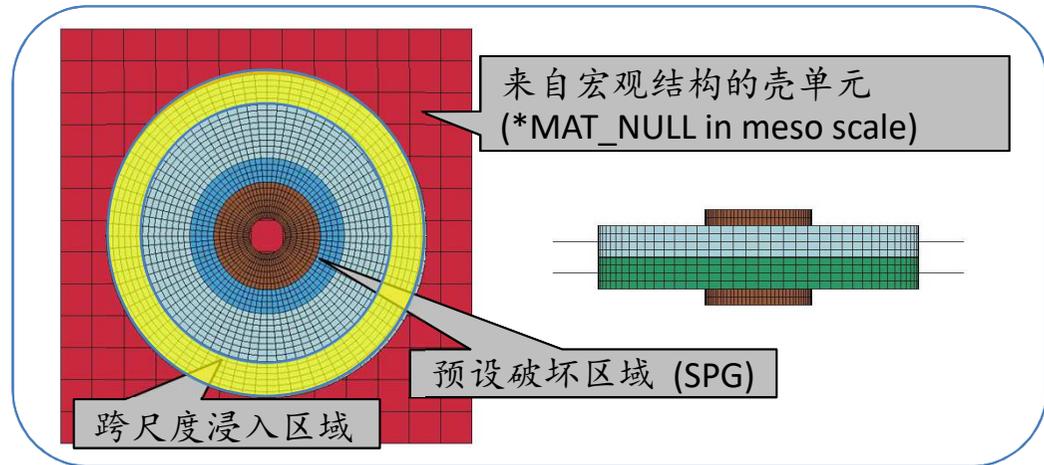


连接结构

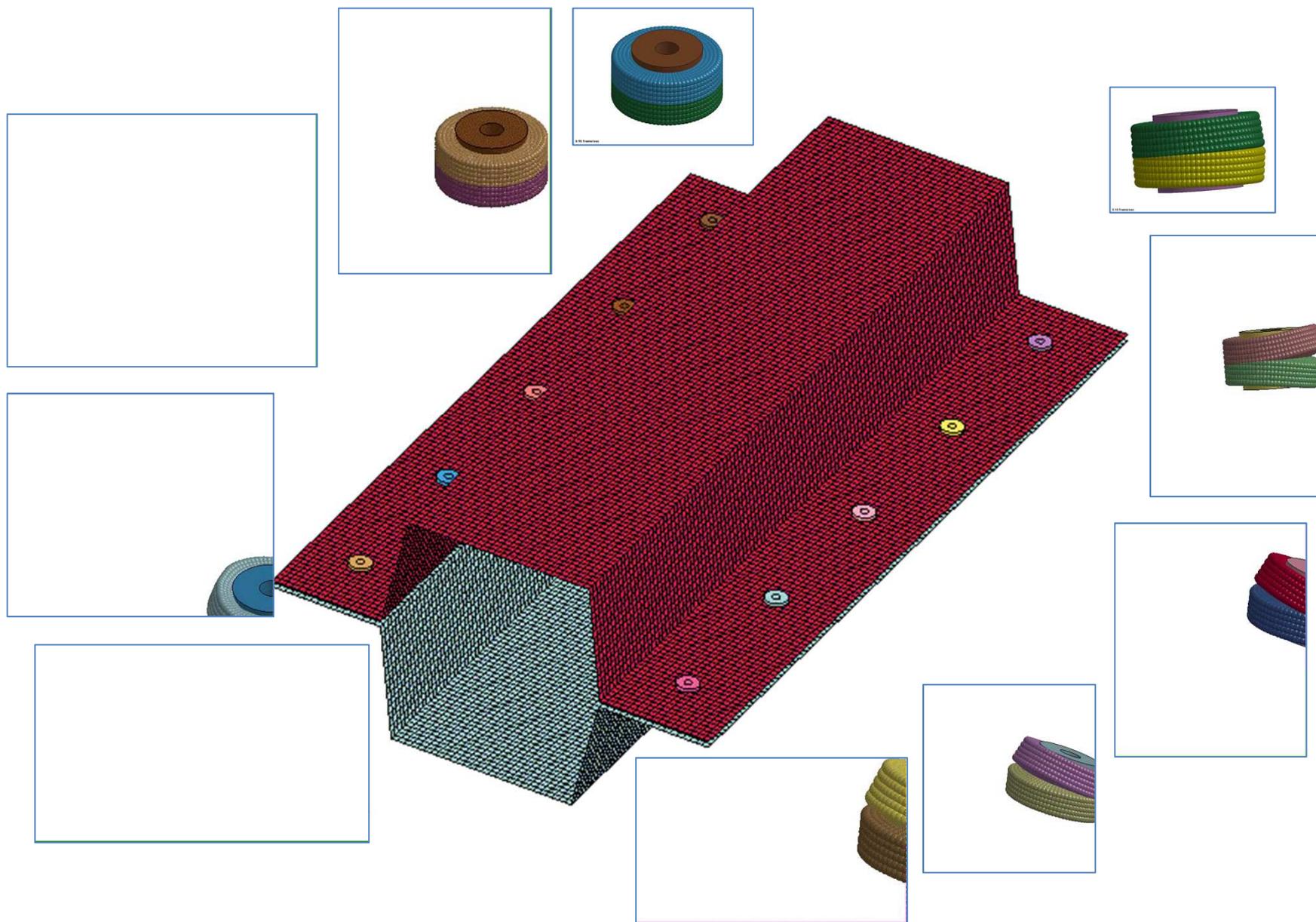


刚体连接件

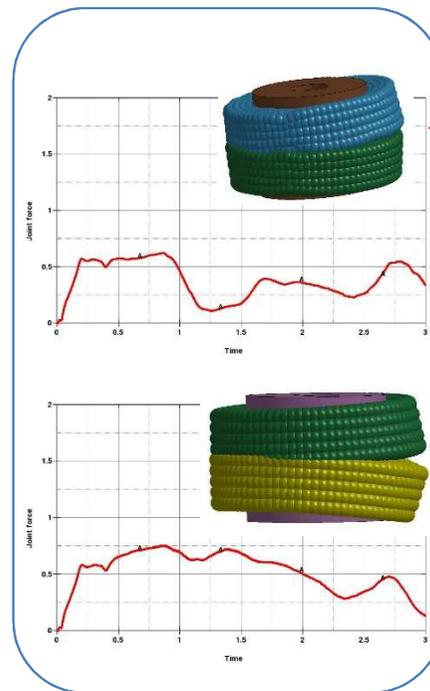
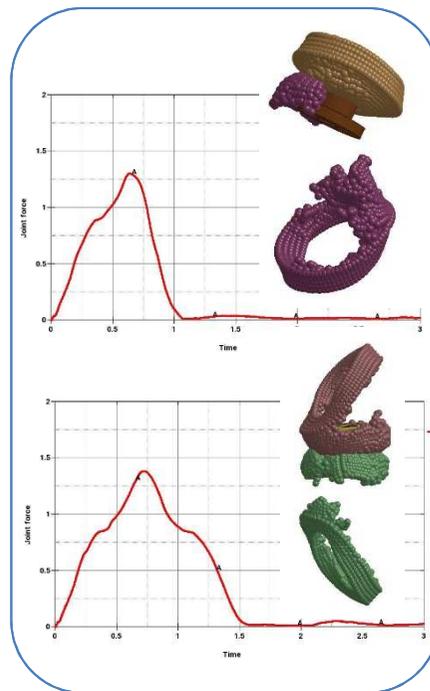
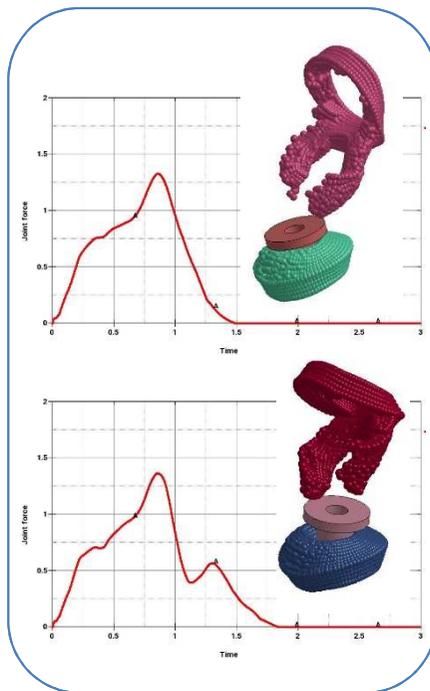
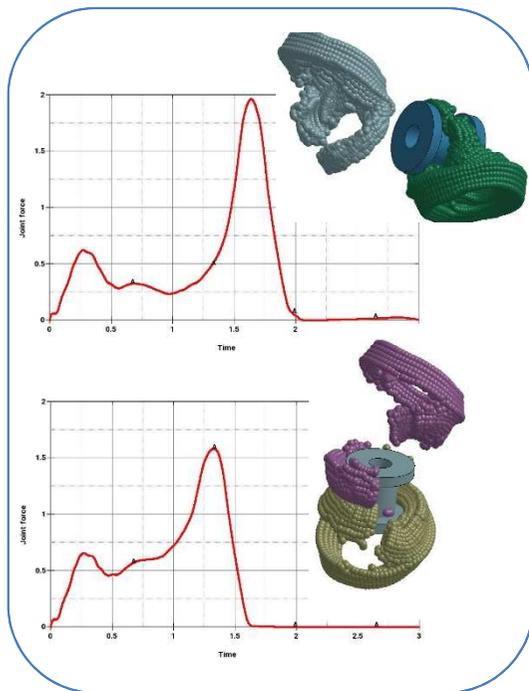
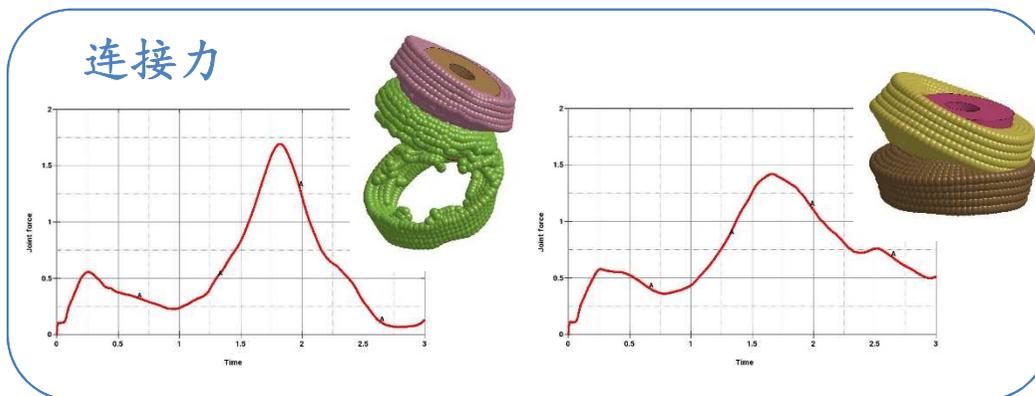
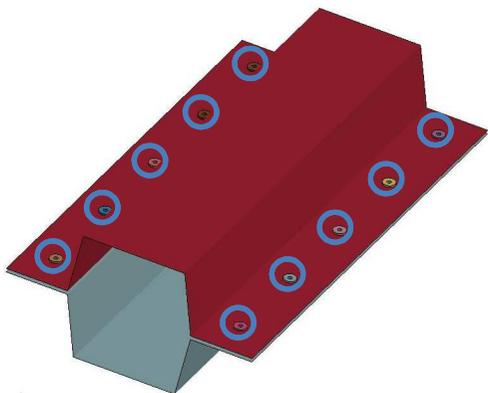
板壳结构的实体单元
对应宏观的壳单元结构



双重尺度算法实例：管结构冲击测试



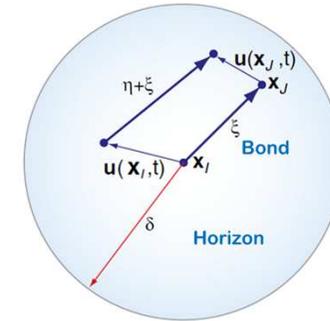
双重尺度算法实例：管结构冲击测试



近场动力学法(Peridynamics)

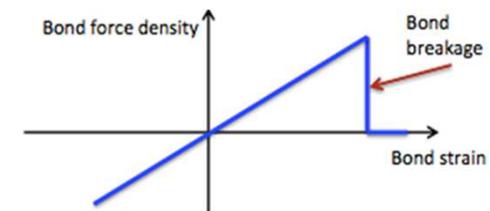
□ 近场动力学

- 基于键模型和其在影响域内的离散积分形式
- 区别于连续介质力学：基于应力应变关系
- 适用于处理脆性材料的复杂破坏行为



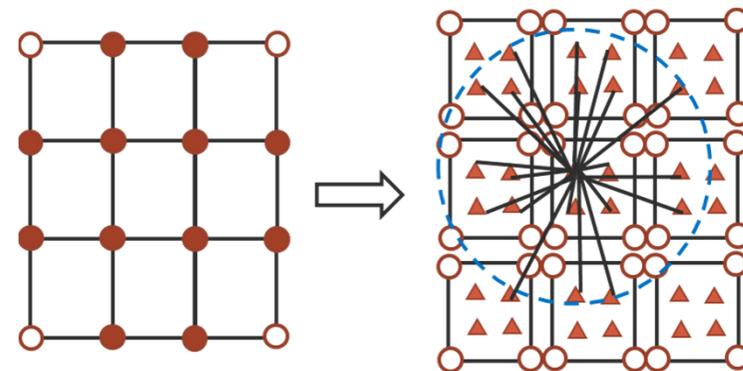
□ 关键字

- *SECTION_SOLID_PERI
- *MAT_ELASTIC_PERI
- *MAT_ELASTIC_PERI_LAMINATE
- *SET_PERI_LAMINATE
- *ELEMENT_SOLID_PERI



□ 目前的功能

- 输入模型
 - ✓ FEM网格(TET/PENT/HEX单元)
 - ✓ 离散单元处理(LS-PrePost功能)
- 脆性材料
- 纤维(UD)层压材料

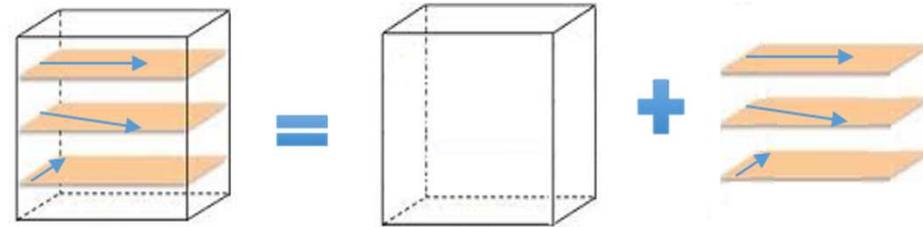


□ R10.0版本开始研发(MPP/SMP)

近场动力学法：纤维(UD)层压材料

□ 层压材料模型解耦

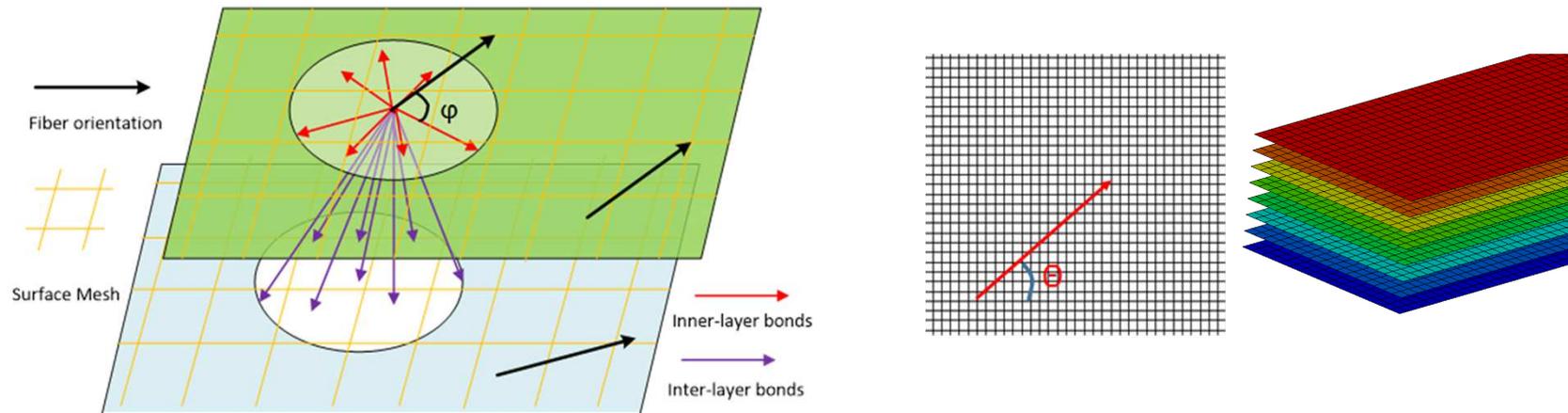
- 基底
- 分层纤维结构



□ 键模型

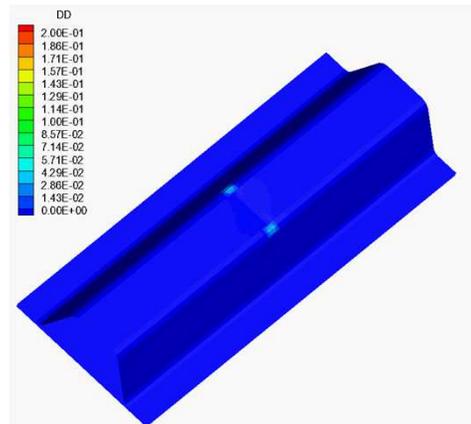
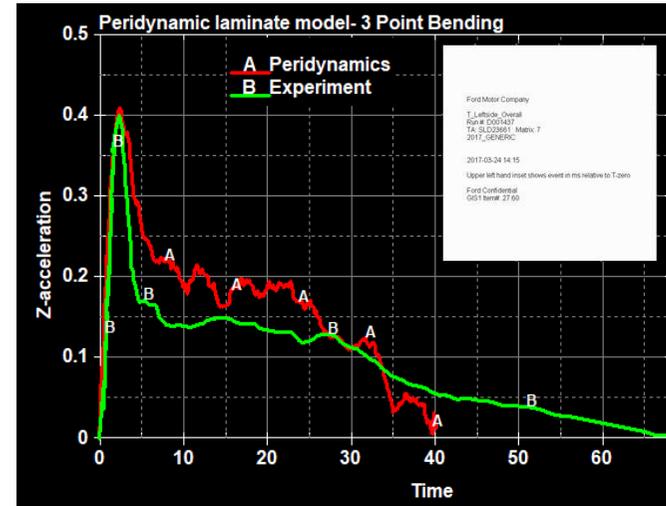
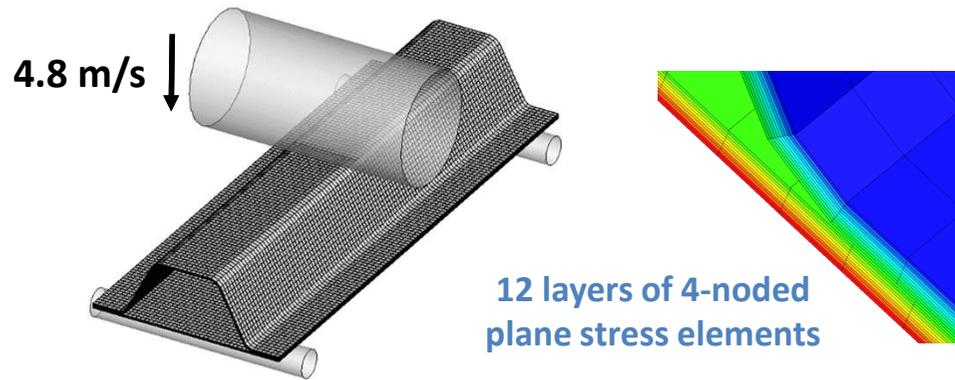
- 层间
- 层内：根据键和纤维夹角改变键模型的参数(Ghajari, *et. al.*, 2014)

□ 同一网格处理有不同纤维方向的层结构

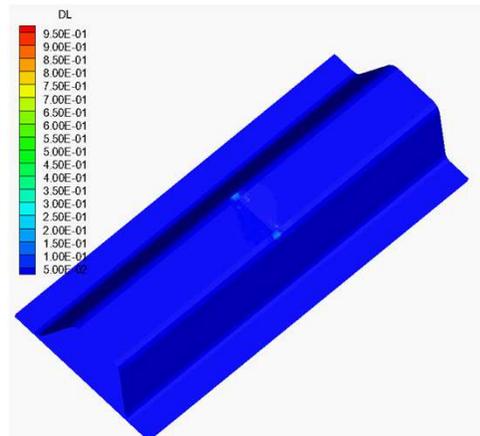


近场动力学法实例1: CFRP三点弯曲测试

□ 碳纤维层压材料(CFRP): UD[0/60/-60/0/60/-60]_s

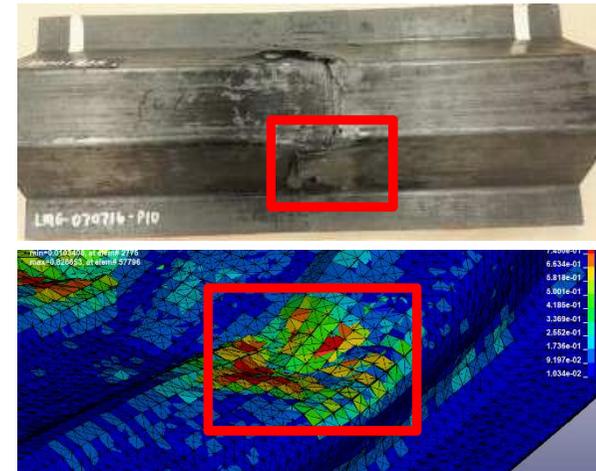


层内破坏值云图

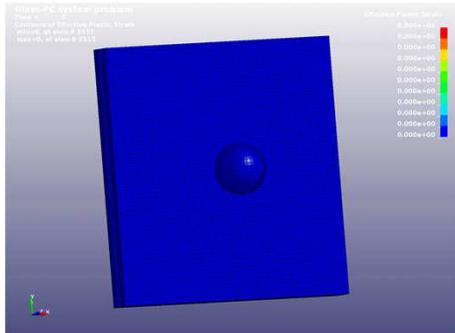


层间破坏值云图

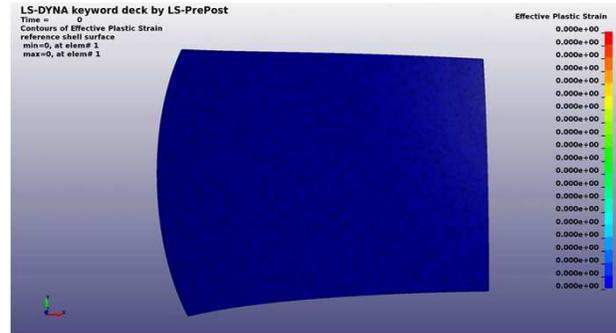
Courtesy of Ford , USA



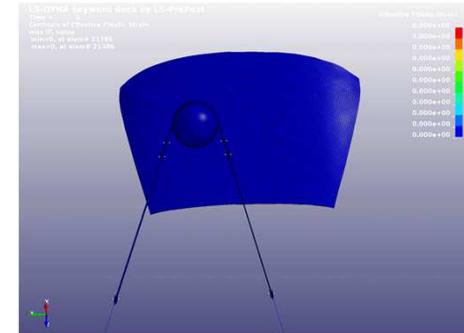
近场动力学法更多实例



Glass-PC-Glass板冲击



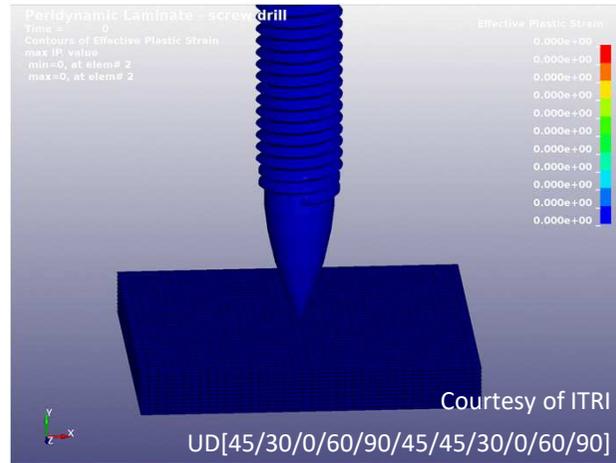
车挡风玻璃三点弯测试



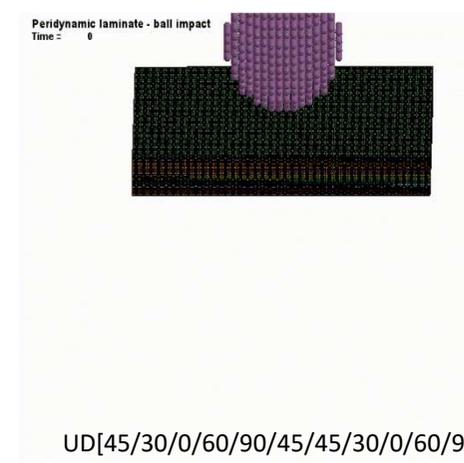
车挡风玻璃冲击



CFRP层压材料冲击



CFRP流钻螺丝



SPH高速冲击
CFRP层压材料

总结

- LS-DYNA拥有目前业内最为丰富和前沿的计算方法来处理材料加工和碰撞测试过程中的破坏问题，包括SPG, Peridynamics, 扩展有限元和SPH
 - 材料破坏本质上是多尺度问题
 - 宏观尺度的数值分析方法不足以精确预测复杂条件下的破坏行为

- 无网格/粒子法在处理大变形和材料破坏方面的优势使其在工业界获得大量应用

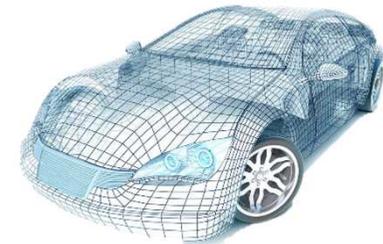
- 未来的研发方向：先进数值分析工具的整合
 - 材料设计，制造和结构分析
 - 跨尺度信息交换和协同分析
 - 超大规模工业应用中分析数据的有效利用

- 我们希望开发出简单高效而非“简化”的新方法



LSTC
Livermore Software
Technology Corp.

谢谢!



LS-DYNA®

LS-PrePost®

LS-OPT®

LS-TASC®

Dummies & Barriers