第三届LS-DYNA中国论坛

2018年10月26日　　上海

LSTC
Livermore Software
Technology Corp.

仿坤软件
LS-DYNA China

Livermore Software Technology Corporation

上海仿坤软件科技有限公司（**LS-DYNA** 中国）

2018 LS-DYNA 中国论坛

动力电池挤压失效机理分析和仿真预测

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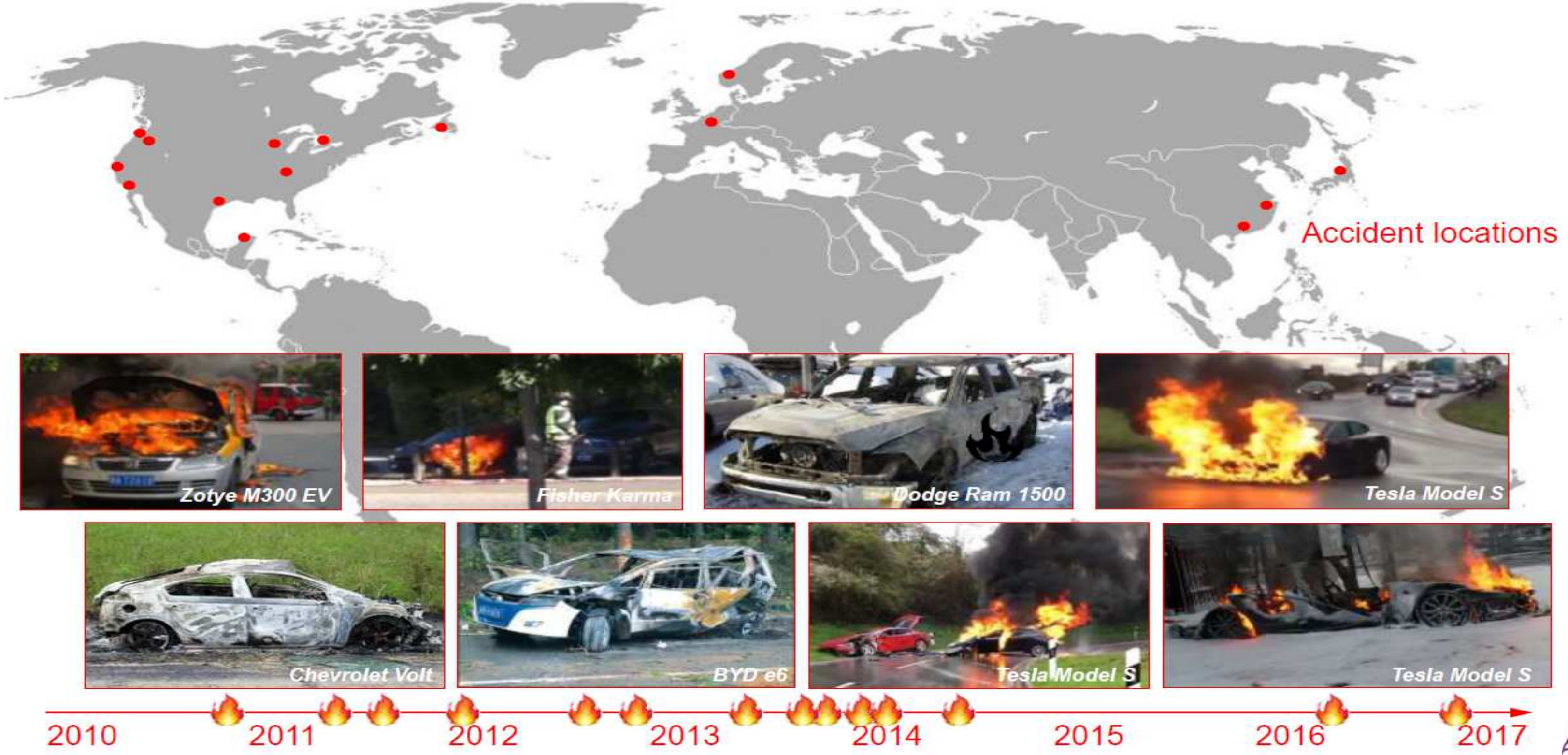
清华大学 汽车安全与节能国家重点实验室

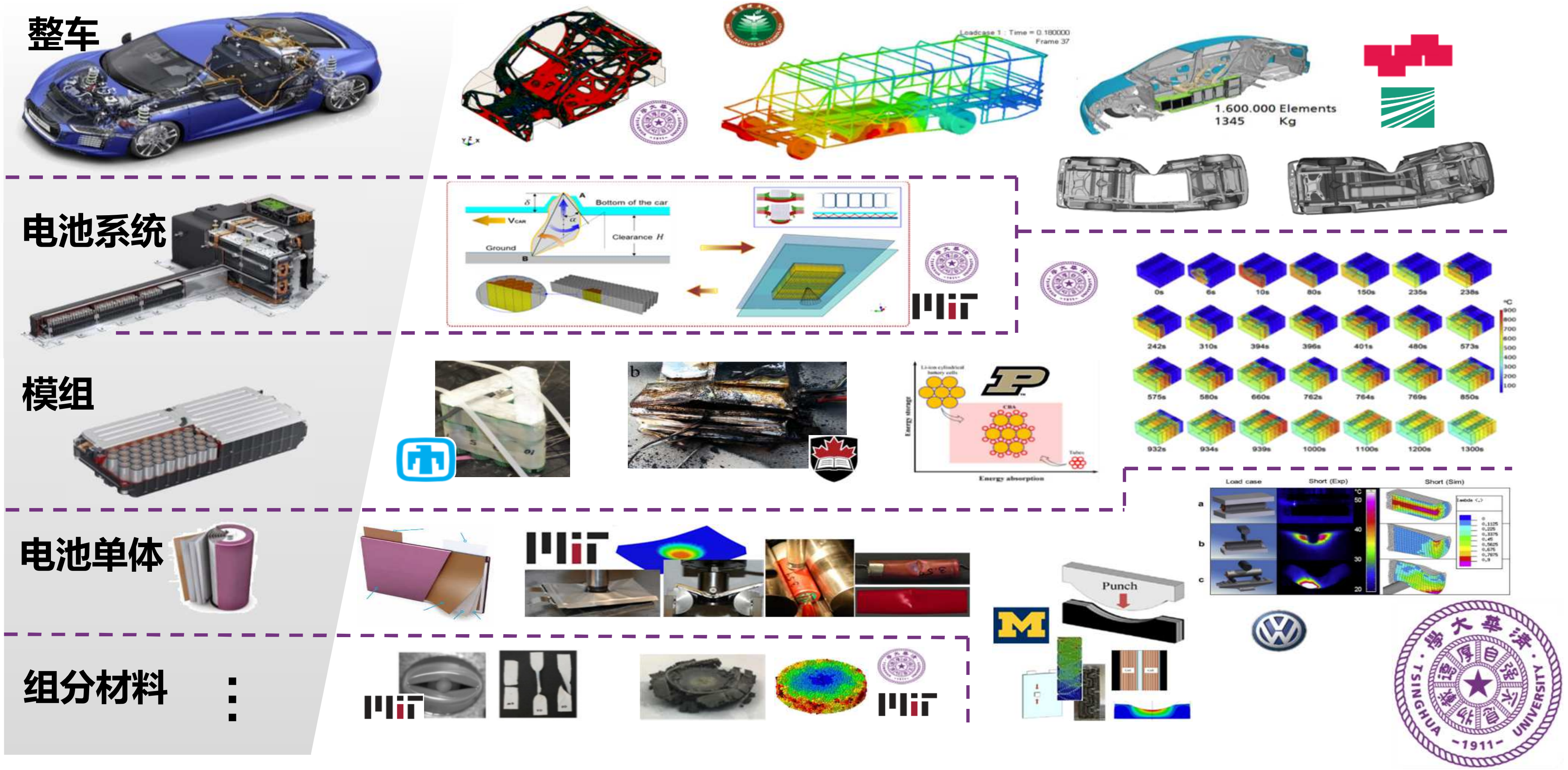
汽车安全与轻量化团队

2018年10月26日

电动汽车碰撞着火事故


Accident locations
Zotye M300 EV
Fisher Karma
Dodge Ram 1500
Tesla Model S
Chevrolet Volt
BYD e6
Tesla Model S
Tesla Model S
2010
2011
2012
2013
2014
2015
2016
2017

背景 —— 动力电池系统层级与碰撞安全研究



整车

电池系统

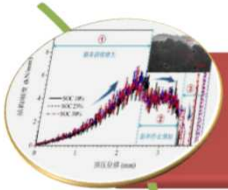
模组

电池单体

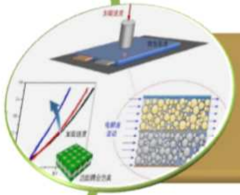
组分材料

⋮

主要内容



电池单体挤压工况损伤过程



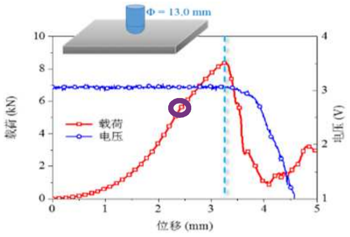
软包电池挤压力学特性与建模

电池模组碰撞响应研究和结构优化

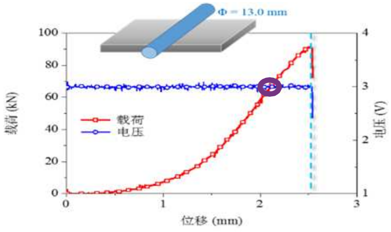
I. 电池单体挤压工况损伤过程

受挤压电池的内损伤演化

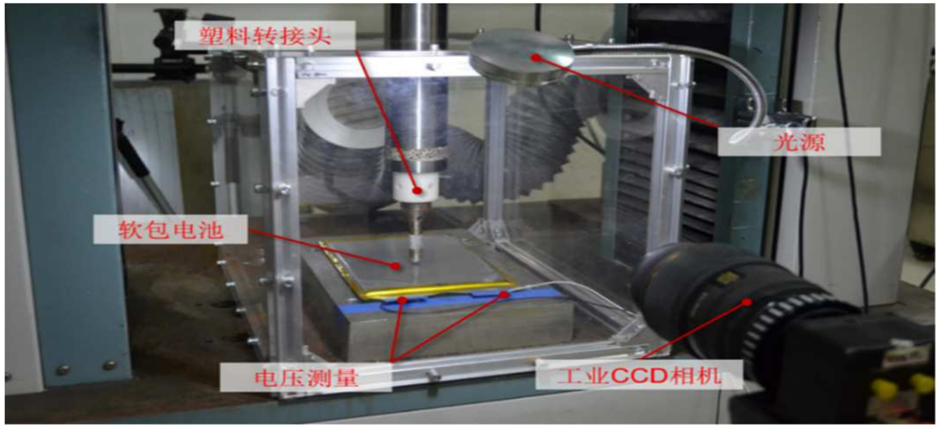
- 结构失效与内短路时刻一致
- 载荷-位移曲线出现“拐点”

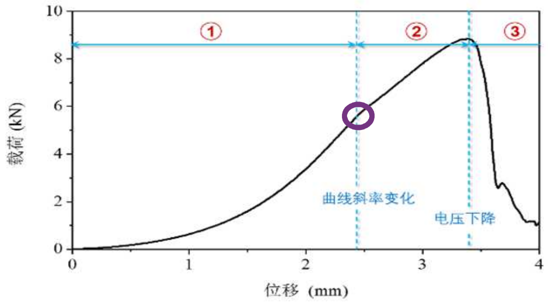


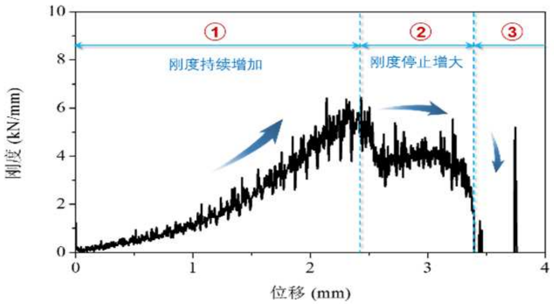
直径13.0 mm球头挤压



直径13.0 mm圆柱挤压





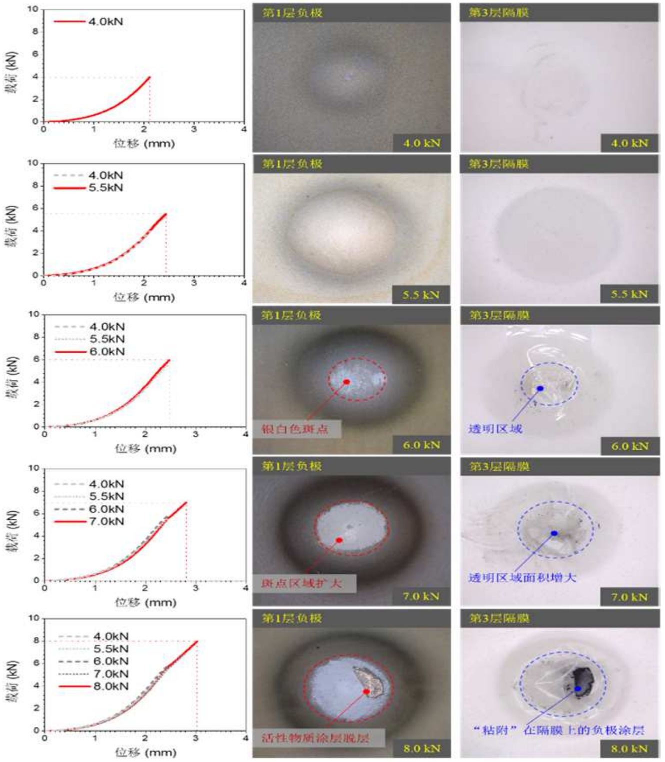


载荷-位移曲线 → 刚度-位移曲线

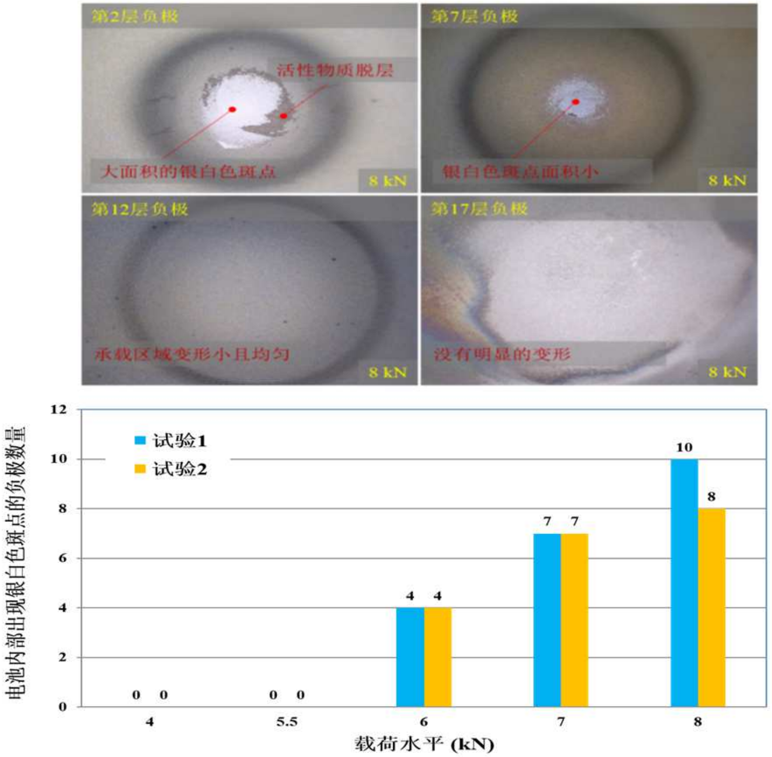
Luo H, Xia Y, Zhou Q. Journal of Power Sources, 2017, 357: 61-70.

软包电池挤压的中断试验（interrupted tests）

- “拐点”现象与电极-隔膜界面变化高度相关



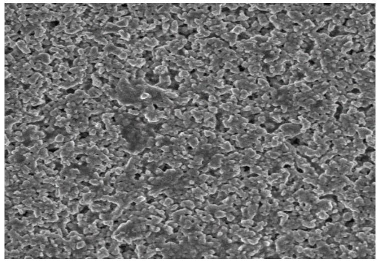
加载到不同载荷水平，观察电极-隔膜界面变化



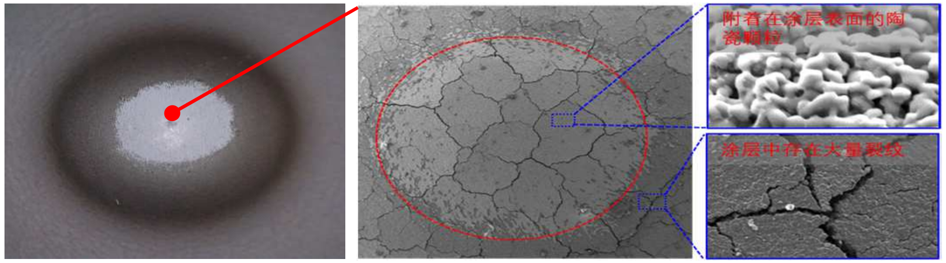
呈现明显损伤特征的电极数量变化情况

软包电池挤压过程的内损伤

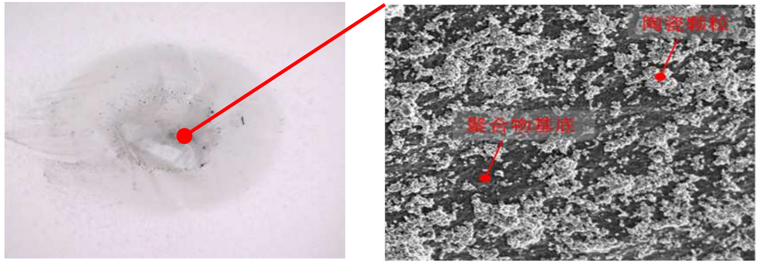
- 电极活性物质涂层断裂/脱层
- 隔膜陶瓷涂层与电极活性物质涂层粘附



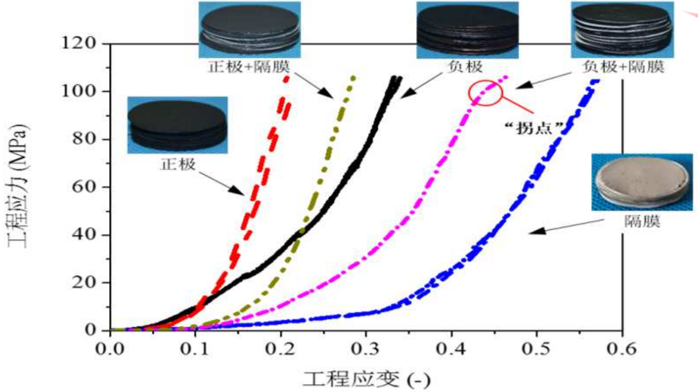
完整的隔膜陶瓷涂层



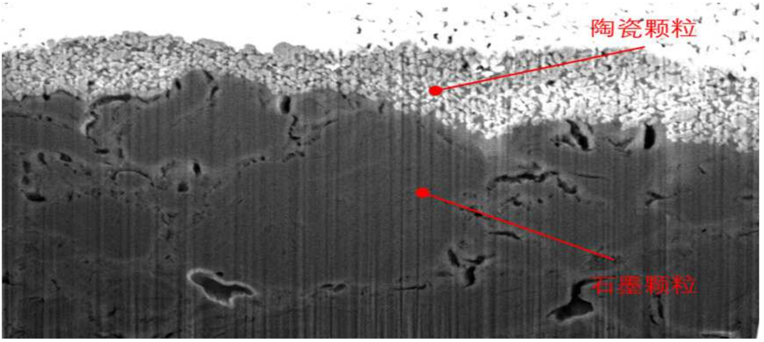
电极活性物质涂层开裂



隔膜陶瓷涂层剥离



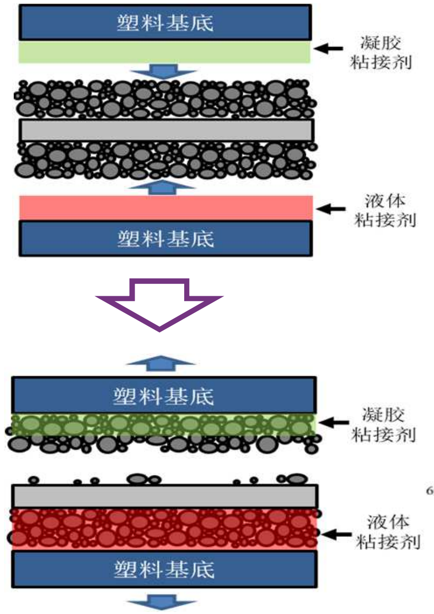
不同组分材料平面压缩试验
负极+隔膜样品出现“拐点”现象



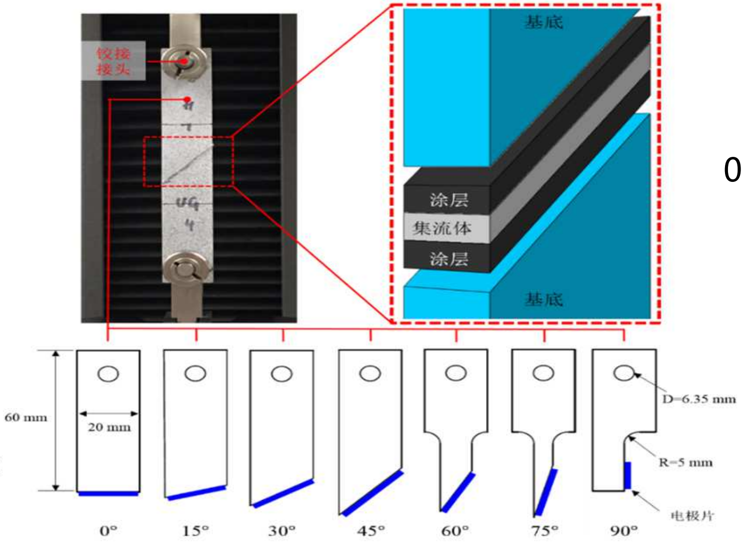
隔膜与负极界面横截面SEM图像
陶瓷颗粒嵌入石墨颗粒间隙

电极活性物质涂层断裂强度

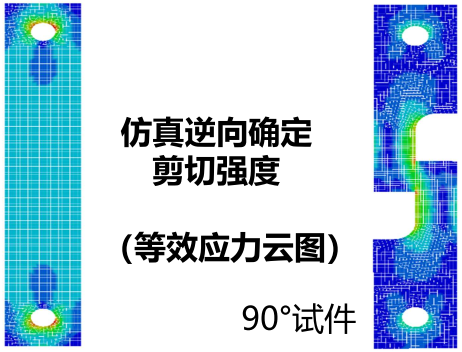
- 建立评估活性涂层强度的方法，分析断裂/脱层失效强度的差异
- 为仿真模型提供界面失效参数



试件准备



试验设置

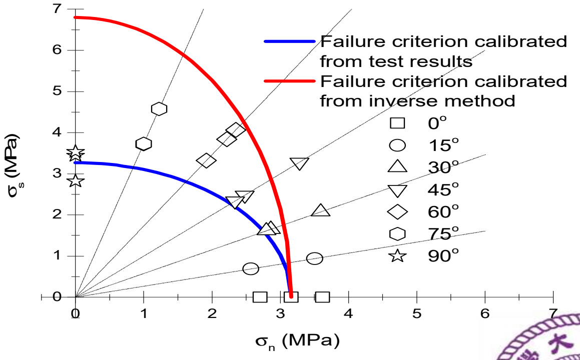


仿真逆向确定剪切强度

（等效应力云图）

0°试件

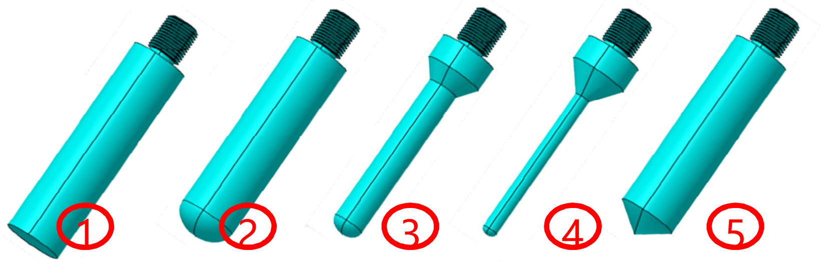
90°试件



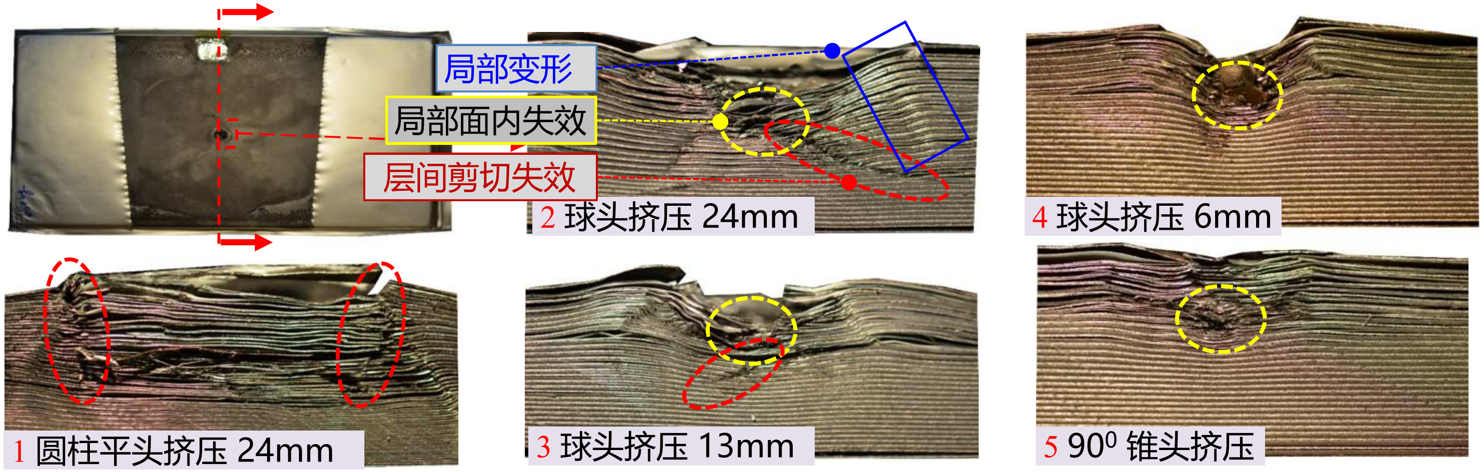
断裂强度测试结果

Luo H, Zhu J, Sahraei E, et al. RSC Advances, 2018, 8(8): 3996-4005.

内短路发生时的断裂模式

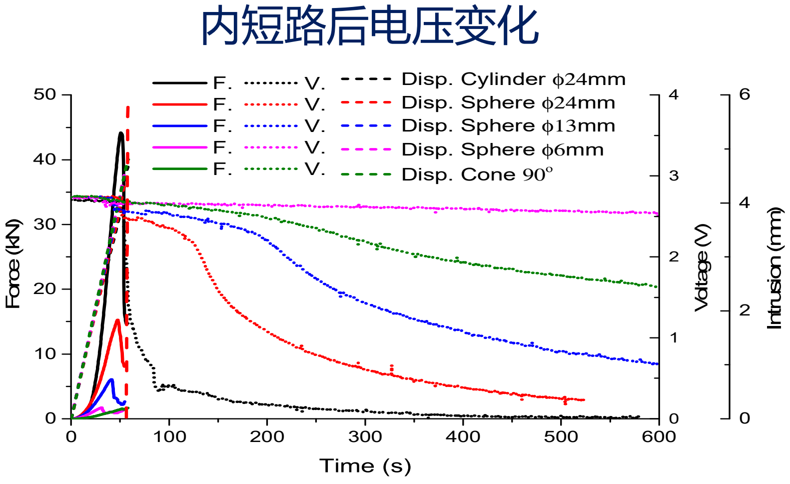


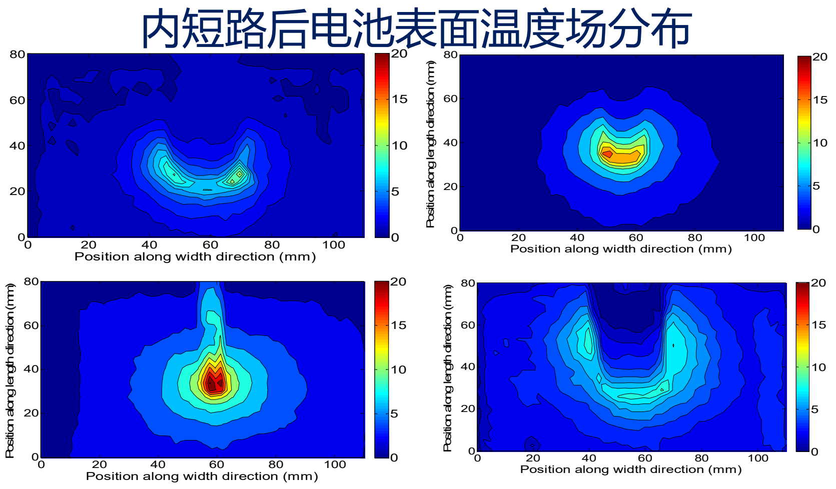
- 两种断裂模式
  - 双向拉伸导致的层内失效
  - 剪切导致的层间失效



Comparative study of mechanical-electrical-thermal responses of pouch, cylindrical,and prismatic lithium-ion cells under mechanical abuse
Wei, Li et al, SCIENCE CHINA Technological Sciences

断裂模式对内短路后电压与温度响应的影响


内短路后电压变化


内短路后电池表面温度场分布

- 层间剪切失效 → 正负极层间错动 → 内短路概率高 → 电压下降快

I. 小结

1. 电池挤压过程，伴随活性涂层的断裂与分层
   活性颗粒与隔膜的相互嵌入会显著影响电池结构刚度

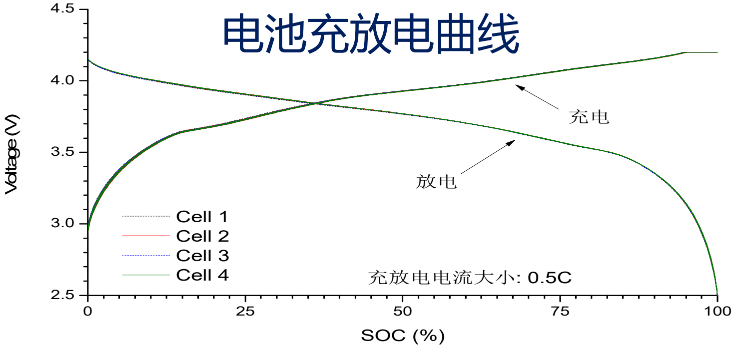
2. 可以通过实验的方法标定，活性涂层失效强度

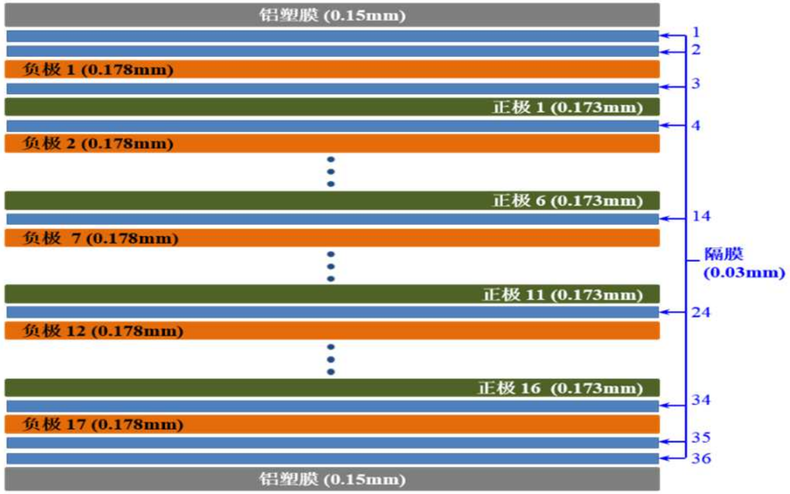
3. 电池内部结构失效模式包括层间断裂与层内断裂
   不同的失效模式会导致不同的内短路严重程度

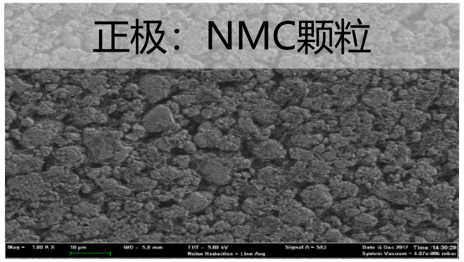
II. 软包电池挤压力学特性与建模

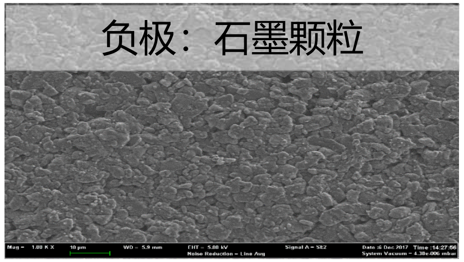
锂离子软包电池材料信息

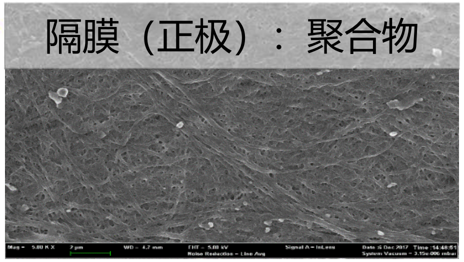
项目	参数
标称容量	20 Ah
标称电压	4.2 V
厚度	7.2 mm
宽度	150 mm
长度	242 mm

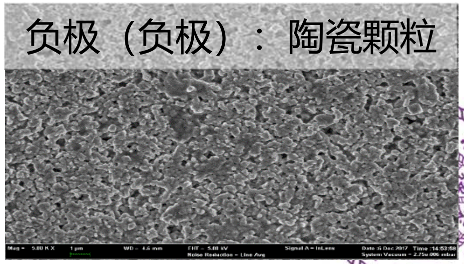





正极：NMC颗粒

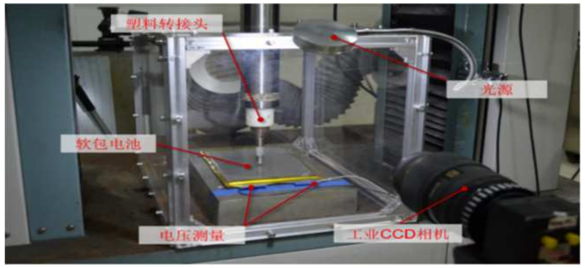

负极：石墨颗粒

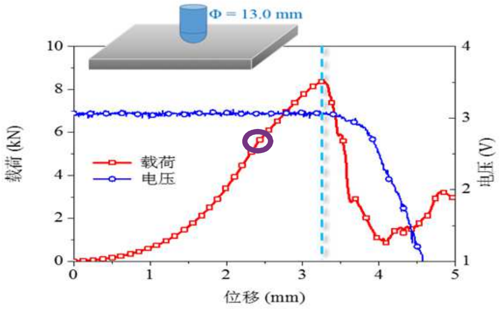

隔膜（正极）：聚合物


负极（负极）：陶瓷颗粒

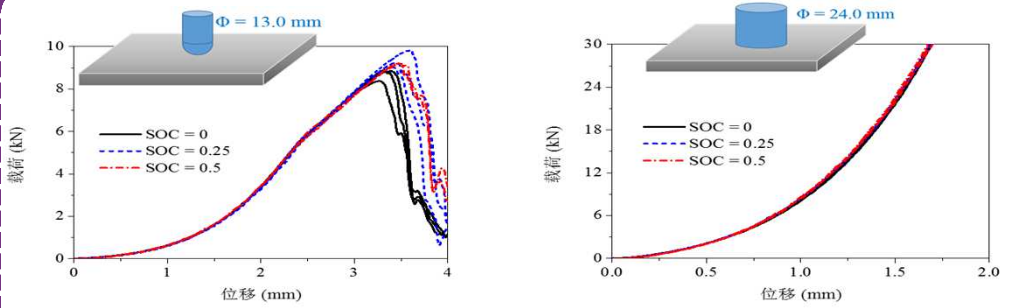
挤压载荷下的变形与失效

- 结构失效与内短路时刻一致
- 载荷-位移曲线与SOC无关

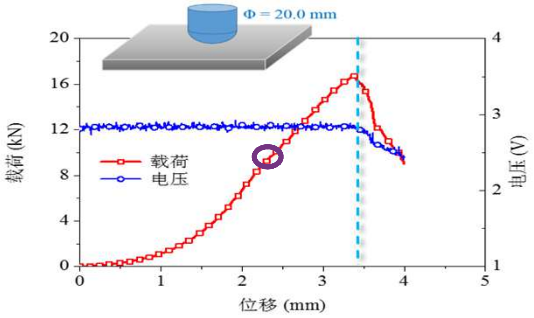




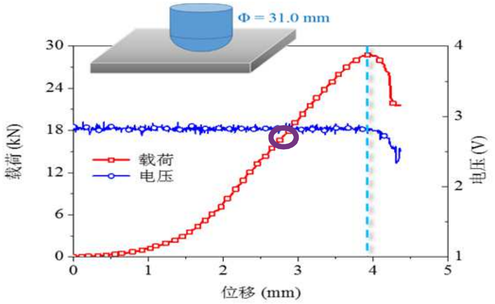
直径13.0 mm球头挤压



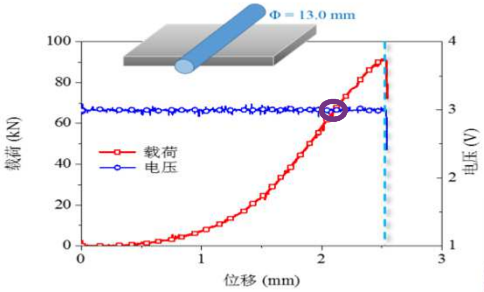
不同SOC下电池挤压响应曲线



直径20.0 mm球头挤压



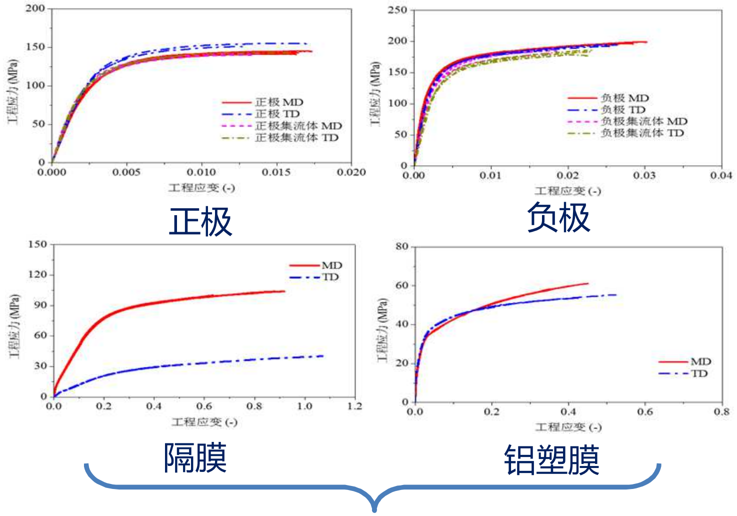
直径31.0 mm球头挤压



直径13.0 mm圆柱挤压

软包电池均质化模型

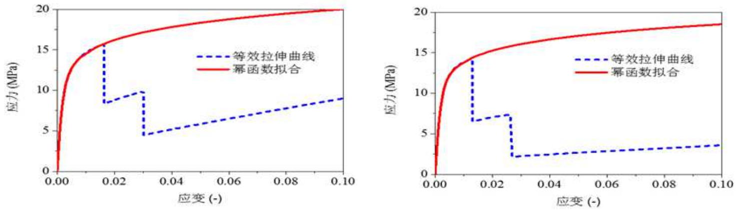
- 电池单体力学行为特征
  - 拉伸性能与压缩性能差异明显
  - 压缩过程中电池结构密实化，硬化率增大
  - 显著的各向异性
- MAT_126_Modified_Honeycomb
  - 孔隙材料反映密实化过程
  - 三个材料方向上允许输入不同应力-应变曲线
  - 输入曲线上通过符号区分拉伸与压缩行为



正极 负极

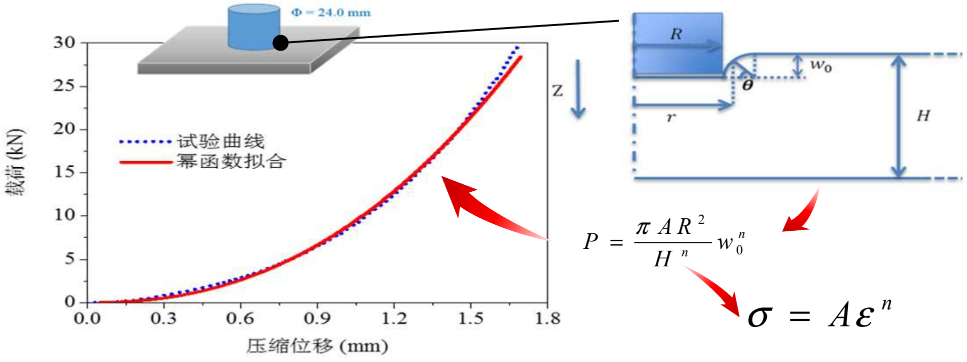
隔膜 铝塑膜

$$\sigma_{average} = \frac{\sum \sigma_i t_i}{\sum t_i}$$



MD TD

电池单体面内拉伸行为标定



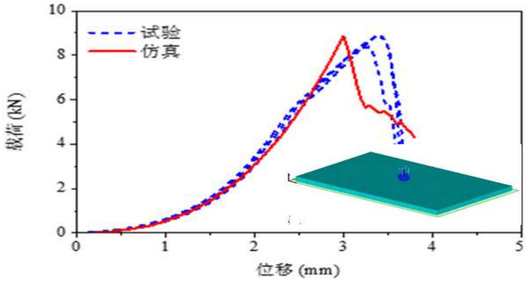
$$P = \frac{\pi A R^2}{H^n} w_0^n$$

$$\sigma = A \varepsilon^n$$

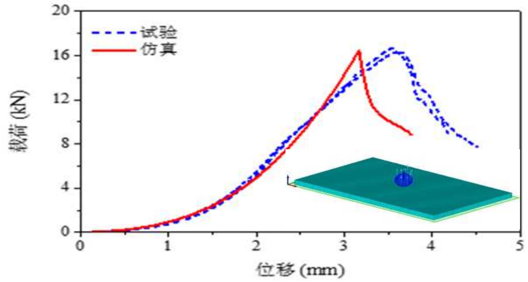
电池单体压缩行为标定

软包电池均质化模型

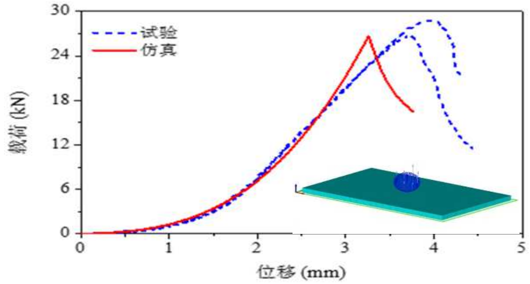
- 采用完全均质化等效，提高计算效率
- 能够准确预测不同工况下的载荷-变形响应



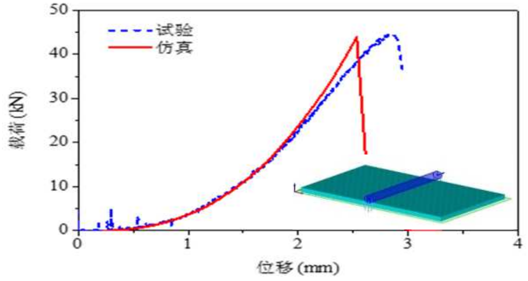
Φ13 球头挤压 ε_f=0.19



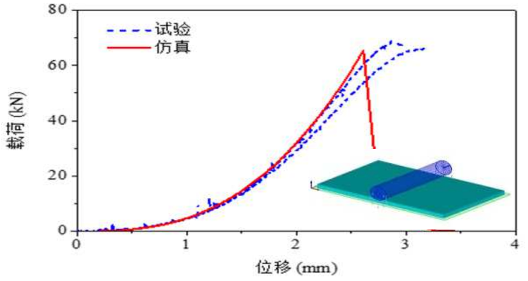
Φ20 球头挤压 ε_f=0.27



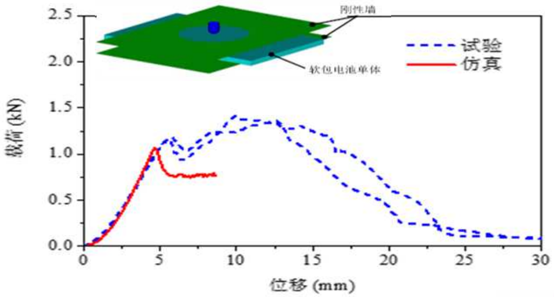
Φ31 球头挤压 ε_f=0.33



Φ13 圆柱挤压 ε_f=0.13



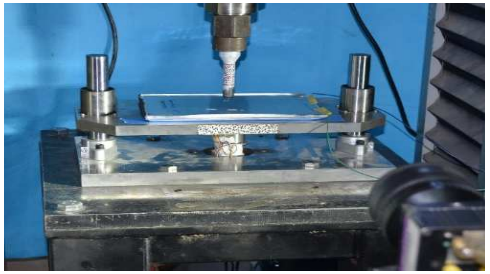
Φ26 柱面挤压 ε_f=0.16



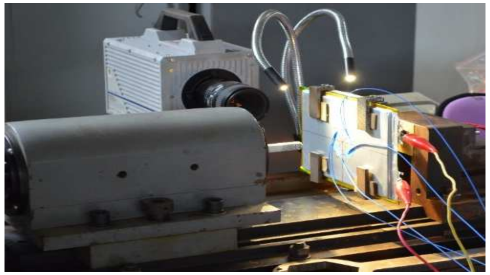
Φ13 球头穿孔 ε_f=0.08

电池冲击加载的动态效应

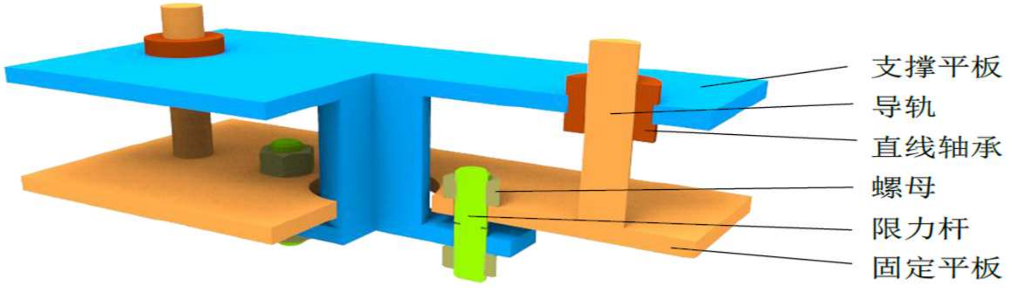
- 电池结构刚度随加载速度增加而增加
- 峰值载荷与变形极限（对应内短路发生）随加载速度增加而减小



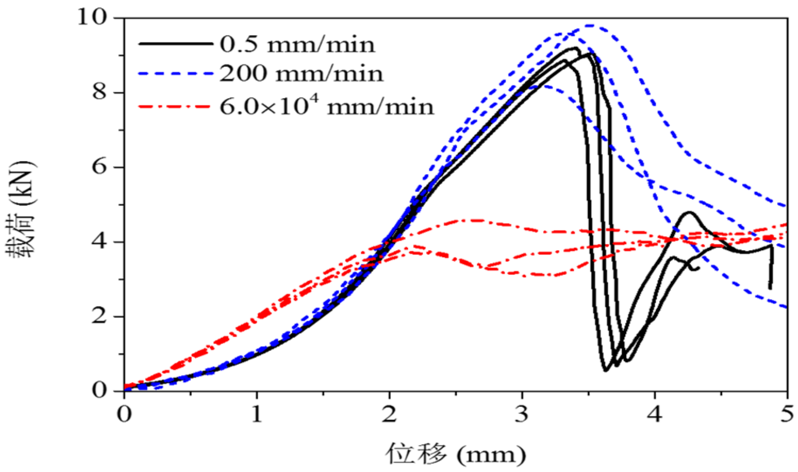
中低速加载设备



高速加载设备



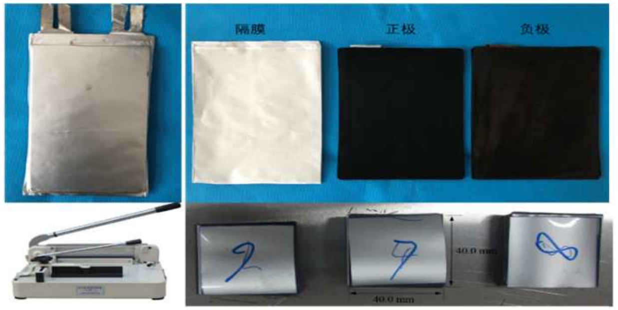
限力机构示意图



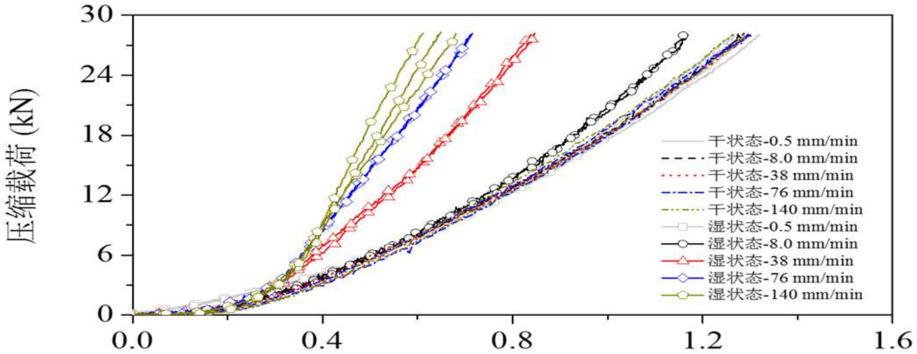
不同加载速度下载荷-位移曲线

电池结构刚度动态增强机理

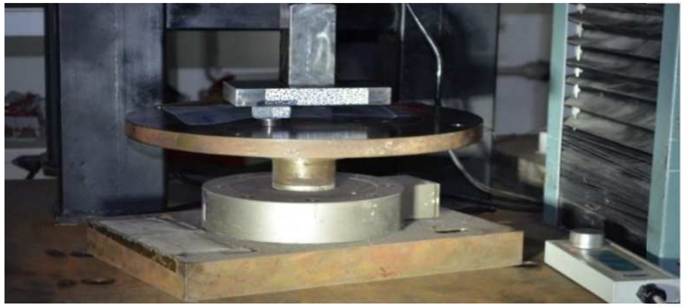
- 干燥后的组分材料压缩行为没有明显的应变率效应
- 电解液的存在对电池动态响应有显著影响



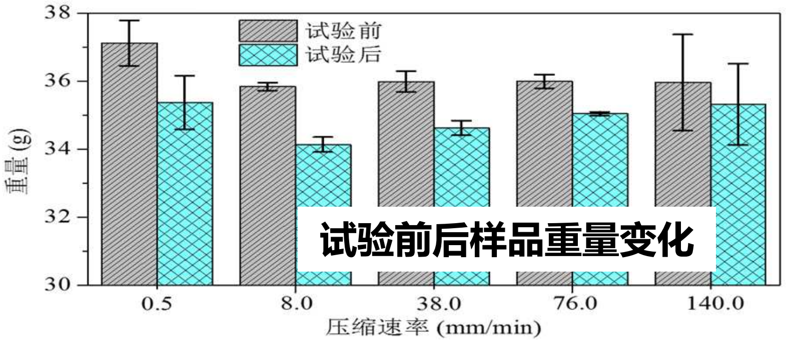
压缩样品准备



不同压缩速度下载荷-位移曲线



平面压缩试验



试验前后样品重量变化

电池结构刚度动态增强效应的解析模型

- 由电解液在多孔结构中的渗流过程导致的额外压缩载荷：

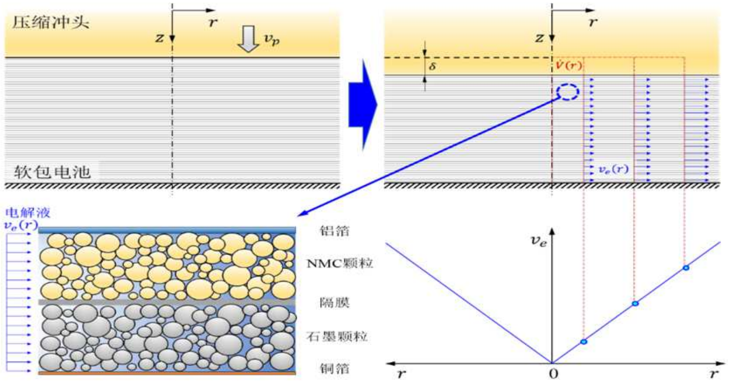
$$F_{\mathrm{electrolyte}}=\frac{\dot{E}}{v_{\mathrm{p}}}=\frac{75\mu}{4\Phi_{\mathrm{s}}^{2}D_{\mathrm{p}}^{2}}\frac{\left(1-\bar{\phi}_0\left(1-\frac{\delta}{H\bar{\phi}_0}\right)\right)^{2}}{\bar{\phi}_0^{4}\left(1-\frac{\delta}{H\bar{\phi}_0}\right)^{4}}\frac{\pi R^{4}}{H-\delta}v_{\mathrm{p}}$$

μ ：动力粘性系数 ↑

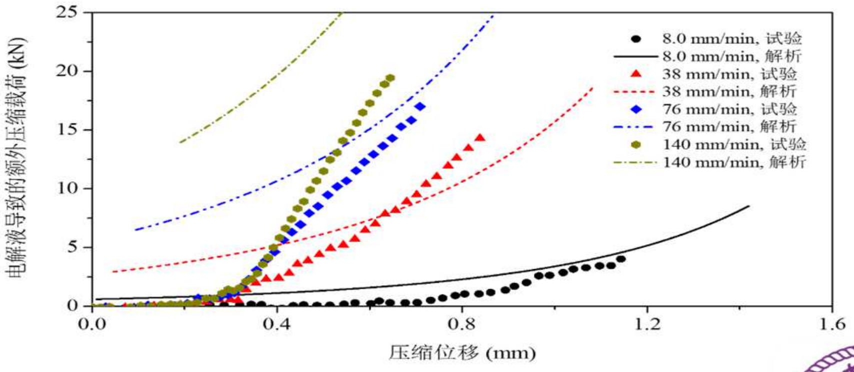
D_{p} ：颗粒平均尺寸 ↓

v_{p} ：挤压速度 ↑

→ $F_{\mathrm{electrolyte}}$ ↑



压缩过程中电解液流动假设



解析模型预测结果

II. 小结

1. 进行了大量软包电池在不同挤压工况下的实验

   探究了软包电池的力学响应规律

2. 建立了能有效预测电池单体变形与断裂的等效有限元模型

   标定了挤压工况下的力学响应及失效准则

   将模型与实际工况进行了验证

3. 探究了软包电池在不同加载速度下变形与失效机理的差异

   解析了软包电池在动态挤压下的力学响应受电解液影响的机理与规律

III.电池模组碰撞响应研究和结构优化

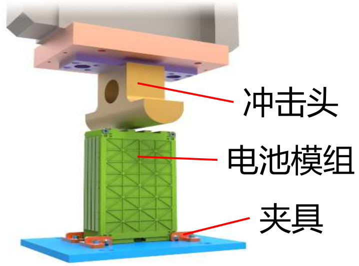
电池模组冲击测试 —— 试验设计和装置

100% SOC

① 81.6 kg
10 m/s

② 81.6 kg
7 m/s

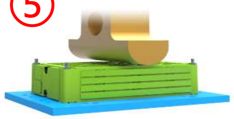
③ 40.0 kg
10 m/s



X方向，R40 圆柱形

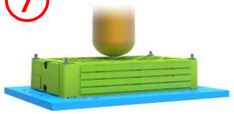
④

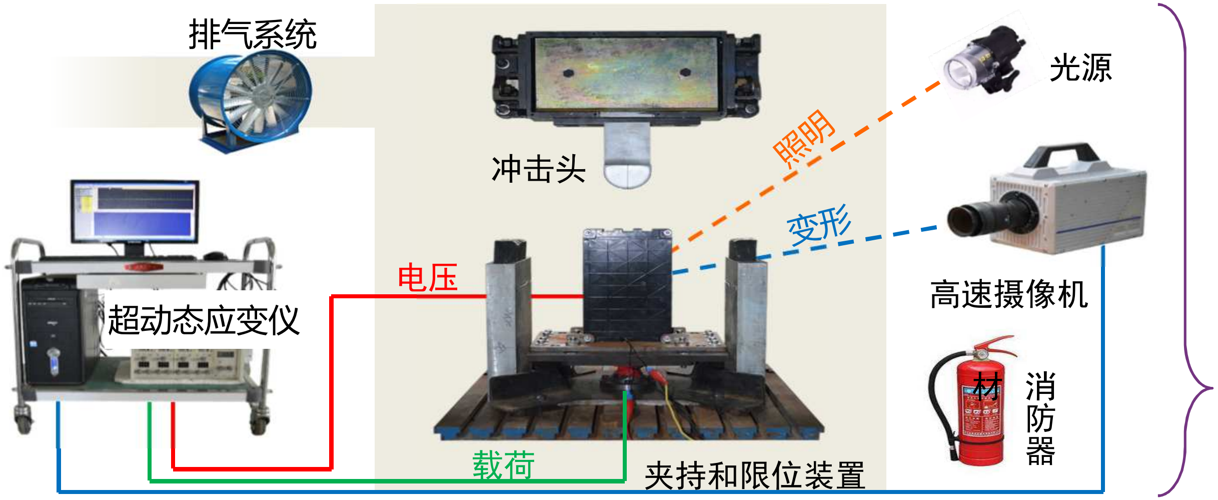
Y方向
R40 圆柱形
40.0 kg
10 m/s

⑤

Z方向
R40 圆柱形
40.0 kg
10 m/s

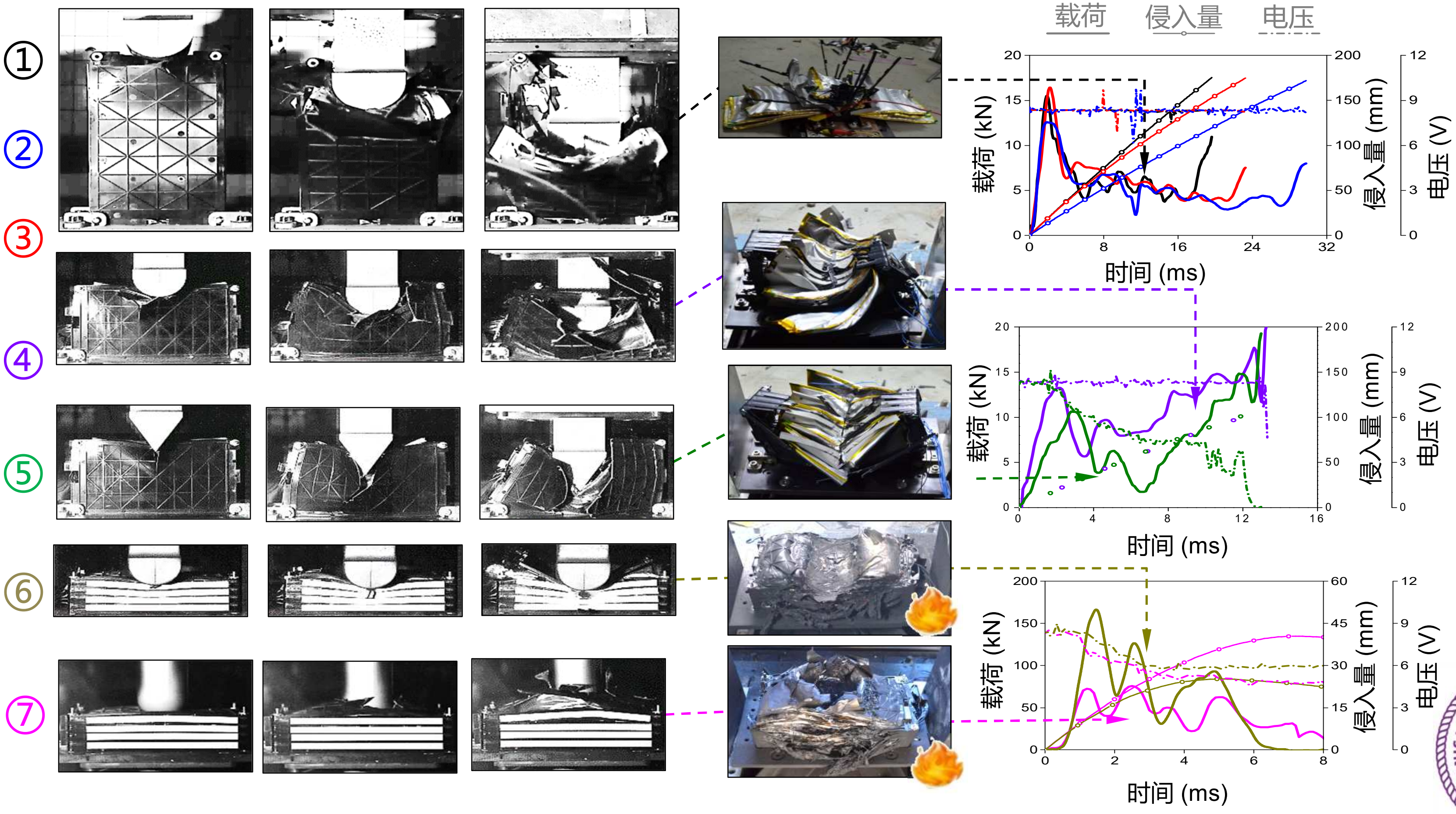
⑥

Y方向
60°楔形
40.0 kg
10 m/s

⑦

Z方向
R40 半球形
40.0 kg
10 m/s

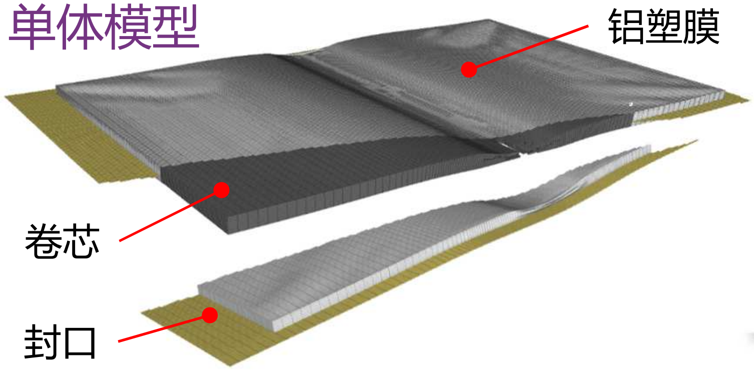


电池模组冲击测试 —— 试验结果



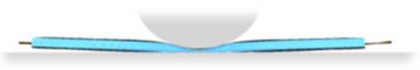
电池单体测试与表征 —— 单体模型的建立和验证

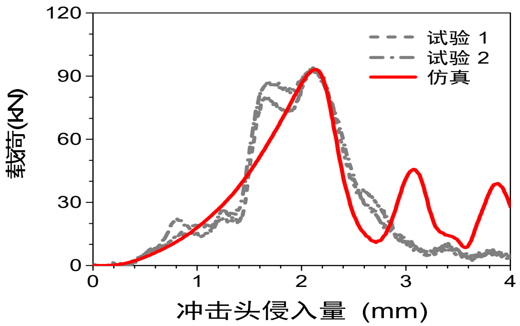
单体模型

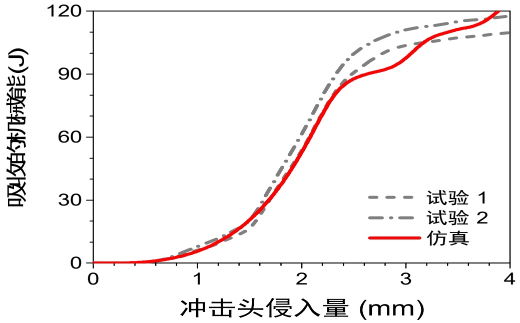


卷芯的变形和失效

单体的变形（侧视）

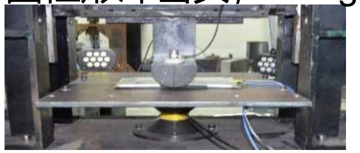






模型验证试验

R40 圆柱形冲击头，46 kg，3 m/s



模型精度的主要评判指标

- ➢ 峰值载荷：冲击严重程度
- ➢ 吸能特性：耐撞性评价关键
- ➢ 变形模式：响应是否合理

与试验结果平均值相差 0.8%

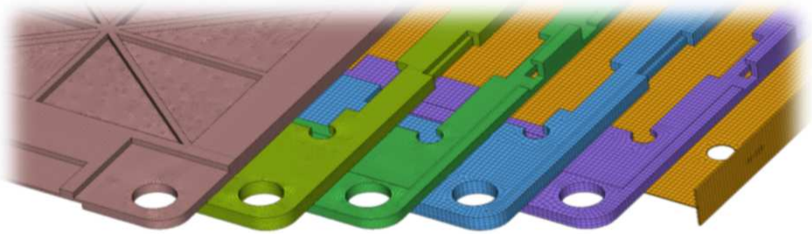
峰值载荷处与试验偏差 6.6%

单体两端上翘、卷芯被切断

主要误差来源

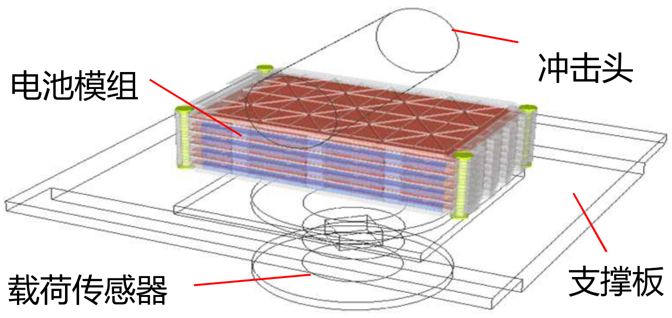
- ➢ 均质化的卷芯和铝塑膜
- ➢ 被忽略掉的材料属性
- ➢ 接触算法和参数的选用

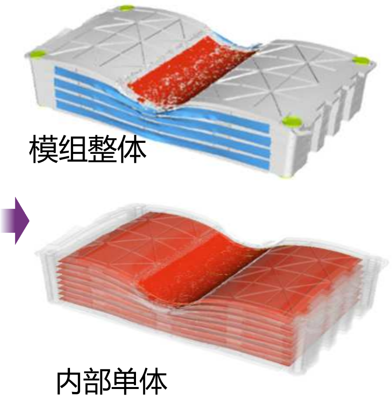
电池模组模型建立与验证 —— 详细结构模型



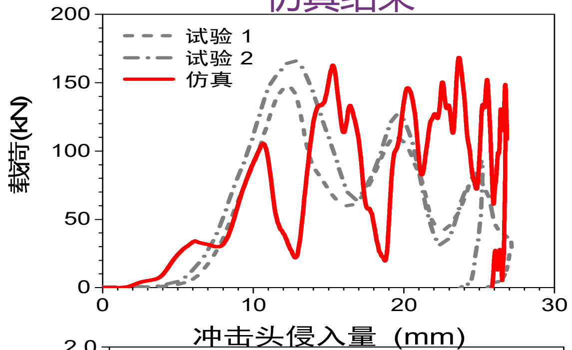
其他组件	网格尺寸	网格数量
电池卷芯	0.92 ~ 3.07	140,288×8
电池铝塑膜	0.92 ~ 3.08	42,189×8
紧固螺栓	1.25 ~ 2.07	861×4

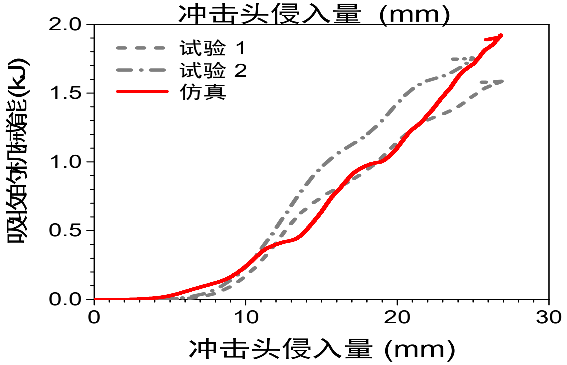
模组有限元模型





仿真结果



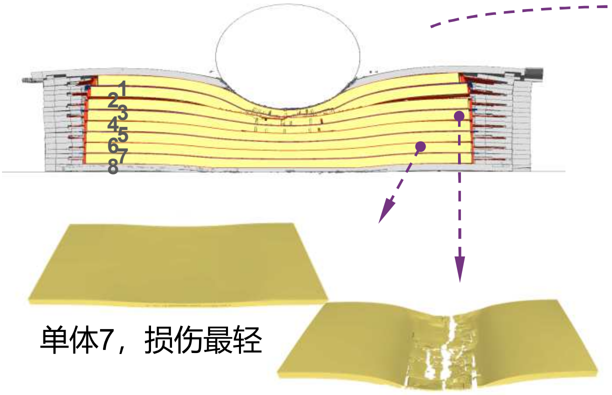


仿真结果与试验对比

- 峰值载荷：6.7% ☺
- 最大侵入量：2.3% ☺
- 吸收机械能：11.8% ☺

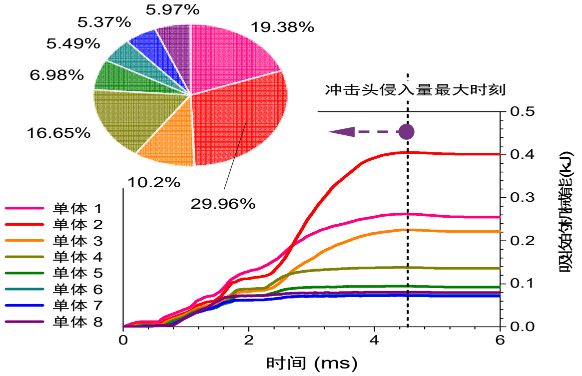
电池模组模型建立与验证 —— 内部损伤分析

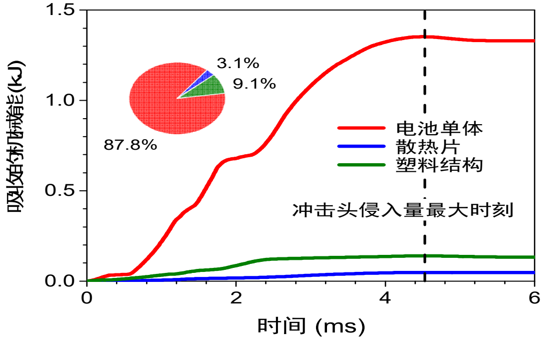
电池模组仿真

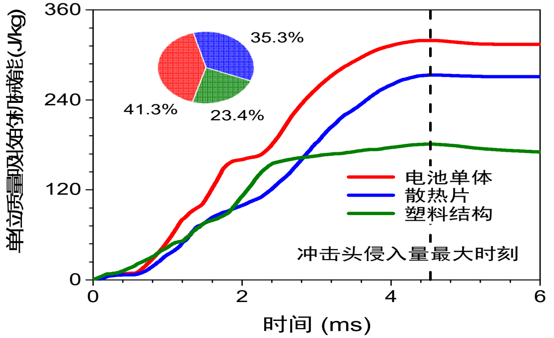


单体7，损伤最轻

单体2，损伤最重



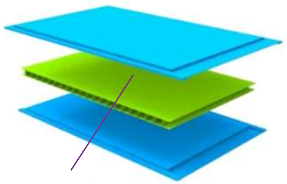




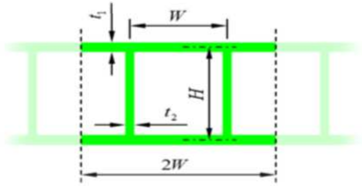
模组的内部损伤特点

- ➢ 单体是模组中承载的主体
- ➢ 顶部单体受损远甚于其他的
- ➢ 散热片具备吸能潜质

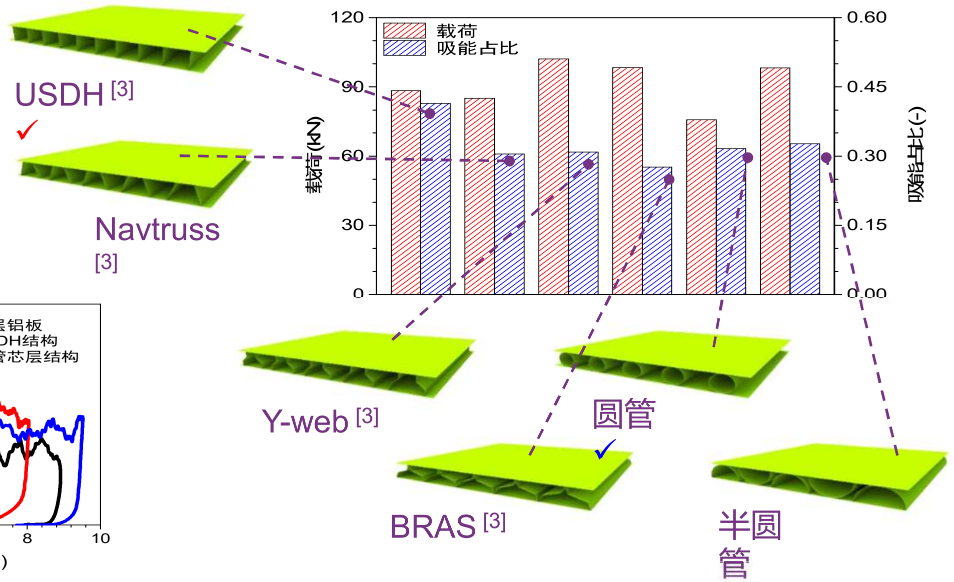
局部结构优化设计 —— 不同构型的对比

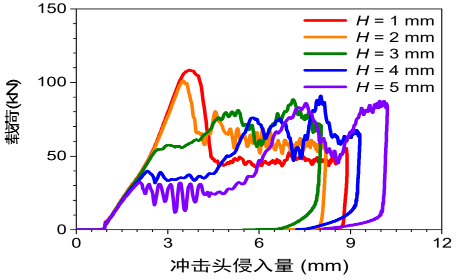


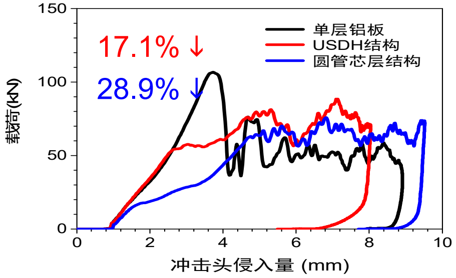
三明治板

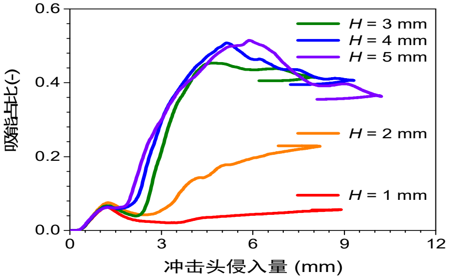


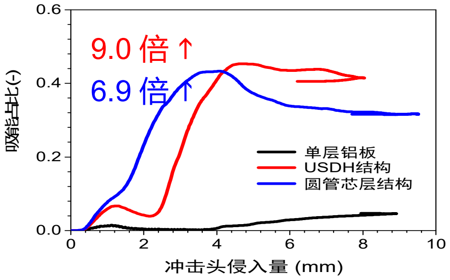
$$m^* = \frac{2(2Wt_1 + Ht_2)L\rho}{2WL} = \left(2t_1 + \frac{H}{W}t_2\right)\rho$$
$$= 3t\rho$$

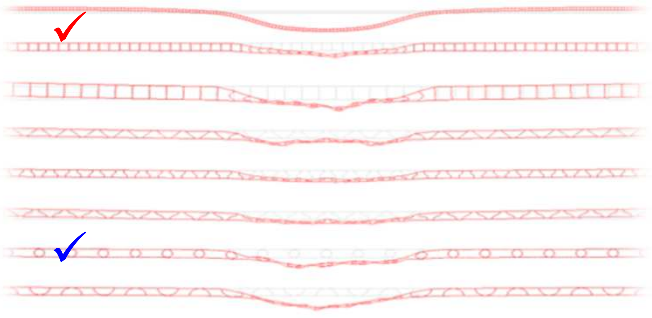












[3] Lee Y. Massachusetts Institute of Technology, 2005.

III. 小结

1. 对电池模组在冲击载荷的响应进行测试
   分析了模组的破坏失效模式和热失控风险

2. 开发了电池模组的冲击仿真模型
   用于分析模组变形和进行损伤预测

3. 提出了电池模组结构改进的优化思路
   分析了电池模组主要部分的承载和吸能贡献
   通过改变散热片结构提高电池模组的耐撞性

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Lightweight Materials & Structures
轻量化材料与结构

Impact testing of materials/joints

Prediction of material/joint deformation and failure

Impact failure and protection of traction batteries

Analysis and design of energy absorbing structures

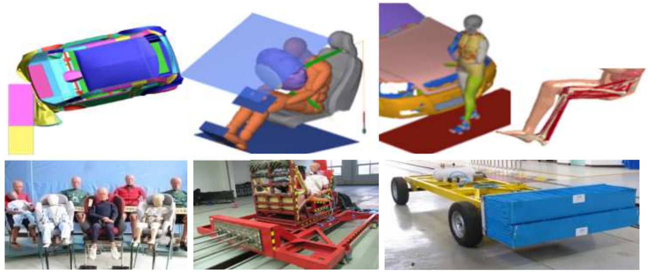
Injury Biomechanics and Prevention
生物损伤力学与防护

Injury biomechanics and injury mechanism of human bodies under impact

Occupant safety and adaptive restraint system

Protection of vulnerable road users

Development of crash dummy models



谢谢大家！

清华大学

汽车安全与节能国家重点实验室

汽车安全与轻量化团队