

# Abuse characterization and simulation of battery cells and cell arrangements

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*16<sup>th</sup> LS-DYNA Forum 2022*

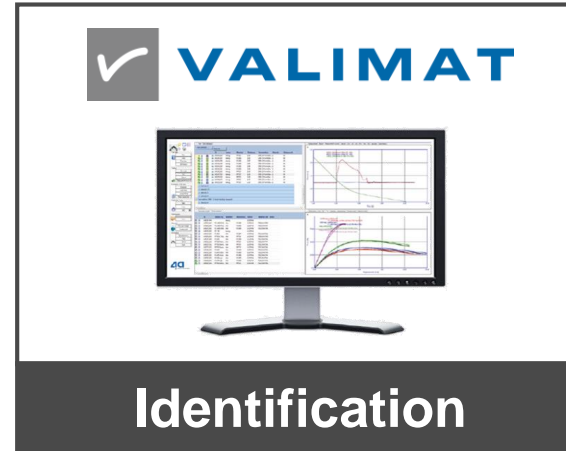
# Testing and Identification



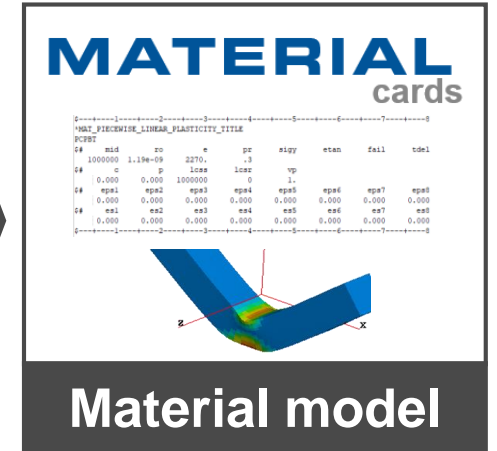
Material



Testing



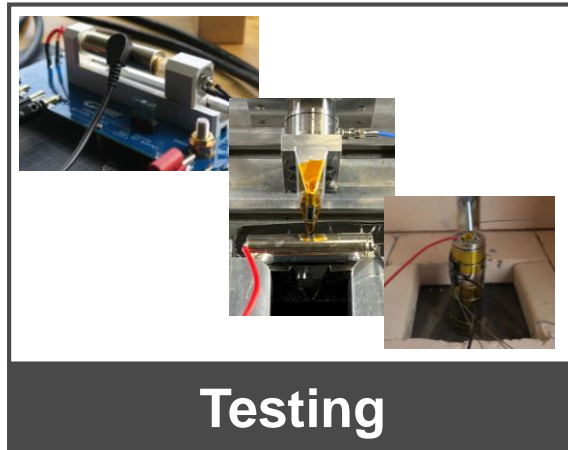
Identification



Material model



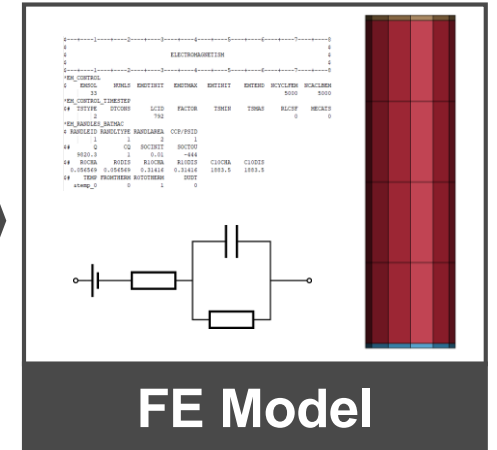
Battery Cell



Testing



Identification



FE Model



# Multiphysics of battery cells

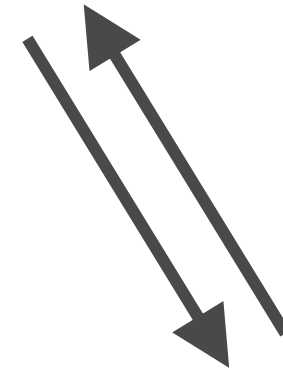
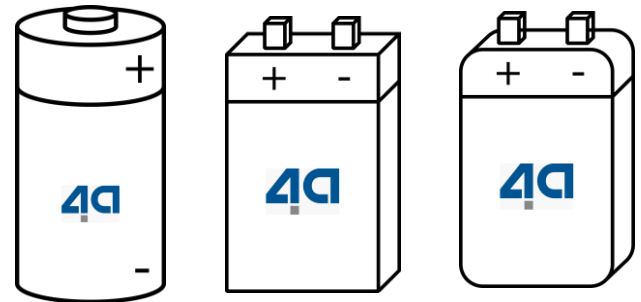
**Thermal**

$\vartheta$   
 $\lambda$   
 $\underline{q}$   
 $T$   
 $p$   
 $k$

$T$   
 $x$   
 $k_1$   
 $k_2$   
 $k_3$

**Mechanical**

$T_{11}$  in MPa  
 $t$  in s  
 $F$   
 $\underline{\underline{\epsilon}}$   
 $u$   
 $\underline{\underline{T}}$   
 $\underline{\underline{\sigma}}$

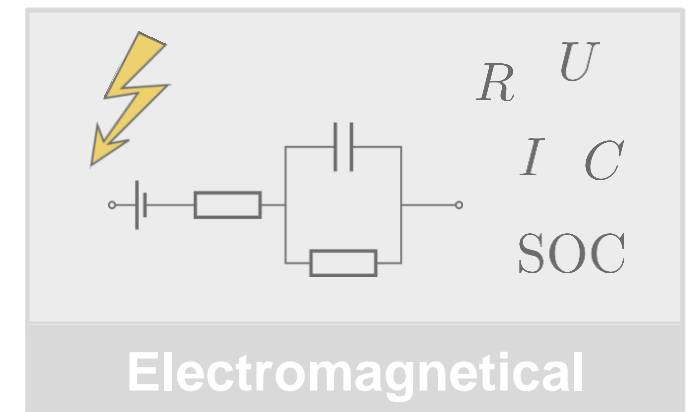
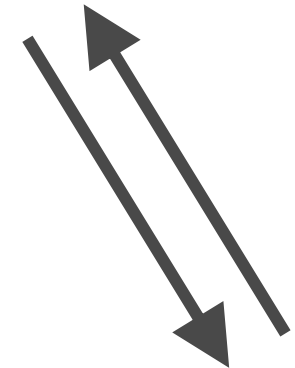
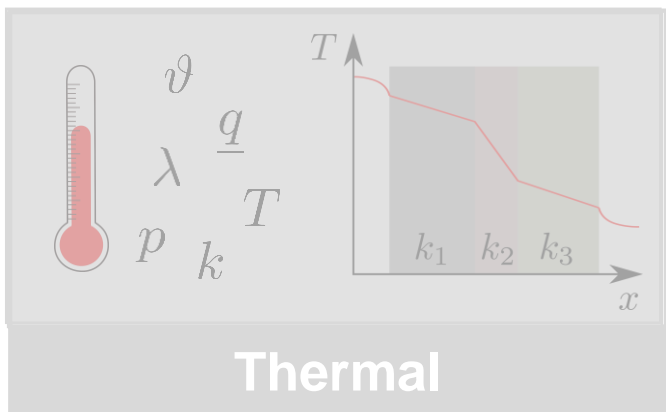
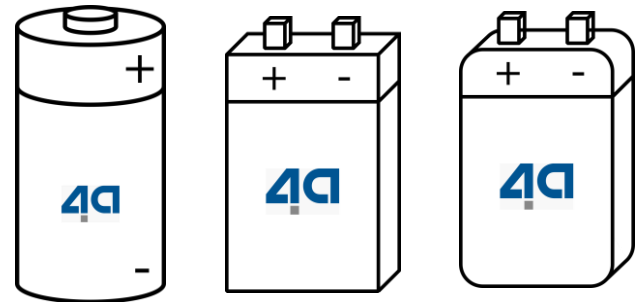
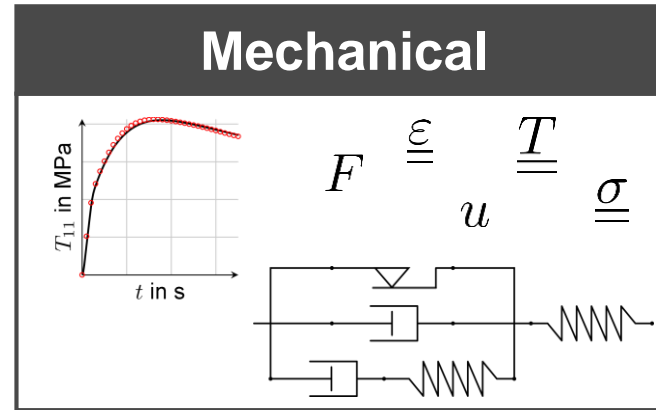


**Electromagnetical**

$R$   
 $U$   
 $I$   
 $C$   
 SOC

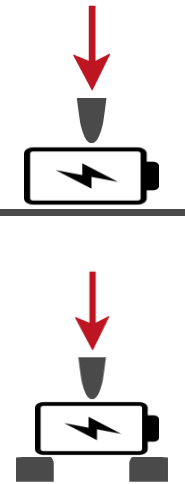
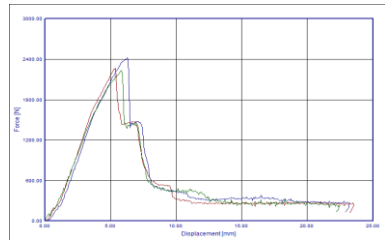
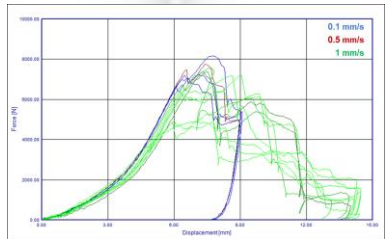


# Multiphysics of battery cells

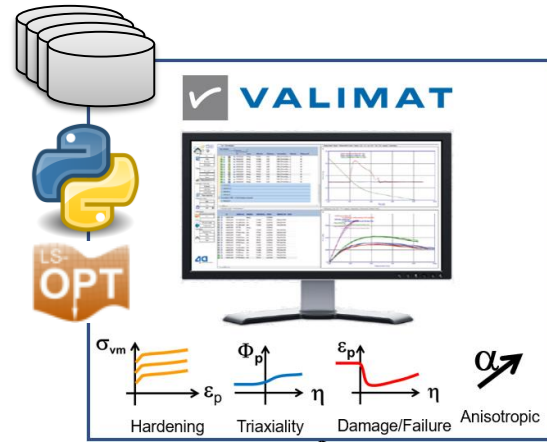


# Creation of the mechanical simulation model with VALIMAT® & LS-DYNA

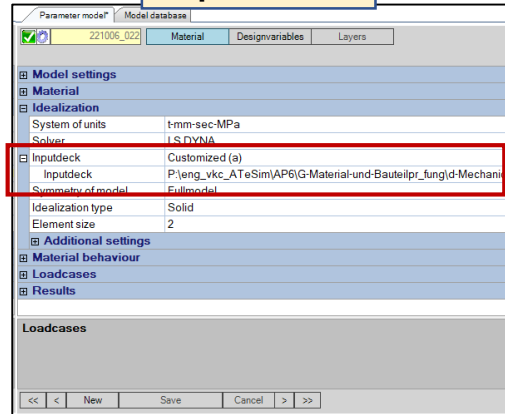
Testing



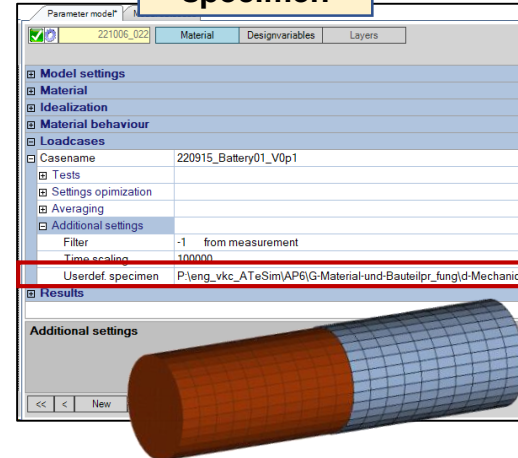
Optimization of material parameters for single battery cell



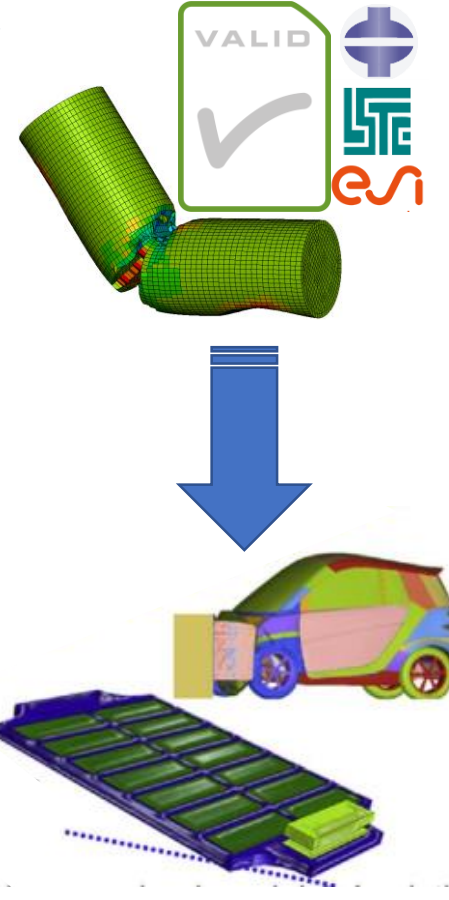
User defined input decks



User defined specimen



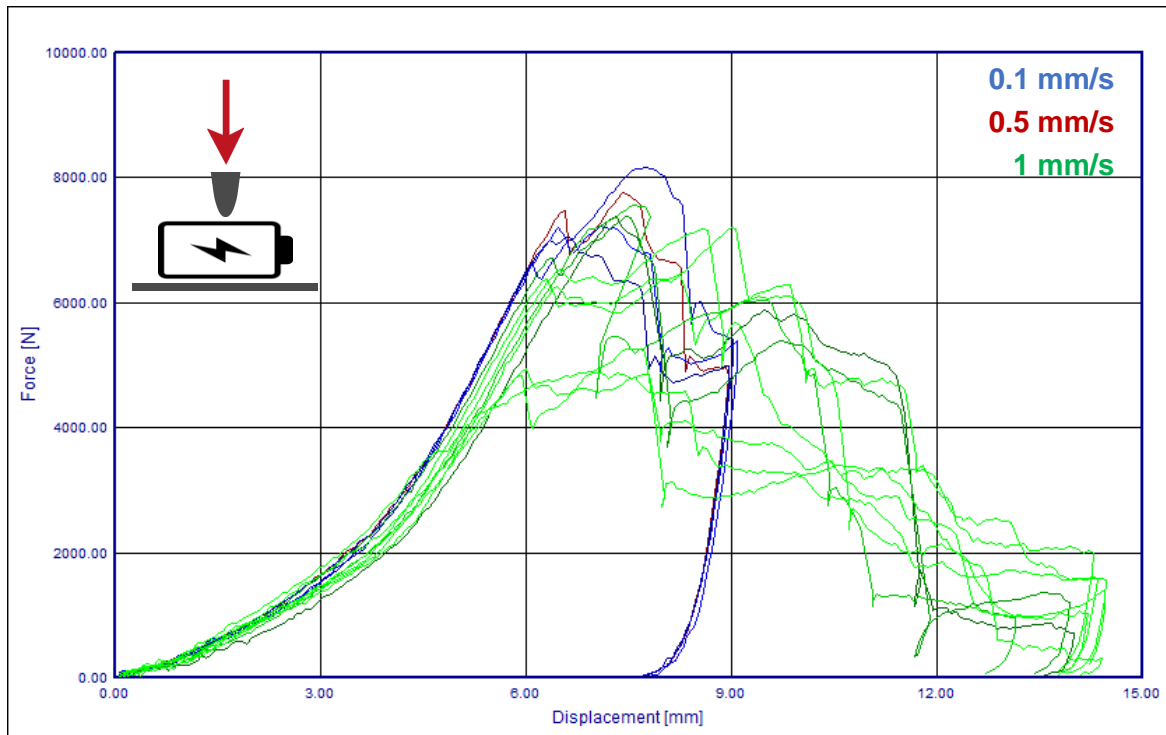
Validation and Implementation to bigger models



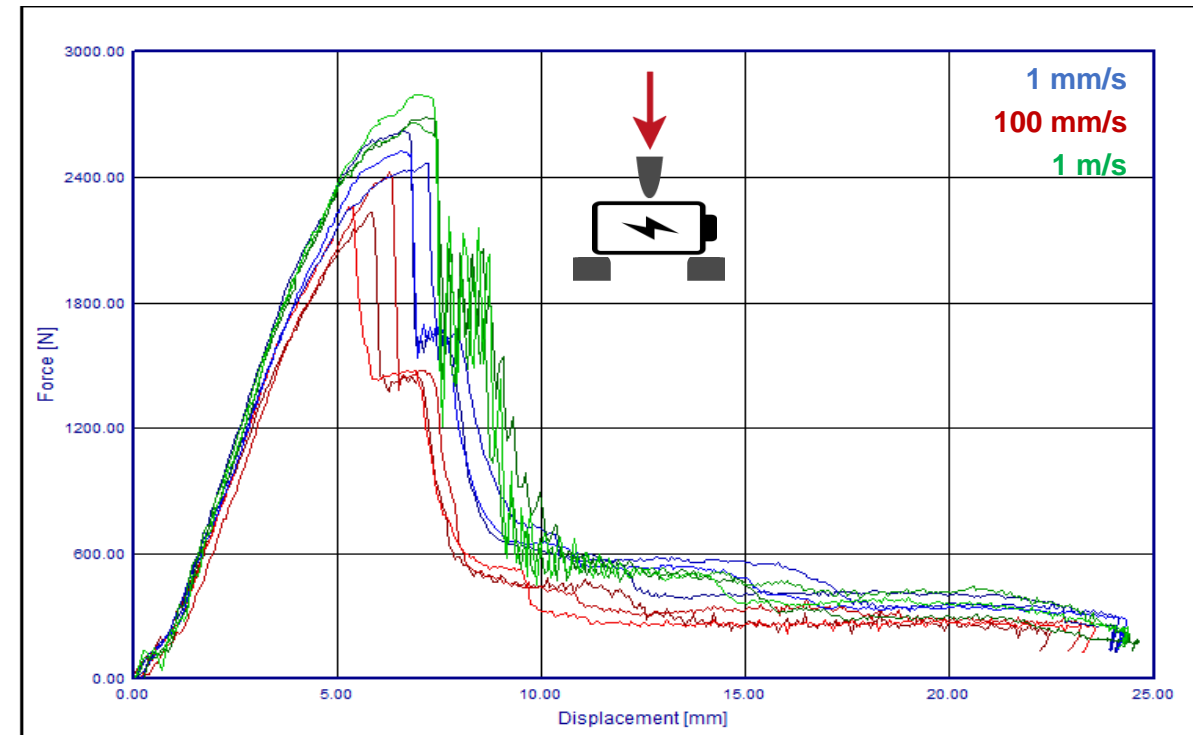
Source: Zhu et. al; „A review of safety-focused mechanical modeling of Commercial lithium-ion batteries“, Journal of Power Sources 378 (2018) 153-168

# Mechanical Test results overview - 18650 battery cell

## Plane strain indentation



## 3 point bending



- Remark: Different test setup used for the 1mm/s (max penetration displacement differs).

# FE model overview – 18650 battery cell

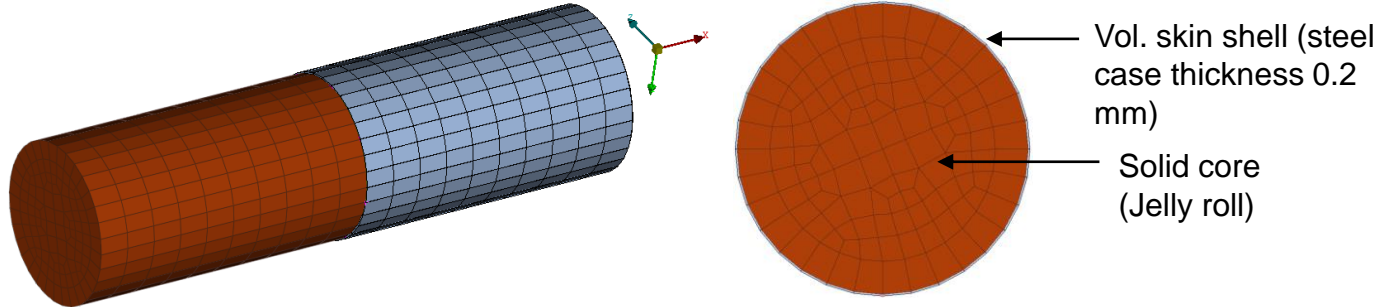
## Geometry

- Cylindrical battery cell 18650
- 65mm x 18mm x 18mm



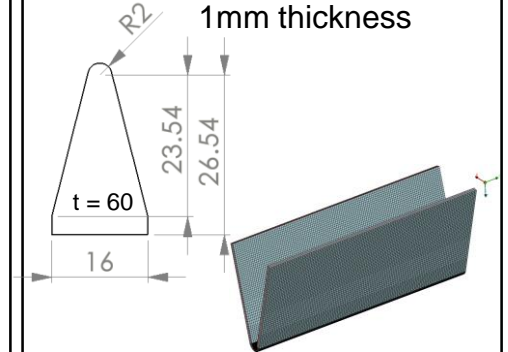
## Battery cell mesh

- Mesh:
  - Jelly roll: Solid, ELFORM 1, approx. size 2 mm, number of elements 2400
  - Steel case: Vol. shell skin, ELFORM 16, thickness 0.2 mm, number of elements 880



## Intruder mesh

- Intruder:
  - Fin 2mm radius
  - Shell rigid body, 1mm thickness

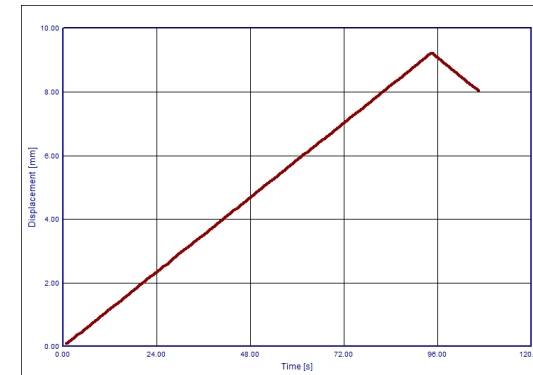


## Material models

- Material models:
  - Jelly roll: \*MAT\_CRUSHABLE\_FOAM (MAT063)
  - Steel casing: \*MAT\_PIECEWISE\_LINEAR\_PLASTICITY\_TITLE (MAT024)

## Load

- \*BOUNDARY\_PRESCRIBED\_MOTION\_RIGID\_ID:
  - Displacement curve from plane crush battery test (VALIMAT® DB)



## Contact definition:

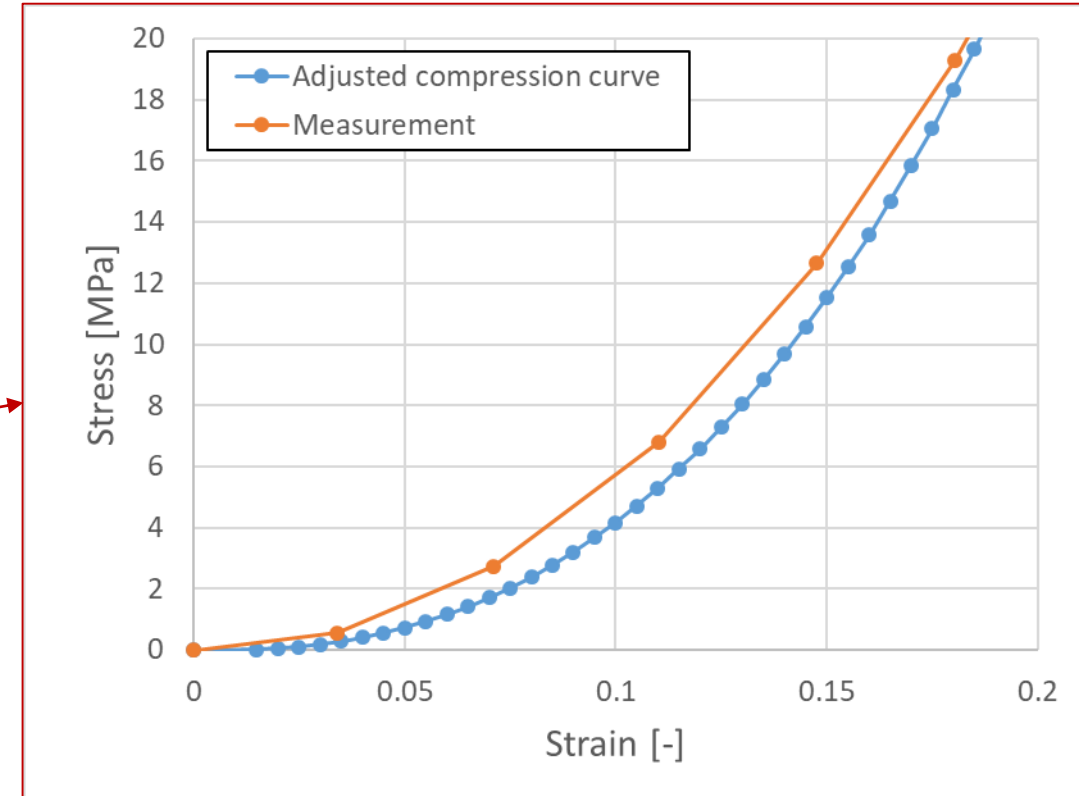
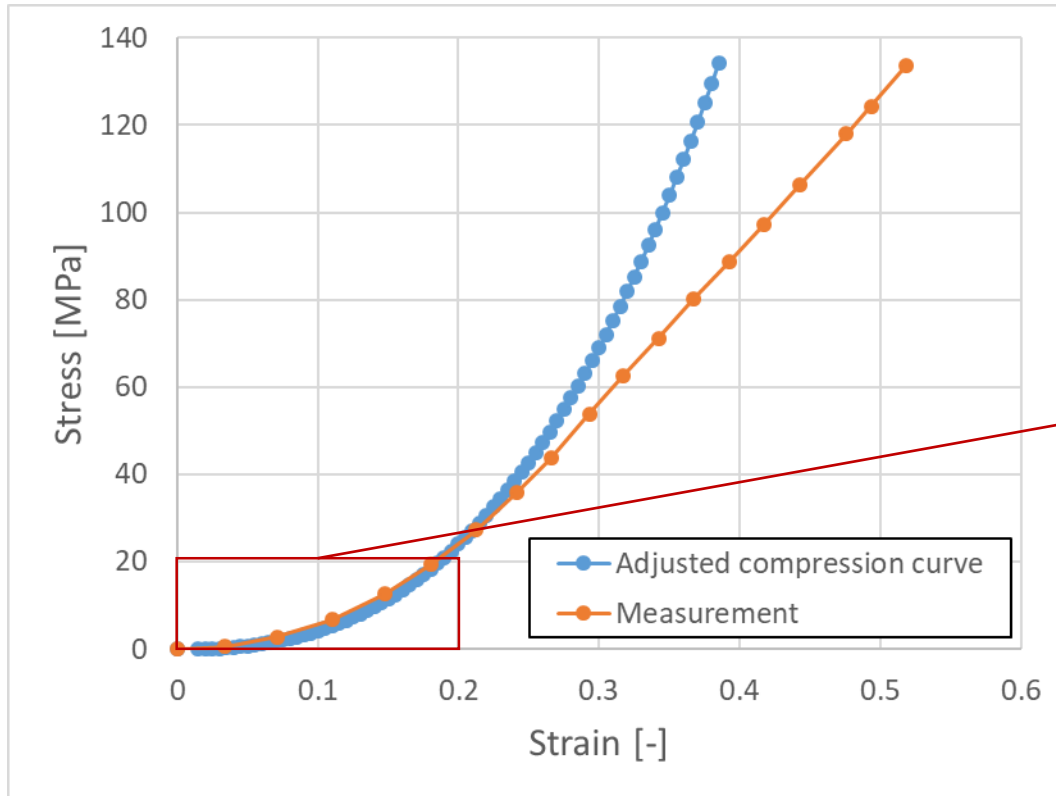
- (\*CONTACT\_AUTOMATIC\_SURFACE\_TO\_SURFACE with SOFT=1):
- Fin - Steel\_case
  - Fin - Jelly\_roll
  - Steel\_case – Jelly\_roll

## Contacts

## Solver

- LS-DYNA R13.1.1

# Crushable foam MAT063 compression curve optimization



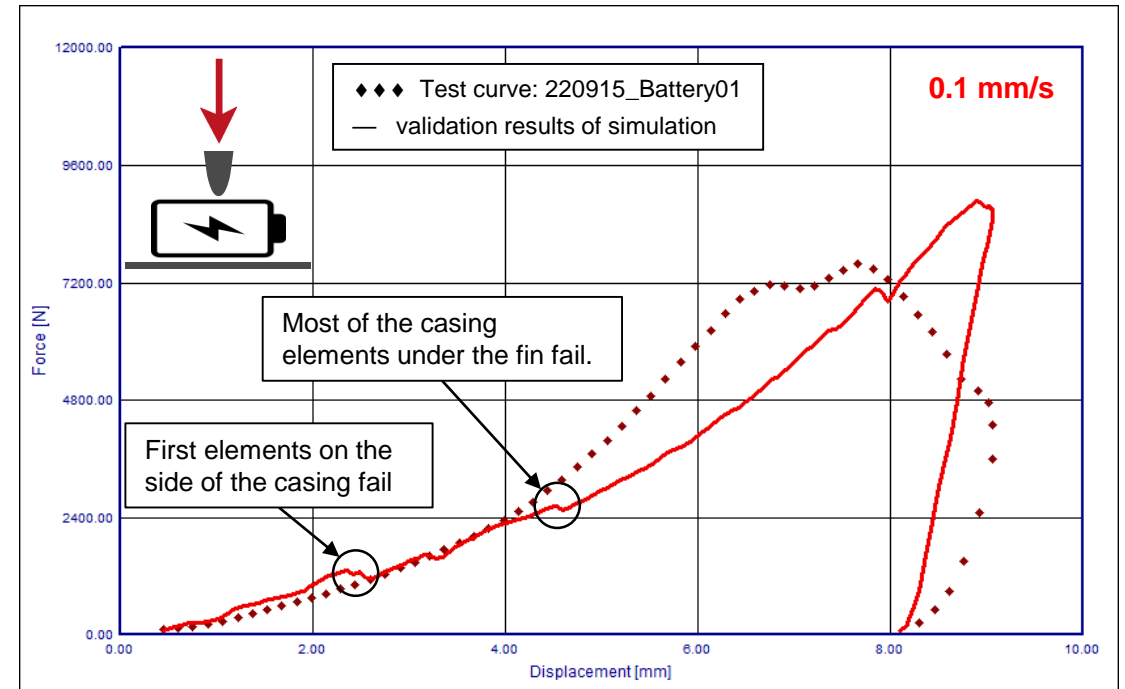
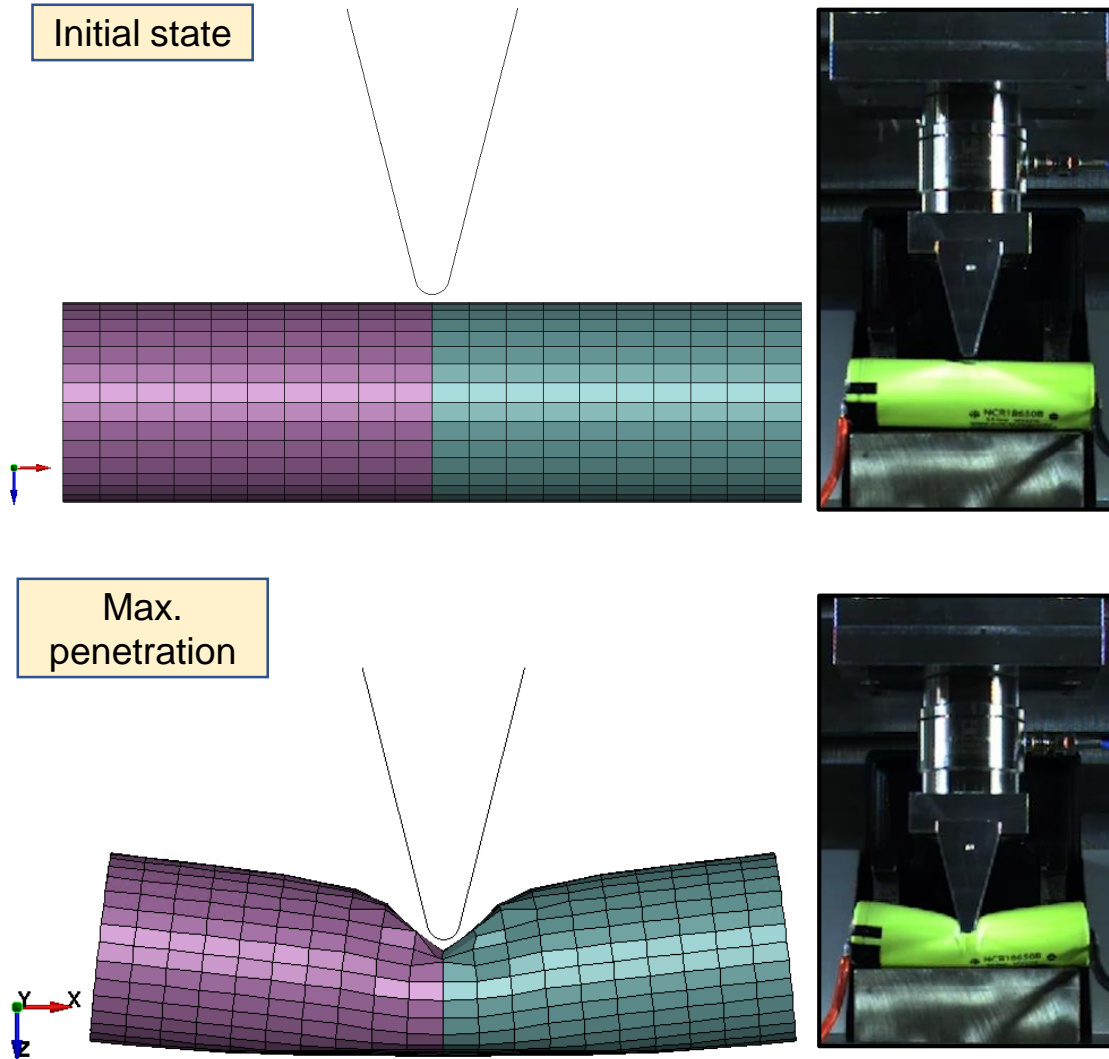
Initial compression curve for start of optimization taken from literature (orange curve).  
Optimized compression curve identified via reverse engineering (blue curve).

Source: Sahraei et. al; „Modelling and short circuit detection of 18650 Li-ion cells under mechanical abuse conditions“, Journal of Power Sources 220 (2012) 360-372



# Analysis results - 18650 battery cell

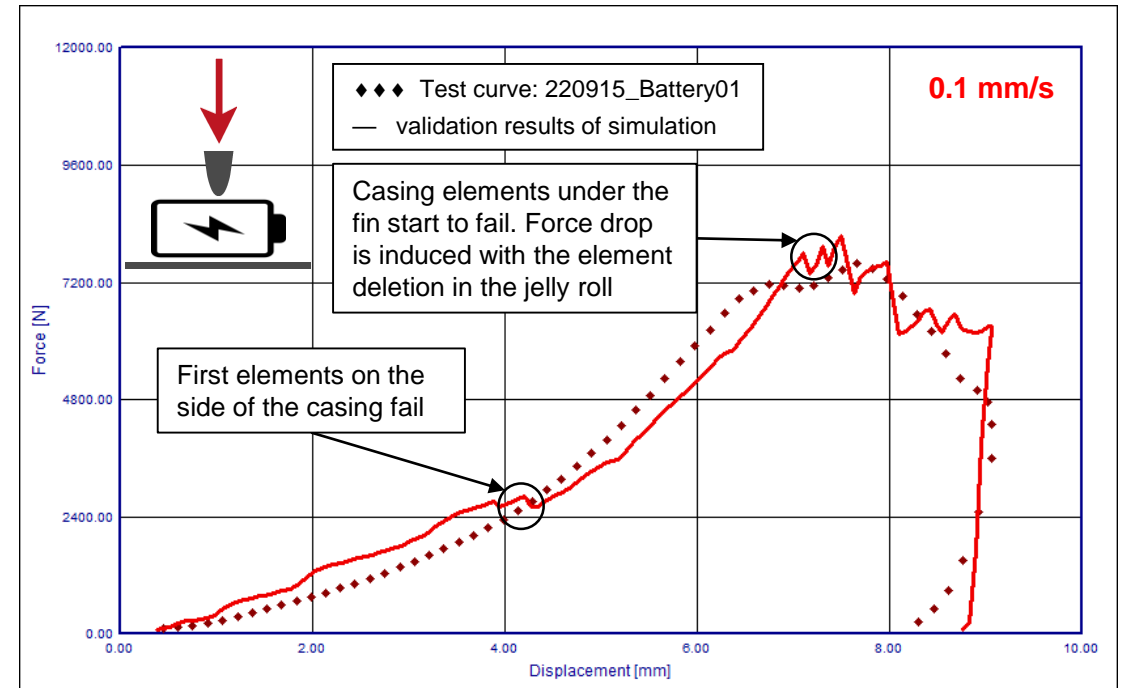
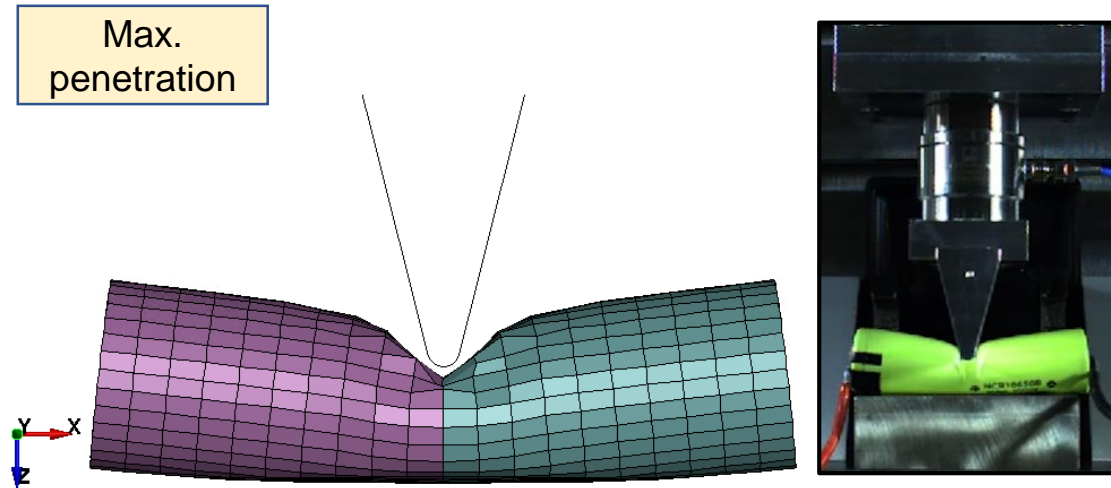
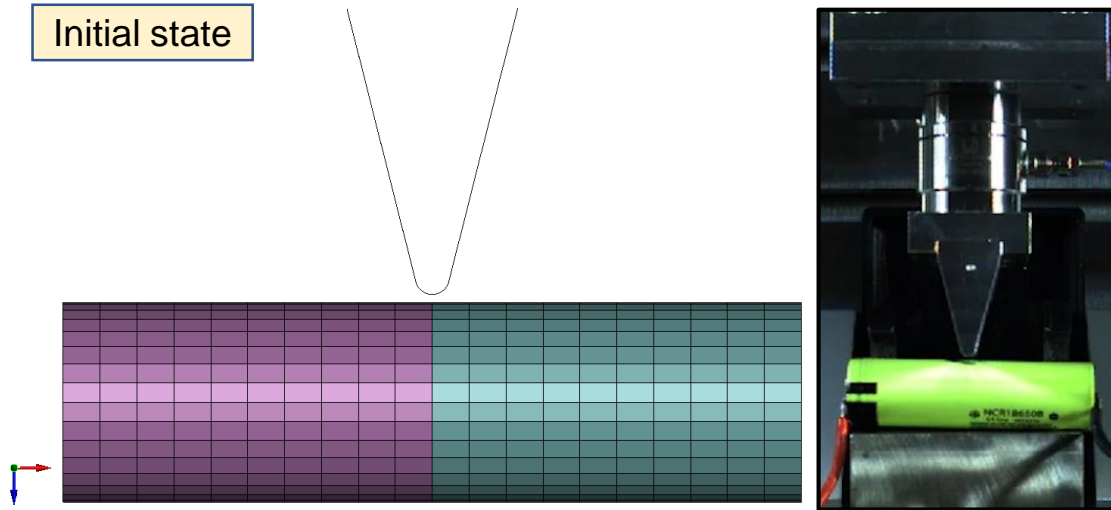
Plane-crush, default MAT024 & MAT063 (based on literature values)



- Plane-crush mechanical simulation model shows similar stiffness up to 4 mm displacement. After this point most of the fin contact switches from the battery casing to the jelly roll of the battery.
- Densification is underestimated → adjustment of compression curve required

# Analysis results - 18650 battery cell

Plane-crush, adjusted MAT024 & MAT063+MAT\_ADD\_EROSION



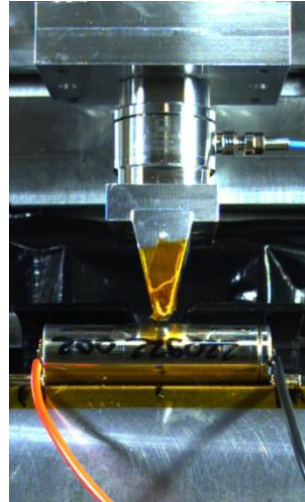
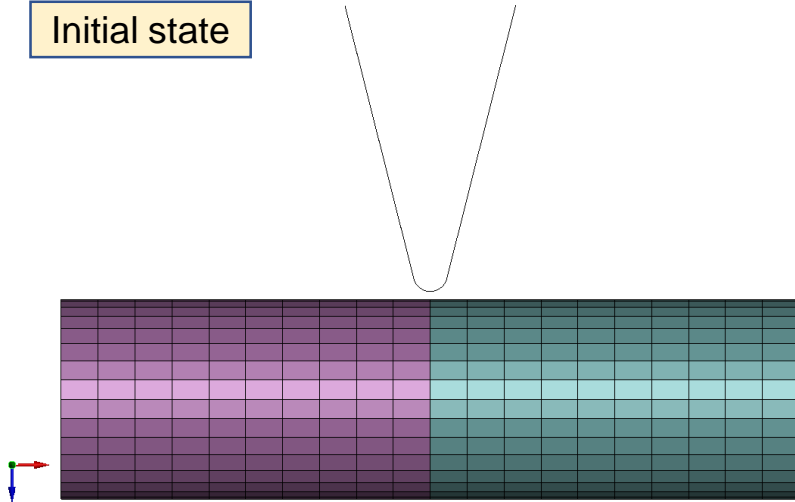
- Element deletion in the MAT063 allowed simulation model to follow the measurement force-displacement curve more accurately.
- MAT\_ADD\_EROSION (MXPRES maximum pressure at failure criterion)

```
*MAT_ADD_EROSION_TITLE
22100502_vkc_custom_18650-JellyRoll_T23_MAT063_MPa
$ MID EXCL MXPRES MNEPS EFFEPS VOLEPS NUMFIP NCS
2000000 50 0.7 1.
$ MNPRES SIGP1 SIGVM MXEPS EPSSH SIGTH IMPULSE FAILTM
0.55
```

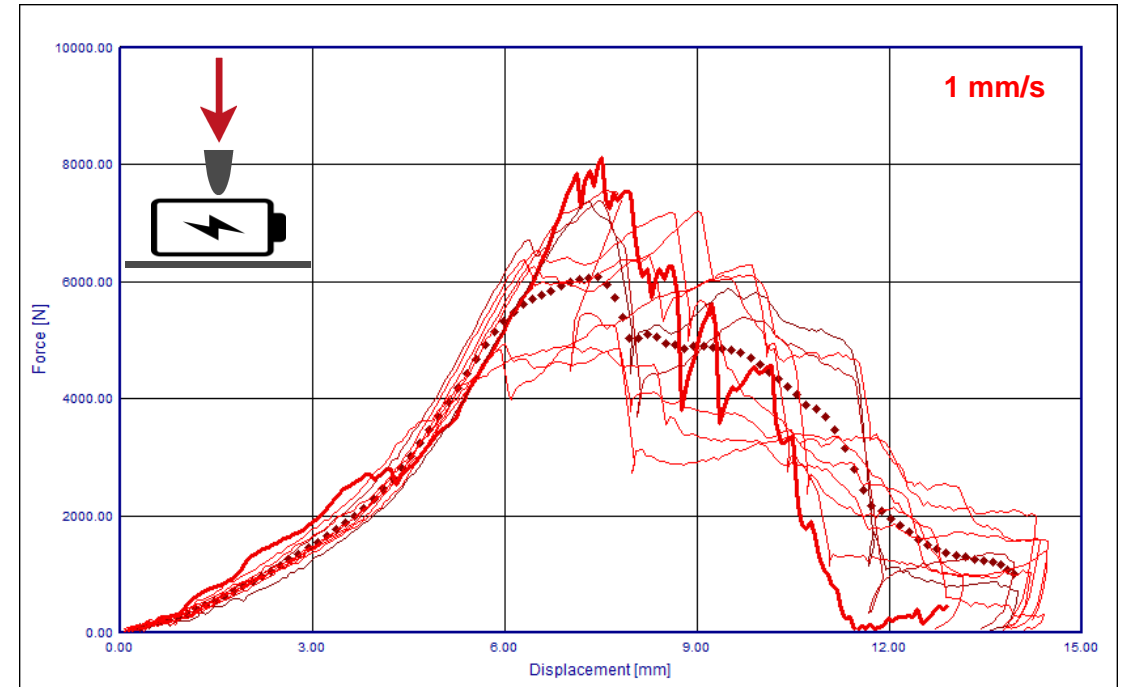
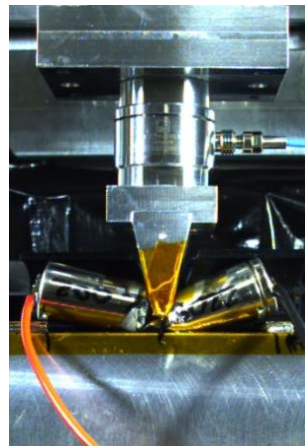
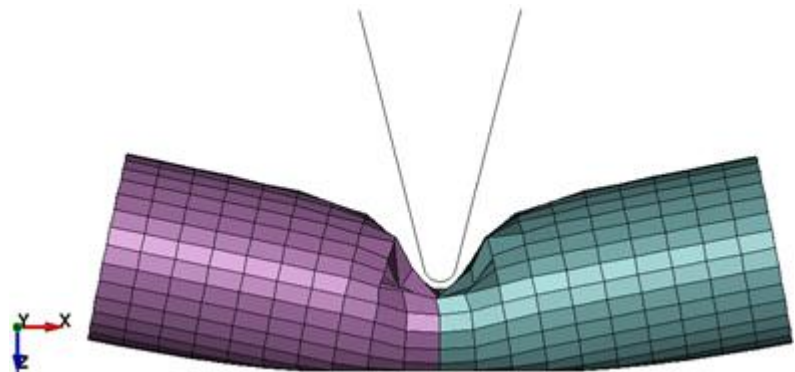
# Analysis results - 18650 battery cell

Plane-crush, adjusted MAT024 & MAT063+MAT\_ADD\_EROSION

Initial state



Max. penetration

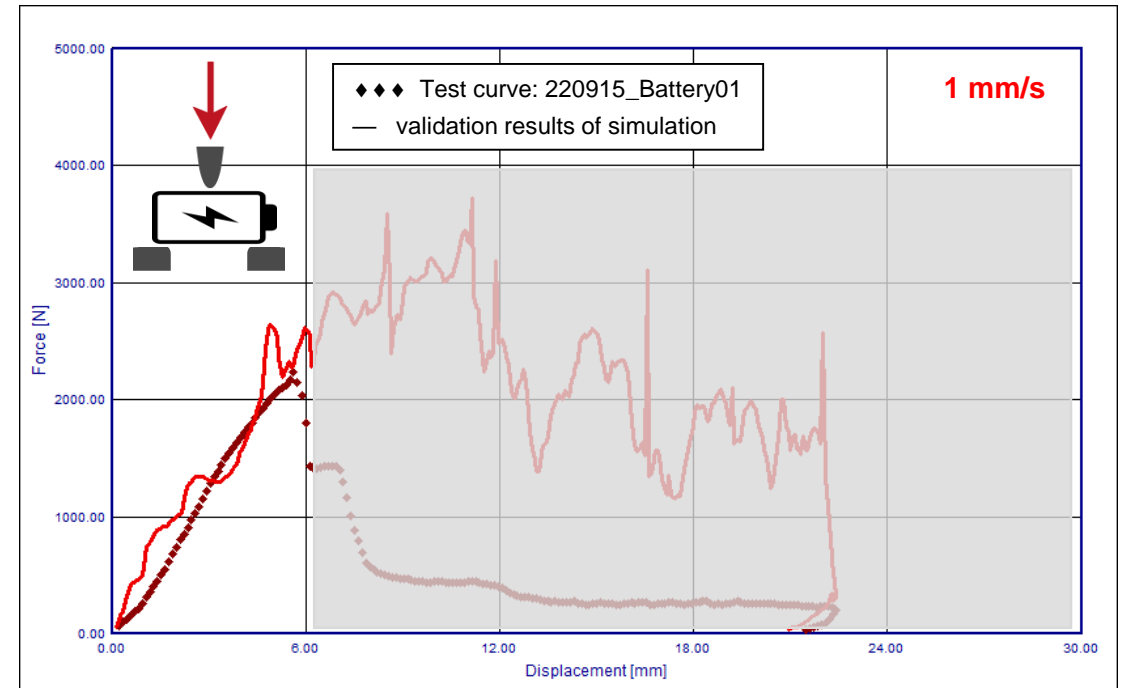
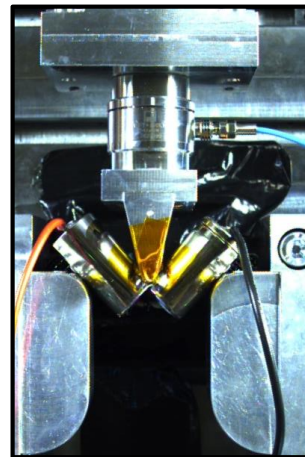
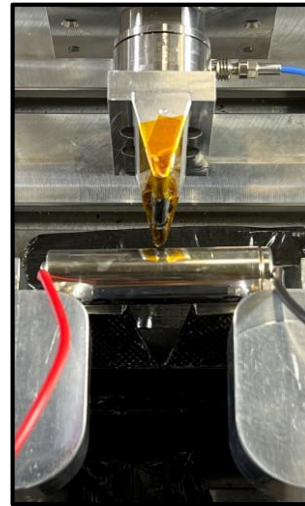
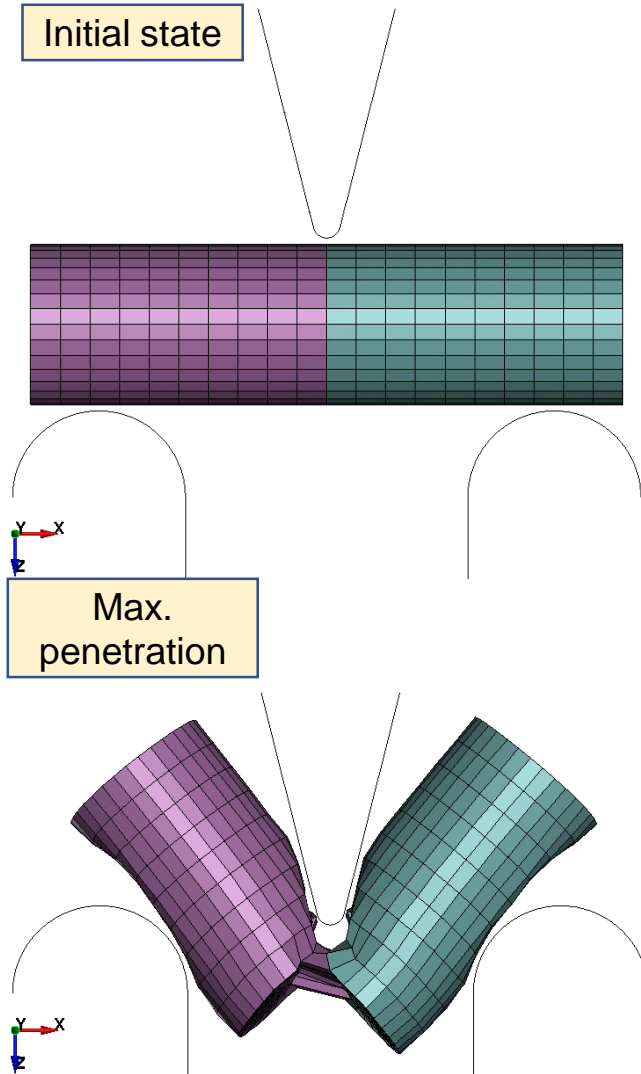


- ◆◆◆ Mean value curves testing
- test curves
- validation results of simulation

- Failure behaviour at higher intrusion also well predicted

# Analysis results - 18650 battery cell

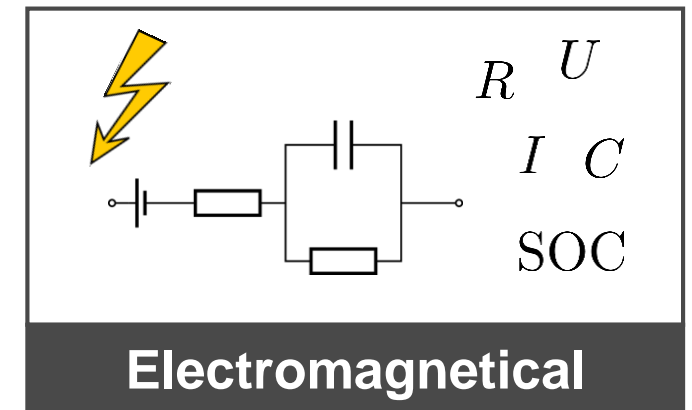
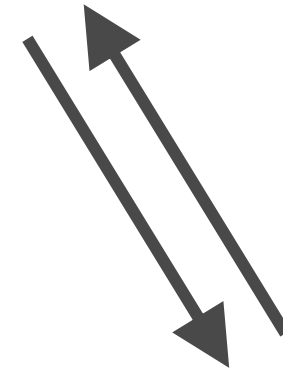
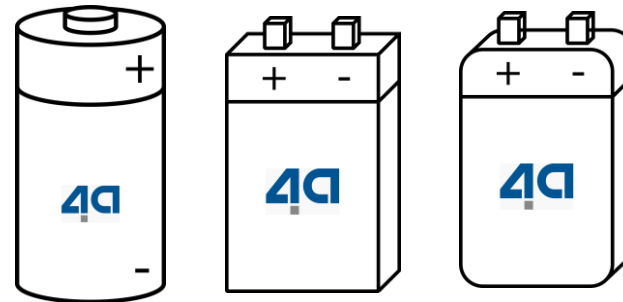
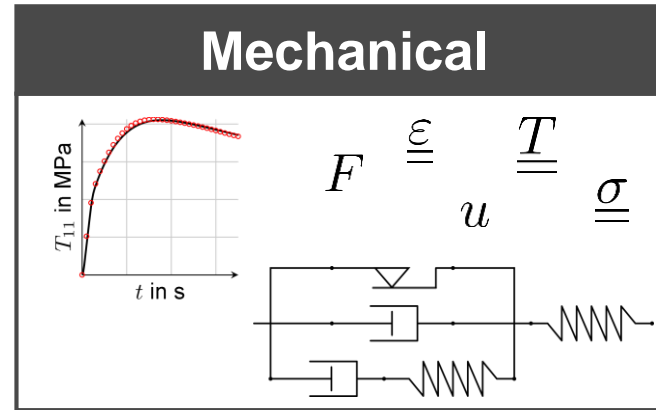
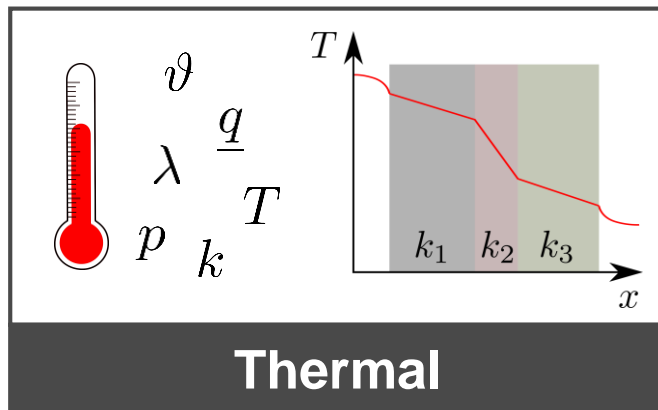
3-point bending, adjusted MAT024 & MAT063+MAT\_ADD\_EROSION



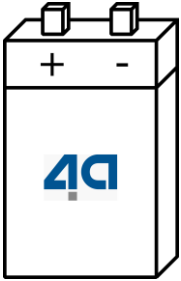
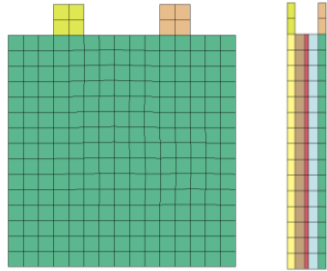
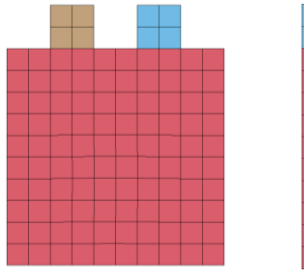
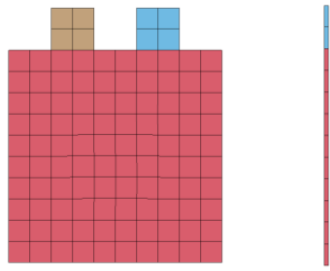
Same model used for 3 point bending load case:

- good representation of qualitative failure mode
- further optimization on post fracture behaviour required
- Work in progress...

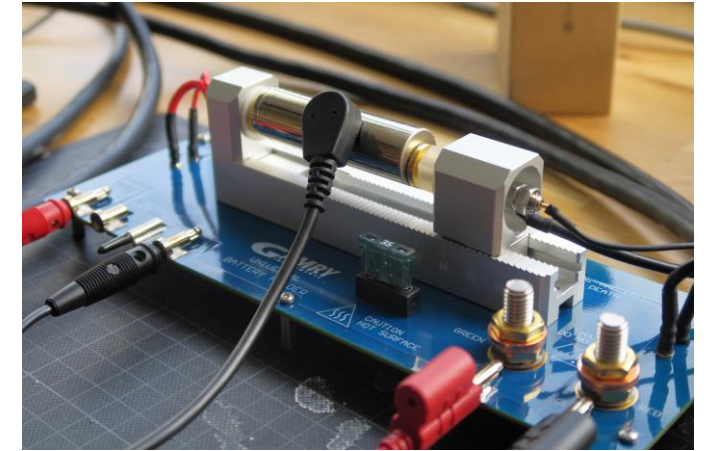
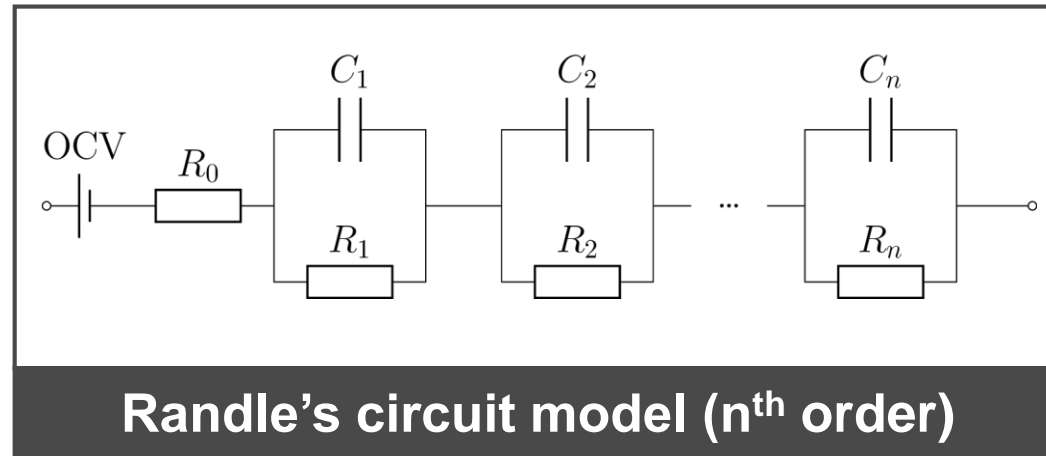
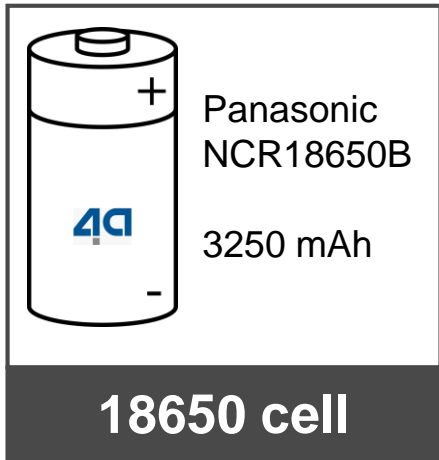
# Multiphysics of battery cells



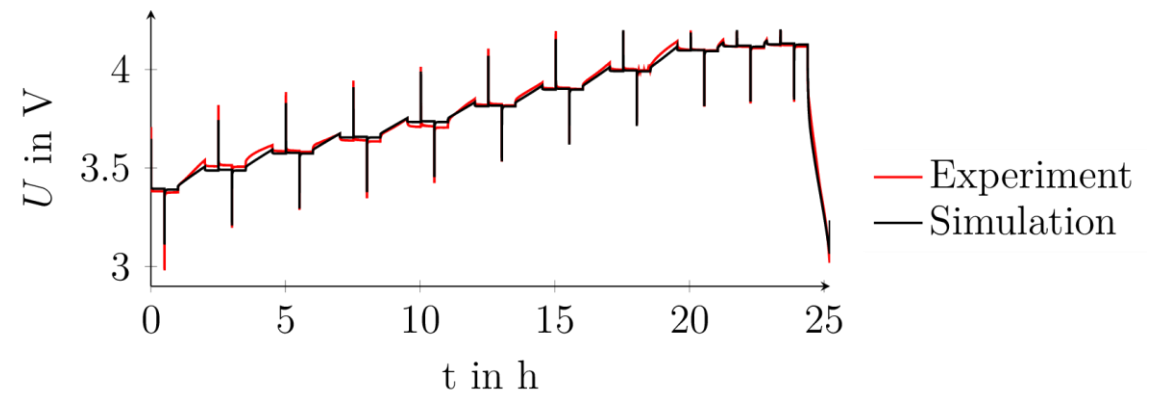
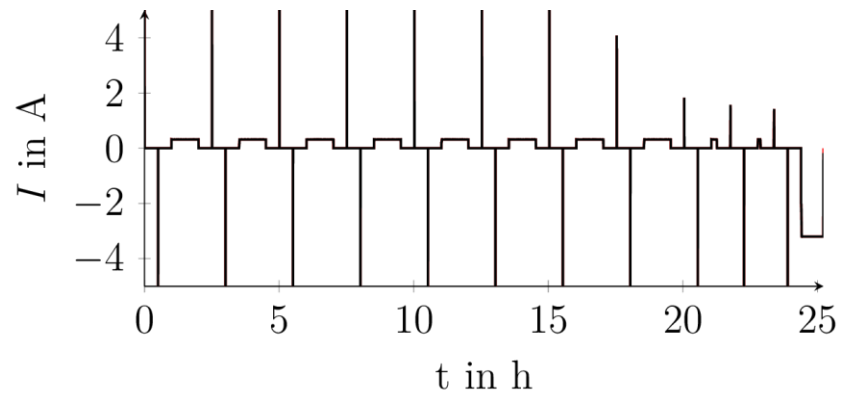
# Multiphysics modeling approaches in LS DYNA

	Solid layer model	Tshell model	Batmac model
			
Keyword	*EM_RANDLES_SOLID	*EM_RANDLES_TSHELL	*EM_RANDLES_BATMAC
Advantages	<ul style="list-style-type: none"> <li>Analysis of the different layers is possible</li> </ul>	<ul style="list-style-type: none"> <li>Beneficial modeling of thin cells</li> <li>Reduced computational effort</li> </ul>	<ul style="list-style-type: none"> <li>Modeling with respect to mechanical and thermal problem</li> <li>Least computational effort</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>Computational effort</li> <li>Characterization of the materials of the layers required</li> </ul>	<ul style="list-style-type: none"> <li>Homogenized mechanical material model</li> <li>Behavior of the layers can not be analyzed in detail</li> </ul>	<ul style="list-style-type: none"> <li>Homogenized material models</li> <li>Behavior of the layers can not be analyzed</li> </ul>

# Electrical modelling and characterization

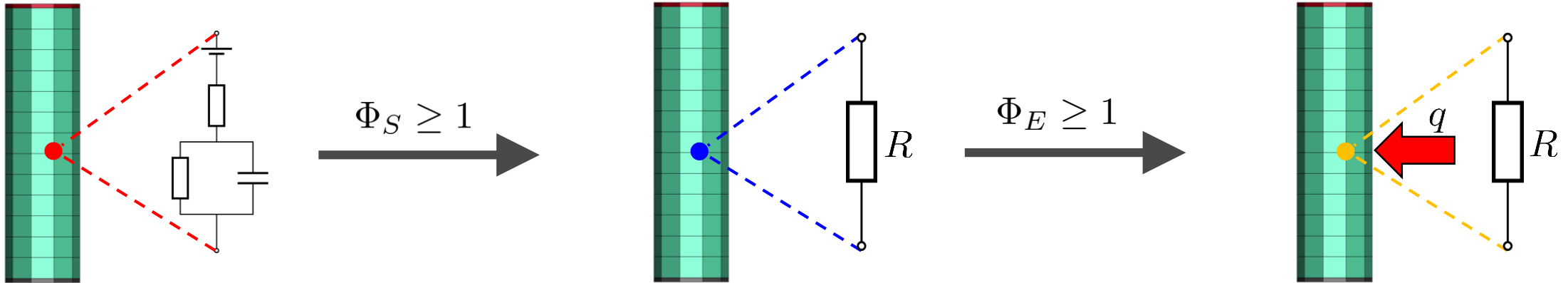


- Identification of the parameter based on the 4a HPPC test



# Abuse simulation of a single cell

- Modeling of the electrical behavior, the internal short circuit and the exothermal reaction



Initiation criterion:

$$\Phi_S (T, \text{SOC}, \underline{\underline{\varepsilon}}) \geq 1$$

Short resistance:

$$R = \text{const.}$$

**Internal short circuit**

Initiation criterion:

$$\Phi_E (T) \geq 1$$

Additional heat source:

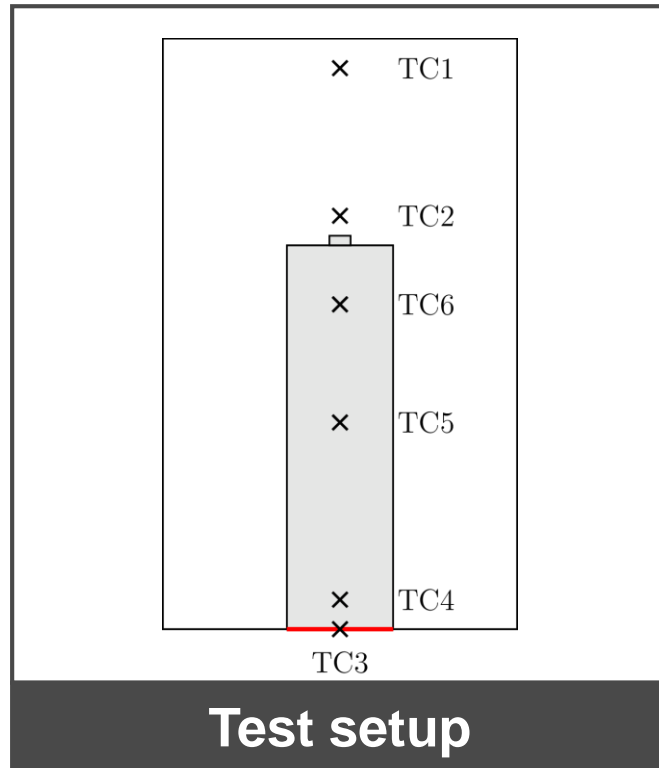
$$q (T)$$

**Exothermal reaction**

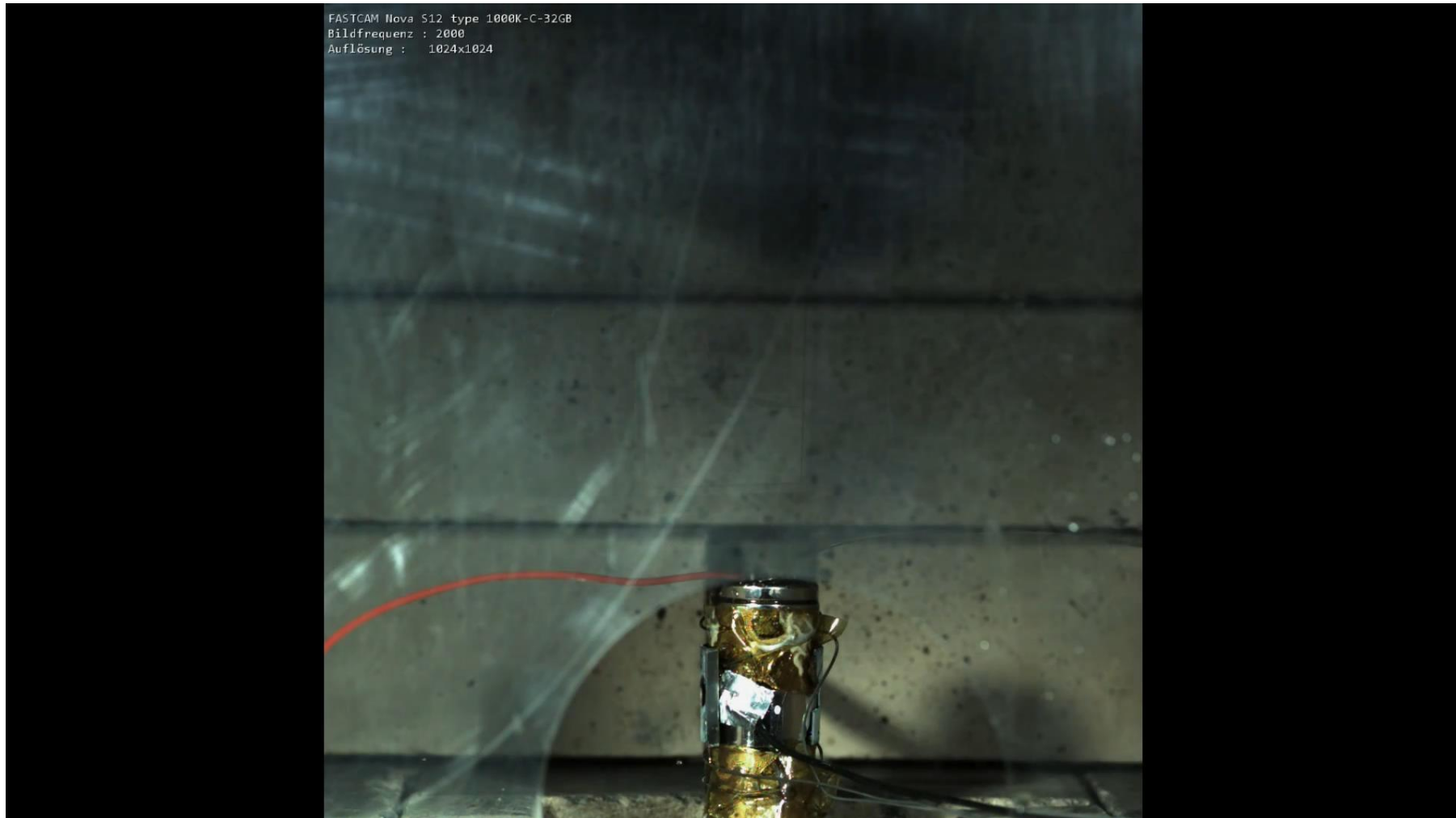


# Overheat test of a battery cell

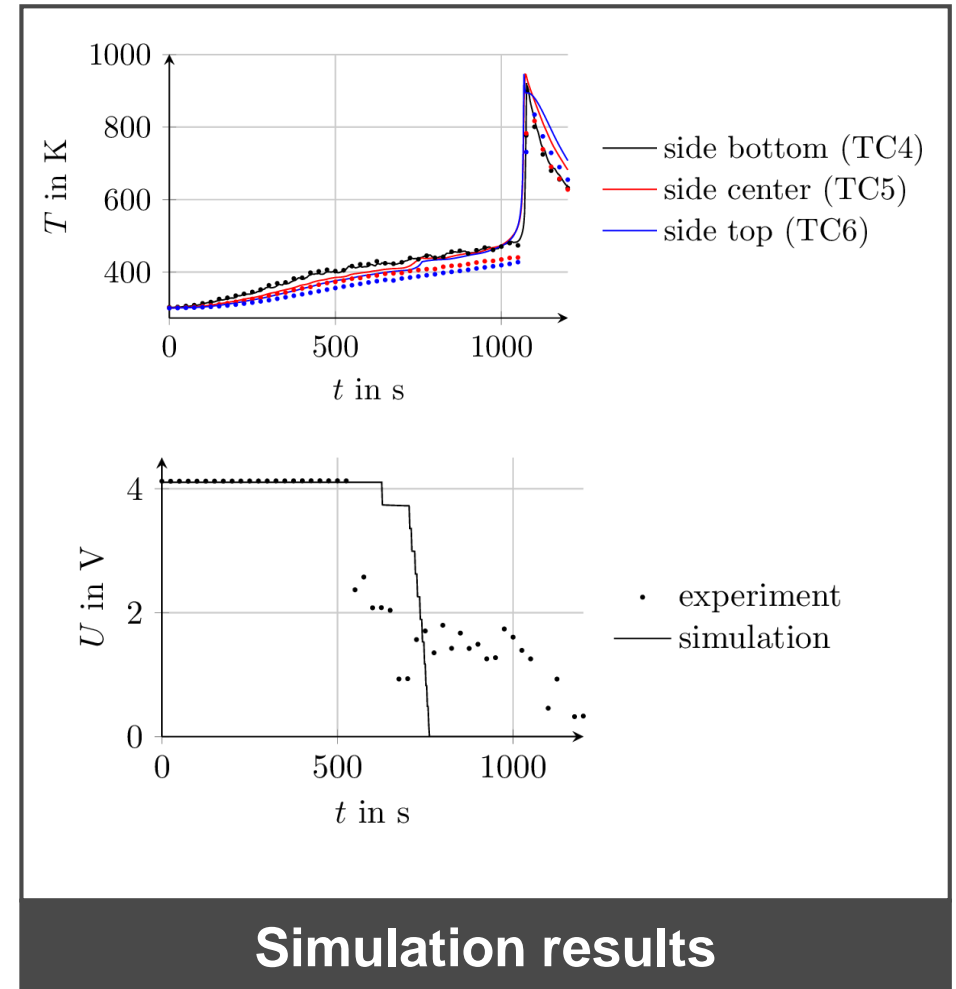
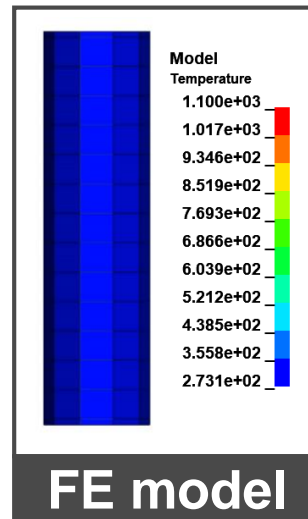
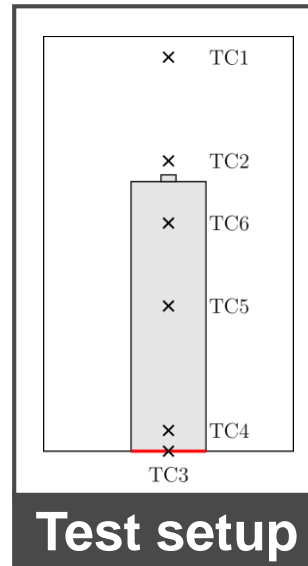
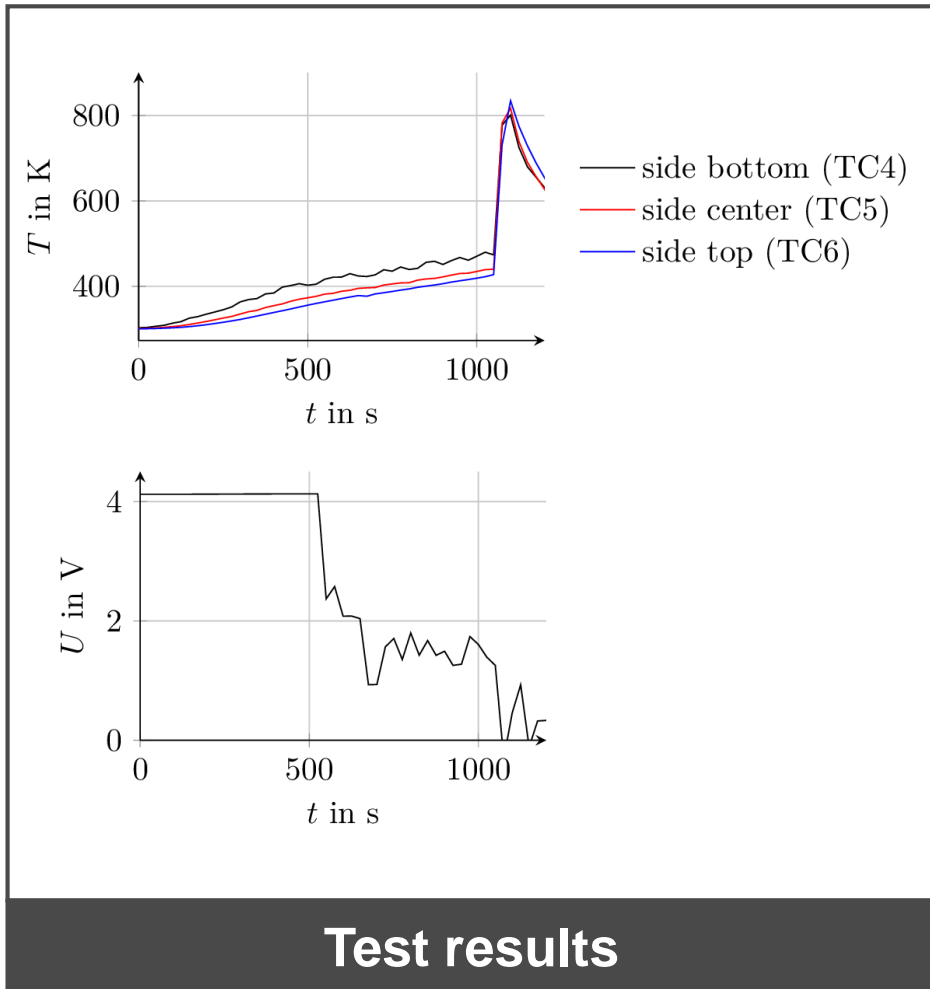
- Overheating of a fully charged 18650 battery cell (Panasonic NCR18650B) at the bottom
- Measurement of the temperature at the cell as well as in the chamber with 6 thermocouples
- Measurement of the voltage



# Overheat test of a battery cell

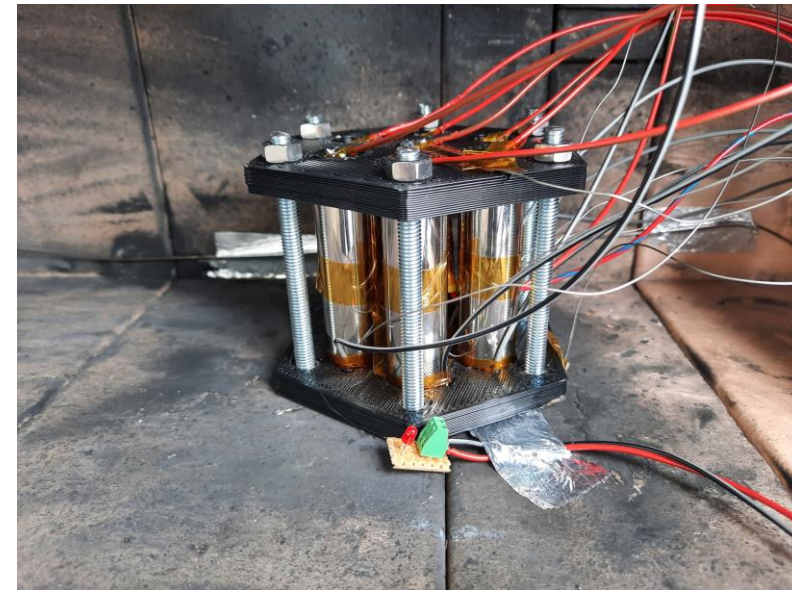
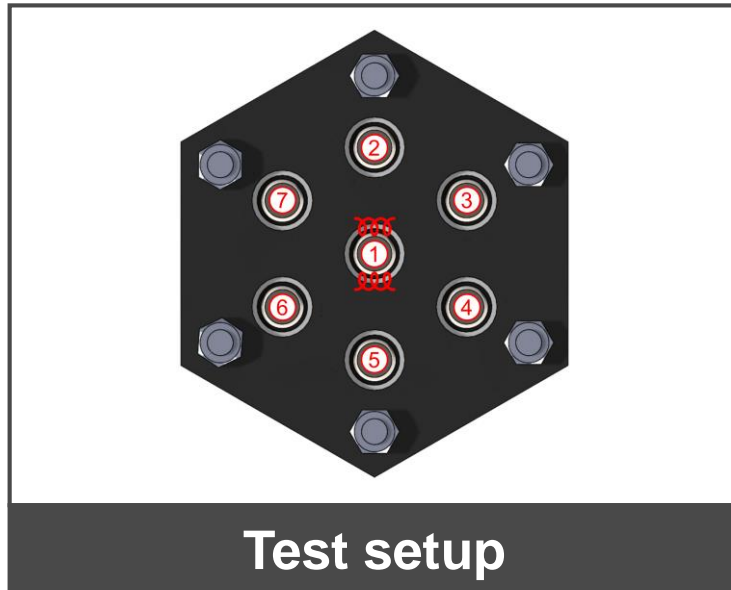


# Overheat test of a battery cell

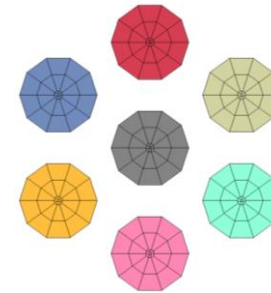
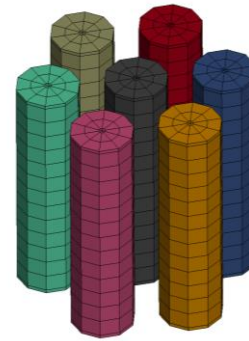


# Multi-cell mockup – experimental investigation

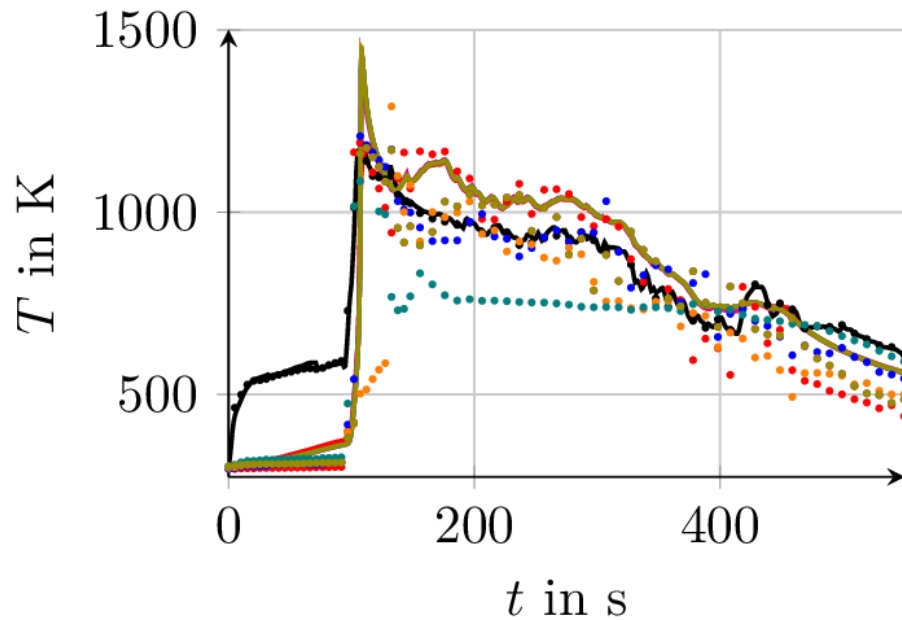
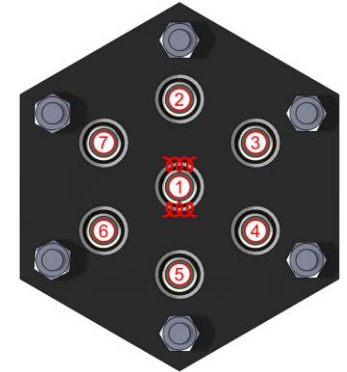
- Thermal runaway of the center cell induced by heating with a heating wire
- Temperature and voltage measurement of each cell
- Video recording with high-speed camera



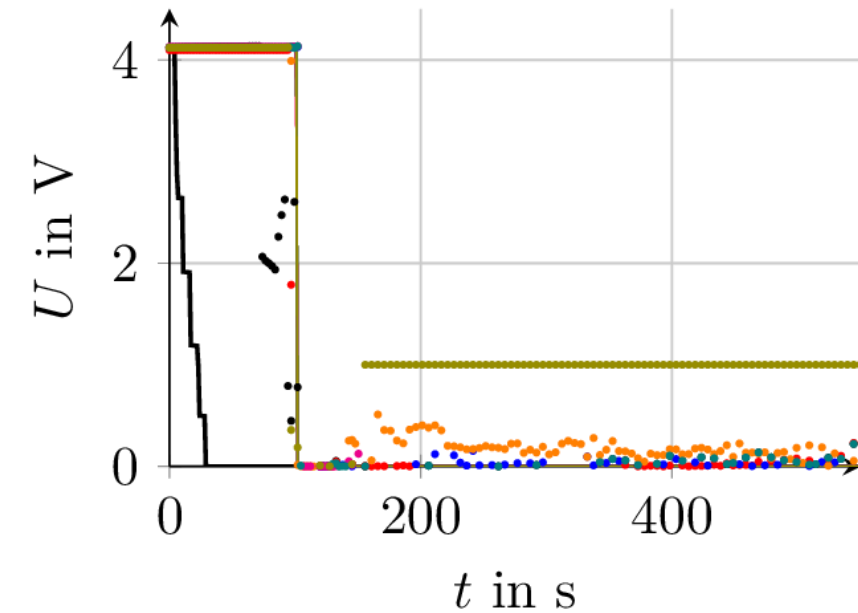
# Multi-cell mockup – simulation results



FE  
model



- cell 1
- cell 2
- cell 3
- cell 4
- cell 5
- cell 6
- cell 7

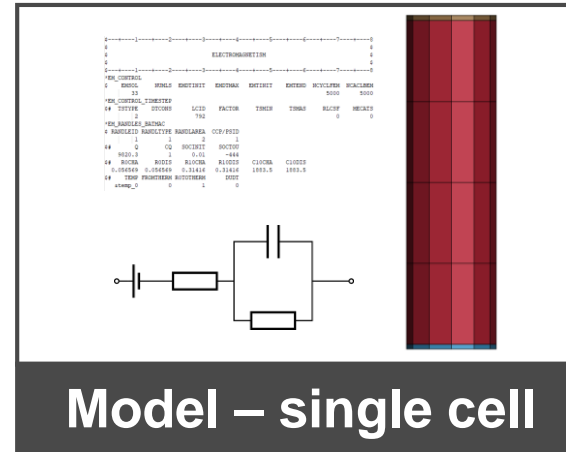
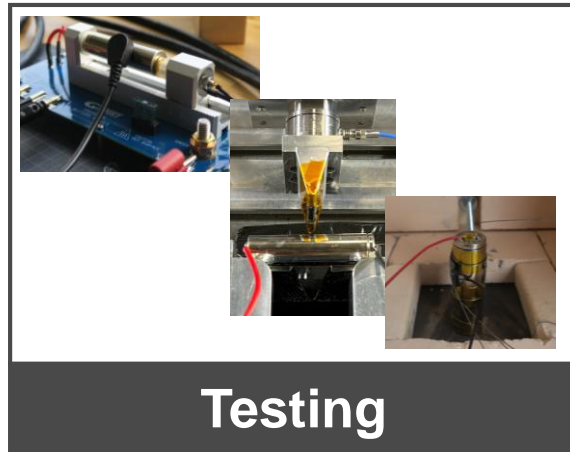


- cell 1
- cell 2
- cell 3
- cell 4
- cell 5
- cell 6
- cell 7

• experiment — simulation

# Conclusion and outlook

# Conclusion



# Outlook

- Development of test setups for further characterizations of battery cells especially with regards to thermal and mechanical abuse
- Automatic identification of the parameters required for the resulting FE model
- Optimization of battery packs addressing the thermal propagation and crash behavior

**Improve your developments with our expertise in testing and simulation!**

Martin Schwab

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