Ref. Ares(2022)3337740 - 29/04/2022

Upscaling **P**roduct development **S**imulation **C**apabilities exploiting **A**rtificial inte**L**ligence for **E**lectrified vehicles

D5.8 Report on methodological approach for battery risk analysis in severe crash scenarios

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04/2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 824306.

Project Details

PROJECT TITLE	Upscaling product development simulation capabilities exploiting artificial intelligence for electrified vehicles
PROJECT ACRONYM	UpScale
GRANT AGREEMENT NUMBER	824306
INSTRUMENT	RIA
CALL	LC-GV-2018
STARTING DATE OF THE PROJECT	November, 1ST 2018
PROJECT DURATION	42 Months

The UpScale Project

UPSCALE is the first EU project with the specific goal of integrating AI (artificial intelligence) with traditional physics-based Computer Aided Engineering to reduce the development time and increase the performance of electric vehicles (EVs).
Nowadays High-Performance Computing (HPC) and Computer Aided Engineering (CAE) play a decisive role in vehicle development processes, thus the two most HPC and CAE intensive parts of the development, which are vehicle aero-thermal and vehicle crash performance, have been chosen as use cases for the endeavour.
Through the combined effort of universities, research laboratories, European automotive OEMs, software companies and an AI-SME specialized in machine learning (ML), the UPSCALE, project will provide a unique and effective environment to produce novel AI-based CAE-software solutions to improve the competitiveness of the automotive industry.

The UpScale Consortium

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1 (Coordinator)	**IDIADA AUTOMOTIVE TECHNOLOGY SA (IDIADA),**	Spain
2	VOLVO PERSONVAGNAR AB (Volvo Cars)	Sweden
3	VOLKSWAGEN AG (VW)	Germany
4	CENTRO RICERCHE FIAT SCPA (CRF)	Italy
5	ESI GROUP (ESI GROUP)	France
6	ENGYS LTD (ENGYS LTD)	United Kingdom
7	Kompetenzzentrum - Das Virtuelle Fahrzeug, Forschungsgesellschaft mbH (VIF)	Austria
8	VRIJE UNIVERSITEIT BRUSSEL (VUB)	Belgium
9	ECOLE NATIONALE SUPERIEURE D'ARTS ET METIERS (ENSAM PARISTECH)	France
10	ALGORITHMICA TECHNOLOGIES GMBH (ALGORITHMICA)	Germany
11	F INICIATIVAS ESPAÑA I MAS D MAS I SLU (FI GROUP)	Spain

Document Details

DELIVERABLE TYPE	Report
DELIVERABLE Nº	D5.8
DELIVERABLE TITLE	Report on methodological approach for battery risk analysis in severe crash scenarios
NAME OF LEAD PARTNERS FOR THIS DELIVERABLE	Centro Ricerche FIAT ScPA
VERSION	4
CONTRACTUAL DELIVERY DATE	Month 30
ACTUAL DELIVERY DATE	Month 42
DISSEMINATION LEVEL	Public

ABSTRACT

The report describes the results of the methodologies developed in the project when applied to a reference crash test simulation involving a full scale Battery Electric Vehicle F.E. model adapted for the project. The short circuit risk predictions obtained from the two approaches used for the battery model order reduction (short circuit risk assessment and short circuit + stiffness modelling) are compared and some final considerations/recommendations are drawn.

Revision History

The following table describes the main changes done in the document since it was created

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
0	01.04.2022	First draft	E. Cortelletti (CRF)
1	12.04.2022	Review	C. Jimenez (IDIADA)
2	13.04.2022	Review	C. Breitfuß (VIF)
3	26.04.2022	Review	A. Dumon (ESI)
4	27.04.2022	Merge of previous drafts	E.Cortelletti (CRF)

Disclaimer

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Acronyms and abbreviations

AI	Artificial Intelligence
CAE	Computer Aided Engineering
D	Deliverable (within the UPSCALE project)
FE	Finite Element
ROM	Reduced Order Model(ing)
VPS	Virtual Performance Solution
WP	Work Package
EV	Electric Vehicle
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
HPC	High Performance Computer
TANN	Thermodynamics-based Artificial Neural Networks

1 Executive Summary

The present deliverable describes the application of the methodological approaches developed in UPSCALE for battery risk analysis in severe crash scenarios.

Three types of implementation at solver level, for the two modelling approaches developed in the project and described in D3.3, have been considered for the final validation on the vehicle. These three types of implementation or code options are focused on two reduced order models: the first two considering short circuit assessment only and the third combining both cell stiffness and short circuit evaluation. More precisely:

1. ROM short circuit risk prediction/assessment through post processing of a homogenized material formulation
2. ROM short circuit risk prediction/assessment from a user plugin material formulation
3. ROM stiffness and short circuit with TANN material with elemental cell approach

CRF analysed the pole crash scenario for the validation. As reported in deliverable D5.4, this crash load case is based on the existing Euro NCAP Side Pole impact scenario, with adaptations for the specific project objectives (i.e. to highlight the battery pack potentially critical conditions/response resulting from severe impacts).

For the load case considered, three different load configurations with different degrees of severity were analysed, with the aim of simulating different loading situations that the vehicle battery pack may be subjected to and that consequently generate different battery cell deformation modes.
The goal is to compare the computing efficiencies, benefits and limitations of the above mentioned approaches. Calculation time, global deformation of the vehicle and battery pack deformation (with a focus on the single modulus and the single cells) are some of the parameters that are analysed.

The authors want to underline that the results of the full scale battery electric vehicle simulations presented in this deliverable cannot be used for evaluating the safety or performance of the vehicle described in D5.3 or even a real vehicle that may look similar.
There are two main reasons for that; firstly, the load cases are settled in such a way that no legislative or consumer test are strictly reproduced and secondly, the reference vehicle used for this part of the project, is not an exact representation of the real production one to which it externally resembles but just a virtual CAE prototype, with no existing physical counterpart, generated specifically for the purposes of the project. Consequently, none of the results and behaviors of the BEV FE model presented in this document shall be assumed, interpreted, considered or used as the real crash response of the resembling vehicle currently on the market.

The deliverable objectives according to the proposal are fulfilled. The time amendment enabled the methodological approaches for battery risk analysis in severe crash scenarios to be completed and finalized; in particular the ROM stiffness and short circuit with TANN material with elemental cell approach required more development than planned.

2 Introduction

Battery electric vehicles are currently designed in such a way that, when tested according to legislative and consumer impact conditions, the battery pack is not subjected to dangerous deformations and/or indentations, preventing damage to the modules and the cells inside.

In the design of future electric vehicles, one of the aspects to be improved is the battery pack design, making its layout design more efficient and exploiting better the available spaces on the vehicle.

First of all, new advanced simulation methodologies for battery packs, usable at full vehicle model level, are important to increase the virtual predictability of the performance of such fundamental components in electric vehicle crash scenarios, by limiting as much as possible the needed amount of physical testing, too.

On the other hand, it's important to have models, tools and methodologies to improve and to reduce the time to market of new designs.

The aim of the work presented in this deliverable is to verify the capabilities of reduced order models and associated approaches (according to methodologies delivered by work packages 1 and 3) from the perspective of a full vehicle crash simulation.

We have three different reduced-order model, the first two consider short-circuit evaluation and the third matches stiffness and short-circuit evaluation. The first two reduced-order model for batteries is expected to increase the predictability of local failure during a typical crash scenario, thus providing prediction of failure risk, e.g. for a short circuit, which is not yet considered in full vehicle simulations. The methodological approach will make it possible to simulate the entire behaviour of the battery pack at vehicle scale with a simulation time in line with the current crash simulation standards. These tools will increase the possibility of assessing the electric risk for EVs in crash scenarios and reduce uncertainties in designing the vehicle crash performance at an early stage, then reducing the time to market and optimising the protection strategy required by battery pack integration.
The third reduced-order model that integrates short circuit and stiffness investigation will be verified with the same crash simulations of the complete vehicle.
In this report, the comparison of the different approaches computing efficiencies, benefits and limitations will be shown.
Although no experimental validation of the computational results were made, qualitative analyses in terms of short-circuit map evaluations will also be presented.

3 The vehicle and battery model

The full vehicle used for the verification of reduced order model approaches is, as already said, a virtual prototype generated specifically for the purpose of the project.
The battery pack model has been developed using the pouch cells proposed by CRF in WP1 and is composed by 17 modules, all of the same dimension and containing 12 cells each.
In each module there are 79296 solid element that means 1.35 million of solid element for the full battery pack.
The mesh dimension for the cell parts is 3 mm, an average value typically used for numerical crash analysis.

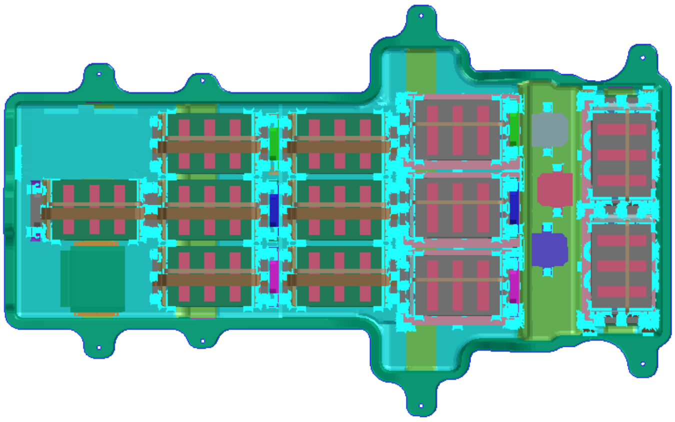


Figure 1: Battery pack model

The pole crash scenario used for the verification is based on the existing Euro NCAP Side Pole impact scenario, with adaptations for the project objectives.

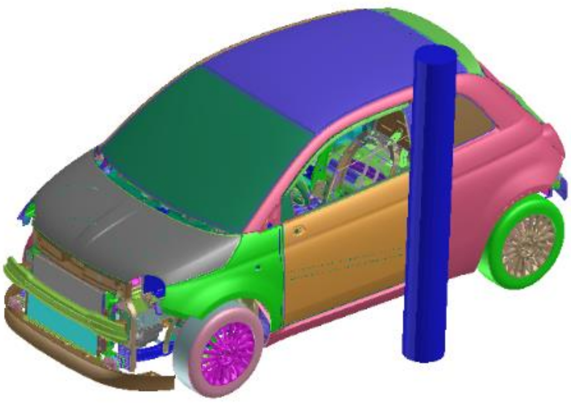


Figure 2: Side pole impact test

More precisely, there are three impact cases, characterized by the same impact location and different initial speeds, selected to have an increasing impact severity (i.e. progressively more severe loading conditions for the battery pack):

a) **Case 1 - Low severity crash**: with this test we consider speed values that do not cause a short circuit in the vehicle.
b) **Case 2 - Moderate severity crash**: with this test we consider speed values that can cause a short circuit in the battery pack.

c) **Case 3 - Very severe crash**: with this test we are in a condition that certainly causes a short circuit in the vehicle batteries.

These three load conditions allow us, on one hand, to evaluate presence and extent of the short circuit prediction and on the other hand, to analyse the different post-processing times the more cells are involved in the crash scenario and the more they are deformed.

The calculations for the three cases were performed with VPS version 2020.5.1 running on 112 CPUs.

4 ROM short circuit methodology

The activity is splitted in two part. In the first one we describe the ROM application for the short circuit forecast and the second one the ROM for stiffness and short circuit forecast.

4.1 ROM for short circuit

Regarding the ROM short circuit methodology, two approaches, developed in the project, have been considered for the final verification on the vehicle:

- ROM short circuit from post processing of homogenized material
- ROM short circuit from user plugin material

This first approach tested is the offline short circuit ROM, trained on the meso detailed model described in D3.2, with a methodology explained in D3.3. It is based on a post-processing tool to evaluate the short circuit risk on the cells of a battery pack, when they are modelled with the homogenized model. The cell mechanical behaviour is based on a homogenized material model with a honeycomb anisotropic plasticity law, as described in D3.3.
The tool is based on an offline training done on macro and meso cell models and it works linking the stresses and the strains of the detailed cell model with the homogenized cell one.

The CPU time for the 3 crash scenario, computed with homogenised cell model and VPS solver, is presented in the following table.

	CPU time (hours)	Offline tool time for post processing (hours)
Case 1	8,5	0,18
Case 2	8,5	0,18
Case 3	8,7	0,18

Table 1: Homogenized material, CPU time for full car crash simulation

For each case, the post processing offline tool reads the ".erf" results file and generate a new ".erf" file with the additional machine learning predicted short circuit risk results.

The tool, used on a standard laptop with 64 GB RAM, takes about 30 seconds per state, about 10 minutes for the total calculation, composed by 20 calculation steps.
The final result file, following post-processing, is 8% larger than the starting file.

The post processing preparation time (through the offline tool) is driven by the output frequency requested in the input file. For calculations where a high frequency is used the post processing preparation time increases proportionally while the CPU time remains nearly the same.

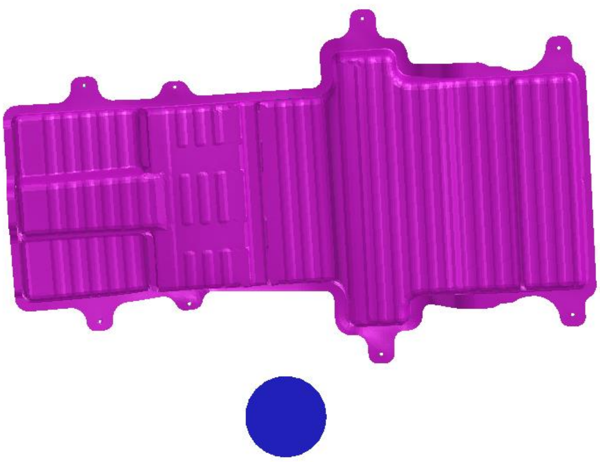
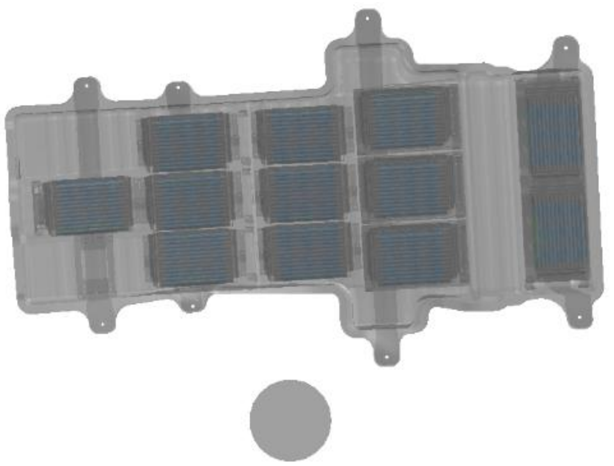
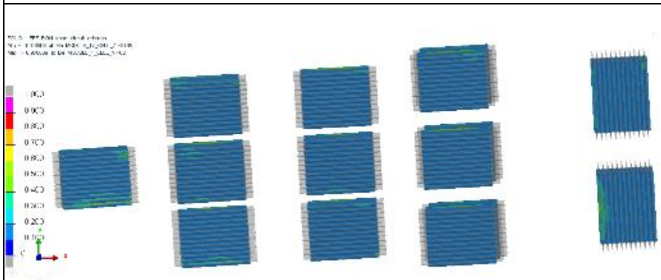
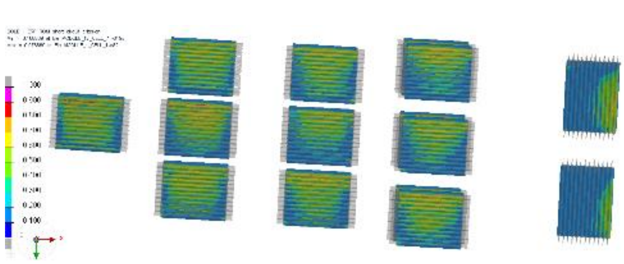
The new .erf results post file, is a bigger file in term of size and contains an additional field called “ERF_ROM_Short_circuit_criterion”, that is visible directly in ESI Visual Viewer Software VPS2020.5.

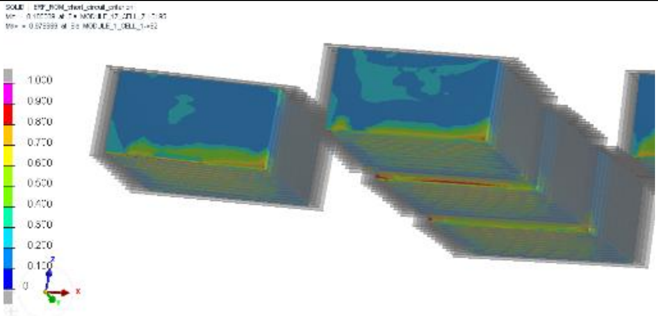
For the three analysed cases, the following multiple pictures represent the results of the simulation in term of short circuit on the battery pack of the full vehicle.

For each case, the figure contains always the same sequence of images, taken at the end of the simulation. These images are:

a) battery pack deformation: external top view;
b) battery pack deformation: top view with transparent cover;
c) battery cells short circuit risk contour map: top view;
d) battery cells short circuit risk contour map: bottom view;
e) other view showing short circuit contour map details (when needed).

We emphasize once again that, the considerations presented in terms of short-circuit map analysis represent qualitative analyses of the results since there is no experimental validation of the computational results.

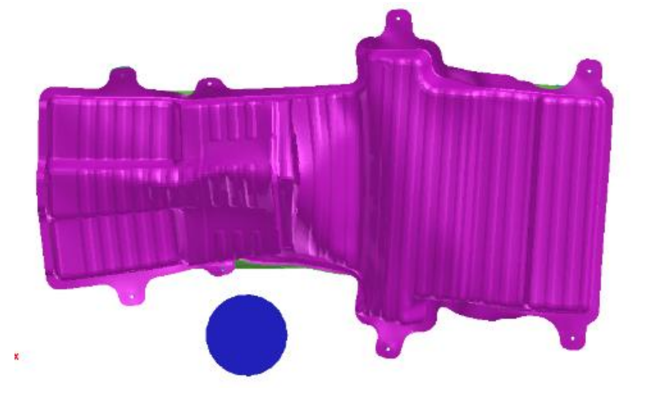
Case 1	
 (a)	 (b)
 (c) Top view	 (d) Bottom view



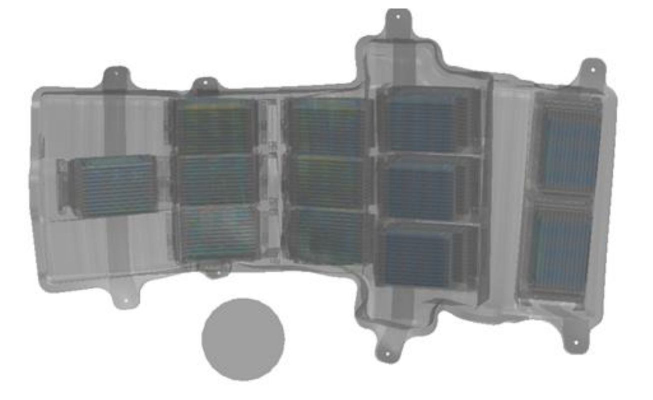
(e) Detail

Figure 3: Homogenized material, Pole impact results - Case 1 (Images taken at 100 ms)

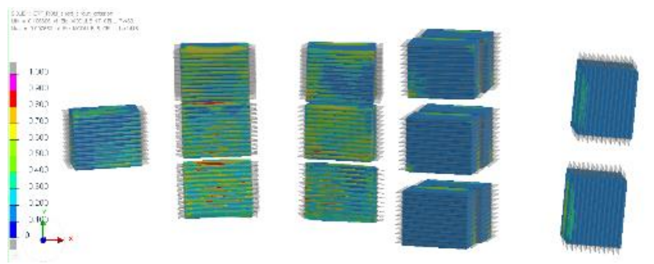
Case 2



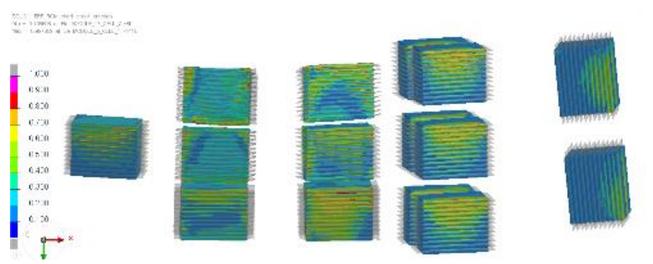
(a)



(b)



(c) Top view



(d) Bottom view

Figure 4: Homogenized material, Pole impact results - Case 2 (Images taken at 100 ms)

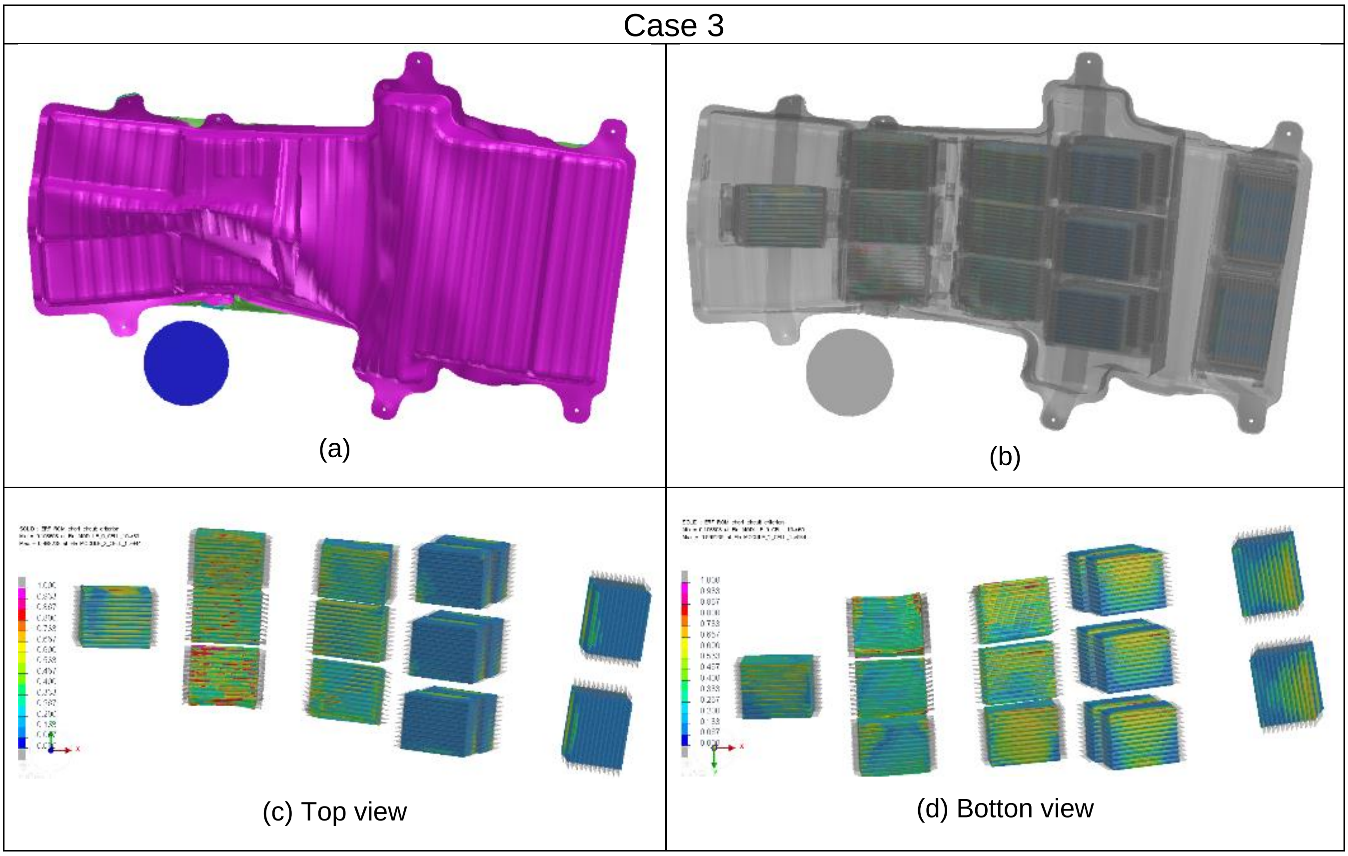


Figure 5: Homogenized material, Pole impact results - Case 3 (Images taken at 100 ms)

Looking at the results of the calculations we can make the following observations:

- the risk of short circuit is increasing as the severity of the impact increases;
- for all the cases, already in the first calculation steps (i.e. starting from 2,5 ms of run calculation) a significant risk of short circuit is predicted;
- risk of short circuit is observed in some areas of the pack away from the pole, too;
- in Case 1:
  - in spite of having no damage to the battery pack, risk of short circuit is predicted anyway; this output appears non-realistic, as in such a situation surely no risk is expected;
  - there are some areas with high risk of short circuit in some elements that are located in the bottom area of the battery pack and near to the module edge (Figure 3(e));
- for the most critical cases, there is an increased risk of short circuit localized in the cells corresponding to the modules closest to the area where the pole strikes the battery pack.

The second approach, that we call ROM short circuit from user plugin material, has the same logic as the previous section. It uses an offline short circuit ROM trained on a meso detailed model but this time the short circuit criterion is "embedded solver side" in the material model itself. This means that the solver is adding a customized ROM field at each time step without the need for post-processing ".erf" file.

The user material plugin for VPS is usually identified by a name “ULIB” and different ID numbers for simple and double precision launch of the solver.
The plugin material is selected at model launch by setting PAMSHARE variable before launching the solver.

The CPU time for the 3 analysed crash test severities is presented in the following table.

	CPU time (hours)
Case 1	6,2
Case 2	6,4
Case 3	6,5

Table 2: Plugin material, CPU time, 112 CPUs

The short circuit risk evaluation is performed directly from the material model implemented in the solver code; this means no post-processing tool is necessary: for the user a specific contour map is presented in the ESI visual viewer software.

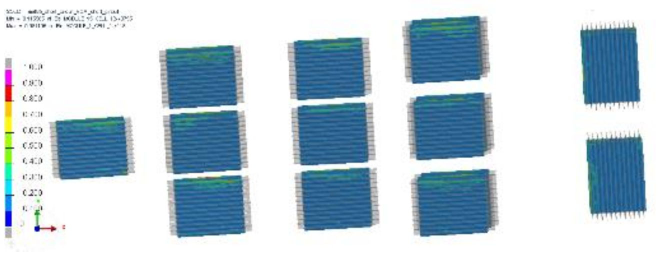
Comparing the results obtained from this approach with the ones coming from the previous one (requiring the already mentioned additional off-line post processing step) the following aspects can be highlighted:

- the overall time needed for the analysis is shorter. In fact, with the user plugin material, the CPU time needed for the full scale simulation is 25% faster than with the homogenised material one. Moreover there is no need to go offline to prepare the post-processing, i.e. further time saving is obtained;
- for the same contour results, the size of the output files is smaller;
- short circuit display is immediate and integrated in the software, which allows an immediate view of the results without any further post processing.

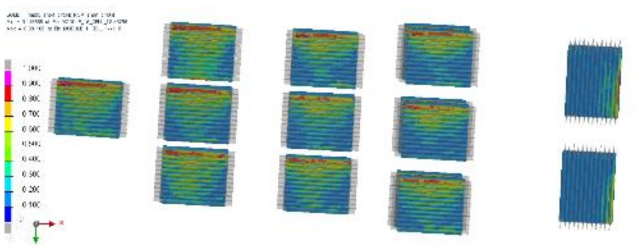
The risk of short circuit contours obtained from user plugin material are presented below, for the battery pack in the 3 test cases taken at the end of the simulation. In details,

a) battery cells short circuit risk contour map: top view;
b) battery cells short circuit risk contour map: bottom view.

Case 1



(a) Top view



(b) Bottom view

Figure 6: Plugin material, Pole impact results - Case 1 (Images taken at 100 ms)

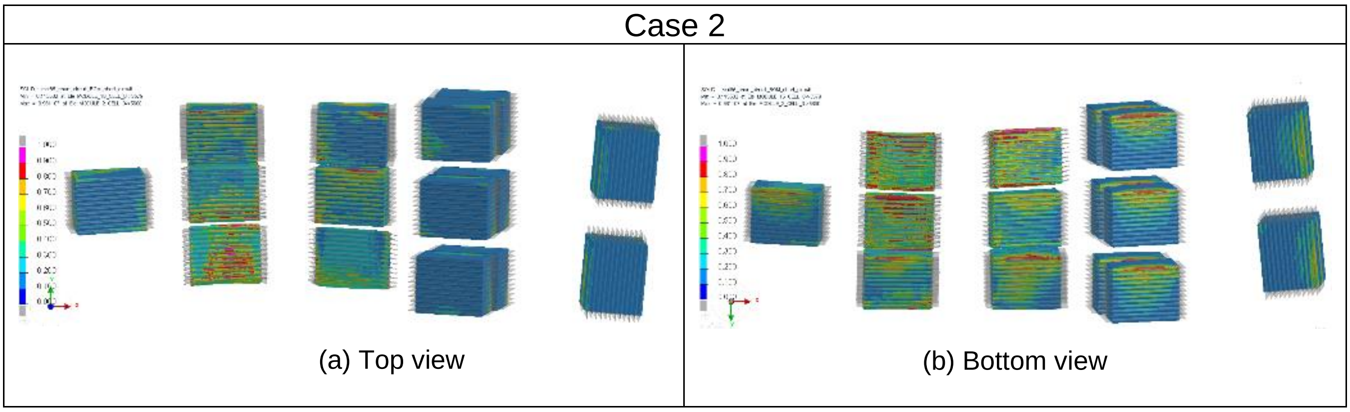


Figure 7: Plugin material, Pole impact results - Case 2 (Images taken at 100 ms)

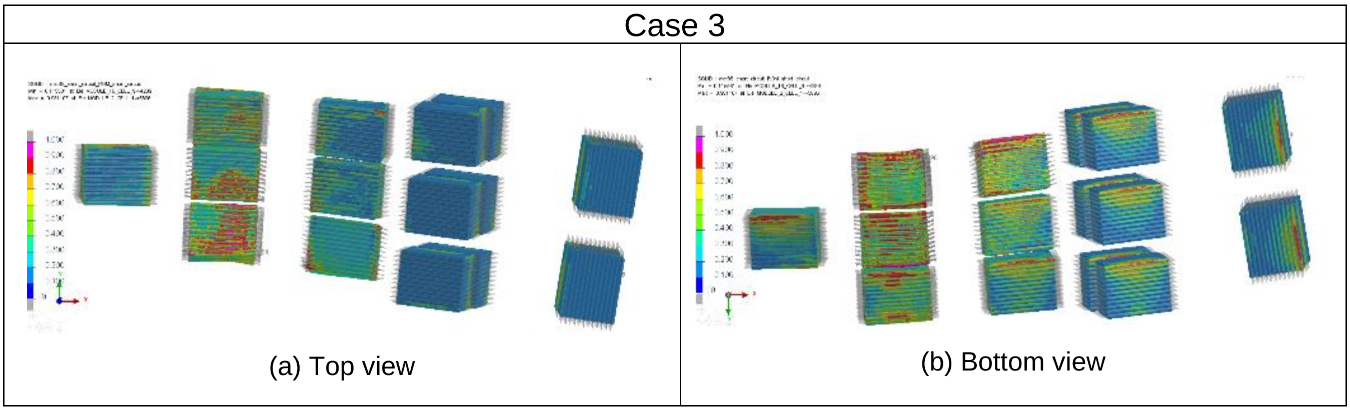


Figure 8: Plugin material, Pole impact results - Case 3 (Images taken at 100 ms)

The next figures show the comparison of the two approaches in more detail. In particular, for the three load cases, the short-circuit maps at the end of the simulation of the cells of the most stressed battery packs are shown.

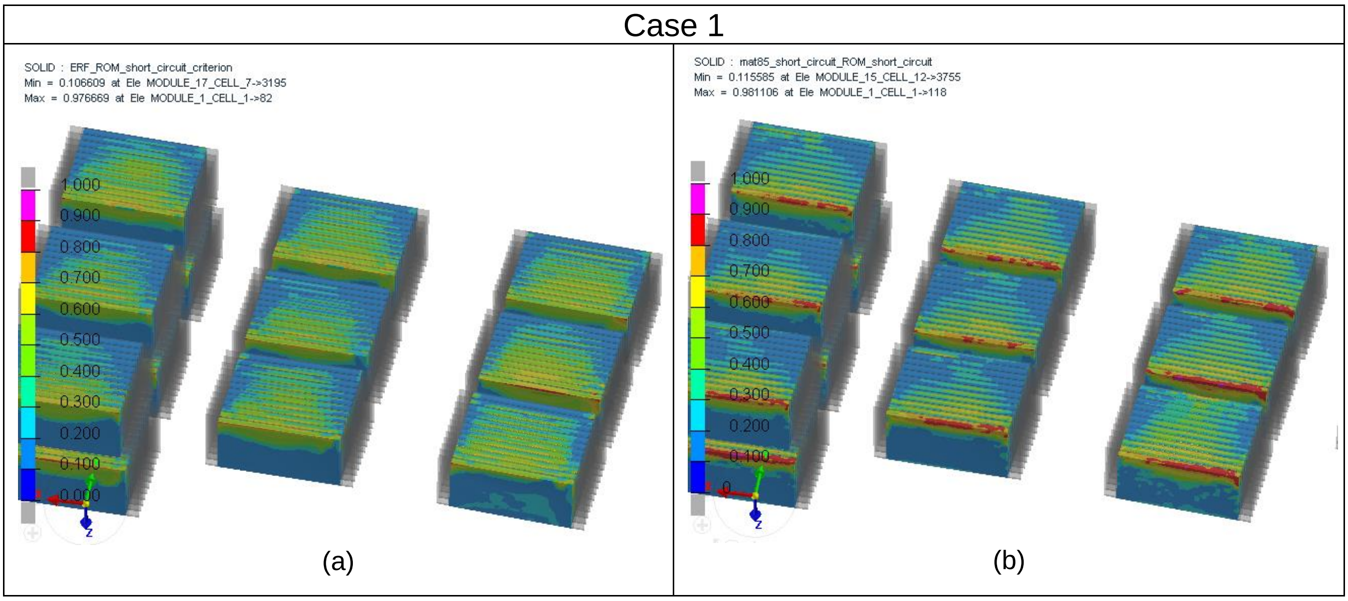


Figure 9: Homogenized material (a) and Plugin material (b) results comparison - Case 1 (Images taken at 100 ms)

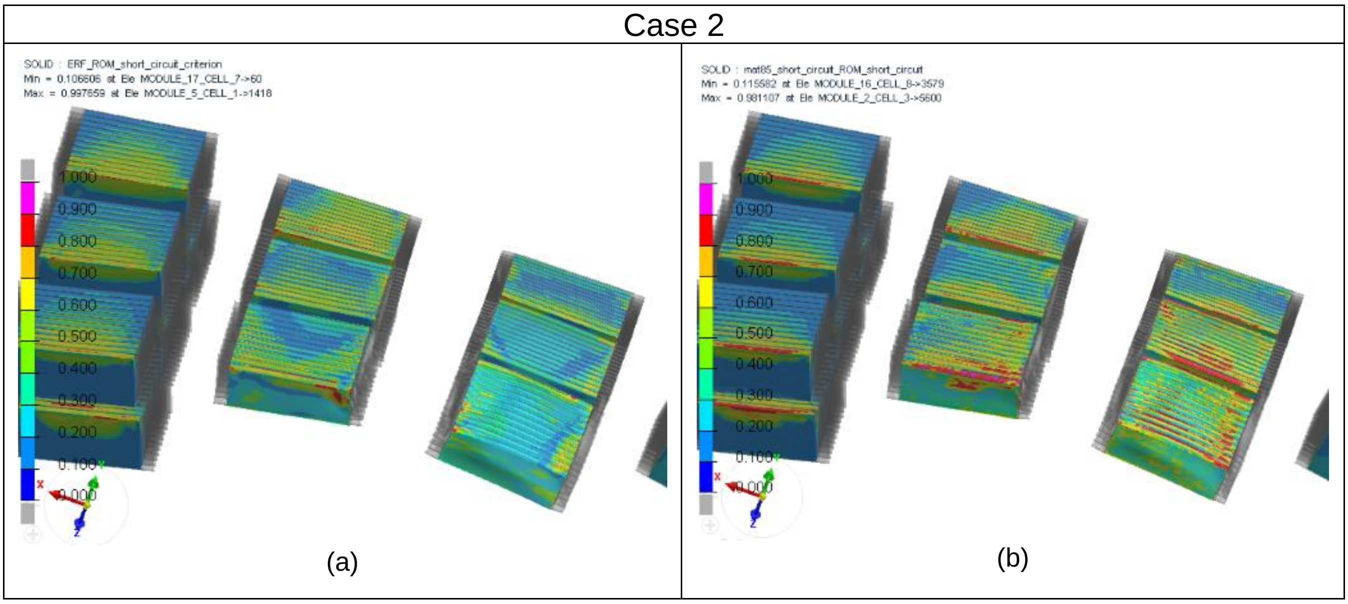


Figure 10: Homogenized material (a) and Plugin material (b) results comparison - Case 2 (Images taken at 100 ms)

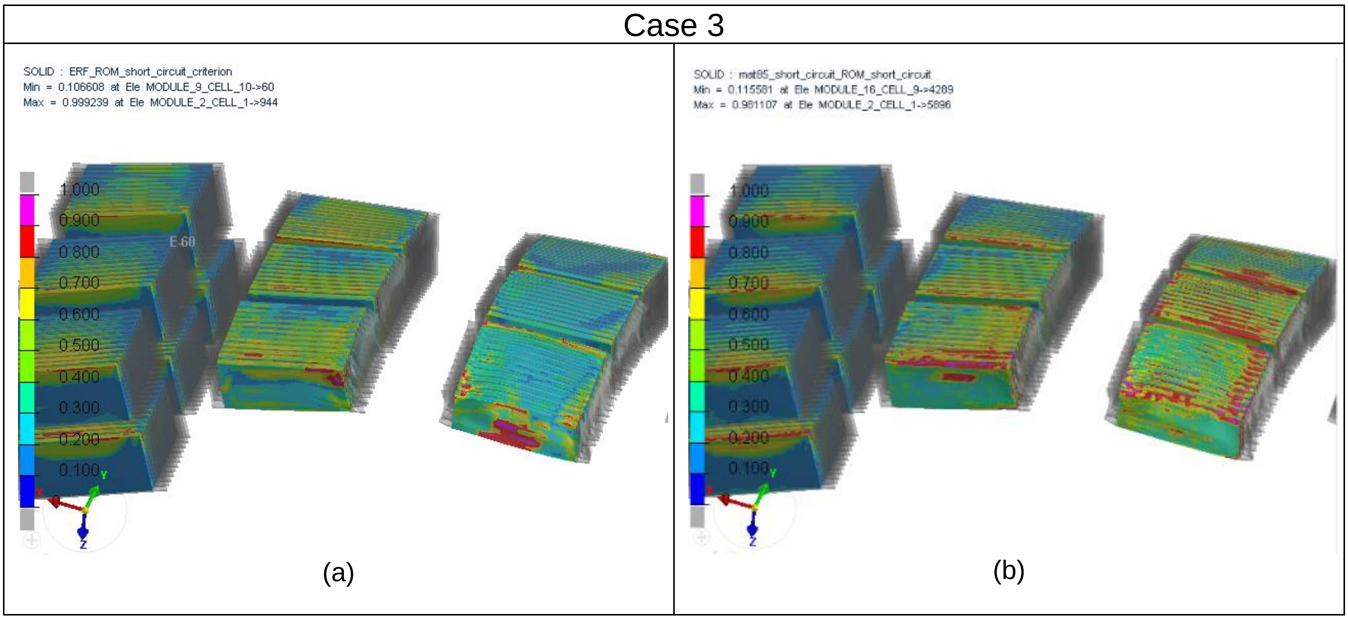


Figure 11: Homogenized material (a) and Plugin material (b) results comparison - Case 3 (Images taken at 100 ms)

Comparing the first and second methodology we observe that:

- the edge phenomenon, i.e., the fact that hot spots are observed in the cells near the edge of the module is more pronounced in the case of plugin material;
- despite this, by analysing the map the distribution of short circuit risk appears more logical/realistic, as it is decreasing progressively along the battery modules width, while moving away from the pole impact location;
- absolute values of short circuit risk are on average higher when predicted via plugin material option.

4.2 ROM for stiffness and short circuit

Regarding the ROM stiffness and short circuit methodology, one approach, developed in the project and described in the project deliverable D5.7 has been considered for the final verification on the vehicle; it is called:

- ROM stiffness and short circuit with TANN material with element cell approach.

As a reminder, this method combines a ROM for stiffness trained on a representative volume element extracted from the detailed cell model with the same ROM for short circuit as described previously.

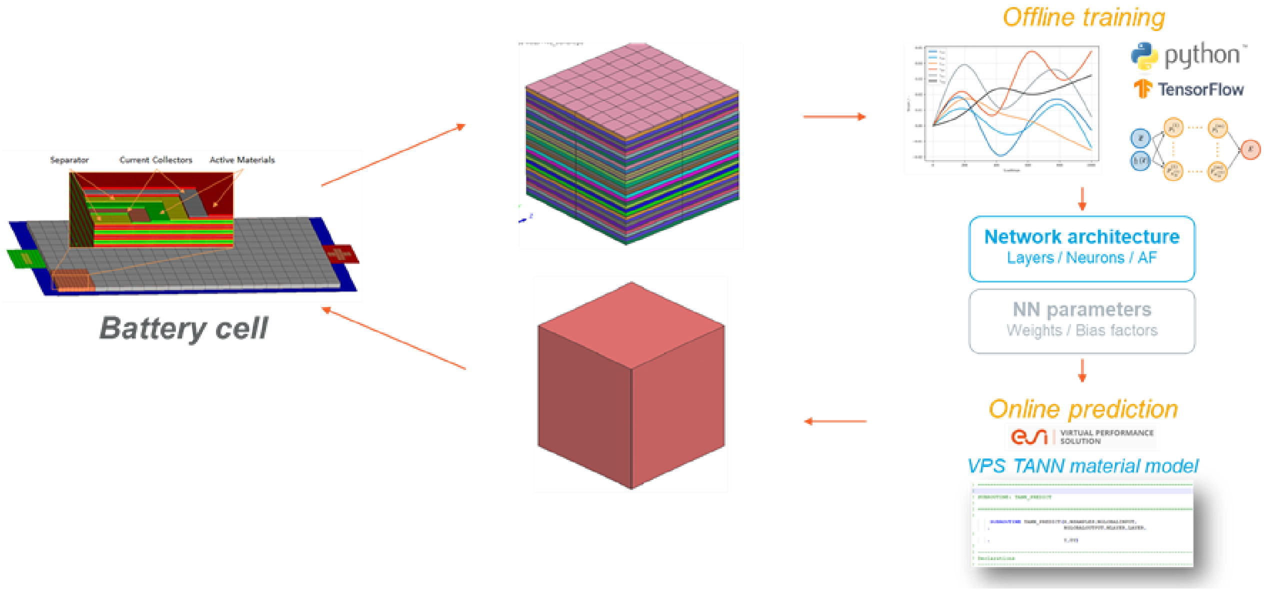


Figure 12: TANN methodology overview (from D5.7)

As in the previous section, the ROMs are implemented in VPS user material plugin identified with a name “ULIB” and an associated binary compiled code library. At each time step, the solver is estimating the stiffness of the material based on the stiffness ROM and adding a customized short circuit ROM field at each time step without the need for post-processing “.erf” file. The plugin material is still selected at model launch by setting PAMSHARE variable before launching the solver. As before, the short circuit risk evaluation is performed directly in the solver and a specific field is presented in the ESI visual viewer software

The CPU time for the 3 crash scenario, computed with homogenised cell model and VPS solver, is presented in the following table.

	CPU time (hours)
Case 1	7,3
Case 2	7,5
Case 3	7,9

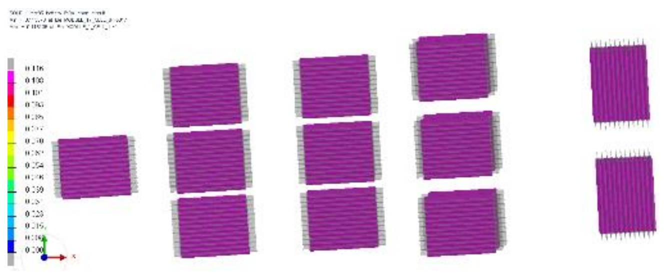
Table 3: TANN material, CPU time, 112 CPUs

Comparing the results obtained from this approach with the ones coming from the previous one (ROM short circuit from user plugin material), the following observation can be done:

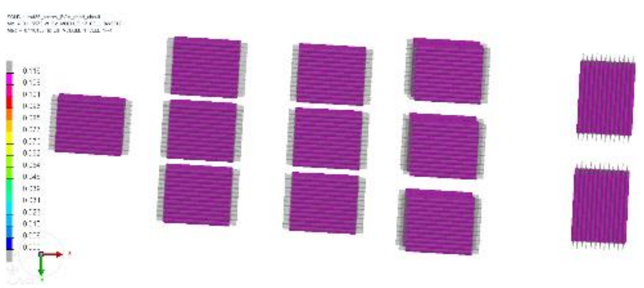
- also in this case the visualization of the short circuit is integrated in the software, so a direct and immediate view of the results without further post-processing is available;
- the overall time required for the analysis is a little bit longer and this is completely attributable to the CPU time required for the full-scale simulation that is about 17% longer;
- for the same contour results, the output file size is in line with the previous case.

Regarding the contour, risk of short circuit for the 3 crash scenario is presented below at the end of simulation in top (a) and bottom view (b).

Case 1



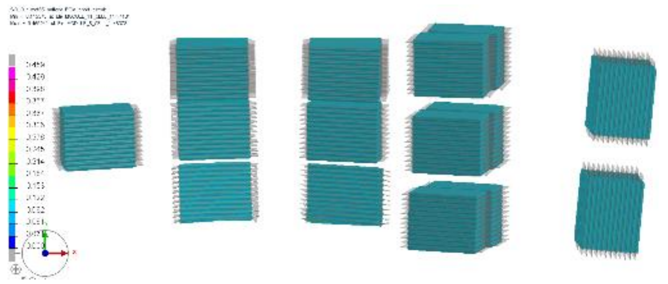
(a) Top view



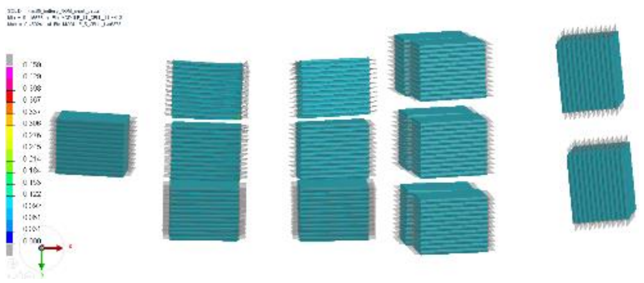
(b) Bottom view

Figure 13: TANN Plugin material, Pole impact results - Case 1 (Images taken at 100 ms)

Case 2



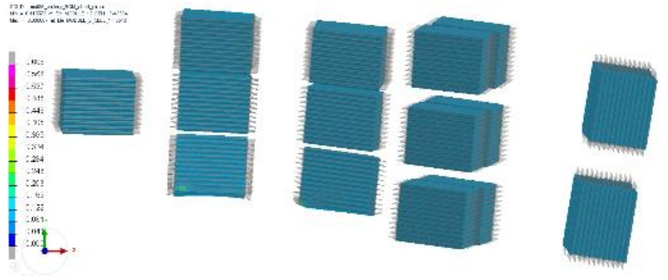
(a) Top view



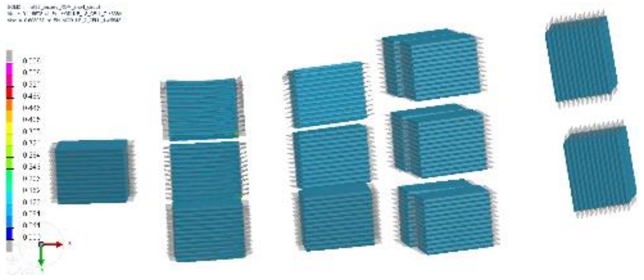
(b) Bottom view

Figure 14: TANN Plugin material, Pole impact results - Case 2 (Images taken at 100 ms)

Case 3



(a) Top view



(b) Bottom view

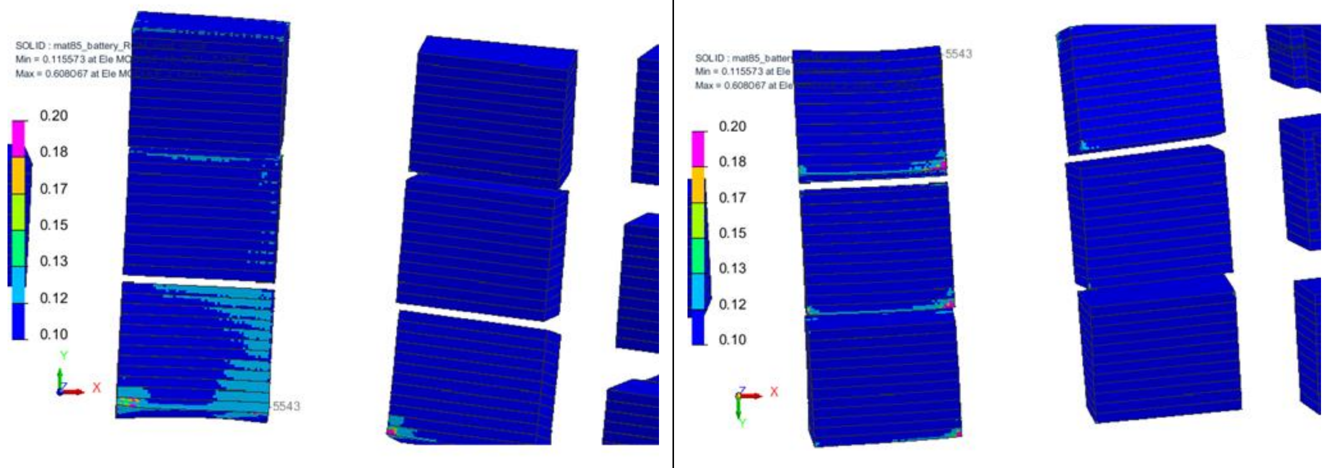
Figure 15: TANN Plugin material, Pole impact results - Case 3 (Images taken at 100 ms)

Analysing the results of the calculations we can make the following observations:

- the risk of short circuit is almost null in all the three cases analysed;
- in the first case the situation reflects the real case since in this situation no risk is expected;
- in the situations of the most severe scenario the forecast does not appear realistic.

The next figures (Figure 16) show in more detail the short circuit risk for the cells within the battery pack, for the most sever crash scenario (Case 3). The predicted internal cell risk remains below 0.2 on the edges with a failure criterion of 1.0.

Case 3



(a) Top view

(b) Bottom view

Figure 16: TANN Plugin material, Pole impact results - Case 3 (Images taken at 100 ms).

To understand the difference with the previous approach in section 4.1, a comparison is performed in terms of deformation, cell strain state and risk.

The cells with ROM stiffness are compared with the physical honeycomb law used in the previous section, and the results are presented below with different colours for the cells within the battery pack. This is performed for the Case 3 of severe deformation and we have:

- in blue the honeycomb material law;
- in red the ROM stiffness and short circuit with TANN material.

The global deformation of the cells is close with few local differences.

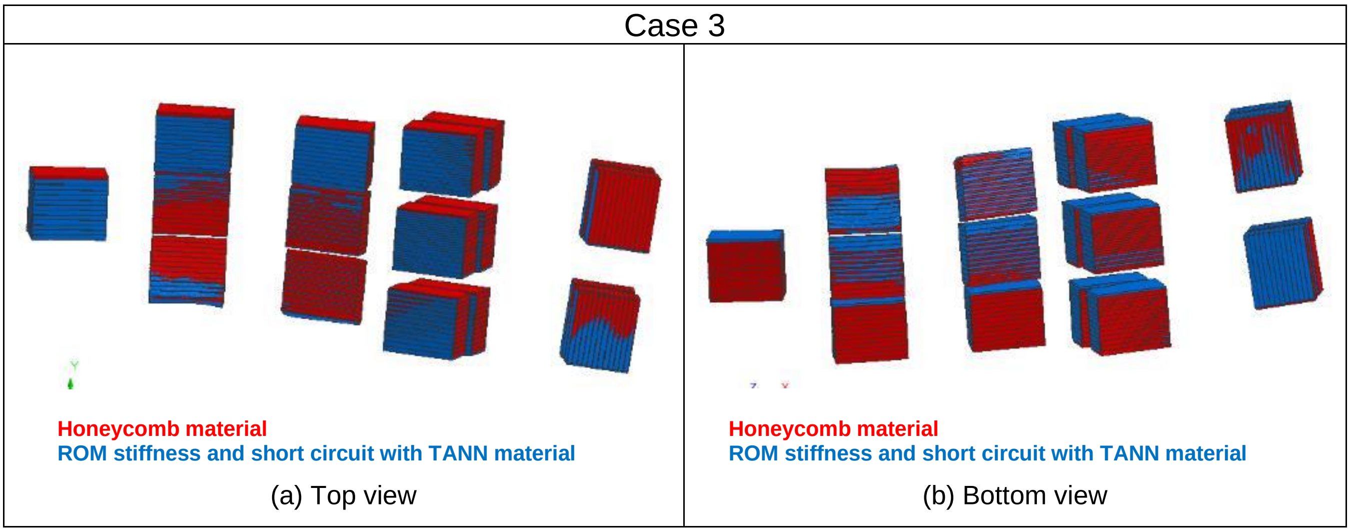


Figure 17: Kinematics comparison, Pole impact results - Case 3 (Images taken at 100 ms).

A similar comparison is performed on the strain state inside the cells caused by the crash. The local strain state with the ROM stiffness is lower by an order of magnitude for the same deformation as the honeycomb material law.

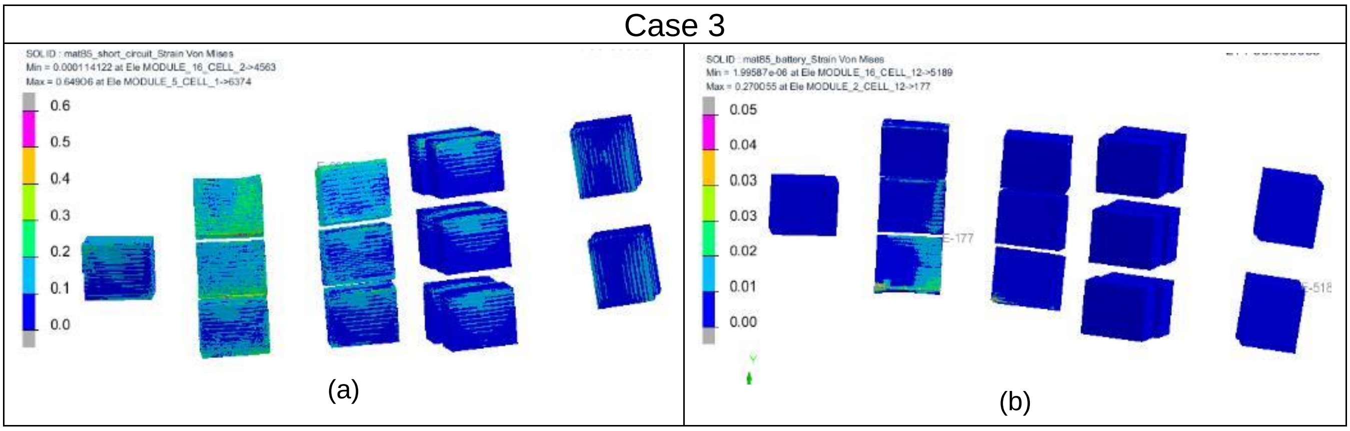
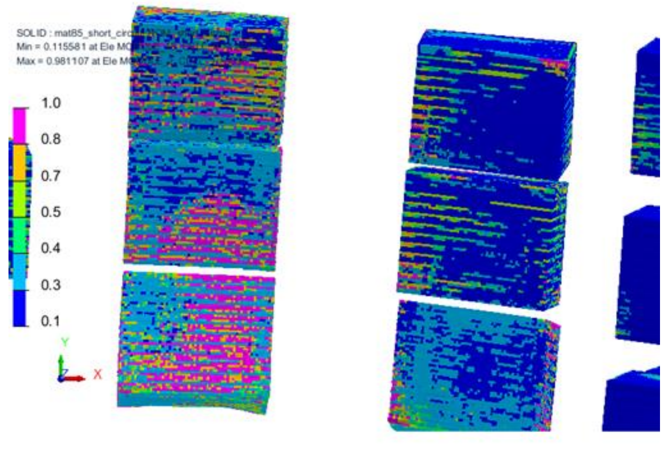


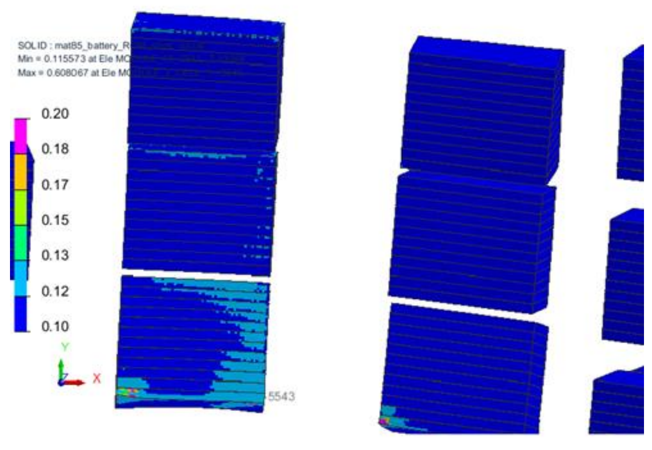
Figure 18: Von Mises Strain map with honeycomb material law (a) and with ROM stiffness material law (b), Pole impact results - Case 3 (Images taken at 100 ms).

The internal cell risk is also compared between the two approaches. The ROM stiffness method predicts lower cell risk than with the honeycomb material law and then expectation with a maximum risk of 0.2. This is explained by the lower strain state for stiffness ROM as the strain state is directly linked to the predicted risk with the short circuit ROM as described in D3.3.

Case 3



(a)



(b)

Figure 19: Short circuit risk with honeycomb material law (a) and ROM stiffness material law, Pole impact results - Case 3 (Images taken at 100 ms).

Local comparison on unit cell tests from D3.2 (3 point bending, indentation, punch, folding) of the ROM stiffness against the honeycomb law shows similar properties in-plane but higher stiffness in the out-of-plane directions. The short circuit ROM was trained based on the response of the honeycomb law. Possible improvements for a consolidated material with both ROM stiffness and short circuit include:

- update the representative volume element model (Figure 12), used to train the stiffness ROM to reduce the differences between the stiffness ROM and FEA mechanical behaviour;
- alternatively, train the short circuit ROM based on the stiffness ROM response instead of the honeycomb law, based on the methodology from D3.2.

5 Conclusion

In order to verify the practical applicability of the methods developed in UPSCALE for the battery short circuit risk evaluation/prediction in full car crash simulation, a series of 3 pole side impact simulations characterized by different (increasing) severity levels was run 3 times, one for each reduced order model approach implemented in the crash solver.
This last verification phase (or first "qualitative" validation/evaluation on the operational applicability of the developed project methodologies) was conducted by the use of a full FE battery vehicle model, a virtual prototype specifically generated for the UPSCALE full scale simulation activities.
The results obtained from the execution of the above mentioned numerical simulation matrix permitted to draw the following considerations/conclusions about the developed approaches/methodologies:

- generally speaking, each new method generated by the project represents a valuable post-processing tool/feature for CAE analysts involved in BEVs (and even HEVs) crash design process, that responds to current practical industrial needs;
- from the practical application point of view, all the 3 tested approach appear to be user friendly enough, even if the ones embedded in the solver are preferable because allow time saving in the results elaboration phase and potentially increase the efficiency in the reduction on product time to market;
- from the solver run time point of view, the one needed for the simulations with the battery ROM implemented in full vehicle model has shown no or little acceptable impact with respect to the more traditional crash simulation of this type (i.e. without short circuit prediction models for the batteries);
- the current level of short circuit risks obtained from the performed numerical simulations reveals that there is still work to do in order to arrive to more realistic short circuit risk predictions, in terms of risk localization (distribution within the battery pack) and even more for the computed absolute values: even if these considerations are made on a rather qualitative basis (no experimental data for validations at full car level were available in the project), it seems that these ROM are currently under trained for what concerns low or null severity crash condition, as they predict high short circuit risk even when battery pack is not touched at all during a low severity impact. Probably the focus on appreciable to heavy battery module damages when training the UPSCALE ROMs induces a non-real high risk prediction due to an excessive sensitivity to low severity crash pulses, as such models are making not reliable extrapolations because they're forced to work out of the training domain. As the main target in the operational use of such ROMs is the capability to detect the transition border from no or neglectable risk to the minimum risk level that can activate a dangerous thermal event in the battery pack, the actual absolute levels of risk obtained in output appears to be not reliable enough, yet;
- another possible reason for the current behaviour of the ROMs could be a non-exhaustive number of cell reference deformation modes used during training phase for the classification of the battery pack situation under crash loading, as the effective dynamic deformation path developed during the full car simulation could not be matched/classified by the implemented deformation mode basis.

Since the primary goal of crash analysis is to identify the short-circuit initiation, as already said before, the main recommendation arising from this final UPSCALE analysis is towards future ROMs developments/refinements efforts, to be focused on the extension of ROMs training domains (i.e. including especially low severity cases and larger reference classification modes), so that a reliable assessment of the risk magnitude levels causing a short-circuit initiation can eventually be identified and operationally applied.

6 Figures

7 Tables