Protection of Lithium-Ion Traction Batteries in the Electric Car

Michael Funcke
Forschungsgesellschaft Kraftfahrwesen Aachen mbH
Germany

Sebastian Lovski
Sebastian Schäfer
Institute for Automotive Engineering RWTH Aachen University
Germany

David Sturk
Dominique Dufaut
Hakan Sundmark
Kyriakos Vavalidis
Per Gustafsson
Autoliv
Sweden

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ABSTRACT

The storage elements in an electric vehicle (EV) remain a key challenge to wide-scale, successful deployment of EVs that are appealing to customers and are adequately functional (e.g. in terms of range and drivability). State-of-the-art electric storage systems are lithium-ion batteries, offering approximately 0.5 km driving range per 1 kg of battery pack mass (see Funcke et al [1]). However, these battery packs require high level safety measures to avoid e.g. mechanical damage of the cells, which increases the pack mass again. In order to make a reliable statement about the battery safety at an early stage of development, detailed knowledge of the mechanical behavior of the cells as well as its reproduction in the virtual development process is necessary.

Based on a sample design of a main battery structure, the development process of the cell model is explained. The first steps are the integration of the design in a full vehicle and the determination of the dominant cell deformations, which are transferred to cell load cases. These mechanical abuse tests of cells deliver the input data for generating an adequate finite-element (FE) model, which offers the opportunity to dimension the battery pack and to add safety measures. With this simulation model inflatable structures as well as passive reinforcements for the traction battery are investigated.

To validate the simulation results, component tests on system level, i.e. complete battery packs, are conducted. The test is based on the full vehicle reference design load case, in this case the EuroNCAP pole side impact with a modified pole position and an impact velocity of 50 km/h. An analysis of the impact position is needed since the vulnerability to intrusion of the battery pack and the stiffness of the vehicle structure varies along the vehicle longitudinal axis.

These component tests confirm the simulation results and show the potential of inflatable structures and passive protection systems. Furthermore, it is possible to generate a FE model for lithium-ion batteries, which is applicable to full vehicle simulations.

Although it is possible to map the mechanical characteristics to the generated cell model, this model is limited to the investigated load cases, which have been the result of the battery position within the vehicle and the corresponding critical design load case. Since the battery may be placed in another position within the vehicle and the arrangement of the cells may change, the cell model is not universal. However, it is extensible to other load cases.

Overall, the results from the study with the inflatable elements show clearly the benefit of those structures. With low additional mass a high positive effect (e.g. lower intrusion) is achieved, which means the ratio of the incorporated mass to the reached protective effect is lower than with passive protection systems.

INTRODUCTION

In the field of electric vehicles, lithium-ion batteries are widely utilized. In general three major types of battery cells are used: prismatic, cylindrical and pouch cells. A representative prismatic cell is protected by a case made of metal or hard plastic. Cylindrical cell cases often consist of aluminium. Pouch cells use lightweight cases made of layered foil consisting of sheets of polymer and aluminium jointed at the edges of the flat cell. Usually multiple cells are grouped into modules and several modules are grouped into a battery pack. Using different circuit conditions (in parallel, in series) different voltages or different capacities at the same voltage are achievable. The assembled main battery pack (MBP) is installed within the electric vehicle, mostly in the safest position e.g. in the tunnel area.
Funcke et al [2] as well as Choi et al [3] reported their effort on modelling lithium-ion pouch cells using FE. Sahrei et al [2] model covered the force-displacement behaviour for 3-point bending as well as for axial and through thickness compressions. The FE model of Choi et al [3] focussed on a more detailed behaviour of the cell layers e.g. local stress and strain. Therefore three-layered shell elements were used, which represented the pure metal substrate (Al or Cu) and the coating (e.g. Cobalt or Carbon coating). The electrolyte layers, which nodally connects the shell layers, were modeled using link elements. However, both simulation models are limited to the tests used for the validation which do not necessarily represent the loads acting when the MBP is placed in an electric vehicle. In addition, the high number of nodes and elements restricts the use of the model to cell tests. With the aim to design a MBP and to apply a passive as well as an active protection system, in means of inflatable elements, for the OSTLER project a battery model was needed which was applicable to full vehicle simulations. The following study was part of the european founded project OSTLER which focused on the development of smart concepts for physical integration of battery packs in electric vehicles. For this purpose, the MBP was placed outside the common safe zone in an area that presents higher frequency of intrusions – i.e. MBP under the front seats, transverse to the driving direction and stretching out into areas close to the vehicle sill. Using a simplified battery cell model, for the given battery location relevant full vehicle load cases as well as associated cell load cases were derived using a simplified FE cell model. For these load cases mechanical tests were carried out and gradually built up a full vehicle-enabled cell model, which enabled the investigation of inflatable elements and passive systems to provide protection to the battery. Using systems tests, the final design of the systems was validated against the simulation results. The following investigation was carried out using the explicit solver LS-DYNA.

**DEVELOPMENT OF A FE MODEL FOR LITHIUM-ION POUCH CELL**

First, the selection of cell type for this study was carried out. For this purpose, it was necessary to determine the full vehicle load cases, which had to be considered for the crash simulations. By analysing the German In-Depth Database (GIDAS) (see Funcke et al [1]) the impact velocity, direction and the impacting object of the 2 % of accidents with the highest intrusion was evaluated.

**Relevant Full Vehicle Load Cases And Derivation of Cell Load Cases**

The 2 %-tile area consisted of 82 collisions. If the incident direction is numbered according clockwise, with 12 clock corresponds to a frontal impact, it was found that in 45 cases the impact object was another vehicle with the predominant impact direction between 12 and clockwise to 7. In the other cases the impact object was an object which were predominant in the area between 8 and 2 with major peaks at 9 and 12. Beside the impact direction the impact velocities were analysed with the result that to cover at least 50 % of all crashes the following load cases had to be considered within the project:

- EuroNCAP ODB
- FMVSS 208 (56 km/h, 0° impact, 50 % male dummies)
- FMVSS 301
- EuroNCAP pole side impact with 50 km/h and varied pole position

First draft designs for MBP, containing the three different cell types each, were installed as part of the electrification process in the FE model of a Toyota Yaris model which was publicly available. Placing the MBP transverse underneath the frontal seats meant the battery reaches in an area where frequently deformations occur in case of an accident. Performing the four load cases and analysing the deformations of the MBP housing as well as the deformation of the cells inside, the pouch cell was identified as cell with the highest deformation and most critical cell type for this MBP location and design. Due to the location relevant intrusions only occurred within the high speed EuroNCAP pole side impact. Out of the occurring cell deformations as well as the plastic strains within the cells (see Figure 1), three load cases were identified, which the simulation model of the cells had to fulfil and which were used for the built-up process. Specifically, these were the load cases through thickness compression, three-point bending and the clamped cell. Within the last-mentioned load case the pouch cell is clamped according to the installation condition in the MBP between two frames.

For the following study, lithium-ion pouch cells with a capacity of 40 Ah and 3.7 V were used, which were fully charged for the tests. This enabled to detect whether a short circuit or internal damage occurs during the
test. To avoid personal injury and to increase security the cell tests were carried out using a freestanding and foreclosed housed test bench, which enables the application of a maximum force of 30 kN. Any escaping gas could get vacuumed by the built-in ventilation.

Based on the experiences made by Sahraei et al [2] the test series began with the through thickness compression in order to determine the material parameters for the solid layers representing the electrolyte. Therefore, the assumption was made that the other layers do not contribute to the overall performance within this load case. Starting from this load case, the simulation model was gradually expanded.

**Through Thickness Compression Test**

Although a pouch cell consists of a high number of layers (e.g. ~205, Choi et al [3]), the number of layers was reduced in order to reduce simulation time and to generate a simulation model applicable to full vehicle simulation. The simulation time step, which depends on the smallest element length within the simulation model and is called courant criterion [4], should not be lower than the value 1.112e^−6 s, which was the time
step defined in the full vehicle simulation. The cell model (see Figure 2) consisted of five solid layers representing the electrolyte layers, six layers of aluminum representing the pure metal layers, a layer representing the border area of the cell which was used for clamping the cell as an element row closing the cell at the sides. The different layers were not coincident connected using shared nodes, like done by Sahraei et al [2]. Instead, the layers could slide to each other using a common LS-DYNA single surface contact [5]. As input for the material model MAT_83 served a stress-strain curve which was calculated out of the testing force-displacement-curves.

![Figure 2. Cell modeling and through thickness compression test results vs. simulation.](image)

Using this approach provided very good results which can be seen comparing the force-displacement curves of the simulation compared to the three tests (see Figure 2).

**Three-Point Bending Test**

The determination of the Al layer thickness, the contact parameters between the electrolyte and the Al layers as well as the cell closure thickness formed the next step. For this purpose, the three-point bending test was the best choice since the cell surrounding does not contribute, or only to a very small part, to the bending stiffness within this load case. As abutment as well as impactor served round profiles with 40 mm diameter (see Figure 3), which covered the entire width of the battery cell. The bending load case was carried out as in the entire vehicle occurring about the vertical axis in parallel to the electrical contact areas of the cell. Using a layer thickness of 0.4 mm for the pure metal layers, a thickness of 0.04 mm for the closure and a friction of 0.15 between the layers it was noted that a good correlation between simulation results and the tests was achieved. Both the force-displacement curves as well as the qualitative behavior were in good agreement.

**Clamped Battery Test**

In the last validation step, the cell was fitted under mounting conditions between two frames similar to the MBP (see Figure 4). As required by the cell manufacturer, the through the frames transmitted clamping force was applied only to the border area of the battery. Since the behavior of the battery should be examined and the mechanical effect of the framework should be kept as low as possible, an impactor with a length of 100 mm and a diameter of 40 mm was used, which was placed centered in height and width of the battery. During the load application, on the one hand the battery slid out of the frames; on the other hand the battery was locally deformed in the impact area as well as in the border area. As a result, the material and the thickness of the border area could be determined as well as the friction parameters between border and frame. The highest agreement with the experimental results could be achieved by using a Part_Composite [5], which enables to apply multiple materials and associated thicknesses to one single layer of shell elements. Most suitable was a layout consisting of a layer of aluminum (thickness 0.4 mm) surrounded by a layer of a plastic material (thickness 0.25 mm).
Both initial force and the force-displacement curves of simulation and experiments were in a good agreement (see Figure 4). It must nevertheless be noted, that the simulation model considered no strain rate as well as temperature effects. After generating a simulation model for the pouch cells the design process of the inflatable element and the passive reinforcement as battery pack protection started.

PROTECTION OF BATTERY SYSTEMS USING INFLATABLE ELEMENTS

Including the gained CAE model of the pouch cells into the full vehicle simulation model, the loads as well as the geometrical interaction between battery system and the surrounding vehicle structure were analysed using different impact points of the pole. In this analysis, it was found the highest intrusion into the battery system occurred when the pole hits the center of the modules. Another finding was that the vehicle structure in means of the inner sill hit the battery with a velocity of 9 ms/s and thereby increased the pole diameter due to the wrapping to 325 mm (see Funcke et al [1]). These parameters were transferred into a battery system test, where the vehicle structure was skipped and the battery was hit directly by the pole with the higher diameter. This test was used to further speedup the virtual design process as well as to run the final physical evaluation of the protection concepts.

Since the development of a passive protection is state of the art in protecting battery systems, the following passages focus on the development process of the active protection system. Nevertheless, there is some information included since the passive protection was used as benchmark for the active system.

Concept of Passive Protection

The passive reinforcement consisted of three stages compared to the unreinforced battery pack; an increased wall thickness, an additional load path by adding longitudinal beams within the battery housing and an energy
absorbing foam block between the battery and the vehicle structure. After the virtual optimisation of the named measures, the passive reinforcement caused a weight increase of 37 kg but reduced the intrusion into the main battery pack (MBP) from 157 mm to 66 mm (58 %) compared to the unreinforced reference structure. The reduction within the simulation loop was predicted with 69 % (from 157 mm to 48 mm). Since the intrusion of the unreinforced battery pack was predicted with a high accuracy, the reason for the inconsistency is not located in the cell model. Rather, the reason is suspected in other model parameters.

**Concept of Active Protection using Inflatable Elements**

The installation of inflatable elements made it possible to create new energy absorption paths and to reduce the load onto the MBP. As a consequence it was possible to reduce the deformation and the stress of the cells in case of a crash. As shown in Figure 5, in the case of a pole side impact with a current lateral in-crash sensing, the active solution of battery pack protection consisted of a “structural” airbag, which provided both a certain structural rigidity against intrusions as well as good energy absorption potential.

![Active Protection concept](image)

*Figure 5. Active Protection concept*

Such a structural airbag resembles a normal airbag from the point of view of its constituent components, i.e. mainly a fabric cushion, a pyrotechnic inflator and a wire harness to the standard airbag ECU, but differs greatly in the performance characteristics. The cushion consists of a highly reinforced fabric capable to withstand gas pressures more than 20-30 times that of a passenger airbag and also capable to resist mechanical aggressions from its surroundings. This high pressure made the cushion becoming almost rigid and, compared to metal reinforcement, had the potential of a lower weight and a reduced packaging (both critical to EVs). It was placed in the free space between the battery pack and the sill, right in front of the lower part of the battery pack in order to take advantage of its rigid bottom plate. The FE model of the battery pack including the FE model of the pouch cells made it possible to define the mechanical requirements for such a structural airbag.

**Active Protection efficiency**

With an added weight of 4 kg (2 kg for both sides of BP) compared to the unreinforced reference structure, the intrusion into the battery pack was reduced from 157 mm to 121 mm in the physical tests. This was a reduction of 23 % taking the unreinforced battery pack as reference. The reduction within the simulation loop was predicted with 28 % (157 mm to 116 mm). Compared to the passive reinforcement of the battery structure, the weight-specific intrusion reduction (intrusion reduction [%]/added weight [kg]) of the active system was over four times higher (1.57 %/kg passive system to 7 %/kg active system).
CONCLUSIONS

The relevant modeling of cells, which could be elaborated through the approach presented, offered the opportunity to dimension and design the battery pack casing and the associated safety measures. It enabled to investigate the protection of the battery pack using an alternative system in means of an inflatable element. The investigation showed that the protection of the main battery pack by an active structure is possible (as presented for the worst load case, with the MBP as defined above). It successfully reduced the intrusion into the battery system. The additional mass of the active system was small compared with the mass of the passive reinforcement.

Smartly combining benefits of the active protection with a passive protection according to the protection requirements of the MBP, along with an optimization of MBP construction allows for a wider MBP and therefore an increase in EV’s driving range with favorable weight balance (added weight by active structure, reduced weight of casing of MBP).

The used approach of identifying the cell loads, generating a cell simulation model and the afterwards design process can also be seen as guideline for future investigation concerning the crash safety of battery packs. Once generated, the cell model can be applied to various investigations (battery pack position, pack dimensions,..) as long as the cells experience the same type of mechanical loads the model was validated for.

REFERENCES