Chapter 2
Battery Modelling for Crash Safety Simulation

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Abstract Finite element battery models used for crash simulation are effective tools for designing safe, lightweight battery systems for electric and hybrid electric vehicles. This chapter describes the currently available methods for integrating batteries into full-vehicle crash models and discusses their limitations at the present state of implementation. Innovative modelling approaches are able to determine the specific battery failure modes, such as short circuits and (electrolyte-) leakage. These methods are discussed and evaluated here based on their future applicability in the vehicle design process.

Keywords Finite element method · Crash simulation · Battery crash safety · Battery deformation and failure · Jelly roll

2.1 Introduction

Due to the conventional areas of application for lithium-ion batteries (e.g. mobile phones or laptops), battery research and the corresponding development of novel modelling techniques has focussed primarily on goals such as improved capacity, power and durability. This is also the main expertise of the battery producers and the associated scientific community. With the increased application of lithium-ion batteries in modern electric vehicles (EV) and hybrid electric vehicles (HEV), the requirement of crash safety has become important. Therefore, the automotive industry requires highly predictable, applicable and efficient methods for simulating battery deformation and failure in crash test situations.

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A. Thaler and D. Watzenig (eds.), *Automotive Battery Technology*,
Automotive Engineering: Simulation and Validation Methods,
DOI: 10.1007/978-3-319-02523-0_2,

2.1.1 Motivation

The demand of electric energy for high vehicle ranges in HEVs and EVs results in batteries with weights of up to several hundred kilograms and considerable volumes. Since the deformation of the battery can lead to hazardous situations, one aim of the current vehicle development is to prohibit any significant deformation of the battery in crash tests. This can only be achieved by tightly restricting the available space for the battery system and high—but heavy—stiffness of the battery pack.

In order to enable the development of long-range, lightweight EVs, the engineer needs a better understanding of the battery deformation and failure characteristics, as well as new simulation tools. These tools must have the same accuracy and reliability as the numerical vehicle development methods in use today. In this way, it will become possible to develop structural battery concepts with optimal use of the available space at minimum weight and with increased crash safety.

2.1.2 Specific Hazards of Electric Vehicles

Crash safety for batteries means that an accident does not cause dangerous voltages, vent gas, heat or fires, which could harm the environment, passengers, pedestrians or rescue teams. This can be accomplished by the battery design itself, together with structural protection measures implemented during the vehicle integration.

Hazardous voltages of 400–800 V can lead not only to human injury, but also to short circuits and arcing, which can generate heat and trigger additional failure modes in the battery system.

Short circuits within the battery cells' active material or due to contact of conducting components with different potentials can cause electrolyte gas to develop and can lead to degassing or the leakage of cell-internal fluids. These vent gases and liquids are flammable and possibly toxic and therefore must not come into contact with passengers.

The worst-case scenario in the car crash is the combination of vent gas or leaking fluids and ignition points, such as arcing or hot spots. This combination can lead to fires and exothermal reactions in the cell itself, with unpredictable consequences for trapped passengers. As an illustrative example, Fig. 2.1 shows the exothermal reaction of a single charged lithium-ion metal-oxide cell caused by severe deformation under laboratory conditions.

2.1.3 Applicable Design Approach for Batteries

In order to design crash-safe batteries for EVs and HEVs, validated and highly predictive battery models are needed in the development process. They must describe

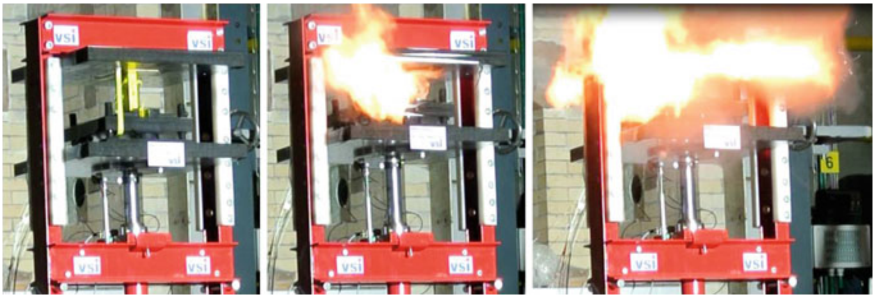

Fig. 2.1 Exothermal reaction of a single charged cell under severe deformation—test conducted in cooperation with TU Graz, Vehicle Safety Institute

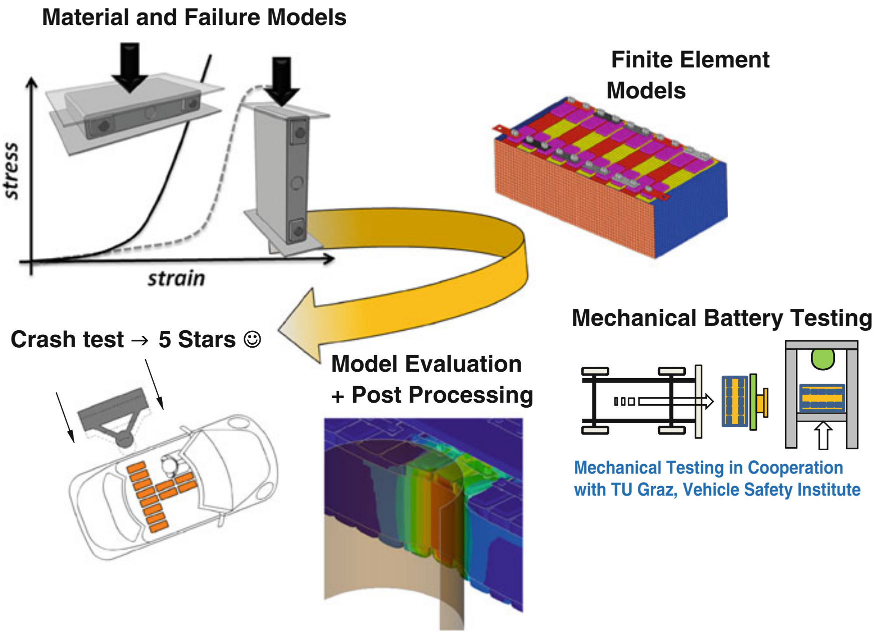

Fig. 2.2 Suggested development approach for validated finite element battery models used for the design of crash-safe electric vehicles

deformation, mechanical and electro-chemical failure and have to be applicable in the current car crash finite element (FE) models.

Figure 2.2 shows the steps suggested for the development of a validated FE model of a battery. The first step is the mechanical testing of a battery cell. This enables the build-up of suitable models for the single cell, with characteristic deformation and failure behaviour. Battery module or pack models can then be created by applying state-of-the-art FE techniques. The derived models must be validated in specially designed battery module or pack tests.

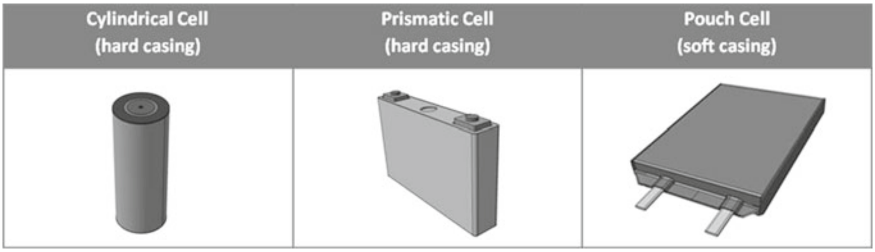

Fig. 2.3 Schematic drawings of the main cell types used in the automotive industry

This chapter describes the boundary conditions of the vehicle development process, the required tests and the individual steps for the derivation of a battery model, followed by summary of the current state of the art and recommended further development.

2.2 Automotive Battery Design

In order to discuss the special task of developing applicable battery crash models for the automotive industry, it is necessary to describe briefly the build-up and design parameters of EV and HEV battery packs.

2.2.1 Modularity and Battery Components

Battery cells are the smallest unit in the battery. The three common types are the cylindrical, the prismatic and the pouch cell, as shown in Fig. 2.3. Due to their sheet metal casing, cylindrical and prismatic cells have a higher structural integrity than pouch cells, but they are also heavier. The casing is often made of quite strong aluminium sheets, in contrast to the polymer, coffee bag like, cover of the pouch cell.

The main component of the cell is the active material, often referred to as jelly roll.

Other components of a working battery cell are current collectors and terminals, the aforementioned cell casing, spacers and isolators within the casing, and a safety pressure valve. A lithium-ion cell usually features a voltage of about 2.5–4.2 V between the two terminals, depending on the chemistry, the load situation and the state of charge (SoC). Since powerful electric vehicle motors work at voltages of about 200–800 V to be efficient, several hundred cells in series connection are needed to provide this elevated voltage. Cells are grouped to modules for several mainly practical reasons, including relatively low voltages (< 60 volts), sizes and weights that can be handled by a single worker, and modularity.

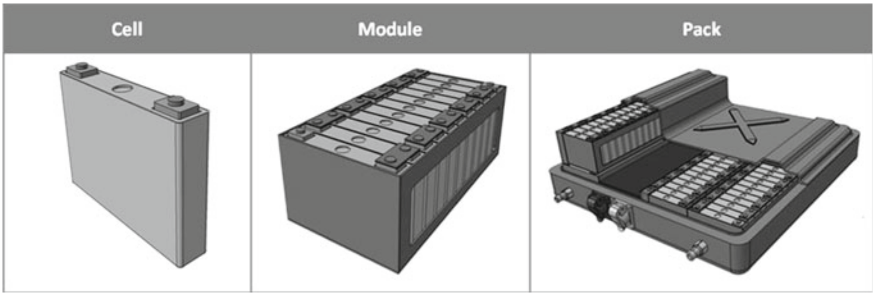

Fig. 2.4 Drawings of the modular parts of a battery: a single battery cell (*left*), a battery module (*middle*) and the complete battery pack (*right*)

Modularity helps reduce the amount of different parts within a battery pack and allows packs to be designed using the same basic modules to handle different energy content, voltage and designs requirements. The battery pack contains all the cells and modules of the battery. It also usually contains the cooling part of an environmental system to keep the cells within their admissible temperature limits, a battery management system (BMS), and its associated hazardous voltage (HV) protection system. Figure 2.4 shows drawings of the modular parts of a battery.

Since safety is a mandatory requirement, the pack is hermetically closed, with degassing vents leading possibly dangerous electrolyte gases away from the passenger compartment. The battery system, as the highest integration level, contains the battery pack and all electrical cables, sockets, and sensors distributed throughout the vehicle, which are needed to run the battery in the vehicle environment. Thus, within the battery system, component size spans several orders of magnitude, from single layer active cell materials of 1/100th of a millimetre thickness to the battery pack of 1–2 m in width and length and several hundred kilograms of weight.

2.2.2 Safety-Relevant Design Parameters

In order to enhance crash safety, dangerous conditions causing short circuits or contact of cathode and anode due to separator damage must be avoided, as they can lead to hot spots and subsequent electrolyte decomposition, heat and vent gas generation. Therefore, one must examine the main influencing factors that determine the hazards in the battery and facilitate their consideration during the design process. The design parameters at the cell level are very much constrained by electro-chemical design requirements, and the chemical reactivity of the jelly roll or active material depends strongly on the chemistry used. Soft or hard casing and the form factor [1] have a strong influence on the module design and module failure characteristics. For the battery module or battery pack, the introduction of crash safety features is a focus of the development. Both crash and transport safety can be improved by the

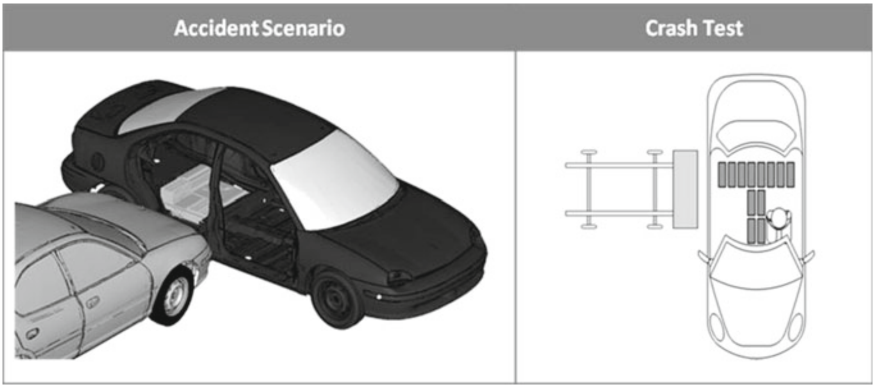

Fig. 2.5 Non-standardized crash test with an EV; FE model of the crash test with masked components for visibility of the battery under the back seat (*left*), schematic drawing of the crash with possible battery positions (*right*); FE Model courtesy of National Crash Analysis Center (NCAC)

appropriate design of casing, joints and isolators. The aims are to avoid possible contacts of electric conductors and to restrict the deformation of the battery cell to uncritical levels.

Finally, the choice of the battery pack geometry and position and the structural design of the vehicle are the main safety-relevant design parameters when integrating the battery pack in the vehicle.

For the design, it is a safe way to prohibit any deformation of the battery itself in order to eliminate the possibility of any hazardous event. Therefore, the batteries are grouped in structurally stiffened and reinforced compartments in the vehicle, where no deformation is expected in standardized crash tests (Fig. 2.5).

2.3 Structural Vehicle Design Process Including Batteries

This chapter gives a short overview of the modern structural vehicle design process and its dependence on FE simulation. The proposed methods are described, and the performance specification for a FE battery model is defined.

Modern vehicles are designed according to many different requirements. Apart from the obvious ones (e.g. saleability, through exterior and interior design or performance and drivability), one very important and legally binding aspect is the vehicle's safety performance in an accident, as schematically shown in Fig. 2.5. The focus is on protecting the individuals involved and reducing accident-related injury. The laws differ from country to country, but generally the United States (US) FMVSS[1] and the European ECE[2] regulations form the basis. On top of these laws, widely accepted

[1] FMVSS: Federal Motor Vehicle Safety Standards.

[2] ECE: Economic Commission for Europe.

consumer test procedures enhance the safety requirements even further. In Europe, this is the Euro NCAP consortium[3] and several smaller national organisations, as well as companies such as the German ADAC[4] or the British Thatcham Research. Modified NCAP programs are also used in China, Australia, Brazil, the US and Japan. In the US, the IIHS[5] establishes additional performance criteria. Common to all these tests is that standardized full-vehicle crash tests that simulate the most common and dangerous real-world accidents must be performed under strict predefined conditions in order to rate and compare the vehicles performance regarding vehicle safety. It is common practice for OEMs to strive for good results in these consumer tests, as they are widely known and respected.

2.3.1 Standard Approach and Requirements

In order to cope with this variety of requirements from legislative and consumer tests and to accelerate development time, simulation methods are used throughout the vehicle design and development process [2]. For structural integrity calculation and crash simulation, explicit FE methods [3] are normally used. Several crash solvers are commercially available. The most common ones are Abaqus, LS-Dyna, Pam-Crash and Radioss.[6]

Although usually cheaper than full-scale crash tests, crash simulations are limited by the costs of computer power. Since calculation time in explicit FE solvers depends on element number and size, only structurally important and necessary components are normally included in the model. As computer power increases, more detailed and better results can be obtained. The FE mesh of a full-vehicle model can therefore easily surpass 2 million calculation nodes and elements, with a characteristic length of between 2 and 10 mm, with 4–5 mm being the current standard. With the introduction of detailed battery models, node and element numbers will increase significantly.

2.3.2 Batteries in Crash Tests and Crash Simulation

As of 2013, a combination of transportation laws and recommendations[7] are used to rate battery safety in traction-battery-equipped vehicles, and standard crash tests must also be passed. However, battery cells show uncritical mechanical deformation potential in specially designed tests. To use this potential, it is necessary to fully understand the mechanical deformation and failure behaviour of batteries. FE battery

[3] NCAP: New Car Assessment Program.
[4] ADAC: Allgemeiner Deutscher Automobil-Club e. V.
[5] IIHS: Injury Institute for Highway Safety.
[6] SIMULIA Abaqus FEA, LSTC LS-Dyna, ESI Group PAM-Crash, Altair Engineering RADIOSS.
[7] 38.3 Drop Tests [4], FreedomCAR [5], EUCAR hazard levels.

Fig. 2.6 Picture of a cylindrical cell with an aluminium casing (*left*), the CAD model of the cell (*middle*), and the FE model (*right*)

models, which must be able to depict this behaviour, are becoming essential for optimising location and structural reinforcement for an acceptable cell deformation.

2.4 Finite Elements Model of the Battery

The integration of the battery pack in crash-safe electric vehicle development also means integrating the battery model into the crash simulation, including all components that are structurally relevant for the battery. This can be done best by using the already established explicit finite element solvers and methods and adapting them where necessary.

FE solvers for full-scale vehicle crashworthiness simulation are limited by element size and time step in order to maintain a manageable model size and thereby keep the calculation time within manageable limits. Generally, FE models are derived from complete three-dimensional computer aided design (CAD) models that accurately represent the real object. Construction drawings can be derived directly from these CAD models. Generally, an FE geometric model mesh is composed of one-dimensional bars and links, two dimensional sheet-like structures and three-dimensional volume components [3]. The reduction of geometric details is one of the constraints when building an FE model, as details smaller than 4–5 mm are omitted or replaced. As an example, Fig. 2.6 shows the differences between a cylindrical cell and its CAD and FE models, and Fig. 2.7 shows the individual components of this cell and the corresponding parts in the FE simulation.[8]

The mechanical description of all structurally important battery components is done in the same way as for conventional ones, that is by using a node and element-based geometry, superimposed with stress-strain curve-based material models. For the simulation of other current carrying components (e.g. busbars and HV cables),

[8] All images of cylindrical cells in this chapter show type 26650 cells (26 mm diameter and 65 mm length).

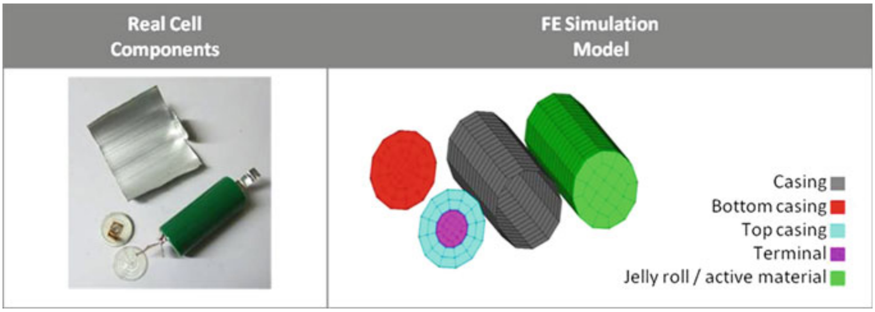

Fig. 2.7 Picture of the battery cell components of a cylindrical cell with an aluminium casing (*left*) and the corresponding parts of the FE model (*right*)

new methods are needed for the modelling of deformation and failure. For all components, suitable material models need to be developed to adequately describe the mechanical behaviour of the different battery components. The following chapter describes and discusses the applicable methods.

2.4.1 Modelling of Mechanical Deformation

The basis of an accurate failure evaluation is the modelling of the deformation which causes the failure. This chapter briefly discusses available methods for the different battery components.

Battery pack: The main load-bearing component of the pack is the casing, which should be leak-tight. The casing can be made of sheet steel or lightweight materials such as aluminium or fibre-reinforced plastics. These materials are also found in the body-in-white structure, and various plasticity-strain-rate-dependent material models are available in the crash solvers [6–12]. The elastic deformation of connectors (e.g. spot welds, rivets or screws) can be modelled by link elements with corresponding elasticity parameters [7, 11].

Battery module: As in the battery pack, the deformation of the casing, conductors, isolators and joints can be modelled with standard FE methods. The main difference is a possible pre-loading of the modules, which is done in order to apply a constant pressure on the battery cells. This is necessary in order to ensure a high electrochemical lifetime of the active cell material. The pre-loading can influence the module's stiffness significantly. In this case, it is necessary to model the pre-loading process and map the elastic pre-deformation and pre-stresses on the crash model. This can be done by the available Forming to Crash methods in most common crash solvers [13].

Battery cell: The cell has very strong anisotropic deformation behaviour, as shown in Fig. 2.8 for a cylindrical cell. Depending on the cell type (Fig. 2.3), the casing can be important for the battery cell stiffness. Here again, available standard FE methods

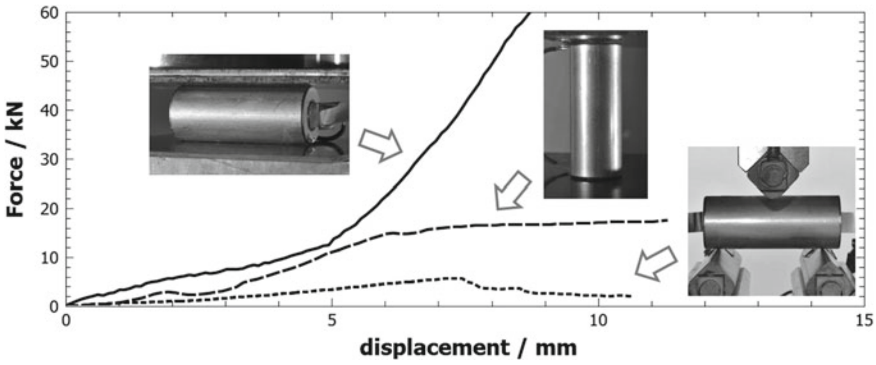

Fig. 2.8 Figure with anisotropic deformation behaviour of cylindrical cells; compression tests normal to cell axis (*solid line*) and in cell axis (*dashed line*) and 3-Point-Bending tests (*dotted line*)—test conducted in cooperation with TU Graz, Vehicle Safety Institute

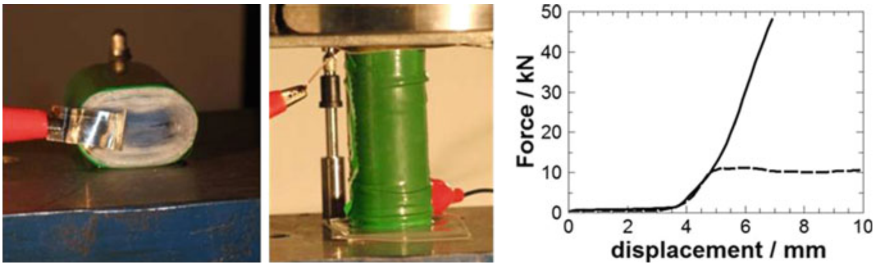

Fig. 2.9 Anisotropic jelly roll deformation of a cylindrical cell without casing; compression normal to the cell axis (*left*) and parallel to the cell axis (*middle*); (*right*) force versus displacement curves of normal (*solid line*) and parallel (*dashed line*) compression tests

are used to model the cell casing. At this level, relatively small features of the cell can also be important for their deformation and subsequent failure behaviour (e.g. current collectors in the cell and details of a cylindrical cell are shown in Fig. 2.13).

Here, it can be necessary to simplify the actual geometry, since an applicable FE crash net has a mesh size of about 5 mm, as shown for a cylindrical cell in Fig. 2.7. This can be done if the local deformation effects are understood and taken into account in the subsequent failure assessment.

The active material, the *jelly roll*, contributes to the cell stiffness. Depending on the loading direction, it can be a major load-carrying component with a strong anisotropic deformation behaviour (shown in Fig. 2.9).

In contrast to the casing materials and joints, the jelly roll itself is a new material in the crash simulation. Depending on the loading direction, mainly the porous active material (e.g. graphite, metal oxide or separator) or the conducting electrodes (e.g. aluminium or copper foils) are compressed and contribute to the cell stiffness.

There are two different approaches to this problem. The bottom-up approach is based on the idea of modelling the individual layers with their appropriate material

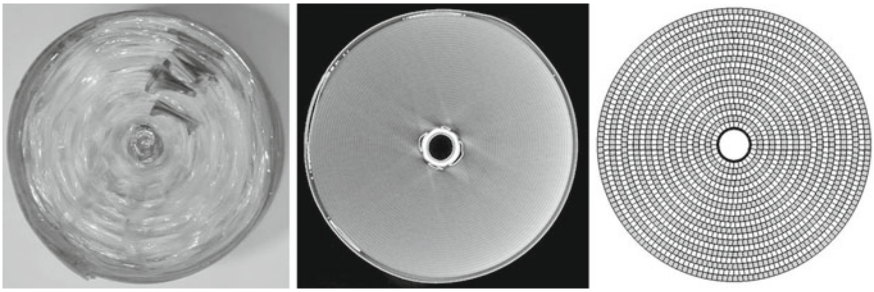

Fig. 2.10 Photo of a cylindrical jelly roll with a steel tube in the *centre* and a diameter of 26 mm (*left*), an X-ray tomography image of the cross section (*middle*) and the associated detailed finite element model (*right*)—X-ray tomography by the Austrian Foundry Research Institute (ÖGI), Leoben, Austria

behaviour [14]. Figure 2.10 shows cuts through a cylindrical jelly roll and a detailed model as an example, although not every single layer is modelled, the discretisation allows the investigation of the microscopic deformation behaviour. The fine mesh, necessary for this method, leads to high calculation times that are not acceptable for the crash simulation. Another problem is the measurement of the material data of the thin metal sheets, the electrolytes, the separator and the porous active material. Since the measurement is quite complicated, the mechanical properties are partly unknown or only available for different testing conditions (e.g. higher sheet thicknesses or different electrolyte levels). This approach is a more scientific one, which is suitable for investigating the deformation mechanisms in the cell and for deriving the macroscopic deformation behaviour from the jelly roll structure.

One applicable top-down approach is based on a macroscopic model of the jelly roll [15, 16]. Substitute models are used for the jelly roll in the crash model. For the parameterization of the model, the anisotropic deformation behaviour is measured by tests on the jelly roll or on individual battery cells (Fig. 2.11). Available honeycomb material models [7, 11] offer the ability to define the stress-versus-strain curves for each direction separately. The resulting model, which can describe the external deformation behaviour and deformation forces, is applicable in the crash simulation. Nevertheless, it does not describe the internal jelly roll deformation mechanisms and therefore cannot be used for the microscopic failure assessment.

2.4.2 Modelling of Material and Joint Failure

The failure assessment is based on an accurate description of the plastic deformation of the battery system's components and on the loads applied to the joints (Fig. 2.12). The mechanical failure has to be described, since it can lead to leakages (e.g. if the casing of a cell ruptures) or to a significant change in the deformation characteristic (e.g. if a load carrying component or a joint fails).

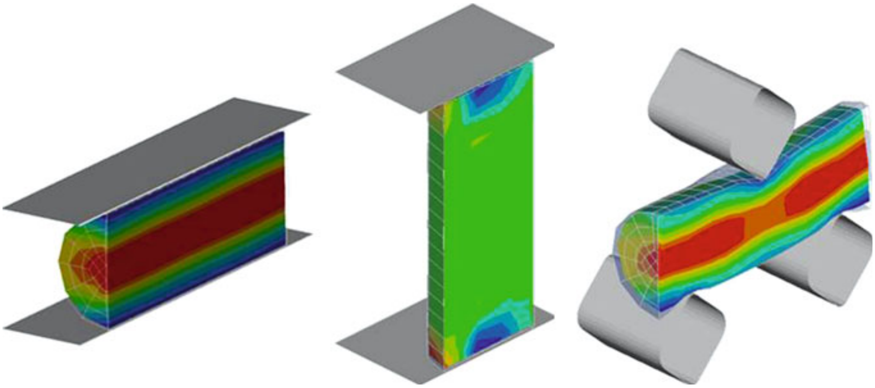

Fig. 2.11 Half finite element models of cylindrical cells with aluminium casing; compression tests normal to cell axis (*left*) and in cell axis (*middle*) and 3-Point-Bending tests (*right*)

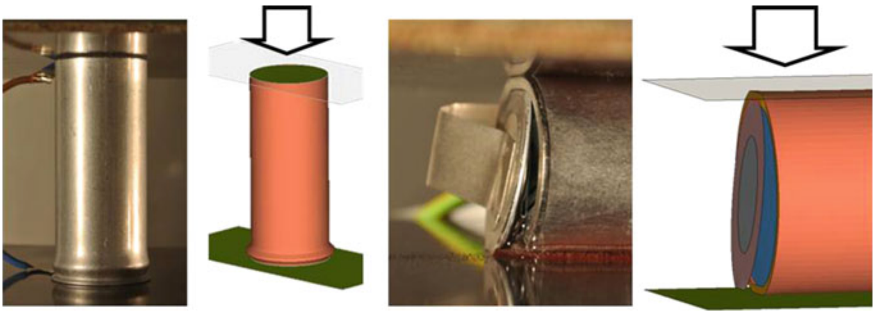

Fig. 2.12 Deformation and failure of compressed cylindrical cells with aluminium casing; comparison of experiment and FE-model wrinkle formation in axial compression (*left*) and failure of a joint line in compression normal to the cell axis (*right*)

Various fracture models are available for describing the failure of *metal sheets*. Most of these calculate a damage value based on the plastic strain weighted by functions of the stress state [11, 17–20]. If the critical areas (e.g. a part of the battery pack or cell casing) are loaded in tension, they will give quite accurate results. One still unsolved problem in the applied simulation is the failure due to the fracture mechanic mode III [21], which means shearing by loading in sheet-normal direction. This failure mode can appear if a relatively sharp and stiff component, which can be a part of the battery pack or an intruding object, cuts into the sheet metal and causes localized failure without major deformation of the surrounding area. This is a challenging task in crash simulation, and novel element models with promising solutions are currently under development [11, 22].

For modelling *composites and isolators*, one must consider that, depending on the polymers used, they can be more brittle than the sheet metals in use. Due to the absence of significant plastic deformation, stress-based criteria are more suitable for describing that failure mode. New failure models for composites and polymers are available and are a focus of current development [23, 24]. Here, the application of Forming to Crash [13] methods is even more important than in sheet metals, since the local material properties caused by the production process depend significantly on parameters such as local fibre or polymer chain direction [25].

The other main factor for the strength of the battery system is the *failure of joints*. Depending on the joining concept, a battery system can contain adhesives, spot welds, laser welds, screws, or rivets, for example. In recent years, the failure of joints has been an important research topic in crash simulation. Therefore, various models for adhesives [26] and single-point connections such as spot welds and screws [27–30] are available and ready to use (see Fig. 2.12).

For the *failure of the jelly roll*, as with the non-active battery components, the failure assessment is based on an accurate description of the deformation. Due to the jelly roll deformation, internal short circuits—between the electrodes or from an electrode to the casing—can lead to heat generation and exothermal reactions. Concerning the deformation modelling, there are two possible approaches to follow.

The first approach is the bottom-up or scientific approach, where detailed FE models are used to describe failure mechanisms (e.g. the fracture of electrode layers, critical contacts or delamination—examples shown in Fig. 2.13) [14]. This microscopic approach can support the understanding of the jelly roll failure mechanisms and the development of suitable macroscopic jelly roll material models. The main problem remains the measurement of the microscopic material or contact zone parameters in tests, which can replicate the conditions in the cell itself. Because various parameters (e.g. fracture strains and stresses of the electrolyte-soaked active materials and conductor foils) have to be derived e.g. from literature or complex tests, the simulation results have to be interpreted with great care.

The top-down approach, which is applicable in the crash simulation, assesses failure by the observed macroscopic deformation of the jelly roll. This deformation and the related electromechanical failure can be tested and measured quite accurately, compared to the underlying microscopic mechanisms. Thus, based on a series of tests with deformations similar to the crash loading, a failure model for a cell can be parameterized. This failure model can be implemented in the jelly roll material model (e.g. based on FE element stresses and strains) or evaluated in the post-processing process, e.g. critical outer deformations (see Fig. 2.14). The disadvantage is that this failure model is not a general solution, but rather is only valid for the specific cell type and loading conditions tested.

2.4.3 Modelling of Electrical Contact and Leakage

The jelly roll modelling introduced the first failure models, which are not implemented in standard FE solvers yet. However, these are not the only failure mechanisms that are currently lacking appropriate modelling techniques. The three

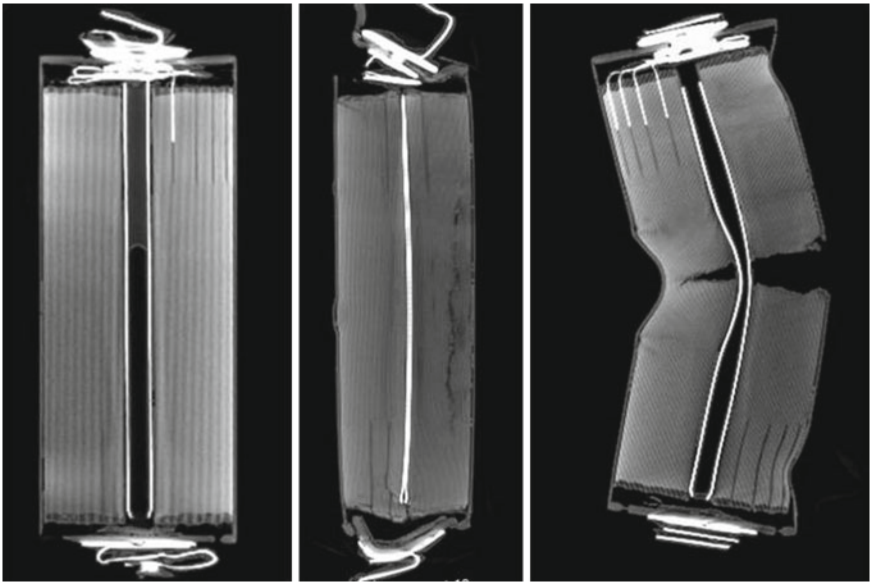

Fig. 2.13 X-ray tomography cross sectional images of cylindrical cell with a diameter of 26 mm of an un-deformed cell (*left*), a cell compressed normal to the cell axis (*middle*) and a cell deformed in a 3-Point Bending test (*right*)—X-ray tomography by the Austrian Foundry Research Institute (ÖGI), Leoben, Austria

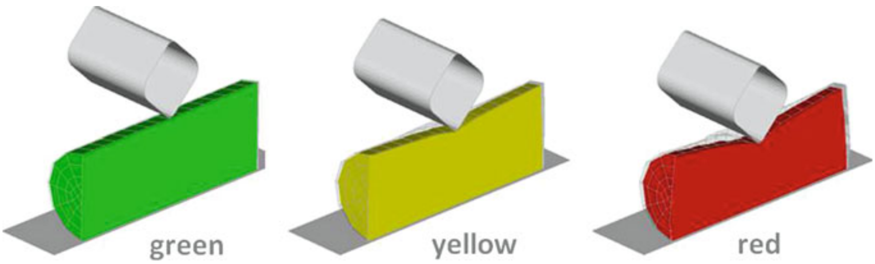

Fig. 2.14 Failure assessment of a cylindrical cell under compression based on the outer deformation; the colours indicate the criticality from *green* (uncritical) to *yellow* (critical) to *red* (failure)

additional main failure mechanisms are electric potential carryover, short circuits and leakage.

Hazardous voltages can emerge on bare conductive parts due to potential carryover, which is caused by contact with conductors following the crash deformation. Therefore, a risk analysis based on the components' potential difference and the contact situation is necessary.

In addition, short circuits due to failure of isolators and insulating layers are hazardous. For example, internal cell contacts from current conductors and casing,

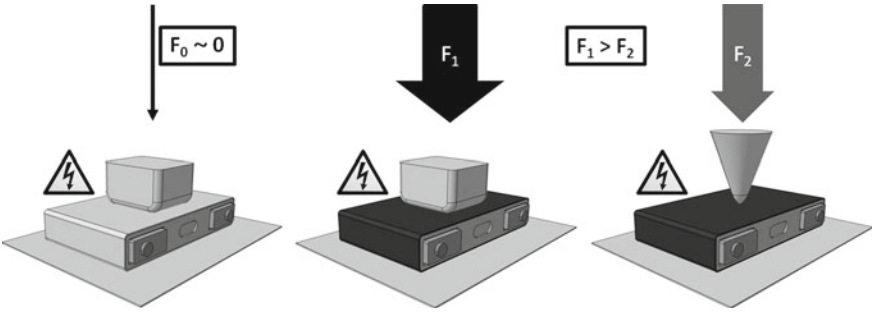

Fig. 2.15 Sketch of different possible short circuit situations between a battery cell and a conductive non-isolated metal impactor; short circuit between non-isolated can and blunted impactor without apparent force F_0 (*left*), isolated can and blunted impactor with high contact force F_1 (*middle*), and isolated can and sharp impactor with low contact force F_2 (*right*)

or an electrical contact between conductors and cell casing (see Fig. 2.15) can cause short circuits, which can lead to heat generation and exothermal reactions. To evaluate this risk, a detailed analysis of the contact situation in the FE simulation is mandatory, for example by evaluating the local pressures, taking into account the real local geometry (e.g. sharp edges) and the component's relative displacement. This difficult assessment of critical pressures and local geometries is not currently available in the crash solvers. Until detailed electrical contact models become available, a suitable post processing analysis is necessary.

Another hazard relevant for the post-crash safety analysis is the leakage of toxic electrolyte fluids and gas [31]. In order to ensure the sealing of the battery system, it is necessary to assess the integrity of the battery cell and pack casing. This can be done with methods for modelling the failure of the casings and joints such as laser welds, as discussed in Sect. 2.4.2, and an evaluation of the deformation and functionality of the seals and safety valves [32].

2.5 Conclusion

The crash safety requirements for lithium-ion batteries are currently met by avoiding any severe deformation on the battery pack, which is accomplished by limiting the available battery space in the car and by heavy structural protection measures in the vehicle.

This stands in strong contradiction to the design goal of increasing the range of electric vehicles by introducing high battery capacities and lightweight design. Thus, it is only possible to achieve this goal by allowing uncritical deformation to the battery (i.e. no heavy-weight battery packs and stiff components) and by developing new car concepts (i.e. optimal use of the available space).

Therefore, it is mandatory to develop reliable finite element deformation and failure models of the battery for the vehicle design process. This chapter has shown that the FE methods currently available and in use are able to describe the deformation and failure behaviour of the classic body-in-white structures and materials, such as the battery pack and module casing or the joints. Nevertheless, important tools are still missing, such as special material models for the deformation and electromechanical failure of the jelly roll, or electrical contact models for the assessment of local contact situations.

Since ongoing research and further development of finite element battery models is already showing promising results, these methods should soon become a standard tool in the vehicle development process.

Acknowledgments The authors would like to acknowledge the financial support of the "COMET K2—Competence Centres for Excellent Technologies Programme" of the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT), the Austrian Federal Ministry of Economy, Family and Youth (BMWFJ), the Austrian Research Promotion Agency (FFG), the Province of Styria and the Styrian Business Promotion Agency (SFG).

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http://www.springer.com/978-3-319-02522-3

Automotive Battery Technology
Thaler, A.; Watzenig, D. (Eds.)
2014, XIV, 129 p. 60 illus., 27 illus. in color., Softcover
ISBN: 978-3-319-02522-3