Modelling And Testing for Improved Safety of key composite StructurEs in alternatively powered vehicles

Collaborative Project
Grant Agreement Number 314182
Start date of the project: 1 October 2012, Duration: 36 months

Deliverable D5.1
Summary of evaluation criteria for evaluating the safety potential of APVs
Status: Revision 2

Lead contractor for this deliverable: FKA

Due date of deliverable: 31.05.2015  Actual submission date: 30.09.2015

Coordinator:
Dipl.-Ing. Dipl.-Wirt. Ing. Roland Wohlecker
Forschungsgesellschaft Kraftfahrwesen mbH Aachen
Steinbachstr. 7 - 52074 Aachen - Germany
Phone +49 241 8861 191, Fax +49 241 8861 110
E-mail wohlecker@fka.de

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)

<table>
<thead>
<tr>
<th>Dissemination Level</th>
<th>PU</th>
<th>PP</th>
<th>SEAM</th>
<th>RE</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public</td>
<td></td>
<td>Restricted to other programme participants (including the Commission Services)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restricted to partners of the SEAM Cluster (including the Commission Services)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restricted to a group specified by the consortium (including the Commission Services)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidential, only for members of the consortium (including the Commission Services)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Filename: MATISSE_20150930_WP5_D51_SummaryEvaluationCriteria_V2_FINAL.doc
©MATHISSE - This is the property of MATISSE Parties: shall not be distributed/reproduced without formal approval of MATISSE SC.
This reflects only the author’s views. The Community is not liable for any use that may be made of the information contained therein.
EXECUTIVE SUMMARY

Within MATISSE possibilities to evaluate the safety potentials of the alternatively powered vehicle (APV) equipped with CNG tanks or adaptive pressurised beams respectively were analysed.

To evaluate the safety of APV with electrified drive-train the hazards of the electricity within the vehicle and especially arising from the correspondent storage systems has been analysed. To quantify the hazards emerging from battery systems in crash situations the EUCAR hazard level table as well as test categories for batteries are recommended. An active EESS protection system using the MATISSE adaptive beam reduces these hazards.

Concerning criteria for the evaluation of the dynamic crash behaviour of the pressurised beams a three phase CAE approach was defined that considers the component, the test-rig and the full car level. To evaluate the adaptive beams safety on the physical level a test-rig set-up and loading conditions considering dynamic and static behaviour was proposed.

Concerning the evaluation of the dynamic loading capacity of CNG tanks evaluation criteria on the vessel level were presented that are on the one hand derived from the ECE R 110 drop test set-up, on the other hand the most relevant test conditions for the simplified impact test-rig developed within MATISSE were identified. To evaluate the damage of the vessel the visual comparison of the damaged area as well as the analysis of residual burst pressure were proposed.

To ensure the safety on the vehicle level the fulfilment of several important requirements given in the ECE R 110 regulation was considered to be indispenisible. Furthermore, criteria that can be read out of the simulation results concerning the vessel and its FRP layers were defined.

CONTRIBUTING PARTNERS

<table>
<thead>
<tr>
<th>Document Manager</th>
<th>Company/Organisation</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partner 1</td>
<td>CRF</td>
<td>Roberto Puppini, Stefano Menegazzi</td>
</tr>
<tr>
<td>Partner 2</td>
<td>Daimler</td>
<td>Matthias Nohr, Jan-Mark Opelka</td>
</tr>
<tr>
<td>Partner 3</td>
<td>FKA</td>
<td>Ralf Matheis, Michael Funcke</td>
</tr>
<tr>
<td>Partner 4</td>
<td>TU Graz</td>
<td>Gregor Gstrein</td>
</tr>
</tbody>
</table>

REVISION TABLE

<table>
<thead>
<tr>
<th>Document version</th>
<th>Date</th>
<th>Modified sections - Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>30.09.2015</td>
<td>All chapters</td>
</tr>
<tr>
<td>V2</td>
<td>30.09.2015</td>
<td>Final version</td>
</tr>
</tbody>
</table>
Table of Contents

1 Introduction .......................................................................................................................... 4
2 Safety of Electric Powered Vehicles .................................................................................. 5
  2.1 Safety Hazards for Occupants of EVs .......................................................................... 6
    2.1.1 Chemical Hazards .................................................................................................... 6
    2.1.2 Electrical Hazards .................................................................................................. 8
    2.1.3 Thermal Hazards .................................................................................................... 10
    2.1.4 Mechanical Hazards .............................................................................................. 10
  2.2 Outcomes of the Project SmartBatt ................................................................................ 11
  2.3 Outcomes of the Project OSTLER ................................................................................ 11
    2.3.1 Project Approach ................................................................................................... 11
    2.3.2 Evaluation Criteria .................................................................................................. 13
  2.4 Safety Potential of Adaptive Structures in EVs ............................................................... 16
3 Criteria for the Evaluation of Dynamic Crash Behaviour of Pressurised FRP Structures .... 18
  3.1 Criteria for CAE-based Evaluation ............................................................................... 18
  3.2 Criteria for Evaluation for Physical Tests ....................................................................... 22
    3.2.1 Mechanical Stiffness of Adaptive FRP Structures .................................................. 22
    3.2.2 Energy Absorption Capability of Adaptive FRP Structures ..................................... 23
    3.2.3 Reliability and Repeatability of Adaptive FRP Structures ........................................ 24
    3.2.4 Remaining Structural Capacity after Failure ............................................................ 24
  4 Criteria for the Evaluation of Dynamic Loading Capacity of High-pressure Storage Tanks 27
    4.1 Evaluation Criteria on Vessel Level ............................................................................ 27
    4.2 Evaluation Criteria on Vehicle Level .......................................................................... 29
  5 Summary ............................................................................................................................ 32
  6 Literature ............................................................................................................................ 33
1 Introduction

Within this deliverable, possibilities to evaluate the safety potentials of the alternatively powered vehicle (APV) equipped with the component analysed in MATISSE, compressed natural gas (CNG) tanks and adaptive pressurised beams, are analysed. For the evaluation process it is considered to exploit the computer aided engineering (CAE) approaches that were developed within the project.

In order to evaluate the safety of APVs it is necessary to analyses which hazards have to be considered. For that reason a hazard analysis with the focus on electric powered vehicles (EV) is presented within this deliverable. Based on the work that has been done in work package (WP) 1 of MATISSE and the project OSTLER the most important mechanisms and evaluation criteria concerning battery electric vehicles are presented.

Additionally, the safety potential of increasing the safety of EVs using the MATISSE adaptive beams is presented using the OSTLER concept vehicle. Furthermore, general evaluation criteria concerning the evaluation of the dynamic crash behaviour of pressurised fibre reinforced polymer (FRP) components are presented. This comprises criteria for the CAE-based evaluation as well as for physical testing. Concerning the evaluation of the dynamic loading capacity of high pressure storage tanks, criteria for the vessel and for the vehicle level are given.
2 Safety of Electric Powered Vehicles

The storage elements in an electric vehicle (EV) remain a key challenge of 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 [OST14]). However, these battery packs may require high level safety measures to avoid e.g. mechanical damage of the cells, which increases in most cases the pack mass and decrease the efficiency of the EV.

In the field of electric vehicles, lithium-ion batteries are already widely utilised for electric energy storage systems (EESS). In general three major types of battery cells designs are applied: prismatic, cylindrical and pouch cells (see Figure 1).

<table>
<thead>
<tr>
<th>Cylindrical cell (stiff housing)</th>
<th>Prismatic cell (stiff housing)</th>
<th>Pouch cell (soft housing)</th>
</tr>
</thead>
</table>

Figure 1. Cell designs (see Trattnig et al [TRA13])

A representative prismatic cell is protected by a case made of metal or hard plastic. Cylindrical cell cases consist in most cases of aluminium. Pouch cells are usually stored in 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 in modules and several modules are grouped to 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 typically in the safest position, e.g. in the tunnel area, to guarantee its structural safety. Additional attributes that affect the safety of the MBP are the structural layout of the MBP and of the vehicle.

Concerning the evaluation of the safety of EVs it is necessary to identify the relevant safety hazards arising from those drive trains and in particular from EESS. Here, the results of the MATISSE work package 1 (see deliverable D1.2 [MAT13]) are also considered as the work that was done within two other projects of the Seventh Framework Programme (FP7), OSTLER and SmartBatt. Taking account of the safety hazards of EV the safety potential of adaptive structures applied in EVs is considered with respect to these projects.
2.1 Safety Hazards for Occupants of EVs

EESS usually consist of a number of battery cells complemented by auxiliary components such as electronics or wiring packed in a protective case. These systems result in battery packs which are often referred to as high voltage batteries (HVB) [MAT13].

In order to deliver an acceptable level of protection for human beings, infrastructure and environment, such battery packs have to be handled under certain conditions. Exposure to mechanical loads not initially intended to be withstood by these EESS, such as crash scenarios, but also simple wrong handling can lead to an enormous hazard potential caused by such battery packs [MAT13].

The high energy density of batteries, i.e. lithium ion batteries, combined with easily inflammable electrolyte substances results in high risk potentials when EESS are exposed to unexpected or disadvantageous loading scenarios, which can occur during vehicle crashes. Thus such hazards have to be considered, if EESS are to be used in a larger number in future vehicle fleets [MAT13].

Examples for hazards and injuries that can occur when the EESS are loaded in a way, which they were not designed for (e.g. mechanical overload during a crash) are [MAT13]:

- Electric strike (EESS can reach high voltage due to serial connection of battery cells within a battery pack.)
- Blast / burst and fire due to spontaneous energy release during a thermal runaway.
- Emission of toxic gasses, electrolyte substances and particles during venting of the battery.

These mentioned hazard potentials are examples for issues and reactions of high voltage batteries to mechanical abuse. The abuse of single lithium ion battery cells or other battery cells can already show intense reactions like smoke emissions, fire and even explosions.

Hazard potentials w.r.t. EESS can be categorised in four large sections [SIN12]:

- Chemical hazards
- Electric hazards
- Thermal hazards
- Mechanical Hazards

These different types of hazards will be described and analysed in the following subsection. For details about the injuries that can arise from these hazards [MAT13] is recommended.

2.1.1 Chemical Hazards

In order to understand the risks inherent to batteries (i.e. lithium ion battery cells), it is crucial to gain a rough overview on the materials used in such components (sources ([MIK11], [SAH10], [WIE11], [DOW08], [YUQ97], [SHI11], [SHE11], [DES10], [FER09], [NGU04], [HEN98]):
MATISSE Project – Grant Agreement # 314182
MATISSE received research funding from the Community’s 7th FP

Ver: 2 Date: 30/09/2015 Page 7 of 35

Deliverable D5.1

- Cathode
  - Current collector: Aluminium
  - Active material (common): Li-manganese oxides, Li-cobalt oxide, Li-Metal-Phosphates (where the metal is a transition metal like iron)
  - Active material (others): Metallic Li (in Li-air-batteries – not relevant yet), Li-nickel oxides, nickel-cobalt-aluminate, nickel-manganese-cobaltite
  - Dopants: Caesium, copper, iron, ruthenium, chromium, zinc, zirconium, titanium, magnesium, calcium, lanthanum or aluminium

- Anode
  - Current collector: Copper
  - Active material: Graphite
  - Active material (other): Carbon, titanate, vanadium, silicon, germanium
  - Lithium Ions
  - Binder: Polytetrafluoroethylene (PTFE) as binder for carbon microbeads

- Electrolyte
  - Solvent: Organic liquid, a mixture of ethylene carbonate, propylene carbonate, dimethyl carbonate, diethyl carbonate, ethyl methyl carbonate (e.g. PC-EC-DMC, PC-DEC)
  - Salt (common): Lithium hexafluorophosphate LiF6
  - Salt (others): Lithium hexafluoroarsenate LiAsF, Lithium perchlorate LiClO4, Lithium tetrafluoroborate LiBF4, Lithium triflate (LiCF3SO3)
  - Solvent/separator: Polymer/Gel
  - Dopants: Vinylene Carbonate (for SEI stabilisation), phosphorous nitrogen compound (flame retardant)

- Separator
  - Polyethylene
  - Polypropylene
  - Ceramics (not relevant yet)

Already in the manufacturing process (the so called ‘cell-formation’ process, where the solid-electrolyte inter-phase (SEI) is created by slowly charging the battery) components of a cell react and form flammable gases like ethylene, propylene, hydrogen and methane [MIK11]. The electrolyte itself is highly flammable (e.g. DMC, DEC and EMC flashpoints: 18-25 °C) and has a considerable heat of combustion (16-21 kJ/ml, approx. half that of gasoline). When a Li-ion battery vents, leaks or catches fire, numerous compounds can discharge or evolve from reactions with other compounds. Some compounds are highly toxic already at marginal doses, in particular phosphorous and fluor-chemicals (e.g. HF and PH3). Others are highly flammable and corrosive (e.g. HF). For the hazard treatment it has to be highlighted, that some compounds react (fiercely) with water or moist air (LiPF6; HF), developing other highly flammable gases (H2). Fire fighting with water therefore is not recommendable. Still water is often recommended to knock down vapours or to cool, accepting the mentioned fierce reactions [MAT13].

A study from Sandia National Laboratories analysed the components emitted from a lithium based battery cell of the type 18650 (Battery cell type 18650: Cylindrical battery cell with a
diameter of 18 mm and a length of 65 mm) [ROT04] during venting, after damaging the cell. The main components are carbon dioxide (CO$_2$) and carbon monoxide (CO). Additionally easily inflammable substances like hydrogen (H$_2$), methane (CH$_4$) and ethylene (C$_2$H$_4$) could be detected. Another aspect gained from this study is, that the electrolyte substances are the main factors for gas generation and temperature raise [MAT13].

The amount of gas delivered by a venting of single 18650 battery cell can exceed its initial volume by 250 times [ROT04]. One of the substances emitted during venting, a product of chemical reactions of LiPF$_6$, which is a common conducting salt in lithium based battery cells, is hydrogen fluoride HF. In combination with moisture, hydrofluoric acid can be formed. Hydrofluoric acid is one of the most dangerous acids, highly toxic and corrosive leading to irritations of the human respiratory system. Furthermore, HF is very reactive, especially with aluminium and steel (iron) leading to even higher emissions of hydrogen gas (H$_2$) [SIN12], [GRO10].

For a more comprehensive report on chemical hazards [MAT13] is recommended.

### 2.1.2 Electrical Hazards

Most electric, hybrid and fuel-cell vehicles are operated using high-voltage (HV), exceeding 60 V in direct current (DC) systems and 25 V in alternating current (AC) systems. BMW’s electric cars for example are operated at 350 V to 400 V. Higher voltages can be found in electric commercial vehicles. The voltage-range 60 V to 1,500 V is rated as voltage-class B [VOG11].

Electrical dangers are those that arise due to the high amount of energy stored in EESSs. While a single battery cell can be seen as a minor but not negligible source of danger, EESS with dozens or hundreds of single battery cells must not be disregarded. In order to meet the requirements for modern vehicle power trains, battery cells are combined (series parallel connection) to deliver the necessary levels of voltage and amperage, thus leading to battery packs with up to a few hundred volts. These preconditions need to be considered in crash safety, to avoid such EESSs to be penetrated, opened or short circuit [MAT13].

Effects on the body depend on the pathway, too (e.g. hand-to-hand, hand-to-foot, foot-to-foot). Lethality increases when the pathway goes through the heart or head. The body’s resistance depends on various factors (time of day, injuries to skin) and can amount up to 100 kΩ, but may be as little as 1 kΩ (wet or broken skin). Due to the so-called dielectric breakdown (when the skin burns), the resistance drops to 500 Ω. Resistance can be increased by protective measures. Rubber boots increase the resistance to 50 kΩ. Assuming now a voltage of 400 V DC, this means a current of 8 mA, which is uncritical [MAT13].

The effects of electric shock on the human body depend on the current type (AC, DC), current-intensity, current path, duration, voltage and body resistance. The latter varies with contact area, contact pressure, thickness of skin, moisture, weight and size of the human [LET09]. The following considerations apply to DC. The minimum current a human can feel
is 5 mA DC. 10 mA to 15 mA will lead to muscle contractions. Higher currents have multiple effects [MAT13].

In general three different types of threats can be categorised for human beings:

- Electric currents passing through the body
- Burns and interactions of electric arcs
- Secondary accidents

**Electric currents passing through the body**

These injuries are considered to be caused by manmade or natural electrical currents passing through the body. Such accidents can cause damage to internal organs, soft tissues, cardiac arrhythmias and respiratory arrests. Conventionally the main factors that influence the severity of these sorts of injuries are type of current (AC/DC), voltage and amperage, duration of exposure, body resistance and pathway of the current. The body resistance is very dependent on environmental conditions and pathway of the current through the body. Depending on moisture on the skin and the path through the body, the resistance can vary between 100 kΩ and 1 kΩ. The chance of currents through a human body crossing the heart region is usually high, since common entrance points are arms and hands and parts being responsible for ground contact can also be hands legs or knees. Alternating current (AC) and/or direct current (DC) are both used in electric powered vehicles. While commonly AC is known to be more dangerous, DC must not be underestimated. The danger considering AC is very much dependent on the frequency. Rather low frequencies like used in the US (60 Hz) or Europe (50 Hz) tend to be more dangerous than high frequencies (kHz or MHz). AC currents however are known to be three to five times higher than DC currents at the same voltage. A low voltage AC (50 Hz) current through the chest of a victim for one second can cause ventricular fibrillations at amperages as low as 60 mA to 100 mA. For a comparable result with DC, about 300 mA to 500 mA are required. Low frequency currents (50 Hz, 60 Hz) also produce extended muscle contractions, which can lead to “holding on” to the source of current in an actual case of accident [MAT13].

**Burns and interactions of electric arcs**

Heating due to resistance (mainly the skin, more precisely the stratum corneum has a high resistance) may cause burns. The higher voltage, the more likely are internal burns. Additionally local burns can be caused by arcing. The majority of people die due to burns and not due to heart failure. Damage is a function of time, voltage-squared, and inverse of resistance. Arc accidents are caused by interaction of electric arcs with human matter, where no direct contact with any parts that carry electric currents has been made. Due to high voltages, electric arcs can occur that use the shortest path to the ground potential [MAT13].
Secondary accidents

Secondary accidents are accidents that happen because an accident with electricity was not avoided and caused involuntarily reactions. Common examples are falls of ladders, or similar elevation devices. These secondary accidents can sometimes be more harmful than the electric accident itself and lead to serious injuries and even fatalities. Also fires that are caused by electric currents can be seen as secondary accidents. Such accident scenarios may not be as important in traffic-accident scenarios, but should at least be considered when thinking of rescue and medical personnel at accident sites [MAT13].

For a more comprehensive report on electrical hazards [MAT13] is recommended.

2.1.3 Thermal Hazards

Some battery cells contain highly inflammable components. Thermal loading of the battery cell can lead to damaging and/or melting of the separating layer between anodes and cathodes. Exposure to heat can thus lead to permanent damage or even spontaneous ignition and explosion of the battery cell itself. This uncontrollable series of reactions within the battery cells is commonly known as “thermal runaway” and usually happens when a temperature around 180 °C is exceeded. A thermal runaway of a single cell is considered to be dangerous and can cause severe injuries [MAT13]. Adding up dozens or hundreds of cells is considered even more fatal.

Possible consequences of thermal exposure of e.g. lithium ion battery cells include:

- Short circuits due to failure of the separation layer between anode and cathode
- Emission of hot electrolyte substances and other components of the battery cell
- Extensive gas and smoke generation of the battery cell
- Spontaneous ignition and/or explosive combustion of components of the battery cell

Other thermal hazards arise due to the high voltage and possible high current when attaching small resistors. These can lead to rapid temperature rises and culminate in thermal runaways. Contact with the resulting emissions like to human skin, or respiratory system can not only cause chemical but also thermal injuries such as erythema [MAT13].

For a more comprehensive report on thermal hazards [MAT13] is recommended.

2.1.4 Mechanical Hazards

EESS are, compared to fuel and gas tanks, heavy components to be stored in vehicles. These mass accumulations on certain positions within the vehicle can influence the dynamic behaviour, leading to other stability issues that need to be addressed. Furthermore, the heavy components have to be attached appropriately within the vehicle structure. Mechanical risks that come along with that mass are mainly related to inertial forces in a crash or in abuse scenarios (curb). Compared with the other risks, though, this risk is manageable [MAT13].
2.2 Outcomes of the Project SmartBatt

In the European funded project SmartBatt different aspects for the development of a battery for an electric vehicle were analysed. The main targets thereby were:

- Minimisation of weight
- Optimisation of safety
- Suitability for a mass-production scenario

The public results (1 deliverable, 9 conference papers/posters) of this project were reviewed regarding relevance for development tasks in the MATISSE project. Thereby, it was found that only general information regarding hazards resulting from drivetrains and EES of APVs was given.

The analysed EES are mainly evaluated in standard tests (e.g. nail penetration), whereby different cell types, battery housings and concepts for the integration into an APV were analysed.

Regarding hazards to car occupants far more detailed information can be found in the MATISSE deliverable D1.2 [MAT13] than in the public SmartBatt results.

Furthermore, pressurised structures were not considered/proposed at the development of a safety concept for the EES.

2.3 Outcomes of the Project OSTLER

The project OSTLER focused on the development of smart concepts for physical integration of battery packs in electric vehicles and the development of possible protection solutions for the main battery pack (MBP). 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. The protection solution could either be active i.e. of an inflatable element or passive i.e. of an energy absorbing element.

2.3.1 Project Approach

Within the project, existing crash standards were analysed with regard to their crash severity. Four full vehicle loadcases were identified, which cause the highest intrusion into the passenger compartment. These load cases were found on the one hand in the consumer test regulation European New Car Assesment Programme (EuroNCAP) and in the US legislative regulations of the Federal Motor Vehicle Safety Standards (FMVSS):

- EuroNCAP front: Frontal 40% offset test with 64 km/h against ODB (offset deformable barrier)
- FMVSS 208: Frontal full overlap test with 56 km/h against rigid, planar wall
- FMVSS 301: Rear 70% overlap test with a moving deformable barrier with 80 km/h against vehicle
- EuroNCAP pole side: Lateral impact on rigid pole with 50 km/h

Using a simplified battery cell model, for a given battery location relevant full vehicle load cases as well as associated cell load cases were derived from finite element (FE) analyses with the OSTLER reference vehicle (public FEM model of Toyota Yaris).

To reflect the defined load cases, mechanical tests were carried out and an FE cell model suitable for full vehicle analyses was gradually built up. Based on this model the investigation of inflatable components and passive systems to provide protection of the battery was enabled. Finally, using system tests, the final design of the systems was validated against the simulation results. All simulations were carried out using the explicit FE solver LS-DYNA.

To investigate how a passive and active protective structure can enhance the crashworthiness of the main battery pack the OSTLER consortium decided on using pouch cells rather than the other two alternatives, cylindrical and prismatic battery cells, as a demonstrator case. The key aspects upon which this decision was based on were:

- Pouch cells offer the highest energy density.
- Within the full vehicle simulations with the simplified cell simulation model, the pack equipped with the pouch cells suffered the highest deformation.
- The add-on protective structures to be tested shall assure high crashworthiness. Consequently, the benefit of high energy density shall be achieved without compromising safety even if the implicit structural protection of pouch cells is softer than cylindrical or prismatic cells.
- The comparison between the three cell types presents evidence (see [OST14]) that adding external protection to a lighter-weight battery pack with higher energy density using pouch cells is more relevant than investigating an external protective structure added to a heavier-weight battery pack with lower energy density using cylindrical or prismatic hard cased battery cells.
- If a lighter-weight battery pack with less pack/cell structural protection can be used together with an external protective structure, in order to achieve high crashworthiness, the reduction in battery weight will offer a longer driving range.

Based on the deformation shape of the simplified cells on full vehicle level, three cell load cases were identified. Their boundary conditions derived from the loading on the cells that occurred under the existing installation condition of the main battery pack within the vehicle (transversal, under the front seats). Using results of tests on the cell level a detailed simulation model of the cells was developed which is able to represent the mechanical behaviour of the cells within any kind of subsystem or full vehicle simulations. This model was then used for the design process of the active and passive solutions. For the final evaluation of the gained
solutions a battery system test was developed which covered the loads on the battery system occurring within a full vehicle test.

### 2.3.2 Evaluation Criteria

To define evaluation criteria the OSTLER consortium focussed on the intrusion into the MBP and the resulting EUCAR hazard severity level table. This table was first presented in the mid of the first decade of the 21st century [OST14]. It was referred to by Sandia National Labs in their 2006 report “Freedom Car” where the table was utilised as guidance for battery cell and pack testing on advanced electric vehicle batteries. As shown in Table 1 the EUCAR hazard severity level table assigns the hazard levels to the ESS technology based on the technology’s response to abuse conditions.

#### Table 1. EUCAR hazard levels

<table>
<thead>
<tr>
<th>Hazard Severity Level</th>
<th>Description</th>
<th>Classification Criteria and Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No effect</td>
<td>No effect. No loss of functionality.</td>
</tr>
<tr>
<td>1</td>
<td>Passive protection activated</td>
<td>No damage or hazard; reversible loss of function. Replacement or re-setting of protection device is sufficient to restore normal functionality.</td>
</tr>
<tr>
<td>2</td>
<td>Defect/damage</td>
<td>No hazard but damage to EESS; irreversible loss of function. Replacement or repair needed.</td>
</tr>
<tr>
<td>3</td>
<td>Minor leakage/venting</td>
<td>Evidence of cell leakage or venting with EESS weight loss &lt;50% of electrolyte weight.</td>
</tr>
<tr>
<td>4</td>
<td>Major leakage/venting</td>
<td>Evidence of cell leakage or venting with EESS weight loss &gt;50% of electrolyte weight.</td>
</tr>
<tr>
<td>5</td>
<td>Fire or flame</td>
<td>Ignition and sustained combustion of flammable gas or liquid (approximately more than one second). Sparks are however allowed.</td>
</tr>
<tr>
<td>6</td>
<td>Rupture</td>
<td>Loss of mechanical integrity of the EESS container, resulting in release of active contents. The kinetic energy of released material is not sufficient to cause physical damage external to the EESS</td>
</tr>
<tr>
<td>7</td>
<td>Explosion</td>
<td>Very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage, depending on the size of the EESS. The kinetic energy of flying debris from the EESS may be sufficient to cause damage as well</td>
</tr>
</tbody>
</table>

While applying the EUCAR levels the criteria and test methods to evaluate EESS safety are divided into two categories:

1. Normal operating conditions
2. Out of normal operating conditions

The first category characterises tests that are designed to verify safety in various situations
that may occur as part of normal driving situations, such as vibration and temperature cycling. While the second category of tests considers abuse situations that are not part of normal vehicle operation, such as crash or fire. Table 2 lists the tests under the respective category.

### Table 2. Test categories and acceptance criteria

<table>
<thead>
<tr>
<th>Category</th>
<th>Tests</th>
<th>Acceptance criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operating conditions</td>
<td>Vibration</td>
<td>1. Hazard severity level 2</td>
</tr>
<tr>
<td></td>
<td>Thermal shock and cycling</td>
<td>2. Voltage to ground isolation resistance ≥ 100 Ω/V</td>
</tr>
<tr>
<td></td>
<td>Overtemperature protection</td>
<td>3. Impedance/capacitance against chassis</td>
</tr>
<tr>
<td></td>
<td>Protection against direct contact</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emissions</td>
<td></td>
</tr>
<tr>
<td>Out of normal conditions</td>
<td>Mechanical impact - shock</td>
<td>1. Hazard severity level 4</td>
</tr>
<tr>
<td></td>
<td>Mechanical impact - integrity</td>
<td>2. Any emitted gases or electrolyte aerosols are vented through designated channels.</td>
</tr>
<tr>
<td></td>
<td>External short circuit</td>
<td>3. Voltage to ground isolation resistance ≥ 100Ω/V</td>
</tr>
<tr>
<td></td>
<td>Fire</td>
<td>4. Impedance/capacitance against chassis</td>
</tr>
<tr>
<td></td>
<td>Overcharge protection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overdischarge protection</td>
<td></td>
</tr>
</tbody>
</table>

Although, this table was referenced within OSTLER, the project’s consortium commented on the applicability of this evaluation procedure critically, since this table has experienced little (if any) revisions since 2006. The table was defined in a time when rigid containers were estimated as the only valid mechanical protection to an EESS. Thus, it may be considered as “design limiting” and consequently has little implementation value for the crashworthiness tests. Nevertheless, it was applied in OSTLER as it is commonly found in older standards handling battery abuse testing. But it was changed in that way, the rupture of the battery housing was not considered as critical issue as long as all cells stay inside the housing. With respect to the simulations only the hazard levels 0, 1, 2 and 6 could be determined since they are correlating to the deformation of the MBP. A gas leakage, voltage drop, fire or explosion of the EESS is not covered by the applied simulation approach.

Within the OSTLER project two solutions were approved. The first one is a passive protection of the EESS comprising of a structural reinforcement; an energy absorbing foam component and an additional load path (see Figure 2). The second one is an active solution with an inflatable element placed between the unreinforced reference EESS container and the vehicle structure (see Figure 3).
Stage 1: structural reinforcement

Stage 2: energy absorbing element

Stage 3: additional load path

Increased wall thickness

Foam material

New load path

Figure 2. Three-staged passive protection

Both, the active and passive solution, decrease the intrusion depth. Within the active protection system the inflatable element is placed in such a manner that the element, when being inflated, will cover a large part of the side wall of the battery pack but with its horizontal centreline matching with the line of the bottom of the MBP. In this way, more load is directed to the MBP bottom. In addition the inflatable structure provides that the load is distributed to a larger impact area. This results in a light weight protective concept which in the described tests achieved a reduction of intrusion of 41 mm (i.e. 26.2%) without an adjustment of the battery system e.g. thicker walls or other reinforcements. Using the passive system, the intrusion is reduced by 91 mm which is a reduction of 58%.

A comparison of the intrusions as well as the occurring hazard level after subsystem testing is given in Table 3. Within the reference testing the pole intrudes 157 mm in the battery system. The analysis of the cells showed leakage of a minor number of cells including venting of...
gases. In addition, some short circuits were observed. Based on these results the severity was classified as level 3. Both the active and the passive solution succeeded (by reducing the intrusion) to prevent the short circuits and the leakage.

Table 3. Evaluation of active and passive measures

<table>
<thead>
<tr>
<th></th>
<th>Reference battery pack</th>
<th>Battery pack with active protection</th>
<th>Battery pack with passive protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrusion</td>
<td>157 mm</td>
<td>116 mm</td>
<td>66 mm</td>
</tr>
<tr>
<td></td>
<td>100 %</td>
<td>73.8 %</td>
<td>42.0 %</td>
</tr>
<tr>
<td>Hazard severity level</td>
<td>Level 3</td>
<td>Level 2</td>
<td>Level 2</td>
</tr>
<tr>
<td>after crash</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Safety Potential of Adaptive Structures in EVs

Based on the outcomes of OSTLER a proposal for the application of the adaptive beams developed within WP3 of the MATISSE project is given in Figure 4. The concept resumes the OSTLER approach of application of an active protection of the battery pack with an airbag. Here, good protection capabilities of the adaptive beams can be assumed because of comparable conditions. The reference load case for the door beam investigated in MATISSE’s WP3 was the pole impact according to EuroNCAP. As shown in chapter 2.3.2 OSTLER considers this load case as well as critical for the MBP and proposes corresponding safety measures. For the active solution the airbag is attached to the sill below the front door, since the MBP is installed below the front seats. For the application of the pressurised beam in the same area this leads to a three point bending in the middle of the beam which is also comparable to the load case analysed for the door beam. For this reasons it can be stated that the MATISSE beam is suitable for the proposed application.

The airbag applied in OSTLER is attached to the rocker and inflates below the under body. This, however, is not possible with the MATISSE beam since it requires significant space already in the unpressurised case. For that reason an application within the rocker is proposed. Additionally this also protects the structure against external influences like moisture or stone-chipping.

In combination with sensor systems the beam can be pressurised depending on the conditions of the impact. If the impact is above the rocker (SUV) or on a large area, no or only low pressure could be applied. In the case of an impact with high severity in the rocker region like the pole impact, the full pressurisation stage has to be ignited in order to protect the battery cells.
Figure 4. Pressurised beam as EESS protection
3 Criteria for the Evaluation of Dynamic Crash Behaviour of Pressurised FRP Structures

3.1 Criteria for CAE-based Evaluation

Accelerated development processes, improved structural designs and the reduction of necessary prototypes are widely known advantages of CAE methods. A new approach is the use of virtual methods when it comes to legislation and crash safety ratings. Therefore objective CAE-based evaluation criteria have to be developed and established.

Based on the experience Daimler made when developing active metallic structures, so-called PRE-SAFE® Structures (e. g. crash adaptive side protection beam in the ESF2009), a three-phase approach for the simulation based crash evaluation of shape adaptive FRP structures is proposed covering the major stages of development (see Figure 5).

![Diagram](image)

**Figure 5.** Three-phase approach for evaluation of shape adaptive FRP structures

For the crash adaptive beam in a first step the activation behaviour of the single component will be investigated without external load acting. Therefore, the beam is fixed in space and inflated with a generic inflator model able to generate an arbitrary, uniform pressure distribution within the closed beam volume (see Figure 6).
In that way different concepts can be easily compared not only with respect to shape and layup but also to the maximum burst pressure, the tightness of the structure, the direction of forming and the bulking for example (Table 4).

**Table 4.** Scheme of evaluation on component level – criteria phase one

<table>
<thead>
<tr>
<th>Inflator n</th>
<th>Concept/ Layup 1</th>
<th>Concept/ Layup 2</th>
<th>Concept/ Layup n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material failure (thermal/mechanical)</td>
<td>Maximum pressure</td>
<td>Pressure drop within 100 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As soon as the design concept for a mass and package reduced FRP beam and a corresponding inflator have been identified a predefined load and deflection will be applied to the beam. Loads and deflections are derived from full car crash simulation and applied to the beam mounted on a specially designed test rig during phase two (Figure 7).
Due to rating and certification reasons there are quasi-static (FMVSS214) as well as dynamic crash requirements (EuroNCAP, IIHS etc.) which have to be fulfilled either not activated in the case of the quasi-static test or with internal pressure for the dynamic load cases.

Within stage two the specific crash behavior of the beam will be investigated in detail. Performance influencing factors like the area of load transmission, the layup, the wall thickness or the pressure curve can be optimised to reach a defined load and energy absorption without losing the structural integrity. Table 5 illustrates an exemplary evaluation sheet for the crash adaptive beam. Criteria like the maximum and the mean force level and the maximum deflection are rated for every concept with and without internal pressure as well as the material failure due to thermal or mechanical loading, the pressure profile and the tightness of the beam.

Table 5. Scheme of evaluation on test rig level – criteria phase two

<table>
<thead>
<tr>
<th>Concept optimization</th>
<th>Maximum force level w/o pressure</th>
<th>Mean force level w/o pressure</th>
<th>Max. deflection of beam w/o pressure</th>
<th>Material failure (thermal/mechanical)</th>
<th>Pressure vs. time (dynamic)</th>
<th>Tightness of structure (dynamic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflator 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concept</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concept</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concept</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflator n</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A detailed analysis of the hardware test results based on this phase two evaluation can be found in the following chapter also containing test criteria like reliability and repeatability. Once the decision for a promising concept has been made the final step is running a full car
crash simulation in which the safety potential not only concerning different laws and ratings but also with respect to real life safety is rated.

While there are requirements that have to be fulfilled in a non-pressurised state like it is described in the FMVSS214 (the focus of the test is on reaching a force-deflection profile that is comparable to a conventional metallic concept and keeping the structural integrity at the same time) the maximum potential of the PRE-SAFE® Structure technology can only be tapped under pressurised conditions during dynamic crash events. For that kind of load cases (e. g. IIHS-barrier, NCAP pole, etc.) the internal pressure is able to reduce the door intrusions and the intrusion velocity. The distance between door interior and occupant will be maximised leading to an increase in time for a proper airbag deployment. Dependent on the future availability of a pre-crash triggering sensor system there is an even higher safety potential for occupants due to a longer time-to-fire range. Thus, for the last phase of the evaluation process the criteria shown in Table 6 can be derived which serve as a basis for a CAE-driven certification at the same time.

Table 6. Evaluation on full car level concerning laws, ratings and real life safety

<table>
<thead>
<tr>
<th>Activation scenario</th>
<th>If pressurization during rating is accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load case</td>
<td></td>
</tr>
<tr>
<td>Passive (no pressure)</td>
<td>In-crash</td>
</tr>
<tr>
<td>Quasi-static (e. g. FMVSSS214)</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Objective</td>
<td></td>
</tr>
<tr>
<td>Force vs. deflection comparable to conventional concept</td>
<td>Reduction of max. intrusions</td>
</tr>
<tr>
<td>Criteria</td>
<td></td>
</tr>
<tr>
<td>Force vs. deflection curve for quasi-static pole intrusion test (FMVSS214)</td>
<td>Existing activation strategy can be adopted / new one has to be developed</td>
</tr>
<tr>
<td>Structural integrity</td>
<td>Tightness during activation and crash</td>
</tr>
<tr>
<td>Door intrusions / acceleration of door inner shell</td>
<td></td>
</tr>
<tr>
<td>Crucial material loading (thermal / mechanical)</td>
<td></td>
</tr>
<tr>
<td>Interaction with door latch – door opening has to be prohibited</td>
<td></td>
</tr>
<tr>
<td>Structural integrity</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Criteria for Evaluation for Physical Tests

Several approaches for the assessment of the crash behaviour can be taken into consideration, depending on the development level of the structure that shall be assessed. If the structure for example, can already be integrated into a car, the assessment can consist of the analysis of the structural behaviour only but also the evaluation of possibly reduced occupant loads.

For the adaptive crash structures developed in WP3 only the mechanical response can be used for assessment. Criteria that are commonly used for such analyses are the stiffness of the structure, the energy absorption capability, reliability and repeatability of the structure’s properties.

The above mentioned criteria were assessed with tests conducted with the prototype beams developed in WP3. In the course of those test series, experiments with pressurised as well as non-pressurised beams were done and in addition a reference beam (non adaptive, aluminium) was examined to derive a baseline for comparison.

3.2.1 Mechanical Stiffness of Adaptive FRP Structures

The structure chosen for the development of adaptive FRP structures is a door side member. This structure is mainly loaded in bending – thus an increased stiffness leads to a load transfer to other surrounding parts (sill, b-pillar), which potentially helps to reduce peak intrusions and intrusion velocity. Therefore, the mechanical stiffness is very important for the assessment of structures.

In deliverable D3.4 [MAT15a] all conducted tests are described in detail. The test configuration is a dynamic impactor test (60 kg, 6 m/s) that induces bending and tensile load within the structure (see Figure 8).

For the comparison of the mechanical stiffness the data of six tests is analysed. The adaptive beams used for these tests are the TUM beams, with and without pressurisation. Thereby, the
influence of the inner pressure on the stiffness can be seen directly. In addition the results of
the aluminium reference beam are plotted (see Figure 9).

![f-s characteristics](image)

**Figure 9.** Comparison of the mechanical stiffness

In Figure 9 it can be seen, that the design of the adaptive beam leads to a comparable
maximum displacement of the impactor. Looking onto the curve it is noticed that already at
earlier deformation levels (100 mm to 180 mm) of the beam, higher reaction forces are
achieved compared to the reference.

When inner pressure is applied, the force level increases even more resulting in a smaller
maximum displacement of the impactor. Compared to the reference a reduction of the
intrusions by 3 cm (15%) is achieved. The difference in the two curves for the pressurised
beams is mainly related to a different inflator configuration used for those two tests.

### 3.2.2 Energy Absorption Capability of Adaptive FRP Structures

The energy that has to be taken by the structure is set by the test-setup. With an impactor mass
of 60 kg and an impacting speed of 6 m/s the deformation energy that is induced into the
structure amounts to 1080 J.

In the Figure 10 the curves for the energy absorption as a function of displacement are
displayed for the same beams as shown in Figure 9.
It can be seen, that the deformation energy of the pressurised structures is always above the reference and the non-pressurised structure. The curves of the latter are comparable.

3.2.3 **Reliability and Repeatability of Adaptive FRP Structures**

During the development of the adaptive beams, only a few repetition tests were carried out, given by the limited number of prototypes.

Generally, it was noticed that the second series of prototypes (final design) shows a good repeatability of the mechanical prototypes. This can be seen particularly in the curves of the two non-pressurised tests in Figure 9 and Figure 10.

Taking into account that all prototypes are handmade, the achieved repeatability and reliability of the test specimens is considered to be satisfying. It is assumed that this promises good potential for possible mass-production applications.

3.2.4 **Remaining Structural Capacity after Failure**

For pressurised structures as developed in WP3 the inner pressure is essential for the structure’s mechanical properties. In real world application it cannot be excluded that the pressurisation fails or the inner pressure cannot be maintained long enough for being beneficial. So as a fallback solution the adaptive structures also have to fulfil some minimum structural requirements in case that they are not pressurised. One criterion for the evaluation of this requirement is the remaining structural capacity after failure.
For the case of the TUM beams this criterion can be evaluated by the comparison of the results of the pressurised and non-pressurised tests. It can be seen that even without inner pressure the results are comparable to the reference beam. It is assumed that in case of an early pressure drop during the loading the mechanical response will change from the pressurised to the non-pressurised curve. This is not necessarily valid as some material damage can occur due to the pressurisation which would most likely result in a lower stiffness of the beam. But this effect cannot be verified for the TUM beams as it was not tested.

For the Airborne beams that were not as far developed regarding in-car application as the TUM beams, some principal test were carried out addressing this effect.

The non-folded square-sectioned beams were sealed and examined in a pure three point bending (3PB) test bench. During the tests the inner pressure, the reaction force and the stroke of the impactor were measured. The main purpose of this test was to correlate the loading of the structure with material failure. This data is essential for the parameterisation of damage/failure models for the numerical characterisation of the material. Figure 11 shows the test setup before and after the test. The inner pressure was set to 17 bar and was kept constant until the bursting of the beam.

![Figure 11. 3PB tests with pressurisation](image)

In Figure 12 the correlation between the inner pressure and the reaction force can be seen. After ~4 s the pressure drops as a result of material failure and/or disintegration of the structure. During the pressure drop also the reaction force reduces significantly but a force level between 1 kN and 2 kN remains until the end even though there is no more inner pressure.

This remaining force level is significantly lower than the results of the non-pressurised TUM beam, but the results cannot be compared directly. The TUM beams were examined in a combined loading (bending and tension), whereas the Airborne beams were loaded in bending only.
Figure 12. Pressurised quasi-static 3PB (Airborne beam)
4 Criteria for the Evaluation of Dynamic Loading Capacity of High-pressure Storage Tanks

4.1 Evaluation Criteria on Vessel Level

CRF has evaluated the correlation between numerical and experimental results. With this aim, a virtual test campaign corresponding to the description in table has been evaluated.

As stated in D4.4 the tests simulated are:

- Test according to the standard ECE R110 “High pressure cylinders for the onboard storage of natural gas as a fuel for automotive vehicles”, in which a drop test is described [ECE13]. The instruction is to drop the vessel in four different configurations: vertical on both boss parts of the vessel, horizontal (on the cylindrical section) and with an angle of 45° (on the dome section, see Figure 13).

In the project it has been reduced the number of tests by adopting only one angle, the most critical one with the impact on the vessel dome corresponding to the configuration at 45°.

- The test rig model developed is adaptable to various angles and configuration of the tank (see Figure 14). The four most relevant ones are for the purpose of the experimental testing versus model characterisation:
  - Configuration 2: No rotation around z- and y-axis; impact on the centre of the tank.
  - Configuration 5: 22.5° rotation around z- and 15° around y-axis; impact on the tank’s centre.
  - Configuration 6: 22.5° rotation around z- and 15° around y-axis; impact on the rear dome.
  - Configuration 7: No rotation around y- and 45° around z-axis; impact on the front dome.
The results have been reported in the IMVITER format that has been considered as the standard form.

Considering the level of results predictability of the vessel model at stage 2 and 3, it has not been possible to fill completely the document. The corresponding report is given in the annex of the deliverable D5.3 “Report including all guidelines and recommendations “ [MAT15b].

The main evaluation criteria identified and useful to state the dynamic load capacity of the vessel are:

Measure of area of the damage due to impact: it is relative to the visible damage around the impact area. This measure is a damage level evaluation after the impact considering the difficulty of the computed tomography scan approach that was proposed during the project. The damaged surface is enveloped in a virtual rectangle whom area represent the output value (see Figure 15).

---

**Figure 14.** Virtual test rig setup adopted

**Figure 15.** Damage area after impact
- Burst pressure evaluation: the measure of the peak pressure in the vessel model after the impact of test-rig simulation or drop-test simulation (see Figure 16). This measure refers to the level of damage of the vessel and to the damage mode that the vessel had been subjected to. The limit at 300 bar in pressurisation of the vessel has been pointed as a proposal in the discrimination between highly damage and partially damage condition.

Figure 16. Damaged condition and burst pressurised condition

- Localisation of the burst pressure damage: the position where the damage reveals during burst pressurization is actually related to the precedent damaged situation. Having a correct individuation of the starting collapse point in the simulation permits to confirm and validate the model results.

4.2 Evaluation Criteria on Vehicle Level

On the vehicle level, the CNG high pressure storage tank is an integrating part of the vehicle structure, therefore it adsorbs coherently all the loads and stresses that distribute during crash.

As a reference, the main evaluation criteria for vehicle application of CNG vessels are reported in the normative ECE R110 (UNITED NATIONS, 2008). Some parts of this normative are reported in the following points:

17.1. General requirements

17.1.1 The CNG system of the vehicle shall function in a good and safe manner at the working pressure and operating temperatures for which it has been designed and approved.

17.1.2. All components of the system shall be type approved as individual parts pursuant to Part I of this Regulation.

17.1.3. The materials used in the system shall be suitable for use with CNG.

17.1.4. All components of the system shall be fastened in a proper way.

17.1.5. The CNG system shall show no leaks i.e. stay bubble-free for 3 minutes.
17.1.6. The CNG system shall be installed such that it has the best possible protection against damage, such as damage due to moving vehicle components, collision, grit or due to the loading or unloading of the vehicle or the shifting of those loads.

17.1.7. No appliances shall be connected to the CNG system other than those strictly required for the proper operation of the engine of the motor vehicle.

17.1.7.1. Notwithstanding the provisions of paragraph 17.1.7., vehicles may be fitted with a heating system to heat the passenger compartment and/or the load area which is connected to the CNG system.

17.1.7.2. The heating system referred to in paragraph 17.1.7.1. shall be permitted if, in the view of the Technical Services responsible for conducting type-approval, the heating system is adequately protected and the required operation of the normal CNG system is not affected.

17.1.8. Identification of CNG-fuelled vehicles of categories M2 and M3 1/.

17.1.8.1. Vehicles of categories M2 and M3 equipped with a CNG system shall carry a plate as specified in Annex 6 of ECE R 110.

17.1.8.2. The plate shall be installed on the front and rear of the vehicle of category M2 or M3 and on the outside of the doors on the right-hand side.

17.2. Further requirements

17.2.1. No component of the CNG system, including any protective materials which form part of such components, shall project beyond the outline of the vehicle, with the exception of the filling unit if this does not project more than 10 mm beyond its point of attachment.

17.2.2. No component of the CNG system shall be located within 100 mm of the exhaust or similar heat source, unless such components are adequately shielded against heat.

It is therefore possible to say that the criteria on vehicle level regarding the crashworthiness assessment are related to the mitigation of damages to the vessels. This traduces in the following criteria adopted within MATISSE project for full vehicle analysis:

- The stress on tank should not reach critical values. If good correlation between experimental data and test-rig simulations was achieved it could have been possible to evaluate the level of damage on the model to consider critical. To arrive to this level of evaluation of the damage entity another loop in vessel modelling is needed.
- There should be no critical retaining system failure. This means that there should not be failure of pretensioning bolts, assuring the vessel is not released in crash.
- There should not be damages on the CFRP layers of the vessel, being the one that resist to the internal pressure of the vessel.
The pretension of the strap mount systems should be defined by the compromise between no damage on external layer of the vessel in the inflated and pretensioned tank and no relative movements between the vessel and the vehicle during impact. Both the conditions should be assessed with and without the normal pressurisation of the vessel.

The areas of contact between tank protection shields and surrounding components should be provided of softening material interfaces, in order to avoid direct contact between vehicle body and external layers.

It should be assessed the burst pressure peak value in the most common impact cases that it has been proven to influence the vessel position in vehicle. FE simulations should permit to investigate this parameter by simulating the inflation of the vessel model reporting the damage situation/stresses of the relative impact simulation. This should be mitigated by the introduction of energy dissipation systems/layout modifications, able to maintain the Type IV vessels safe after the crash scenario.

Because of the increase of stiffness in the surrounding chassis parts, due to the vessel presence, it is important to evaluate the effect of this phenomenon and provide reinforcement or crash energy dissipation to avoid intrusions.
5 Summary

To evaluate the safety of APV with electrified drive-train the hazards of the electricity within the vehicle and especially arising from the correspondent storage systems has been analysed within MATISSE. It has been identified that occupants are exposed to chemical, electrical, thermal as well as mechanical hazards. To quantify the hazards emerging from battery systems in crash situations the EUCAR hazard level table as well as test categories for batteries were presented. It could be shown that in the OSTLER project passive as well as active protection systems led to a reduction of the hazard severity in side collisions. For this reason an active EESS protection system using the MATISSE adaptive beam was proposed.

Concerning criteria for the evaluation of the dynamic crash behaviour of the pressurised beams a three phase CAE approach was defined that considers the component, the test-rig and the full car level. Additionally, templates for the evaluation were proposed. To evaluate relevant crash conditions a table concerning the activation scenarios of the beam and the relevant load cases was proposed considering objectives and corresponding criteria.

To evaluate the adaptive beams safety on the physical level a test-rig set-up and loading conditions considering dynamic and static behaviour was proposed. Here, corresponding measures to evaluate the stiffness, energy absorption and reliability as well as repeatability were presented.

Concerning the evaluation of the dynamic loading capacity of CNG tanks evaluation criteria on the vessel level were presented that are on the one hand derived from the ECE R 110 drop test set-up on the other hand the most relevant test conditions for the simplified impact test-rig developed within MATISSE were identified. To evaluate the damage of the vessel the visual comparison of the damaged area as well as the analysis of residual burst pressure were proposed.

To ensure the safety on the vehicle level the fulfilment of several important requirements given in the ECE R 110 regulation was considered to be indispensible. Furthermore, criteria that can be read out of the simulation results concerning the vessel and its FRP layers were defined. Also guidelines for the pretension of the mounting structure and the contact to the vehicle were given.
6 Literature

[DES10] DESHPANDE, R.; QI, Y.; CHENG, Y.
Effects of concentration-dependent elastic modulus on diffusion-induced stresses for battery applications II

[DOW08] MCDOWALL, J.
Understanding Lithium-Ion Technology

[FER09] FERGUS, J.
Recent developments in cathode materials for lithium ion batteries

Sicherheitsaspekte beim Testen von Lithium-Ionen Batterien
Entwicklerforum Batterien und Ladekonzept, Munich, Germany, 2010

Lithium/iron sulfide batteries

[LET09] LETEINTURIER, P.
Challenges & Solutions for HEV & PHEV Diagnosis,
On-Board Diagnostic Symposium

[MAT13] N.N.
MATISSE Project
Deliverable 1.2
Report on new hazards for occupants
European Commission, Brussels, Belgium, 2013

[MAT15a] N.N.
MATISSE Project
Deliverable 3.4
Results of Sub-Component Testing and Evaluation
European Commission, Brussels, Belgium, 2015

[MAT15b] N.N.
MATISSE Project
Deliverable 5.3
Report including all guidelines and recommendations
European Commission, Brussels, Belgium, 2015
[MIK11] MIKOLAJZAK, C.; KAHN, M.; WHITE, K; LONG, R.
Lithium-Ion batteries hazards and use assessment - Final Report
The Fire Protection Research Foundation, Massachusetts, USA, 2011

[NGU04] NGUYEN, J.; TAYLOR, C.
Safety Performance for phosphate based large format lithium-ion battery
26th annual international telecommunication energy conference, Illinois, USA, 2004

VAVALIDIS, K.
OSTLER Project
Deliverable 3.21
Evaluation report on active and passive protection solutions
European Commission, Brussels, Belgium, 2014

Advanced Technology development program for lithium-ion batteries: Thermal
Abuse Performance of 18650 Li-Ion Cells
Sandia Report
SAND2004-0854, 2004

[SAH10] SAHRAEI, E.; WIERZBICKI, T.; HILL, R.; LUO, M.
Crash Safety of Lithium-Ion Batteries towards development of a computational
model
SAE Technical Papers, 2010

Mechanical Characterisation of a Lithium-Ion Battery Separator using a dynamic
mechanical Analyzer
SAE Technical Papers, 2011

Stress Analysis of the separator in a lithium-ion battery
SAE Technical Papers, 2011

[SIN12] SINZ, W.; E. A.
Concepts for mechanical abuse testing of high-voltage batteries
SAE International, Graz, 2012

[TRA13] TRATTNIG, G.; LEITGEB, W.; THALER, A.
Modelling the crash behaviour of batteries
Evaluation report on active and passive protection solutions
Automotive CAE Grand Challenge, Hanau, Germany, 2013
[VOG11] VOGT, M.
Integrale Sicherheit - Integrale Betrachtung von Sicherheitsaspekten in der Elektromobilität
safe emobility 2011, Stuttgart, Germany, 2011

Modeling of Lithium-Ion prismatic batteries for mechanical integrity: Experiments, Calibration and Validation
Battery Congress 2011, Michigan, USA, 2011

[YUQ97] YUQUIN, C.; HONG, L.; LIE, W.; TINAHONG, L.
Irreversible capacity loss of Graphite electrode in lithium-ion batteries