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STRUCTURAL ANALYSIS OF A BODY IN WHITE FOR BATTERY INTEGRATION USING FINITE ELEMENT AND MACRO ELEMENT WITH THE FOCUS ON POLE CRASH OPTIMIZATION

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Abstract. *This paper deals with crashworthy high voltage battery integration into a vehicle within the FP7[th] EU-Project "SmartBatt". The objectives of the project are to develop a battery housing for an electric energy storage system that will be safe, lighter than state of the art housings and will show innovative design solutions. The focus of this work lies on the safety aspect of the battery housing, which was developed as an integrated structure for the Body in White of an actual internal combustion engine driven vehicle. The requirements for this structure were different impact scenarios, for example the Euro NCAP Front Offset Deformable Barrier (64 kph) or the Euro NCAP Side Pole (29kph) test, whereas the relevant test for this paper is the Pole test which is a very critical loadcase due to the high intrusions. Generally, the battery integration process is subjected to multi criteria limitations coming from functional, ecological, safety or technological reasons, which make the design process complex and potentially increases the number of design iterations between groups of competences taking a part in the overall vehicle design process. Reduction of design iteration time is therefore very important. For this purpose, the finite element method is combined with the macro element method and a battery volume optimization tool. It can be successfully shown that the combination of these tools can be used for a fast structural integration of the electrical energy storage system into a conventional vehicle.*

1 INTRODUCTION

In the past centuries conventional oil discoveries decreased. The amount of reserves which will be found in future and production capacity are less than the actual forecasted demand until 2050.[31] Additionally to limited resources of oil the a price increase could have been observed with a few falls due to demand changes.[21]

The world energy outlook 2011 from the International Energy Agency for oil consumption for transport concludes that the amount used will rise to 99million barrels a day until 2035. Also, CO2 emissions will play a dominant role for future mobility due to reduction of about needed 25-40% (20% fixed European Union (EU), can move to 30%) related to the level of 1990 [19, 38]. Therefore electric vehicle (fuel cell electric vehicle (FCEV), battery electric vehicle (BEV), hybrid electric vehicle (HEV)) sales have been present over the past few years and will probably rise. The market sales in the next years should continuously grow [11]. Hacker et al summarize the market penetration scenarios for electric vehicles and draw the conclusion that a market share of 25%-50% will be possible in 2050 [24]. But until then a lot of research has to be done in many engineering fields to improve safety and the range of battery electric driven vehicles. One of these topics is the crashworthiness of future electric vehicles. This work will introduce a new method in development of electric vehicles for pole crash optimization. The work will carry out safe locations and envelopes for an electric energy storage (EES) integration in a defined load case. This is important because of different hazard modes of cells (e.g. venting, fire, rupture) under critical loading conditions [16, 27, 34]. The content of this paper is based on the EU-FP7th-project “SmartBatt – Smart and Safe Integration of Batteries into Electric Vehicles” [7] whose objectives were to design a novel modular battery housing for the future implementation in different electric vehicle concepts. One aim was to integrate the battery as a structural component into the body of a vehicle, introducing new material combinations and an optimized design space. Further, the development of a lightweight and easy to manufacture housing was a very important target of the project. Some limitations in this work can be defined as there was no view on costs or thermal issues while searching for the “ideal” location of the battery housing. Starting with a literature overview for state of the art battery housings, the method will be described. As an example case for this work the “SmartBatt” procedure will be illustrated.

2 STATE OF THE ART BATTERY INTEGRATION AND BOUNDARY CONDITIONS DUE TO CRASH TESTING

This chapter will give an overview of state of the art battery integration and describe recent developments for housing types and intrusions depths with reference to side collisions. The results of this part should help to identify possible pack positions in first place and additional boundary conditions for electric energy storage integration.

Starting with the development of an electric vehicle there are two options for doing this. One of those alternatives is a so called conversion design, where an actual road vehicle (internal combustion engine (ICE) vehicle) is taken for the integration of a new technology. The second possibility is a purpose design of a new vehicle whose development process starts with a blank sheet of paper, for example the Nissan Leaf [30]. For both design processes (conversion, purpose) an electric vehicle shows completely new possibilities because of different constraints of the whole system there will be a lot of reasonable concepts, but only a few which are ideal. To identify in the end a novel approach for battery integration into the whole system, some examples for actual concepts and the response of these systems according to the crashworthiness of the vehicle have been considered. The major problem for the development of battery housings for present battery technologies are deformations due to high mechanical loadings. This can cause cell failures and in the end an exothermal reaction. Until safe crushable batteries would not be developed, their use would be limited to locations protected from impacts and deformations. For the future a crushable batteries could be foreseen (not existing yet), playing a role as energy absorbers, what could revolutionize the vehicle design.

2.1 Examples for electric vehicles and concept battery packs

Nowadays, a lot of electric vehicles e.g. the well-known Tesla Roadster or the Mitsubishi iMiev are introduced to the automotive sector. To get a better overview on the battery housings which are built into this vehicles the next part will sum up some different integration concepts of already manufactured or developed electric vehicles. In Table 1 some examples for electric cars are listed.

Brand & Vehicle Model	Battery Pack / location	Energy [kWh]	Range [km]	System weight [kg]
BMW Mini E (EV)	Below rear seats	35	249	260
Daimler Smart ED (EV)	Below front seats	16.5	132	140
Mitsubishi i-MiEV (EV)	Floor panel	16	150	150
Tesla Model S (EV)	Floor panel	40-85	>250	454
Tesla Roadster (EV)	Below rear seats	56	392	450
Chevrolet Volt (EV with range extension)	Below rear seats and tunnel	16	40-80 (electric)	198
Nissan Leaf (EV)	Floor panel	24	141	294

Table 1: Electric vehicles, battery location and system data [1-6, 10, 12, 13, 15, 20, 29, 36]

The cars listed above differ in size and weight. Therefore, the available space for battery integration is not the same and their battery envelope and position is slightly different, but as it can be seen they are all located in the center of the vehicle. This is of course not only due to crashworthiness. Also the vehicle dynamics and space usage for other components influence the location of the pack. There was no electric vehicle found where the battery was built into the front or rear structure of the car within the stored energy range in the table. Also an area from the rocker lateral to the inside is not an intended battery space as it can be seen from the review.

According to these boundaries the preferred position is identified. Comparing the vehicles, the housing envelopes vary from a sandwich floor to a t-shaped [17, 37] solution. All of them are closed parts which are fixed to the car after the completion of the manufacturing process. Benefits of such a solution are that the battery will be developed as a safe part for itself and the production process can be done separately. They can be defined as “rigid parts” in comparison to the surrounding structure, of course only to a certain level of loading. This is done because of the possible hazards of cells which could be a problem in accidents due to acceleration and high deformations.

In addition to different envelopes and positions, also lightweight design is an important issue because of improvements in range extension due to weight savings. Research projects by Fraunhofer were developing a lightweight battery housing welded from aluminium profiles and reinforced plastics or with carbon fiber and few aluminium parts that are able to withstand different impact scenarios and keep the cells safe from intrusions. A further issue for a lightweight design is the multifunctionality of the housing parts. The structural components for example, were used for transportation of the cooling fluid. To protect the inside from potential intrusions all carbon fiber parts can withstand high punctual loadings at impact speeds up to 60 km/h and accelerations up to 10 g. [32, 33]

Only a few works can be found where the battery is described as a kind of energy absorber. This was discussed by Eckstein et. al (Project: e-performance) and Friesen (General Motors). Both packs are t-shaped solutions located under the rear seats and in the transmission tunnel. The deformable battery of the e-performance project gains the capability to absorb energy by deformation of v-shaped volumes which are included in the modular layout of the pack. The advantage of such an approach is that the problems caused by possible intrusions of the seat cross member into the transmission tunnel in side collisions can be minimized .[17, 22]

2.2 View on different crash scenarios

As described before, all high voltage battery packs are built-in nearly at the same position in the car. To show why this is a reasonable design space, the accident statistics and testing of cars in different test scenarios are taken into consideration, looking first at the statistics because of a wider range of possible impact scenarios. To analyze typical deformations in different collisions information can be found in the GIDAS database. Vogt et. al describes a method for the estimation of the deformation frequency with the input of this database [39]. A further step is shown by Justen et. al. They overlaid the information from the database with crash test deformations and defined three protection zones according to the results which can be seen in Figure 1 [25]. A critical view on this study can be done as there are only accidents with bodily injury included and possible crucial impacts could be missing. Also the structural behavior with an integrated battery pack and the vehicle dynamics can be different. [34]

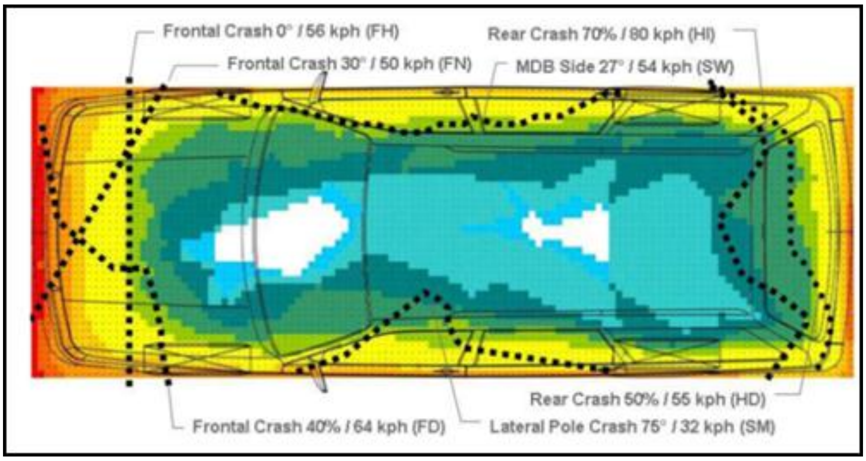


Figure 1: Deformation frequency of a passenger car in real life accidents overlaid with crash test deformations – vehicle sill level [25]

From the figure above it can be derived that only with a crashworthy redesign of the structural parts, enough space for the housing integration remains. Otherwise, the safe space would be only a very small area of the whole car which could not be large enough to integrate a battery which is capable of providing an acceptable range. Transferring this “safe” space to the SuperLIGHT-car (SLC) body structure the maximum volume for the whole battery is about 55 dm³. Regarding the ratio between cell volume and battery system volume is about 40 % [26], so the volume for cells in this room can be calculated at 22 dm³. This allows a range of

38 km. The main problem considering only side impacts is the collision with narrow "rigid" objects because of high deformations.

Sinz et. al discussed the mechanical abuse tests for high voltage batteries and described the same problems with reference to side collisions. Additionally, they have done a step forward and suggested new testing procedures for electric vehicles in terms of different impact points for a side pole collision or a floor impact. [34]

In comparison with United States New Car Assessment Programme (US NCAP) test results, the maximum side intrusion depth at the b-pillar sill level can be traced back to such objects as listed in Table 2. The data has been taken from the National Highway Traffic Safety Administration (NHTSA) database [28]. The relevant values are out of the documentation report which has to be generated for each test. The chosen tests for the investigation have been the US NCAP Pole (32 kph, 75°Degree, d=254 mm) test and a side moving deformable barrier (MDB) test (61 kph, 27° Degree, 1368 kg) [14]. Assuming that a battery will not be integrated in the door or at the roof of the vehicle, the floor panel and the space below the rear seats will influence the decision which test is more harmful for the battery system. Analyzing the test results the crush distance at the sill top height (rocker beam) is far deeper in the pole test than in the MDB test. A comparison of the results shows a difference between 155 mm – 355 mm of both impact scenarios. This was calculated from the minimum and maximum crush distances of the investigated cases. These values can be seen as a first guideline for further steps as different vehicles do not have the same stiffness and weight.

Due to battery cell testing in the SmartBatt project with two types of cells it can be assumed that in first place the intrusion potential is more important than different acceleration pulses (Euro NCAP).

Pole & MDB testing (NHTSA Data of different vehicle models):

Vehicle Model	Crush distance [mm]	Test Configuration	Weight [kg]
2011 KIA Optima	370	US NCAP Pole	1595.0
2011 Honda CR-Z	300	US NCAP Pole	1310.4
2011 VW - Jetta	370	US NCAP Pole	1573.5
2011 Toyota Prius	320	US NCAP Pole	1476.5
2011 Mazda 3	440	US NCAP Pole	1416.3
2011 Mazda 3	65	MDB Side Impact	1493.8
2008 Nissan Versa	145	MDB Side Impact	1452.0

Table 2: US NCAP test results for pole and side impact [28]

The focus for further side structure improvements and safe battery housing concepts will therefore be on the pole impact with possible different impact positions as this seems to be the critical load case. Some design levels are as well checked for MDB side impacts but they are not shown in this work. For the next chapters the important information is that no deformation on the cells is preferred as well as a minimum distance to the rocker beam is required for battery housing integration. The location of the battery can be pre-defined near the center and rear part of the vehicle. With 200 kg of battery weight (150 kg cell weight) the needed volume will be at approximately 60-70 liters with cell data compared by Sit et. al [35].

3 METHOD FOR SAFE EES INTEGRATION WITH THE FOCUS ON SIDE POLE CRASH OPTIMIZATION

For the evaluation of a crashworthy battery integration method the following section describes the main parts of work that has to be done. The focus lies thereby on the concept evaluation and optimization process for the Euro NCAP pole impact test set-up [18]. For doing this, firstly the requirements and specifications of the desired battery were defined. Then a valid body in white of a vehicle was taken and used to demonstrate the integration process for the EES. Due to the fact that a fully developed computer aided design (CAD) and explicit finite element (FE) model of the SLC Body in White (BiW) was available the investigation was done with this data [23].

Based on the literature, concepts for a safe battery housing integration were analyzed. The CAD data of the car was taken to find the usable space for battery housings and to modify the surrounding structure as well as to implement the final concept. The valid FE model of the original vehicle was analyzed to generate some boundary conditions for possible locations and the results needed for the next step, a fast evaluation process of different concepts.

For this purpose, a macro element (ME) model was set up. A advantage of this method is the computing time, two orders of magnitude shorter than for FE simulations, and easiness of body development in the step by step, iterative process of structural design [8, 9]. After successfully finishing the validation, the macro element model can be adjusted and modified to all reasonable battery housing designs.

If one of the evaluated battery housings fulfills the requirements, the original CAD and FE model of the space frame can be upgraded with the new design data and the first design loop is closed. After that, details can be discussed when analyzing the simulation results of the redesigned FE model. This allows a fast integration process of the battery into different body structures. The overall process is described in Figure 2**.**

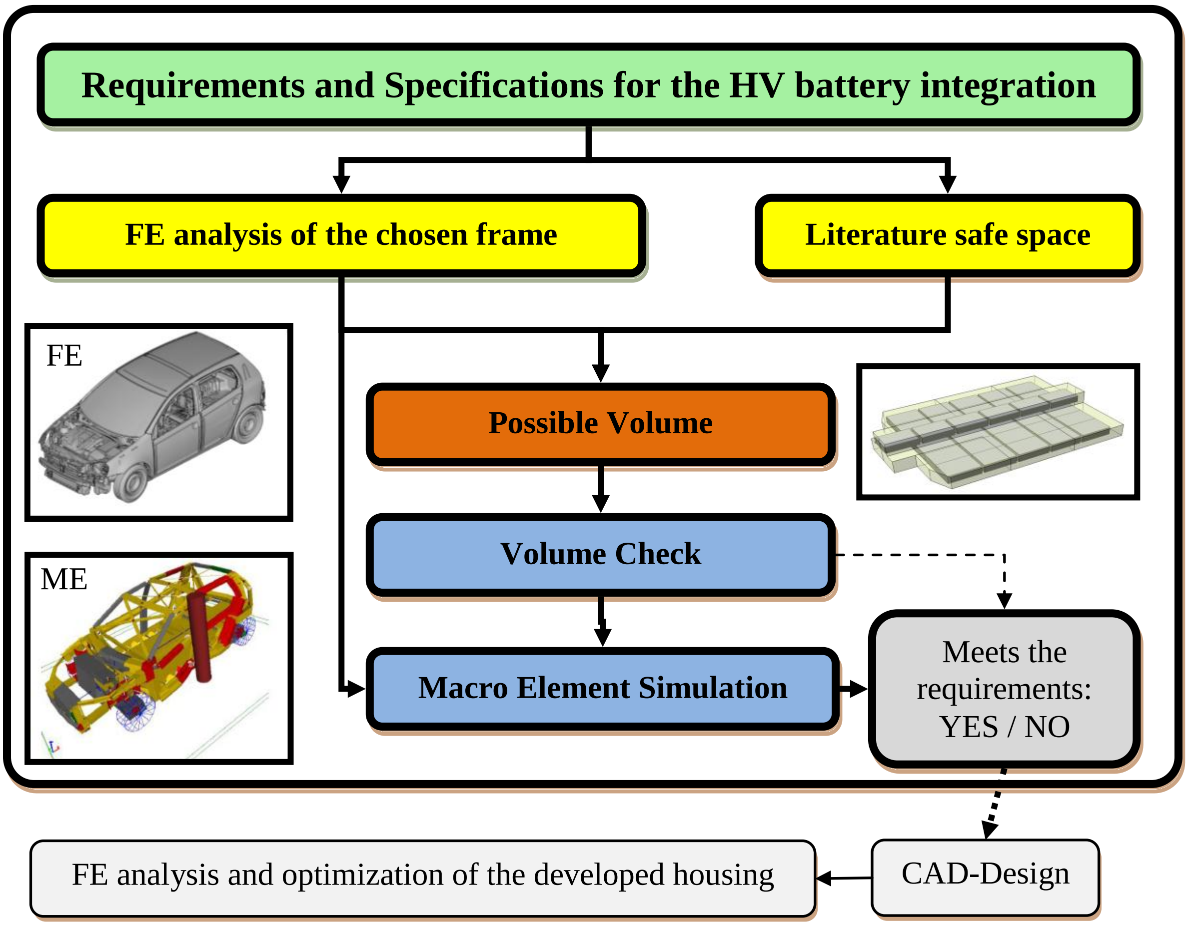


Figure 2: Sketch of the methodology for fast and safe battery integration

4 OVERVIEW OF HV-BATTERY REQUIREMENTS

In this chapter the specifications and requirements for a battery are described. At the beginning of the project the requirements for the battery system were discussed and the following decisions were made. The amount of stored energy in the cells should be 20 kWh and the voltage to drive the electric engine without many losses has to be greater than 300 V. The acceleration will be measured at five points (tunnel and seat rail for pole crash) in the vehicle and the modified version shouldn´t give worse results than the ICE version of the vehicle. The intrusion into the passenger compartment should be less or at least the same as in the original vehicle.

For a crashworthy integration some of these parameters are picked out. Those which are not relevant for energy management in crash-scenarios such as cooling, the battery management system and costs will not be described here. From the discussion above some parameters can be identified and included in this study. They are split up into two sets of parameters. One set describes the volume needed for an acceptable range and the other parameters mostly influence the location of the envelope regarding the needed volume.

Parameters for needed system volume:

- Energy of EES [kWh]
- Voltage of EES [V]
- Cell measures length x width x height [mm]
- Cell data [V], [Ah]

Parameters for a safe system location in the BiW:

- Acceleration [g]
- Intrusion depth [mm]
- Usable Volume [m³]
- CoG X-,Y-,Z-axis [mm]

Starting with the system volume parameters, a cell has to be chosen to calculate the values and check if the selected requirements are fulfilled. In the project a small prismatic cell (4.4 Ah and 3.7 V) has been identified as the best choice of the suggested cells but this will not be explained more deeply. To achieve the requirements, a serial and parallel combination of these cells has to be realized. The calculated minimum volume needed is 58.4 dm³, with 82 cells in series and 16 cells in parallel (1312 cells, 44.5 cm³/cell) the maximum stored energy is 21.4 kWh, has 303 V and a weight of approximately 120 kg (cell weight). This volume has to be found in the SLC BiW structure. A restriction is imposed by the distance between battery housing and rocker beam of the car as discussed in chapter 2.2.

Figure 3 shows the SLC with the possible design spaces. In this kind of Conversion Design vehicle structure the battery space is a global compromise of battery and people package requirements. Due to the conversion from a combustion to an electrical drivetrain free package space for the battery in the floor structure can be achieved. The three colored areas are the most valuable locations for the battery. This volume includes the transmission tunnel and the space below the front seats (1), the space of the fuel tank below the rear seats (2) and an additional floor panel surface (3) as far the people package will be limited in this kind of solution.

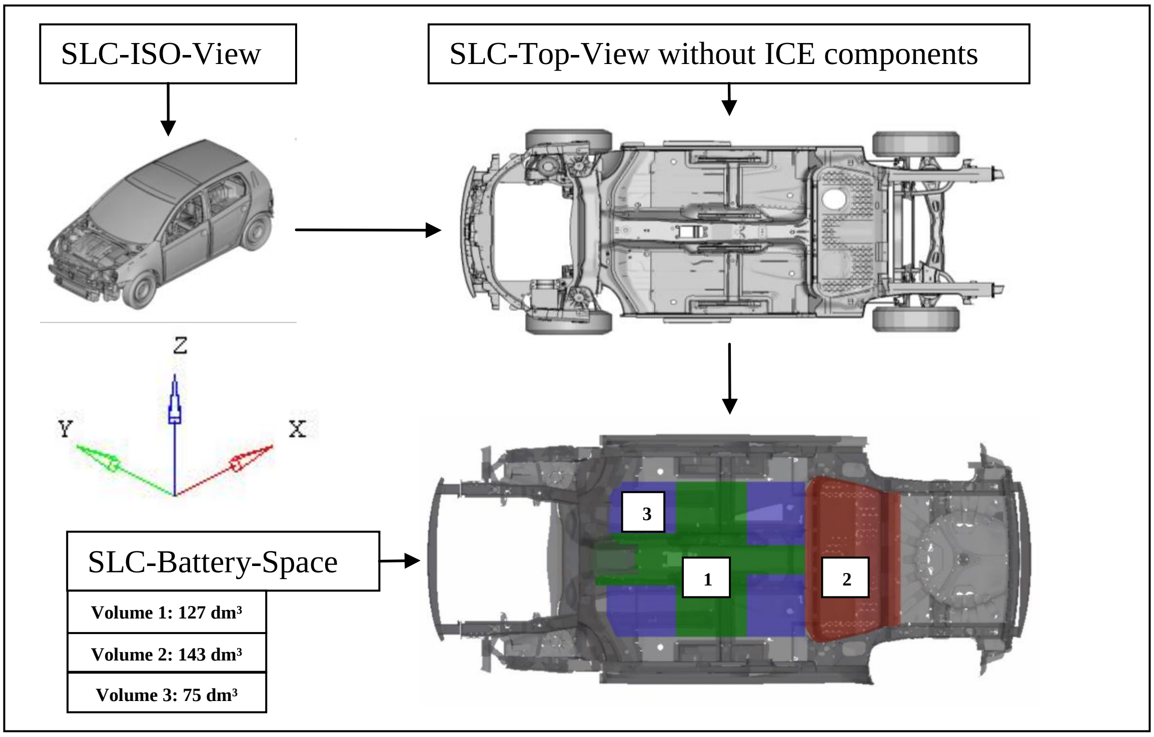


Figure 3: SLC-FE model and possible pack locations

5 FE ANALYSIS OF THE CHOSEN FRAME AND REMODELING INTO AN ELECTRIC VEHICLE MODEL

For this matter the original FE model of the SLC was simulated with an explicit FE solver to get the relevant reference values. The reference vehicle was then remodeled into an electric vehicle according to the specifications (e.g. drivetrain, EES). Therefore, all ICE parts were removed from the BiW and a rigid dummy volume with the mass of all relevant electric drivetrain components with 97 kg was assumed and built into the model. Also a rigid dummy battery (part_inertia) with 200 kg (described in chapter 2) was integrated below the rear seats in the model. This area was chosen because of a worst case scenario for the change in mass distribution and crash safety aspects of the SLC model and helped to identify different behavior of the vehicle. Additionally, information for the validation process of the macro element model was generated. Moments of Inertia for the part_inertia card were generated with drawing software. Additionally the original SLC model includes a dummy mass on the front driver seat and extra weight in the rear of the model (m=223.51 kg). Combined with the weight in the table below the physical mass of the simulation model can be calculated. In Table 3 the results of both simulations are compared against each other. The remodeling showed a slight increase in mass of the electric vehicle model with the assumed battery weight of 200 kg (+4.7%). Due to the lower mass in the front and the additional dummy battery in the rear the CoG moved rearwards.

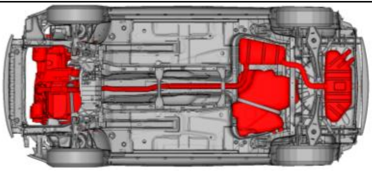
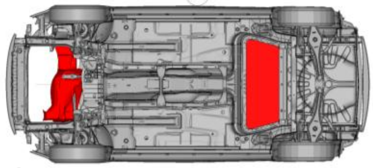
	SLC-Reference	SLC-Electric
Undeformed mesh ICE version and electric version		
Vehicle mass / kg	1213	1270
Change of Center of Gravity (CoG), X/Y/Z [mm]	+190 / +5.6 / -21 (movement according to coordinate system in Figure 3)	

Table 3: Comparison between the Original SLC and the EV-SLC FE-model

A closer look on the deformation pattern of both models in Table 4 shows that the effect of the CoG movement to the rear end of the car and of course some changes in vehicle stiffness causes a different deformation pattern. This is because of the new mass distribution and changed moment related to the pole axis. It can be seen that the modified version has similar displacements relative to the pole in the rear and front of the vehicle. This causes higher deformation (+25 mm) as there is less rotation around the pole axis and therefore a lower kinetic energy at the end of the collision. For example, the absorbed energy for a sub-part of the b-pillar is around 300 J higher than in the original version. The last chart in Table 4 compares the accelerations and velocities of the transmission tunnel. The rotational effect can be ascribed to a higher acceleration pulse in this point because of less stopping distance.

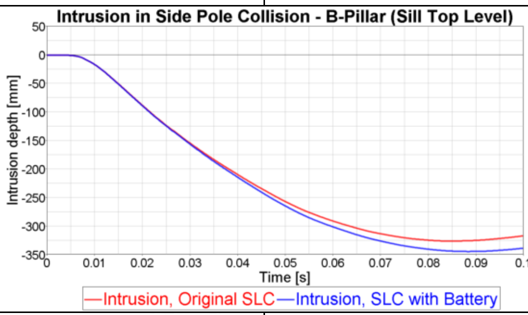
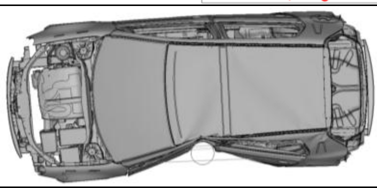
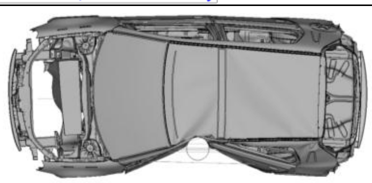
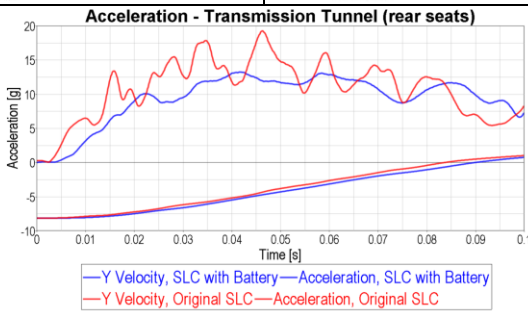
	SLC-Reference	SLC-Electric
Intrusion depth:		
Deformation pattern: Top View @100ms		
Acceleration, Velocity Rear Tunnel:		

Table 4: Comparison between the simulation results of the Original SLC and the modified worst case

In a next step the simulation results can be combined with the literature study and the possible concept envelopes of the body in white shown in Figure 3. It can be suggested that the volume one and three between front and rear seats could be a dangerous location for a battery because of high intrusions to the passenger compartment. However, a minimum distance is required to the side panel of the vehicle. In this case the first approach without structural optimization of the frame will be displaced by around 300 mm lateral to the rocker beam. This seems reasonable as the listed pole crashes from the NHTSA database show nearly the same intrusion depth in the height of the side rocker beam.

The boundary conditions for the battery housing integration are known and the envelopes can be chosen with the data above. The second part of the implementation method, namely the macro element model of the SLC, is discussed in the next chapter.

6 USING THE ME METHODE FOR EES INTEGRATION

Design of battery housing and redesign of the surrounding structure, incorporating additional energy absorbers, were the main issues in this stage of the project. In present automotive structures thin walled beam frames are responsible for most of the body strength and crash parameters. Typical FE crash models are very complex in terms of their geometry, number of elements, and, by universality of the FE method, do not directly provide important engineering information (like limit loads of cross-sections, their average crush forces, length of the folding waves, etc.). Computing times and problems with manipulation of the geometry lead to expensive design efforts. Moreover, due to the nonlinear and nonsmooth nature of the crash optimization problem, no practically acceptable topology optimization procedure is known.

To overcome such problems a crash macro element method can be used for engineering first order effect optimization. Its genesis lies in smart observations of nature, caught in mathematical solutions of large, plastic deformations of thin walled parts. The geometry of a structure can be divided into sets of parts, whose cross-sections can be discretized into basic superfolding elements (SFE). Analytical solutions of large deformations of each SFE´s are performed and folding modes of cross-sections and its characteristics for axial, bending and torsional deformations are calculated. Structural interaction curves are being recalculated during simulation time steps. Cross-sections are integrated into superbeam (SBE) characteristics, consisting each of two cross-sections based on deformable cells at each end, and an elastic beam element in the middle (figure 4). Folding propagation can be transferred to the next internal cells generated inside the elastic part, replacing its properties, as well as to neighboring SBE elements.

ME model creation requires greater structural knowledge and experience than use of the FEM. The user has to perform the discretization in a proper way, understanding mechanisms of thin walled crash mechanics and limitations of this method. Current macro elements implemented in this environment can be used for simulating behavior of prismatic or cone shaped beams (vehicle frame members) and shear panels (roof or floor sheets). Responses of complexly casted parts have to be introduced by use of user defined characteristics, or by equivalent elements in terms of their mechanical characteristics. Computing times for typical assemblies of full vehicles like cars, buses or trains are about tens of seconds, instead of hours comparing to FE. Users also have access to direct properties of the cross-sections, like their limit loads, average crushing forces or lengths of folding waves, thus simplifying and speeding up the design process. In this paper a Visual Crash Studio (VCS) program was used.

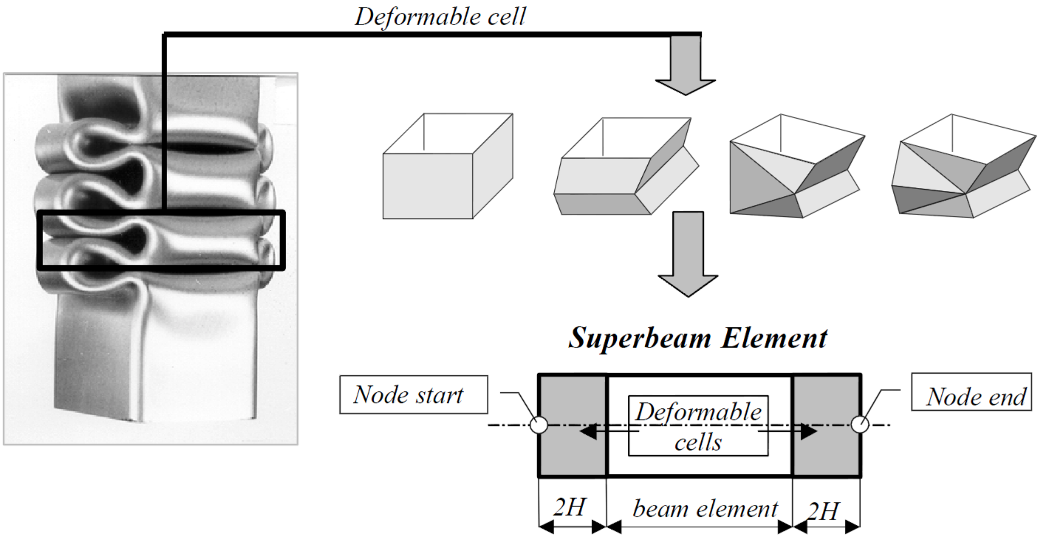


Figure 4: Illustration of the Superbeam macro element concept [9]

6.1 Creation and validation of the ME model – comparison to FE model

Basing on a shell mesh of the SLC, superbeam elements were created in the VCS (figure 5). All shear panels, like floor, roof sheets as well as the windshield, were modeled by use of equivalent diagonal strips. Nonstructural effects, like behavior of crushed pneumatic wheel, were simulated by user defined elements with predefined characteristics. Typical computing time of the model was around 14 seconds on a single core of modern PC per 100 ms of simulation time. The macro element model has been validated by a comparison to results of the FE model simulations.

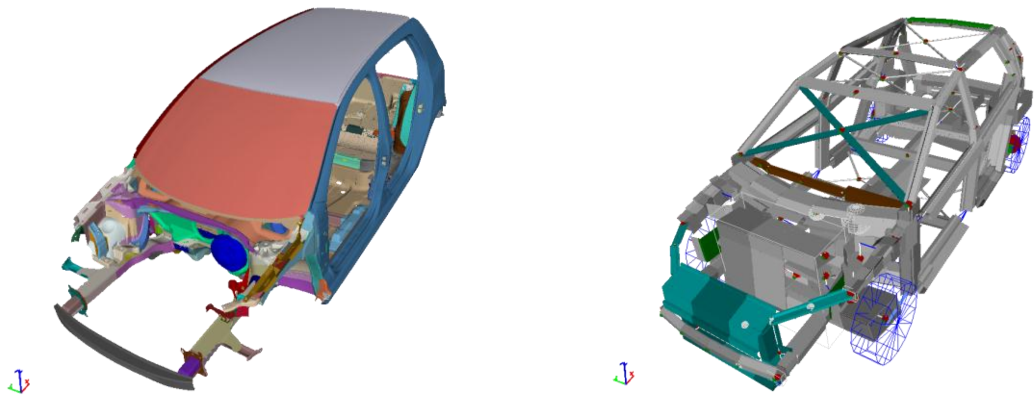


Figure 5: SLC-FE model and its macro element representation

Selected results for side pole impact cases are presented in figures 6 and 7. Colours on the macro element model results express the state of each superbeam element: grey-elastic; green-limit load; yellow-post collapse; red-deep collapse (fully formed plastic folds of thin walled surfaces). Deformation plots show good convergence between detailed and simplified models. Velocities are differing in case of lateral crush, due to the not modeled denting effect of central tunnel and side rocker panel. Histories of acceleration show convergence on average accelerations only. It reveals the vibrating nature of the macro element model which is caused by differences in mass granulation and wave propagation and influence of simplifications in the macro element model. For comparison, the number of nodes in the FE model is as much as 954 thousands, while in the macro element model of the SLC only 172 are needed.

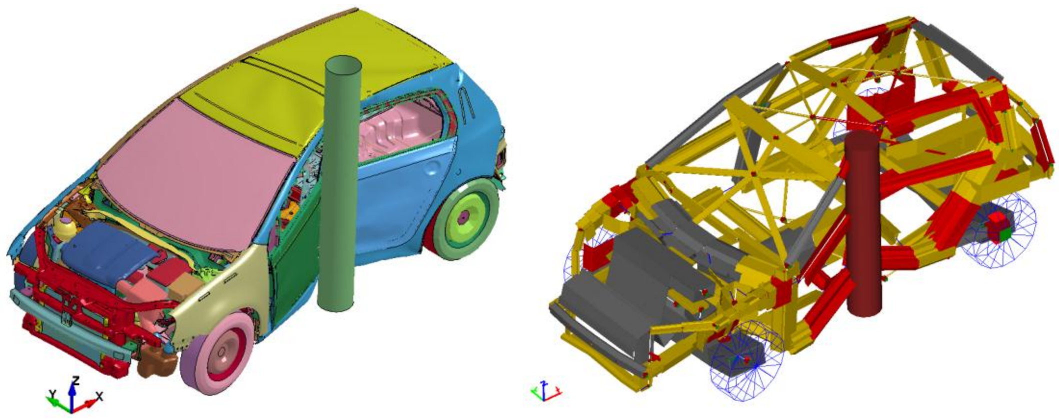


Figure 6: Comparison between FE and ME models results for pole crash. Deformations at 100ms of simulation time.

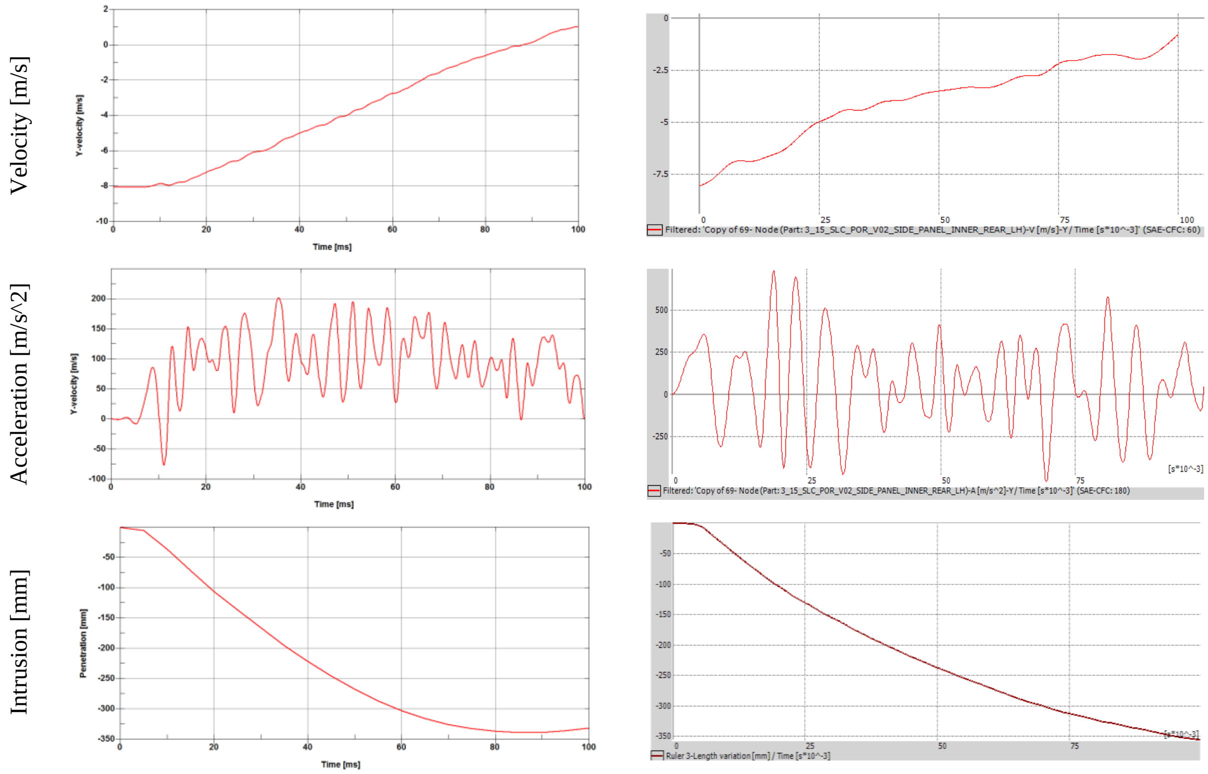


Figure 7: Comparison between FE and ME models results for pole crash. From the top:

velocity [m/s] of node of lower B-pillar on side opposite to impact; acceleration [m/s^2] of node of lower B-pillar on side opposite to impact; penetration [mm] measured between lower parts of B-pillars. All curves displayed as a function of time [ms]. Results from finite elements on left, results from macro elements on right

The next section describes the use of an initial packaging data defining battery locations used for modification of the floor subassembly, incorporating battery housings.

6.2 Different Pack locations in the macro element software tool – Faster development process

During the concept phase, several configurations of battery pack locations were tested in the used macro element model software. Among others, two most interesting versions (figure 8), derived from the volume defined in chapter 4, were selected for presentation in this paper. Version A includes central and side battery pockets plus a rear battery housing. The second pack, namely version B, consists of version A and additional side pockets spread along the whole floor of the passenger compartment. Both packaging concepts use space under second row seats (fuel tank location of the ICE vehicle) for battery storage. The central tunnel was closed from the bottom side, allowing for additional package location (i.e. for power electronics or extra batteries).

Version A incorporates space under first row seats, where lateral battery housing was located. This configuration keeps initial occupant space intact, while version B needs an increase of "H point" locations of all passengers, and movement of the roof surface upwards.

The lateral battery housings were used as structural parts providing support of lateral crash absorbers. This concept was created to improve side and pole impact characteristics, as well as for increased protection of stored batteries, allowing for centered position of the CoG. None of the versions were strictly optimized, being only subjected to engineering optimization based on an iterative process of modification-check loop scheme, what is sufficient for concept assessment.

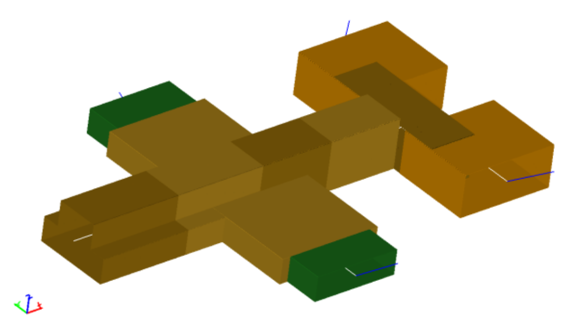
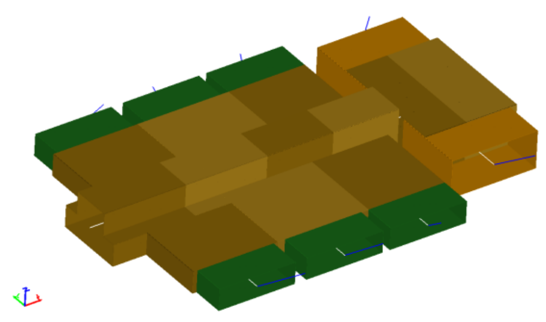
Version A	Version B
	

Figure 8: Main parts of the floor assembly of version A and B. Battery housings are marked in gold, lateral impact absorbers are green.

6.2.1. Lateral pole crash at B-pillar location

Standard Euro NCAP lateral pole crash simulation, with initial velocity equal to 29 km/h and impact point located near B-pillar, was calculated for both considered versions. Some results are presented in Figure 9, including force-displacement curves for both cases, where reaction force on the impacting pole was presented in function of lateral distance between rocker panels (intrusion). Lateral crushing (denting) behavior of rockers was not covered in the simulation. As it can be seen in Figure 9 version A achieved a maximum intrusion depth of 200 mm, while for version B it was 230 mm.

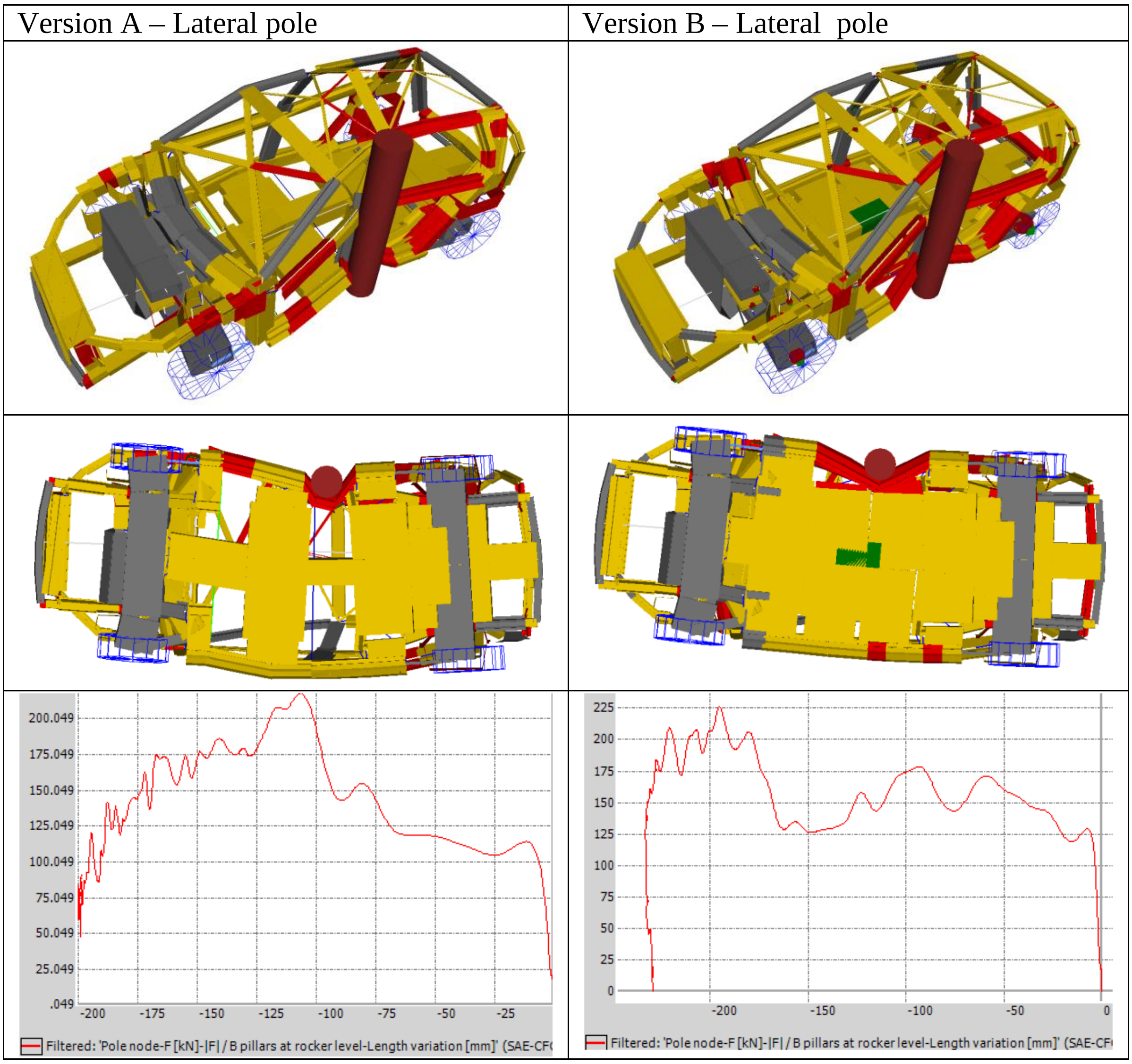


Figure 9: Results of the pole crash at 29km/h with normative pole location at B-pillar area. Left side shows A, right side B versions results. From the top: isometric view of deformed ME model at 100ms of simulation, bottom view and crash force [kN] versus intrusion depth [mm] plots.

6.2.2. Lateral pole crash at front door location

The performance of both versions (A and B), having intrusion at standard B-pillar pole test from 200 mm to 230 mm is considerably better than the original configuration of the SLC, not equipped with side impact energy absorbers. Electric versions are mutually comparable in terms of additional test results. For example in test with the impacting pole moved to the middle of the front doors, intrusions were in range of 175 mm to 210 mm (shown in figure 10).

Battery pack location is influenced by several different conditions, which are mostly multidisciplinary. From a crash engineering scope, distributed lateral impact absorbers have multiple advantages, which may be observed on force-crush plots, where distributed absorbers in version B have better force-displacement curve filling (near idealized square). This provides also an almost equal support of the rocker during crash in different impact positions. However, packaging limitation has not made it applicable for further development steps.

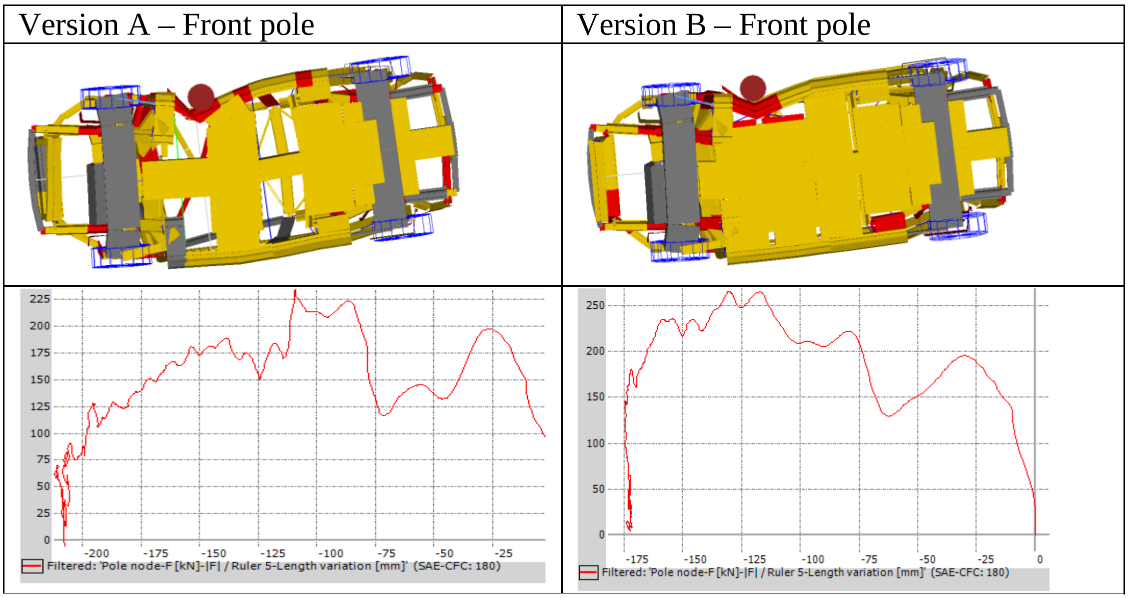


Figure 10: Results of the pole crash at 29 km/h with pole in location at middle of front doors. Left side shows A, right side B versions results. From the top: isometric bottom view of deformed ME model at 100ms of simulation and crash force [kN] versus intrusion depth [mm] plots. An intrusion depth was measured between rockers centroids at point of impact.

6.2.3. Detailed model development based on version A

On the starting point the ICE version of the SLC was discretized into a macro element model. Its floor panel was replaced with battery housings, and proposed structural members represented with simplified cross-sections, with equivalent properties. After the above described concept phase, design version A was selected for further development.

Example characteristics, of a thin walled rectangular cross-section, are shown in figure 11. Axial crushing, two plane bending and twisting characteristics are defining the behavior of a superbeam member. Influence of their mutual interactions to resultant response is simulated by the software, however not taken directly into account in the methodology. Fully identical responses between simplified and final members are not needed, limiting it rather to most important parameters like: axial limit load (*Pmax*), average crushing force (*Pm*), length of plastic folding wave (*2H*), bending limit torques (*Mxx_max*, *Myy_max*), approximate character of post collapse bending characteristics and torsion limit load (*Tmax*).

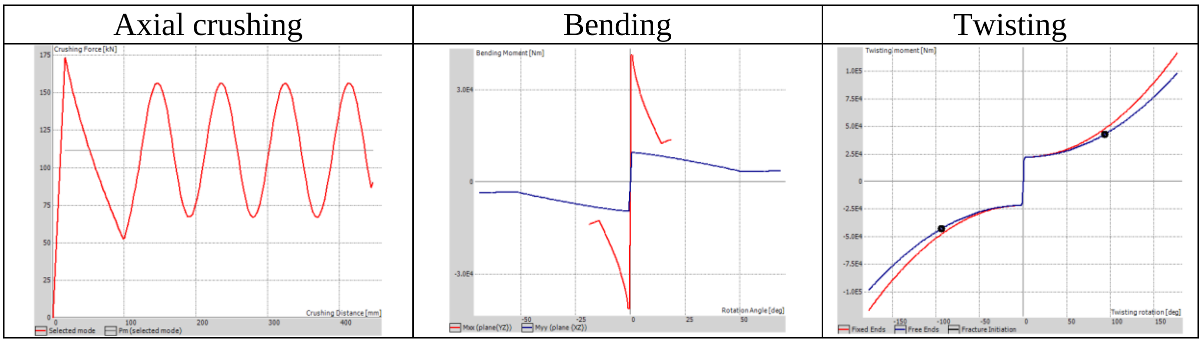
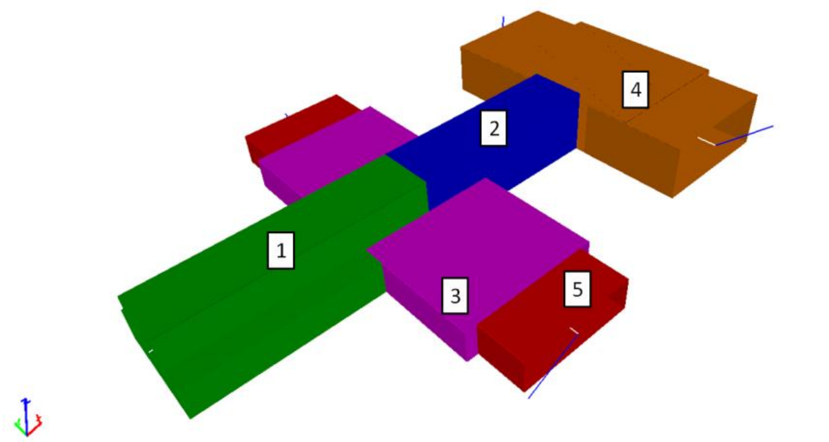
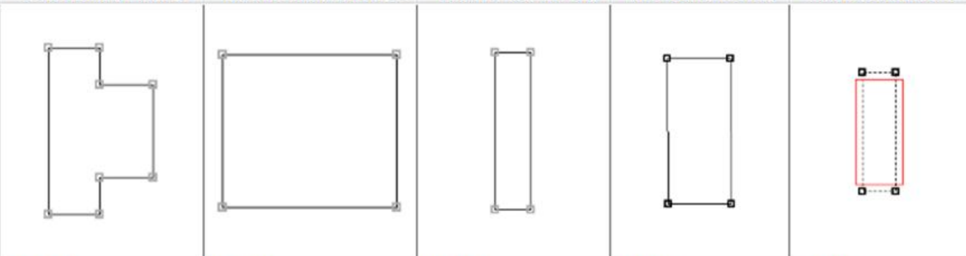


Figure 11: Example characteristics for axial crushing, bending in two principal directions and torsion for a rectangular cross-section.

Basic structural crash parameters for central tunnel and side pockets of version A design are shown in table 5. Shapes obtained on this level, cannot be treated as direct design cross-sections, but rather as equivalent shapes defining an approximate design envelope, with determined minimal strength parameters for a more detailed structure.

Cross sections of equivalent super-beam elements and their basic strength parameters





	*Central battery housing1	*Central Battery Housing 2	*Lateral battery housing	*Rear battery housing	*Side impact absorber
Pmax [kN]	231.1289	264.2503	247.8043	108.9953	238.9368
Pm [kN]	105.947	117.9981	150.2441	65.3936	111.6429
2H [mm]	76.06	108.72	133.98	122.23	122.03
Mxx Max(+) [kNm	26.0623	18.6912	50.2565	20.2024	41.315
Myy Max(+) [kNm	13.2843	24.0293	9.9368	8.8619	9.5062
Tmax [kNm]	20.1635	26.5852	27.0841	16.844	22
	1	2	3	4	5

Table 5: Properties of the equivalent cross-sections of the A version.

The next step of the development process incorporates more detailed design of the cross-sections, and interferes with design space modifications, what usually occurs very often at early stages. In this particular example, version A based on floor modules was developed with modifications (figure 12) due to addition of front seats to BIW attachment points and final battery packs dimensions. The lateral absorber body is proposed as a four cell thin walled profile, made of aluminum alloy, connected to the internal side of the rocker. After this stage a first CAD design and finite element design-assessment loop can begin.

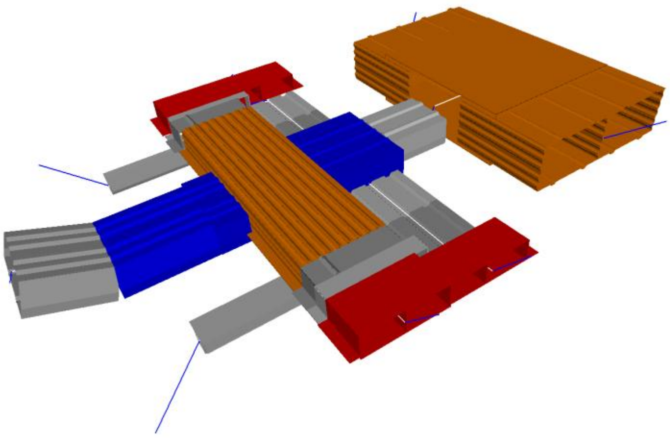


Figure 12: Visualization of detailed macro-element model of a new floor assembly developed from version A

8 CONCLUSIONS

This paper has shown that the high simulation speed and reasonable accuracy of a macro-element based simulation can be used to significantly improve the design of a battery pack for a BEV. The method presented in this paper can be applied to different investigation issues (structural optimization, battery integration, fast boundary development). One of them, the battery integration process described above was improved with this method in quality, time and costs.

Some advantages can be listed as:

- Element/Node Reduction: 954000 Nodes in FE against < 200 Nodes in ME
- Time reduction from 14 hours (8 cores) by usage of the FE model to approximately 14 seconds on a single core for the ME model
- This allows a broader view (~1000 simulations on different concept types with defined crash scenarios) and a better understanding of the possible concepts

An enhanced battery housing was the result.

A significantly speed up of the integration additionally allowed fast engineering optimizations even on the structural components of the BiW (30% less intrusion was reached for pole crash). That is a reasonable way as the focus on battery integration cannot exclude the surrounding structure because of problems in stiffness variations. These parts (front longitudinals, floor panel, side rocker, energy absorbers) should buckle/collapse before the housing is destroyed. Additionally, the view can be on the battery housing when a predefined plastic hinge, acting as a structural fuse, is included to minimize loadings on the relevant housing parts. The results of the method then can be used for integration in the FE model of the vehicle and there further optimized with only one last concept envelope.

The final battery housing envelope described above cannot be seen as the optimum for every vehicle type as some restrictions in the design process and the main focus in this study was only a crashworthy integration of the battery housing.

Table 6 gives examples of the pros/cons:

Battery envelope from Figure 12	
pros	cons
• Meets the SmartBatt targets • High grade of integration into the BiW structure • Crash protected battery modules • Using upper housing part as “floor panel” gives advantages in weight reduction, cost effectiveness and easy assembly	• Structural defined BiW • Sandwich was excluded due to “vehicle movement in Z-axis”

Table 6: Pros and Cons for the final battery envelope

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