CRASH SAFETY OPTIMISATION METHOD FOR THE INTEGRATION OF THE TRACTION BATTERIES INTO POWERED-TWO- WHEELERS

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Abstract

The number of electric powered two-wheelers (E-PTWs) shows a constant increase in the last years and most PTWs manufacturers have at least one E-PTW in their product portfolio. In order to achieve the desired performances high-energy batteries are used, which can lead to considerable hazards for people and the environment in case of damage, as for example in case of crash. Due the absence of crumble zones of E-PTWs and to the relevant influence on the vehicle dynamics that a battery protection structure can have, the safe integration of the traction battery represents a challenging process.
In this study, an optimization method for a crash safe integration of the traction batteries into E-PTWs is proposed.
Crash configurations for E-PTWs were analysed from the current literature and relevant scenarios were identified. The crash scenarios were used as inputs in a multi-step optimisation process, based on Finite Element Method, with the goal to identify the safest placement configuration of the cell in a representative vehicle and to define an optimal protection structure in case of crash.
The crash performance of the design concept was assessed through a substitutive crash and compared to a baseline concept of the traction battery.
The results showed that through the optimisation process, the intrusion into the traction battery could be reduced by 50 % in comparison with the baseline concept and a short circuit could be completely avoided without mass increase of the protection structure.
This method paved the way to achieve a safe integration of traction batteries in E-PTWs without affecting the mass and therefore the dynamic and the electric range of the vehicle negatively.

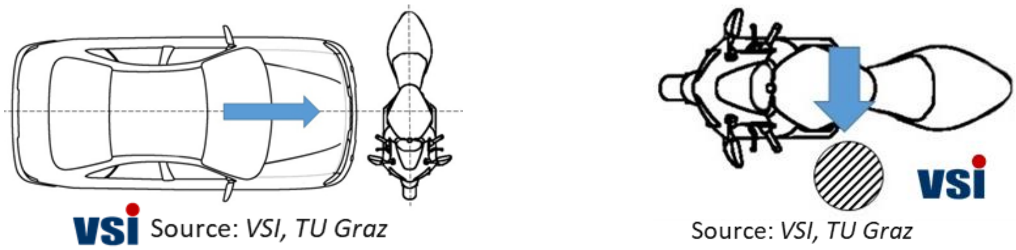
Introduction

The reduction of the emission of greenhouse gases is a worldwide goal. The negative effects of greenhouse gases on the humans health and on the environment have already be assessed in various research projects and publications [1–4]. Due to the relevant role that mobility plays for greenhouse emissions, notable focus is posed to this field in order to reduce the emissions of vehicles, especially on the road [5].

One of the applied strategies is the electrification of the vehicles powertrain, both for passengers and goods transport. This trend do not apply to four-wheelers only, but to two-wheelers too [6]. Electric Powered Two Wheelers (E-PTWs) can bring relevant advantages for the mobility and for the greenhouse emission reduction, especially in urban area [7].

In order to meet the range and performance requirements of electrified vehicles, currently lithium-ion batteries are used for the traction of these vehicles. While this technology brings relevant advantages in terms of volumetric energy density [8], in case of failure, relevant hazards can arise [9–11]. A failure of the traction battery can happen for example in case of electrical damage, i.e. caused by charging or discharging, but also in case of mechanical damage of the unit, i.e. caused by a crash [9,11].

Possible mechanical crash loads acting on the traction battery of E-PTWs were analysed by [11] and [12]. In these studies, relevant crash configurations with the potential to damage the traction battery of the vehicle were defined. In particular, two configurations are found relevant for the safety of the traction battery of an E-PTW: a side impact with a passenger car (Figure 1 a) and the collision with an object of the road infrastructure, such as a pole (Figure 1 b) [11]. In particular, this last configuration is considered as worst case scenario [13].



(a) (b)

Figure 1 - Relevant crash scenarios (a) side impact with a passenger car (b) collision with a pole

In order to ensure the safety of the traction battery in case of crash, in case of four wheelers, the current State of the Art strategy is the integration of the battery into zones of the vehicle that experience reduced to no deformation. Nevertheless In powered two wheelers (PTWs), no deformation-free zones of the vehicle in case of crash can be found.

Other strategies can also be found in the State of the Art for the safe integration of the traction battery in electric vehicles.

One approach consist in the possibility to adopt a damage tolerant battery pack thanks to an appropriate module design, as proposed by [14]. In [14] energy dissipation components, in form of small tubes, are inserted between the cells in order to absorb the deformation energy in case of crash. The possibility to introduce a damage tolerant battery pack with an appropriate module design as described above leads inevitably to an increase of the mass and volume of the traction battery. These as consequence can lead to a violation of the boundary conditions of the design, to negative influence in the vehicle dynamic or to violation of the requirements of performance.

Another approach consists in the use of a crash absorber to limit the intrusion in the battery pack in case of crash and avoid the consequent cell deformation, as commonly found in passenger cars [15,16] and also in E-PTWs [12] in form of crash absorption brackets. Nevertheless, in [12] this strategy was combined with the use of the motorcycle frame as protective structure.

The use of a stiff structure for the protection of the traction battery can be found in various studies [14,17].This approach could be found also in [11], where the safety of a KTM Freeride E-XC was analysed. In the study the author highlighted the use of a reinforced battery housing for the protection of the cells. Furthermore, in this case, the frame of the vehicle offers consistent protection to the traction battery in case of crash.

It can therefore be resumed that the safe integration of a traction battery in E-PTWs is challenging due to the limited dimensions of the vehicle itself and the vehicle mass increase linked to use of extra protection components or a stiffening protection structure. Such strategies can lead to a reduction of the electric range and performance of the vehicle [10].

The goal of this study is the development of method for the crash optimisation of the traction battery of an E-PTW that can improve the crashworthiness of the traction battery without negative influence on the mass of the vehicle. A central pillar of the method is the substitution of the motorcycle frame with the traction battery, in order to avoid a mass increase of the vehicle.

Method

To achieve a crash safety optimised traction battery for an E-PTW a multi-step approach was used (see Figure 2).

In a first step a Finite Element (FE) based Metamodel optimisation of the traction battery is used to identify the optimal placement of the battery cells in the available space of the traction battery and the optimal thickness of the battery housing with the goal to increase the crashworthiness in a worst case scenario, a side collision of an E-PTW with a pole-similar object, while minimising the vehicle mass.

In a second step the concept of the housing of the traction battery, derived from the first step, is subjected to a topology optimisation. By use of FE simulations an optimal material distribution, to assess the stiffness requirements of a typical motorcycle frame is achieved.

The results of the two steps are combined to obtain a crash and stiffness optimised battery pack. The optimised battery pack design is prototyped and subjected to a crash test representative of the worst case scenario and compared to the results of a baseline concept.

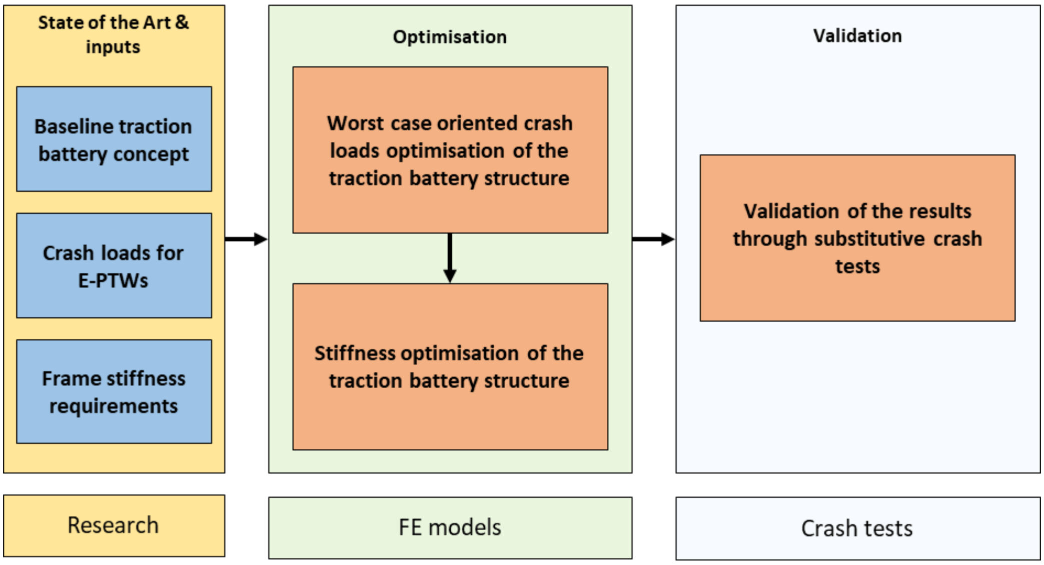


Figure 2 – Schema of the used method

The analysis is developed with a concept E-PTW for urban and commuting purposes. The baseline concept of the traction battery used in this study (see Figure 3) is composed by 3 identical modules, connected in series. The modules are composed by 18650 cells with the axial cell axis oriented in the Y direction of the traction battery.

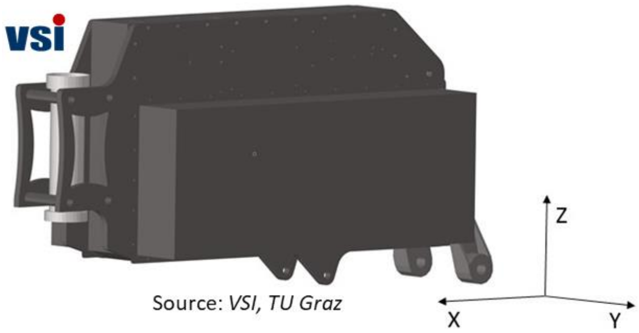


Figure 3 – Baseline concept of the traction battery

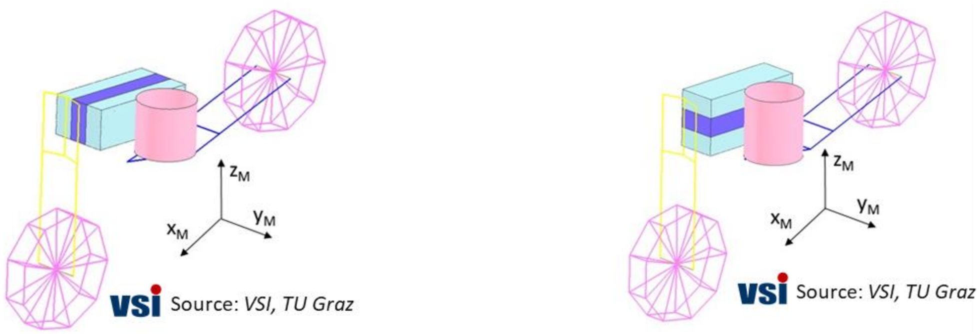
Crash loads optimisation of traction battery structure

In order to evaluate the influence of the placement of the cells in the volume of the traction battery and define the minimal thickness requirements of the battery housing, a FE based Metamodel optimisation through the software LS-Opt is used.

Metamodel optimisation refers to an optimisation process in which a simple and computationally inexpensive surrogate model of the phenomena under observation is built and used to analyse the influence of the variables´ variation on the phenomena instead of direct experiments or simulations. [18,19] A common metamodeling technique, which was used also in this method, is the surface response methodology (RSM). [20,21] The name "response surface" derives from the fact that using this method a response surface is fitted to the response values using a regression analysis. [22]

Two simplified vehicle models, representative of the concept vehicle, were modelled with FE (see Figure 4) and simulated in the defined worst case scenario. The simplified vehicle models are identical except for the orientation of the cells in the traction battery. In the Concept Y (see Figure 4 (a)) the axial axis of the cell is oriented in the lateral direction of the traction battery (Y_M in the coordinate system of Figure 4), as in the baseline concept. In the Concept Z (see Figure 4 (b)) the axial axis of the cells is oriented in the height direction of the traction battery (Z_M in the coordinate system of Figure 4)

The crash configuration uses a half cylindrical impactor with a diameter of 150 mm to reproduce the case of the side impact with a pole. The diameter of 150 mm is chosen in accordance with the test configuration defined in the SAE J2464 [23].The vehicle impact speed is 8,88 m/s as representative of a typical collision speed in an urban scenario.



(a) (b)

Figure 4 – Simplified FE model of the motorcycle and the impactor used for the safety evaluation: (a) Concept Y and (b) Concept Z

The simplified motorcycle model consist of two main groups: the traction battery and the rest of the motorcycle. Components of the rest of the motorcycle influence the inertia and mass of the vehicle, but do not have any other impact in the selected load conditions. They were therefore modelled using one-dimensional rigid elements. The density of the one-dimensional elements was chosen to achieve a mass and a longitudinal position of the center of gravity of the simplified model as in common motorcycles.

The model of the traction battery (Figure 5) itself consists in the following components:

- ***The housing***: the housing is composed by two components: the external plates, that defines the external contour of the housing, and the longitudinal plates, that are placed between the modules. Both components of the housing are made from aluminium and are modelled as shell elements using an elastic-plastic material model with failure criterion;
- ***The modules***: the modules consist in the following subcomponents:
    - *The cell holder*s, responsible for holding the cells together, are modelled with a combination of shell and solid elements using an ABS elastic material model with failure criterion.
    - *The cell*s are modelled using a combination of shell and beam elements, as described by Raffler et al [24]. Furthermore a short circuit criterion based on the results of the same paper is implemented.
- ***The connection between modules and housing***: is modelled with elastic one-dimensional elements.

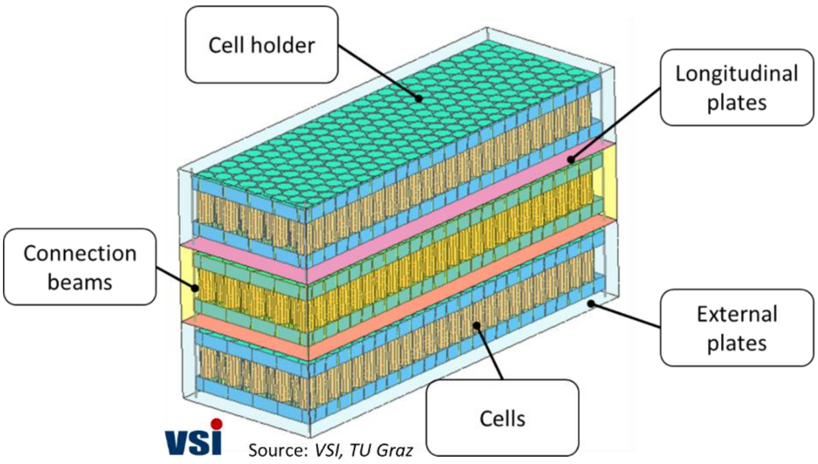


Figure 5 – FE model of the traction battery with its components for the Concept Z. Note that the external plates are semi-transparent in order to show the inner components of the traction battery

As the optimisation process aims to improve the crashworthiness of the traction battery while minimising the mass, two independent variables were considered: the thickness of the longitudinal plates and the thickness of the external plates. These two variables influence the mass and the crashworthiness of the traction battery. The crashworthiness is evaluated with the use of a deformation based short circuit criterion implemented in the FE model of the cells. In order to offer a comparison between the models a short circuit risk is defined based on the short circuit criterion. A short circuit risk of 0% indicates no deformation of the cell, while a short circuit risk of 100% indicates the achievement of the short circuit deformation. A short circuit risk major than 100% does not have a physical meaning but indicates the deformation of the cell exceeded the short circuit deformation.

The variables with their boundary conditions and the goals of the optimisation are exposed in Table 1.

Category	Parameter	Lower limit	Upper limit
Variables	Thickness external plates	3 mm	20 mm
	Thickness longitudinal plates	3 mm	20 mm
Goals	Vehicle mass	Minimise	
	Short circuit risk	Minimise	

Table 1 – Resuming table of the variables and goals of the optimisation

Four Iterations are considered in the analysis for every battery pack concept, while for every iteration 20 simulations with a different combination of the variables are used.

Stiffness optimisation of traction battery structure

As the traction battery structure should substitute the entire frame of the motorcycle, it should withstand not only crash loads but should also achieve the desired stiffness requirements. In order to assess this goal, a topology optimisation based on the Solid Isotropic Material with Penalisation (SIMP) technique is used.

In the SIMP method, a fixed finite element discretisation is used and every element is associated to a density function $\rho(x_i)$, whose values lays between 0 and 1 where 0 denotes a void element and 1 a "full" solid element. The index i indicates a general element of the structure subject of the optimisation. [25]

The Young modulus E_i of the element are then described by the function:

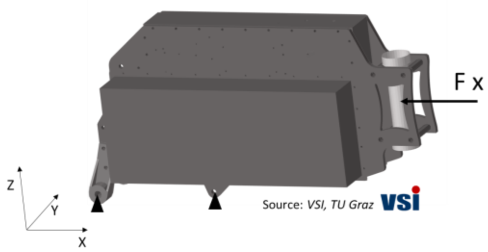
$$E_i = E_o \rho(x_i) \qquad \text{Equation 1}$$

Where E_o defines the Young modulus of a "full" element (i.e. with a density function $\rho(x_i)=1$).

If the density function is allowed to vary continuously between the values of 0 and 1, the resulting density represents an artificial density which can be interpreted as a material mesostructure containing holes. [26]

As these material mesostructures are mostly not reproducible in the practice, homogenisation methods are needed in order to obtain a structure characterised by elements with a density of 1 ("full" elements) or 0 ("void" elements).

In order to fulfil the stiffness requirements of a motorcycle frame, three load conditions were defined and used for the topology optimisation (see Table 2) and the mass is limited to a maximum of 8 kg.

Direction	Lower limit	Sketch
Longitudinal stiffness	5 kN/mm	

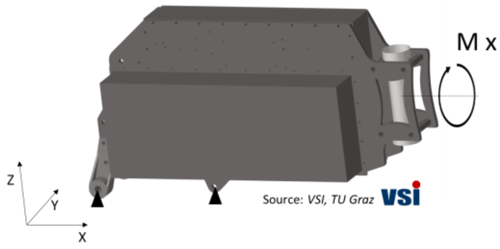
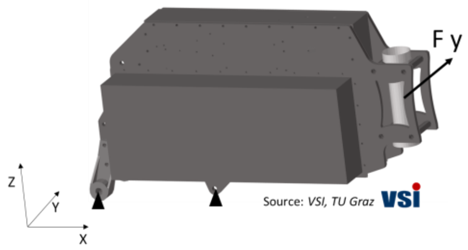
Lateral stiffness	1 kN/mm	
Torsional stiffness	3 kNm/°	

Table 2 – Load cases and minimal stiffness requirements of a motorcycle frame based on Motorcycle dynamics [27]

Crashworthiness assessment

The crashworthiness assessment is developed based on substitutive crash tests representing the worst case scenario, considered also for the crash safety optimisation. A comparison between a baseline model and the optimised model is developed in order to assess the effect of the optimisation.

The represented worst case scenario is reproduced through the impact of a moving trolley with a mounted half-cylindrical impactor into the traction battery that is fixed on a crash wall (see Figure 6).

The trolley with a mass of 475 kg was accelerated until a an impact speed of 4,16 m/s. The half-cylindrical impactor with a diameter of 150 mm was mounted to the trolley. Between the impactor and the fixation plate two three axis load cells (Kistler Z20730A linearity error ≤± 2,5 kN) with a maximal force in axial direction of 500 kN were used (see Figure 6).

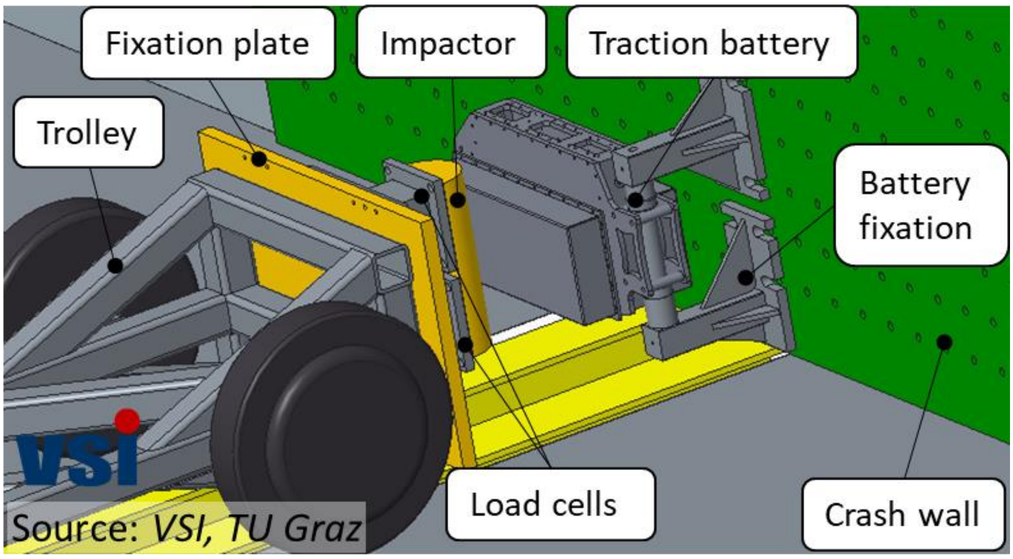


Figure 6 – CAD model of the crash environments with the main components

The traction battery is mounted to a crash wall with the use of two mounting structures resembling the way the traction battery is mounted in the vehicle.

The housing, the connection to the swingarm and the steering head resemble the respective components of the concept vehicle. No electronic component (i.e. BMS, charging system, etc.) were integrated in the test traction batteries as the test focuses in the assessment of the analysis of the crash behaviour of the traction battery, in particular observing the cells deformation.

The cells were discharged to a state of charge (SOC) minor 10 % before performing the tests. In the most extern module, which is supposed to achieve the highest deformation, the voltage of 12 cells is measured in order to detect a short circuit in the cells.

To measure the occurring intrusion of the traction battery, a laser based measurement system was mounted above the traction battery. The tests are filmed by three high speed cameras with 1.000 fps to observe the behaviour of the traction battery from different point of views.

Results

Crash load optimisation of the traction battery structure

The Metamodel surface for the Concept Z, describing the variation of the short circuit risk, is presented in Figure 7. The short circuit risk is depicted dependent on different combinations of values of the thickness of the external and longitudinal plates of the battery pack.

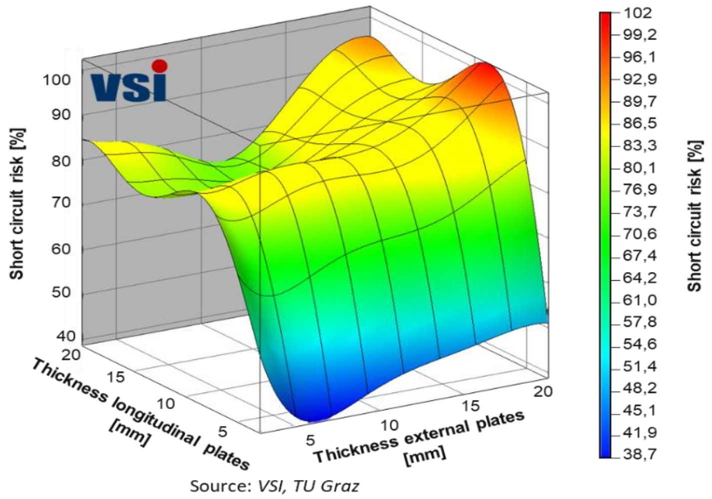


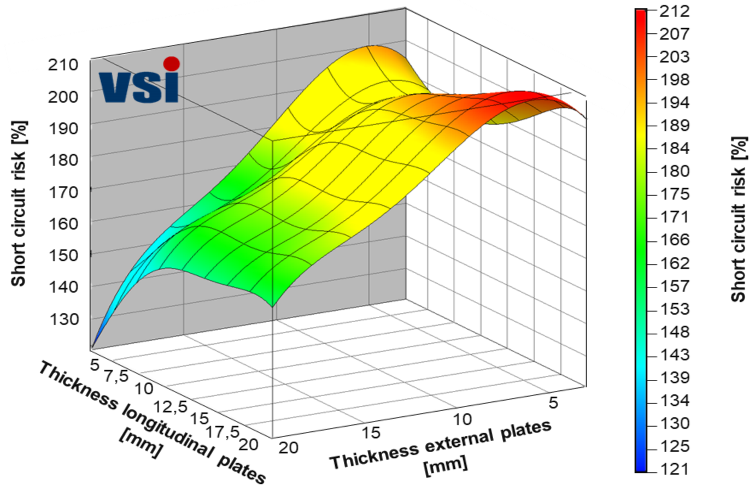
Figure 7 – Metamodel surface for Concept Z

Based on the boundary conditions of the analysis and the load case the short circuit risk ranges from 38,7% to 102%. It has to be noted that a short circuit risk bigger than 100% is not physically possible but indicates that a cell has achieved a deformation bigger than the short circuit deformation.

The minimal short circuit risk is achieved when the thickness of the longitudinal plates is at its minimum (3 mm as defined in Table 2). A variation of the thickness of the external plates, starting from the minimal thickness of 3 mm) cause at first a decrease of the short circuit risk until a thickness of 6,5 mm. After this thickness an increase of the short circuit risk can be noted.

An increase of the thickness of the longitudinal plates of the traction battery housing in case of Concept Z leads to a monotone increase of the short circuit risk until a thickness of 9 mm. After this thickness, it is not possible to observe a monotone behaviour of the short circuit risk function. Based on the combination of the longitudinal plates thickness and external plates thickness local increase or decrease trend of the short circuit risk function can be observed.

In case of the Concept Y, the Metamodel surface describing the short circuit risk in function of the thickness of the components of the housing is visible in Figure 8.



Source: *VSI, TU Graz*

Figure 8 - Metamodel surface for Concept Y

In case of Concept Y the short circuit risk ranges from 121% to 212%. No combination of the variables, with the defined boundary conditions, can avoid the onset of the short circuit in at least one cell of the traction battery.

As it can be noted by Figure 8, a decrease of the thickness of the external plates or an increase of the mass of the longitudinal plates leads almost monotonically to an increase of the short circuit risk.

In order to compare the two concepts, a comparison of the short circuit risk of the two models, for the same model mass, was calculated (see Figure 9).

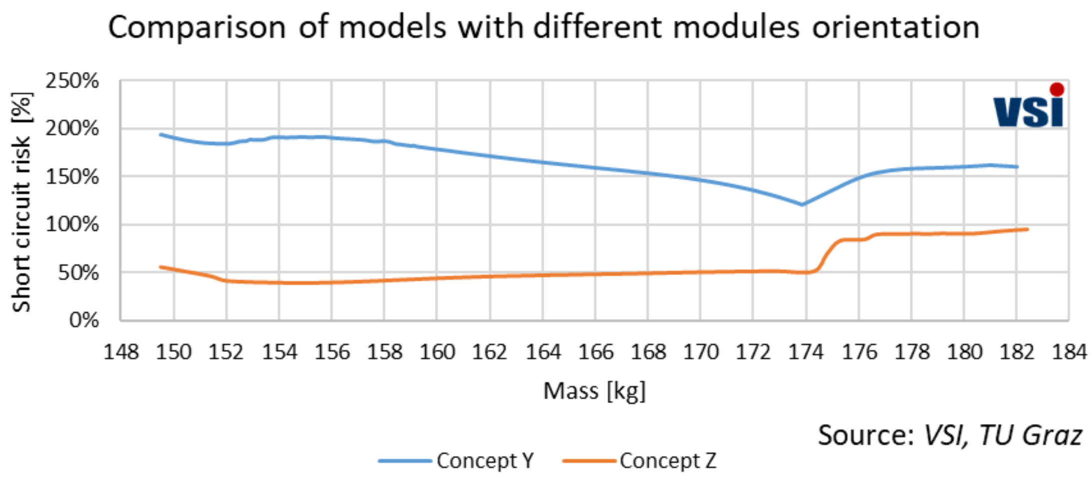


Figure 9 – Short circuit risk vs. mass comparison for the two concepts

Both curves show a decreasing trend of the short circuit for a vehicle mass between 149,77 kg and 151,44 kg. After this mass different trends are observable: in case of Concept Z a further short circuit reduction until a mass of 155,7 kg is visible, while in case of Concept Y an increase of the short circuit risk can be found in a mass range between 151,44 kg and 155,7 kg.

After this vehicle mass, the short circuit risk is increasing for Concept Z and decreasing for Concept Y direction until a mass of 174,3 kg. After a mass of 174,3 kg a short circuit risk increase is observable in both battery pack concepts.

It can therefore be assessed that concept Z achieve lower short circuit risk in the entire mass range. In particular in order to minimise the mass a combination of the battery pack housing of 3 mm both for the external plates and longitudinal plates is chosen for the next steps of the analysis.

Stiffness optimisation of traction battery structure
Based, on the cell orientation of concept Z, a FE-model of the traction battery for the topology optimisation was developed (Figure 10). The model consists of 948.722 tetrahedral elements with aluminium properties. Modules are not integrated in the model, as the goal is to obtain the optimised material distribution in the battery housing. The total mass of the traction battery housing at this stage is 17,63 kg.

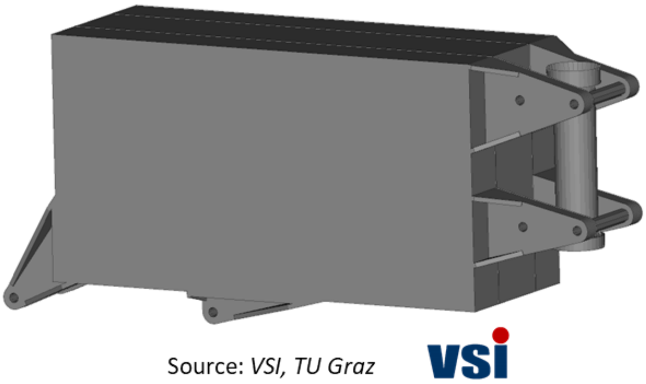
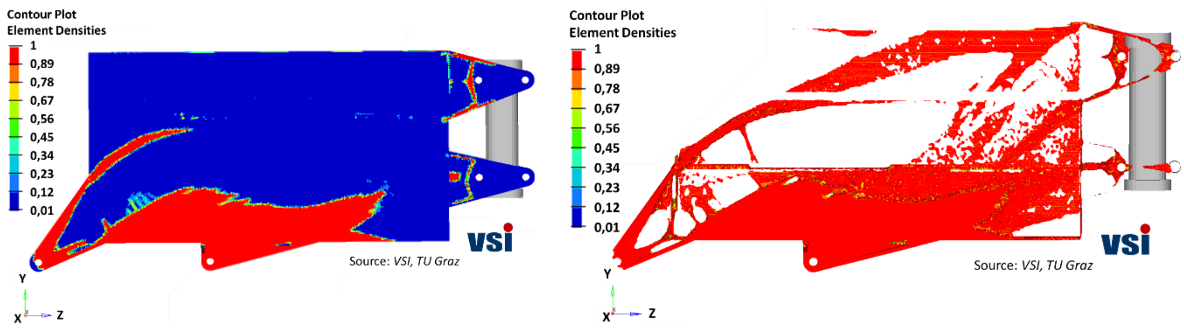


Figure 10 – FE model of the traction battery used for the topology optimisation

The results of the topology optimisation are presented in Figure 11. The topology optimisation converges to a feasible solution after 31 iterations. The traction battery housing achieves:

- A mass of 8 kg;
- A longitudinal stiffness of 36,36kN/mm
- A lateral stiffness of 8,13 kN/mm
- A torsional stiffness of 3,49 kNm/°



(a) (b)

Figure 11 – Results of the topology optimisation showing: (a) all the elements and (b) only the elements with a density higher than 0.85

The results of the topology optimisation show an intense material reduction in the middle and upper area of the traction battery, while in the lower region high material density can be observed.

A reinforced structure which connects the rear connection to the swingarm to the front upper region of the traction battery is build. Moreover patterns of elements with high density can be observed connecting the lower region of the traction battery to the connection with the steering head.

While observing Figure 11 (b) it has to be noted that a connection between the elements seems missing in the upper half of the model. In this area the longitudinal plates of the traction battery are present that increase the stiffness of this area and therefore the elements in this area achieve a reduced material density during the optimisation and are not displayed in this figure.

The results of the Metamodel optimisation and the topology optimisation were combined to obtain an optimised structure capable of withstand a worst case crash load scenario as well as achieve minimum stiffness requirements.

The final structure consist in a “basic housing” with a thickness of 3 mm, as retrieved by the results of the Metamodel optimisation, with reinforcements of 5 mm, in the region resulted from the topology optimisation. The final model can be seen in Figure 12.

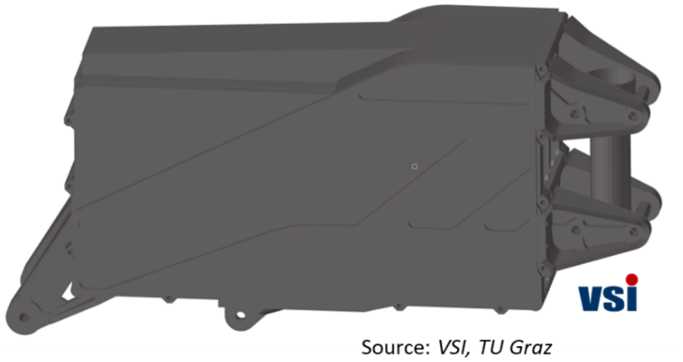


Figure 12 – Optimised traction battery pack housing

Crashworthiness assessment

A prototype of the optimised traction battery housing was built through CNC machining of aluminium and is visible in Figure 13 (b). The optimised traction battery is compared with a baseline concept of a traction battery visible in Figure 13 (a).

(a) (b)

Figure 13 – Photo of the: (a) baseline concept of the traction battery and (b) the optimised battery concept

The displacement versus time curve of the tests with the two traction battery concepts is presented in Figure 14. A displacement equal to zero represent the contact position between the impactor and the traction battery. The measured speed of the trolley at the impact was 4,17 m/s, therefore there was no relevant deviation from the reference impact speed of 4,16 m/s.

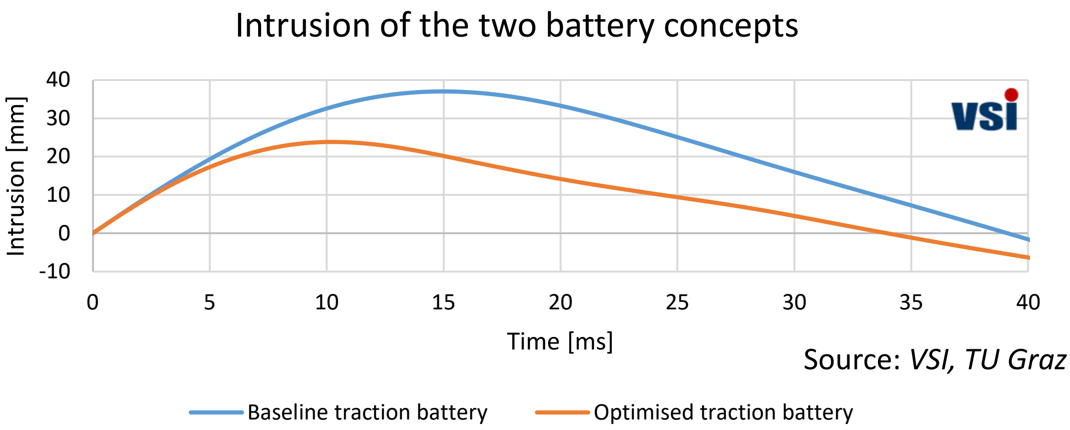


Figure 14 – Displacement versus time for the substitutive test with the baseline and optimised battery pack

The maximal measured displacement in the crash test with the baseline concept is 37,0 mm at 14,8 ms after the first contact. The maximal achieved displacement by the impactor do not represent the intrusion of the traction battery, as a deformation of the fixation points of the traction battery occurs which is visible in the test pictures and videos (see Figure 15).

(a) (b)

Figure 15 – Comparison of the deformation of the baseline traction battery at: (a) first contact and (b) the maximal measured displacement

In case of the optimised traction battery, the maximal registered displacement is 23,9 mm at 10,6 ms after the first contact.

As it is observable in Figure 16, the most of the achievement of the displacement is due to the deformation of the fixation components from traction battery to the crash wall. Moreover it is observable that minor screws for the fixation of the upper cover of the traction battery break during the impact. Anyway, the upper cover has little structural importance and the traction battery can support the crash loads without relevant cell damage.

(a) (b)

Figure 16 – Comparison of the deformation on the optimised traction battery at: (a) first contact and (b) the maximal measured displacement

In the baseline scenario the short circuit of 6 cells were measured, while in case of the optimised traction battery housing no short circuit was detected during the test.

Discussion

The results of the crashworthiness optimisation showed relevant differences between the concepts with different cell orientation. It has anyway to be noted that the optimisation was developed based on one load case only. Although the simulated load case is defined as worst case scenario in the current literature, the different concepts could show different results on different crash scenarios. The same can be stated also for the use of different materials or cells in the traction battery.

It has also to be considered that, although the use of metamodels gives the possibility to analyse in a resource and time effective way large design spaces, it lacks, due to its intrinsic nature, the possibility to find local minima or maxima of the optimisation function to be analysed.

A topology optimisation is a common method for mass reduction of components in the automotive sector. In this study the topology optimisation was developed on the battery pack housing only, without considering the inner components. While the inner components, as example the cells, should not be mechanically loaded during the normal working conditions in order to ensure a safe use, their consideration in the topology optimisation process could potentially influence the results of the topology optimisation and result in a further mass reduction.

Lastly, the authors would like to note that, although the prototypes were build considering also requirements for a large scale manufacturing, it was not possible to satisfy them all in the prototype phase, as for example in the case of connections between different components. Therefore successive crash tests could be needed in further phases of the traction battery development.

Conclusions

In this study a method is described for the design of the traction battery of an E-PTW with the goal to optimise the crashworthiness, while maintaining stiffness and mass boundary conditions.

With the use of two optimisation processes based on a metamodel optimisation, first, and topology optimisation in a second phase, an optimised structure could be found.

Substitutive crash tests and the comparison to a baseline concept offer on one side the validation of the optimisation process and deliver relevant feedback about the improvements that the method could deliver.

In particular the final derived traction battery concept exhibited a mass reduction of 7% in comparison with the baseline concept but, still more important, could withstand a worst case scenario crash load without cell short circuits.

While the method was specifically applied on an E-PTW for urban commuting purposes, it can be used also for different E-PTWs, by varying the boundary conditions of the optimisation process.

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