A METHOD TO ESTIMATE DEFORMATION ENERGY LEVELS OF BATTERY AND FUEL CELL SYSTEMS DEPENDING ON THEIR LOCATION BY USING REAL ACCIDENT DATA (GIDAS)

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ABSTRACT

Due to an increasing number of hybrid and electric vehicles in traffic the safety of battery packages as well as of fuel cells becomes more and more interesting. It is another reason to develop appropriate safety ideas to protect all traffic participants and rescue teams of possible threats. In order to reach high safety levels for possible accidents very hard cases protect the high voltage systems or fuel cells in cars. To meet the future safety requirements those housings are subject to various safety tests.

To point out some key requirements for the testing procedures the approach of the FaSeA study has to be continued with the focus on energy levels depending on the installation location of batteries or fuel cells. The aim of this publication is the design and development of a well defined 3-dimensional deformation energy model, which can be used to specify the testing requirements for future battery and fuel cell development or testing.

The model is designed on the basis of the German-In-Depth-Accident-Study (GIDAS) database, which contains about 20.000 deformed cars including the crash energies as a result of a detailed reconstruction of every single accident.

These deformations are then used to form a 3-dimensional-deformation-frequency-model using a similar method like the FaSeA project. After designing this deformation frequency model all deformations and crash energies of the reconstruction are being merged in the energy model. As a last step the energy model will be used to explain some example fuel cells or batteries regarding their installation location.

The paper will provide a better understanding for the development and the design of battery packages or fuel cells. It will also explain a method for specifying battery package and fuel cell test requirements depending on the vehicle type and the installation location.

INTRODUCTION

Placing battery -packs, fuel cell systems or high-voltage parts in a car is a big issue in the construction process of actual and future cars. Thus gives the necessity to find out some possibillities for getting the deformation energy levels depending on the installation location of those systems or parts. The following paper will give further possibillities for getting information about energy-levels based on a existing method to get deformation frequency models.

3D-deformation models

Basis of the developed method is the creation of 3-dimensional-deformation-models, which is also explained in a previous publication [1]. To create such deformation models out of the accident database GIDAS two important steps have to be done: First step is the calculation and interpolation of the database deformation values and the second step is the 3-dimensional description of those deformations.

Calculation and interpolation In the GIDAS database deformation values for every accident participating car are coded. The deformation values are investigated following the next schemes.

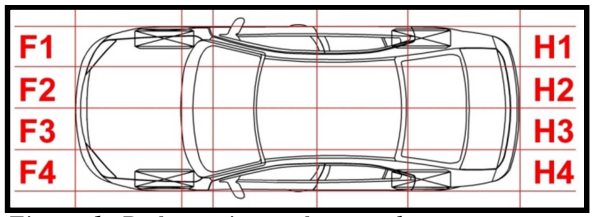

Figure 1: Deformation at front and rear

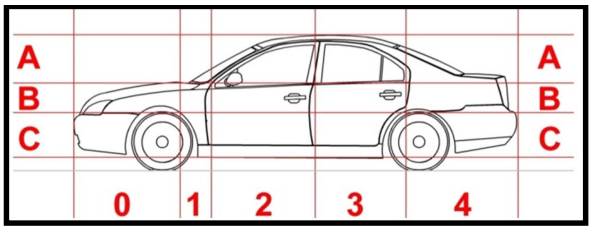

Figure 2: Deformation at the side

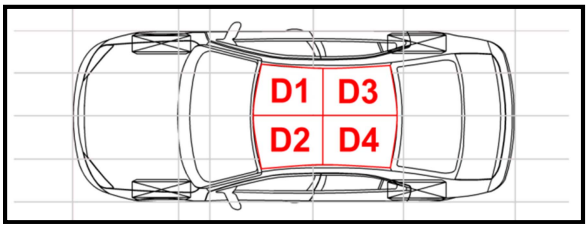

Figure 3: Deformation at the roof

The investigation of following those shemes by finding out the deformation depth of every zone deliveres a scaled overview about the whole deformation at the car.

A linear interpolation of the deformation steps deliveres deformations lines. The deformation line of the vehicle front or rear is shown in Figure 4.

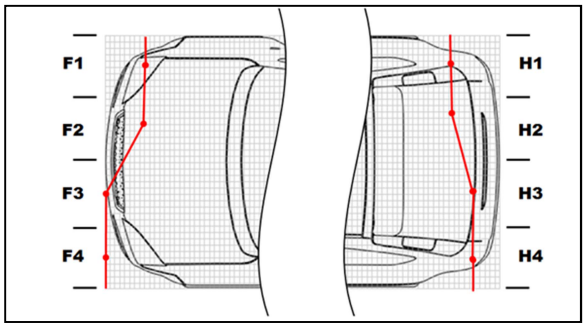

Figure 4: Deformation line of front and rear

The deformation lines of the vehicle side are result of a 2-dimensional interpolation step. First dimension of this interpolation are the deformation lines of the vehicle side of the top view.

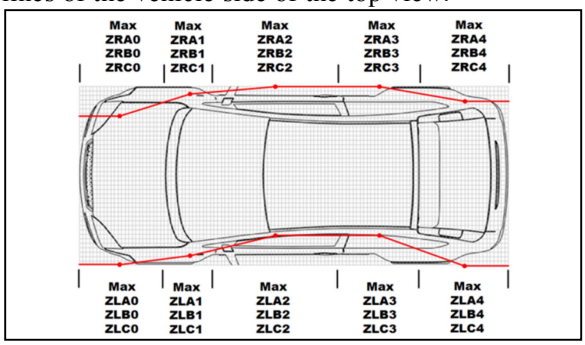

Figure 5: Side deformation lines (topview)

Second interpolation dimension are the deformation lines of the vehicle side of the rear view.

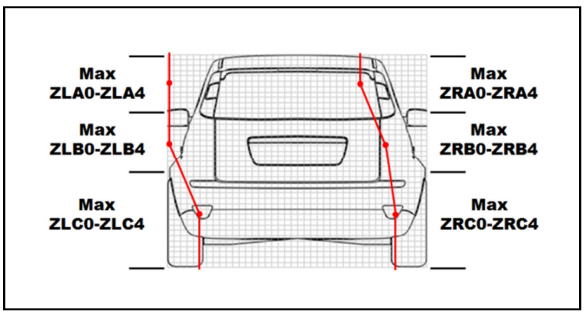

Figure 6: Side deformation lines (rear view)

Last interpolation is done for the vehicle roof (see Figure 7)

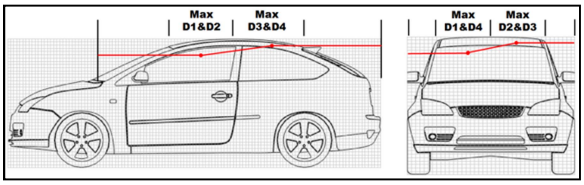

Figure 7: Deformation interpolation at the roof

The resulting deformation lines are afterwards blended with a vehicle Voxel-model which is explained in the next chapter.

<u>Basic car-voxel-model</u> To calculate and print the calculated 3-dimensional deformations a basic model is needed. This basic model will be a 3-dimensional vehicle-model. To build up this vehicle model a 3-dimensional (120x40x40) Voxel matrix is blended with a vehicle shape (Figure 8).

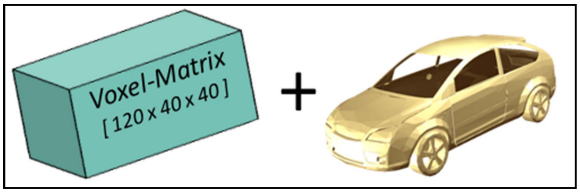

Figure 8: Blendig process for basic-voxel-model

The result of this blending process is a 3-dimensional vehicle-voxel-matrix (Figure 9).

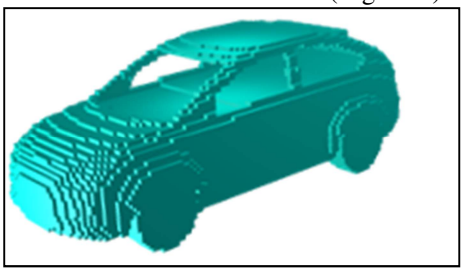
Figure 9: Basic car-voxel-model

Blended results The basic-car-voxel-model and the interpolation planes are blended to get the resulting 3-dimensional-deformation-model. Figure 10 shows an example vehicle out of the GIDAS-database.

Figure 10: Deformed real vehicle (GIDAS) [6]

The calculated result blended with the car-voxel-model is shown in Figure 11. This figure shows four plot variations of the deformation model of the example car.

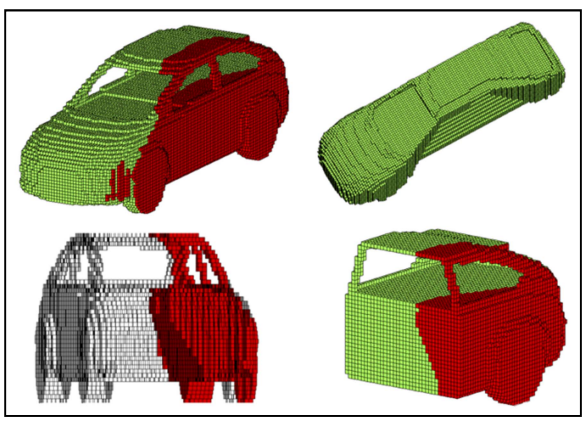

Figure 11: Vehicle-deformation-model

3D-Energy-models (EES-models)

The GIDAS-database also includes information about the deformation energy of every collision. This deformation energy is coded as a speed value called the EES (energy equivalent speed).

Deformation energy It is possible to calculate the deformation energy (E_{ges}), using the equation of the kinetic energy by the vehicles crash mass (m) and the EES-value (EES).

$$E_{ges} = \frac{m}{2} * EES^2 \tag{1}$$

The calculation of the deformation energy is followed by an own distribution approach.

Energy distribution approach Main point of the distribution approach is the fact of the increasing force (F) by the deformation distance during a crash until the maximum compression is reached.

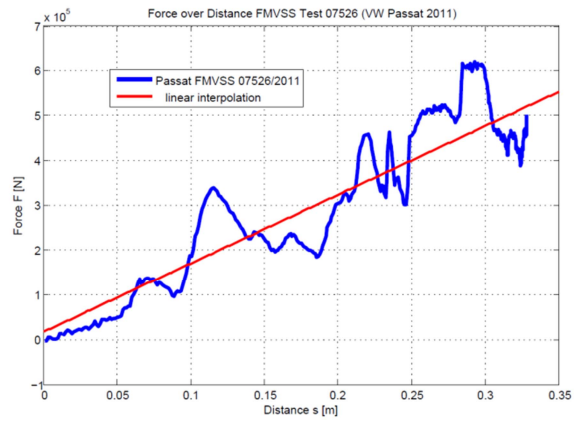

Figure 12: Force over distance, NHTSA [2]

Figure 12 shows the force over the distance during a crash test of a VW Passat in the NHTSA FMVSS 208 Nr. 07526 [2]. Based on this the integration of a linear increasing force is a quadratic increasing deformation energy (Figure 13).

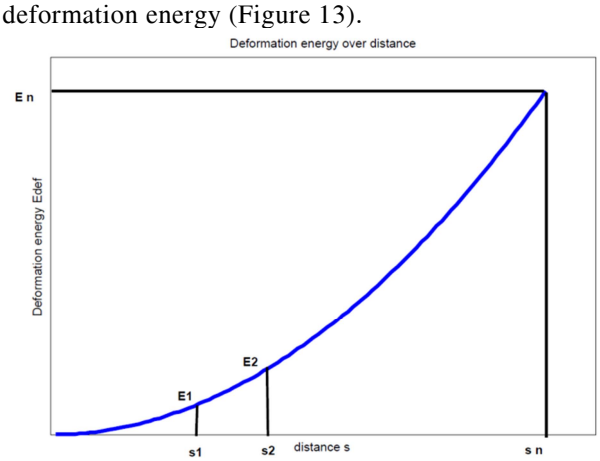

Figure 13: Deformation energy over distance

The whole deformation energy (E_{ges}) is the sum of the single energies in all distance steps (i). Thus the following equation can be set.

$$E_{ges} = \sum_{i=1}^{n} E_i \tag{2}$$

where $= i = 1, \dots, n$.

To calculate the distribution of this deformation energy a simple quadratic equation and a weighting factor (b_i) is used.

$$E_i = b_i \cdot a \cdot s_i^2 \tag{3}$$

The deformation distance (s) is taken out of the deformation area of the vehicle and the direction of the impact pulse. The direction of the impact pulse is coded in the GIDAS-database as well and is called the "VDI 1". This parameter divided in 12 clockwise parts for every "VDI 1" direction an energy distribution matrix is calculated as a 2-dimensional matrix [120 x 40].

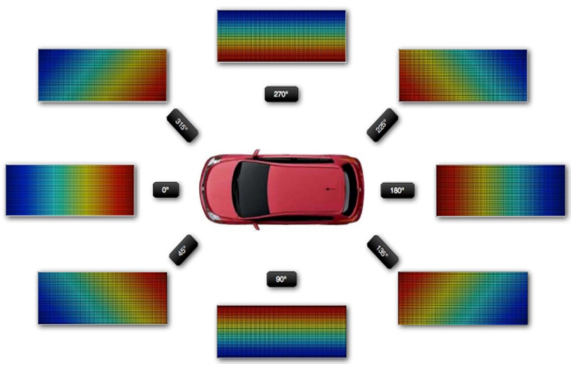

Figure 14: energy distribution by VDI 1

This energy distribution matrix is taken into a 3-dimensional model, which matches the basic-voxel-matrix.

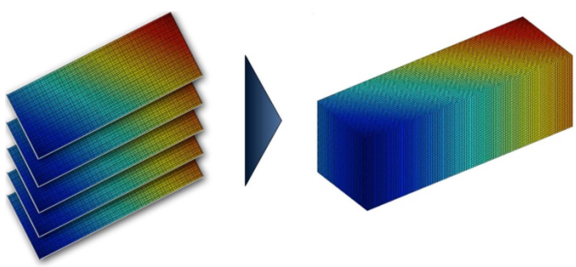

Figure 15: 3-dimensional energy distribution matrix

This 3-dimensional energy distribution matrix is blended with the vehicle shape and the deformations, similar to the basic-voxel-matrix.

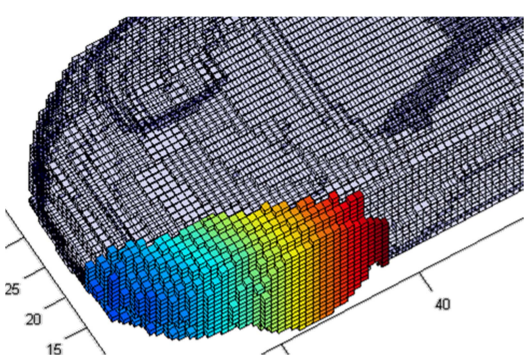

Figure 16: 3-dimensional energy distribution direction

Figure 16 shows an example of this distribution direction. With the number of deformed voxel, the distribution direction, the length and the width of the vehicle it is possible to calculate the deformation distance (s) of the actual deformation.

Due to the very asymmetric distribution of the deformation volume during the real crash (e.g. Figure 11), a weighting factor (b_i) has to be created.

$$b_i = \frac{anz_i}{Vox_{total}} \tag{4}$$

where anz_i are the deformed voxel in each deformation distance step s_i

and Vox_{total} the number of totally deformed voxel in the collision.

This is necessary because there might be a larger deformation volume in some first deformation distance steps than in the following ones.

The placement of equation (3) and (4) into equation (2) delivers the following equation.

$$E_{ges} = a \cdot \frac{1}{Vox_{total}} \sum_{i=1}^{n} anz_i \cdot E_i \tag{5}$$

To calculate the term a the equation has to be transposed.

$$a = \frac{E_{ges} \cdot Vox_{total}}{\sum_{i=1}^{n} anz_i \cdot s_i^2} \tag{6}$$

In the next step the deformation energy of each distance step (k) is calculated by the following equation.

$$E_k = \frac{E_{ges}}{\sum_{i=1}^{n} (anz_i \cdot s_i^2)} \cdot anz_k \cdot s_k^2 \tag{7}$$

, where $= 1, \dots, n$.

Last step is the calculation of the deformation energy for every single voxel (E_{Voxel}) with the following term.

$$E_{Voxel,k} = \frac{E_k}{anz_k} \tag{8}$$

Grouping the results After the calculation of the deformation energy of each voxel in the whole deformation at one vehicle the results for every vehicle have to be grouped. The fact that the deformation energy of each vehicle depends on the vehicle mass leads to the conclusion, that a grouping of this value delivers wrong information. Thus, a mass free energy value is needed. The best way to set a mass free energy level value in a model is the EES (energy equivalent speed) as used before to calculate the deformation energy. The EES-value of every voxel can be calculated by using the crash mass of the vehicle which is coded in the GIDAS-database.

$$EES_{Voxel} = \sqrt{\frac{2 \cdot E_{Voxel,k}}{m}} \tag{9}$$

After the calculation of the EES-value of every voxel in the deformation area of one vehicle a mean value for each voxel location in a vehicle shape can be calculated regarding all vehicles in the group.

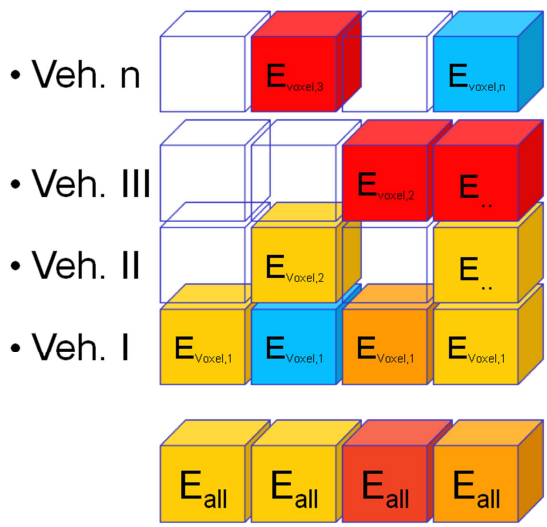

Figure 17: calculation of the mean EES of a vehicle group

Figure 17 shows the scheme of the calculation of the mean values of a vehicle group.

Vehicle groups The development of the passive safety elements in vehicles causes a variation of the deformation and crash behavior between older and newer cars.

Figure 18 EuroNCAP Test Opel Corsa B 1997[3]

Figure 18 shows an old EuroNCAP crash-test with an Opel Corsa B from 1996.

Figure 19: EuroNCAP Test Audi A6 2011 [3]

And figure 19 shows an EuroNCAP crash-test with a newer Audi A6 from 2011. In both tests the EES-value is 64 km/h. But there are two main differences between the tests.

1. The year of construction
2. The vehicles mass

Thus, the basis for the distribution of the EES has to be divided in four groups:

1. Younger, light vehicles
2. Younger, heavy vehicles
3. Older, light vehicles
4. Older, heavy vehicles

The borders for the groups are taken out of the particular distributions of the year of construction and the vehicle weight of the basic dataset.

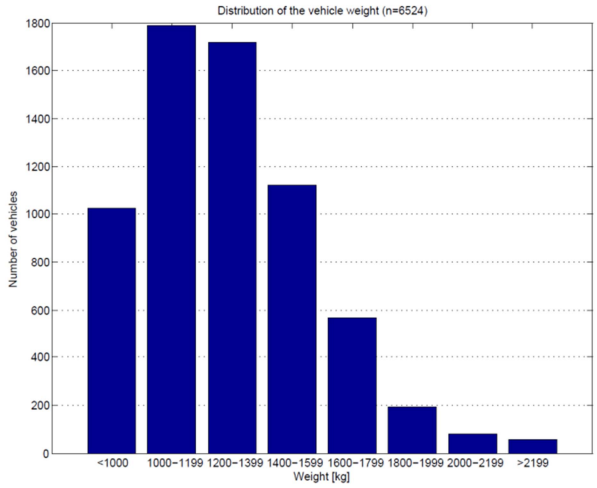

Figure 20: Distribution of the vehicle weight

Figure 20 shows the distribution of the vehicle weight in the basis-dataset. The spread is from 618kg to 3015kg and the median is at 1244kg. Thus, all vehicles with a weight up to 1300kg are light vehicles and vehicles with a weight of more than 1300kg are heavy vehicles.

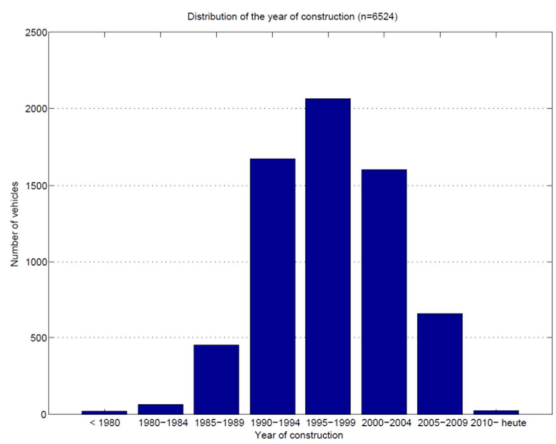

Figure 21: Distribution of the year of construction

Figure 21 shows the distribution of the year of construction of the basis-dataset with the minimal value at 1961 and a maximum value at 2011. The median is at 1997. Based on this median all vehicles which are built up to the year 1997 are old vehicles and all vehicles which are built from 1997 to 2011 are new vehicles.

Results The results of the energy and EES distribution for all four groups deliver the following results for example for young heavy vehicles.

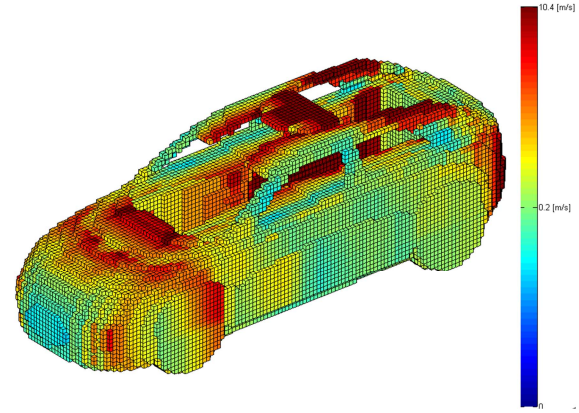

Figure 22: EES distribution of young heavy vehicles

In Figure 22 a distribution of EES values per voxel is shown. The dark red areas have an EES value up to 0.4 [m/s] per voxel and the lighter blue areas have an EES-value down to 0.1 [m/s] per voxel. A more precise overview about the result gives a top view where all EES-values in z-direction are averaged.

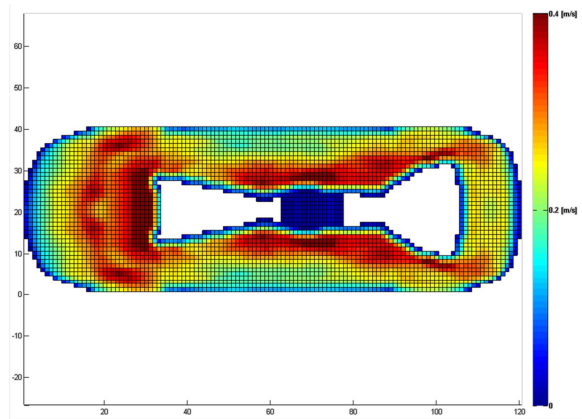

Figure 23: EES distribution (top view, young, heavy)

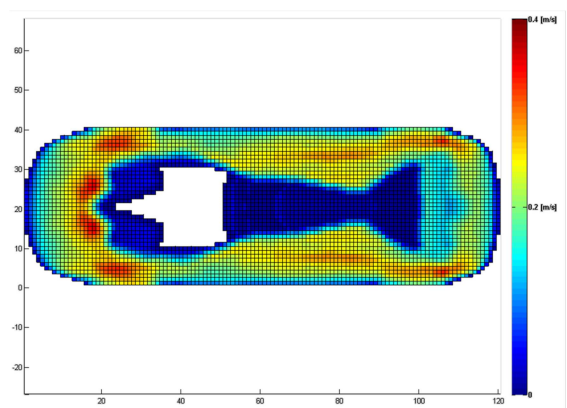

Figure 24: EES distribution (top view, young, light)

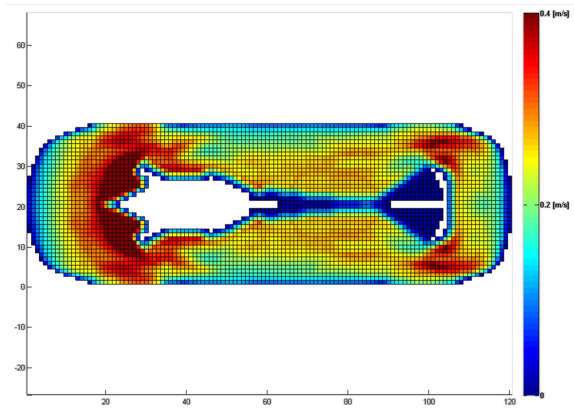

Figure 25: EES distribution (top view, old, heavy)

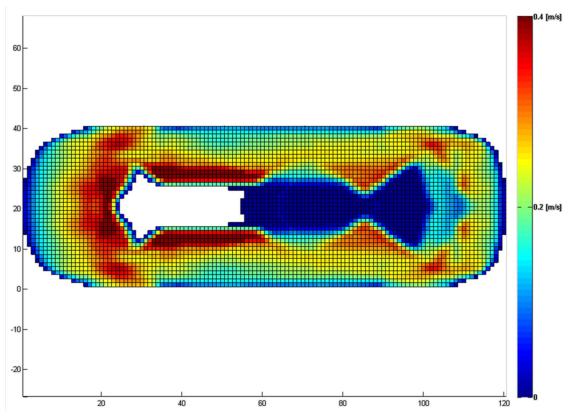

Figure 26: EES distribution (top view, old, light)

These four results show very good the different EES distributions of the four groups. Especially the engine, the absorbing deformation elements and of course the axles have a relative high EES distribution. A difference between newer and older vehicles can also be seen at the sides.

Usage of the Energy (EES) models

There are many ways the Energy (EES) models can be used. Exemplary uses can be: to point out the stiffness of GIDAS vehicles for an automated crash calculation, to build up an EES-catalog or to validate reconstruction calculations. This paper will give a possibility how these models can be used to get some first ideas for testing battery or fuel cell systems or to determine the energy level at their installation locations.

Crash Tests For validation of these EES models a simulative crash test can be done. Therefore a FMVSS 208 with 52 km/h against a rigid barrier is chosen. The EES distribution of an old heavy car delivers the vehicle model for this test. The vehicle mass is defined with 2000 kg.

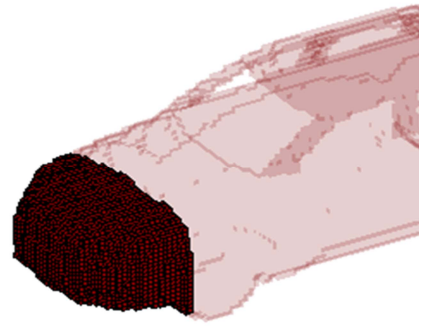

Figure 27: Vehicle deformation after validation crash test FMVSS 208

A similar real test with the number 3455 of a Honda Accord is shown in the figure below.

Figure 28: NHTSA Crash Test 3455 [5]

Both pictures show equivalent deformations. The absorbed crash energy is shown in another picture.

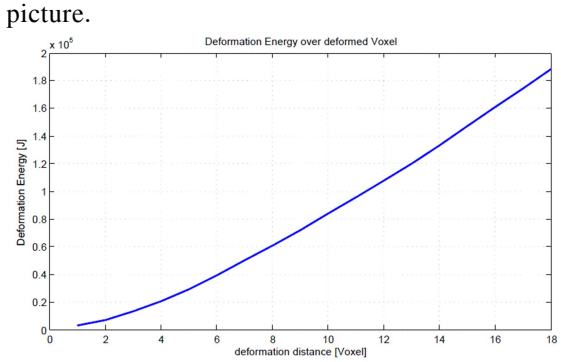

Figure 29: Deformation energy during the crash simulation

This deformation energy over deformation distance matches also good with the energy recorded in FMVSS 208 crash tests.

Rebuilding of the system For further analysis with installed battery and fuel cell systems a geometric definition of the volume of interest is needed.

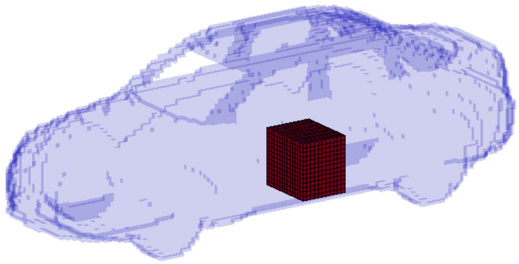

Figure 30: geometric definition of volume of interest

The example volume is defined at the back of the vehicle shape between the wheels (Figure 30).

Calculation of the resulting deformations

The first analysis which can be done with 3D Energy or EES models is to analyze how the crash behavior of all recorded real accidents in the GIDAS database will be modified by using very stiff battery packs or fuel cell systems. To analyze this crash behavior the volume of interest or the installation location of one car is configured very stiff and the crash is simulated again. The next figure shows a calculated example accident, which is a side collision with high speeds.

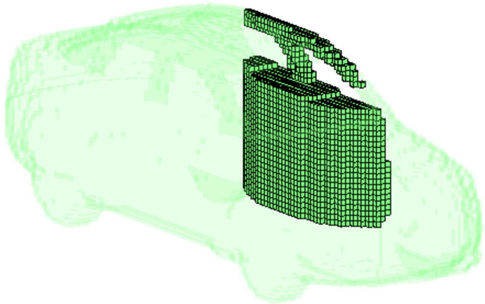

Figure 31: deformation behavior of the pushed vehicle without stiff cells

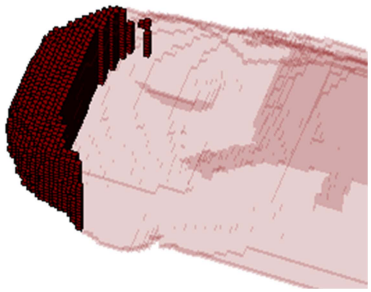

Figure 32: Deformation behavior of the striking vehicle without stiff cells

After that calculation the pushed car is equipped with a very (exorbitant) stiff element at the left side (Figure 30). And the same crash is simulated again. The results of this second crash are shown in the next figure.

Figure 33: deformation behavior of the pushed vehicle equiped with stiff cells

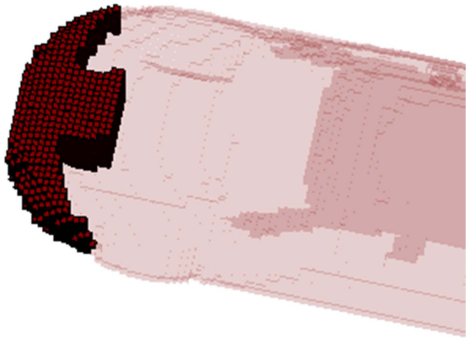

Figure 34: Deformation behavior of the striking vehicle equiped with stiff cells

The last both pictures show, that the deformation behavior in the real crashes will be very different depending on the stiffness level of the battery packs and fuel cells in future vehicles. This may have further influences to the development of new cars, battery packs or fuel cells.

Calculation of resulting energy levels The next possibility how the Energy (EES) models can be used for battery and fuel cell safety development is the possibility to find out which energy level in the deformed zones of the vehicle is important. Or what does the battery packs and the fuel cells have to absorb. This question can be answered again with the definition of a volume of interest or installation location in the car. After this definition all deformation energy is distributed as explained before and the area of interest is recorded in detail. This means, that the still left deformation energy at the area of interest is coded into a several matrix without calculating a mean value. At the end there will be maximum energies

relative to the installation location. The next picture shows an example battery pack between the rear axle of a vehicle.

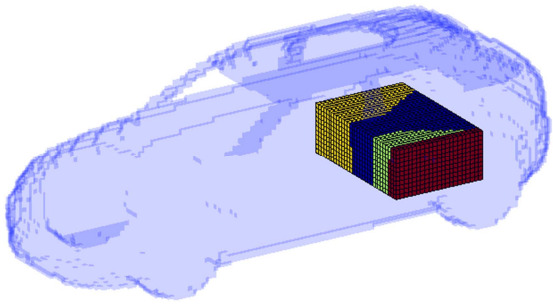

Figure 35: Energy level of battery pack example 1

In Figure 35 the left deformation energy at the chosen installation location is shown. The picture gives the possibility to check, where the critical areas for the installation of battery packs or fuel cell systems are. For this example there are three levels of left deformation energy, using a 2000kg vehicle.

1. Green – 15.210 J
2. Orange – 21.160 J
3. Red – 51.840 J

This is only an example result to show the possibilities of the energy (EES) models method.

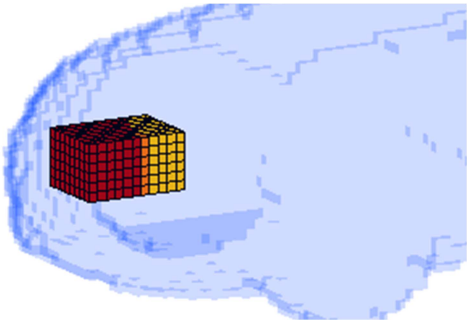

Figure 36: Energy level of battery pack example 2

Figure 36 shows the battery pack in the front of the vehicle with the following energy levels for a 2000 kg vehicle.

1. Yellow – 11.560 J
2. Orange – 15.210 J
3. Red – 23.040 J

These deformation energy levels are much lower than the energy levels between the rear axle but there is a much higher deformation frequency at this location. So the analysis of the safety of the installation location of battery packs and fuel cell systems should be also done in dependency of the deformation frequency at the vehicle out of the real accident scenarios e.g. GIDAS.

CONCLUSIONS

This paper gives an overview about new methods to get a better understanding of the installation locations of battery packs or fuel cell systems. Basis of the method are deformed vehicles of the GIDAS database. The deformations of those vehicles are calculated into 3-dimensional deformation models. The deformation energy of the particular deformation is then distributed by an own new approach with 3-dimensional energies (EES) models as a result. Those models can then further be used to point out relevant information of the safety of the installation locations of fuel cell systems or battery packs according to real accidents. At last three important issues can be taken out of the analysis.

1. 3-dimensional energy (EES) models can deliver statements to the safety of fuel cell systems and battery packs
2. The safety of the installation location of those systems has to be analyzed for
    a. Deformation behavior
    b. Energy levels
    c. Deformation frequency
3. The development of stiff fuel cell systems or battery packs may have a principle influence to real accident scenarios

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