CRASH SAFETY ASPECTS OF HV BATTERIES FOR VEHICLES

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ABSTRACT

Undisputed, the current safety standards for high voltage batteries address the chemical and thermal performance of battery cells during mechanical loads, i.e. pressure forces and intrusion. However, they do not represent the typical loads to the battery in vehicle crashes:
- The battery intrusions specified in the standards, namely 50 % of the battery dimension, cannot be achieved with the typical battery on standard compression machines due to the high forces needed.
- The maximum forces specified in the standards, namely the thousandfold of the battery weight, are unrealistically high even for small batteries in mild hybrid vehicles (i.e. the 24 kg battery of the Mercedes-Benz S 400 HYBRID). The loads applied to the battery rarely exceed 200 kN.
Even with 240 kN applied to the battery package, the battery intrusion achieved is only approx 11 %, which is well below the targeted 50 %.
There are two main differences between the loads applied to the battery in a vehicle crash versus the quasi-static battery tests: 1. Due to the crash propagation, the load is applied indirectly by the surrounding structure and components via multiple and distributed load paths; 2. Due to the short period of the peak loads, the battery can withstand much higher dynamical forces than the maximum static loads.

In order to assess the safety performance of HV batteries in severe crashes more realistically, a comprehensive series of dynamical impact tests was conducted with all types and sizes of HV-batteries used in the current Mercedes-Benz hybrid and electric vehicles. The load profiles were derived from both, the relevant vehicle crashes, and the quasi-static battery standards, applying even higher loads and battery intrusions. The tests were conducted at the crash test facility of the TÜV SÜD, utilizing two different test methods:

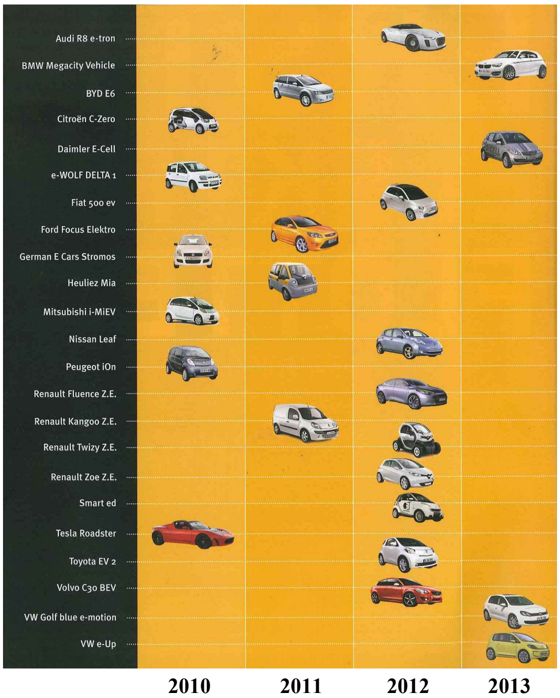
a) The moving battery hitting an impactor attached to the rigid barrier;
b) The moving impactor hitting the battery attached to the rigid barrier.

Despite the high loads and the resulting major battery intrusions, no thermal or electric reactions occurred, neither short circuits, nor electrolyte leakages, nor fire or explosion. The shock-proof protection was ensured in all tests. Given the very realistic test method along with the high loads applied, a very high crash safety performance could be demonstrated for all the batteries. Furthermore, the tests confirmed that there are major differences in the load characteristic between the quasi-static battery test standards, and the dynamic crash loads. As a result, more realistic component tests for traction batteries must be specified as soon as possible.

INTRODUCTION

Driven by severe fuel economy and CO_2 emission regulations, there is no doubt that hybrid and battery electric vehicles will play a major role in the future individual traffic. It goes without saying that the consumers expect an equally high safety standard for alternatively driven vehicles as established for conventional cars. While many car lines already offer a hybrid version, the availability of battery electric vehicles (BEV) is still restricted to small series, or special vehicles, and the number of purchasable electric car models (Table 1) is still limited [1]. While currently only approx. 40,000 hybrid and electric vehicles are currently licensed in Germany, of which only 2,300 are BEV's [2], this number is expected to increase to up to 1 Mio by 2020 [3]. All major OEMs have announced new electric cars in the near future.

Table 1.
List of BEV purchasable in Germany [1].



A roadblock for the acceptance of electric vehicles is their still limited cruising range. The key to success is intrinsically tied to the energy storage technology, Lithium-ion high-voltage batteries (HV) obviously being the base for the near future hybrid and electric vehicles. As any energy storage, also HV-batteries implicate some challenges to both the functional safety and the crash safety, which must be addressed appropriately. As discussed in the ESV-paper “Crash Safety of Hybrid- and Battery Electric Vehicles” [4], the crash performance of hybrid and electric vehicles is mainly affected by two key factors: 1. the crash performance of the battery itself, and 2. the crash protected integration of all the HV components in the vehicle. While the protection zones for the best possible integration of energy storages were evaluated in another study [5] by analyzing the damages of approx. 9,000 vehicles involved in severe real world accidents (Figure 1), the focus of this paper is on the crash safety performance of the HV batteries.

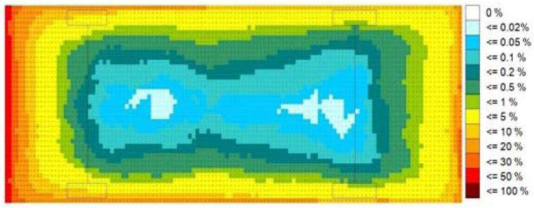


Figure 1. Deformation probability in severe real world accidents (passenger cars, top view, vehicle front on the left).

MOTIVATION

The current safety standards of high voltage batteries address the chemical and thermal performance of individual battery cells and its composites during mechanical loads, i.e. pressure forces and intrusion / deformation. Typically, due to the high loads, the cells will be destroyed with the result of electrolyte leakage. The break out of a fire depends on the temperature level generated during the test, or any extraneous ignition. Although these tests are very useful in evaluating the safety performance of battery cells, there are many arguments that these tests do not represent the typical loads to traction batteries in crash tests or in severe real world accidents.

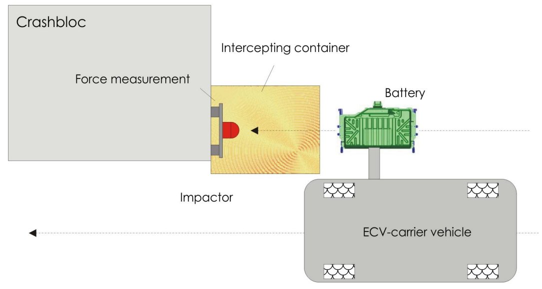
Already the implementation of the test requirements encounters some major difficulties. Generally, the traction battery is packaged in the vehicle as a module with a housing including the electronics, the cooling system and other elements. Due to the high deformation resistance of such a battery module, the battery intrusions specified in the current test standards, namely 50 % of the battery dimension, could only be achieved with extremely powerful test benches. Moreover, the maximum forces specified in the current standards (i.e. SAE J2464), namely the thousandfold of the battery weight, are not high enough to achieve the targeted intrusion: i.e. only 11 % deformation of the battery housing could be achieved (~ 24 mm) by applying the thousandfold of the small 24 kg battery with 0.8 kWh of the Mercedes-Benz S 400 HYBRID [6,7,8]. Due to the structural design of the battery, no battery cells will be impacted at such minor intrusions. Applying this requirement to the battery of full hybrid vehicles with 1,5-3 kWh, or to the battery of electric vehicles with 15-35 kWh, resulting in battery weights of 50 to 200 kg, the minimal load would be 500 to 2000 kN, which is totally unrealistic compared to the loads applied even in the crash tests: In crash simulations the maximum loads rarely exceed 200 kN.

There are two main differences between the loads applied to the battery in vehicle crashes versus the quasi-static battery tests:
1. The crash load is propagated to the battery by the surrounding structure and components via multiple and distributed load paths, thus being applied only indirectly, i.e. the battery may move or dodge, the battery mounting and housing may be designed deformable, the battery protecting cage and the surrounding vehicle structure may absorb energy, and many other compliances and reinforcements may cushion the peak loads to the battery.
2. Another crucial difference of crash loads versus quasi-static tests is the time scale: due to the very short period of the whole crash of approx 100 ms (the blink of the eye) peak loads are applied only for milliseconds. Same as any component, the battery can withstands much higher short-period dynamical forces than the maximum static loads. On the other hand, due to the high peak values of the vehicle acceleration during the crash – up to 80 G's – high inertial forces will be generated in the battery interior, and must be taken into account in the mechanical design of the battery.

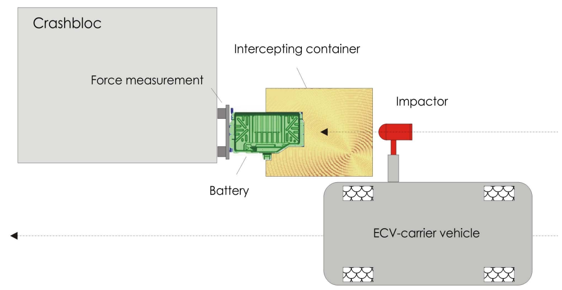
In order to evaluate the safety performance of traction batteries in vehicle crashes realistically, the parameters of the corresponding component tests must be defined appropriately. In particular, misconstrue of the battery due to an unrealistically high mechanical stability required, and the resulting in unnecessary high costs must be avoided. Therefore, a comprehensive series of dynamical crash tests with all types and sizes of HV-batteries used in the actual Mercedes-Benz hybrid and electric vehicles has been conducted.

TEST METHOD

The tests were conducted at the crash test facility of the TÜV SÜD, utilizing an impactor with variable mass and geometry hitting the battery. In order to cover a wide range of impact energy, speed, mass and geometry, two different test methods were applied (Figure 2):
a) The moving battery was hitting an impactor attached to the rigid barrier;
b) The moving impactor was hitting the battery fixed to the barrier.



a) Impactor fixed to the barrier, battery moving



b) Battery fixed to the barrier, impactor moving

Figure 2. Impact test configurations.

The set-up (a) was mainly used for larger batteries. For smaller batteries, the test method was inversed (b) when the targeted kinetic energy could not be achieved with the limited impact speed. In these cases, the batteries were fixed to the barrier and impacted with 40 kph by the energy equivalent mass. In these cases, the high inertial forces resulting from the battery acceleration could not be simulated, unfortunately. In either case, the moving part was mounted to the support shaft of a truck approaching the barrier with the selected test speed. Shortly before the impact, the moving mass was decoupled from the support shaft and flying free against the barrier, while the truck was passing the barrier on the side.

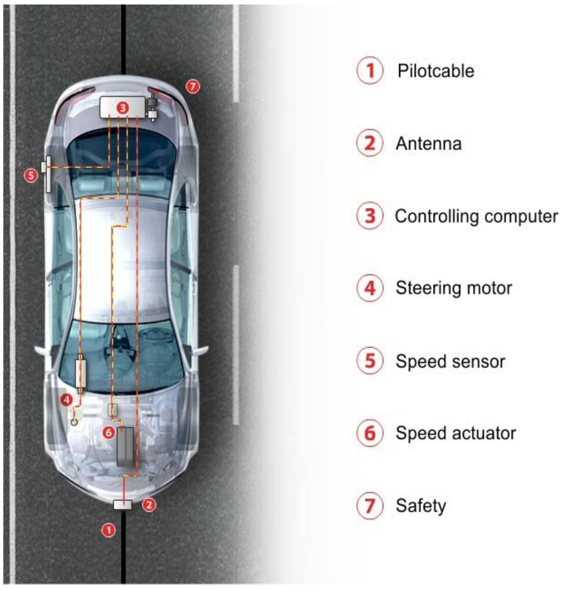


Figure 3. Electronically controlled vehicle system (EVC).

The truck was controlled by the Electronically Controlled Vehicle system (EVC). It was developed by TÜV SÜD to enable most realistic and reproducible crash tests for all vehicle sizes, from small cars up to big trucks, in any possible configuration [9, 10]. EVC (Figure 3) guarantees an accurate control of a driverless vehicle with respect to speed and course. With a wire on the road defining the driving course, and an antenna in the front bumper, the control unit in the vehicle enables autonomous acceleration, braking and steering. Any corrections to the direction are calculated continuously and applied to the steering by an electric motor. Similarly, the vehicle speed is controlled by automatically adjusting the throttle. Shortly before the crash, the control elements can be decoupled, and the vehicle can be stopped at any time by an independent radio signal.

This test configuration (Figure 4) allows impact speeds up to 55 kph, impact masses up to 500 kg, resulting in maximum impact energy of 60 kJ, using different impactor geometries as illustrated in Figure 5, i.e. half cylinder, hemisphere or wedge.

Figure 4. Test build-up for dynamic battery impact.

The impact loads were monitored with load cells on the barrier, and the intrusions to the battery were measured as well. The batteries were monitored for 48 hours after the tests.

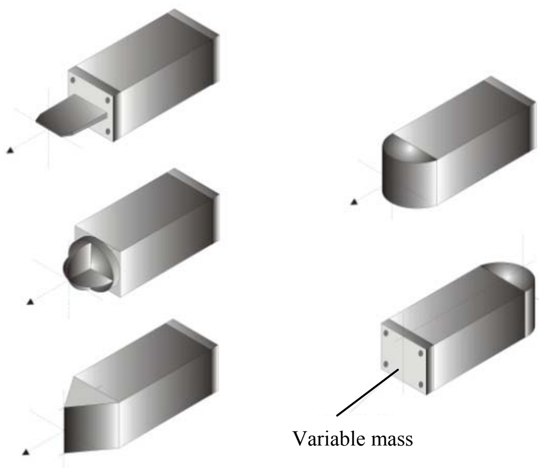


Figure 5. Impactor geometries.

TEST SAMPLES AND DYNAMIC LOAD PROFILES

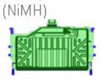
Vehicle	S 400 HYBRID 	ML 450 HYBRID 	B-Class F-CELL 	Smart ED 
Battery Typ	Mild-Hybrid (Li-ion) 	F-CELL (Li-ion) 	Full-Hybrid (NiMH) 	BEV (Li-ion) 
Battery Location	Front 	Rear Axle 	Rear Axle 	Floor 

Figure 6. Batteries of actual Mercedes-Benz hybrid and electric vehicles.

Figure 6 shows the batteries used in the actual Mercedes-Benz hybrid and electric vehicles.

A Lithium-Ion 0,8 kWh mild hybrid battery (24 kg) in the S 400 HYBRID, a NiMH 2,4 kWh full hybrid battery (83 kg) in the ML 450 HYBRID, a 1,4 kWh Li-Ion battery (48 kg) in the B-Class F-CELL, and a 14 kWh Li-Ion battery (148 kg) in the Smart ELECTRIC DRIVE. 2-3 samples of each battery were available for the dynamic crash tests.

In all Mercedes-Benz hybrid and electric vehicles, the traction battery is well protected against any critical loads or damages in vehicle accidents. This is true for the battery located in front of the compliant firewall of the S 400 HYBRID, for the battery placed above the stiff rear axle of the ML 450 HYBRID or of the B-class F-CELL and for the battery of the Smart ED located on the vehicle floor between the solid side rocker panels.

Battery Type	Mild-Hybrid (Li-ion) 	F-CELL (Li-ion) 	Full-Hybrid (NiMH) 	BEV (Li-ion) 
Battery Data	0,8 kWh, 24 kg	1,4 kWh, 48 kg	2,4 kWh, 83 kg	14 kWh, 148 kg
Test Type # 1	B (Battery fixed)	A (Battery moving)	A	A
Test data # 1	m=280 kg v= 18 km/h E=3,5 kJ	v=40 km/h E=3 kJ	v=40 km/h E=5 kJ	v=32 km/h E=6 kJ
Test Type # 2	B	B	B	A
(Test data # 2	m=300 kg, v= 22 km/h E=5,6 kJ	m=200 kg, v=35 km/h E=9 kJ	m= 200 kg, v=35 km/h E=9 kJ	v=40 km/h E=9 kJ

Figure 7. Dynamic battery impact test parameters.

The parameters of the dynamic battery tests (Figure 7) were based on the maximum loads (both force and intrusion) achieved in the quasi-static battery tests and in addition, the load paths in the relevant crash tests were evaluated utilizing crash simulation. For reasons of comparability, similar load cases were applied to all batteries. In the base test, a kinetic energy of 3-6 kJ was applied according to the force-deflection characteristics of the quasi-static tests. Although this energy is above and beyond the loads experienced in the vehicle crash tests, the energy was significantly increased (between 1.5 and 3 times) in a further test. While a half cylinder with 300 mm diameter was used for the larger batteries, a smaller diameter of 150 mm was used for the smaller batteries in order to take into account the smaller battery dimensions.

TEST RESULTS

Mild-Hybrid Battery (Li-Ion)

In the quasi-static test with a cylinder of 150 mm diameter, 24 mm intrusion was achieved at 270 kN maximum load. In order to apply the equivalent energy of 3.5 kJ to the small 24 kg battery in the dynamic impact, the battery attached to the barrier was impacted with 280 kg mass at 18 kph. Similar to the static test, a maximum deformation of 25 mm was achieved at a maximum force of 300 kN. While an almost linear load characteristic was measured in the static test, the slope of the dynamic load is flat up to 10 mm, increasing progressively with higher intrusion. In the 2^{nd} tests, the energy was increased by 50 %, which is equivalent to 300 kg impactor mass and 22 kph, resulting in 35 mm intrusion at 380 kN (Figure 8). Same as in the static tests, the battery enclosure did not break despite the high deformation, and no thermal reactions or electrolyte leakages occurred. The battery state of charge (SOC) was 80 % in both tests, and the shock-proof protection was fully ensured. Since the battery cells are mounted individually in the housing, no damages are expected even at very high inertial forces during battery acceleration. Although the crash energies applied in the tests are far above the loads expected even in very severe real world accidents, the crash safety performance of the battery is excellent, mainly to the extremely stiff high quality steel cage.

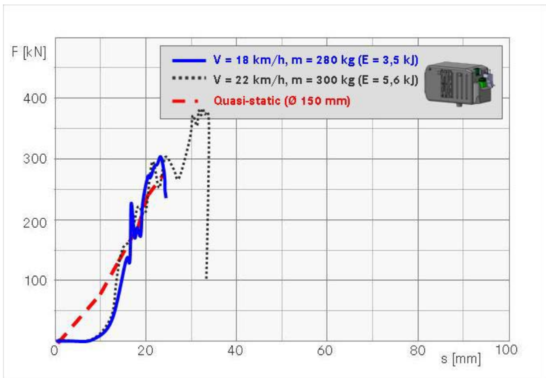


Figure 8. Load characteristics of the mild-hybrid Li-ion battery.

F-CELL Battery (Li-Ion)

Again, the parameters of the dynamic impact were based on a quasi-static test with a cylinder of 300 mm diameter. According to 90 mm intrusion at 60 kN, 3 kJ kinetic energy was applied with 40 kph battery impact speed. Interestingly, only one third (35 mm) intrusion was achieved at the double peak load (130 kN) versus the quasi-static test, the dynamic load characteristic significantly deviating from the linear slope. Since no thermal or chemical reaction occurred in a quasi-static test with 90 mm intrusion, the kinetic energy was tripled to 9 kJ in the 2nd test, by impacting the battery attached to the barrier with 200 kg at 35 kph. Despite 110 mm intrusion 150 kN peak, still no electric or thermal reactions could be measured (Figure. 9). The battery SOC was 90 %, and the shock-proof protection was ensured.

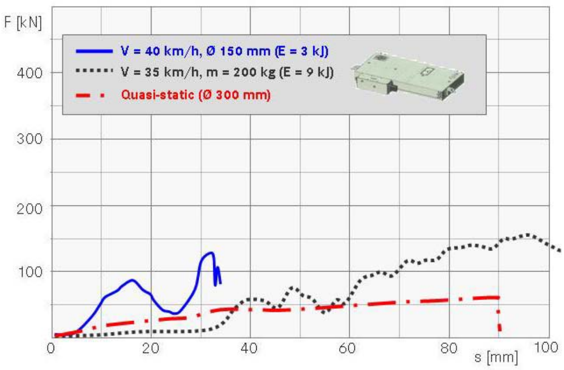


Figure 9. Load characteristics of the F-CELL Li-ion battery.

Full-Hybrid Battery (NiMH)

In the quasi-static test, the battery failed at 90 mm intrusion at 180 kN due to the contact between conduction parts in the electronics, resulting in short circuits and spark generation. In the energy equivalent dynamic test, the battery was impacted by a half cylinder with 40 kph, with a diameter of 150 mm in the 1st test, and 300 mm in the 2nd test. Despite the higher dynamic forces (200 and 250 kN), the resulting battery intrusions (50 and 55 mm respectively) were significantly lower than in the static test (Figure 10). Due to rotary motions during the impact, only approx. 2/3 of the kinetic energy was transferred in deformation energy. This could be the reason why, interestingly, the higher intrusion was achieved with the bigger impactor diameter. The slope of the dynamic load is significantly steeper as the quasi-static characteristic. In the 3rd test, the battery was attached to the barrier, in order to apply higher energies to the battery. As a consequence, the back side of the battery, being weaker than the center, was deformed significantly, while the intrusion at the impact side were similar as in the prior tests. Again, no electric or thermal reactions occurred, the shock-proof protection was ensured, and the battery SOC was 75 %.

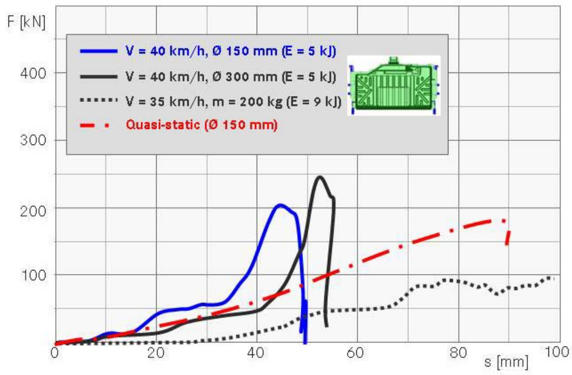


Figure 10. Load characteristics of the full-hybrid NiMH battery.

BEV-Battery (Li-ion)

Due to the size of the battery, no quasi-static tests were performed. Alternatively, the parameters of the dynamic impact test were evaluated from the battery loads experienced in the relevant crash tests. Utilizing crash simulation, a maximum energy of 6 kJ was estimated. Accordingly, the battery was impacted with 32 kph against a pole (300 mm diameter) in the 1st test, resulting in 35 mm deformation of the battery housing (Figure 11). Although the energy was 50 % higher in the 2nd test (9 kJ, 40 kph), resulting in 55 mm at 230 kN maximum load, no electric or thermal reactions occurred in either test. The shock-proof protection was ensured, and the battery SOC was 95 %.

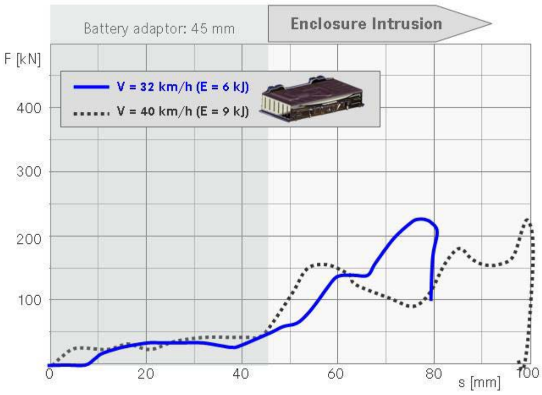
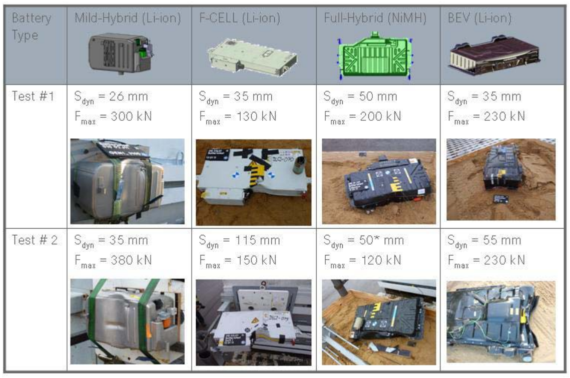


Figure 11. Load characteristics of the BEV Li-ion battery.

DISCUSSION OF THE TEST RESULTS

Despite the high loads applied and the resulting major battery intrusions, no critical thermal or electric reactions occurred in the described test series (Figure 12), and the shock-proof protection was ensured. No short circuits, no electrolyte leakages, no fire or even explosion occurred. Given the very realistic test method along with the loads applied being much higher than in severe accidents, a very high crash safety performance could be demonstrated for the batteries currently used in the actual Mercedes-Benz hybrid and electric vehicles.

While some of the dynamic impact tests correlated relatively well with the equivalent static tests with regard to maximum loads and intrusions, major differences were observed with the bigger batteries, the load characteristic in particular. This is also true for the performance data of the different battery types in the dynamic impacts. Evidently, the mechanical stability of the battery housing, and the interior compliance of the battery play a key role in the crash performance. Both concepts, a very stiff housing allowing only minor intrusions (i.e. the mild hybrid battery), and a compliant battery interior tolerating major intrusions (i.e. the F-CELL battery), have been proven as crash-safe even if directly impacted in a crash. Nevertheless, the traction battery should always be located in a very stiff area which is protected against major deformations.



Battery Type	Mild-Hybrid (Li-ion)	F-CELL (Li-ion)	Full-Hybrid (NiMH)	BEV (Li-ion)
Test #1	S_{dyn} = 26 mm F_{max} = 300 kN	S_{dyn} = 35 mm F_{max} = 130 kN	S_{dyn} = 50 mm F_{max} = 200 kN	S_{dyn} = 35 mm F_{max} = 230 kN
Test # 2	S_{dyn} = 35 mm F_{max} = 380 kN	S_{dyn} = 115 mm F_{max} = 150 kN	S_{dyn} = 50* mm F_{max} = 120 kN	S_{dyn} = 55 mm F_{max} = 230 kN

Figure 12. Test results of dynamic impacts with HV-batteries.

CONCLUSIONS

It is obvious from the test results, that the current test standards for high voltage batteries, based on quasi-static tests, do neither reflect the mechanical loads experienced in the vehicle crash tests, nor in the dynamic impact tests. This is true for the specification of a minimum crush of the battery package, and it is even more for the correlation of the maximum load to the battery weight. As a result, these battery standards must be modified appropriately. I.e. a minimum load could be specified where no battery cells must be damaged resulting in electric short circuits or electrolyte leakages. The current standards only address the chemical safety performance of individual battery cells.

As a next step, the partially major differences in load characteristic between the dynamic impact and quasi-static tests must be further analyzed, with the ultimate goal, to specify relative simple and reproducible and most realistic component tests for traction batteries. Finally, these tests must be verified in tests with different crash loads and different battery types.

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