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Crashworthiness Analysis of Electric Vehicle With Energy-Absorbing Battery Modules

As a clean energy technology, the development of electric vehicles (EVs) is challenged by lightweight design, battery safety, and range. In this study, our simulations indicate that using a flexible structure of battery module has the potential to overcome the limitations in battery-powered EVs, contributing to a new design. Specifically, we focus on optimizing the structure of vehicle battery packs, aiming to improve the crashworthiness of EVs through frontal crash simulations. In addition, by considering battery packs as energy-absorption components, it is found that occupant compartment acceleration (OCA) is greatly reduced at an optimal working pressure of 4 MPa for battery module. [DOI: 10.1115/1.4035498]

1 Introduction

As the concentration of CO_2 keeps increasing, many negative externalities are introduced to the ecosystem, including global warming. Thus, it is essential to explore feasible technologies in the motor industry to gradually break away from the dependency of oil by developing EVs [1,2]. However, the development of EVs encounters various challenges, such as the lightweight design and range of EVs. Moreover, battery safety is another critical factor, even if the advanced EVs suffered from this issue, causing a fire during crash [3]. These three factors are of great importance, consisting the design theme of EVs.

Regarding the commercial EVs, the competitive EV can deliver up to 270 miles on a full charge, while most other EVs have the ranges below 100 miles [4,5], much lower than the ranges of their counterpart gasoline-based vehicles. To increase the range, more batteries should be added to EVs, provided that the specific battery capacity is constant. As high-efficient EVs, lightweight design needs to be conducted, in order to compensate the additional weight of batteries and thus reduce electricity consumption. As a result, there exists a balance between vehicle weight and range. In addition, battery packs occupy a large space and the weight ratio of the battery packs to EV is extremely high, which could induce safety issue, in particular during crash. Despite the roles these three factors play in designing EVs, it is difficult to achieve all the three goals by a single solution. In this work, we aim to provide a possibility, concentrating on battery packs, toward new designs in future.

As for the state-of-the-art EVs, battery packs are carefully protected from external crashes to avoid catching fire and are located away from the front of vehicle. However, thermal-runaway mitigation concepts have recently been proposed, by using positive thermal coefficient materials [6], phase transfer materials [7], and damage homogenizer [8,9], with the mechanisms of increasing the internal impedance and lowering heat generation rates as the battery cell is subjected to an impact loading. Thus, it could offer a new path to use battery packs as multifunctional components. Inspired by those novel concepts, battery modules can provide not only electricity but also buffering effects during a crash.

Given that our team has produced safety-guaranteed battery [8,9], this study focuses on the structural optimization of battery packs, which is expected to benefit the lightweight design and range of EVs. To this end, we propose to place energy-absorbing battery modules in the front of the vehicle and postulate optimized designs using computer simulations, a low-cost method to simulate mechanical behaviors [10,11]. Due to energy-absorbing battery modules, the frame of vehicle can be weakened for weight-savings. As a result, multifunctional battery module could serve as vehicle bodies in future, granting EVs lightweight designs and range increase.

This research is split into three sections: We first investigate vehicle acceleration during the crash as a criterion of determining the optimal structure of the battery module; by analyzing the occupant compartment acceleration and energy absorption, we hope to determine the optimum working pressure of the battery module in order to effectively protect the driver; finally, a roof crush simulation is conducted to evaluate the roof strength of the vehicle. In this simulation, we ensure that the EV can withstand an applied force of 2.5 times the weight of the unloaded vehicle, while the displacement of roof is below 127 mm, the safety cutoff specified by FMVSS 216.

2 Model and Method

Dodge Neon, an original gasoline-based model, is selected as the representative vehicle for our finite element methods (FEMs) simulations. The model used in the simulation, developed by the National Crash Analysis Center, is extremely attentive to real-life

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details and has been validated against the crash test data in terms of displacement, velocity, and acceleration during frontal impacts [12]. The model consists of an unloaded delivered vehicle with a weight of 1155 kg, rated cargo and luggage weighing 52 kg, and two Hybrid III dummies weighing a total of 152 kg. The latter two are simplified as masses in our simulations. To simulate the EV, the original engine located in the front of the car is replaced by an energy-absorbing battery module under the hood. In addition, the rigid electric motor, with a weight of 110 kg, is fixed between two rear wheels.

In our unpublished experiments, we found that mechanical property of battery module can be tuned by structural design, such as the specific assembly of batteries. Those experiments indicated that the mechanical behavior of battery module we previously developed can be described by the ideal elastic–plastic constitutive relation, as shown in Fig. 1(*b*). At the initial stage, the battery body is elastically deformed when subjected to a low stress, and the deformation is reversible. However, as it comes to the energy-absorbing plateau, a part of the strain should remain, even if the external force is completely unloaded, similar to an elastoplastic material. According to our experiments, Young's modulus $E = 1$ GPa is used in our simulations, and the density of battery module is set to be 1.9 g/cm^3. In the experiments, it is demonstrated that the working pressure σ_s is tunable, as the result, σ_s is considered as a key designing parameter in our optimizations

$$\sigma = E\varepsilon, \quad \varepsilon \le \varepsilon_0 \tag{1}$$

$$\sigma = \sigma_s, \quad \varepsilon > \varepsilon_0 \tag{2}$$

The National Highway Traffic Safety Administration (NHTSA) has established regulatory requirements through the tests for motor vehicle manufacturers. Federal Motor Vehicle Safety Standards (FMVSS) contributes to improving the motor safety design. A variety of test configurations (car-to-car and car-to-fix) have been investigated to evaluate vehicle crashworthiness. More specifically, full frontal fixed barrier crash and roof crush resistance are taken into account to conduct our simulations. For the nondeformable barrier crash simulation of FMVSS 208, the acceleration is explicitly employed to assess the vehicle crashing performance, including the vehicle acceleration and OCA.

In the full frontal fixed barrier crash simulation, the vehicle runs into the rigid barrier with an impact velocity of 35 mph. To obtain the optimum performance, the structure of battery packs is optimized by using the vehicle acceleration as the criterion, with the consideration of four different designs. For the material properties of battery packs, OCA is considered to determine the optimal working pressure σ_s, and the accelerator is located on the driver seat crossmember. In order to provide a comparative analysis, a simulation of the original Dodge Neon as the baseline vehicle is also conducted. FEM, as implemented in LS-DYNA, is employed to carry out the simulations of frontal impact, which is an effective method to investigate the crashworthiness of EVs [13–15].

3 Results and Discussion

3.1 Optimizing the Structure of Battery Packs. In this section, we compare the crashing performance of four different structures of battery pack, i.e., S_1, S_2, S_3, and S_4 in Fig. 2. Based on the impact direction, these structures represent four oriented structures. The first one is a bulk, and the last three consist of plates. The longitudinal direction of plates in S_2 is perpendicular to the

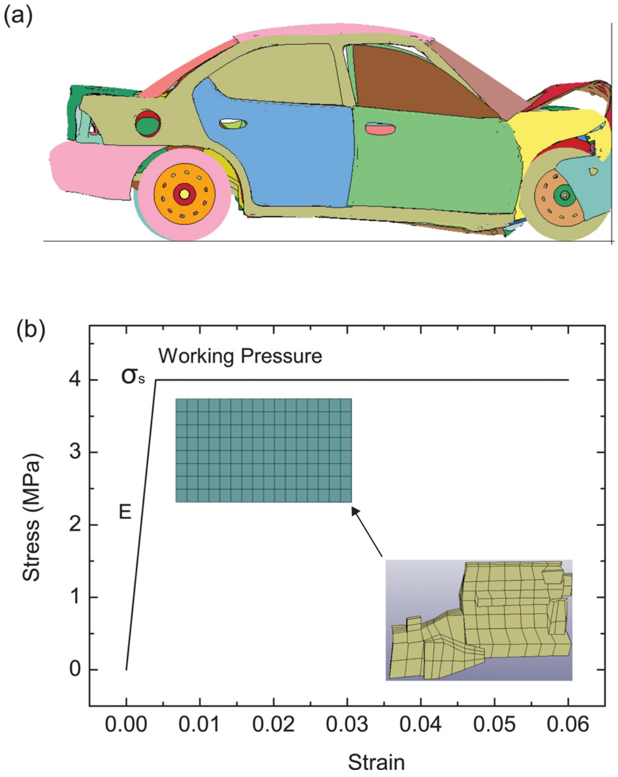

Fig. 1 (*a*) A snapshot of vehicle in the frontal crash simulations, with a speed of 35 mph according to FMVSS 208 and (*b*) the constitutive relation for battery model

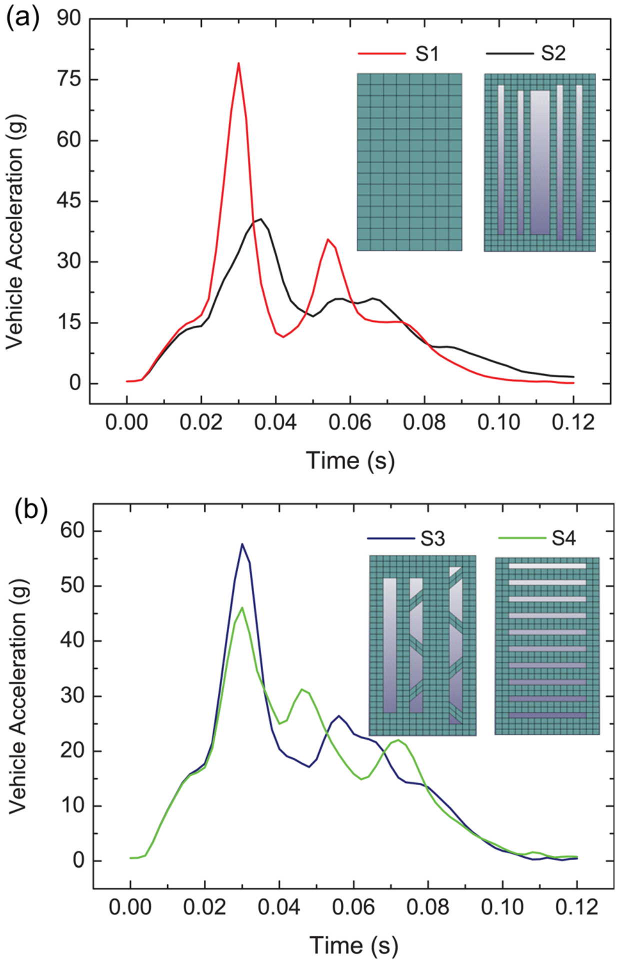

Fig. 2 Four different structures of battery model, denoted as S_1, S_2, S_3, and S_4, and the corresponding vehicle acceleration curves in the frontal impact simulations

impact direction, while the longitudinal direction of plates in S_4 is parallel to the impact direction. In addition to the similar structure in S_2, S_3 has inclined plates between vertical plates. For the original gasoline-powered counterpart, the maximum vehicle acceleration is 46 g, where g is the acceleration of gravity. With respect to S_1, however, the value reaches as high as 80 g. The structure of bulk S_1 is too stiff, and the compressibility leads to an excessively high vehicle acceleration, though it possesses a considerable energy-absorbing capacity. Moreover, the battery module occupies a large space under the hood with insufficient deformations, thereby limiting the plastic deformations. As a result, it is essential to reduce the acceleration by using more compressible battery packs.

To improve the crashworthiness and maximize passenger protection, the optimum design is selected with respect to the structure of battery packs. In Fig. 2(*b*), S_3 is established by removing parts of the battery body from S_1, producing a structure that incorporates transverse plates with sloping plates. More importantly, the overall vehicle acceleration is largely decreased compared to that of S_1, with the maximum acceleration of 58 g. Furthermore, it should be noted that there is only a 60 kg reduction in weight of battery compared with S_1 (420 kg). In Fig. 2(*b*), S_4 has a more regular structure with the horizontal plates, possessing the same weight around 360 kg as S_2. The maximum vehicle acceleration is reduced to 46 g.

Alternatively, the battery model is designed to be a structure consisting of transverse plates, denoted as S_2 in Fig. 2(*a*). Among the four configurations, this structure exhibits the best performance, as the maximum acceleration is 40 g, which is a 50% reduction from its counterpart S_1 without the structure design in Fig. 2(*a*), keeping in mind that the gasoline-powered counterpart has a value of 46 g. In comparison with other three acceleration-time curves in Fig. 2, it can be seen that the time corresponding to the first peak is significantly delayed with respect to S_2. Thus, it implies that the reduction in acceleration of S_2 is attributed to its flexible structure, which greatly buffers the frontal impact by means of bending deformation. In addition, though S_4 has the similar plate-shaped structures, all the plates undergo the impact force at the same time during the crashing, leading to a relatively stiff structure. In contrast, the impact force is gradually transferred to the plates of S_2 along the crashing direction, resulting in a more effective buffering effect.

3.2 The Optimum Working Pressure of the Battery Model.

In the following, we aim to improve crashworthiness by optimizing the working pressure of battery. The energy absorption and OCA are used to evaluate the vehicle crashing performance. Figure 3(*a*) shows the internal energy absorbed by battery packs S_2, indicating that as the working pressure decreases, energy absorption is enhanced until it reaches the peak under the working pressure of 3 MPa. Regarding the original gasoline-powered counterpart, the engine absorbs as little as 0.05 kJ of kinetic energy during the frontal impact. On the other hand, the peak in Fig. 3(*a*) corresponds to a value of 29.1 kJ, contributing to 17% total energy absorption. Even though the battery model of S_2 experiences a large bending deformation in the simulation, the entire battery structure is not severely damaged due to its flexibility.

Next, we focus on occupant compartment acceleration with the working pressure of battery model as the design variable. As shown in Fig. 3(*b*), OCA has a minimum value of 35 g under the working pressure of 4 MPa. As the working pressure of battery model exceeds 8 MPa, the acceleration then grows remarkably. At the same time, it maintains relatively low values for the working pressures ranging from 2 MPa to 8 MPa. It should be noted that the original OCA of Dodge Neon with a gasoline-based engine is 42 g. As studied here, most of our results are smaller than this value.

It should be noted that there is a peak for each optimization in Fig. 3. The underling mechanism is the competition between elasticity and energy-absorbing plateau. In the case of the high working pressure, the elastic deformation of battery packs is greatly extended, thereby hindering the energy-absorbing process. In contrast, the capability of energy absorption is weakened under the low working pressure, because of the limited volume deformation of battery module.

Based on the previous optimization, the optimum working pressure of battery packs is about 4 MPa, which is able to balance crashworthiness and the energy absorption. If battery packs absorb more impact energy, there will be fewer damages for other components in EV. Furthermore, if occupant compartment acceleration has a lower value, it can lead to a situation that is safer for passengers. Combining with these two aspects, the working pressures around 4 MPa is used as the optimum working pressure.

3.3 Roof Crush Resistance Simulation.

Due to the extra weight of battery packs and motor over the engine, roughly 190 kg, certain safety issues arise. To reduce the risk of fatalities and injuries from rollover crash, roof crush resistance is a crucial element to consider. For implementing the battery modules into the vehicle, the applied force to the roof will raise during the rollover accidents due to the increase in the total mass of the unloaded EVs. To address this problem, in this section, we investigate the strength of the roof by means of the displacement under an applied force to the vehicle roof.

By complying with FMVSS 216, the simulated model is depicted in Fig. 4. The standard relates the strength of the roof to

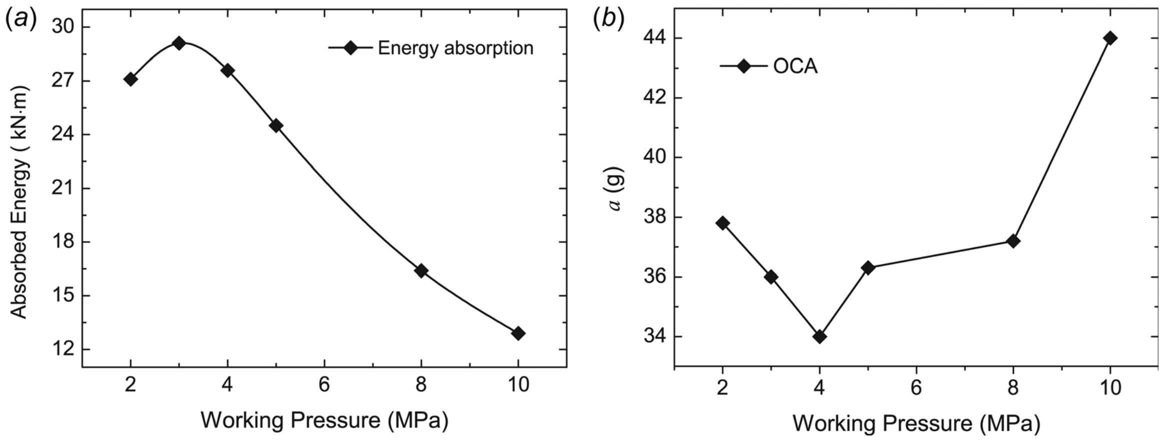

Fig. 3 Impact energy absorbed by battery packs and OCA with varying working pressure of battery module

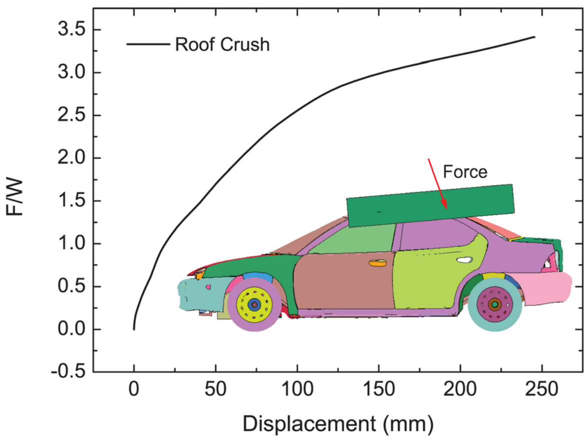

Fig. 4 Simulation for roof crush resistance, where *F* and *W* represent the applied force and vehicle weight, respectively

occupant protection in rollover accidents. In the new regulation, the loading device should not exceed 127 mm under the force that 2.5 times the unloaded vehicle weight in our simulation. A specified force is applied through a rigid 762 mm by 1829 mm above the roof as specified by the FMVSS 216, and the two sides between the frontal wheels and the rear wheels are fixed to constrain the vehicle. In Fig. 4, it indicates that a displacement of 77 mm occurs under the force that 2.5 times the unloaded vehicle. It can be concluded that the whole structure can hold a sufficient force during the rollover crush because the rigid ram only moves 77 mm, far less than the regulated one 127 mm.

4 Conclusion

In summary, we investigated the crashworthiness of EV through using the FEM. As multifunctional components, in addition to supplying the power, battery packs also absorb kinetic energy during crashes. According to the frontal crash simulations, it turns out that the vehicle acceleration can be reduced by designing a flexible battery structure, resulting in a comparatively large squash of the front of the vehicle to absorb more energy. The working pressure also has significant impacts on the energy absorption and occupant compartment acceleration. Thus, the structure of battery module and working pressure are two critical factors that can improve crashworthiness based on the crash simulations. In addition, roof crush resistance simulation demonstrates that the loading device moves less than 127 mm under the force that 2.5 times the unloaded vehicle weight.

Through this work, the optimization of battery module results in a great potential to improve the vehicle performance. Therefore, it could reduce the weight of critical components of vehicle for lightweight design and thus further increases the range on a full charge. Our work provides a new direction to solve the issues that EV designs are facing.

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