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Crash analysis of a conceptual electric vehicle with a damage tolerant battery pack

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ABSTRACT

In current electric vehicles, batteries fulfill only the role of power source and are stored within the passenger cabin, protected from external impact loads. This study considers a multifunctional, damage tolerant battery system which combines the energetic material with mechanically sacrificing elements that control mechanical stresses and dissipate energy. With such a multifunctional battery system in place it is proposed to place the battery pack into the secondary safe zone of a unibody-type vehicle. Full-vehicle crash analyses via finite element simulations are conducted for several battery pack configurations, thereby comparing the multifunctional battery system to battery packs with batteries alone and battery packs where cellular solids are used as energy absorbers. The analysis demonstrates the use of a multifunctional (damage tolerant and energy storage capable) battery system to ensure battery safety and aid in the energy absorption in a crash overall. The use of the multifunctional battery systems can aid in solving technology limitations of electric vehicles.

1. Introduction

Electric vehicles (EVs) provide propulsion using the energy stored in batteries on-board. Electric vehicles are understood to be highly efficient in converting stored electrical energy into mechanical energy. Yet, EVs also face several challenges associated with driving range, weight, and safety. Multifunctional energy storage systems, addressing both energy storage and mechanical function are seen as necessary technological solutions in advancing EV and related technology [1]. Following [2] two directions of multifunctionality are relevant. In a combination of electrical energy storage and load carrying capacity, multifunctional structural elements compose part of the primary and secondary vehicle structure. Relevant material and system level solutions have been demonstrated, e.g. [3–11]. Alternatively, a combination of electrical energy storage and mechanical impact mitigation capacity can be envisioned. Then, a multifunctional battery system would contribute simultaneously to battery and vehicle safety. This direction of research has less been explored. In [12] a possible embodiment of a damage tolerant battery pack system was proposed whereby battery macrocells of trapezoidal shape (each composed of multiple cylindrical battery units) are combined with crash elements to absorb energy. In [13] a related concept is considered but without the additional requirement of packing individual battery units into macrocells. Thereby, individual cylindrical battery units are combined with tubes in a bimodal packing structure given by the diameters of battery units and tubes.

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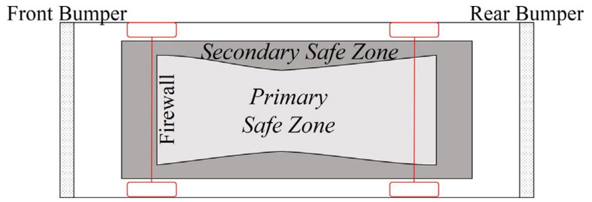

Fig. 1. Safe zones in a vehicle based on data in [15] on vehicle intrusions in real world accidents and laboratory crash tests.

Safety under crash condition is a special concern for vehicles with alternative energy storage systems [14]. Based on consolidated data of real world accidents and laboratory crash tests for unibody-style vehicles [15], two safety zones are defined as depicted in Fig. 1. The passenger cabin is considered as the *primary safe zone* and is protected from external impact loads by an appropriately designed vehicle structure. For most current electric vehicles, the *primary safe zone* is utilized for the placement of the battery pack. Since batteries are co-located with the passenger space, and even if located in the *primary safe zone*, batteries require heavy protection against mechanical failure and consequences arising from failure. Furthermore, space in the passenger compartment is restricted and thus battery volume is limited, leading to constraints on EV range.

The present study investigates if battery packs could be located outside of the *primary safe zone* of a unibody-based EV. In particular, it is considered to place battery packs into the *secondary safe zone*. Then, the battery pack can no longer be considered as a rigid body since it will interact with the crumple zone of the vehicle. On the other hand, the battery pack will require appropriate protective mechanisms because the battery pack might experience failure under extreme conditions, such as a crash [14]. This study considers the multifunctional energy material system introduced in [13] which combines energy storage capacity with stress control and energy dissipation. The concept of the Granular Battery Assembly (GBA) is depicted in Fig. 2.

GBA utilizes the *cushion-in-advance* principle [16] in the form of an embedded energy dissipation component. The plastic deformation of sacrificing tubes packed between the batteries limits the loads on batteries and dissipates energy. The overall mechanical response of GBA is similar to that of a cellular solid [13] exhibiting an initial elastic response, a plateau regime due to the tube collapse process, followed by a densification regime. GBA acts as a power source during normal operation of an EV. Under extreme mechanical loading during crash, GBA simultaneously dissipates impact energy and limits stresses on the battery units.

When considering multifunctional material solutions, overall system performance is the goal but penalties can arise on individual functionalities. The present study investigates conceptual EV configurations under crash conditions to assess the degree of effectiveness of the GBA approach and the degree of the emerging penalties due to the use of GBA.

2. Methods

A typical IC powered unibody-based sedan style vehicle was used as the starting point of the present study. The model corresponds to the structure of a 2012 Toyota Camry sedan (total vehicle mass = 1421 kg). The model and the finite element discretization for this structure were obtained from the National Crash Analysis Center (NCAC) [17]. Finite element (FE) simulations of a full frontal barrier crash against a rigid impact wall for each of the vehicle configurations were used to evaluate the crash safety response. The crash simulations for this study were performed on LS-DYNA platform [18]. In the analysis the constitutive response of the steel components representing the vehicle frame follows the constitutive model of Cowper and Symonds [19]. The specific property data are those made available from NCAC [17] and correspond to the material properties used in the validated crash model. The crash response for the model was validated with the New Car Assessment Program (NCAP) Frontal Impact Test number 7520 (35 mph, 56 km/h) [20] and good overall agreement between experimental and simulation data was obtained.

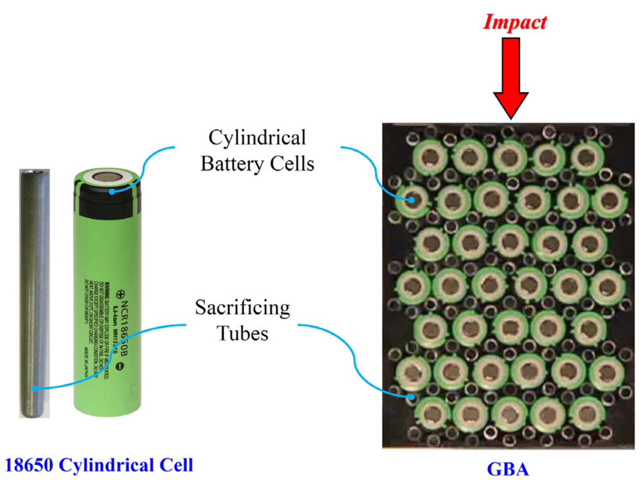

Fig. 2. Granular Battery Assembly (GBA) as a combination of cylindrical battery units and sacrificing cellular unit elements.