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Mechanical integrity of 18650 lithium-ion battery module: Packing density and packing mode

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ABSTRACT

The crash safety of lithium-ion batteries (LIBs) has recently become a hot research topic because of the wide application of LIBs in vehicle. This paper investigates how packing design of battery cells influence the energy density (volume specific) and structural of LIB pack. Firstly, three packing geometrical parameters (one packing angle parameter and two cell number parameters) are extracted to describe the packing modes, packing density and sizes of the module. Then a detailed computational model is established and validated through experiments, with the implementation of a failure criterion for short-circuit. An anisotropic elasto-plastic model is introduced to describe the mechanical response of the cylindrical jellyroll. Based on the computational results, we quantitatively describe the relationship between structural strength and packing parameters of battery module. The deduced empirical equations from the model are validated against numerical examples, and provide a reliable path to predict the mechanical integrity of battery packs with the knowledge of packing information. This developed modeling approach can serve as an efficient tool for safety design of LIB packs.

1. Introduction

Electric vehicles (EVs) are widely acknowledged as environment-friendly transportation devices because of their pollution-free nature and low petroleum consumption [1,2]. Among other candidate power sources, lithium-ion batteries (LIBs) have been widely used in EVs due to their relatively high energy and power density, high capacity, and long lifecycle [1,2]. Given the increasing number and proportion of available EVs on roads, the number of catastrophic accidents continues to increase due to the safety risks associated with LIB cells and packs [3–5], including electrical short-circuit, firing [6] and explosions [7,8].

Pioneering studies investigated the mechanical behaviors of LIB cells with various loading conditions [9,10] on pouch cells [9,11,12]. The mechanical behaviors of LIB components, such as cathodes [13], anodes [13], battery shells [9,14], and separators [15,16], were also investigated comprehensively to understand the mechanical integrity of LIB cells as a structure. To satisfy engineering needs, Greve, and Fehrenbach [9] and Xu et al. [17] explored the quantitative relationship between the internal short-circuit and mechanical stress status of LIBs caused by external mechanical loads which can describe the mechanical integrity of LIBs under various complicated loading conditions. Zhang et al. [18,19] studied the interaction between mechanical failure status and consequential electrical and thermal responses. These criteria have opened up a new area to examine the short-circuit phenomenon

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Nomenclature

b	The number of cells placed each row
d	diameter of single cell
E_{xx}, E_{yy}, and E_z	modulus in x, y, and z direction
E_s	the reference modulus when $\rho_p = 1$
E^*	effective modulus of the battery pack
F	force
G_{xy}, G_{yz}, and G_{xz}	corresponding shear moduli in different directions
l	the number of cells placed each column
L	height of the battery packs
S	section area of the battery packs
W^*	nominal strain energy density of battery pack
θ	packing angle
ρ_p	packing density
$\rho_{p,\ \max}$	the maximum packing density
ε_{ik} and $\gamma_{ik}(i = x, y, z; k = x, y, z)$	strains in different directions
ε	strain
ε^*	nominal strain of battery pack
ε_f^*	nominal failure strain of battery pack
ε_p	plastic strain
ε_{pc}	critical plastic strain
$\bar{\varepsilon}^{eq}$	equivalent plastic strain
$\bar{\varepsilon}_f^{eq}$	equivalent failure plastic strain
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}^*$	dimensionless plastic strain rate, equals $\dot{\varepsilon}/\dot{\varepsilon}_0(\dot{\varepsilon}_0^w = 1\ \mathrm{s}^{-1})$
σ	stress
σ^*	nominal stress of battery pack
$\sigma_p{}^*$	relative strength of the battery pack
$\sigma_s{}^*$	relative strength of the battery pack when $\rho_p = 1$
σ_{Hill}	Hill'48 equivalent stress
σ_0	yield stress
σ_{ik} and $\tau_{ik}(i = x, y, z; k = x, y, z)$	stresses in different directions
$\nu_{ik}(i = x, y, z; k = x, y, z)$	Poisson's ratio
ϕ	structural parameter

Superscripts

j	jellyroll
w	winding nail and shell

from a mechanical perspective. The vibration characteristics of LIBs were also experiment ally studied to understand the electrochemical performance of batteries in vehicles [20,21].

From the perspective short-circuit in a battery pack, Xia et al. [22] investigated the mechanical behavior of LIB square packs subjected to dynamic penetration from stone using a single-cell finite element model. Zhao et al. [23] studied the electrochemical behavior of nail penetrated LIB, and then developed a system to prevent thermal runaway for a square pack of LIBs. Some other studies employed various methods for detecting or monitoring short-circuit in situ to prevent thermal runaway [9,17] with the introduction of engineering-applicable devices to protect LIB packs from short-circuit [5]. Moreover, Nguyen et al. [24] and Kukreja et al. [25] preliminarily suggested new designs of battery module through enhancing the overall crash energy absorption capability of the module.

The safety of LIB packs highly depends on their mechanical integrity, which remains uninvestigated. The lack of research on this subject hinders the designing of better LIB packs. Given the light weight and small size of EVs, more space and weight limitations have been imposed on LIB packs such that the packing density and layout of these batteries have become prioritized and optimized targets. Trade-offs must be considered through battery safety, packing mode, and packing density. Therefore, the mechanical safety of LIB packs with various packing modes and densities must be investigated.

Based on the previous suggested mechanical model of a single battery [26], this paper establishes mechanical models for LIB packs with various packing modes and investigates the mechanical integrity of LIB packs upon previously correlated short-circuit criterion. This paper is organized as follows. Section 2 establishes a short-circuit criterion for single cell batteries and uses three parameters to characterize packing modes and pack sizes. Section 3 presents and analyzes typical numerical simulation results to demonstrate the mechanical integrity of LIB packs. Then how the mechanical integrity of these batteries changes across different governing parameter values is investigated and a method for rapidly predicting the mechanical responses of LIB packs is proposed. Section 4 concludes the paper.

2. Methods

In this work, we consider a rectangular battery module of cylindrical LIB cells (18650 cells). To study the pack design, we firstly develop a geometry model to describe the packing modes and packing sizes. Packing density, a measure of energy density of the battery module, is then calculated based on the geometry parameters. For mechanical integrity study, finite element method is used to predict the structural failure and initiation of short-circuit for LIB packs during a uniform constrained-compression condition.

2.1. Geometrical model

We examine cylindrical LIB cells (i.e., 18,650 LIBs), which may be regarded as the “circle packing in a square” problem from the perspective of geometry [27]. We focus on the “$b \times l$” problem, where a number of b and l cells are placed in each row and column, respectively (to distinguish b and l more clearly, l is defined as the number of cells in each column along the loading direction). Fig. 1 defines the packing angle θ. $\frac{\pi}{3} \le \theta \le \pi$ can be packed in several ways. Specifically, the cells in the same row do not come in contact with one another when $\frac{\pi}{3} \le \theta \le \frac{2\pi}{3}$, but may touch one another when $\frac{2\pi}{3} < \theta \le \pi$ as shown in Fig. 1(a).