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Mechanical behavior of representative volume elements of lithium-ion battery cells under compressive loading conditions

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HIGHLIGHTS

- Present stress–strain curves for $LiFePO_4$ battery cells under in-plane constrained compression.
- Correlate experimental stress–strain curves to deformation patterns of battery cells.
- Model the buckling of cell specimens and justify the length selection of cell specimens.
- Correlate the buckling of cell components to the buckling stress of battery cells.
- Present a physical kinematic model for formation of kinks and shear bands in battery cells.

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ABSTRACT

The mechanical behaviors of lithium iron phosphate battery cells are investigated by conducting in-plane and out-of-plane compression tests of representative volume element (RVE) specimens of dry cells. The test results of cell RVE specimens under in-plane constrained compression indicate that the load carrying behavior of the cell RVE specimens is characterized by the buckling, the kink and shear band formation, and the final densification of the cell components. The SEM images of the active materials on electrodes and the test results of the cell RVE specimens under out-of-plane compression suggest that the porosity in the components and the macroscopic gaps between the components is up to 40%. The test results suggest that the lithium-ion battery cells can be modeled as anisotropic foams or cellular materials. The elastic buckling analyses for a beam with lateral constraints indicate that the higher order buckling modes and the critical buckling stresses in general agree with those observed in experiments. The elastic buckling analyses also justify the length selection of the cell RVE specimens. Finally, an idealized kinematic model is presented to explain the physical mechanisms of the kink and shear band formation in the cell RVE specimens under in-plane constrained compression.

1. Introduction

Lithium-ion batteries have been considered as the solution for electric vehicles for the automotive industry due to its lightweight and high energy density. The major design considerations for lithium-ion batteries involve electrochemistry, thermal management and mechanical performance. The electrochemistry has been widely studied since it directly determines the battery performance and its life cycle. Different active materials on electrodes form different types of lithium-ion batteries. However, the basic chemical reactions of battery cells are similar. For automotive applications, the mechanical performance is of great importance for crashworthiness analyses. Mechanical tests such as shock, drop, penetration, roll-over, and crush tests for abuse conditions of battery cells, modules and packs were documented in SAE J2462 [1]. Research works were conducted on the safety performance of the battery cells under mechanical tests such as nail penetration tests, round bar crush tests, and pinch tests, for example, see Refs. [2–4]. However, the research works on the mechanical behavior of the representative volume elements (RVEs) of lithium-ion batteries are quite limited.

Sahraei et al. [5] conducted a series of mechanical tests and computational works on commercial $LiCoO_2$/graphite cells used for

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Nomenclature

RVE	representative volume element
ROM	rule of mixture
P_m^i	buckling load of the i-th component with the two unattached elastic foundation
m	number of half waves
E_i	compressive elastic modulus of the i-th component
$I_i = bh_i^3/12$	moment of inertia of the i-th component
L	length of the cell component
p	lateral pressure on the beam
z	deflection of the beam
k_1, k_2	spring constants of the harder and softer elastic foundations on the two sides of the beam
$\phi = k_1/k_2$	spring constant ratio
α	coefficient depending upon the value of m in Equation (1)
$\overline{m}$	parameter defined in Equation (2)
b	width of the cell component
h_i	thickness of the i-th component
E_i'	effective compressive elastic modulus of the i-th component under plane strain compression conditions
E_i	compressive elastic modulus of the i-th component
ν_i	Poisson's ratio of the i-th component
k	spring constant of the elastic foundation
E	out-of-plane compressive elastic modulus of the cell RVE specimen
h	thickness of the neighbor cell components
P_c^i	critical buckling load of the i-th component
P_n^i	buckling load of the i-th component with an unattached elastic foundation on one side and a rigid wall on the other side
n	number of waves
$\overline{n}$	parameter defined in Equation (10)
ε_m^i	compressive strain of the i-th component with the two unattached elastic foundation
ε_n^i	compressive strain of the i-th component with an unattached elastic foundation on one side and a rigid wall on the other side
A_i	cross sectional area of the i-th component
P_{cell}	buckling load of cell RVE specimen
n_i	number of the i-th component in the cell RVE specimen
σ_{cell}	buckling stress of the cell RVE specimen
A	cross sectional area of the cell RVE specimen
α	kink angle
w	width of the cell RVE specimen
d	kink length
θ	shear band angle
θ_{i}	initial shear band angle
θ_{f}	final shear band angle
$\varepsilon_{Y'}$	nominal normal strain in Y' direction
$\varepsilon_{Z'}$	nominal normal strain in Z' direction
$\gamma_{Y'Z'}$	nominal shear strain in $Y'Z'$ plane
$\varepsilon_Y^{\mathrm{T}}$	total nominal strain of one unit cell in cell RVE specimen
h_{s}	shear band height
E'_{cell}	effective compressive elastic modulus of the cell RVE specimen
f_i	volume fraction of the i-th component
f	void volume fraction

cell phones. The results indicate that the compressive mechanical behavior is characterized by the buckling and densification of the cell components. Other testing and modeling data available were also conducted on commercial $LiCoO_2$ cylindrical or prismatic battery cells [6,7]. However, this information is of limited use for researchers to model the mechanical performance of automotive high-voltage $LiFePO_4$ battery cells and modules for crashworthiness analyses. Sahraei et al. [5] indicated that computational effort is quite significant to model local buckling phenomenon of battery cells under in-plane compression. Therefore, macro homogenized material models of the representative volume elements (RVEs) for both the battery cells and modules have to be developed for crashworthiness analyses with sacrifice of the accuracy at the micro scale.

One of the primary objectives of this investigation is to develop testing methods to determine the detailed mechanical properties of lithium-ion battery cells and modules [8] in a systematic fashion. The other is to provide the necessary experimental data for the development of macro homogenized material models in the companion papers [9,10]. At this point, there is no test standard for characterizing the mechanical properties of the representative volume elements (RVEs) of lithium-ion batteries under large deformation because it is difficult to test a live battery due to the safety concern. Even in the discharged state, the volatile and toxic electrolyte still poses a severe safety concern. Further, standard compression tests in an in-plane direction of cell specimens do not provide useful information since there are almost no bonding forces between the anode, cathode, separator and cover sheets. The cell specimens fall apart when no out-of-plane constraints are applied. Therefore, a constrained compression test procedure needs to be developed and provide other researchers a way to conduct tests and compare the test results. The results presented in this paper can also help to understand the deformation process and mechanical behavior of battery cells such that homogenized material models can be developed for battery cells.

One ultimate goal of this investigation is to provide test data for development of computational models for multi-scale multi-physics analyses of battery packs in vehicles under crash loading conditions. Battery pack designs are different for different electric vehicles. Battery packs can have various shapes of plastic or metal shells that enclose a cooling system, electronics, and battery modules, that contain battery cells with electronics cover plates, control electronics, pressure plates, laser welded bus bars, heat sink plates, interconnected covers and compression bands. Battery pack designs are usually quite complex. Different types of finite elements such as shell elements, solid elements, rigid elements, and weld elements are typically used in computational models to reduce the sizes of the models. However, the sizes of the computational models for battery packs can still be quite large for crashworthiness analyses since the sizes of finite elements have to be small with consideration of small thicknesses of pack components and deformation patterns of interest. It is not possible to model the details of all battery pack components for computational efficiency in full vehicle crashworthiness analyses.

Finite element models for small cell specimens under compression in Sahraei et al. [5] showed the complexity of the finite element analyses at the length scale of cell components. Finite element models for cell RVE specimens under in-plane constrained compression in Ali et al. [9] also showed the complexity of the finite element analyses at the length scale of cell components. Sahraei et al.