

Compressive Behavior of Representative Volume Element Specimens of Lithium-Ion Battery Cells under Different Constrained Conditions

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ABSTRACT

The compressive behavior of lithium-iron phosphate battery cells is investigated by conducting in-plane constrained compression tests and out-of-plane compression tests of representative volume element (RVE) specimens. The results for cell RVE specimens under in-plane constrained compression tests without pre-strains and with pre-strains in the out-of-plane direction indicate that the load carrying capacity is characterized by the buckling of cell specimens. As the pre-strain increases, the nominal compressive stress-strain curve becomes higher. The nominal stress-strain curves in the out-of-plane direction were also obtained and used to determine the elastic moduli for the elastic buckling analyses of the cell components in the cell RVE specimens with different pre-strains. Based on the elastic buckling analyses for a beam with different lateral constraints due to different pre-strains in the out-of-plane direction, the number of half waves and the buckling stresses were obtained. The results indicate that the number of half waves and the buckling stress increase as the pre-strain increases. The general trends of the numbers of half waves and the buckling stresses are in agreement with those obtained from experiments.

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INTRODUCTION

Lithium-ion batteries have been considered for electric vehicles for the automotive industry due to its lightweight and high energy density. 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 [2, 3, 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 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.

Recently, Lai et al. [8,9] investigated the mechanical behaviors of lithium-iron phosphate battery cells and modules by conducting tensile tests of individual cell and module components, constrained compression tests of RVE specimens of dry cells and modules, and a punch test of a small-scale dry module specimen. For in-plane constrained compression tests of cell RVE specimens, the results indicate the load carrying behavior of cell RVE specimens is characterized by the buckling of cells with a wavelength approximately in the order of the thickness of the cells and the final densification of the cell components. They also tested module RVE specimens with different heights and the results indicate that the load carrying behavior of module RVE specimens is also characterized by the buckling of cells with a wavelength approximately in the order of the thickness of the cells and the final densification of the module components but relatively independent of the height of the tested specimens. For the cell RVE specimens, the initial elastic buckling mode of the cell RVE specimen under in-plane constrained compression can be

correlated to the elastic buckling solution of a beam with lateral constraints. The development of the higher order buckling modes of the component sheets and the critical stresses observed in experiments are in agreement with the results of the analytical buckling solutions and the corresponding finite element analyses. The elastic buckling analyses also justify the length selection of the cell RVE specimens.

In this investigation, cell RVE specimens were first made from the individual cell components. In-plane constrained compression tests with different pre-strains in the out-of-plane direction were then conducted. Out-of-plane compression tests were also conducted. The nominal stress-strain curves, the numbers of half waves and the buckling stresses of the cell RVE specimens under in-plane constrained conditions with different pre-strains in the out-of-plane direction were also obtained from the experiments. Elastic buckling analyses of a beam with lateral constraints were then conducted. The numbers of half waves and the buckling stresses for the cell RVE specimens with different pre-strains from the elastic buckling analyses are then compared with the corresponding experimental results. Finally, some conclusions are made.

SPECIMENS

Figure 1(a) shows a schematic of a pouch cell and a cell RVE specimen with the X-Y-Z coordinate system. Here, X and Y are referred to as the in-plane directions and Z is referred to as the out-of-plane direction. A battery cell consists of five major components: cover sheet, anode, cathode, separator and electrolyte. Since the electrolyte is difficult to handle during assembly due to its toxicity, all the cell RVE specimens tested in this study were made without electrolyte at the University of Michigan. Table 1 lists all the detailed material and thickness information of the cell components. The cover sheet is composed of aluminum foil with polyamide and polypropylene layers on both sides bonded together by polyester-polyurethane and urethane-free adhesive, respectively. The thickness of the individual layers of the cover sheet are shown in Table 1 and the total thickness of the cover sheet is 0.111 mm. The anode and cathode selected for this study are graphite coated on copper foil and LiFePO_4 coated on aluminum foil, respectively. The copper foil has a thickness of 9 μm and the total thickness of the anode sheet is 0.2 mm. The aluminum foil has a thickness of 15 μm and the total thickness of the cathode sheet is 0.2 mm. Both the anode and cathode sheets are double-side coated. The separator is made of polyethylene with the porosity ranging from 36 to 44% and a thickness from 16 to 25 μm . All the cell components are purchased commercially.

A small cell RVE specimen with the dimensions is shown in Figure 1(b). Due to the slight thickness variation of each component sheet, four cell RVE specimens have the size of 25 mm $\times$ 25 mm $\times$ 5.0 mm and 25 mm $\times$ 25 mm $\times$ 4.7 mm. Figure 1(c) shows a side view of a portion of a cell RVE specimen with the individual cell components. The large red arrows shown in the figures indicate the in-plane compressive direction. As

shown in Figure 1(c), the anode (shown in orange) and cathode (shown in gray) form alternating layers with two cover sheets (shown in light blue). The separators (shown in white) are located between electrodes and cover sheets. The cell RVE specimen is composed of 10 anode, 10 cathode, 21 separator and 2 cover sheets. The cell components were manually cut and assembled. No electrolyte was added for the dry cells. Due to the large specimen width in the X direction compared to the specimen thickness, the specimen width does not change before and after in-plane compression tests. Therefore, the specimens are subject to the plane strain conditions in the X direction under in-plane compression tests.

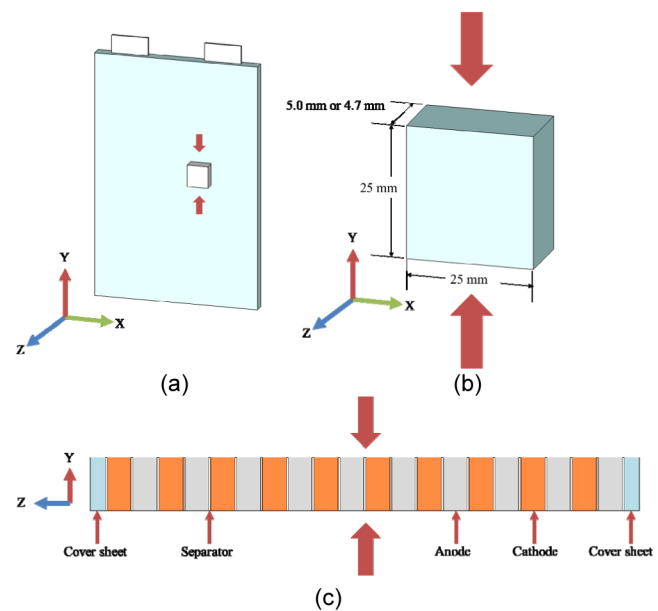


Figure 1. A schematic of (a) a pouch cell and a cell RVE specimen for the in-plane constrained compression test, (b) a cell RVE specimen with the dimensions, and (c) a side view of a small portion of the cell RVE specimen showing the individual cell components. The large red arrows indicate the compressive direction.

Figure 2(a) shows again a schematic of a pouch cell and a cell RVE specimen with the X-Y-Z coordinate system. A small out-of-plane compression cell RVE specimen is shown in Figure 2(b) with the dimensions. Figure 2(c) shows a side view of a small portion of the cell RVE specimen with the individual cell components. The large blue arrows shown in the figure indicate the out-of-plane compressive direction. The out-of-plane compression cell RVE specimen was smaller than the in-plane compression cell RVE specimen in order to avoid exceeding the load limit of the load cell. The size of the out-of-plane compression cell RVE specimen is reduced to 10 mm $\times$ 10 mm $\times$ 4.8 mm as shown in Figure 2(b). The layered structure of the cell RVE specimen is the same as that of the cell RVE specimen for in-plane constrained compression test.

Table 1. Specifications of cell components.

	Material	Thickness	
Cover sheet	Polyamide (JIS Z1714)	0.025 mm	0.111 mm
	Adhesive (Polyester-polyurethane)	4-5 g/m ²	
	Aluminum foil (JIS A8079, A8021)	0.040 mm	
	Adhesive (Urethane-free Adhesive)	2-3 g/m ²	
	Polypropylene	0.040 mm	
Anode sheet	Copper foil	9 μm	0.2 mm
	Graphite		
Cathode sheet	Aluminum foil	15 μm	0.2 mm
	LiFePO ₄		
Separator sheet	Polyethylene (PE)	16-25 μm	

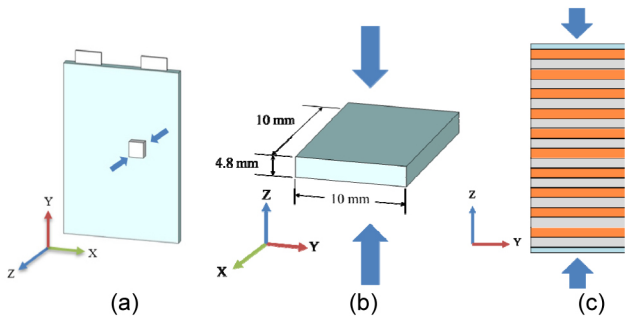


Figure 2. A schematic of (a) a pouch cell and a cell RVE specimen for the out-of-plane compression test, (b) a cell RVE specimen with the dimensions, and (c) a side view of a small portion of the cell RVE specimen showing the individual cell components. The large blue arrows indicate the compressive direction.

QUASI-STATIC COMPRESSION TESTS OF CELL RVE SPECIMENS

In-Plane Constrained Compression Tests of Cell RVE Specimens

Battery modules are usually held together by adhesive between the cells and the neighbor foam layers and aluminum heat dissipater sheets as well as two wrapping bands with tension. In the middle portion of a module, the cells are constrained by the neighbor foam layer and aluminum heat dissipater sheet. In an individual cell, the cell components can buckle individually with constraints from the neighbor cell components since there are no bonding forces between the cell components. Hence, a fully constrained die set was designed for constrained compression tests of cell RVE specimens. The punch and die setup for the in-plane constrained compression tests of cell RVE specimens is shown in Figure 3. The setup is composed of a male rectangular punch and a female die such that the specimen slot can be adjusted for different specimen geometries. A PMMA side window was made for recording the deformation process during the compression. The specimen slot in the die has an

opening of 5 mm × 25 mm. Rectangular thin metal spacers with a thickness of 0.4 mm were made to adjust the width of the specimen slot such that different pre-strains of the specimens in the out-of-plane direction can be imposed. For the slot size of 4.6 mm × 25 mm and 4.2 mm × 25 mm, one and two spacers were inserted into the slot before tightening the two pieces of the die. For each of the specimen with a given pre-strain, a matching rectangular punch was made and used in the corresponding compression tests. These compression tests were conducted using a MTS Insight testing machine with a 10 kN load cell. The displacement rate is 0.5 mm/min (nominal strain rate of 0.0003 s⁻¹). The punch displacement was taken from the cross-head displacement recorded during the experiments.

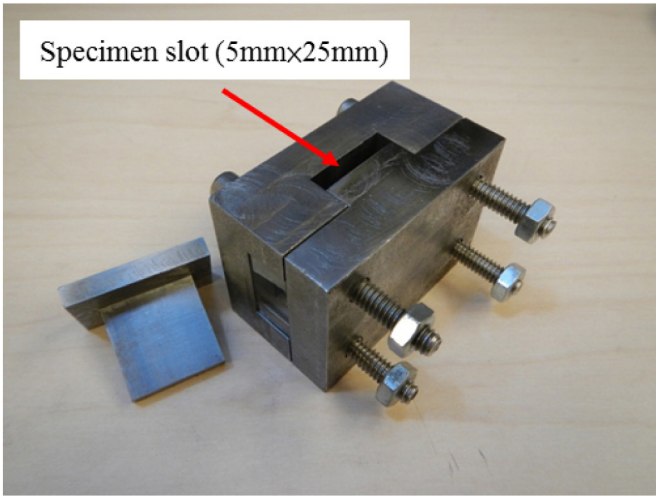


Figure 3. A punch and die setup for in-plane compression tests of cell RVE specimens.

Figure 4 shows the nominal compressive stress-strain curves of four cell RVE specimens tested at a displacement rate of 0.5 mm/min. The results in the figure show a nearly linear behavior in the beginning with the estimated effective compressive elastic moduli of 394 MPa, 665 MPa and 1032 MPa for the specimens with the out-of-plane pre-strains of 0.0%, 3.2% and 11.0%, respectively. As shown in Figure 4, for the results of the two specimens without the out-of-plane pre-strain, a noticeable change of slope takes place when the strain increases to about 1%. The change of the slope is due to the onset of the buckling of the cell components. Due to the buckling, the slope becomes smaller when the strain is larger than about 1%. As the strain continues to increase, the slope then gradually increases. Some minor stress drops were observed after the initial linear stage due to the development of kinks and shear bands.

For the specimen with the out-of-plane pre-strain of 3.2%, the estimated effective compressive modulus is larger than that of 0.0% in the initial linear stage. A noticeable change of slope takes place when the strain increases to about 1%. Again, due to the buckling, the slope becomes smaller when the strain is larger than about 1%. As the strain continues to increase, the slope then gradually increases. Some minor stress drops