Design of a Testing Device for Quasi-Confined Compression of Lithium-Ion Battery Cells

by

Eric Roselli

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

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ABSTRACT

The Impact and Crashworthiness Laboratory at MIT has formed a battery consortium to promote research concerning the crash characteristics of new lithium-ion battery technologies as used in automotive applications. Within a broad range of tests, there was a need to perform compression tests with a variable amount of confinement. A spring-loaded detainment device was designed which allows the battery to be confined in the axis perpendicular to compression without completely rigid walls. This provides a testing environment far more similar to the conditions of a real world crash situation. During an automobile crash event, the battery pack acts as a unit where each individual cell may experience a range of stresses from nearby cells or pack walls. An appropriate device was designed in Solidworks and used in the MIT ICL for testing with adjustable confinement during compression testing.

MIT's research as a part of the consortium will continue for 3 more years beyond these initial tests. Never the less, the coming computational and constitutive models will be built using initial individual cell testing. Any model of a complete battery pack will use the material properties derived from cell testing.

Thesis Supervisor: Tomasz Wierzbicki
Title: Professor of Applied Mechanics

Acknowledgements

I would like to thank Professor Tomasz Wierzbicki for his continued guidance and for constantly providing me with opportunities to learn about new automotive technologies. Professor Wierzbicki has allowed me to participate in MIT's Impact and Crashworthiness lab for the last year of my undergraduate degree. I have been able to learn about automotive technology, observe consortium meetings, and experience research in academia though a UROP and as a thesis student. I would also like to thank Rich Hill for his help in learning about the testing methods used in the ICL and for explaining the virtues of testing individual battery cells. Thanks to Kirki Kofiani and Elham Sahraei for teaching me a great deal about the battery consortium and the papers published with in the research group.

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Introduction

The purpose of the last 2 semesters of research is to characterize the crash behavior of lithium ion battery cells as applied to automotive applications. The following research and testing was conducted at the Impact and Crashworthiness Laboratory (ICL) at the Massachusetts Institute of Technology (MIT). The research described in the following paper is only a portion of the larger plan for research in the works for the ICL. The ICL operates as part of a large automotive consortium at the Institute. This is a partnership between research institutions, automobile manufacturers, and part suppliers with in the industry. The goal of the partnership is to provide the automobile industry with a common standard for evaluating lithium ion battery safety for applications in new electric and hybrid-electric vehicles. A multi-year plan was developed about 10 months ago for continued research at different levels of battery composition. The research plan is laid out in a later section of this paper.

Although, the research is extensive, this paper will focus on a few specific aspects of the cell level testing. Namely, confined compression in both directions and the need for a testing apparatus that can provide adjustable confinement in both the width and length directions. This paper will provide the overall testing context within MIT's ICL and the lithium-ion battery consortium and then provide design specifications for the adjustable confinement testing device.

Overview of Battery Consortium

The MIT consortium is organized as a long-term research plan over approximately 4 years. The consortium consists of research institutes (such as MIT), automotive parts manufacturers, and automobile manufacturers. The ICL consortium is under the supervision of the principal investigator Professor Tomasz Wierzbicki. Professor Wierzbicki has ling been involved in industry research within the automotive OEMs. Through the ICL, Professor Wierzbicki has led similar automotive consortiums during times of changing automotive technology. One example is Professor Wierzbicki's leadership of a cooperative research effort during the late 1980's to study new airbag technology for automotive application. Lithium ion battery technology use in automotive applications is increasing quickly. As electric cars and hybrid electric cars gain mainstream acceptance, the number of cars requiring safe battery technology will grow. The MIT consortium supports the future of lithium ion battery technology. As with any new technologies, large-scale use of lithium ion batteries will require all automobile manufacturers to understand how to safely design lithium ion battery packs. By combining resources in an academic setting, the consortium members can leverage research funding as well as advance the whole industry. Consortiums, such as this one, can greatly speed up the adoption of new technology by consumers. Apart from the environmental advantages alternative fuels may offer, there is inherent value in promoting new technology through research.

ICL Research Plan

Modern automotive safety advancements can be largely attributed to advancements in computer modeling and computer driven numerical analysis methods. With advanced modeling techniques full-scale body structures can be load tested and compared to the numerical analysis. While other technologies have benefited from new modeling techniques, lithium ion batteries lack a complete computational model within the automotive industry.[1] MIT's ICL consortium will develop a complete constitutive and computational model of prismatic and cylindrical cell lithium ion batteries. In order to form a complete model of the complete battery pack, it is necessary to build a multi-level model, which first examines each individual battery component. The battery pack as a whole is simply a collection of many individual battery cells. Within each of these cells, an individual battery is composed of a layered and repeatable combination of cathodes and anodes. Table 1 below demonstrates to multi-layer nature of a lithium ion battery pack. By correlating models and conducting tests at each scale level it is possible to build an accurate method for testing the safety of future lithium-ion battery packs. Although overall pack geometry may change as technology advances, MIT's research will create a model based on the micro-

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[1] Wierzbicki (2010)

scale. As a result, the model can be applied with the appropriate changes in coming years.

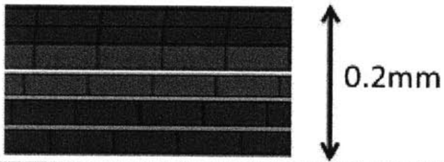
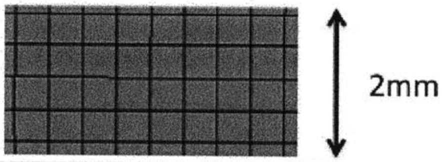
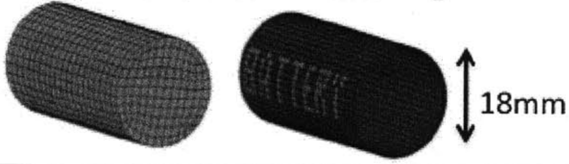
Scale Level	
1	Single Layer  20μm
2	Electrode/Seperator Assembly  0.2mm
3	Homogenized Element  2mm
4	Battery Cell = Jelly Roll + Shell Casing  18mm
5	Battery Pack 200mm  LITHIUM-ION BATTERY PACK

Table 1: Multi-layer breakdown of a lithium-ion battery pack. Each scale level represents a sub-component of the pack as a whole. Testing and computational models with be built from scale level 1 to level 5.[2]

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[2] Wierzbicki (2010)

Anatomy of a Lithium Ion Battery

Table 1 shows an overall view of battery pack as broken down by major components. It is still useful to examine the anatomy of a single lithium-ion cell. At its base function a battery is an energy storage device. Lithium-ion batteries store electrochemical energy by separating opposite charge. In lithium-ion batteries, and other types of batteries as well, there are five basic components. Table 2 below shows the five components of a lithium ion battery.

Battery Component	**Material Composition**	**Size**
Negative electrode (anode)	Graphite	~20 – 80 μm
Positive electrode (Cathode)	Transition metal oxide or phosphate ($LiCoO_2$)	~20 – 80 μm
Polyolefin separator	Nano-pourous polyethylene/polypropylene film	~16 – 40 μm
Negative electrode current collector	Copper foil	~10 μm
Positive electrode current collector	Aluminum foil	~14 μm

Table 2: The basic components of all lithium-ion batteries. Each material is taken into account in testing and modeling.

In addition to these five solid components of the battery, the electrolyte is an equally important component. Lithium-ion batteries use $LiPF_6$ dissolved in a solution of organic carbonates.[3]

Like any battery, a lithium-ion battery provides its stored energy by discharging electric current across the cell. In charging or discharging, lithium-ions (Li+) travel between the positive and negative current

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[3] Wierzbicki (2010)

collectors. The ions diffuse through the crystal lattice of the active materials listed in Table 2. Lithium ion batteries are built using a "stacking" method. The active materials are in sheet formed and are stacked on top of each other in repeating layers. Regardless of how these layers are stacked, the lithium-ion cell must be sealed from moisture and other environmental factors. Figure 1 below shows the most common four form factors for lithium ion cells.

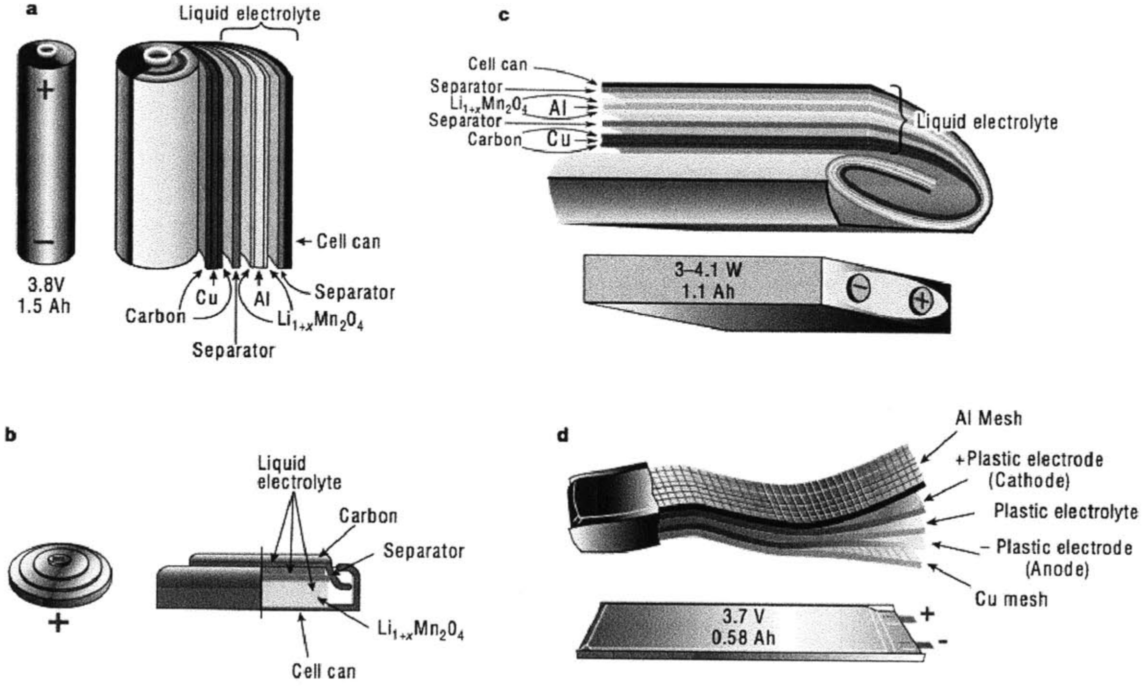

Figure 1[4]: A diagram of each of the four most common lithium-ion form factors.
(a) Cylindrical (b) Coin (c) Prismatic (d) Thin and Flat

The four form factors shown in Figure 1 all take advantage of the same lithium-ion layered construction (shown in more detail in Figure 2 below) but they each encase the cell in a different way. MIT's research will primarily focus on the prismatic and cylindrical cell lithium-ion batteries. These form

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[4] Tarascon and Armand (2001)

factors are common in current automotive applications and will likely continue to be a form of choice.

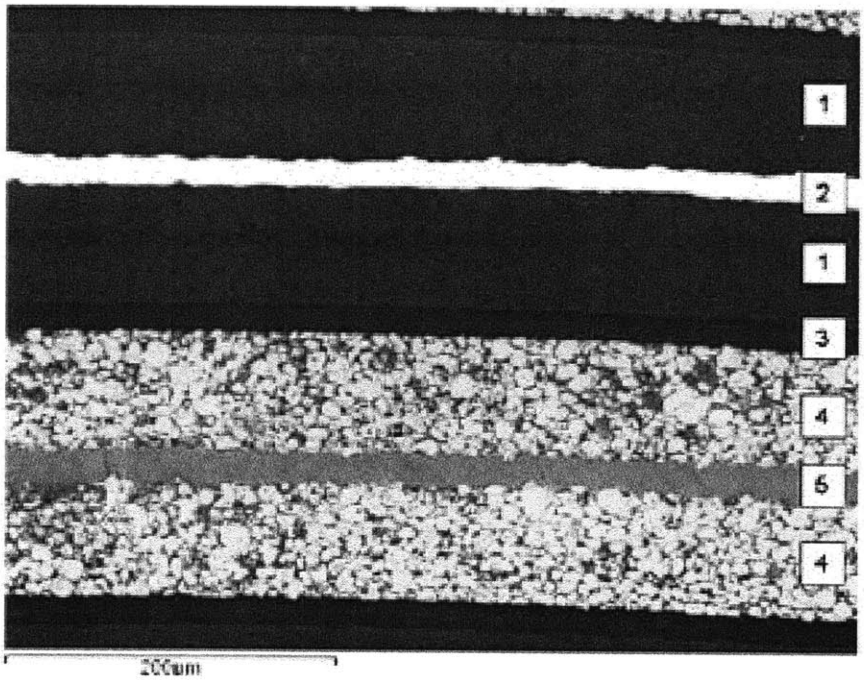

Figure 2[5]: A scanning electron microscope detail of one complete layer (one positive and one negative) of a lithium-ion cell. (1) Negative electrode coating (graphite powder) (2) Negative electrode current collector (copper foil) (3) Separator (polyethylene/polypropylene film) (4) Positive electrode coating (LiCoO2 powder) (5) Positive electrode current collector (aluminum foil)

Testing Methods

The testing methods for each type of cell are primarily concerned with the mechanics of the exterior shell of the cell. The failure of this shell and its intrusion into the lithium-ion layers is of interest during crash situations. Testing methods are designed to simulate the possible deformations and stresses that may occur during a vehicle crash. This paper will simply outline a couple simple examples of cell and micro-scale testing to provide an overview of the ICL research. The confined compression device described

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[5] Wierzbicki (2010)

later is for cell level testing. Figure 3 below shows a possible high intensity crash situation involving the most common 18650 cylindrical cell lithium-ion.

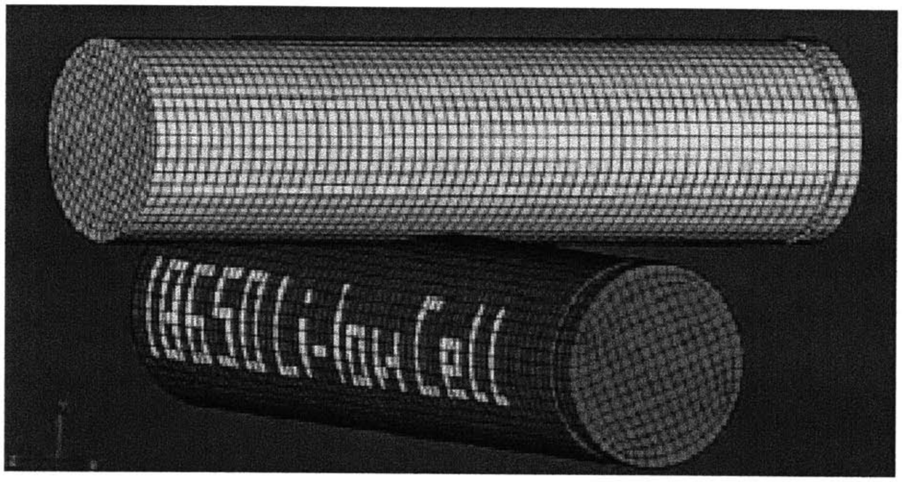

Figure 3[6]: A finite element (FE) model of two 18650 cells within a larger battery pack. This shows the possibility for cell-to-cell contact during severe crash situations. Cell-to-cell contact presents the possibility of short circuit and thermal run away.

This testing situation is an example of internal pack damage that could lead to a dangerous failure in a sever crash setting. The damage induced during a cell-to-cell contact situation depends on the shell casing of the battery and how the deformation of the cell casing can disrupt internal battery layers. Figures 4 and 5 below show the equivalent physical testing method using lateral indentation by a rigid rod.

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[6] Wierzbicki (2010)

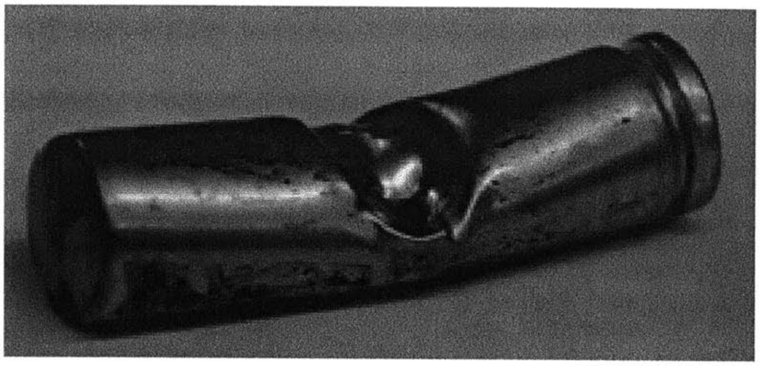

Figure 4[7]: A cylindrical cell after indentation by a rigid rod. This test is equivalent to the FE picture of cell-to-cell contact shown in Figure 3.

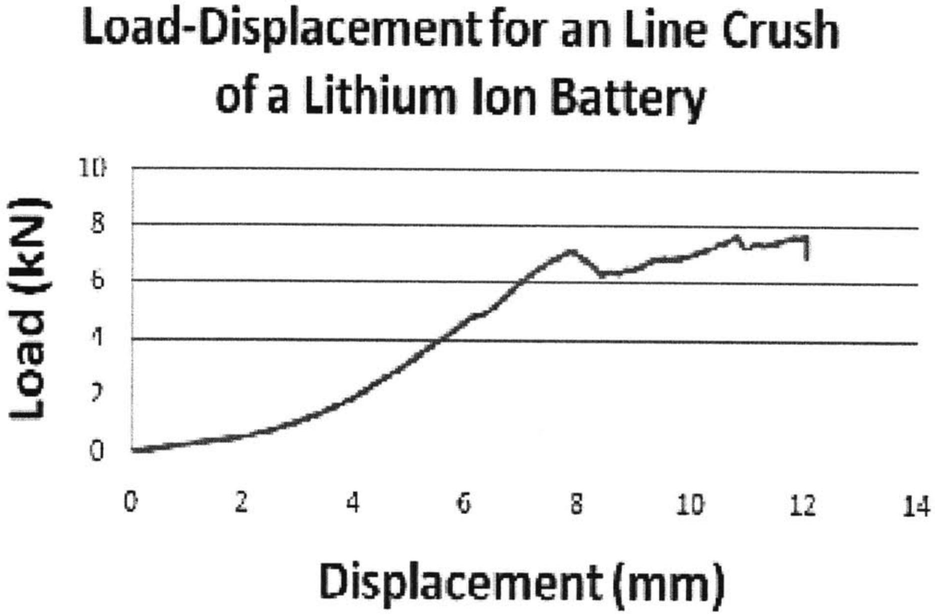

Figure 5[8]: A graph of Load (kN) versus Displacement (mm) during the lateral indentation test. This is just one example of how a physical test can be used to verify computational models.

Other tests performed on the cylindrical cell batteries include lateral crush, axial crush, and pure material strength tests using the shell casing samples. The shell casing tests are very important for the ICL research. The casing of the battery is the key failure mode in a crash event. Once the shell is

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[7] Sahraei, Hill, and Wierzbicki (2010)
[8] Sahraei, Hill, and Wierzbicki (2010)

punctured or deformed enough to contact internal layers, there is opportunity for further electro-chemical decomposition within the cell and the pack as a whole. Figures 6, 7, and 8 below show examples of each additional testing method for cylindrical cell batteries.

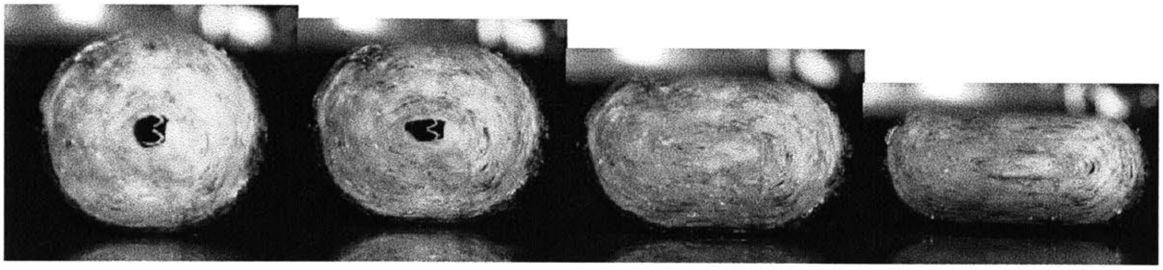

Figure 6: Lateral compression test. Performed with internal jellyroll intact.

Figure 7: Axial compression test. Buckling modes are shown in the later sequences.

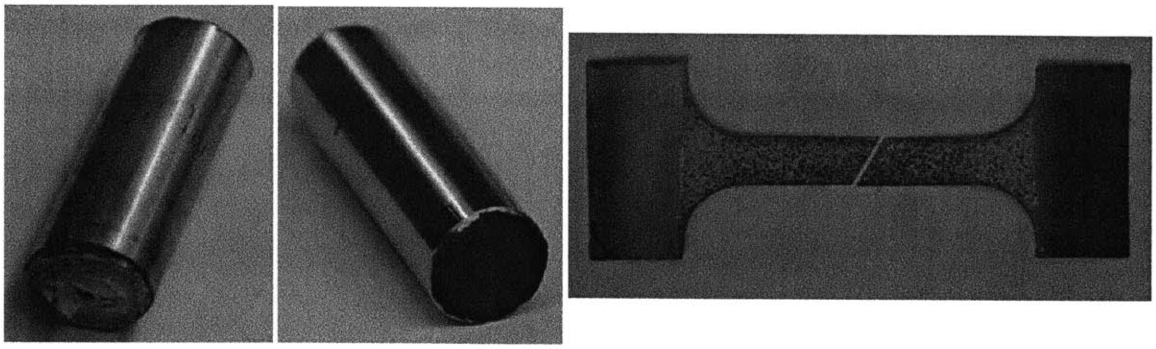

Figure 8: Shell testing for fracture strength. The end caps are removed from the cylindrical cell and the internal jellyroll is removed. From the casing a "dog bone" specimen is cut and testing in compression and tension for material characteristics.

Figure 8 shows the aforementioned shell casing tests. The ICL research tests for material properties to more accurately provide inputs for the finite element analysis.

A similar set of tests is performed to characterize different strength modes for prismatic cell lithium-ion batteries. Figure 9 shows 4 pouch cell lithium-ion batteries that are used in the ICL for testing.

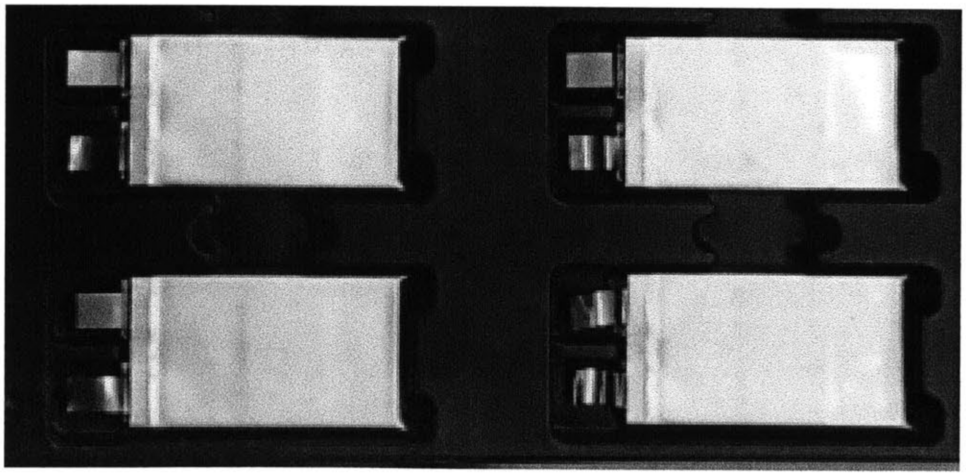

Figure 9: Lithium-Ion prismatic pouch cells. 40 x 60 mm

The pouch cells shown in Figure 9 are commonly stacked in large quantities to form battery packs for automotive applications. The confined compression device is designed for testing on these pouch type batteries. These specific pouch cells utilize a Mylar casing, which makes a significant contribution to the overall strength of the cell.[9] Although tests were performed with the casing removed as well, the majority of confined compression tests will be performed with the Mylar casing intact. The physical tests performed on the prismatic cells are as follows:

1. Compression of the Pouched Cell Between Two Plates
2. Lateral Indentation of the Cell by a Hemispherical Punch
3. Unconfined Axial Crush of the Cell in the Length and Width Direction
4. Confined Compression Test of the Cell in the Width Direction
5. Three-Point Bending Test of a Medium-Sized Cell

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[9] Wierzbicki, Sahraei, and Hill (2010)

Figure 10 below shows an image of each of the tests listed above.

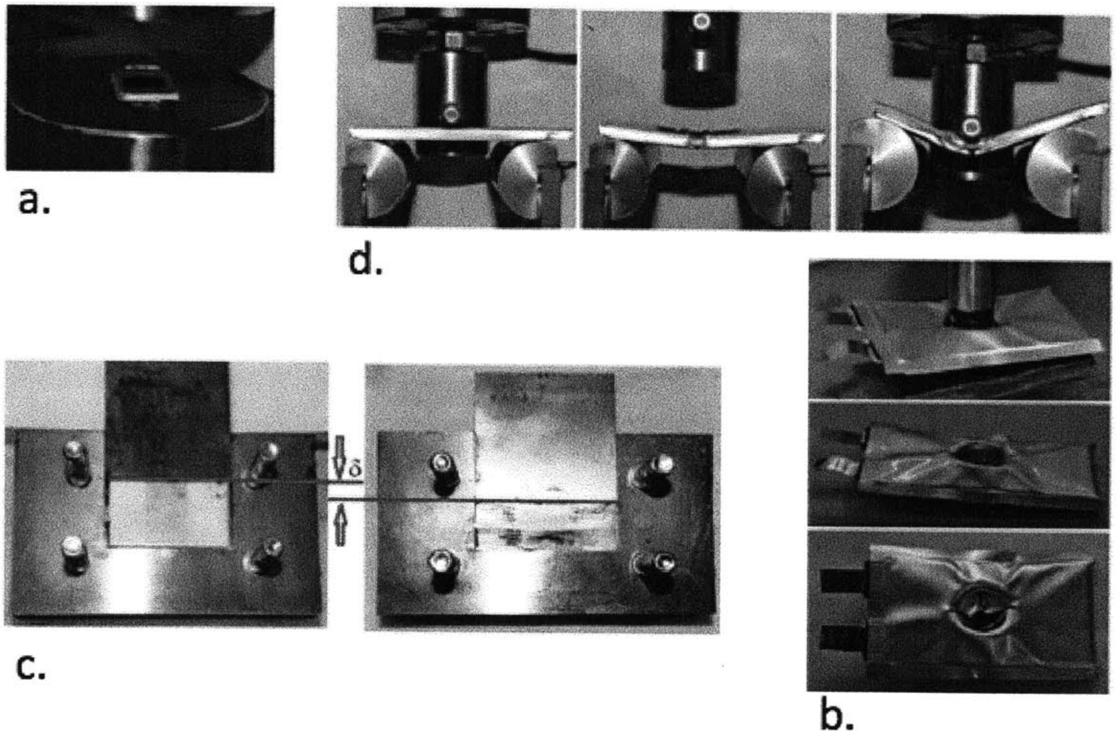

Figure 10[10]: (a) Compression of the Pouched Cell Between Two Plates (b) Lateral Indentation of the Cell by a Hemispherical Punch (c) Confined Compression Test of the Cell in the Width Direction (d) Three-Point Bending Test of a Medium Sized Cell NOTE: Test number 3 is not shown.

The testing device described in the next section is derived from a need to perform tests in the regime between confined compression and completely unconfined compression. The above tests have been performed with satisfying results. Never the less, as a complete pack, it is unlikely individual cells would experience completely confined or unconfined compression. Therefore it is necessary to allow compression in a single direction while providing some amount of support in the perpendicular direction.

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[10] Wierzbicki, Sahraei, and Hill (2010)

Quasi-Confined Compression Device

There is a need to provide an adjustable amount of confinement to truly simulate crash situations. For this need, the ICL developed a design for an adjustable containment device. This would allow for testing more closely aligned with real-world battery stresses.

Confined versus Unconfined Compression Testing

First, it is worth noting that all three testing conditions (confined, unconfined, and quasi-confined compression) are necessary for completely modeling the battery pack as a unit. Fully confined compression is useful for quantifying the uniaxial strain in the cells. As the foil layers buckle and fold over each other, the cell quickly loses compressibility and the testing numbers can become inaccurate. Unconfined compression was able to provide the most insight into the strength effects of the Mylar pouch. Compression tests were performed in both the length and width directions. Figure 11 below shows the difference in yield strength when the pouch is left on the testing cell.

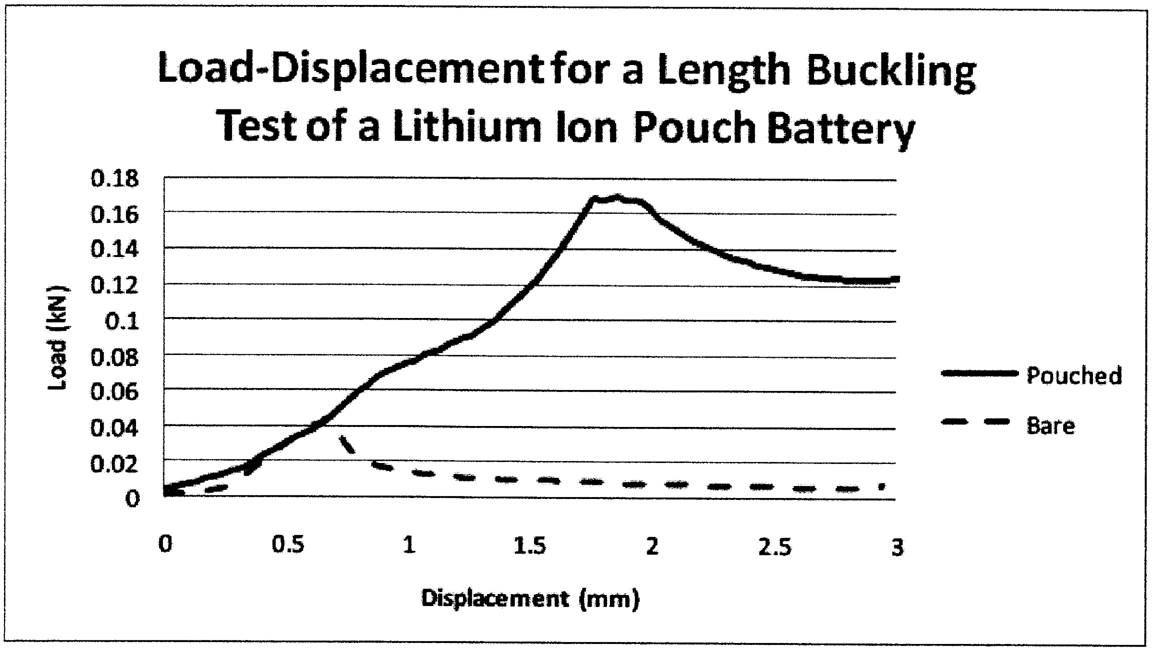

Figure 11[11]**: A graph of load (kN) versus displacement (mm) for prismatic cells. One cell retains the Mylar pouch and the other is bare.**

Notice in the above graph that the maximum load in the bare case is less than one fourth of the pouched case. The curves are similar under 0.75 mm of displacement before the layers yield and start to fold independently of each other. The Mylar casing provides a significant amount of the overall cell's strength in both directions.

Device Requirements

The device must allow the battery to expand perpendicular to the axis of compression with out allowing a complete deformation and separation of the internal layers. The device has three main design requirements. First, the device must fit with in the Instron machine without interfering with the

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[11] Wierzbicki, Sahraei, and Hill (2010)

apparatus. A punch can be used for to allow the Instron arm to reach the testing cell. The second is requirement demands that the device is adjustable in the perpendicular axis. This means that the springs used must be able to provide a variable amount of perpendicular compression depending on the testing situation and battery cell. The third requirement demands that prismatic cell lithium ion batteries must be able to fit in both the length and width directions. In these specific tests the device is designed for a 40 x 60 mm pouch cell. These design requirements direct the initial prototype and solid model development of the "anti-buckling" device. The testing of quasi-confined compression stems from the idea of preventing buckling.

Design of the Quasi-Confined Compression Device

Using Solidworks and the given the device requirements, a prototype was developed over the last semester. The device has a central section capable of holding a 40 x 60 mm pouch cell in both the length and width direction. Materials were selected using data from previous compression testing. The forces on the battery depend on the direction of compression as well as the amount of confinement. Figure 12 below shows the forces present in a uniaxial compression test. The forces present in this experiment should be the maximum the specimen will experience since adjustable containment will always be less than a rigid wall.

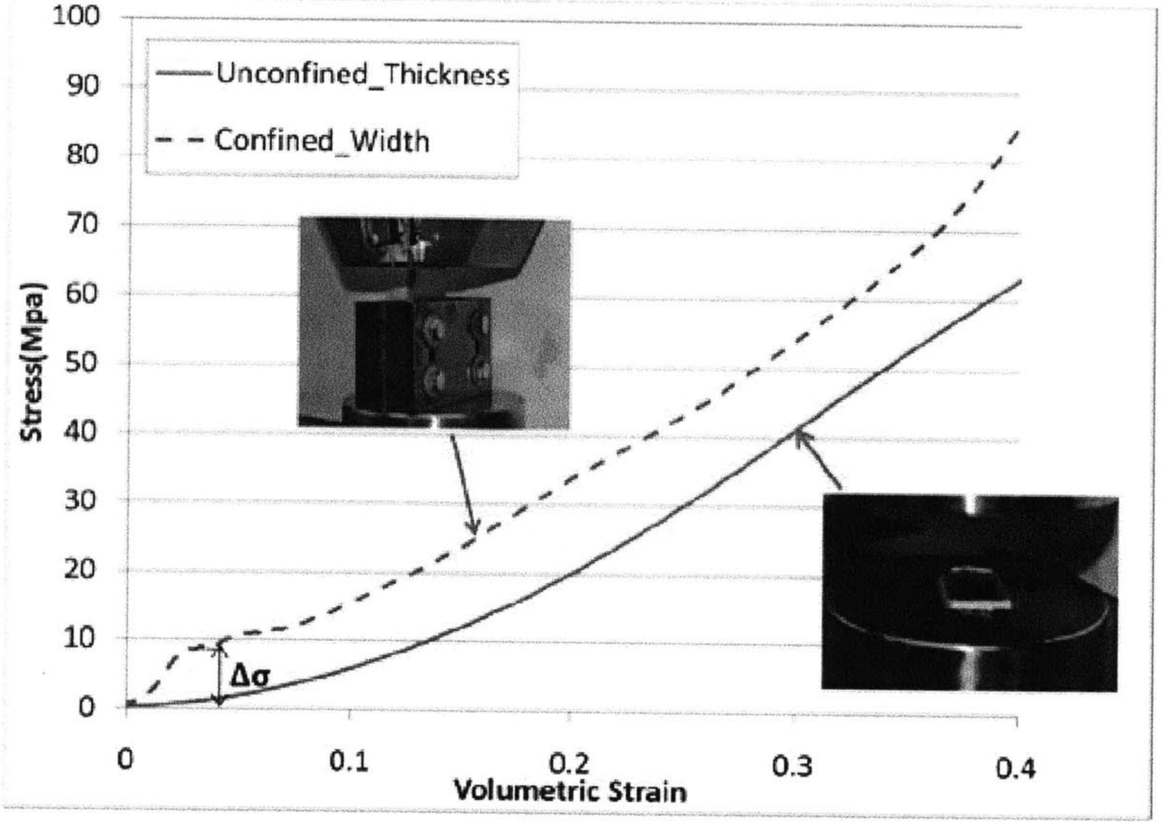

Figure 12[12]: Stress versus Volumetric Strain for a confined width test. From this curve and other data, it is apparent that the forces on the battery do not exceed 15 KN. The confined width picture above the curve shows the fully confined case.

The design calls for 3 plates, each of the dimensions 120 x 60 mm. The plates are 5 mm thick and are machined from stock steel. The bottom plate is a fixed plate on which the battery is placed for testing. The three plates are joined by 16 bolts, which run through the thickness of a three plates and leave a gap section in the middle for placing the testing cell. The bolts have coil springs around them between the top two plates. These springs control the force of the confinement that the device provides. Once the gap is set for the battery, the distance between the top two plates can be set to provide the appropriate spring constant. Linear springs are used in the device and the springs can be

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[12] Wierzbicki, Sahraei, and Hill (2010)

switched out if a testing case calls for a force outside the range of the original springs. Figure 13 below shows a schematic of the testing device.

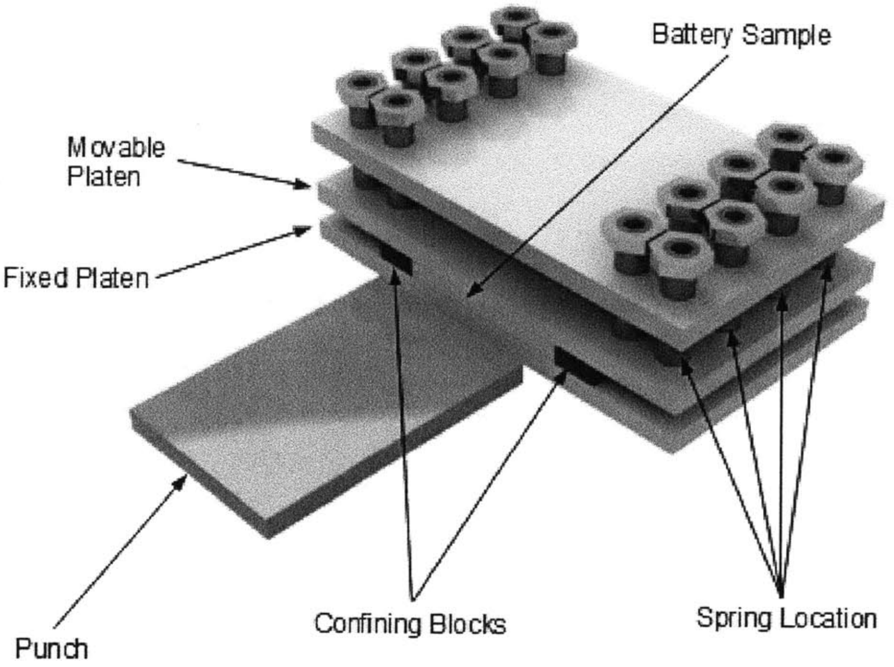

Figure 13: The Quasi-Confined Compression device as built in Solidworks. Notice the spring location on the outer 4 bolts. More springs can be added to any of the 16 through bolts. Confining blocks are added on each of the interior sides to isolate expansion to the perpendicular axis. A punch is used underneath the Instron arm to compress the battery.

The design allows for maximum adjustment and has been created simply based on the design requirements. The device in Figure 13 is still the first iteration of the apparatus and more testing is needed. The spring-loaded confinement is a design feature that stemmed from the need to prevent buckling within the test specimen. When the battery is fully confined the cells fold over on each other and buckle. This causes unrealistic stacking and produces extreme force readings during the test. The quasi-confined compression device can be thought of as an anti-buckling device. Figure 14 below is a photograph of the first "anti-buckling" prototype built in the ICL.

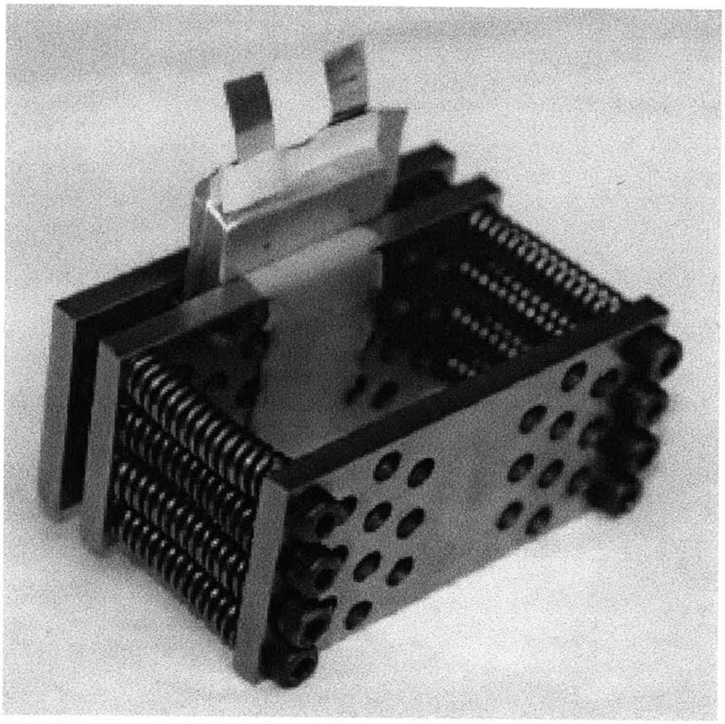

Figure 14: Adjustable confinement device prototype. This prototype can only provide confinement when the cell is tested in the length direction. There is the possibility for more springs to increase force.

This device is for testing prismatic cell lithium ion batteries. As discussed earlier, the in-depth shell testing is very important for the 18650 cylindrical cells. Similarly, the Mylar casing is an important consideration for prismatic cell batteries. This device will allow the battery to be tested with casing and the simulation of surrounding cells.

The following pages show Figures 15, 16, and 17. These are algebraically dimensioned sketches of the prototype design. Each dimension can be adjusted depending on the type of battery that needs to be tested. The prototype in Figure 14 is based on a 60 x 40 mm pouch cell battery but the dimensions given in the sketches can be easily modified.

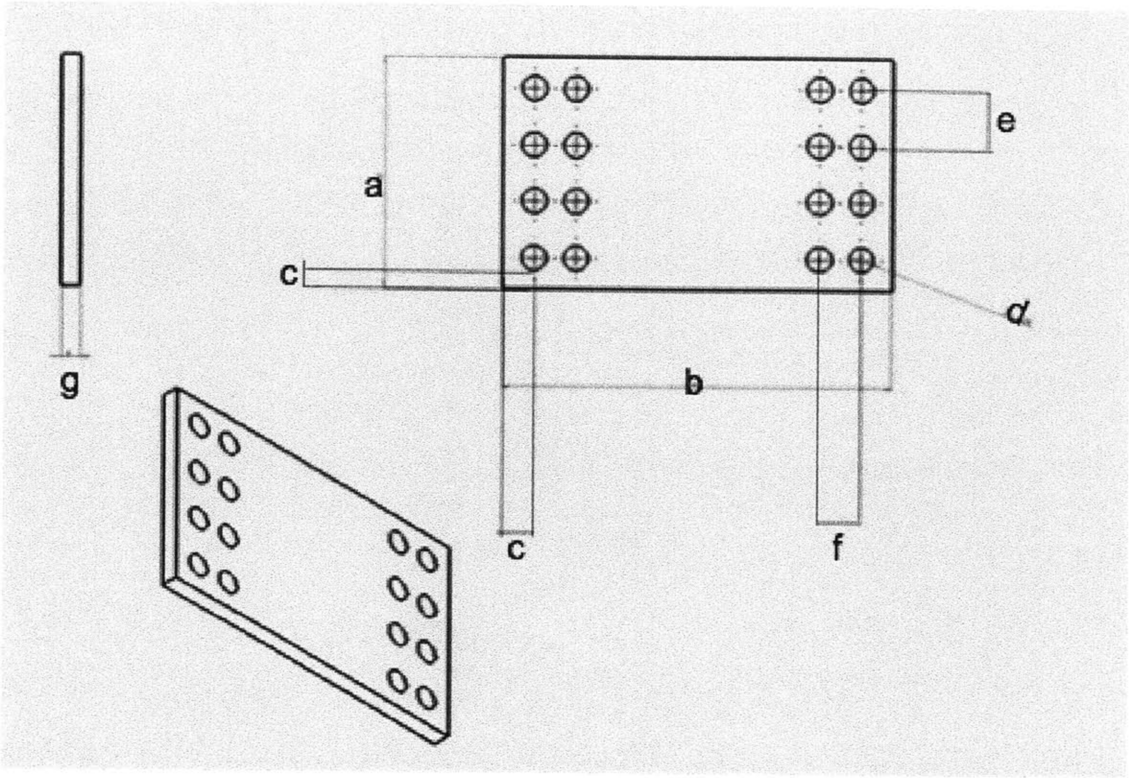

Figure 15: Compression Platen. Dimensions: (a) width of platen. (b) length of platen. (c) hole gap to edge. (d) hole radius. (e) hole-to-hole gap (f) platen thickness

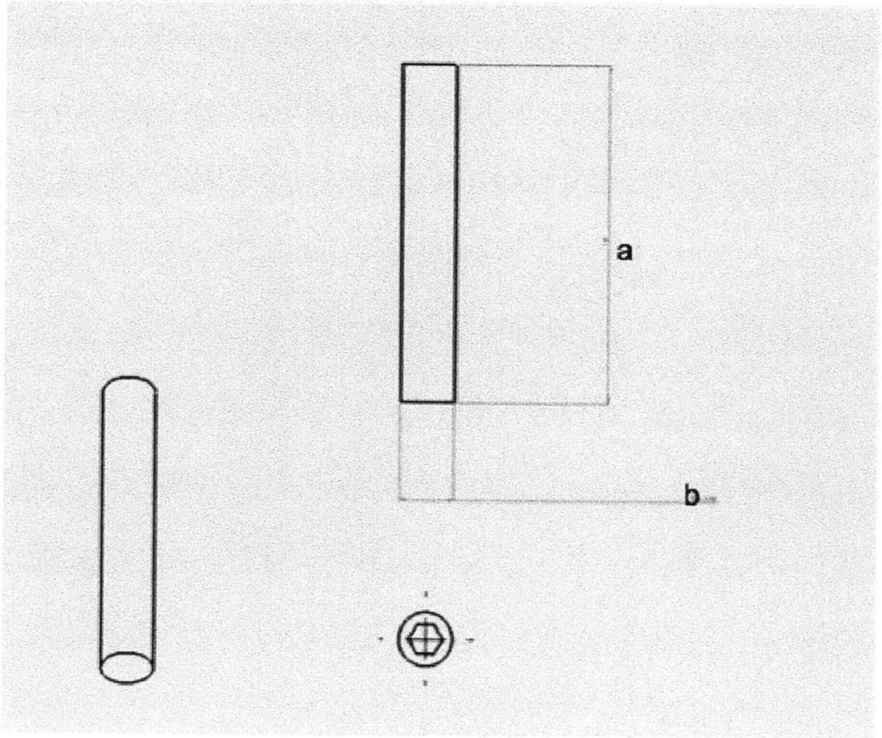

Figure 16: Bolt. Dimensions: (a) length. (b) diameter.

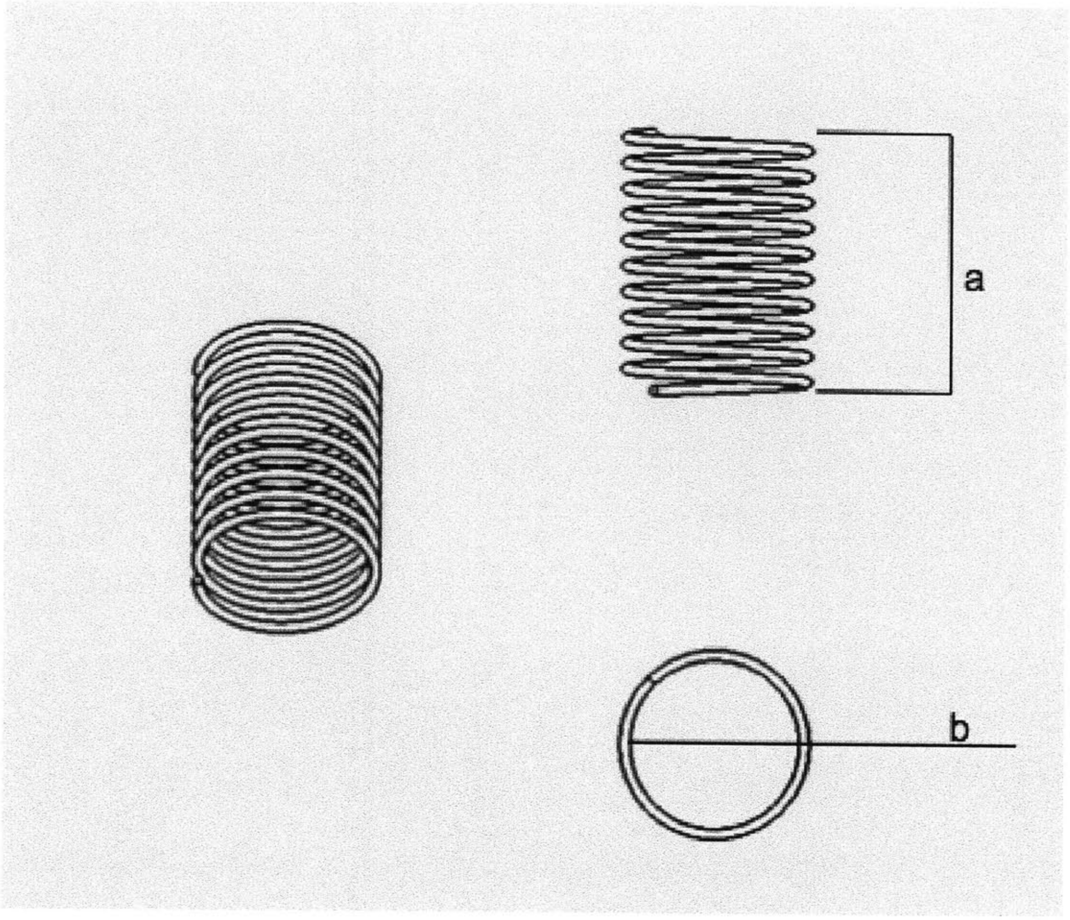

Figure 17: Spring. Dimensions: (a) spring length. (b) spring diameter. In the case of the spring the length and spring constant will depend on the testing situation. A stronger spring may be required for heavy duty battery testing.

The algebraic dimensions are loosely tied. For example, the dimension "a" in figure 16 (bolt length) should account for the thickness of three platens (dimension f in Figure 15) in addition to the spring length and the battery thickness.

Conclusion

The adjustable confinement device is an important part of the overall research plan of the battery consortium at MIT. Early individual cell testing is the basis for later models, both computational and physical. Complete pack testing is important for developing actual crash regulation and guidelines. But repeated pack testing is cost prohibitive. Therefore it is very important that initial models remain accurate and consistent throughout testing.

Future Work

The ICL's research will continue for 3 years beyond the initial phase of research. The model will continue to grow and develop as testing progresses. There may in fact be a need for future adjustable confinement devices based on the current model.

If I could make further changes to my model, I would add inserts for adjustable confinement of cylindrical cell batteries. When compression testing is used for 18650 cells, a similar buckling pattern occurs. Although this may be more representative of a pack crash situation, a quasi-confined compression test could examine further the reactions of these cells.

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