Polymer Rivet and Frame Optimization for the MES Composite

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The MES project of the Stanford Structures and Composites Laboratory (SACL) integrates Li-ion battery cells in a carbon fiber composite structure to improve its mechanical performance. That dramatically reduces the overall battery system weight, avoiding the current industry standard of requiring heavy structures around the battery cell in order to protect it from mechanical load. One of the key components of the MES composite cell design is a polymer frame and rivet pattern around the battery cell, connecting a carbon fiber face sheet at the top and at the bottom to create a mechanical stiff sandwich structure. The geometry of this polymer highly influences the battery's mechanical and electrical performance shall be examined in this research project. To populate the criterion space of this multidisciplinary problem, the mechanical strength is optimized for constrained battery cell energy density. The goal is to define a set of Pareto optimal polymer geometries.

I. Introduction

THE current cell design incorporates a battery stack sandwiched between two polymer frames that allow the battery to attach to the carbon fiber face sheets. The geometries of the battery were arbitrarily assigned to span a small sample space to give some insight into the mechanics of the layup. It has already been determined that the cells containing rivets are much better at distributing shear stress, and hence reducing the shear stress in the battery itself. However, not much research has been done to find a geometry layout for the optimal tradeoff between battery capacitance and mechanical performance. The current cell design can be observed in figure 1.

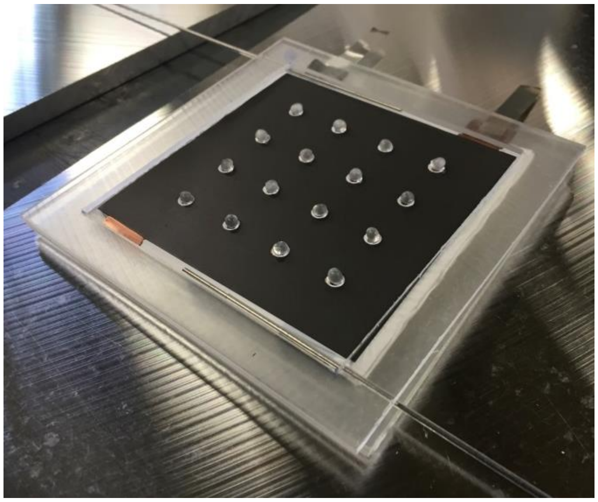

Figure 1 Layup of the MES Composite. Clear areas are the polymer geometries to be optimized.

II. Theoretical Approach

All of the dimensions of the polymer frame are possible parameters for optimization. That includes overall cell length and width, number of rivets, rivet spacing, rivet diameter, frame length and width, and polymer thickness. For simplicity this paper only covers configurations which vary rivet diameter, number of rivets, and frame width. With these three variables, an analytical function can be generated from fewer data points. The definitions of the parameters are represented graphically in figure 2.

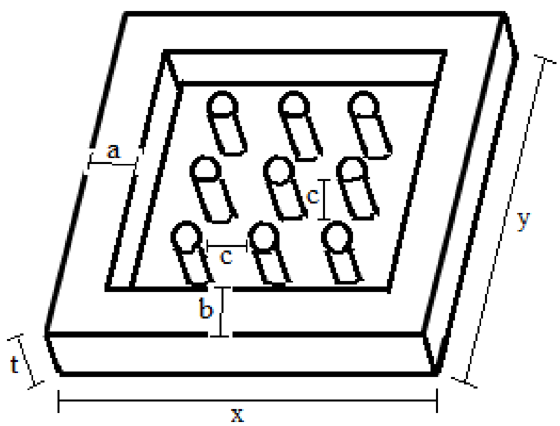

Figure 2 Definition of optimization parameters

The foundation of the optimization is a finite element analysis (FEA). For a 6th order function fit of three design variables, 3^3 data points are required. The FEA is therefore run with 27 different geometries in a three point bending scenario. Using Reis/Patrick thesis for advanced sandwich theory, the effective shear modulus G is then back calculated from Eq. 1, serving as the indicator for the mechanical performance of the configuration.

A polynomial regression model can now be used to represent G as an analytical function of the design variables.

$$\Delta = \frac{PL^3}{48EI} + \frac{PL}{4GA}\left[1 - \frac{I_f}{I}\right]^2 (1 - \frac{tanh\,\theta}{\theta})$$

where

$$\theta = \frac{L}{c}[\frac{G}{2E}\frac{c}{t}\left(1 + \frac{3d^2}{t^2}\right)]^{0.5}$$

The electrical performance is measured as the effective mass energy density E of the cell. With known densities of the polymer, carbon fiber facesheet and battery cell material and an energy density of 210 Wh/kg of the core cell, the overall E is derived depending on the polymer geometry.

To solve this multidisciplinary problem, a Pareto front is created using the constraint method. The desired energy density is iterated over multiple values as the constraint variable while maximizing the shear modulus G. The problem is further constrained geometrically through polymer characteristics and the manufacturing process.

III. Optimization

In order to approximate the analytical function for mechanical stiffness, a model was built in Abaqus CAE. Figure 3 shows the model, with a rod in the center inflicting an evenly distributed vertical load of 500 N.

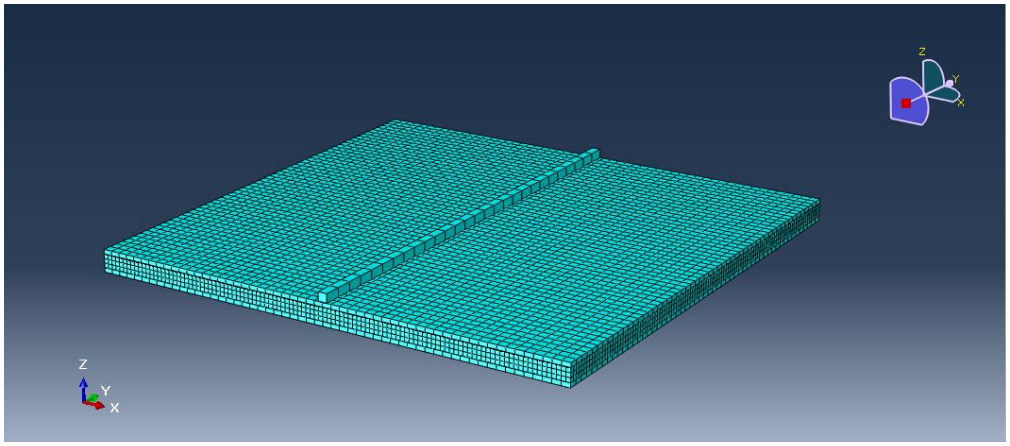

Figure 3 FEM model for mechanical stiffness approximation

Following the lead of the Reis Thesis, the model was constrained vertically on the edges, to create a three point bending test. Some results of the 27 different tests can be observed in Table 1.

Table 1: Data for Analytical Function Generation

W_{fram} (mm)	D_{rivet} (mm)	N_{rivets}	Deflection
5	2	3	1.728
10	2	3	1
:	:	:	:
10	2	5	0.9917
15	2	5	0.7051
5	3	3	1.71647
:	:	:	:
15	4	4	0.6967
5	4	5	1.632
10	4	5	0.965517
15	4	5	0.687384

The analytical function which fits the data with a mean square difference of 0.0031 is shown below.

$$
\begin{aligned}
f(x) = -9 + 0.43x_1 + 3.8x_2 + 1.3x_3 + 0.3{x_1}^2 - 0.07{x_2}^2 - 0.05{x_3}^2 - 0.6x_1x_2 + 0.8x_1x_3 \\
- 0.7x_2x_3 + 0.03x_1x_2x_3 - 0.01{x_1}^2x_2 - 0.3{x_1}^2x_3 + 0.03x_1{x_2}^2 + 0.03{x_2}^2x_3 \\
+ 0.05x_2{x_3}^2 - 0.2x_1{x_3}^2 + 0.05{x_1}^2x_2x_3 + 0.05{x_1}^2{x_3}^2 + 0.02x_1x_2{x_3}^2
\end{aligned}
$$

In order to effectively constrain the problem, we implemented the following geometric constraints based on the manufacturing ability of the lab.

Table 2: Geometric Constraints
Rivet diameter no less than 2 mm
Rivet diameter less than the size of rivet spacing
Number of rivets no less than 0
Number of rivets no greater than 7 by 7
Frame width no less than 5 mm
Rivets must not span outside the frame

A Nelder-Mead Simplex algorithm and a gradient based Quasi-Newton algorithm were both independently run with incremented values for the energy density constraint along with the geometric constraints of Table 2 and the objective function from Eq. 2 to generate a Pareto curve. Then random points within the constraints were generated to show that the optimized values actually coincide with the Pareto front that was generated.

IV. Results and Discussion

It can be seen from figures 4 and 5 that both optimization algorithms generate results close to the Pareto front, clearly demonstrating the tradeoff between electrical and mechanical quality. The Nelder-Mead simplex algorithm however uses only between 300 and 600 function evaluations versus 10,000 evaluations used by the gradient based Quasi-Newton method and generates more optimal results, showing that it is much better suited for this problem.

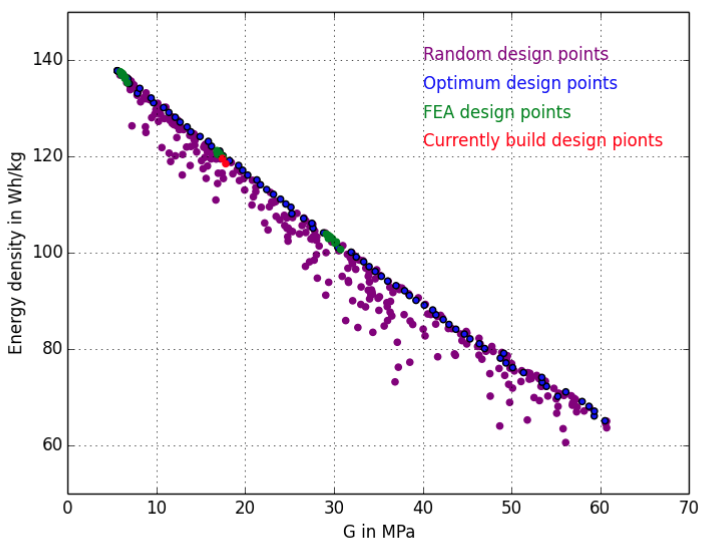

Figure 4 Pareto front generated with gradient based Quasi-Newton

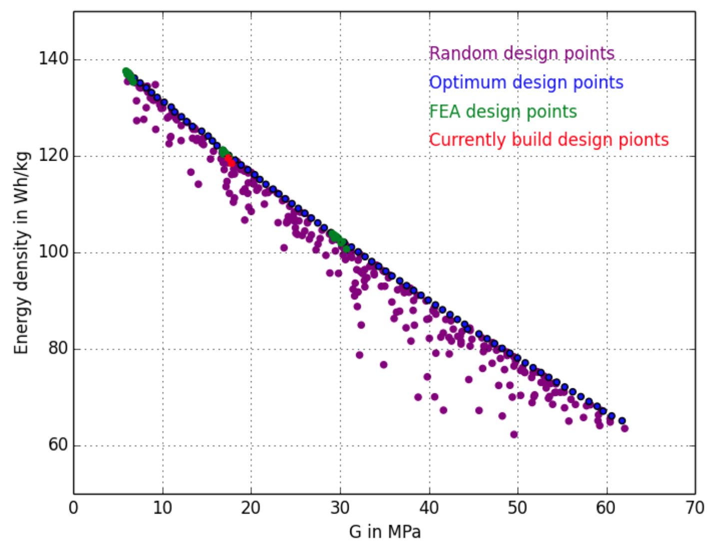

Figure 5 Pareto front generated with Nelder-Mead Simplex

The FEA data points, as well as the two cells currently in production in the lab, are highlighted in the Pareto diagrams. For a deeper analysis of the obtained results, figure 6 depicts selected design points that are currently being considered to be built. This demonstrates the capability of the results to be used for design evaluation and intuition.

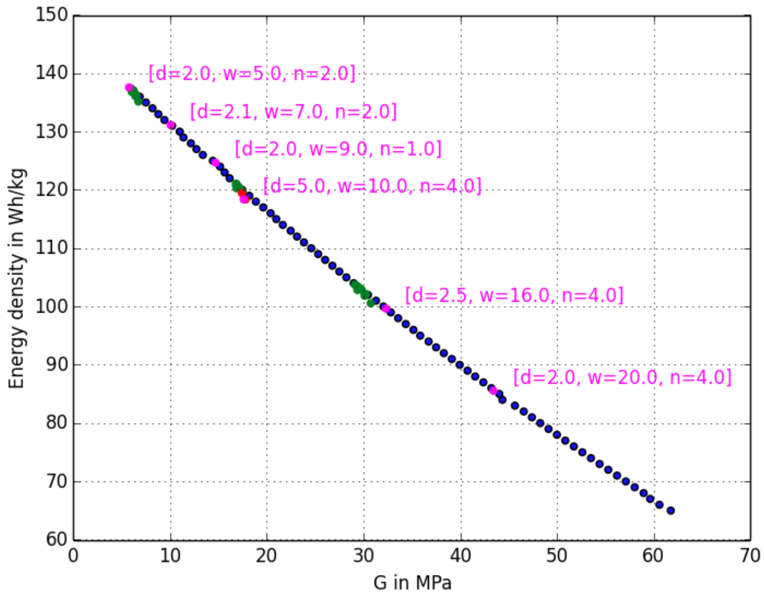

Figure 6 Pareto curve showing possible future cell designs

The data shows that major changes in G and E are caused by a change in frame width. Rivet number and diameter only have a very small influence on the result. This can be observed from the fact that the three distinct clusters of green points are grouped by having the same frame width. Additional analysis of the data showed that there is an optimal ratio between rivet diameter and number of rivets that produces the most efficient cell.

Displaying the underlying FEA data points shows that the analytic function and optimization is based on very closely spaced data points. Without constraining the design variables to values close to the original FEA results, the polynomial fit might not be as good of a representation for data points which are far away. For a more comprehensive future analysis, a wider range of FEA results has to be fed to the polynomial model in addition to including a larger selection of design variables like the thickness or overall width of the cell.

The next steps of this research project will be to build, test, and verify the accuracy of the computational model. Because of the complex mechanics within an actual cell and its interaction with the frame, the absolute values for mechanical properties can't be simulated at this point. When these interactions can be modeled, the model will have to be updated. The current qualitative results however already serve as a very good tool for design choices.

V. References

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