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Nuclear Packaging Internship Final Report

Savannah River National Laboratory
Nicholas Manning
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Site Supervisor: Edward Ketusky, PhD

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Introduction

The goal of this internship is for the student to become proficient in modeling the stress and deformation of mechanical structures in the ABAQUS FEA software. The research specifically performed by the student during the internship concerns measuring the crush strength of honeycomb stainless steel through FEA modeling. The student is working in the nuclear packaging department at the Savannah River National Laboratory (SRNL). The nuclear packaging department is developing a new package, dubbed 9982, which is a new Type B shipping package being proposed by the DOE Environmental Management program for the safe shipment of small quantities of nuclear materials (e.g. fissile contents). It is being proposed to implement honeycomb stainless steel as an energy absorber in the design for the new Type B nuclear shipping package. However, to properly implement this material, more data must be collected concerning the crush strength of different honeycomb stainless steel structures. The research makes measuring the crush strength of different honeycomb stainless steels through analytical means a viable option. This saves time and money as opposed to performing real drop tests and can verify the material's performance as an impact energy absorber.

Background

Common uses for honeycomb materials are in composite structural components and in energy absorption applications. The biggest advantage of a honeycomb material is that it is nearly as strong as the base material while being a fraction of the weight of a solid specimen. Honeycomb materials are excellent for energy absorption applications because the geometry allows for a constant crush strength during extensive buckling; the failure is very predictable. Data concerning the deformation of stainless steel honeycomb structures is not widely available and obtaining mechanical properties through analytical means is a favorable alternative to performing real material tests.

Previous studies have empirically measured the crush strength of honeycomb stainless steel specimens by performing numerous drop tests for different density honeycomb structures [1]. Each layer in the honeycomb is secured to adjacent layers through brazing; the density differences in these structures indicates the amount of brazing done to the material during manufacturing. An example of a honeycomb metal structure can be seen in Figure 1.

Figure 1: Honeycomb Stainless Steel Example

The honeycomb material to be investigated in this research is made of a 304 Stainless Steel material with fourteen sheets, which works out to seven hexagon layers. The shape used for testing was a 1.84” x 2.1” x 2.5” rectangular prism, identical to the one seen in Figure 1. The results of the research include an analytically measured value for the crush strength of the material along with an accurate depiction of a dynamic crush test on a stainless-steel honeycomb structure. The research was validated by comparing the results to the results measured in the previous drop tests [1] for a honeycomb material of the same density.

Internship Goals and Milestones

The Internship Proposal outlined a timeline for the summer. The proposal maintained a focus on comparing static vs. dynamic loading of the honeycomb structure. The focus was changed to simply analyzing a dynamic loading event, as the static event is not of primary concern. The focus was changed to obtaining a working model of only one or a few layers of the honeycomb material in the first half of the summer, while attempting to model the entire honeycomb structure during the second half of the summer and obtain the desired results.

The first few weeks of the internship involve practicing with modeling in ABAQUS and becoming proficient enough to model a honeycomb material structure. This milestone was achieved.

The next few weeks were spent developing the geometry, meshing, and boundary conditions to obtain an accurate model of one to two layers of honeycomb material. This was completed and many different circumstances were observed and compared.

The rest of the internship was spent finalizing an FEA model for an entire honeycomb piece and obtaining meaningful results from the model.

The final report was written in the last week or so of the internship and encompasses all the research done towards this project.

Creating the Model

The model was made to resemble a drop test in which a 50 lb plate is dropped on the structure from a height of 30 ft. Initial tests under these same conditions were already performed on a few different honeycomb structures at SRNL. This model will be able to predict the results of future dynamic loading tests on honeycomb materials, and will be validated if the results from the model can match the results found in the initial tests. In the initial tests, the honeycomb structure sometimes buckled in the middle of the structure as seen in Figure 2. However, for most of the tests buckling occurred at the bottom where the structure contacts the ground.

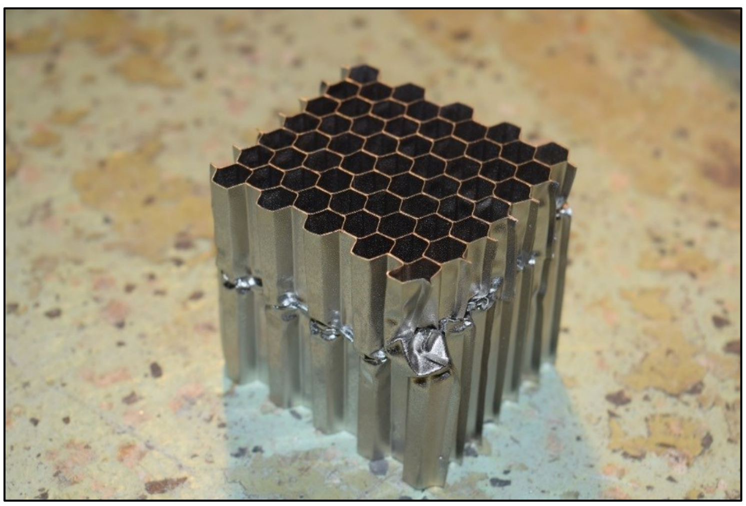


Figure 2: Deformed example from one of the initial tests

The preliminary FEA models only included one or two layers. This was done to try to simplify the system before trying to simulate the entire matrix. Simplification allowed for faster computing time and quicker results. The first model consisted only of two half-layers placed together with no filler in between. The model was a single column made to represent a single layer of the honeycomb material. Figure 3 shows this layer along with the deformed state of this layer. The bottom plane is the ground and is fixed in position, while the plane floating above the structure is the plate being dropped on top of the structure. The plate weighs 50 lb and was given an initial velocity equal to that if it had fallen 30 ft and was restricted to only move vertically.

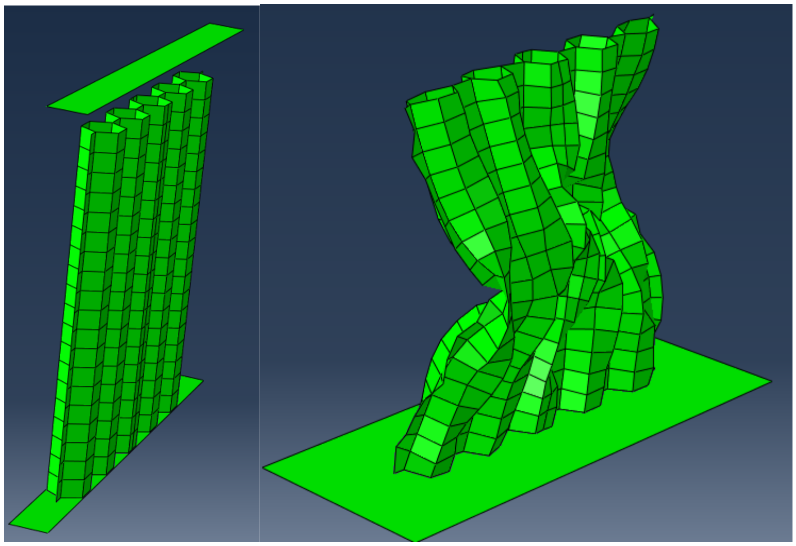


Figure 3: Initial model, one layer with no brazing in between, friction only

This model used only penalty friction between the sheets to hold them together. The sheets deformed by buckling near the middle, which was expected from normal column buckling. However, the structure also rotated under failure, which was not expected. The hypothesized cause of this unexpected failure mode was the lack more adjacent layers to keep the single layer in position and stop it from rotating.

Next, another layer was added to the single layer and braze fill was added between all the sheets to include the brazing finish in the model. The brazing is modeled as a thin sheet of steel. The thickness of the brazing used in the models in this report is 0.004 inches, and is the one of the thickest brazing options being studied for use in the package. This model is shown in Figure 4.

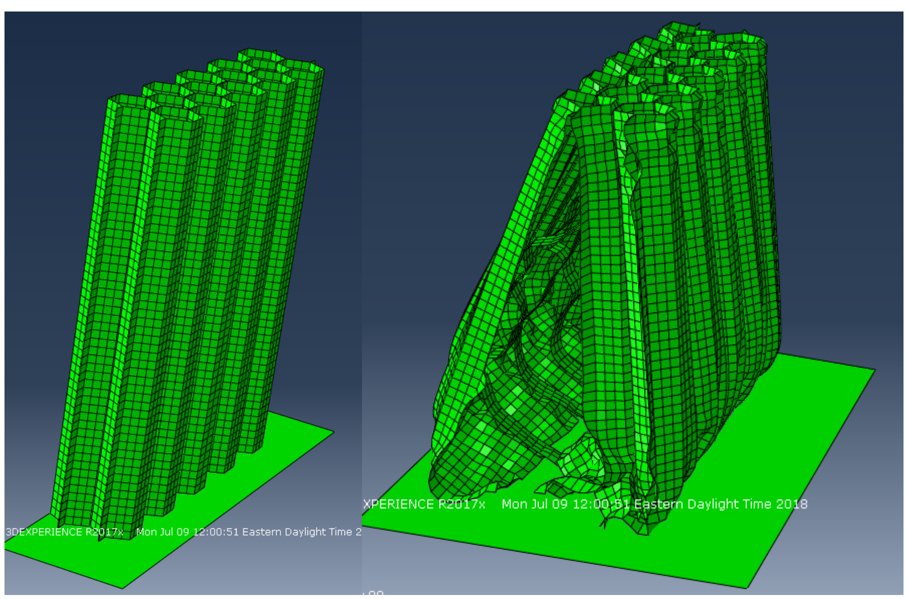


Figure 4: Two layers with brazing in between, friction only

With the brazing fill and the extra layer added to the model, the failure mode involved splitting along the brazed seam. Friction between the surfaces was no longer strong enough to hold the sheets together in this configuration. Only a small amount of buckling was present at the top and the bottom of the structure before separation occurred. To combat this problem, each surface pair in contact was manually selected and set to be "stuck" together through hard contact and rough friction. In addition to sticking the surfaces together, walls were also added to either side of the structure. These walls served to simulate the reaction of the two honeycomb layers to the layers surrounding them in a whole honeycomb matrix as in a real sample. Figure 5 shows the un-deformed structure with the walls added.

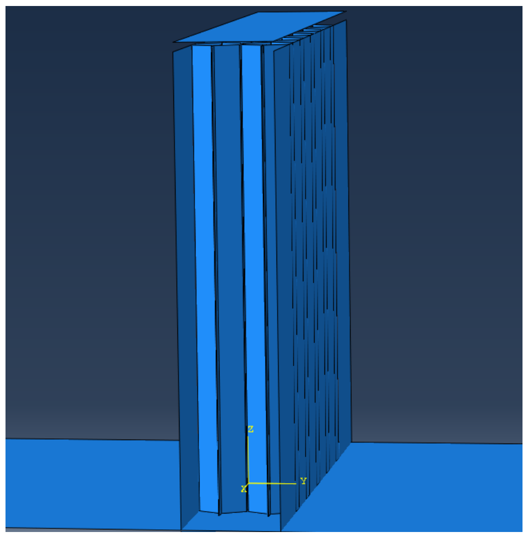


Figure 5: Two layers with walls on either side

The walls were placed exactly on the face of the outer surfaces. This was done because adjacent layers in a real honeycomb structure directly touch and are secured to each other. The only interaction between the added walls and the structure was a small amount of penalty friction, so the structure could slide along the walls' surfaces allowing for proper deformation. The walls were also perfectly rigid in this model, and fixed in every direction. The falling plate was just smaller than the space between the walls and was restricted to only fall in the vertical direction. A few different steps in the deformation of this model can be seen in Figure 6.

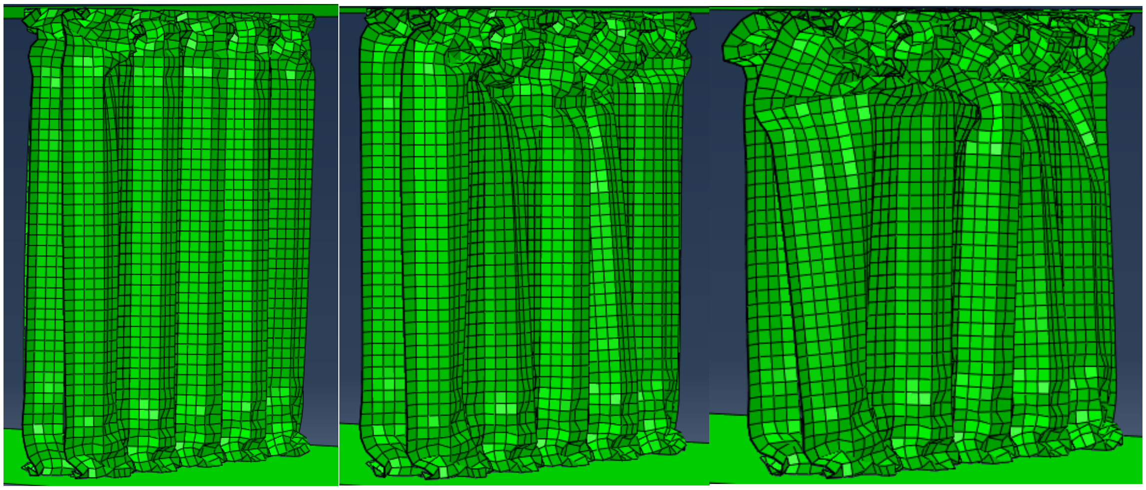


Figure 6: Deformation steps for two layers with rigid walls

The deformation shape of this model was a lot closer to what would be expected from reality than the previous models; the deformation resembled classic buckling failure. One detail noticed in Figure 6 was that when the structure buckled, it appeared to be caving in and folding over itself. Another key detail from Figure 6 is that the buckling occurs as the top and bottom ends of the structure only. This is on the right track to resembling the initial tests where the structure often buckled only at the bottom.

The next improvement made was to set the walls to be "soft" so that the structure could penetrate or push the walls back a small amount. The idea was that the wall would still hold the structure, but would have some give, just as a neighboring layer would act in a full honeycomb matrix. Different steps in the deformation results for the model with softer walls can be seen in Figure 7.

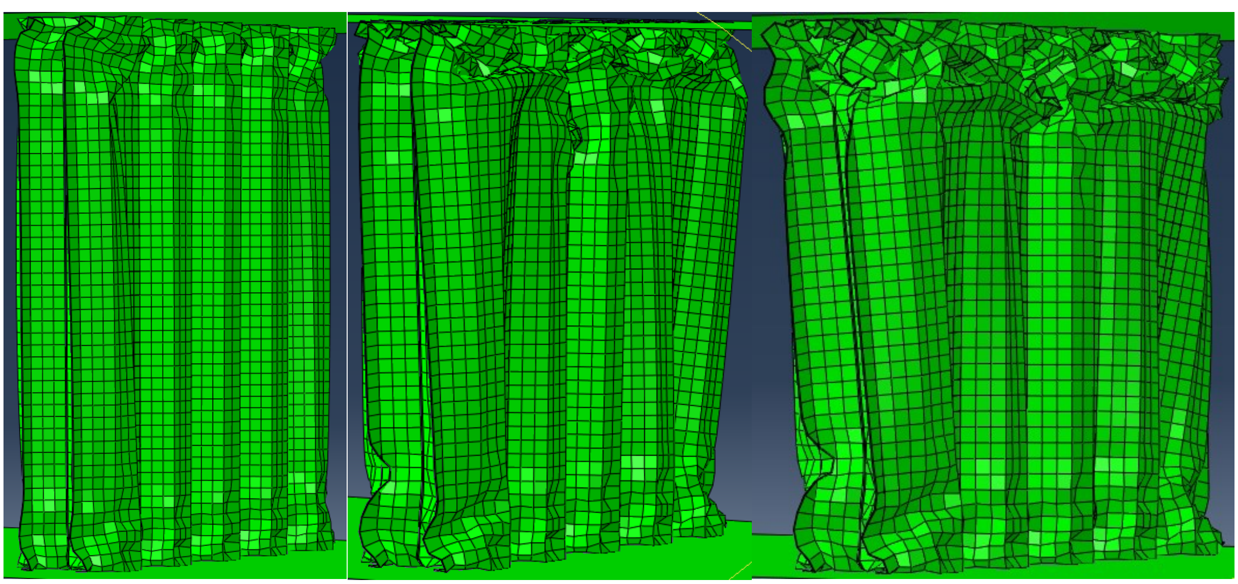


Figure 7: Deformation steps for two layers with soft walls.

The buckling of the model in Figure 7 with softer walls follows a more realistic scheme. The structure folds both inwards and outwards as it buckles, rather than appearing to only fold inwards as with the rigid wall model. The structure still buckled at both ends under failure.

The next step in creating the model was to adapt the two-layer model to a full-size specimen. More layers were added with brazing in between to make the model the same size as the real specimen from the initial tests. The full-size model can be seen in Figure 8.

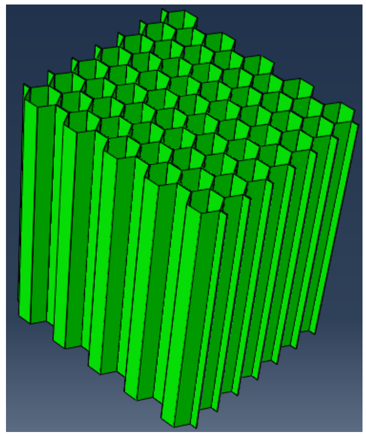


Figure 8: Full size honeycomb model in ABAQUS

At first, the full-size honeycomb model failed in a similar manner to the two-layer model in Figure 7; buckling occurred at both ends of the specimen under failure. At this point, it was hypothesized that changing friction conditions at the ends of the specimen during the real drop tests could have caused the specimen to buckle only at the top, only at the bottom, or in the middle of the structure. Three different frictional cases were tested with the model to address this hypothesis. The three cases include excessive friction between the top of the specimen and the plate, excessive friction between the bottom of the specimen and the ground, and excessive friction at both interfaces. To model excessive friction between the top of the specimen and the falling plate, all the outermost nodes, the nodes which would directly contact the plate, were set to be fixed so that they would only move in the vertical direction. The idea is that the impact would effectively stick the top of the specimen to the falling plate when contact occurs, either from high amounts of friction at the contact interface or from local surface deformation of the plate. Excessive friction at the bottom of the specimen was modeled in the same way as the top, by fixing the bottom layer of nodes. The addition of excessive friction to the model produced a deformation consistent with that of the initial drop tests, the deformation the research intended to produce. An example of excessive friction between the specimen and the ground can be seen in Figure 9.

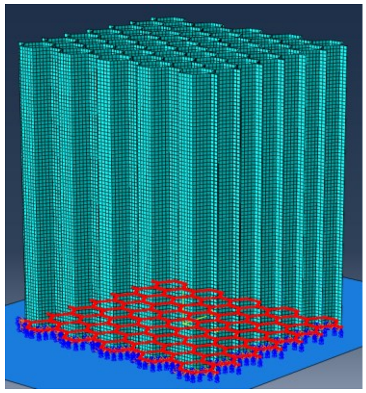


Figure 9: Model with excess friction between the base of the specimen and the ground. Fixed nodes shown in red. Falling plate hidden in this image.

Now that the full-size honeycomb structure was created and deforming properly, the crush strength needed to be measured to further validate the model. The analytical value for the crush strength was obtained from the deceleration of the plate. The deceleration data along with the mass of the plate and the projected area of the honeycomb specimen yielded a value for the crush strength of the material in units of psi. The measurements gathered with the ABAQUS model in this study were compared with results from a real drop test on a stainless-steel specimen for validation purposes [1].

Results and Discussion

The first frictional case studied was excess friction between the bottom of the structure and the ground upon impact. In this model, buckling failure developed at the top end of the structure where the plate impact occurred. The deformed state of this model can be seen in Figure 10.

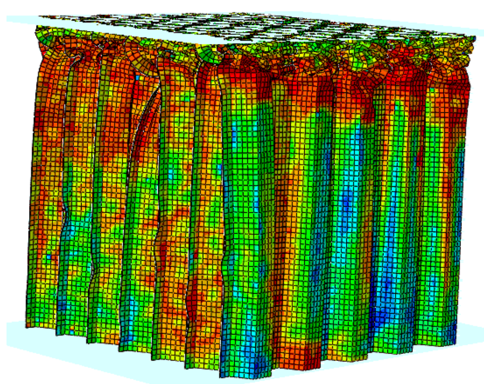


Figure 10: Deformation of the specimen with excess friction at the bottom.

The crush strength measured in this model for the honeycomb specimen was 875 psi. A plot of the crush strength versus crush strain for this test is shown in Appendix A.2 and follows the same scheme as a curve from a real drop test on a honeycomb specimen [A.1]. The value measured for a honeycomb specimen of equivalent density from the real drop test was 805 psi. There is a 9% difference between the empirical crush strength value for this specimen and the analytical value generated in this study. The similarities in the crush strength curves and the measured crush strengths for the empirical tests versus the analytical model validate that the simulated model was working as intended.

The case where excess friction occurred between the top of the specimen and the plate upon impact was studied next. In this scenario, buckling occurred at the bottom of the specimen, along with some ripples along the edges of the specimen. The deformed state of this model can be seen in Figure 11.

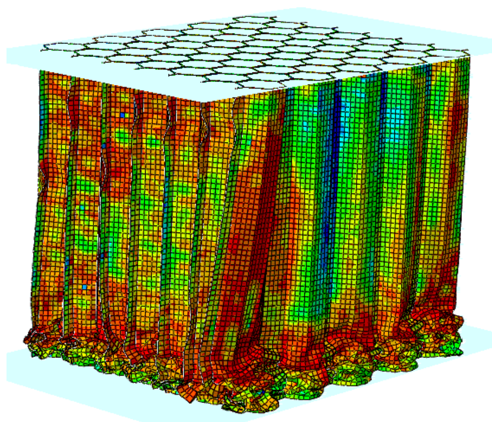


Figure 11: Deformation of the specimen with excess friction at the top.

With excess friction between the top of the specimen and the plate, the crush strength was measured to be 875 psi, just as it was with friction at the bottom end of the structure. The graph of the crush strength versus strain [A.3] also matches the graph recorded before [A.2]. Furthermore, the deformation scheme in this case is consistent with the most common result from the real drop tests. Most of the real tests resulted in the bottom of the specimen buckling while the top remained untouched, just as what happened in this model. The result indicates that under the conditions in the initial drop tests it was likely that there was more contact friction at the interface between the specimen and the plate compared with the friction at the interface between the specimen and the ground. If the result was not driven by friction, then the cause of this phenomenon can be explained by the plate having a lower material hardness than the ground and experiencing local deformation upon impact. Local deformation of the plate would result in the plate jamming itself onto the top of the honeycomb structure eliminating the possibility of buckling propagating from the top end.

The third case studied consisted of excess friction present at both the top and bottom interfaces of the specimen. In this scenario, the specimen exhibited buckling failure at both the top and the bottom ends. The deformation of this model can be seen in Figure 12.

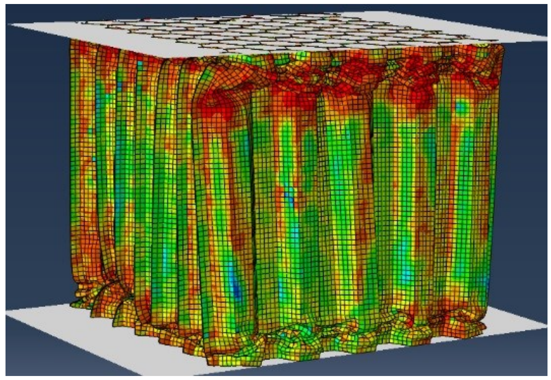


Figure 12: Deformation of the specimen with excess friction at both the top and bottom.

The crush strength measured when both ends were fixed was 860 psi. This is 7% different from the real drop test result, while the crush strength versus strain graph [A.4] shows the same trend. This result is also consistent with the crush strengths measured for the top fixed only and bottom fixed only scenarios indicating that the deformation scheme is independent of the measured crush strength.

The goal in simulating this case was to attempt to obtain a deformation scheme consistent with the second most common result from the real drop tests: buckling occurring in the middle of the structure. The simulation did not prove consistent with the real tests in this case indicating that buckling in the middle is caused by some factor other than high friction at either end of the structure. The likely cause of deformation in the middle of the structure is imperfections along the height of the specimen. Real specimens are not perfectly aligned, do not have a perfect brazing finish, and will inevitably have small dimples or bends throughout the sheets in the specimen. The analytical model is perfect in these aspects. Evidence to this claim can be found by comparing the measured crush strength in the simulated models versus the real drop tests. The analytically measured crush strength for the specimen was consistently larger than the empirically measured crush strength due to the lack of imperfections in the analytical model.

Conclusion

The research performed over the course of the internship lead to the creation of a working FEA model for a honeycomb stainless steel structure. The model has been verified to measure the material's crush strength consistent with real test results while also producing a deformation physically comparable to real test results. The model will be passed on to the department and potentially used to obtain more crush strength values for a range of honeycomb specimen to aid in the design of a honeycomb stainless steel absorption structure.

Closing Remarks

I am now on the final few days of my internship. I succeeded in creating a working FEA model for a honeycomb stainless steel structure and have verified that it can measure the material's crush strength consistent with real test results. My model can be applied to different density and size honeycomb materials to obtain a breadth of data without needing to perform extensive drop testing. I believe I have gained from this course the intended student learning outcomes. I identified the lack of data concerning the crush strength of honeycomb stainless steel as an engineering problem and developed a unique solution to the problem using FEA software. During my research and the creation of my model, I maintained the responsibility to eliminate bias by coming up with a range of solutions when I encountered a bump in the road. I frequently consulted my mentor with where I was at in my project to remove any confirmation bias about how my model was working not only as intended but as a general model. During my internship this summer I have come to understand that an engineer working in industry never stops learning. Every task assigned is another bit of experience a little different than the tasks accomplished before, and every day requires learning something new to accomplish new tasks on the job. There is a need to pursue life-long learning throughout a career to perform a job to the best of one's ability.

References

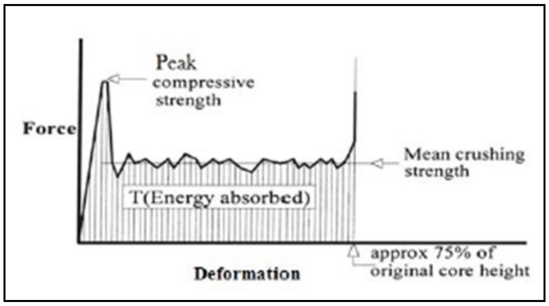
[1] SRNL-M-TRT-A-00032, Revision 0, "Static and Dynamic Compression Testing of Stainless Steel Honeycomb Material for Radioactive Material Packages." (2018)

[2] V. Jeyasingh, "Analytical Modeling of Metallic Honeycomb for Energy Absorption and Validation with FEA," (2005).

[3] HexCell, "HexWeb Honeycomb Attributes and Properties," (1999)

[4] Packaging and Transportation of Radioactive Material, Code of Federal Regulations, Title 10, Part 71, Washington, DC (2016).

Appendix A.1

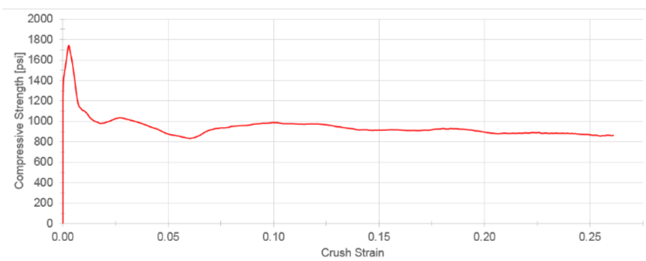


A.1: Typical crush force vs deformation curve for a honeycomb material. [1]

Appendix C.3

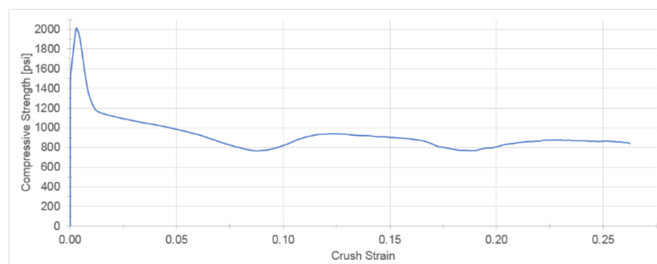
A.3: Crush Strength vs. Strain for FEA model with excess friction at the top.

Appendix B.2



A.2: Crush Strength vs. Strain for FEA model with excess friction at the bottom.

Appendix D.4



A.4: Crush Strength vs. Strain for FEA model with excess friction at both ends.