AC 2012-4920: STUDYING THE PHYSICAL PROPERTIES AND AUXETIC BEHAVIOR OF 3D-PRINTED FASTENERS

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ABSTRACT

Fasteners are used in every industry, and in virtually every component. The ideal fastener would be relatively easy to insert or push into a hole, but take much more force to remove or pull out of the hole. Such fasteners would not require nuts screwed onto bolts, or other retaining rings. The current work attempts to develop a simple fastener with a low Insertion Force / Removal Force ratio by exploiting auxetic behavior. Auxetic materials or negative Poisson's Ratio materials have properties that are counter-intuitive. A rubber band, for example, becomes thinner in width when pulled lengthwise Auxetic materials, however, will expand in width, when pulled along their length, or when compressed along their length, will also contract in width. Hence, normal materials have positive Poisson's Ratios while auxetic materials are revealed to have negative Poisson's Ratio. By exploiting the theory behind negative Poisson's Ratios, a suitably designed fastener can exhibit auxetic behavior. Specifically, a properly designed fastener will decrease in diameter when pushed/compressed through a hole and increase in diameter when pulled out of the hole. Using previously developed theory, several cylindrical fasteners were fabricated that exhibited auxetic behavior. Aluminum sleeves were fabricated with holes of slightly different diameters, such that when the fasteners were inserted they must contract slightly. Insertion/Removal force ratios as low as 18% were observed. The project is considered a success and could lead to patents and be a boon to the fastener industry.

Based on the research experience a learning module to be implemented in an Algebra I class has been designed. The paper describes the learning module that is based on an active learning methodology known as Legacy Cycle. It will be implemented in the spring semester in Algebra I classes in a high school with majority of Hispanic students.

***** please note that some details of this work have been removed, until after a patent application can be made. ******

INTRODUCTION

The optimal fastener is one that assembles with little force yet can withstand incredible stress when attempted to be disassembled. This can be achieved in a fastener by taking advantage of the Negative Passion's Ratio and creating a fastener with auxetic properties. When pulled through axial tension, a material will show evidence of lateral displacement (strain). The ratio of negative lateral strain to axial strain is known as Poisson's Ratio after the French mathematician Simeon Denis Poisson. In Dr. Larry Peel's previous research, it was revealed that a positive angled braid interacting with a negatively angled braid would display positive Poisson's Ratios while two positive angled braids acting against each other would result in a Negative Passion's Ratios as displayed in Figure 1[1, 2].

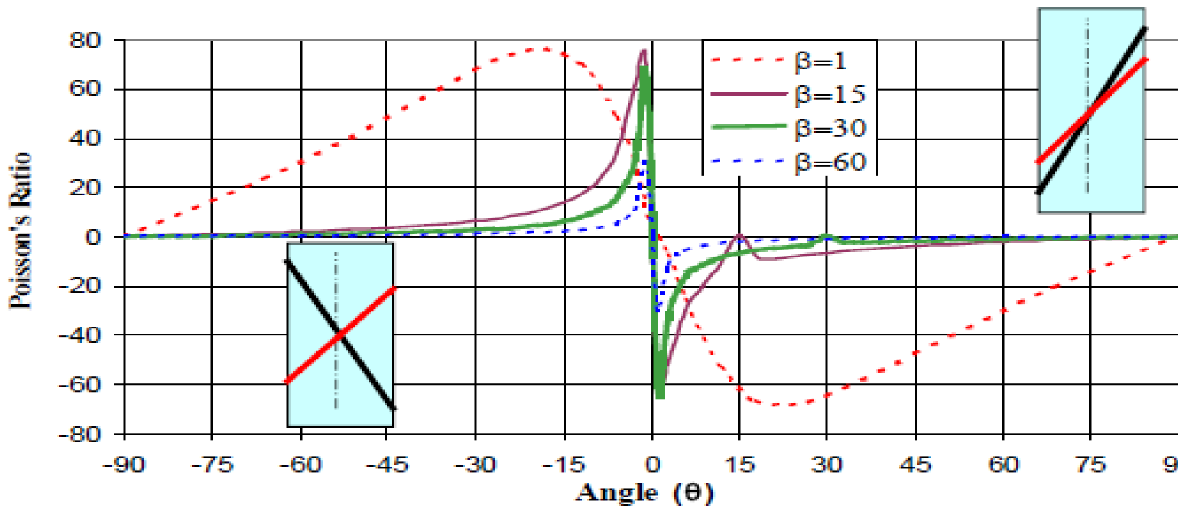


Figure 1: Poisson's Ratios of Elastomer Matrix Composites [1]

Furthermore, it was discovered that while some angle sets provided greater negative ratios, they also resulted in greater axial shear, which for an ABS 3D printed fastener could mean it would fracture under stress. A balance between negative Poisson's Ratio and axial shear had to found and considered for the manufacturing of the fastener. Consequently, angle sets with lower ratios were best for the fastener due to their much lower shearing possibilities. A series of optimal sets of angles for this auxetic fastener design were chosen and implemented.

INITIAL DESIGN

Initially, Google Sketchup software was chosen for designing the fastener because of its user-friendly controls and capacity to produce helical curves. The program, however, proved to be inappropriate for the project. The file had problems with resolution under the required STL format for 3D printing and helical curve was unable to be altered to achieve the tapered end we desired. Additionally, the fastener was unable to be virtually tested for flexibility, or stress constraints before printing. The initial design of the fastener, Figure 2, proved to be flawed as well. The individual braids were too thin in relation to the total volume of the fastener resulting in unfortunate outcomes due to axial stress before testing as shown in Figure 3.

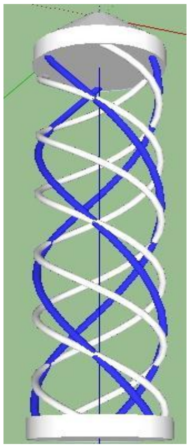


Figure 2: Initial Design using Google Sketchup

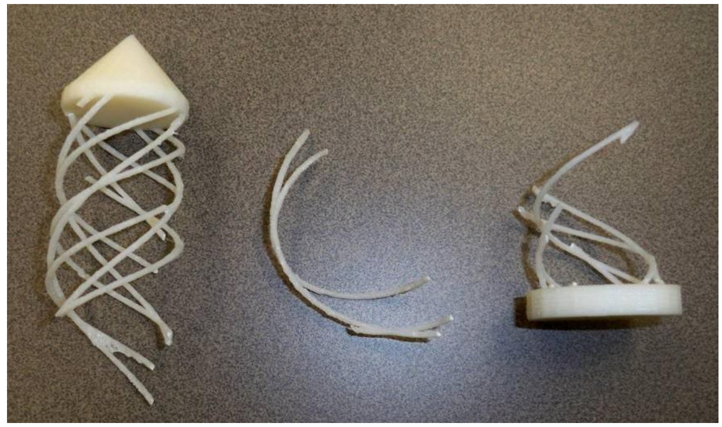
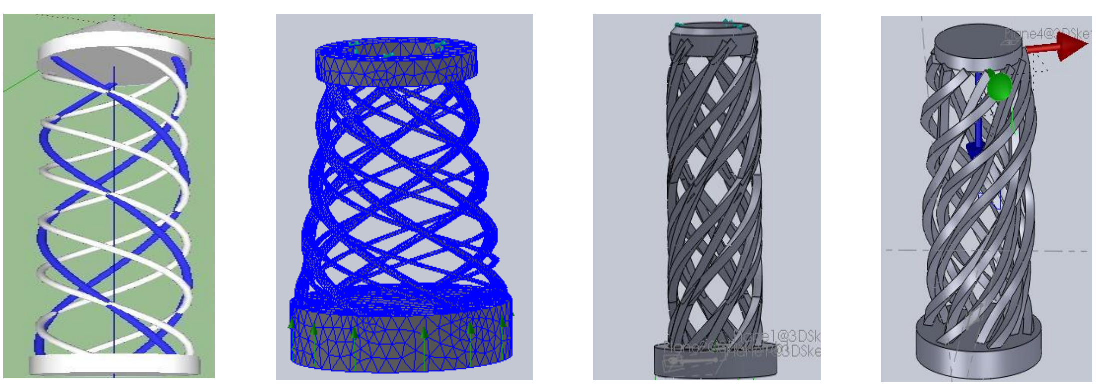


Figure 3: Results of thin braids on manufactured fastener before testing

Some design considerations were made to correct some flaws in the initial fastener. The individual braid diameter needed to be increased for 3D printing requirements and to achieve a minimum volume prerequisite of lateral stress. The number of braids per offsetting angle was also adjusted to six from four to further assist in achieving the minimum volume requirements. The nominal diameter of the fastener would also need to be tapered in order to allow an easier assembly process. The back end of the fastener would also need an alteration to help in the removal process of the fastener. The percent of contraction and expansion of the nominal diameter of the fastener was reduced from the sought after 5% to a maximum of 2%. Furthermore, the program for future designs would have to be changed to the more sophisticated NeiFusion in order to alter the helical curves for required tapering and provide stress indicators through NeiNastran virtual simulations.

OPTIMIZING THE DESIGN

Multiple ensuing drawings of the fastener were modified throughout the research time frame but all fell under four main designs. Figure 4 shows the evolution of the fastener design as the research progressed. Each of the four major designs was repeatedly adjusted to reach the optimal performing fastener. Degree of taper, length of the braid, number of braids, and the cross-section of the braids with the base were some of the fastener characteristics that were modified throughout each design.



Design 1 Design 2 Design 3 Design 4

Figure 4: The design evolution of the fastener

As discussed before, design 1 had its share of limitations and errors. Design 2 displayed the required auxetic reactions of the fibers but was changed due to the lack of a constant diameter throughout the fastener before the taper initiation. Design 3 saw the correction of taper initiation and the introduction of a square cross-section instead of the circular braids. This design demonstrated great potential during NeiNastran simulation but needed better pivoting range at the braid intersection points. Design 4 established the undulating braid as a possible design parameter. MATLAB was used to create the undulating braid formulas before transferring the plot data to NeiFusion for completion of the design and simulation. After some mixed results were attained with design 4, modifications were made to design 3 with the required specifications and simulation tests confirmed the sought after auxetic behavior. Diameter changes were concluded at 1.71% of the nominal diameter of 0.7 inches during compression and 1.5% during axial tension.

FABRICATION AND TESTING

The orientation of the fastener during 3D printing was also changed due to the laying of the ABS plastic during manufacturing. Printing the fastener horizontally would provide better axial strength to the braid fibers in comparison to vertical printing of the fastener. Besides the thin braids in the initial design, the layering method of the 3D printing machine is believed to have compromised the axial strength of the fastener. The orientation of the fastener during 3D printing was changed from printing the fastener vertically to printing it horizontally. Printing the fastener horizontally will provide better axial strength to the braid fibers in comparison to vertical printing of the fastener.

Figure 5: Design 3 after modifications

fabricated at four different diameter dimensions (Figure 6). The diameters of the four sleeves included 0.77, 0.762, 0.758, and 0.755 inches representing the approximate percent contractions of 0%, 1%, 1.5%, and 2%. A tensile test machine was used for measuring both compression and removal forces. For compression testing, the fastener was placed in the aluminum sleeve up to the point where the taper is introduced. A small sheet of acrylic glass was placed on top of the fastener end to ensure that the pressure was disbursed evenly throughout the fastener (Figure 7). Additionally, the tests were run at a slow enough speed to self-correct any misguided fasteners. For removal force testing, an attach point was placed through the back end of the fastener and placed in the tensile test machine. The aluminum sleeve was then pulled out by hand to measure the force exerted on the tensile machine, making sure to pull straight out to not be compromised by the axial deformation of the fastener's auxetic nature.

Figure 6: aluminum sleeves and 3D printed fastener

Figure 7: Universal test machine during compression test with acrylic sheet.

TEST RESULTS

The fasteners were treated with an epoxy finish for added strength to the 3D printed fibers. Both treated and non-treated fasteners were tested. The compression/insertion test results for the non-epoxy fasteners illustrate an average of 4 pounds of force required for fastener A while the fastener B required an average of 8 pounds of force (Figure 8-11).

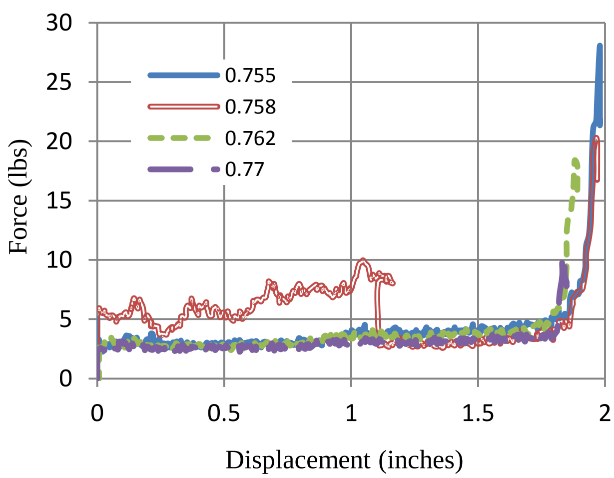


Figure 8: Insertion Force vs Displacement Fastener A Non-treated Sample 1

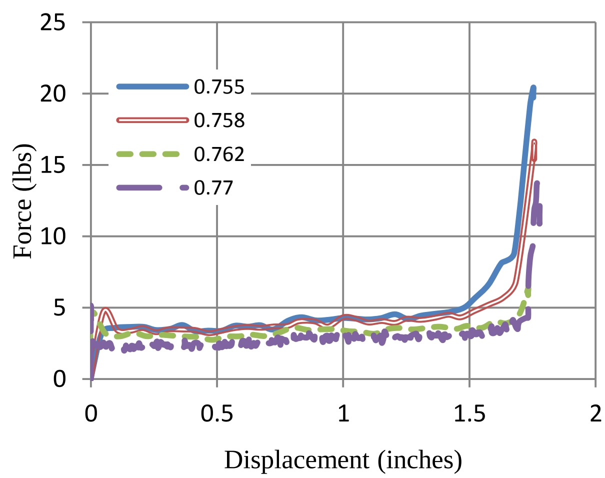
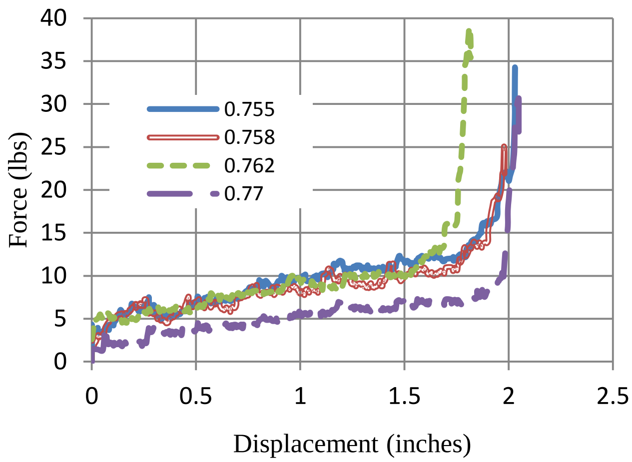


Figure 9: Insertion Force vs Displacement Fastener A Non-treated Sample 2



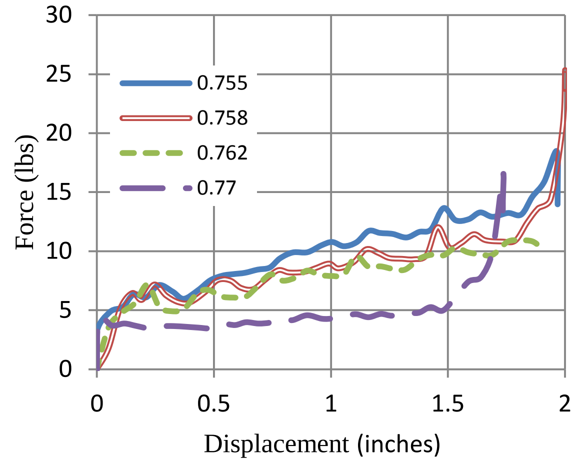
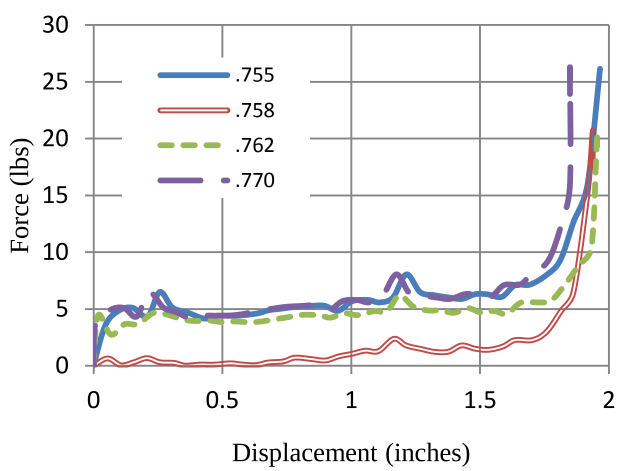


Figure 10: Insertion Force vs Displacement Fastener B Non-treated Sample 1

Figure 11: Insertion Force vs Displacement Fastener B Non-treated Sample 2

Compression results for the epoxy-treated fasteners show an increase of insertion force for both sets of fasteners. This increase in force is a result of two factors: the diameter increase of the fastener with the layer of epoxy and the epoxy's rigid effect on the flexibility of the braids during compression. The compression test results for the epoxy-treated fasteners show the average of 5 pounds of force required for the 30/45 degree fastener and an average of 15 pounds of force for the 30/60 degree fastener (Figure 12-15).



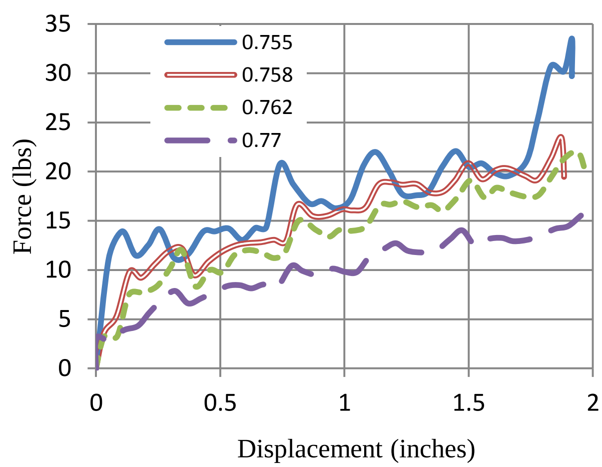
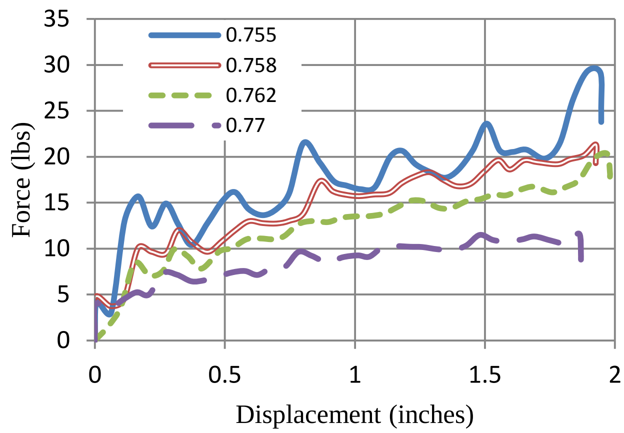


Figure 12: Insertion Force vs Displacement Fastener A Epoxy-treated Sample 1

Figure 13: Insertion Force vs Displacement Fastener A Epoxy-treated Sample 2



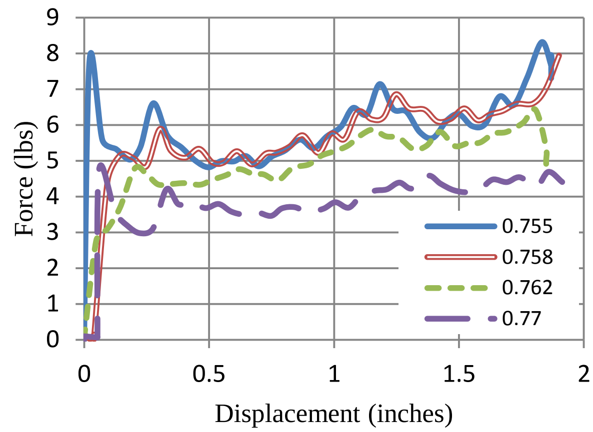
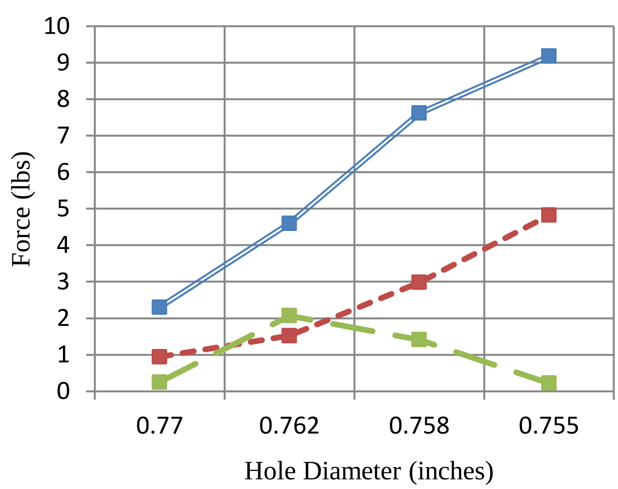


Figure 14: Insertion Force vs Displacement Fastener B Epoxy-treated Sample 1

Figure 15: Insertion Force vs Displacement Fastener B Epoxy-treated Sample 2

The epoxy-treated fasteners displayed insertion force increases of 25% and 87.5% of the A and B fasteners respectively when compared to insertion forces of their corresponding non-treated fasteners. Test results show the same increase in removal force for epoxy-treated fasteners, similar to the insertion force increase, but with much greater increase percentage. Non-treated fasteners had a removal force average of 2.5 pounds for the A fastener and 6 pounds for the B fastener, while the epoxy-treated fastener had removal forces of up to 9 and 39 pounds for the A and B respectively (Figure 16-17). The percentage increase of the A degree fasteners reaches 100% while the B fastener reaches increases over 500%.



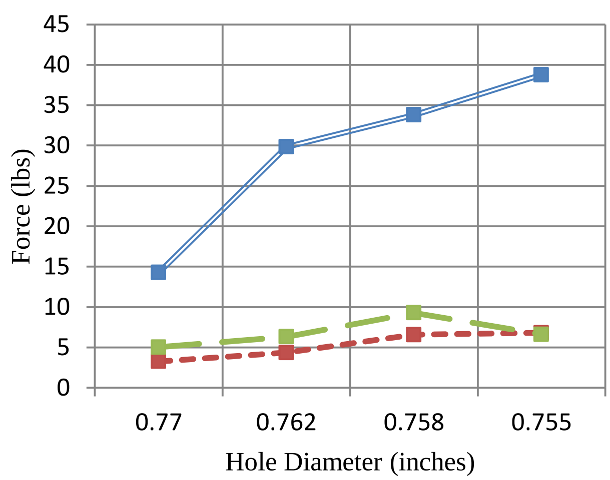


Figure 16: Removal Force A Fasteners, epoxy-treated in blue.

Figure 17: Removal Force B Fasteners, epoxy-treated in blue.

While the added diameter change from the epoxy-treated fastener would result in an increase of removal force, the epoxy's rigidness should have caused the auxetic flexibility in the braids to be subdued. The results however show great increases in removal force with the epoxy-treated fasteners with greater auxetic behavior patterns (Figures 18, 19).

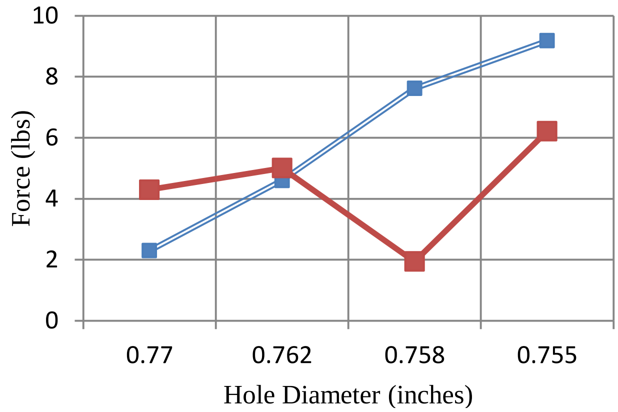


Figure 18: Insertion (red) vs Removal (blue) Forces, for treated A Fasteners.

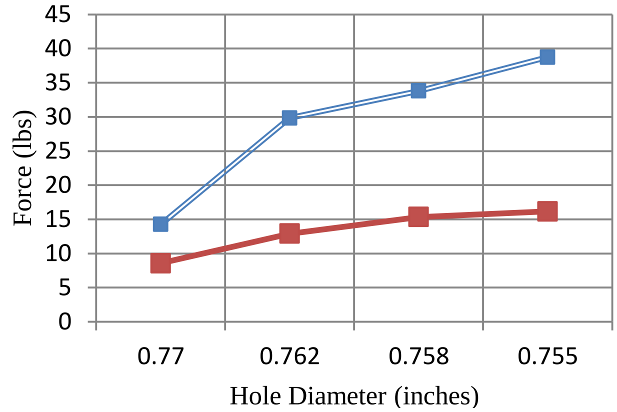


Figure 17: Insertion (red), Removal Force (blue), for treated B Fasteners.

LEARNING MODULE

The proven model for this modular instruction tool is the Legacy Cycle Module[7] based on the research findings of the VaNTH project group. The Legacy Cycle lesson format consists of six stages:

1) a challenge question,
2) generate ideas,
3) multiple perspectives,
4) research and revise,
5) test your mettle, and
6) go public.

The cycle is based on current learning theory presented in How People Learn: Mind, Brain, Experience, and School[6]. During the summer research institute, a two-day Legacy Cycle workshop was presented to the teachers. The workshop provided the framework for the teachers to develop their instructional materials and is delivered early enough in the summer to allow for brief checks of progress during the summer institute.

It is anticipated that the teachers will beta test components of their modules during the Fall and Spring semesters following the summer research experience. Using feedback from the Evaluation of the legacy cycle, the teacher participant will present a final Legacy Cycle Module at the scheduled Legacy Cycle Module Conference in June, a calendar year after the summer research institute.

The learning module developed by the teacher based on the above research project was targeted for an Algebra I class. It has been a challenge to find a learning module that builds on some of the concepts acquired by the teacher during the summer experience while being applicable in an algebra class in a low socio-economic school with limitations imposed by the administration. At the time of writing this paper the legacy cycle has not been yet implemented and hence results from applying the learning module below are still pending. Table 1 below describes the components of the learning module in the form of the legacy cycle.

Table I: Components of the Legacy Cycle

Component	Elements
Challenge Question	*Students are employed by a toy company to design a spring loaded launcher to eliminate the use of metal springs. The students' task will be to design a small launcher and test several 3D printed springs for their capabilities and physical properties as compared to metal springs. Students will develop a mathematical expression to describe the operation of the launcher?*
Generate Ideas	▸ How will 3D printed springs differ from standard springs? ▸ What design should you use for your small spring loaded launcher? ▸ How will the springs be positioned for optimal range as well as optimal control? ▸ What size and dimensions of spring would work best for the launcher? ▸ What will be your maximum range? ▸ What percentage of accuracy will your launcher achieve? ▸ Students will discuss what they know about ◦ 3D printing ◦ Spring loaded launchers ◦ The geometric shape and properties of a spring ◦ The effect of dimensional changes of a spring on its strength and control ◦ Collecting, tabulating, and plotting data ◦ Interpreting and identifying trends in given data ◦ Using data to establish formulas for accurate deployment of the launcher
Multiple Perspectives	▸ Presentation teacher about research project ▸ Presentation by graduate student about 3D printing ▸ Web search about 3D printing
Research and Revise	▸ Students will research: ◦ The growing 3D printing industry ◦ The differences, limitations, and functionality of 3D printed objects and their materials ◦ Axial and tension forces of the 3D printed springs ◦ The compression force and generated force ◦ Collecting and tabulating data ◦ Graphing linear and non-linear data ◦ Identifying trends and generating accurate and consistent formulas
Test Your Mettle	▸ They will design a small launcher with varying angles of deployment and test for compression force and generated force ▸ Students will test both types of springs (regular and 3D printed) and look for differences in performance ▸ Data trends will be used to establish accurate formulas for friendly competition
Go public	Students will publicize their work to get others excited about Math, Science, Engineering, and Technology.

The learning module is related to the summer research which was based on discovering the physical properties and limitations of a 3D printed materials. Relevant factors that were considered during the summer research that will be relevant in the learning module are:

- Developing an optimal design to attain the desired characteristics of a 3D printed structure
- The contraction force of the spring helix design
- The axial displacement of the fastener
- The force generated from compression and removal of the fastener

CONCLUSION

Average insertion forces and removal forces were compared between the different angled fasteners. For the B fastener, it was found that the insertion force was less than the removal force in non-treated samples and significantly less in epoxy-treated samples. Additionally, it was found that the insertion force and removal force had a weaker correlation between the A fasteners than in the B fasteners. This can be attributed to the negative Poisson's ratio to be greater in the B fastener than the A fastener. As a result it was harder to remove the B fastener. The best or minimum Insertion/Removal force ratio is about 18%. Other testing observations include that the fasteners can be removed by twisting them in the correct manner.

A learning module that share some of the basic concepts used for the research experience has been designed. The module targets students in Algebra I class and is based on the Legacy Cycle methodology. It will be implemented in the spring 2012 in a high school with majority Hispanic students.

FUTURE WORK

Future work for auxetic fasteners should center on designing more efficient testing methods for removal forces, printing different angle sets of braids, additional testing for insertion and removal forces, patent of design, continuation of undulated braid design to include more contact at intersecting points. Other 3D printing methods should be considered as well for differentiation of physical properties and limitations. Results from the implementation of the legacy cycle will be compiled and shared in teacher conferences.

ACKNOWLEDGEMENTS

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