ABSTRACT

Title of thesis: IN-SITU CONFORMAL 3D PRINTING FOR TARGETED REPAIRS

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Additive manufacturing enables the construction of near-arbitrary structures with the help of computational tool-path planning and print material properties. We explore an application of the technology to targeted repairs, such as mending holes or cracks, on 3D printed parts by using conformal tool-pathing, combining the precision of additive manufacturing with the strength and homogeneity of material adhesion. Repair configurations varying in shape, size, material, infill and loading type are tested in 3-point bending for structural strength and strain. We provide and summarize the collected data in addition to a structural analysis and optimization of parameters relevant to reparative 3D printing.

Team PRINT Thesis

by

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We pledge on our honor that we have not given or received any unauthorized assistance on this assignment.

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Chapter 1: Introduction

- *Additive manufacturing increasingly used in many industries*
    - *Examples: Rocket engine, airplane wings, rover wheels, ...*
- *Printed parts get damaged over time*
    - *Get examples of damage with numbers and pictures*
- *Being able to reprint only in damaged areas clearly saves tremendous time and material compared to reprinting a brand new part*

If the damage to a structure or component is severe enough that leaving the damaged component as is is not an option, the typical solution is to simply replace it with a brand new part. Since the types of damages we are investigating are concentrated on only small sections of the overall structure, it would be far more advantageous if targeted repairs, in which the damaged area is filled in with material, could be applied directly to the damaged parts. Such repairs would clearly be more desirable with more costly or difficult to manufacture parts. In additive manufacturing, printing times and material costs are often the limiting factors; a targeted repair to a damaged part would consume a fraction of the material needed to reprint the part, as well as take up a fraction of the time. (Our demonstrated repairs typically accounted for ___% of the overall mass of the structure and took around 15 minutes to print compared to ~3-3.5 hours for the full undamaged part. See Ch. 3 Methodology for more information.)

- *Problem: we don't know whether the strength of such a repair is adequate in comparison to the strength of the original structure (aka is repairing worth it?)*

There are several questions that need answering before we can say for certain that repairing damaged components is worthwhile: How effective are such repairs in comparison to the strength of the original part? How much improvement do we get from the repair in comparison to the damaged part? Secondary questions branch off of these such as: How can the strength to cost of the repair be maximized? Can we apply our findings to more generalized additive manufacturing processes?

- *We investigate strength vs strain, strength to weight ratios, printing times and material amounts to evaluate:*
  - *whether such repairs are adequately strong in comparison to original structure*
  - *what is the best method of printing to maximize performance/cost*

To answer these questions, we will use the parameters of strength vs strain, strength to weight ratios, printing times, and material costs to quantitatively evaluate the quality of our proposed repair method. By thoroughly collecting and analyzing data, we will be able to give unambiguous answers to the above questions and identify new questions that we believe would be worth investigating in the future.

- *Roadmap for the rest of the thesis*

  The following chapter will delve deeply into the background of the problem and provide context for our proposed solution. After that, a discussion of the methodology used will provide full detail of our experimentation, data collection, and data analysis methods as well as the motivation behind them. Following the methodology, we will present and discuss our results, and in doing so, we will answer the questions we have identified as being relevant to determining whether our proposed repair method is “effective.” Finally, we will end with a discussion of what future research we recommend be done in order to build off of our work and progress further towards an implementable solution.

Chapter 2: Literature Review

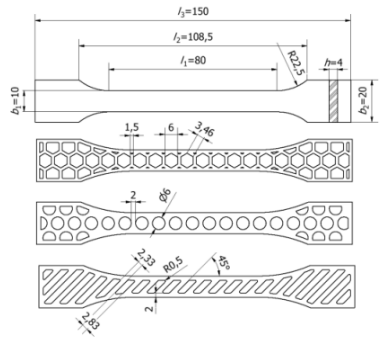
- What structures will commonly wear down (specifically 3d printed ones)
  - When is repair appropriate or desired
  - What shapes of voids occur
- A review of materials susceptible to our reparative method
  - Look at qualities like cohesion, temperatures, etc.
- A review of common structural analysis methods
- Current related work
  - Case studies
  - What did they do/not do?
  - Where to improve

Sections:

1. Case Studies
2. Materials
3. Structural Analysis
   a. Bend Testing
   b. Other methods that we don’t do because of *x,y,z* reason(s)
   c. Data Analysis
4. Related Work
5. Applications
   a. 3D Printed Materials on ISS
   b. Commonly worn 3D printed motor shafts, etc

Source 1 -- Influence of structure on mechanical properties of 3D printed objects

- Researchers used a model Z310 3D printer.
- Tested 3 different types of hollowed-out structure
    - Honeycomb
    - Drills (circles)
    - Stripes (slanted rectangles)



- Tensile strength is calculated by taking the breaking force and dividing it by the minimum cross-sectional area.
- Honeycomb structure exhibited the highest strength

Source 2 -- Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures (mostly all for tensile testing)

- Varied conditions such as infill pattern, infill density, and infill speed.
- Tensile, bending, and compression testing were used for an in-depth analysis
- RESULTS
    - Young's modulus increased as infill density increased
    - PLA parts with 100% infill density had the highest Young's modulus of 1538.05 MPa
    - 90mm/s infill speed showed the highest Young's modulus for PLA
    - The optimal temperature for PLA is 215 degrees Celsius
    - **Bottom Line**: 100% infill density, 90mm/s infill speed, 215 Celsius nozzle temperature, and linear infill pattern were most effective for maximizing the strength of parts.
- Scanning electron microscopy (SEM) revealed that the strength of the samples was dependent on the arrangement of their layers
    - This would lead us to believe that it is worthwhile to pursue the optimal infill pattern for 3D printed repairs
- Advantages of 3D printing -- could use for introduction/applications
    - Complex geometries as a single unit
    - Lower material and labor cost
    - Manufacturing advantages (CAD model -> print -> install)

- Material saved will only matter for mass production. PLA/ABS is very cheap, so would we be worried about a little extra material in exchange for greater strength? *Brainstorm applications with this*
- Increases in printing speed should be paired with increases in nozzle temperature
- Higher temperature = increased strength, but up to a certain point. If the temperature gets too high, it can lead to poor layer bonding, which can actually be detrimental to the printed parts' overall mechanical strength. Therefore, it is important to note that the change in one parameter may have an effect on another parameter. For example, in our case, we are varying the infill pattern and infill density. If we vary the infill pattern, we may also alter the layer connections. This is something that we need to take into account
- Adding carbon fiber to ABS, so carbon-fiber-reinforced ABS filaments, significantly increased the tensile properties of the printed parts
- **Important:** magnitude of bending modulus of the five materials follows the same trend as the tensile modulus. Below is an image of the bending modulus of different materials

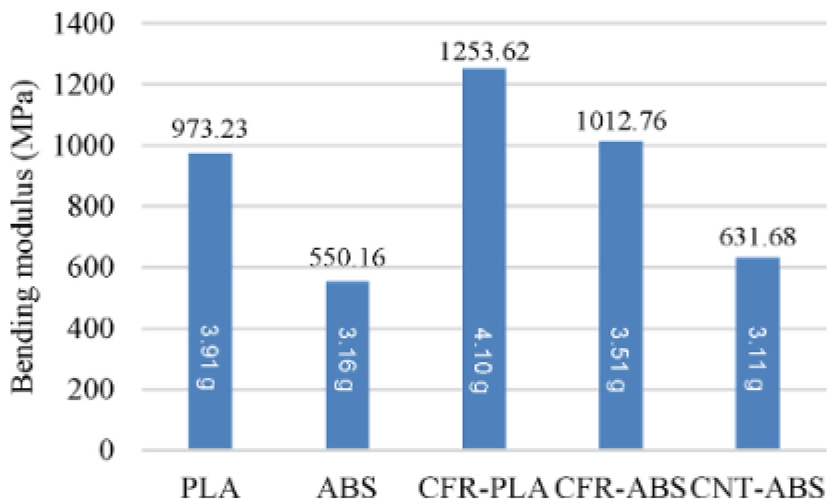


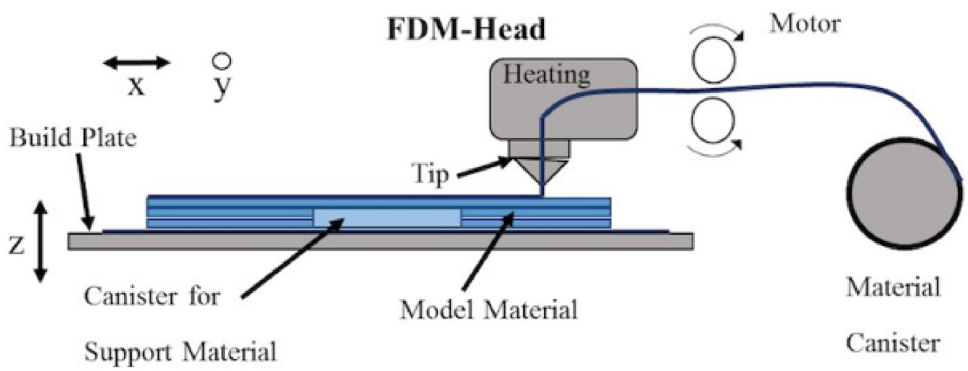
Fig. 14. Variation of the bending modulus of five test materials used in this study.

Challenges with 3D printing

- Knowledge gaps, lack of suitable materials, lack of expertise, part size limitations

Source 3-- Study of infill print design on production cost-time of 3D printed ABS parts

- The lowest infill density enabled cost savings, but mechanical properties decreased as infill density went down
  - Companies and real-world applications will have to do an independent analysis on this kind of thing
- Researchers analyzed various infill patterns combined with different mechanical properties (according to ASTM testing standards), and production cost-time



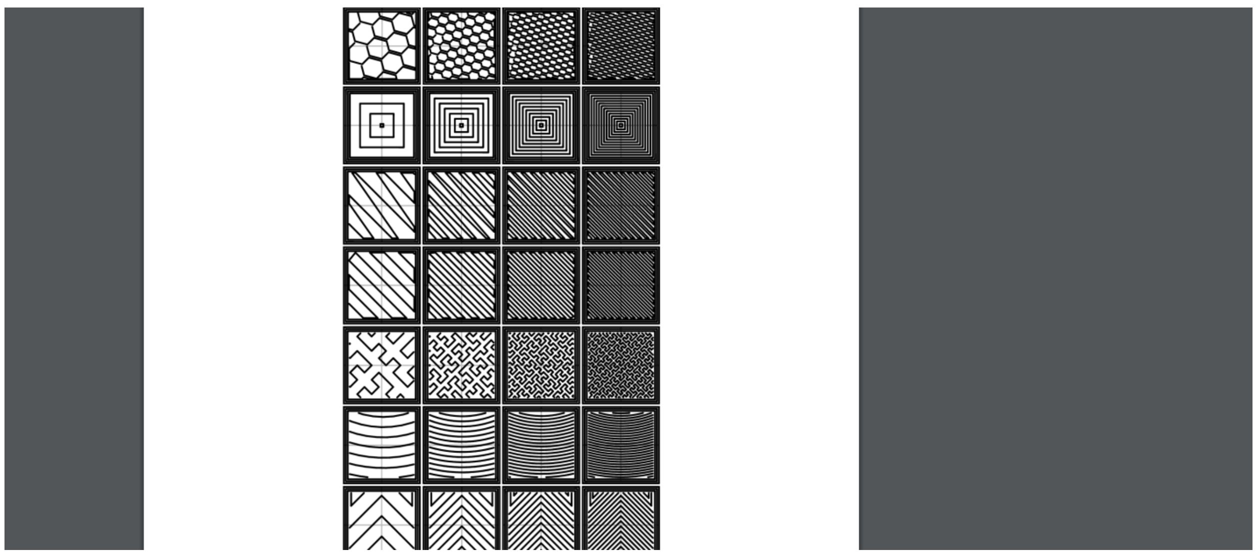
A good picture to describe the 3D printing process. Source, Bagsik and Schoppner (2011)

- Found that Honeycomb is really good
- The researchers found that for bending, low density had notable cost savings with a minimal loss in strength

- Time requirements are particularly important
  - How long does it take to print each sample?
  - When would this spec be important?
- Choosing an optimal infill pattern can benefit mechanical properties, material cost and production
- Different software can be used to generate tool-paths for different infill patterns; in this project, we are using Slic3r
- Specimens that they studied were based on ASTM standards
  - Ours are as well
- They tested compression, testing, and bending
  - We focused on bending
- They determined cost per sample
- Production cost is defined as print cost × print time
- Cost is calculated by finding the cost per minute of printing and then find
- The researchers tested a low density infill, high density infill, double dense infill, and solid infill
- Researchers found that higher reduction in cost means greater cost savings and higher reduction in mechanical strength
- Concluded that print cost had more of an impact on production cost than material cost (when using PLA)
- For bending applications, low density had good cost savings with minimal loss in strength
- Source suggests additional analysis on ‘custom’ infill patterns is required
  - Thats where we come in
- Good first step, but didn’t test specific infill patterns that we were interested in. We should do our own production-cost analysis to determine these specs for ourselves.

Source 4 -- Observing the Effects of Infill shapes on the tensile characteristics of 3D printed plastic parts

- Analyzed strength of four different infill patterns
  - Rectilinear, diamond, honeycomb/hexagonal, solid
- Samples had an infill density of 15%
- The hexagonal pattern gave the highest strength, and the solid pattern at 100% infill density had the weakest properties. The 100% solid behaved like a brittle material (Our data backs this up)
- Used ASTM standards



Is there a way we can make something like this for our team?

Chapter 3: Methodology

3.1 Background/Motivation

- Want to evaluate strength of repaired piece compared to original - common way to evaluate mechanical strength - stress vs strain
- 3-point bend tests are widely used for collecting stress vs strain of a structure
- Basic beam shape for test specimens chosen for simplicity and easier data analysis

3.2 Hypothesis(es)

- 1) A damaged 3D printed structure can be repaired by filling in (printing on) the damaged area, and the strength of the repaired structure will be not significantly different from the original undamaged structure
- 2) The repair method can be optimized for strength/time/(material)cost based on infill percentage/pattern
- 3) This method of repair is applicable to a variety of additive manufacturing processes (suggesting other materials or types of 3D printers can go in future work)

3.3 Testing Standards

- ASTM standards
  - 6 pieces for each test

3.4 Materials & Equipment

- Ender 3 printer
- Test specimens (lots of pictures)
  - Geometries, infill percentages, infill patterns, different materials
  - Wanted a variety of damage geometries so findings can be applied to a generalized damage area
  - Different infills were for determining the best method of repair
  - Different materials used to make sure findings aren't specific to PLA
- Test equipment
  - No lab equipment thanks to covid
  - Description of setup (lots of pictures)
    - Press, force sensor, strain gauge, arduino circuit/code

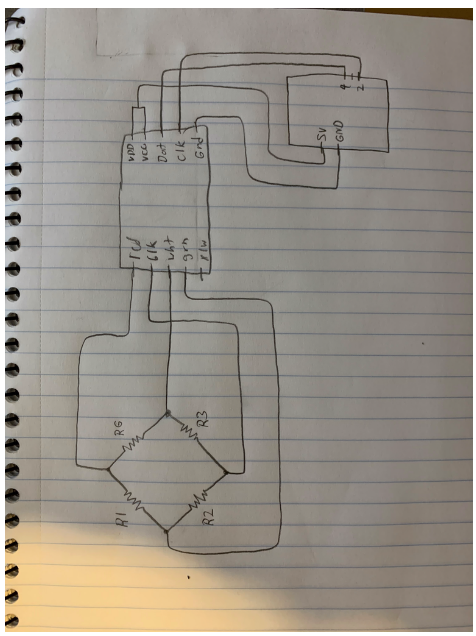
3.5 Experiment/Steps Taken

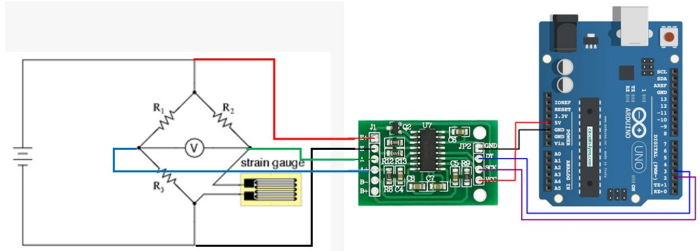
- Experimentation Design
  - The first tests completed were control pieces of 3D printed PLA pieces printed at 100% infill with full rectangular geometry. These pieces allowed the test procedure to be practiced while finding initial data that further testing could be compared too. Using the load cell~~force sensor~~, the force applied to part was measured in kilograms and used to calculate the ultimate strength of the part before failure. The strain of the part was measured in millistrains to ideally note strain at the point of failure. After the full rectangular geometry pieces were

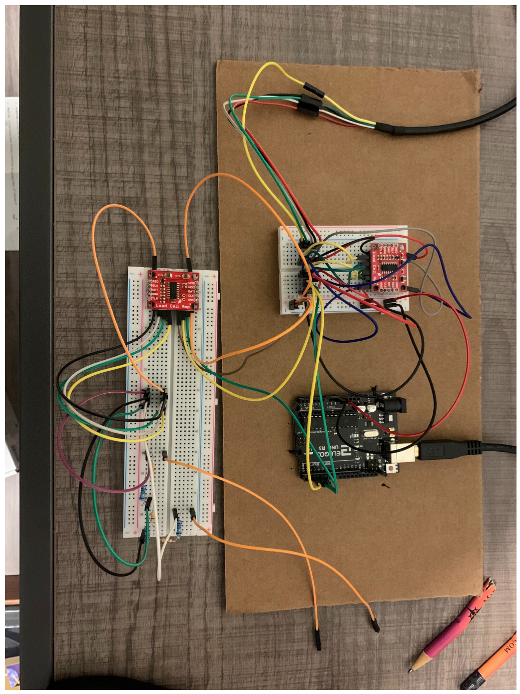
tested, damaged pieces with an empty void were tested to find the lower bound of the control.

- Control testing was followed by infill testing using the T1 damaged geometry. The infills used for repairs were 20, 40, 60, 80 and 100% while the damaged initial part was kept at 100% for all tests.
- After infill testing, the T4 damaged geometry was tested for control, repaired and damaged load.
- Damaged and repaired pieces could be tested with the void/repair either on top of the beam (compression) or on the bottom (tension). T1 damage geometry did not allow us to test these pieces with the void in compression (applied force would have been in the void and hence at an angle). T4 damaged pieces could be tested in compression because the void did not span the entire width of the piece. (pictures here would be helpful). Data for both tension and compression were collected for all other pieces
- Infill pattern was then tested with the damaged parts in the T1 geometry being kept at 100% infill and varying patterns and percentage of infills were used for repairs. This included rectilinear (which was previously used for all prior testing), aligned and hexagonal at 20, 40, and 80% infill.
- Finally, ABS was tested in T1 geometry

- Printing methods
    - Printer set to 200C on extruder 70C for bed for PLA
    - ABS: 200C extruder, 95C bed
    - Printer settings, etc…

    - Nozzle size: 0.4mm
    - https://github.com/UMDTeamPRINT/.Slic3r
  - Printing repairs
    - Print base piece, leave on bed and wait for it to cool down
- Test procedure
  - Attaching strain gauge
    - Glued to underside of test article
  - Soldering and connecting to Arduino
    - 

- 

- 

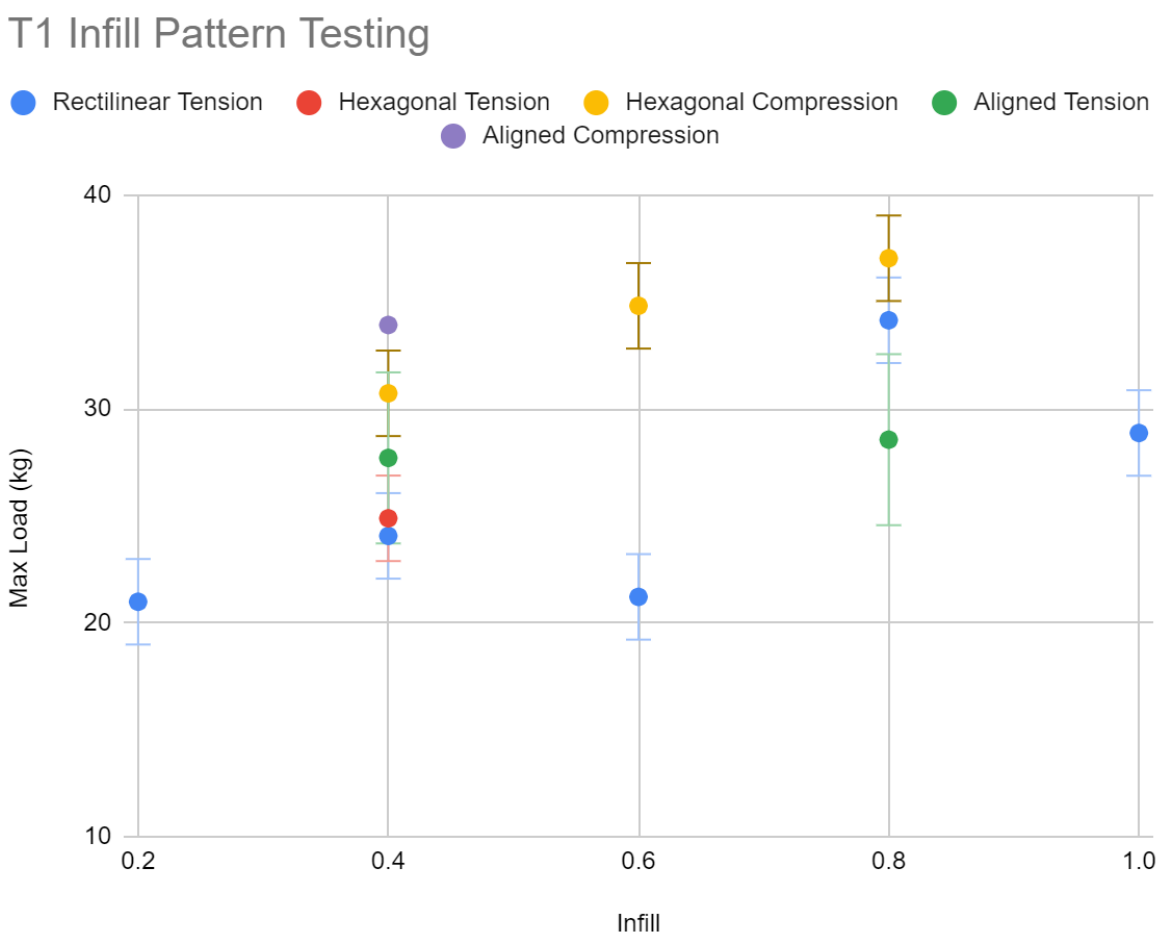
- Press rate
    - ASTM standards dictate 5% strain per second, however, with the hand-pump operated press, accurately controlling this speed is not feasible
    - Test takers used their best judgement to keep the press rate consistent
- Recording data
    - Arduino script outputs force sensor data in kg, strain gauge data in milistrain

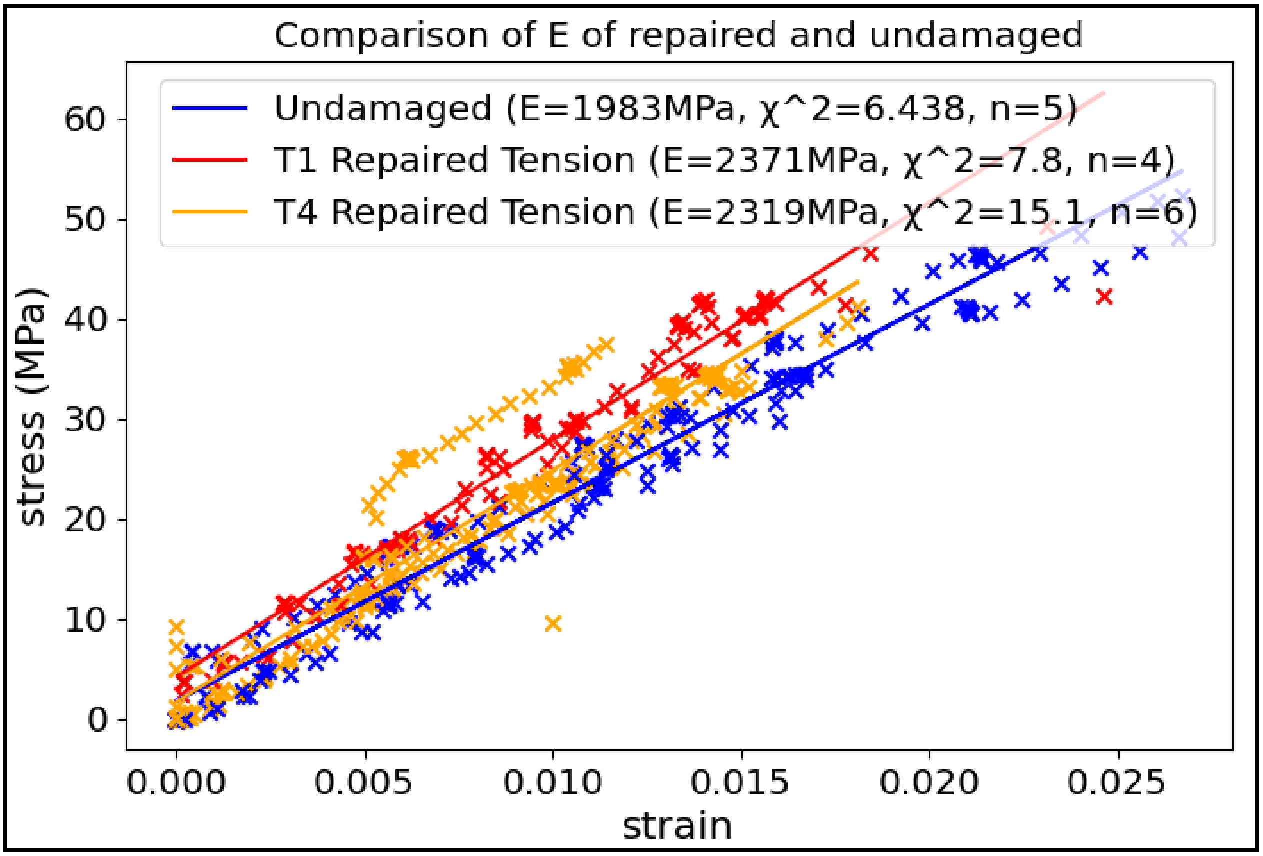
- Processing Script writes data to csv file on computer (3 columns: time, force, strain)

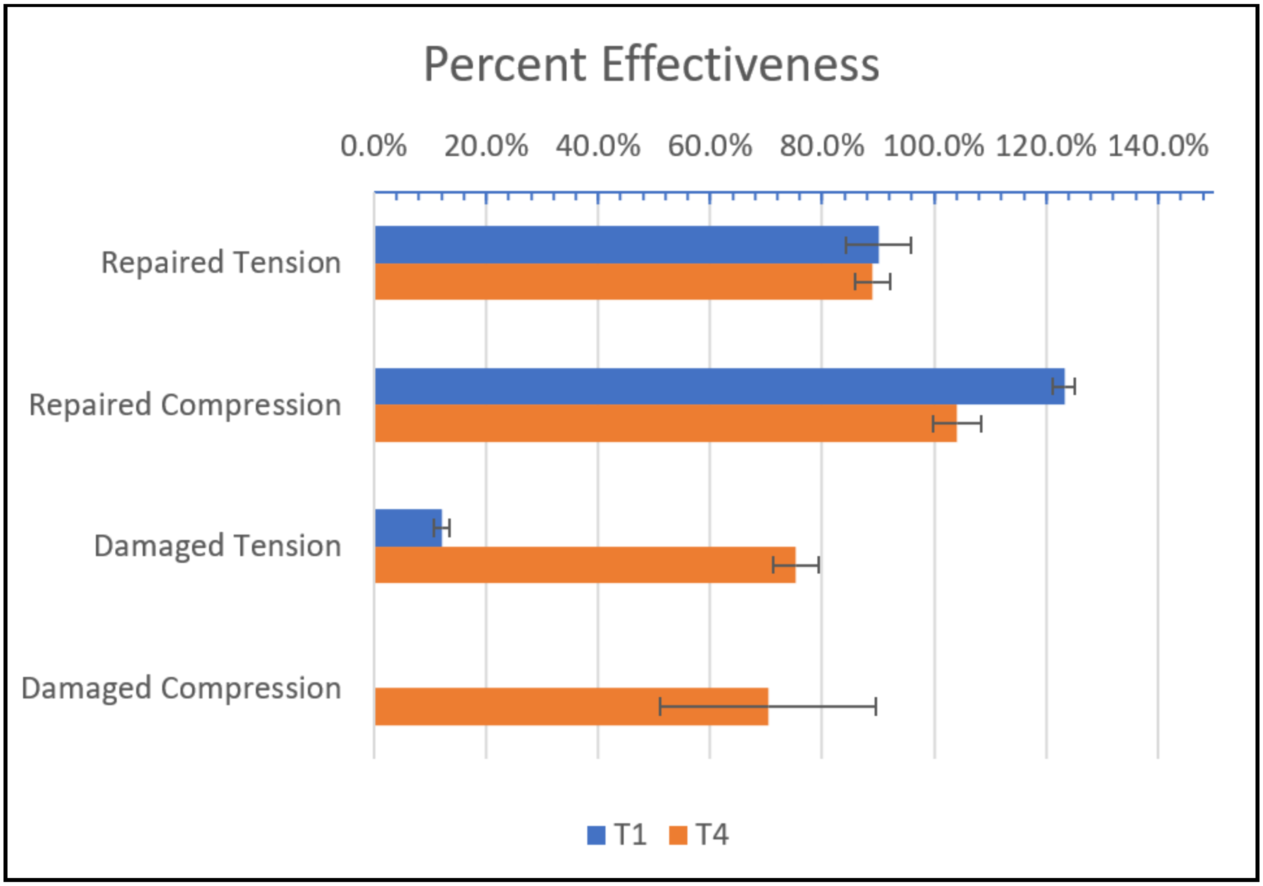
Chapter 4: Results

4.1 Overview

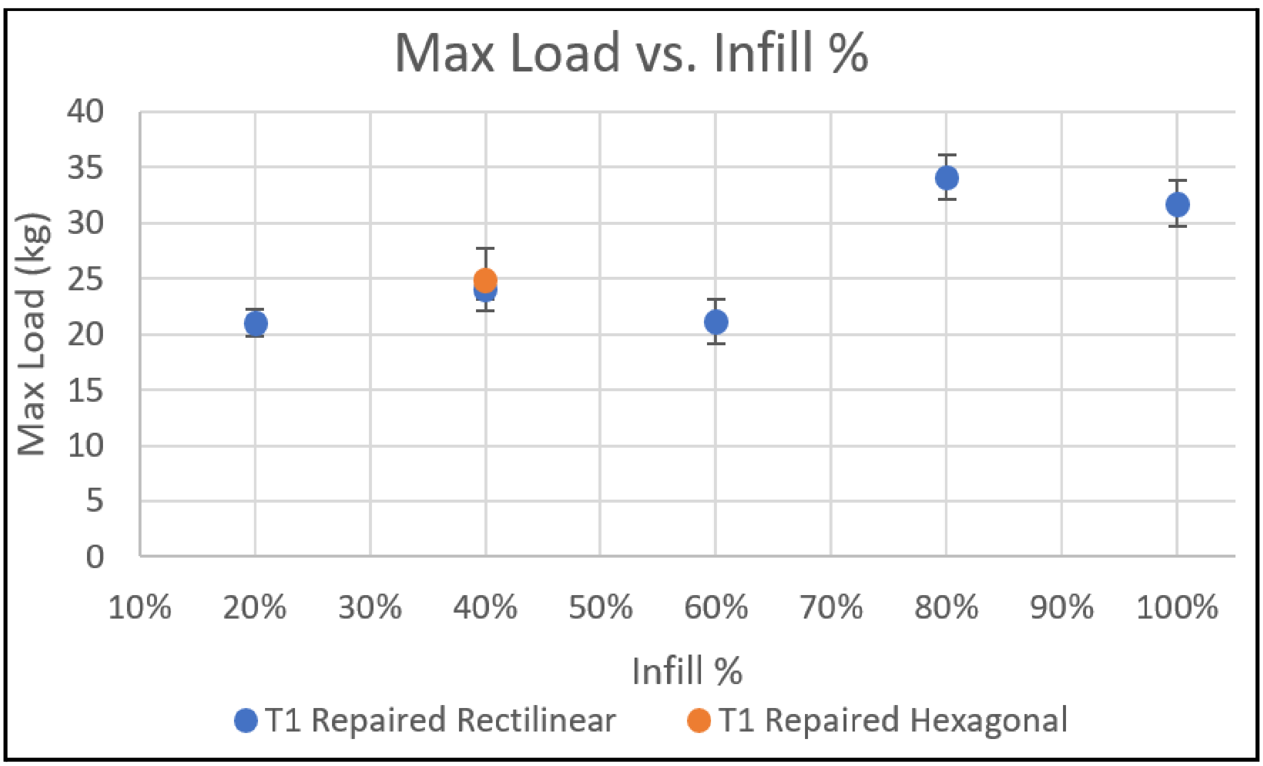
4.2 Collected Data




Comparison of E of repaired and undamaged
Undamaged (E=1983MPa, χ^2=6.438, n=5)
T1 Repaired Tension (E=2371MPa, χ^2=7.8, n=4)
T4 Repaired Tension (E=2319MPa, χ^2=15.1, n=6)
stress (MPa)
strain
0
10
20
30
40
50
60
0.000
0.005
0.010
0.015
0.020
0.025



Percent Effectiveness
0.0%
20.0%
40.0%
60.0%
80.0%
100.0%
120.0%
140.0%
Repaired Tension
Repaired Compression
Damaged Tension
Damaged Compression
T1
T4



Max Load vs. Infill %
Max Load (kg)
40
35
30
25
20
15
10
5
0
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Infill %
T1 Repaired Rectilinear
T1 Repaired Hexagonal

4.3 Data Analysis

4.3.1 Optimization

4.4 Structural Analysis

4.5 Discussion/Conclusion

Chapter 5: Future Work

5.1 Adaptive In-Situ Printing

5.2 Materials

5.3 Robotic Manipulation

5.4 Extreme Environment

Appendix

I. Timeline

II. Budget

III. Mentor Feedback

IV. Glossary

References