In Situ Conformal 3D Printing for Targeted Repairs

Rohith Chintala, Brendan Cutick, Tyler Han, Elizabeth Myers, Eric Oh, Aidan Sandman-Long, Cynthia Sheng, Nathan Spicer-Davis
Team PRINT
Mentor: Dr. Steven Mitchell

GEMSTONE
Honors College
University of Maryland

Abstract

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.

Research Question:

How effective is repairing 3D printed structures with conformal 3D printing?

Overview

Background:

- 3D printing is typically used in quickly prototyping parts but has recently garnered interest in more complex projects such as rocket engines, bone repair, and in-orbit manufacturing
- Large-scale engineering projects will require data on the limitations of 3D printing

Methodology:

- 3D printed parts are tested using the *3-point bend test*, which provides data on the structure's ultimate strength, failure method, and deformation under load
- Provided a 3D printed object and full information about a region of damage (such as a cavity), a surface-conforming print fills and repairs the damage while meeting repair shape and infill constraints

Results:

- By subjecting repaired parts to the 3-point bend test, our data suggests **significant improvements in structural strength**
- **Repaired structures in compression exceed structural strength of original, undamaged structure**

Example Test Samples

An Ender 3 Pro 3D Printer is used to print simulated damaged samples. We chose to investigate triangular cutouts (T1) and hemispherical cutouts (T4).

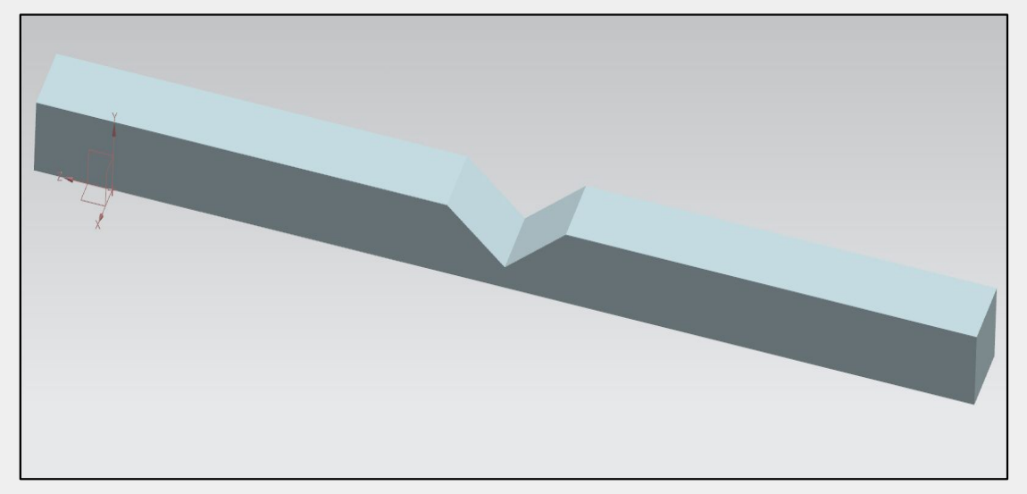


Figure 1. T1 CAD model

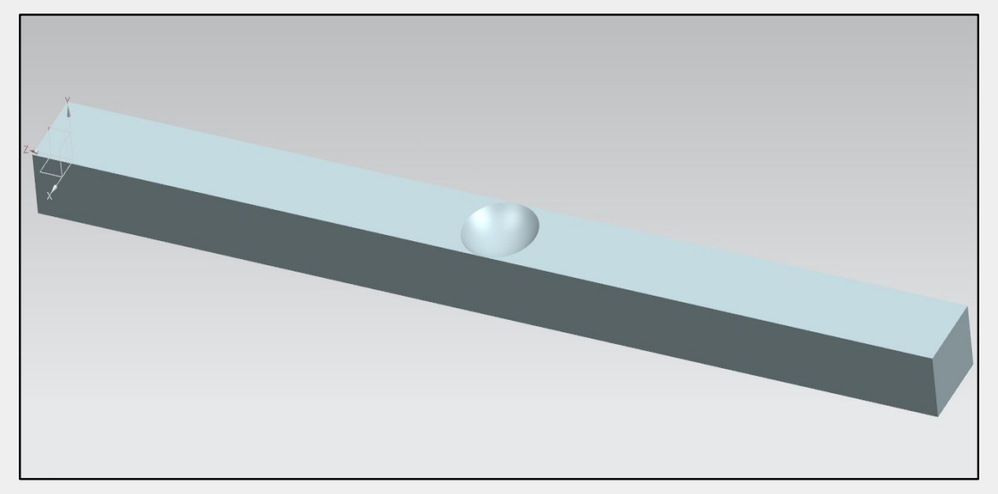


Figure 2. T4 CAD model

Once the damaged piece is printed and cooled, the Ender 3 Pro runs a separate repair print that varies in infill pattern and infill percentage. Below is an example of a T1 sample before and after a repair.

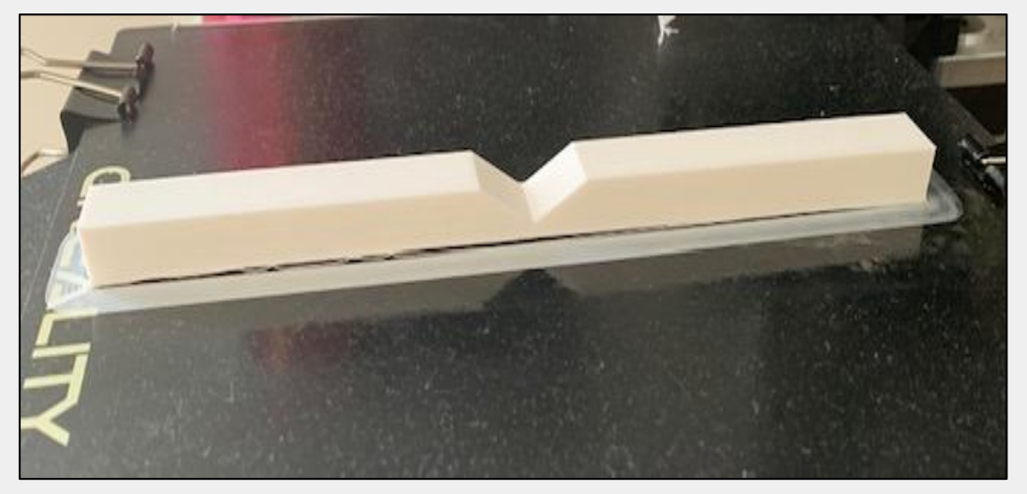


Figure 3. T1 pre-repair

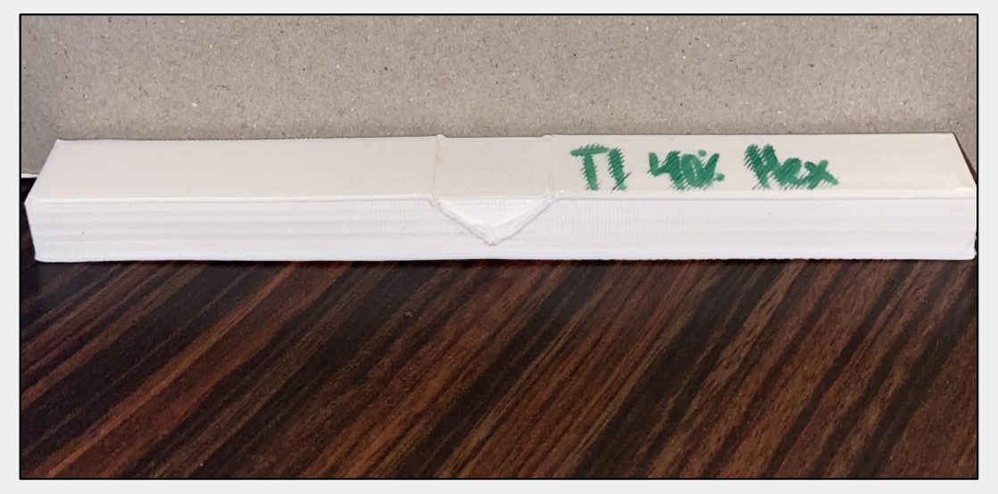


Figure 4. T1 post-repair

Methodology

The following properties were chosen for experimentation of the repaired samples:

- **Percentage Infill:** relative density of the internal structure (100% = solid)
- **Tension vs. Compression:** loading configurations where the repair was in tension (bottom of sample) or in compression (top of sample)
- **Infill Pattern:** geometric pattern of interior supportive structure (hexagonal or rectilinear)

The controls for these experiments are whole-printed, 100% infill samples, which function to simulate undamaged 3D printed parts. The number of samples tested abide by the ASTM standard.

Details of these experiments can be summarized by the following tables:

Infill Testing	
Infill of repair	T1 Geometry
20%	6 parts
40%	6 parts
60%	6 parts
80%	6 parts
100%	6 parts

Control	
Undamaged	Damaged
6 parts printed at 100% with no damage or repairs	6 parts printed with T1 damage
	12 parts printed with T4 damage (6 compression, 6 tension)

Infill Pattern	
Hexagonal	Concentric
12 T1 parts printed at 40% infill (6 compression, 6 tension)	12 T1 parts printed at 40% infill (6 compression, 6 tension)
12 T1 parts printed at 60% infil (6 compression, 6 tension)	12T1 parts printed at 60% infill (6 compression, 6 tension)
12T1 parts printed at 80% infill (6 compression, 6 tension)	12 T1 parts printed at 80% infill (6 compression, 6 tension)

Tension Vs. Compression	
T1	T4
6 parts printed with conformal repairs facing down at 100% infill (Tension)	6 parts printed with conformal repairs facing down at 100% infill (Tension)
6 parts printed with conformal repairs facing up at 100% infill (Compression)	6 parts printed with conformal repairs facing up at 100% infill (Compression)

Without access to a testing facility, a 3-point bend test apparatus was instead designed and assembled using a hand-operated hydraulic jack, steel shafts for support and point loading, and a force sensor and strain gauges for taking measurements.

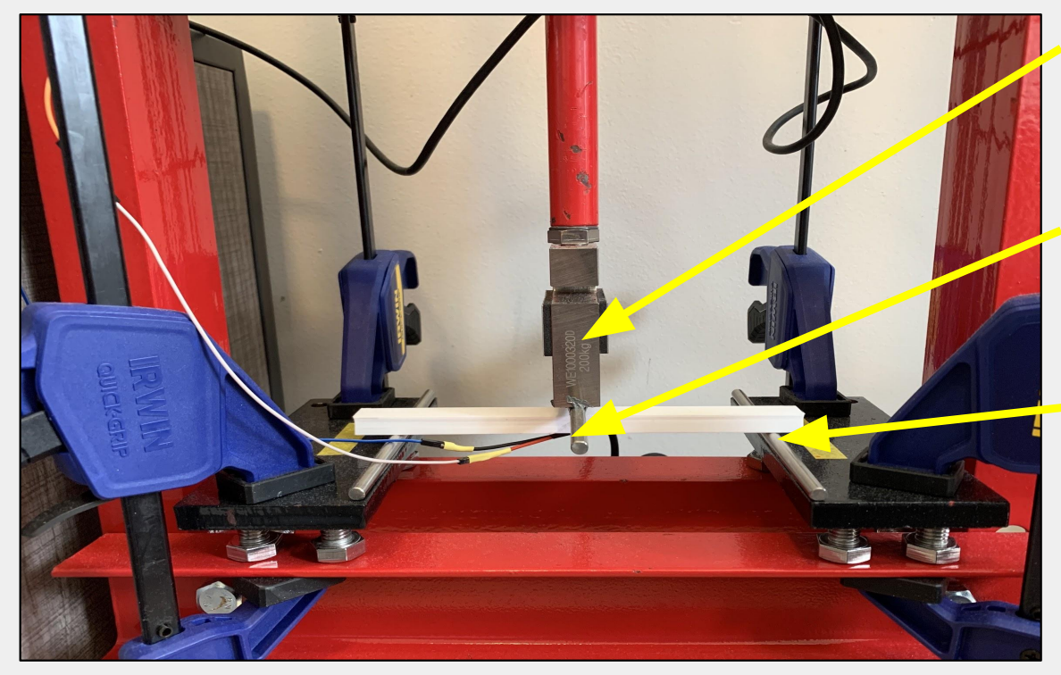


Figure 5. 3-point bend test setup

- Force sensor mounted on press measures applied load
- Strain gauge attached to bottom side at loading point
- Rounded D-shafts at supports and loading point ensure loads on beam are applied at single points

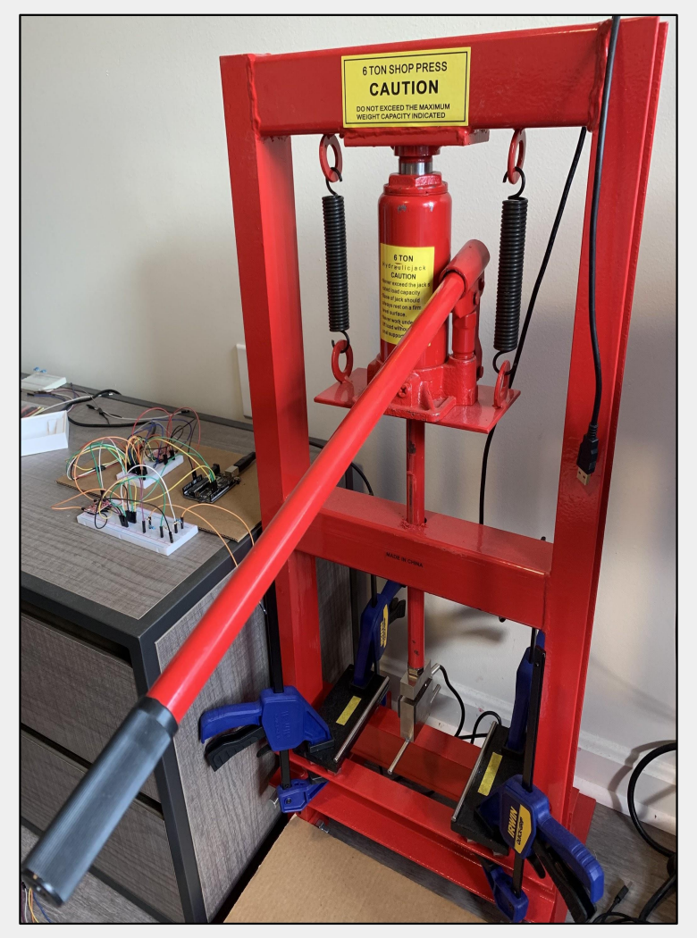


Figure 6. Full apparatus

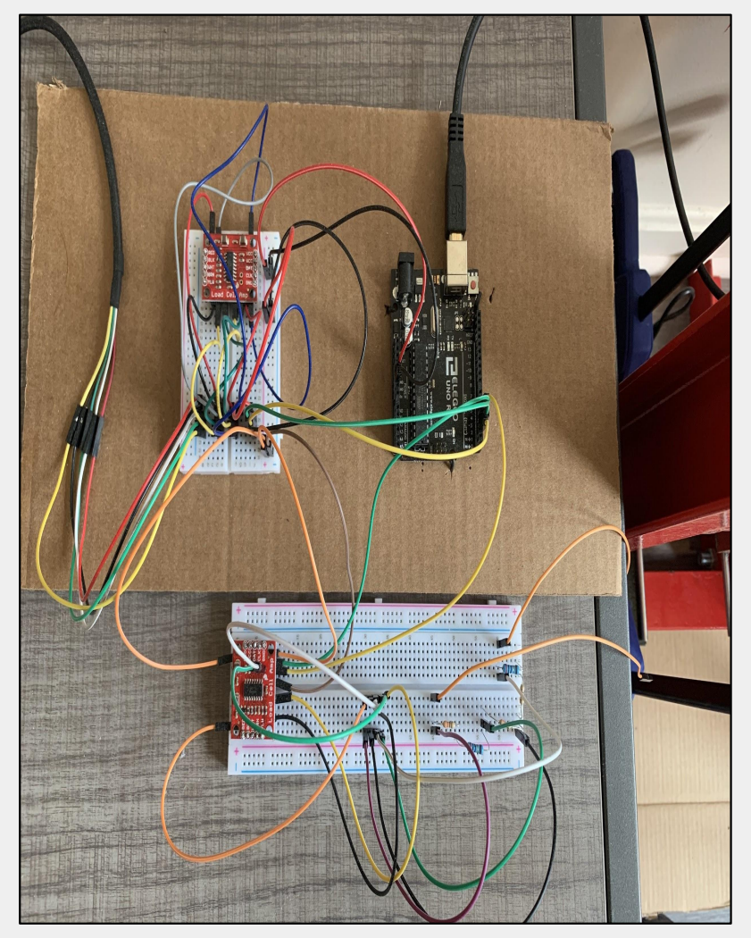


Figure 7. Full Arduino circuit

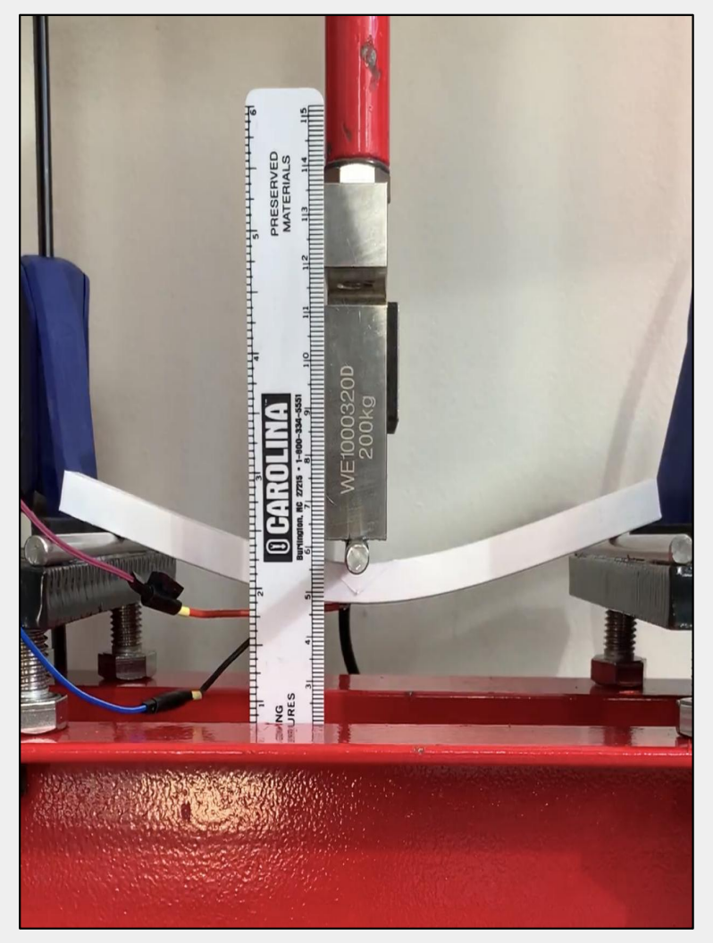


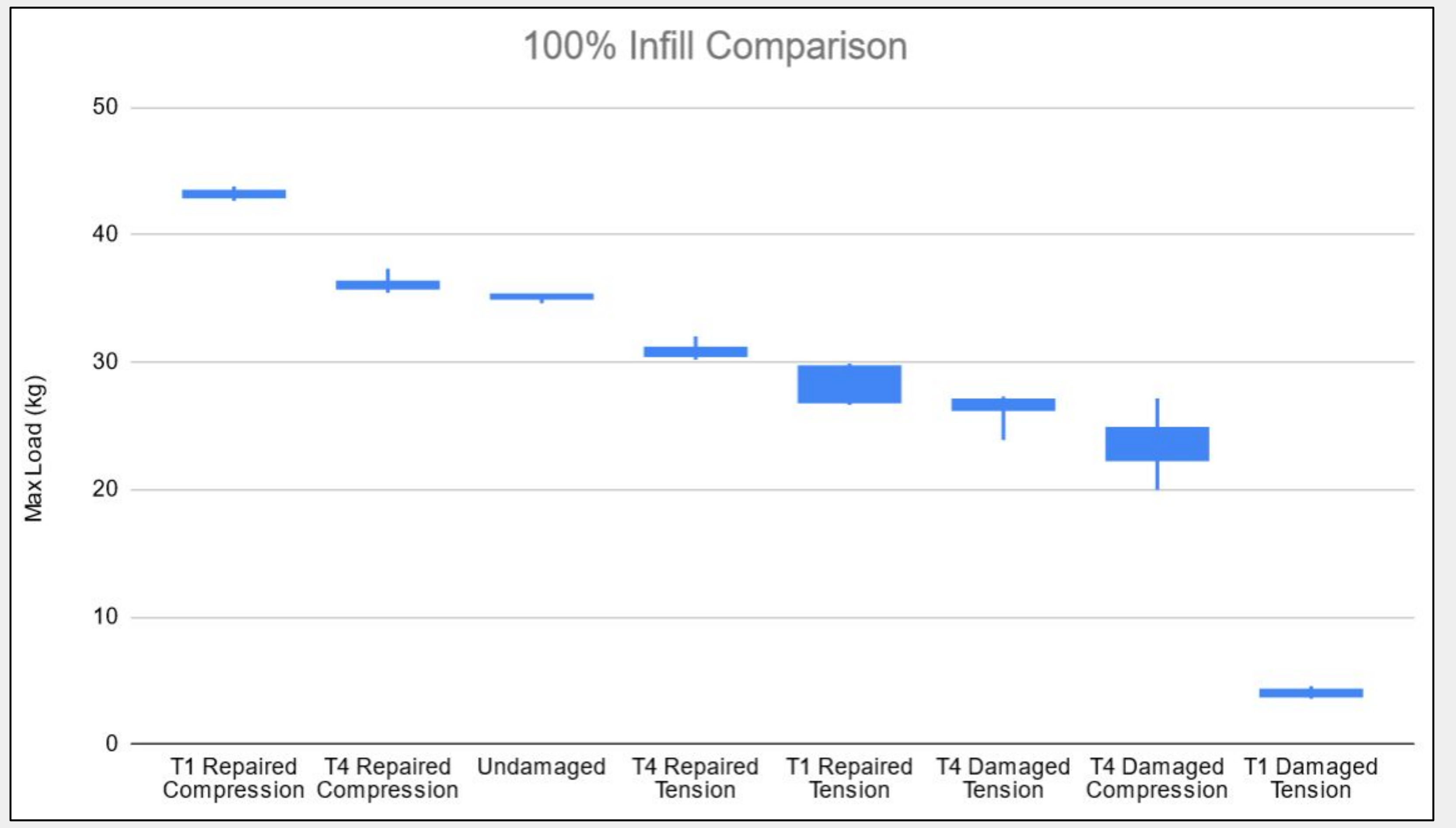
Figure 8. Repaired piece in compression

A test is conducted in the following manner:

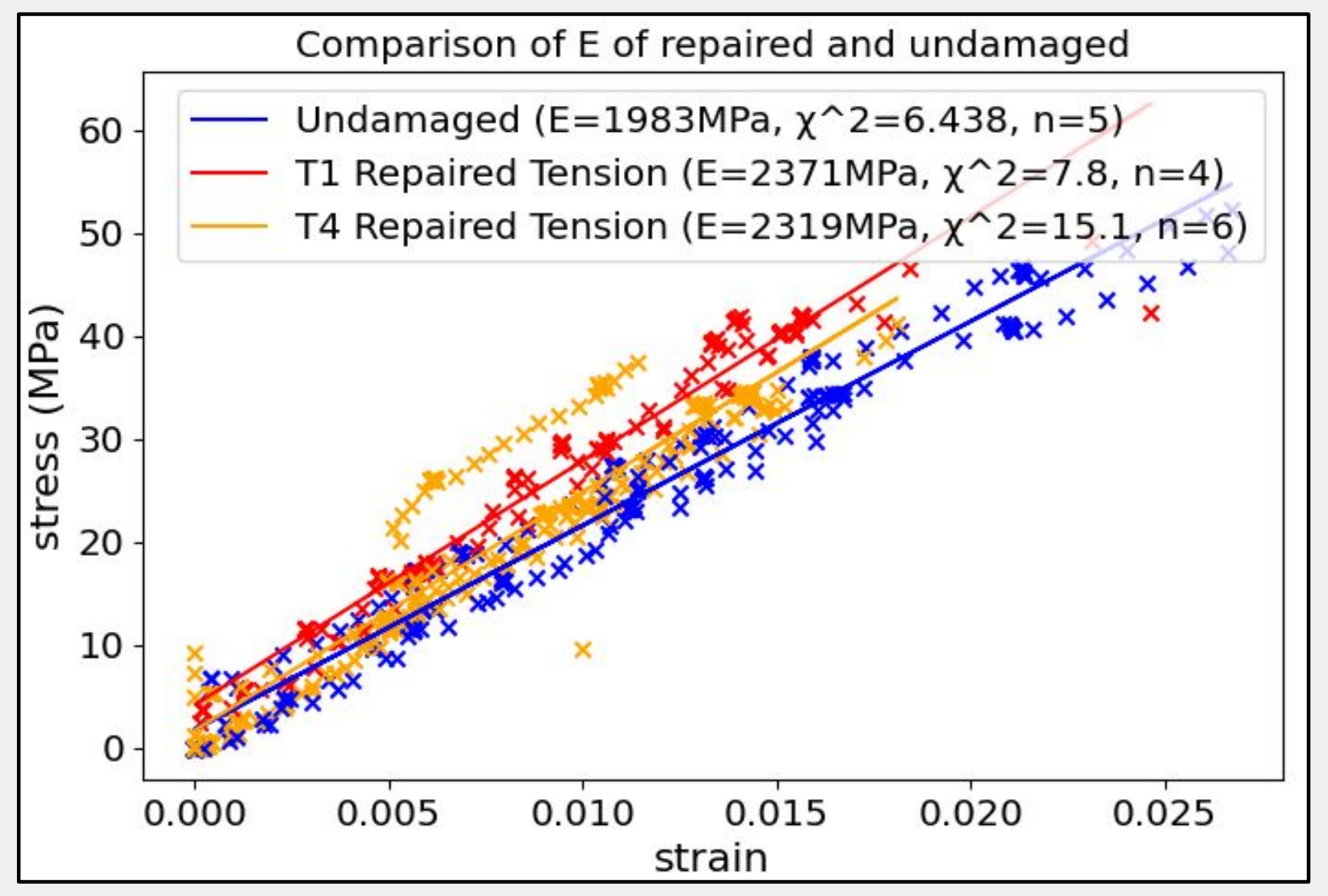
1. Pump the hand lever to increase the applied load with each downstroke until failure (snapping, cracking, extreme stretching)
2. An Arduino circuit reads in data from the force sensor and strain gauge, providing the necessary information to determine the failure load and stress/strain curve

Results

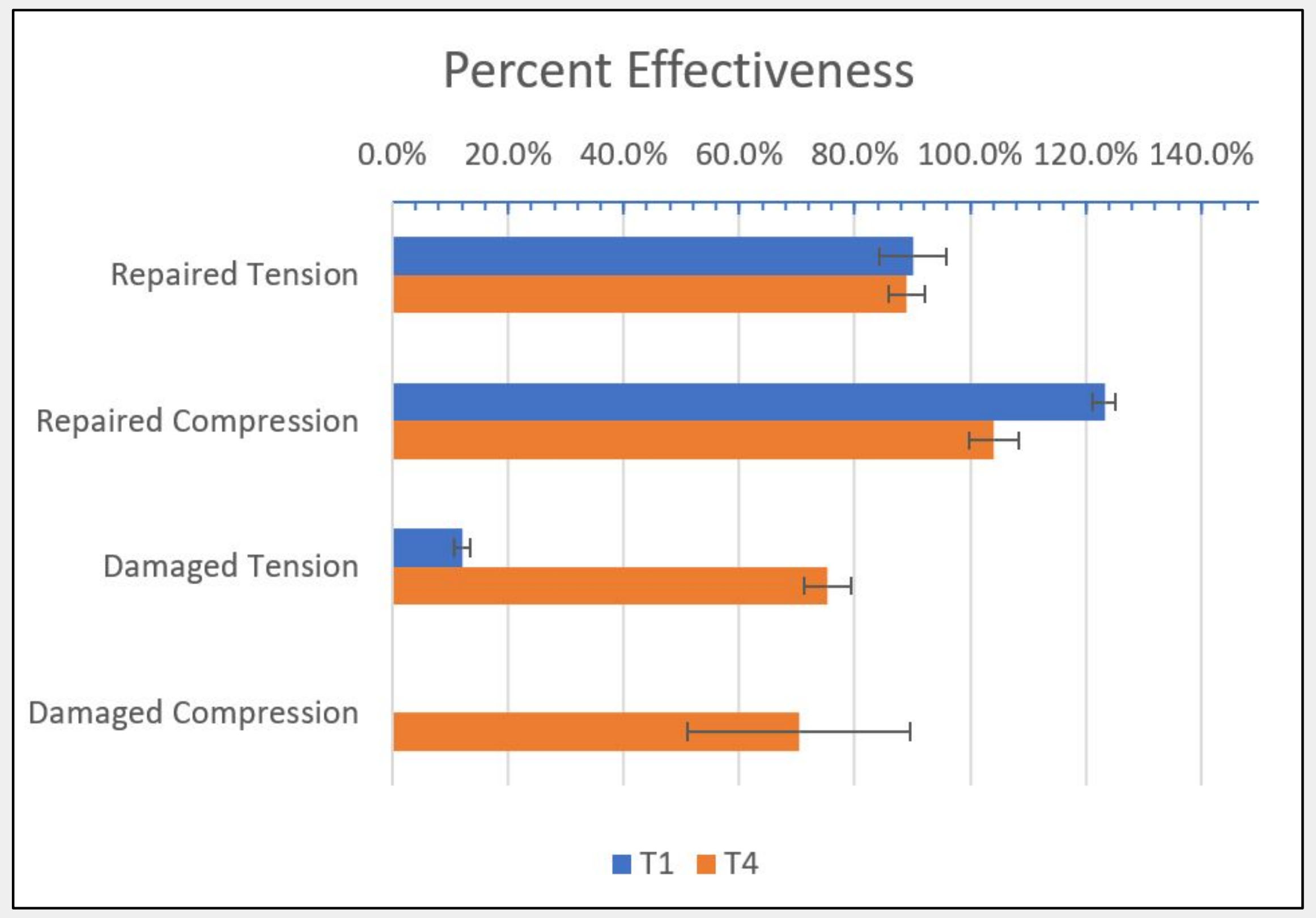
Shown to the right is a box plot summarizing the tests conducted thus far, depicting the distribution of maximum load before failure. From this we can see the effectiveness of the repair.



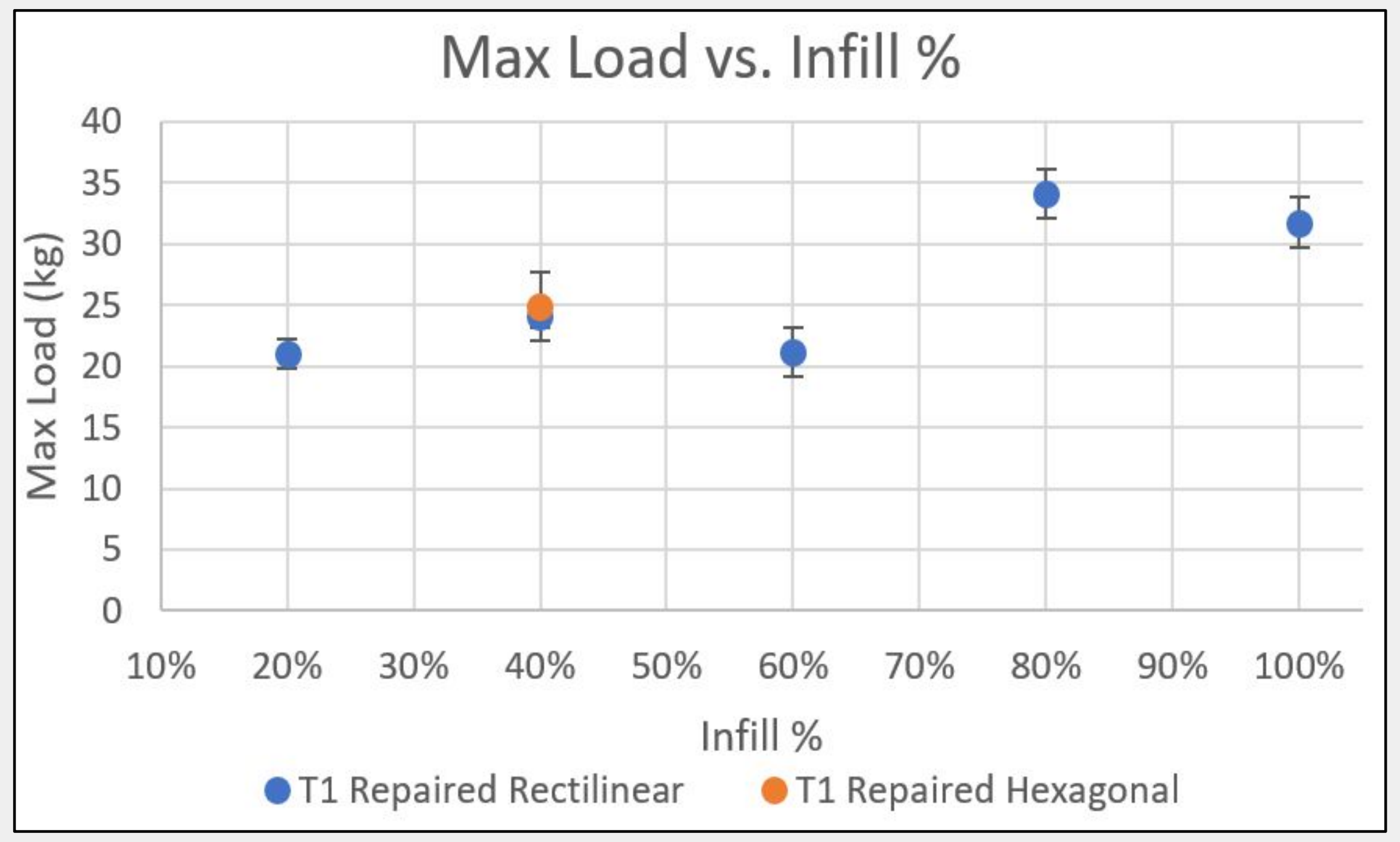
Strain (elongation) data is also collected for the repaired and undamaged specimens to see changes in Young's modulus:



An effectiveness rating better compares the load held by repaired vs. undamaged specimen. Percent effectiveness is defined as the load held normalized by the load held by the average undamaged specimen.



Below is a summary of the current data collected from tests while varying infill % and infill pattern:



Acknowledgements and Citations

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Discussion

Conclusion:

- **Testing demonstrates that repair to the structure results in a statistically significant improvement in the maximum load** as demonstrated in either the T1 tension repaired and T4 tension repaired with rectilinear infill using a two-tailed t-test (T1 repaired vs. Undamaged: $t(5)=6.2$, $p=0.0016$), T4 repaired vs. Undamaged: $t(9)=6.2$, $p<0.001$).
- More work is needed to in order to understand how adjusting other parameters, such as 3D printer settings, can affect performance.
- Testing data corroborates the result observed in literature that optimal infill % for maximum load is *not 100%* but instead ~80%

An unexpected result is that **repairs perform better than undamaged specimen when experiencing compressive loading** ($t(8)=17.2$, $p<0.001$). It is possible that this is a phenomenon similar to why 80% infill is stronger than 100% infill: the space created in lowering infill % allows the internal geometry of the 3D print to maintain its structural integrity as opposed to a solid print which would be compromised almost immediately.

Future Work

Goals planned:

- T1 design testing while different infills pattern, allowing an analysis of which infill pattern may be more effective than others
- Testing various damage types in order to improve repair methods in addition
- Testing new materials such as ABS and Carbon Fiber PLA
- Multivariate data analysis for optimization of printing, structural, and material parameters
- Physical analysis supporting why repaired structures in compression perform better than their undamaged counterpart
- Study of parameters vital in obtaining information about damaged regions (assumed given in this work)

In general, reparative printing has many applications. Provided that these printing methods have well-studied limitations, automated reparative printing is a promising material-efficient alternative to whole replacement and/or manual repair.

While this project limits testing to primarily plastics, it is equally possible to additively manufacture other materials like metal or biological tissue, from which general reparative printing can benefit greatly.