Abstract

We here at Skunk Works have been hard at work trying to figure out the limitations of our 3d printer, and we have put together some data for everyone.

Through destructive testing of 3D printed test coupons, we have come up with a rough idea of the maximum and minimum operating condition for 3d printed parts. We used a Stratasys Fortus 250mc printer to print these coupons, and tested for both compressive and tensile strength.

Our maximum compressive strength with our medium test coupon survived 3,600 pounds. On our least dense compressive test, the coupon survived 1,800 pounds.

In tensile testing, our most dense test coupon survived 340 pounds. Our least dense test coupon survived 120 pounds.

Probably the most useful discovery was that the print orientation matters. The greatest difference being as much as 2,000 pounds between medium density coupons printed in different orientations.

The attached report contains our lab setup and specific results.

Hypothesis:

Based upon rough calculations (See Appendix A) for the compressive and tensile strengths of traditionally manufactured 100% dense ABS test coupons we expected the 3D printed compressive coupon to fail before 9400 lb. and the tensile coupon to fail before 100 lb.

Test setup:

Materials:

1 arbor press
1 aluminum square bar, roughly 3 ft. long to extend the lever arm of the Arbor Press
1 bucket, used to contain weighted items
1 fishing scale, for measuring weight of bucket
1 bathroom scale for calibration of the arbor press's mechanical advantage
9 test coupons
Assorted items to place in the bucket in order to apply weight to the arbor press arm

Calibration:

As it is difficult to generate 9400 lbs of force directly, we used an arbor press to provide a mechanical advantage that could take an easier to generate force and increase it to the levels we predicted were required. In order to use an arbor press as a force source, we needed to

determine its mechanical advantage. In other words, we needed to determine what force applied to the level arm resulted in what force from the arbor press.

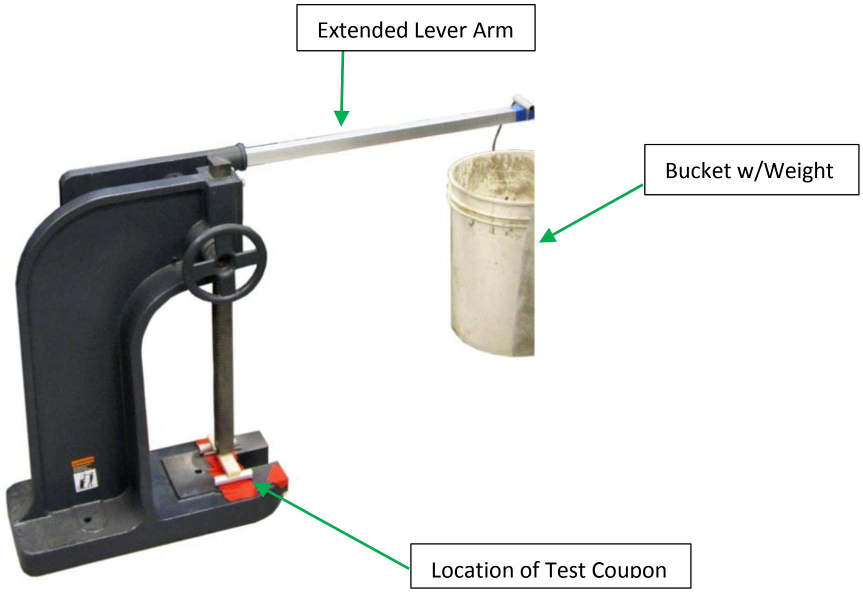


Figure 1: Test Setup

Step 1: We marked a position on the lever arm to hang a bucket. This was to ensure we got the same mechanical advantage out of the arm each time.

Step 2: We noted the weight of the bucket and items using the fishing scale.

Step 3: We noted what force resulted from this applied weight using the bathroom scale set under the press.

Step 4: We repeated Steps 2 & 3 for four more different bucket weights for a total of 5 points See Appendix B for the specific data

Using these data points we determined that the arbor press with extended lever arm had a mechanical advantage of 42.3 times the applied force.

Test Coupons

All test coupons were printed using a Stratasys Fortus 250mc with Ivory ABS-P430 Model filament material. Three different densities were printed for each test coupon used. The three densities were:

Sparse – Low Density (Lowest Density)

Sparse – Double Dense (Medium Density)

Solid – Normal (Highest Density)

The compression test coupons were 1in x 1in x 5in and printed in two orientations for a total of six coupons One orientation was where the coupons were printed on their 1in x 1in end, so that the layers were perpendicular to the force applied by the arbor press head (as seen in Figure 2). The other orientation was caused by the coupons being printed on their 1in x 5 in side such that the layers ran parallel to the force applied by the arbor press head (as seen in Figure 3).

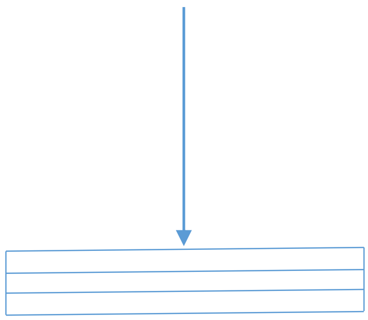


Figure 2: Perpendicular Application of Force

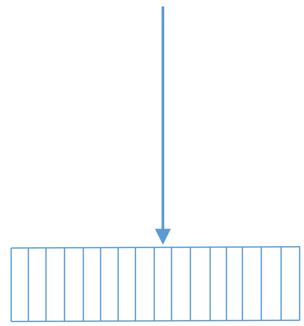


Figure 3: Parallel Application of Force

The tensile test coupons were 1in x 0.5in x 6in and were only printed on their 1in x 6in side and in three different densities for a total of three coupons. Their layers ran perpendicular to the arbor press head like in Figure 2.

Compression

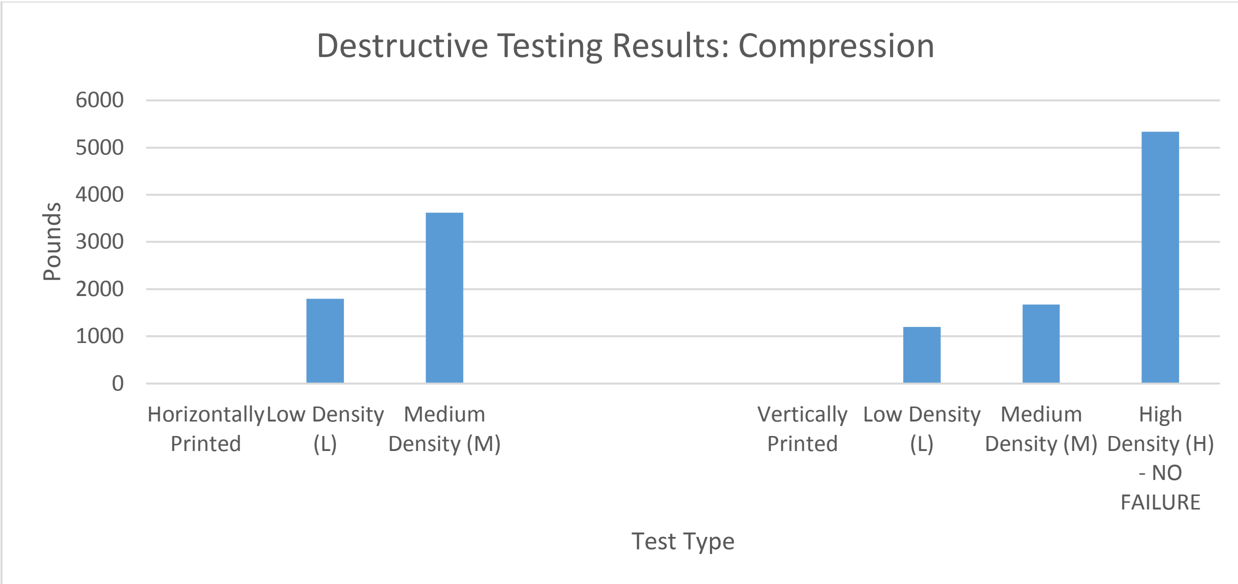
The same setup was used for the compression tests as for calibration (see Figure 1).

Step 1: A test coupon was placed on its 1in x 1inx side beneath the ram of the arbor press.

Step 2: The bucket was loaded until the coupon showed signs of failure. Failure consisted of visible cracks, permanent distortion visible by discoloration, or catastrophic breaking.

Step 3: The bucket was removed and the weight measured with the fish scale.

At total of six compression tests were performed.



See Appendix C for exact results and images of each test coupon after failure.

Tensile

For tensile testing the same setup for calibration was used with a minor adjustment. In order to approximate the three single points of applied force required for bending, three metal rods were used as seen in Figure 4. The test coupons were placed sideways on two rods roughly 5 inches apart with a third rod placed on the exact centerline of the coupon. We did this because the force required to break the test coupon changes depending on the distance between where the force is being applied and where the print is being supported.

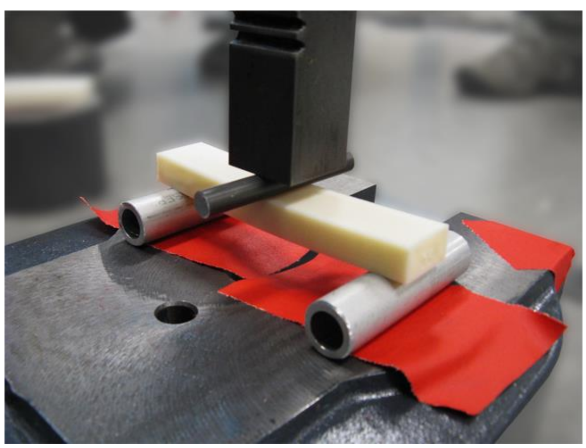
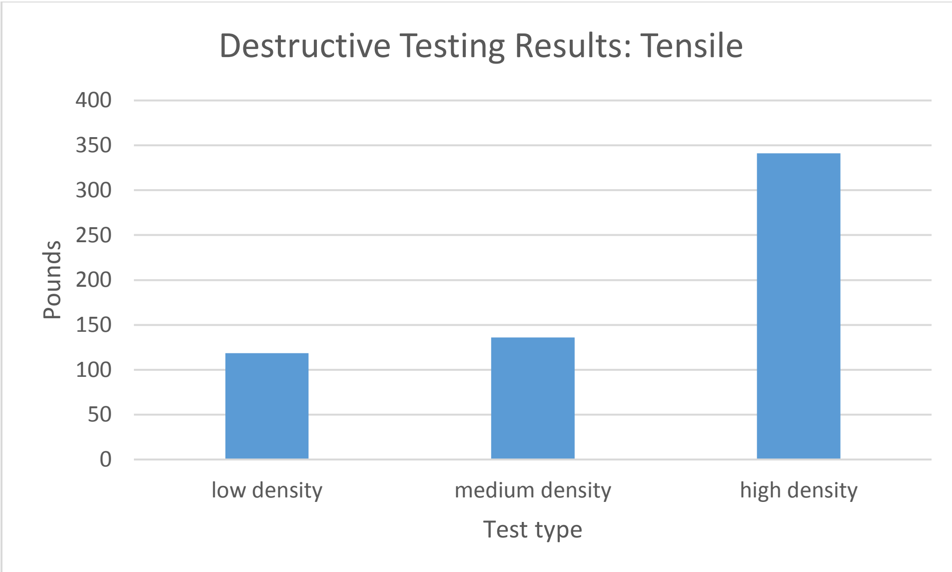


Figure 2: Modification for Tensile Testing

The coupons were tested like the compression testing with a total of three tests performed.



See Appendix D for exact data and images.

Unusual data and Inaccuracies:

Mechanical Advantage

From our testing, we knew that the mechanical advantage of the arbor press is roughly 42 x the weight applied to the arm. This also compounds by 42 any inaccuracies in the measurement of the applied weight.

There was a minor problem with the bucket slipping on the arm during testing, which would also change the amount of mechanical advantage of the arbor press.

Bucket Height

A few times during testing, the lever arm allowed the bucket to get so low that it touched the floor. Each time this happened, we had to remove the bucket, ratcheted the arbor press arm further back to allow for a greater range of movement, and replace the bucket onto the lever arm. This release of force and sudden reapplication causes uncertainty in the final force to failure.

Incremental Weight

For the applied weight to the lever arm, various items from around the shop were used, resulting in incremental force being applied instead of gradual force. The items in the bucket would occasionally shift and sometimes cause the bucket to drop off of the lever arm. This resulted in sudden and temporary extra force applied to the test coupon and uncertainty in the final force for failure.

Replacing the Weight

During testing there were times where the bucket was completely filled with items without failing. The bucket would then have to be removed and the items switched out for heavier but smaller items that resulted in roughly equal weights so that more weight could be continued to be added. This added to an uncertainty of the final force to failure.

Failure Point

In our compression tests it was difficult determining the point of failure. Some prints would fail catastrophically, while some would instead slowly collapse in on themselves over time with minor visible indications.

Too Much Initial Force

The low density tensile coupon shattered under the weight of just the bucket. This means we could only determine that it failed at under 120 lbs but could not be more accurate. Thus we can only determine that it can take at least 5000 lbs of force.

Failure to Fail

During the compression test of the "Highest Density and Parallel" coupon, we were unable to induce failure, despite applying 5000 lb. of weight.

Data Analysis

Compression

We were surprised at how strong the prints turned out to be. Even the weakest print from the compression tests held a very large weight (1,200 lbs). The "Highest Density and Perpendicular"(like figure 2) print from the compression testing withstood over 5,000 lbs. and the final force of failure remains unknown since the coupon was stronger than our test equipment could handle. However, all of the medium and low density prints failed before reaching 2000 lbs, roughly 1/5th of the predicted 9400 lbs.

Tensile

The tensile strength tests were different in that they bent to an extreme before catastrophically failing. The low-density print failed at roughly 120 lbs, which was the minimum force we could apply. All 3 prints lasted longer than the predicted 100lbs with the high density piece failing at over 3 times that (340lbs).

Potential Uses:

Obviously, the prints aren't as strong as aluminum. We don't recommend using 3D printed parts for components under a lot of stress like the robot chassis or for rivets holding pieces together.

The prints do have a significant load bearing capability if the load is applied correctly (perpendicular to the print layers), but if it is printed such that the load is parallel then it is much less durable.

Clips

One particular use for the prints is custom clips to hold down all of the electronics. One of the issues Skunkworks faced on occasion last year was the Ethernet cords for the router not being secure in their plugs. A fix would be to print a piece to hold the plugs and keep them from coming loose.

Covers

Another potential use for the 3D printer is covers. Custom covers can be made to protect electronics or other delicate pieces from dirt, impact with the ball or, to a lesser extent, collision with robot mechanisms extended into the frame perimeter.

Other Custom Complex Geometry

The 3d printer can also be used to create complex shapes that cannot, or is difficult to, be manufactured with other available tools. The 3d printer has the ability to make things like herring bone gears (See Figure 3) which are extremely difficult to machine and thus are expensive to purchase. Another good example is a modification for the Logitech joysticks to improve the ergonomics of gameplay.

Figure 3: Herring Bone Gears [1]

[1] http://www.bncgears.com/product_view.jsp?id=119

In conclusion, anything that is small enough for your printer and doesn't take any major impact would work well for 3d printing.

Appendix A

The compression test coupons were 1in x 1in x 5in and the tensile test coupons were 1in x 0.5 in x 6in.

Compressive Calculations

We know:

The Equation for Stress

$$\sigma = \frac{F}{A}$$

$\sigma = Stress$ F = Force   A = Area

with

$$A = 1in^2$$

According to our source, Yield Strength (σ) of ABS is:

$$\sigma = 65\ Mpa$$ [2]

Or

$$\sigma = 9427\ psi$$

Therefore, for a 100% dense 1in^2 surface area of a ABS plastic prism, the compressive failure force is:

$$F = 9427\ lb.$$

Tensile Calculations

We know:

The Equation for Stress from a Moment

$$\sigma = \frac{M * y}{I}$$

$$\sigma = Stress, M = Moment, y = Height\ from\ Center\ of\ Gravity, I = Inertia$$

[2] http://www.matweb.com/reference/compressivestrength.aspx

The Equation for Moment

$$M = r * F$$

M = Moment, r = Distance from Force to Pivot, F = Force

With

$$r = 2.5\ in$$

The Equation for Inertia of a Rectangle

$$I = \frac{b * h^3}{12}$$

I = Inertia, b = Base length, h = height

with

$$y = 0.25\ in$$

$$b = 1\ in$$

$$h = 0.5\ in$$

According to our source, ultimate tensile strength of ABS is:

$$\sigma = 40MPa$$ [3]

Or

$$\sigma = 5801.5\ psi$$

Solving for the force, we get the equation:

$$F = \frac{\sigma * b * h^3}{r * y * 12}$$

[3] http://www.matweb.com/reference/tensilestrength.aspx

Therefore, for a 100% dense ABS plastic prism of 1in x 0.5in x 6in dimensions, the tensile failure force is:

$$F = 96.7\ lb$$

Appendix B – Calibration Data

Calibration	Applied Weight (lbs)	Resulting Force (lbs)
No Bucket	0	35
Empty Bucket	2.12	112
Bucket, Wood	3.01	155
Bucket, Wood, Clamp	3.79	187
Bucket, Wood, Clamp, Aluminum	6.3	300

Mechanical advantage of the arbor press was determined by the fitted line through these points

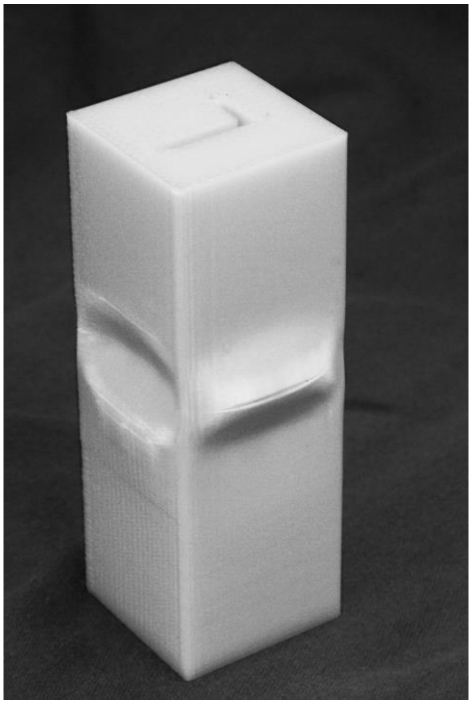
Equation of Best Fit Line:

$$y = 42.3x + 28.9$$

Thus the mechanical advantage is 42.3

Appendix C: Compressive Testing Data

Test 1:



Density: Low

Orientation: Perpendicular

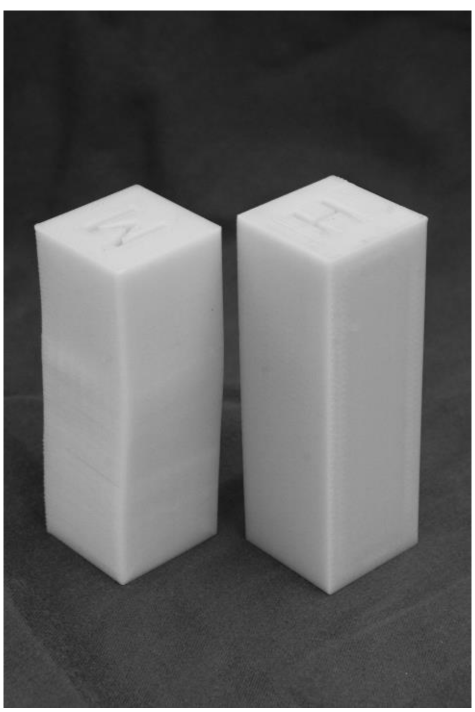
Fail Weight: 1797.04 lbs

Observations:

Upon failure, 2 opposing faces collapsed inwards while 2 opposing faces collapsed outwards.

Failure: Gradual

Test 2:



Density: Medium

Orientation: Perpendicular

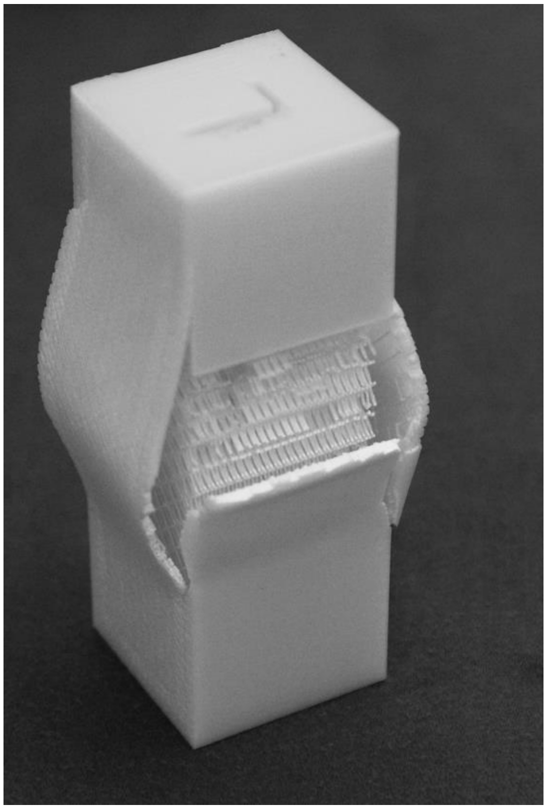
Fail weight: 3622.71 lbs

Observations:

Test 2 coupon is on the one on the left. Upon failure, the coupon began warping and the test resulted in a shorter test specimen.

Failure: Gradual

Test 3:



Density: Low

Orientation: Parallel

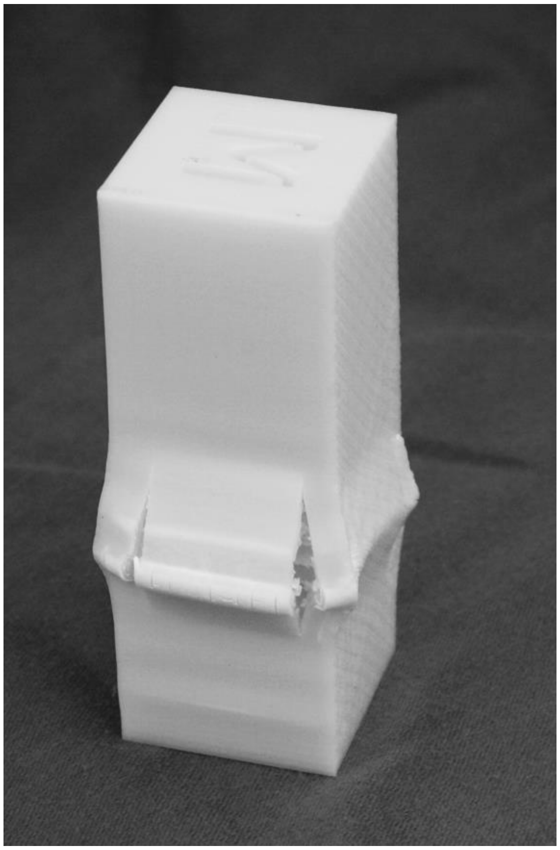
Fail Weight: 1200.61 lbs

Observations:

Upon failure, the outer shell de-laminated, detaching from the central support.

Failure: Catastrophic

Test 4:



Density: Medium

Orientation: Parallel

Fail Weight: 1674.37

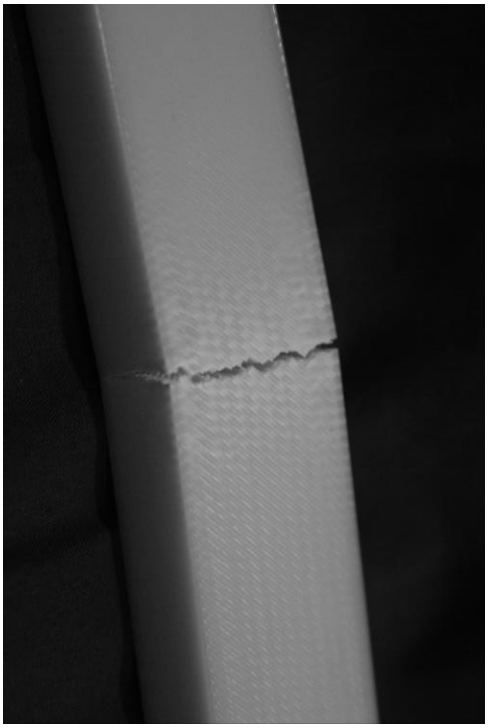
Observation:

Upon failure, print de-laminated and crumpled outwards.

Failure: Catastrophic

Appendix D: Tensile Testing Data

Test 1:



Density: Low

Orientation: Perpendicular

Fail weight: 118.58 lbs

Observation:

Print had a deflection of ½ in to 1 in

Failure: Catastrophic

Test 2:

Density: Medium

Orientation: Perpendicular

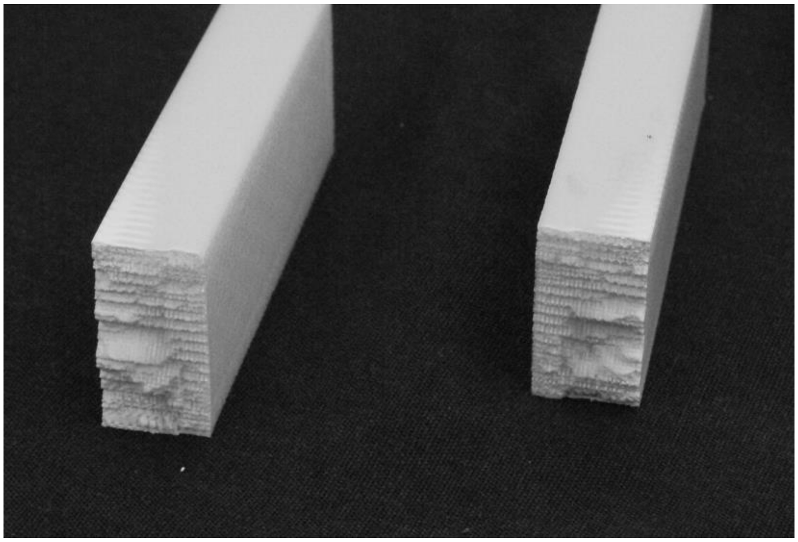
Fail weight: 135.92 lbs

Observations:

Print had a deflection of ½ in to 1 in. immediately surrounding the fracture is the visible deformation as the print compressed.

Failure: Catastrophic

Test 3:



Density: High

Orientation: Perpendicular

Fail Weight: 341.07 lbs

Observations:

Print had a deflection of ½ in to 1 in. in lower picture above the fracture, you can see the compression deformation of the print.

Failure: Catastrophic