# Additive Manufactured Polymers in Bending Stress

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**Abstract:** This module requires use of a fused deposition modeling (FDM) 3D printer, and associated gcode-producing (slicer) software. Optionally, CAD software may be used to modify included designs, or design new bending test specimens. Polymer specimens will be created using additive manufacturing methods, tested in 3-point bending, and analyzed quantitatively and qualitatively.

**Objectives:** Students will create polymer materials testing samples using additive manufacturing technology. Students will make a test matrix and conduct an experiment to characterize the differences between samples.

**Key Words:** Additive manufacturing, I-beam, bending stress, 3-point bending

**Activity:** Multi-day classroom experiment, including sample manufacturing and testing

Time Required: One or more 45 min. class periods (or lab periods) depending on level of the class

Grade levels: secondary or post-secondary

**Equipment and Supplies needed:**

- Safety glasses (or sufficient containment box for bending testing apparatus)
- Fused Deposition 3D printer
- Chosen FDM polymer filament, most likely ABS or PLA
- Simple CAD software or provided STL file
- 3D printing / slicer software appropriate to your printer
- Calipers
- Either:
  - Standard 3-point bending testing apparatus

Or:

  - Two sturdy tables with hard, smooth edges (or other suitable suspension gap)
  - 5-gallon contractor bucket with a round, hard, smooth dowel or wire handle
  - 50kgs (110 lbs) sand
  - Scale in the 1-50kgs range

**Instructor background and notes:**
In this experiment, we will make test specimens using additive manufacturing and test them in 3-point bending. If you have CAD software, it is recommended to design these in class. Free online software should be available for simple designs (SketchUp or TinkerCAD, for example), and designing these models will only require a 2D sketch or draft and one extrusion.

By using fused deposition modeling printers with polymer filament, and testing samples printed at different orientations on the build plate, we are essentially testing the difference between the strength of secondary bonds between polymer molecules extruded together versus those formed when layers are added together. Secondary bonds will vary by the production conditions of the filament, the amount of moisture filament has absorbed from the atmosphere, the extrusion temperature, the layer height, extrusion rate, print speed, ambient temperature, the algorithms of your slicer software, and more.

Students need to keep these factors in mind when controlling for the sample production. If well controlled, then each type of sample should have fairly consistent behavior. It will most likely be found that when the plane of printing is perpendicular to the long axis of the samples, the samples are weakest. This should lead to the conclusion that secondary bonds between layers are weaker than secondary bonds within layers.

**Additive Manufacture of I-Beam Specimens**
The goal of sample preparation for bending tests is to create objects with consistent cross-section and properties along their length. An I-beam or boxbeam is designed to resist bending stress, and has a flat bottom surface that will resist rolling as it is loaded.

Our samples will fit inside a 2cm x 2cm printing footprint and be 15cm long, optionally with slight bumps on one side to prevent shifting of their load, and to test in bending across a 10cm gap. Because additive manufacturing may produce anisotropic properties, you will print specimens in different orientations and observe the effect of the different manufacturing conditions on the performance of the product.

Your class may also consider using different printing settings as additional variables, other than just printing orientation. Good candidate variables include extruder temperature, number of shell layers, infill settings, and print speed.

**Classroom Experiment – 3-Point Bending**

**Procedure**:

Sample prep:

1) Print your samples in their different orientations. To ensure that each sample is made as intended, it is best to print one at a time. This may require technician attention throughout one or more days of printing.
2) Do not trim, file, or otherwise clean or repair any flaws or mess in your samples. Their as-printed condition is part of the experiment.
3) With a permanent marker, label the length of each sample at 2.5cm, 7.5cm, and 12.5cm. Support edges will contact the sample at the first and third lines, and load will be placed on the second line.
4) Create a sample matrix with columns for sample number, printing orientation, as-printed dimensions, mass of the sample, and the load at which the sample failed. This will require a system for indicating printing orientation, and a decision on how many samples of each orientation will be made and tested.

Sample testing:

1) Wear protective eyewear while testing samples. Shards of plastic may be thrown during sample failure.
2) Position your supports 10cm apart from each other, and place your first sample to test across the gap with the 2.5 and 12.5cm lines on the edges. If you have a standard 3-point bending apparatus, fixture your sample appropriately.
3) Ensure that your load (bucket handle) is over the 7.5cm centerline, and that your sample position is level so that it will not shift.
4) Load the sample by adding sand to the bucket evenly and slowly. Do not drop weight into the bucket in a way that creates pulses of force, or the sample may fail from impact or fatigue before the weight alone would cause failure.
5) Continue loading until failure occurs, and then measure the total weight of the bucket and sand (or other weight) at the moment of failure.
6) Record test results in this way for each sample.
7) Preserve the failed specimens by gathering any broken pieces.

**Discussion:**

Collect your results as a class and create a scatter plot of each sample's failure. Find the mean and standard deviation for each printing orientation and add these to the plot.

Analyze the information in your scatter plot. Which failed most easily? Was the difference significant?

Did the way samples failed indicate anything about them? Examine the broken/bent pieces and look for clues such as where any cracks in the sample spread. Failure should propagate along the weakest connections in any material. What were the weakest parts of each type of your samples?

How would you print a structural member that you wanted to resist stress best? Did anything about the experiment suggest there could be value in testing additional orientations? Are there post-processing methods, such as ways of applying heat after the initial printing, which could prove useful? Consider testing these as a class if time allows for additional experiments.

**Student Evaluation Questions**

1. Explain the process of additive manufacturing. What are its advantages and disadvantages?
2. Discuss the safety of the process to the user. What safety precautions did you take?
3. Were you able to produce useful parts using this process? Why or Why not?

**References:**


SketchUp free design software
https://www.sketchup.com/plans-and-pricing/sketchup-free

Autodesk TinkerCAD free design software
https://www.tinkercad.com/

I-Beam Section Properties Calculator on AmesWeb
https://www.amesweb.info/SectionalPropertiesTabs/SectionalProperties.aspx

ASTM D790: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

For additional testing of polymer fibers, consider:
Properties of Fibers and Fabrics, Luke Ferguson PhD
http://materialseducation.org/educators/matedu-modules/



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