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# Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions

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ABSTRACT

The recent development of the RepRap, an open-source self-replicating rapid prototyper, has made 3-D polymer-based printers readily available to the public at low costs (< $500). The resultant uptake of 3-D printing technology enables for the first time mass-scale distributed digital manufacturing. RepRap variants currently fabricate objects primarily from acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), which have melting temperatures low enough to use in melt extrusion outside of a dedicated facility, while high enough for prints to retain their shape at average use temperatures. In order for RepRap printed parts to be useful for engineering applications the mechanical properties of printed parts must be known. This study quantifies the basic tensile strength and elastic modulus of printed components using realistic environmental conditions for standard users of a selection of open-source 3-D printers. The results find average tensile strengths of 28.5 MPa for ABS and 56.6 MPa for PLA with average elastic moduli of 1807 MPa for ABS and 3368 MPa for PLA. It is clear from these results that parts printed from tuned, low-cost, open-source RepRap 3-D printers can be considered as mechanically functional in tensile applications as those from commercial vendors.



## 1. Introduction

Historically, expensive commercial rapid prototypers have enabled accurate fabrication of products or scale models, been useful as production and design tools, and the development of additive manufacturing (AM) for rapid prototyping in a number of technologies has been substantial [1–5]. Recently an open source (OS) model, the RepRap, has been developed that can be built for under $1000 (now Prusa models can be made for about $500), greatly expanding the potential user base of rapid prototypers. Between 2008 and 2011, it is estimated that the number of RepRaps in use had increased from 4 to 4500 [6], and can be assumed to have continued to increase in the last two years. In addition, other versions of at-home desktop 3-D printers are also selling rapidly. Makerbot, whose printers are derived from open-source RepRaps, for example, has sold over 13,000 3-D printers since 2009 [7]. The resultant uptake of 3-D printing technology enables for the first time mass-scale environmentally-beneficial distributed digital manufacturing [8,9]. The RepRap was created by Adrian Bowyer and is supported and influenced by many contributors largely through the online wiki, which provides detailed assembly instructions for several variants of 3-D printers [6,10]. Thus following the OS model has created rapid technological evolution with the printers improving rapidly with time [11]. While OS models have limitations compared to commercial processes [12–14], they are capable of creating highly accurate parts with positioning accuracy of 0.1 mm [6]. RepRap variants currently fabricate objects primarily from acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), which have melting temperatures low enough to use in melt extrusion outside of a dedicated facility, while high enough for prints to retain their shape at average use temperatures. These machines are already used for art, toys, tools, household items (see Thingiverse an online repository of open 3-D printable designs) and to make high-value scientific instruments [15–16]. In addition, it has been proposed that RepRaps could be used for small-scale manufacturing or as an enabling tool for sustainable development [17]. In order to make RepRaps useful tools in this context and for standard engineering practice basic mechanical properties are necessary.

As RepRap 3D printers become more prevalent among home users they are being used to manufacture more diverse objects. This has included more load-bearing components that either replace items normally purchased or are uniquely designed for

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**Table 1**
RepRap 3-D printer slicing variables.

| | |
|---|---|
| Pattern orientation (°) | 0/90, +45/−45 |
| Layer height (mm) | 0.4, 0.3, 0.2 |
| Infill (%) | 100 |

**Table 2**
Printers used for specimen printing.

| Number | Type | Filament |
|---|---|---|
| Printer 1 | MOST RepRap | Natural ABS, Clear PLA |
| Printer 2 | Lulzbot Prusa Mendel RepRap | Natural ABS, Purple PLA, White PLA |
| Printer 3 | Prusa Mendel RepRap | Black PLA |
| Printer 4 | Original Mendel RepRap | Natural PLA |

the specific needs of the user in terms of geometry and function. Both cases require the component to have the necessary strength properties to perform properly and safety. Most home users have no way of testing the strength of their parts and no extensive information is currently available about the mechanical properties of parts printed specifically on RepRaps.

To rectify this technical omission this study quantifies the basic tensile strength/stress, and elastic modulus of printed components using realistic environmental conditions for standard users of a selection of low-cost, open-source 3-D printers.

## 2. Methods

To determine the mechanical properties of 3-D printed parts and the variability in these properties when different user-controlled printing and slicing parameters are used, this investigation looked at the relationship between deposition pattern orientation and layer height to tensile strength, strain at tensile strength, and modulus. Table 1 shows the printing parameters used.

To gather a comprehensive data set covering a wide range of 3-D printers and their settings, a .STL file (as shown in Fig. 1) of a tensile test specimen conforming to the ASTM: D638 was created and distributed online for anyone to print and send to the researchers for testing [18]. An extra, unattached cylinder was added to the .STL file to aid in proper printing, but was not a part of the specimen.

A complete set of 10 specimens of each of the combinations of variables shown in Table 1 was printed on a variety of open-source 3-D printers including an original Mendel RepRap, a Prusa Mendel RepRap, a Lulzbot Prusa RepRap, and a custom MOST RepRap. The printers used (listed in Table 2) varied from each other with regard to mechanical design, including frame, stepper motors, and extruder head, as well as electronically with regard to firmware, with the open-source created Sprinter and Marlin firmwares being the most commonly used. A different software was used for slicing the .STL files into machine readable g-code, which included Skeinforge, Slic3r, and Cura.

In order to determine realistic mechanical property values that RepRap users might encounter, the experiments diverged from the ASTM: D638 standard because of uncontrollable specimen conditioning and geometry variability. To replicate realistic environmental conditions for distributed manufacturing, the environmental conditions during printing, storage, and shipping could not be controlled and no intentional specimen conditioning was performed.

While all specimens were created from the same .STL file, they were sliced and printed with different settings such as extruder temperature, based on which settings resulted in the best prints

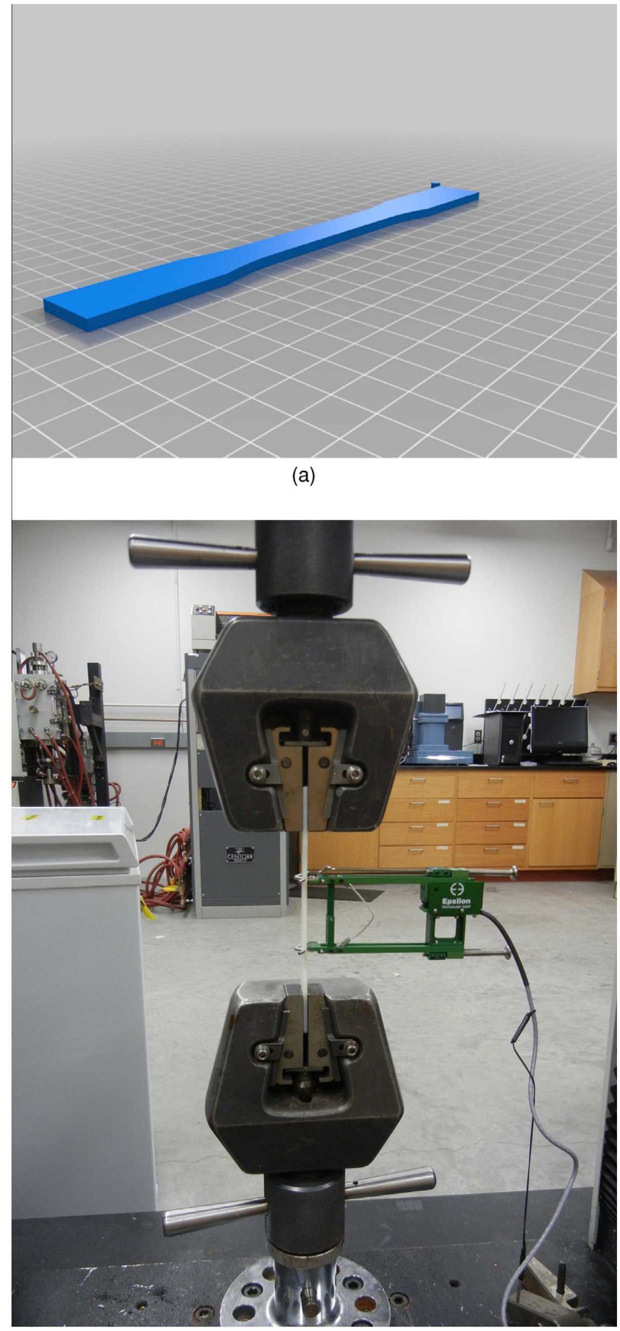


**Fig. 1.** (a) Rendering of the shared .STL filed of the ASTM: D638 tensile standard [18] and (b) digital photograph of a specimen in load frame.

on each printer. Due to the nature of RepRaps and other user assembled 3-D printers being highly customizable, they can vary in construction and components resulting in different settings used in slicing and control software as well as in the firmware. One example of printer variability is how the temperature of the extruder is measured. Many different extruder models exist with most utilizing a thermistor for temperature measurement. Thermistor placement can vary substantially between models relative to the extruder heating element and nozzle. Thermistor calibration is also rarely, if ever, performed. This causes different printers to be set to different extruder temperatures to get high quality prints. Likewise, when two printers are set to the same temperature in software the actual extrusion temperature may be different.