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MECHANICAL TESTING OF FUSED FILAMENT 3-D PRINTED COMPONENTS FOR DISTRIBUTED MANUFACTURING

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MECHANICAL TESTING OF FUSED FILAMENT 3-D PRINTED COMPONENTS FOR DISTRIBUTED MANUFACTURING

By

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A THESIS

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Dedicated to my parents for all their support

Contents

Preface

This is a manuscript based thesis, which is composed of two submitted papers. The author's contributions are described hereafter.

Chapter 2: "Tensile strength of Commercial Polymer Materials for Fused Filament Fabrication 3-D Printing"

Co-Authors-Ben Wittbrodt, Joshua M. Pearce

N. Tanikella was responsible for experimental design, fabrication, experimental data collection, results analysis, figures, tables and writing the paper.

B. Wittbrodt was responsible for some experimental data collection, results analysis and writing the paper. J. M. Pearce contributed on writing, experimental design, editing and consultation.

Chapter 3: "Viability of Distributed Manufacturing of Bicycle Components with 3-D Printing: CEN Standardized Polylactic Acid Pedal Testing"

Co-Authors-Benjamin Savonen, John Gershenson, Joshua Pearce

N. Tanikella was responsible for experimental design, fabrication, experimental data collection, results analysis, figures, tables and writing and editing the paper.

B. Savonen was responsible for experimental design and writing.

John Gershenson was responsible for consultation and writing. J. M. Pearce contributed to writing, experimental design, editing and consultation.

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Abstract

Fused filament fabrication (FFF)-based open-source 3-D printers offer the potential of decentralized manufacturing both in developing and developed countries. Unfortunately, a severe lack of data and standards relating to material properties and printed components limit this potential. This thesis first investigates the mechanical properties of a wide-range of FFF materials and provides a database of mechanical strength of the materials tested. The results demonstrate that the tensile strength of a 3-D printed specimen depends largely on the mass of the specimen, which provides a means to estimate the strength of 3-D printed components. Then this information is used to evaluate a bicycled pedal, which was 3-D printed and tested following the CEN (European Committee for Standardization) standards for racing bicycles. The results show the pedals meet the CEN standards and can be used on bicycles at lower costs than standard pedals. This investigation indicates the viability of distributed manufacturing.

1. Introduction

Fused filament fabrication (FFF)-based open-source self-replicating rapid prototyper (RepRap) 3-D printers offer the potential of decentralized manufacturing both in developing and developed countries. Unfortunately, the severe lack of data and standards relating to material properties and printed components limit this potential. Specifically, it is challenging to 3-D print functional parts with known mechanical properties using variable open source 3-D printers.

The goal of this thesis is to overcome this challenge by exploring a method to create functional parts without the necessity of expensive equipment for mechanical tests.

First, to meet this goal, Chapter 2 provides a database of mechanical properties of a wide range of the commercially available 3-D printable thermoplastic materials. It also provides a method of estimating the mechanical properties of a component for a given material with low-cost and widely accessible equipment. This data provides the background data necessary to begin considering making components with known mechanical properties using low-cost RepRap 3-D printers.

To investigate this potential with a specific example, Chapter 3 explores a component that can be used in the real world: a bicycle pedal and shows that 3-D printed components can be a convenient, and in some cases less-expensive alternative to purchasing a new or replacement component even in a developing world market.

Finally, Chapter 4 provides conclusions of the thesis and makes suggestions for future work to scale distributed manufacturing.

2. Tensile Strength of Commercial Polymer Materials for Fused Filament Fabrication 3-D Printing

2.1. Introduction

Due in a large part to the open-source release of the RepRap (self-Replicating Rapid prototyper) [1-3] there was a distinct rise in popularity of 3-D printing, particularly at the small scale [4]. RepRap 3-D printers fabricate parts using fused filament fabrication (FFF) (material extrusion by ASTM Standard F2792-12a[1]) and various RepRap printer designs make up the majority of 3-D printers in use now [5]. Decentralized manufacturing is possible with at-home 3-D printing both in the developing [6] and developed countries [7]. Previous studies have shown that such manufacturing not only allows for a lower cost of goods for the consumer [8], but a lower impact on the environment as well [9,10]. With users from various 3-D printing repositories (e.g. Youmagine, Libre3D, NIH 3D Print Exchange, etc.) publishing thousands of designs an exponential growth of open-source designs for 3-D printing has been observed is expected to continue growing as consumer level 3-D has been proven to be an economically viable purchase for the developed-world middle-class [8] and particularly the maker community [11-13].

In the maker community poly-lactic acid (PLA) is the most popular FFF 3-D printing material, being available for the vast majority of 3-D printing supplies vendors. PLA has a relatively low melting point, 150°-160° C, thus requiring less energy to print with the material, which also provides advantages for off-grid applications in the developing world [14-16]. In addition, PLA has been shown to be a safer alternative to toxic ABS plastic fumes, the second most popular 3-D printing material as gaged by availability [17, 18]. The mechanical properties of 3-D printed PLA have been investigated in some detail [19, 20]. However, there are many other materials available on the market for prosumer FFF 3-D printing including nylon, polycarbonate (PC), high-density polyethylene (HDPE), high impact polystyrene (HIPS), and others [21]. In addition, with the continued development of novel and affordable 3-D printing technologies, the types of materials that may become common for FFF is expected to grow [22,23] and involve the use of additives [24] such as strengthening agents to common 3-D printable materials [25,26]. Other techniques involve treating 3-D printable materials to increase strength [27]. With the introduction of the recyclebot [28], an open-source prosumer plastic filament extruder, and its open source technological cousins (e.g. Lyman Filament Extruder, Plastic Bank Extruder, Filastruder,

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[1] This is trademarked as fused deposition modeling or FDM by Stratasys.

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FilaFab, Noztek, Filabot, EWE, Extrusionbot, Filamaker and the Strooder, Felfil (OS)), these potential strengthening mechanisms can be implemented and tested by the end-user (prosumer) directly.

Unfortunately, there is a severe lack of peer-reviewed data and standards relating to these prosumer FFF 3-D printing material properties, which limits the ability of prosumers to develop more sophisticated designs. Recent work with closed-source commercial grade powder printers have described what effect the orientation of layers may have on the properties of a printed part [29] and commercial grade fused deposition modeling (FDM [the IP limited subset of FFF]) printers have shown a strength dependency on different types of infill patterns and internal structures [30,31] and print orientations [32]. In addition, past results have shown that 3-D printed parts perform between 65% and 72% as well in comparison to injection molded parts of the same material [33]. Proprietary printers have been used to show a difference in layer adhesion when parts were printed using various fabrication preferences, including temperature [34].

In order for users to manufacture functional items with open source RepRaps, a recent study investigated mechanical properties of PLA and ABS in realistic environmental conditions, which showed RepRap prints can perform match and even outperform commercial 3-D printers using proprietary FDM in terms of tensile strength with the same polymers [19]. A follow up study [20] found that coloring agents altered the microstructure (percentage of crystallinity) and had an impact on the strength as is well established in the literature [35, 36]. In addition, as the nature of these studies had different 3-D printers running at the users chosen optimal conditions the processing temperatures varies and this has a major impact on print quality and thus strength. These factors added to the inconsistencies found in a random sampling of RepRap users [19] making it difficult for prosumers to gauge the strength of their individual prints.

To expand on this preliminary knowledge this study investigates the mechanical properties of RepRap 3-D printed parts using a commercial open-source RepRap (Lulzbot TAZ) for a wide range of materials including: Ninjaflex (5 colors), Semiflex (4 colors), HIPS (5 colors), T-Glase (5 colors), polycarbonate (1 color), Nylon (2 Types), and ABS (1 color). The samples are tested for tensile strength following ASTM D638 [ASTM]. The results are presented and conclusions are drawn about the mechanical properties of various FFF printing materials to promote the open-source development of RepRap 3-D printing.

2.2. Methods

Ten specimens of each material were printed considering the ASTM D638 standard using Lulzbot TAZ 3.1 [38] and Lulzbot TAZ 4 [39]. All materials are from the same supplier, Lulzbot [40]. Flexible filaments such as Ninjaflex, Semiflex and Nylon Bridge were printed on Lulzbot 3.1 as the “flexystruder” tool head [41] was installed on it. All other materials, which were rigid were printed using Lulzbot TAZ 4. Cura 15.04 [42], an open source slicer, was used to generate a G-code from the specimen model [43]. All specimens were printed indoors in a temperature controlled environment with 100% infill. Additionally, samples were printed with varying extruder temperatures depending on the material. These temperatures and all the materials tested are summarized in Table 1-1. Other printing parameters such as layer height, speed and custom controls were fine tuned for each material using the supplier's recommendations as a baseline to produce acceptable print quality and uniformity.

Table 2-1 . 3-D printing materials, printing temperature and density of the filament.

Material Type	**Printing Temperature (^oC)**	**Density of filament (g/cm^3)**
ABS	230	1.0311
HIPS	230	1.0280
Polycarbonate	250	1.1950
T-Glase	230	1.2767
Nylon	235	1.1277
Semiflex	230	1.2216
Ninjaflex	230	1.1869

Only the reduced section of the specimen was considered as the gauge length and the extension of the tapering section was ignored. The geometry of the specimens had a thickness of 3.2 mm, width of 13 mm and a gauge length of 60 mm. The density of the unextruded filament was determined by applying Archimedes principle: a small length (around 2”) of the filament was taken and massed in air (m_1) and in water (m_2) separately on an electronic balance with least count of 0.0001g. The filament density, d_f, was then calculated using the formula:

$$d_f = d_w \times \left(\frac{m_1}{(m_1 - m_2)} \right)$$

Where d_w is the density of water. The different colors of the same material were grouped together and measured as the difference in the density between the colors was below the error (+/- 0.001g) of the apparatus. The sample size was ten for each material group. The density of each material group are also included in Table 1-1.

The slicer (Cura) has an inbuilt mass measurement, which uses a density of 1.244g/cm^3. The slicer showed a mass of 11.6g for the geometry. This was used to determine the volume to estimate the ideal mass of the specimen for each material type using the measured density.

Ten printed tensile samples for each material/color combination were then subjected to tensile testing consistent with ASTM D638 standards [37]. The rigid specimens were tested for tensile strength on INSTRON 4206 with a 10kN load cell for load measurement and cross head data was used for the extension measurement. Test Works 4 [44] was used to perform the tests. It should be noted that a 2” extensometer was initially used for measuring the extension of rigid materials. However, most of the samples broke close to the neck, and significant extensions were observed outside the extensometer range. Hence cross head data was used uniformly for all materials. Maximum tensile stress values and corresponding strain values were obtained for rigid materials.

The extension of flexible materials (Ninjaflex, semiflex, and Nylon Bridge) was found to be greater than allowed by the INSTRON 4206, hence flexible materials were tested on INSTRON 4210 using the same load cell using Bluehill 2 software [45]. Most of the flexible materials did not break using the INSTRON 4210, and the proportionality limit was found to be very low. Hence, stress-load values at a particular extension value (60mm) were measured for comparison between the different materials and colors.

The orientation of all the rigid materials was diagonal (diagonal to the direction of the pull). The flexible materials were printed in two different orientations to compare the difference in flexibility between the orientations. The orientations printed were vertical (along the direction of the pull) and diagonal.

2.3. Results and Discussion

The results of the tensile tests for the 3-D printed materials are summarized in Table 2-2 and Table 2-3 for rigid and semi-flexible materials, respectively.

Table 2-2. The average maximum extension (mm), average maximum load (N), average mass (g) and average tensile stress (Mpa) for all the 3-D printed rigid materials

Material	**Average maximum extension (mm)**	**Average maximum Load (N)**	**Average Mass (g)**	**Average Maximum Tensile Stress (MPa)**	**Standard deviation of maximum Tensile Stress (MPa)**
ABS	3.70	1196.12	8.70	28.75	3.15
HIPS (black)	4.52	813.09	8.83	19.55	2.15
HIPS (Blue)	3.20	832.67	9.58	20.02	1.61
HIPS (White)	3.04	882.51	9.00	21.21	0.88
HIPS (Clear)	4.91	890.48	9.00	21.41	0.55
HIPS (Gray)	3.48	888.05	9.21	21.35	1.14
Nylon 618	41.71	1314.42	11.79	31.60	3.20
Polycarbonate	8.57	2041.64	9.89	49.08	3.03
T-Glase (Gray)	5.77	1241.89	10.44	28.79	3.26
T-Glase (Clear)	6.22	1312.85	10.34	31.56	2.81
T-Glase (Blue)	6.31	1360.52	10.73	32.70	3.98
T-Glase (Green)	5.65	1470.97	11.17	35.36	5.47
T-Glase(Red)	5.50	1428.28	10.39	34.33	5.51

Table 2-3. The orientation of the print, average mass (g), average load at 60mm extension (N) and average stress at 60mm extension (MPa).

Material	**Orientation of print**	**Average Mass(g)**	**Average Load at 60mm extension (N)**	**Average Stress at 60mm extension (MPa)**	**Standard deviation of Stress at 60mm extension (MPa)**
Ninjaflex (Black)	Diagonal	11.27	202.79	4.87	0.25
Ninjaflex (Blue)	Diagonal	8.86	147.62	3.55	0.64
Ninjaflex (Green)	Vertical	10.92	211.75	5.09	0.15
Ninjaflex (Red)	Diagonal	11.355	199.64	4.8	0.28
Ninjaflex (White)	Vertical	9.192	161.88	3.89	0.1
Nylon Bridge	Diagonal	10.666	1102.87	26.51	3.65
Semiflex (Black)	Diagonal	12.14	422.04	10.15	1.02
Semiflex (Blue)	Diagonal	12.08	416.88	10.02	0.58
Semiflex (Red)	Vertical	10.65	382.37	9.2	0.89
Semiflex (Red)	Diagonal	11.41	406.89	9.78	1.18
Semiflex (White)	Vertical	9.94	348.72	8.38	0.65

Analysis of load and mass for all the materials shows a significant co-relation between mass of the specimen and the load. This is apparent in Figures 2-1 to 2-8, which show the load as a function of mass for ABS, HIPS, nylon 618, polycarbonate, T-Glase, NinjaFlex, Nylon Bridge, and Semiflex, respectively.

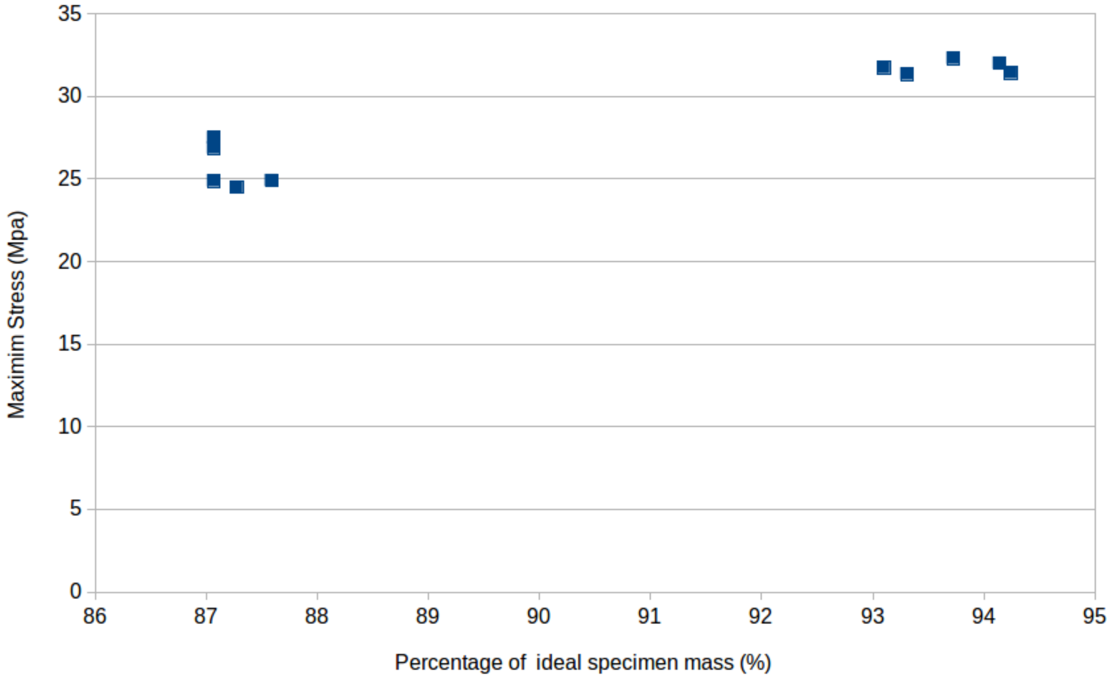

Figure 2-1. The maximum stress (MPa) of ABS as a function of sample mass to filament mass percentage.

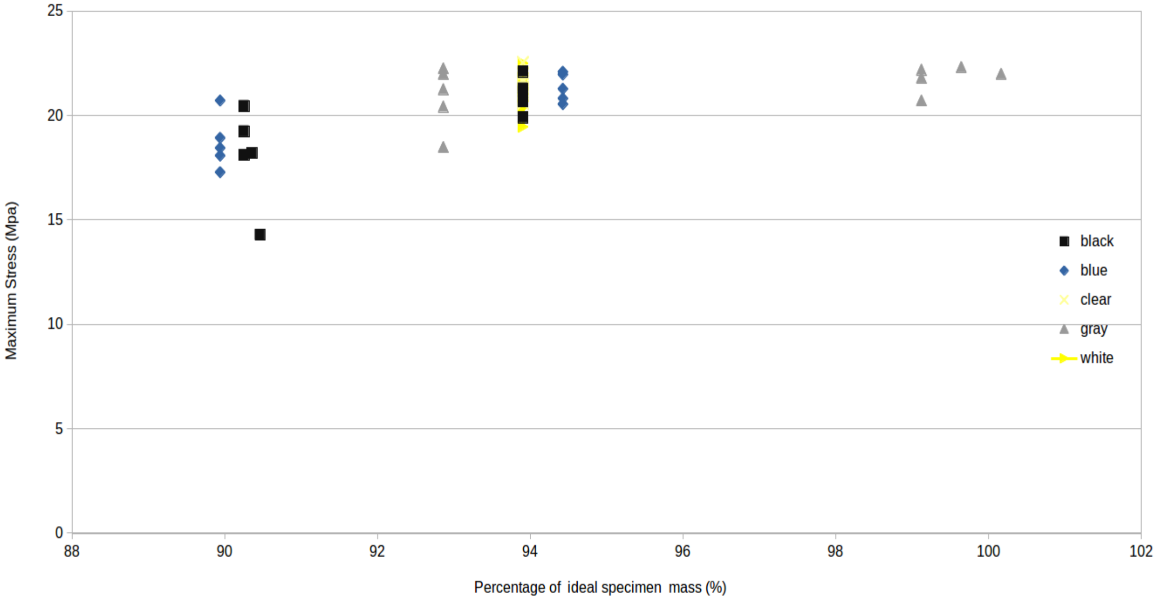

Figure 2-2. The maximum stress (MPa) of HIPS as a function of sample mass to filament mass percentage.

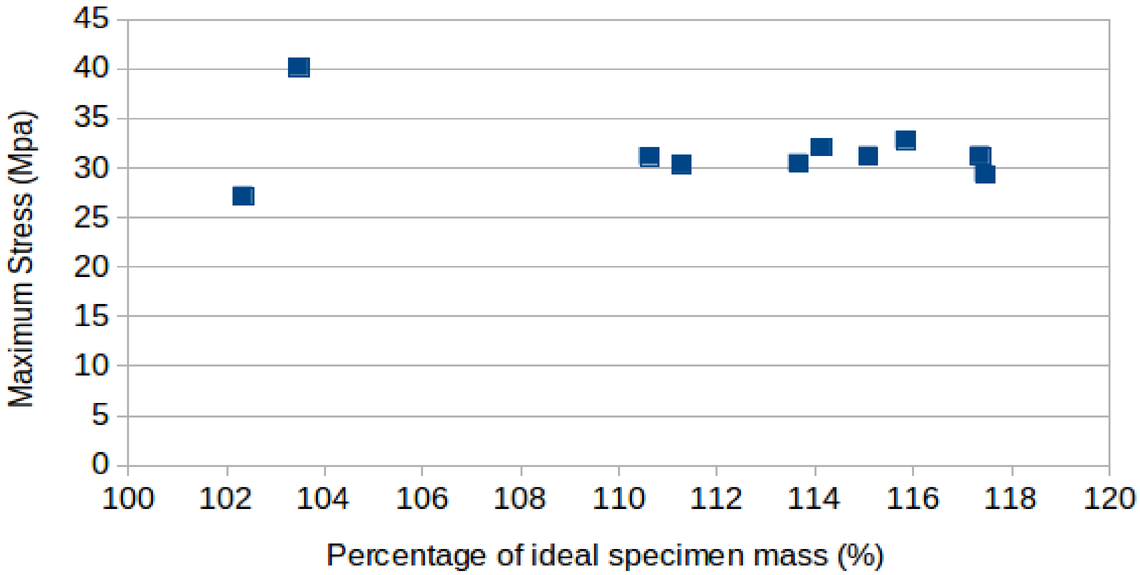

Figure 2-3. The maximum stress (MPa) of Nylon 618 as a function of sample mass to filament mass percentage.

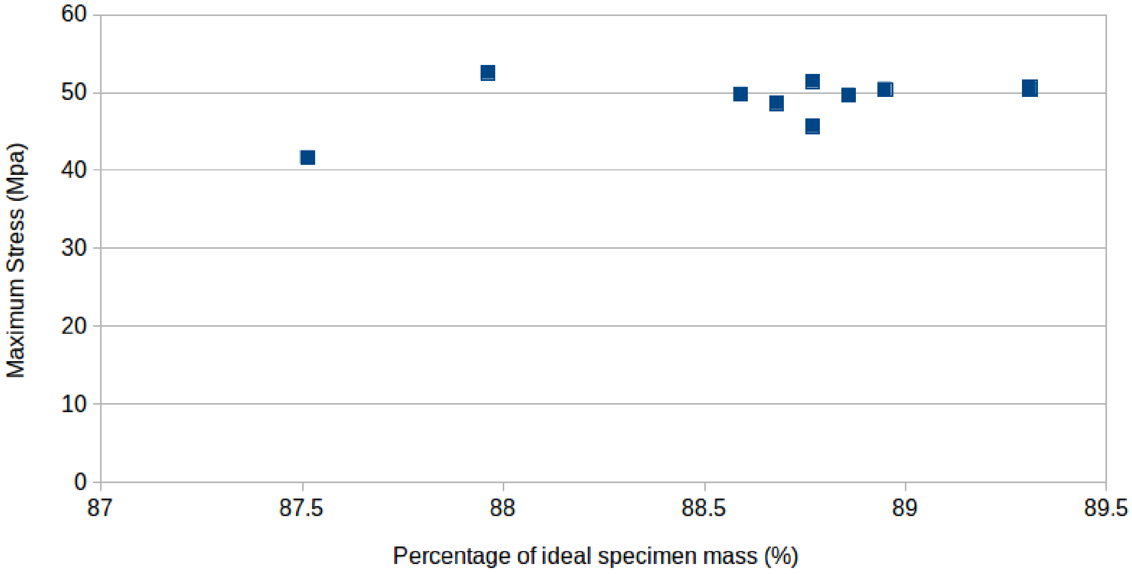

Figure 2-4. The maximum stress (MPa) of polycarbonate as a function of sample mass to filament mass percentage.

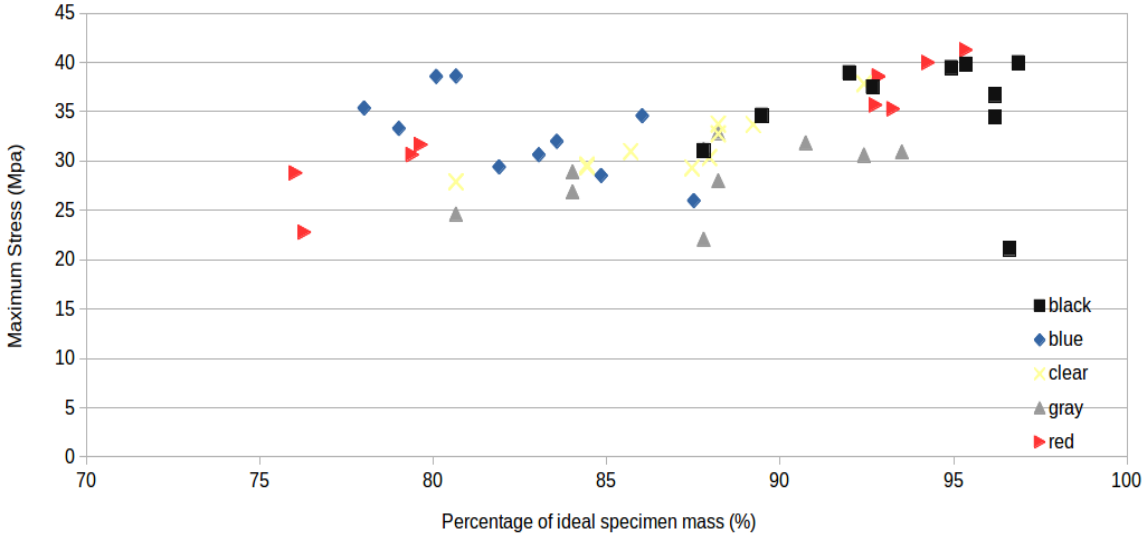

Figure 2-5. The maximum stress (MPa) of T-Glase as a function of sample mass to filament mass percentage.

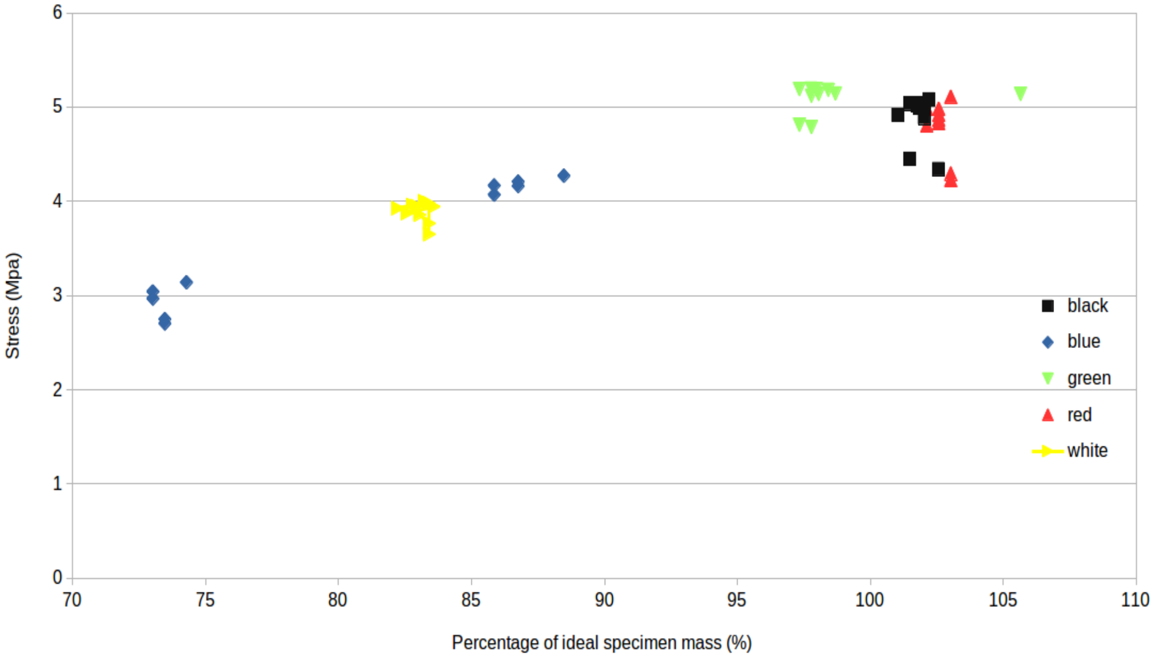

Figure 2-6. Stress at 60mm extension (MPa) of Ninjaflex as a function of sample mass to filament mass percentage.

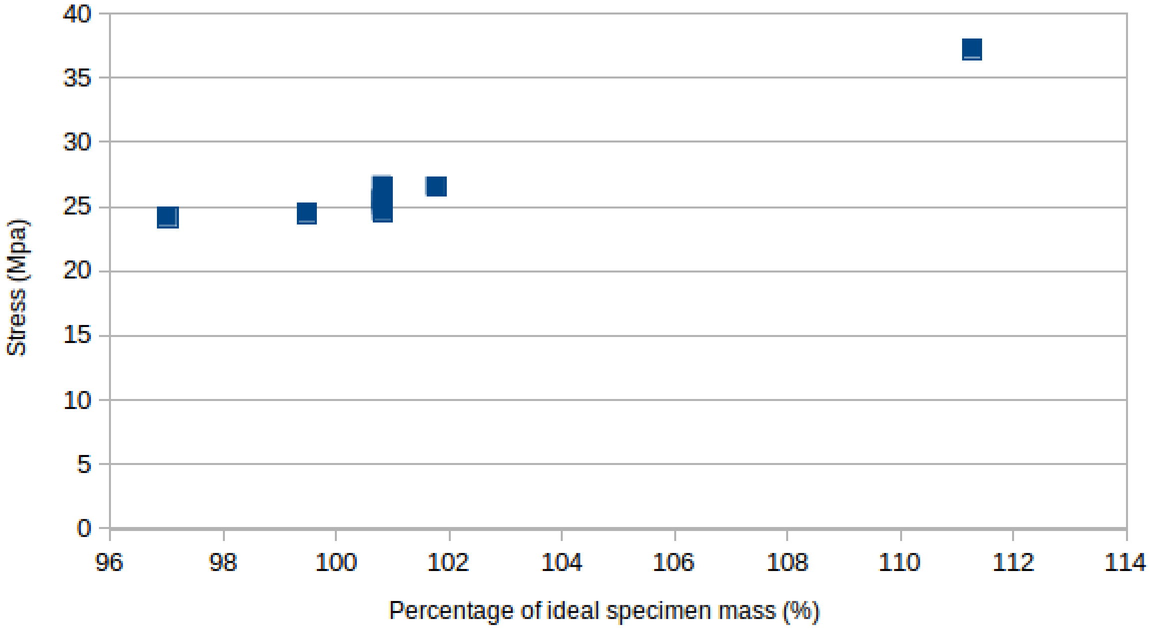

Figure 2-7. Stress at 60mm extension (MPa) of Nylon Bridge as a function of sample mass to filament mass percentage.

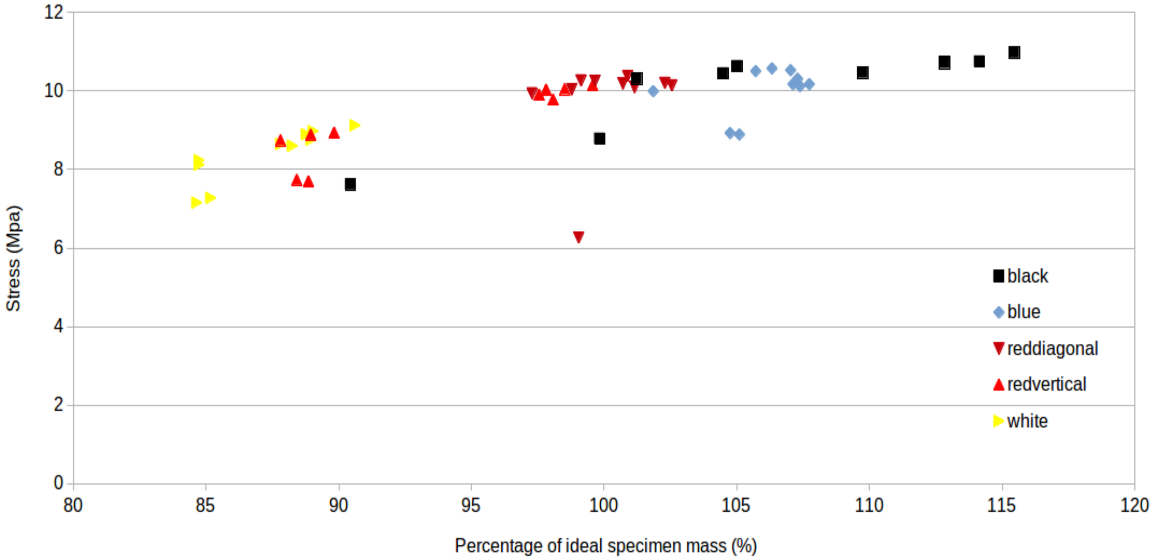

Figure 2-8. Stress at 60mm extension (MPa) of Semiflex as a function of sample mass to filament mass percentage.

As can be seen in the results of Figures 2-1to 2-8, the strongest material among those tested was polycarbonate with a maximum tensile strength of 49.08 MPa. The most flexible material was Ninjaflex, which did not break after an extension of about 800%. The tensile stress for Ninjaflex at 800% extension was 12.69 MPa (average of all colors). Nylon materials were stronger than Ninjaflex and Semiflex, and much more flexible than ABS, HIPS, T-Glase, and polycarbonate, providing a good balance between strength and flexibility. It is also clear from the materials where multiple colors were tested (HIPS in Figure 2-2, T-Glase in Figure 2-5, Ninjaflex in Figure 2-6 and Semiflex in Figure 2-8) that color of the material can have a significant impact on the maximum stress a 3-D printed material can withstand. It should also be pointed out that whereas the variance within a single material and color is small for most tests, some significant variance was still observed indicating the need for conservative safety factors for mechanically important components.

It can be seen that the strength is proportional to the mass of the specimen. It has been shown that crystallinity of the printed material has effects on the tensile strength of a color [20]. The crystallinity difference between various colors may be due to addition of coloring agents. Each color has a slightly different optimum temperature for printing. The mass of different colors may be different due to various other factors such as: slight difference in density, moisture, and weaker chemical bonds due to addition of coloring agent. Currently, the coloring agents and other additives to the commercial filament suppliers is not known. This points to the necessity of the open source developmental model, which has been so successful in 3-D printing itself to be expanded beyond materials science software [46-51] to open source materials development [24,52,53]. This can occur within the maker community itself (e.g. openmaterials.org) or as recyclebot technology is investigated [54-56] and deployed throughout the developing world to produce ethical filament or fair trade filament [57-59].

Despite these limitations it is possible to reliably estimate the strength of a 3-D printed with a known plastic. Based on the results of this study a two-part process can be followed to have a reasonably high expectation that a part will have tensile strengths described here for a given material. First, the exterior of the print should be inspected for sub-optimal layers from under extrusion. If for example, under extrusions are detected on the outer surface as shown in Figure 2-9, then the part should be reprinted if mechanical stability is important for the specific application. Second, in order to determine if there has been any under-extrusion in the interior, the samples are massed. Prosumers without access to lab grade scales can use a digital food balance to get acceptable precision and accuracy. This mass is compared to the theoretical value using the densities from Table 1 for the material and the volume of the object.

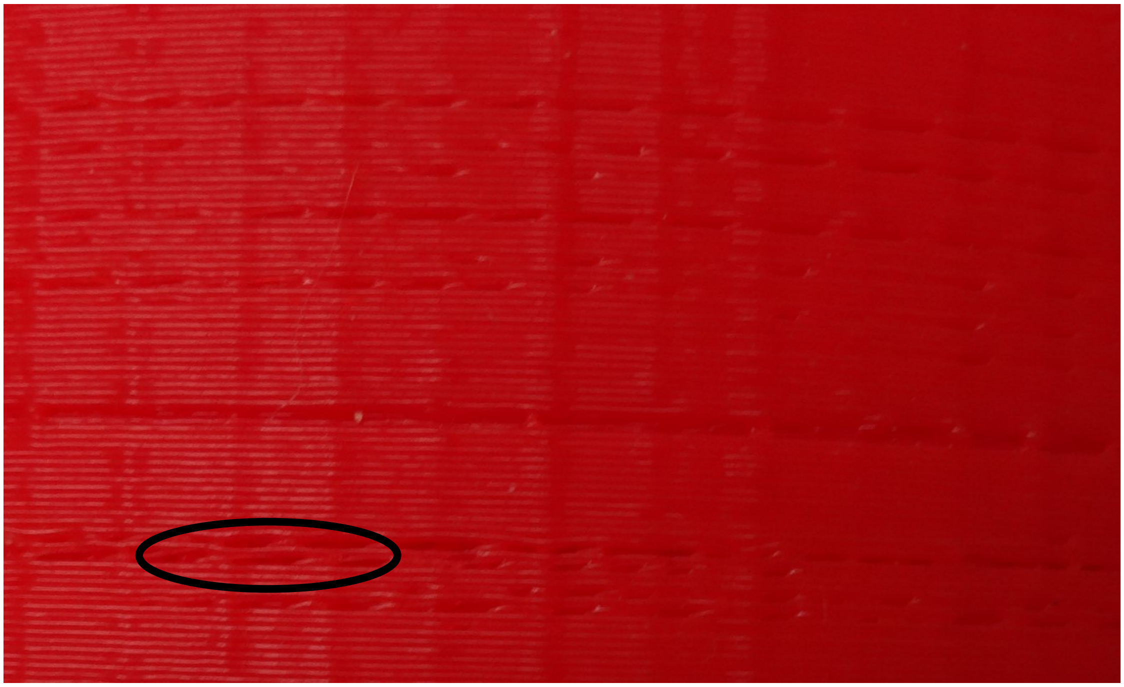

Figure 2-9. Under extrusion on exterior surface of 3-D printed object (observable as dark lines).

This study has some limitations. The density of the samples is measured for a material group and not for individual colors of the same material. There may be a small difference in density among the various colors, which may explain the mass difference between the colors of a material. The density measured depends on the density of the water, and various environmental factors can produce slight errors. Although such errors would be insignificant in most other cases, the filaments in this study have densities close to the density of water, which can create significance. It should also be pointed out that the cross head extension is applied only to the reduced section of the specimen. The tapering section will have some extension, but it would affect the strain values only, not the maximum stress value, which is the focus of this study. Load difference due to orientations was limited only for two materials in this study, but has been observed before [30-32].

These limitations lead to several potential sources of future work. The reasons behind the difference in mass for various specimens can be studied in a fully controlled and measurable environment. In addition, the material can be printed with the length of the specimen being vertical on the printer and tensile strength can be tested. This is the weakest of the axes as there are gaps between the layers of seemingly solid infill in FFF [20] and easiest to break. Specimens should be printed using other slicing software and other variable parameters such as the tool paths. In addition, the impact of the geometry of the part need further study to determine the limitations of FFF for manufacturing [60]. Materials can undergo significant property changes during storage. To account for this an identical material subjected to different storage conditions both pre and post printing and subsequently tested can indicate the sensitivity to environment that printing materials exhibit. Finally, as the prosumer 3-D printer material market continues to expand there will be other materials (e.g. polymaker PC-plus) and composites that could be useful for mechanically loaded parts, which will need to be tested.

2.4. Conclusions

The study demonstrates that the tensile strength of a 3-D printed specimen depends largely on the mass of the specimen, for all materials. This enables prosumers to solve the challenge of unknown print quality using a two-step process to estimate the tensile strengths described in this study for a given material. First, the exterior of the print is inspected visually for sub-optimal layers from under or over extrusion. Then, to determine if there has been under-extrusion in the interior, the samples are massed. This mass is compared to what the theoretical value is using the densities provided in this study for the material and the volume of the object. This provides a means to assist low-cost open-source 3-D printers expand the range of object production to functional parts. The strongest material among those tested was polycarbonate with a maximum tensile strength of 49 MPa. The most flexible material was Ninjaflex, which did not break after an extension of about 800%. The tensile stress for Ninjaflex at 800% extension was over 12 MPa (average of all colors). Nylon materials were stronger than Ninjaflex and Semiflex, and much more flexible than ABS, HIPS, T-Glase, and polycarbonate, providing a good balance between strength and flexibility.

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3. Viability of Distributed Manufacturing of Bicycle Components with 3-D Printing: CEN Standardized Polylactic Acid Pedal Testing

3.1. Introduction

Recent advances in additive manufacturing and 3-D printing have been forecast to bring on the next industrial revolution [1, 2]. With the technological evolution of the self-replicating rapid prototyper (RepRap), an open-source 3-D printer that can fabricate more than half of its own parts [3-5] the costs of 3-D printers have fallen from tens of thousands to a few hundred dollars. Already RepRap printer designs make up the majority of 3-D printers in use now [6]. This allows for the radical re-arrangement of production [7, 8] to follow peer-to-peer methods [9-11] and even for consumers to become prosumers and make their own products [12-14]. A study has already shown that ownership of a RepRap 3-D printer is economically beneficial for American consumers if it is used to fabricate a modest number of products in a year, offsetting conventional purchases thanks to the rapid expansion of free and open source designs for products on the Internet [15]. In addition, this form of distributed manufacturing has an environmental benefit due to the decrease in shipping and often less intensive additive manufacturing [16, 17].

3-D printing has been touted as democratizing manufacturing in the developed world, there have also been proposals to use 3-D printing for sustainable development in marginalized communities [18]. The application of 3-D printers in the developing world has been used for manufacturing necessities in the field following a humanitarian crisis by groups such as Field Ready [19]. 3-D printers can also be used directly for development in the developing world [20]. This can be done by recycling thermoplastic post-consumer waste into 3-D printing filament using recyclebot (waste plastic extruders) [21-25]. In addition, 3-D printers can be used to fabricate appropriate technology. Appropriate technology is generally recognized as encompassing small-scale, decentralized, labor-intensive, energy-efficient, environmentally sound, and locally controlled technologies [26]. Appropriate technology can be developed using open source principles, which have led to open-source appropriate technology (OSAT) [27] and thus many of the plans of the technology can be freely found on the Internet [27, 28].

In order to investigate the potential of distributed manufacturing of OSAT this study makes

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Bicycles serve as a primary form of transportation for people throughout much of the developing world. Greater access to working bicycles can also provide long term benefits to developing communities by giving people an expanded range of travel, and enabling increased access to health care, markets, and education. Bicycles are used not only for personal transportation, but also for the transporting of goods and materials making the bicycle a tool for agriculture, commerce, and general economic empowerment.

Specifically, this study tests pedals fabricated by poly-lactic acid (PLA), a biodegradable and recyclable bioplastic. First, a CAD model of the pedal was created. Then the material was selected among the various commercial materials based on strength and cost. Then the pedal was 3-D printed on a commercial RepRap and tested following the CEN (European Committee for Standardization) [29] standards for racing bicycles with 1) static strength testing, 2) impact testing and 3) dynamic durability testing. The results are presented and discussed in the context of distributed manufacturing of OSAT in the developing world.

3.2. Methodology

The methodology includes first selecting among the various commercial materials based on strength and cost, then developing an open source design using only open source tools, and describing the open source 3-D printer used and the settings to fabricate the pedal. Then the tests for the pedal performance are detailed to meet CEN standards.

3.2.1. Material Selection

In the RepRap community PLA is the most popular 3-D printing material, being available for the vast majority of 3-D printing supplies vendors. PLA has a relatively low melting point, 150°-160° C, thus requiring less energy to print with the material, which also provides advantages for off-grid applications in the developing world [30, 31]. In addition, PLA has been shown to be a safer alternative to toxic ABS plastic fumes, the second most popular 3-D printing material as gauged by availability [32, 33]. The mechanical properties of RepRap 3-D printing materials have thus been investigated in some detail [34-36]. The strength of the printed specimens and the costs of various commercial materials [37] are compared in Table 3-1:

Table 3-1: Comparison of strength, cost of various commercially available materials

Material	**Cost of the Filament Tested (USD/kg)**	**Average Maximum Tensile Stress (MPa)**	**Standard Deviation of Maximum Tensile Stress (MPa)**	**Strength to Cost ratio (Mpa.Kg/ USD)**
ABS (Tanikella, 2016)	42.95	28.75	3.15	0.67
ABS (Tymrak, 2014)	42.95	28.5	NA	0.66
HIPS (Tanikella, 2016)	24.95	20.71	1.27	0.83
Nylon 618 (Tanikella, 2016)	43.50	31.60	3.20	0.72
Polycarbonate (Tanikella, 2016)	74.95	49.08	3.03	0.65
T-Glase (Tanikella, 2016)	66.00	32.55	4.21	0.49
PLA (Wittbrodt and Pearce, 2015)	24.95	53.77	1.46	2.16
PLA (Tymrak, 2014)	24.95	56.6	NA	2.27

As can be seen in Table 3-1, PLA has the highest strength to cost ratio and was chosen for this study.

3.2.2. Open Source Design

The pedal was designed for ease of printing (e.g. minimizing overhangs) and least number of parts. It was designed on an open source CAD software [38]. The bicycle pedal was designed using the dimension of the spindle for the stock 100mmx77mm pedal of the Black Mamba bicycle [39] as a reference. The Black Mamba is the East African common name for the most popular mass used bicycle in the developing world. However, the pedal can be used on other spindles with slight modifications to the parametric design. The top, side, front, and axonometric views are shown in Figure3-1.

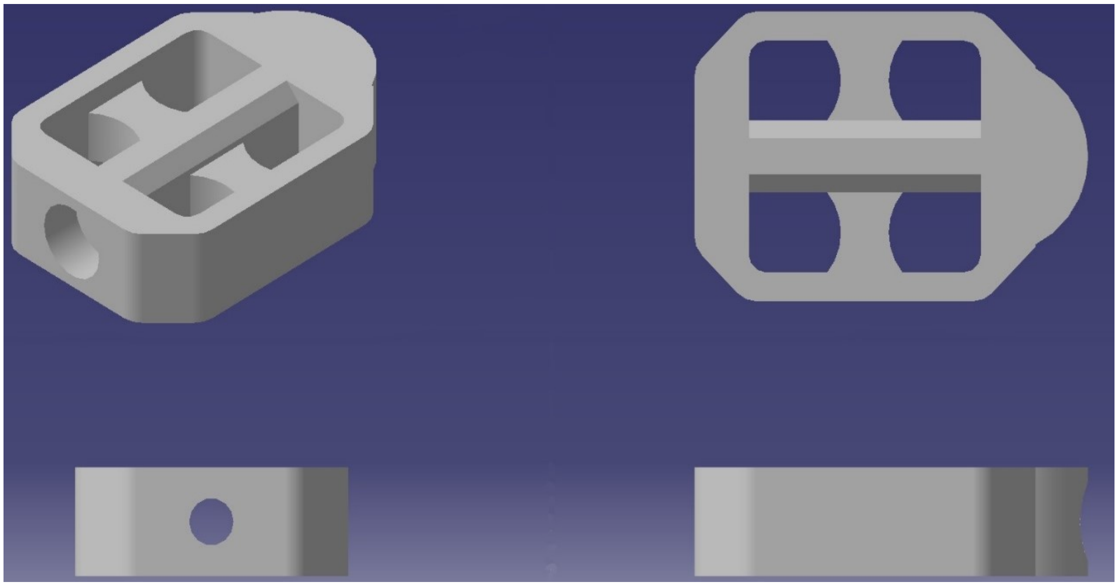

Figure 3-1. Open source 3-D printable bicycle pedal

3.2.3. RepRap 3-D printer

A commercialized version of the RepRap 3-D printer was used (Taz 4) [40]. It is a completely open sourced printer [41]. The cost of the printer is US$2200. The print area is 290mm x 275mm x 250mm. The printer is designed for a 3mm diameter filament, it has a heated bed for better adhesion and has dual extruders. The pedal requires 80mm x 30mm x 116mm. Hence, 3-D printers of smaller print area (and thus less expensive) can be used to print the pedal.

3.2.4. Print Settings

Cura 15.04 was used as a slicer for generating Gcode from the CAD model [42]. Other research has described what effect the orientation of layers may have on the properties of a printed part [43] and commercial grade fused deposition modeling (FDM [the intellectual property limited subset of fused filament fabrication (FFF), which can only be used by the trade mark owner]) printers have shown a strength dependency on different types of infill patterns and internal structures [44]. The pedal was printed at 50% infill with 1mm thick solid outer shell. 100% infill would have increased the weight of the pedal. The solid outer shell helps retain the shape during print and also helps absorb impact energy. The mass of the pedal was estimated by the software to be 111g (118g including the supports for printing). The pedal was printed using Lulzbot Taz 4 printer. The mass of the pedal was 104.44g. The print time was 6 hours 18 minutes.

3.2.5. CEN Testing

The CEN standards for pedals requires the passing of three different tests: 1) static strength test, 2) impact test and 3) dynamic durability test.

3.2.5.1. Static strength test

The test requires the pedal to be subjected to a 1500N vertically downward force as shown in Figure 3-2. The test is satisfied if there are no fractures anywhere.

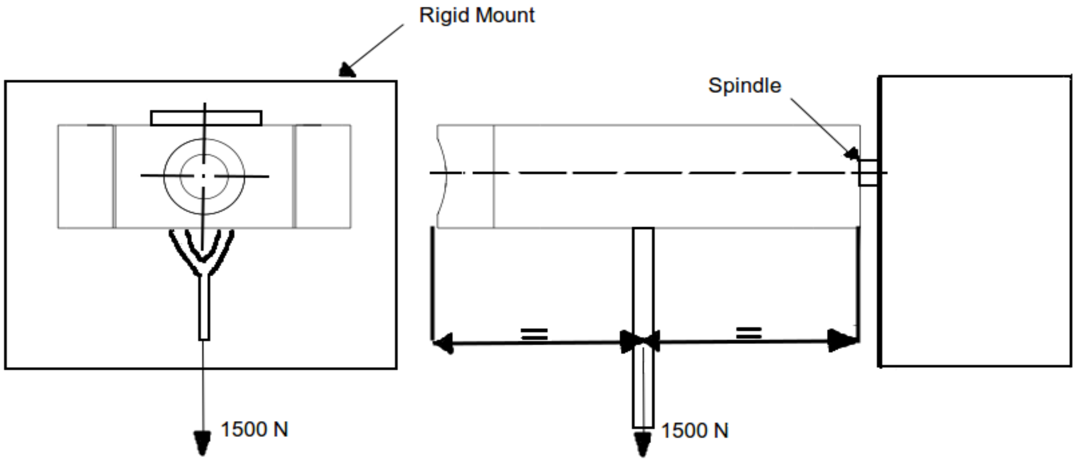

Figure 3-2. CEN static strength test method schematic.

The pedal was tested on a Universal Testing Machine and the setup was as shown in Figure 3-3.

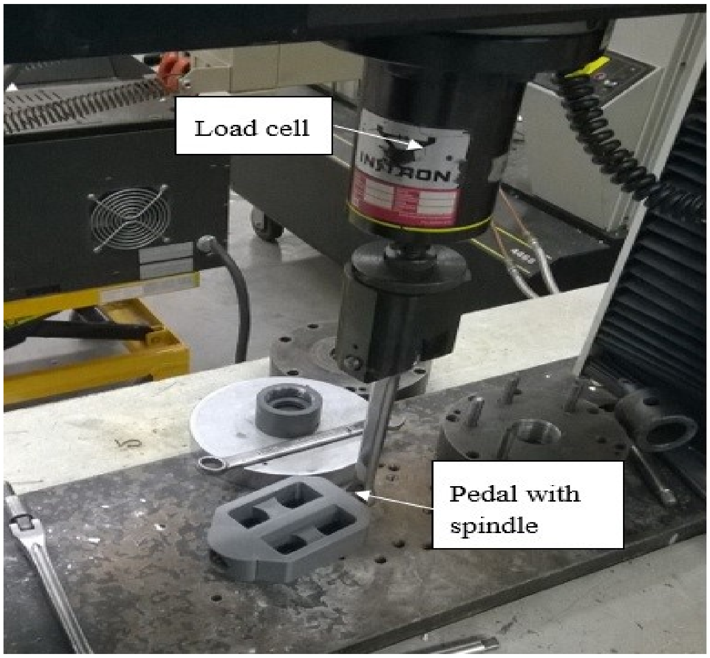

Figure 3-3. Test setup on a Universal Testing Machine.

The test equipment is an Instron 4206. Compression load was applied uniformly on the pedal. A load of 3000N was applied, which is double the prescribed amount**.**

3.2.5.2. Impact test

The CEN impact test for bicycle pedals requires that a mass of 15 kg be dropped on the pedal from a height of 400mm at 60mm from the mounting face, as shown in Figure 3-4. The test is satisfied if there are no fractures or permanent sets beyond 15mm.

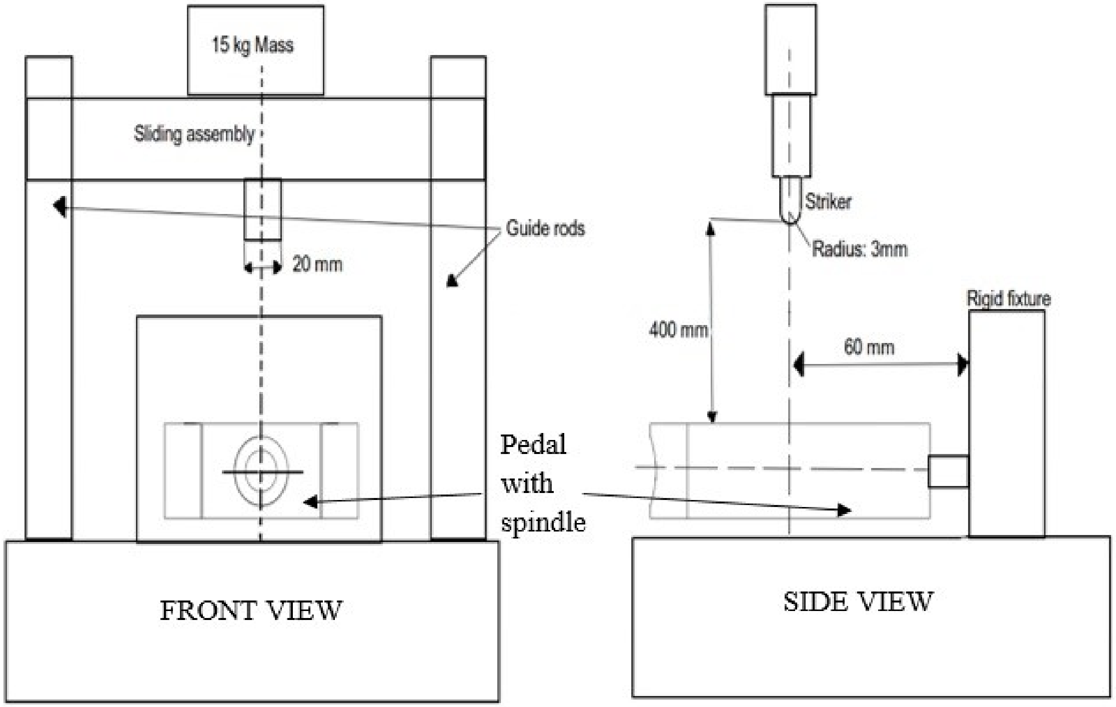

Figure 3-4. CEN impact Test method schematic.

A small aluminum rod of radius 3mm and length 20mm was stuck on the pedal at 60mm from the mounting face using super glue. The mass assembly (Figure 3-5-a) was dropped on the pedal with the help of the rigid guide assembly fixture (Figure 3-5-b). The mass consists of three 4.54Kg masses along with approximately 2kg of the aluminum assembly, adding to slightly over 15kg.

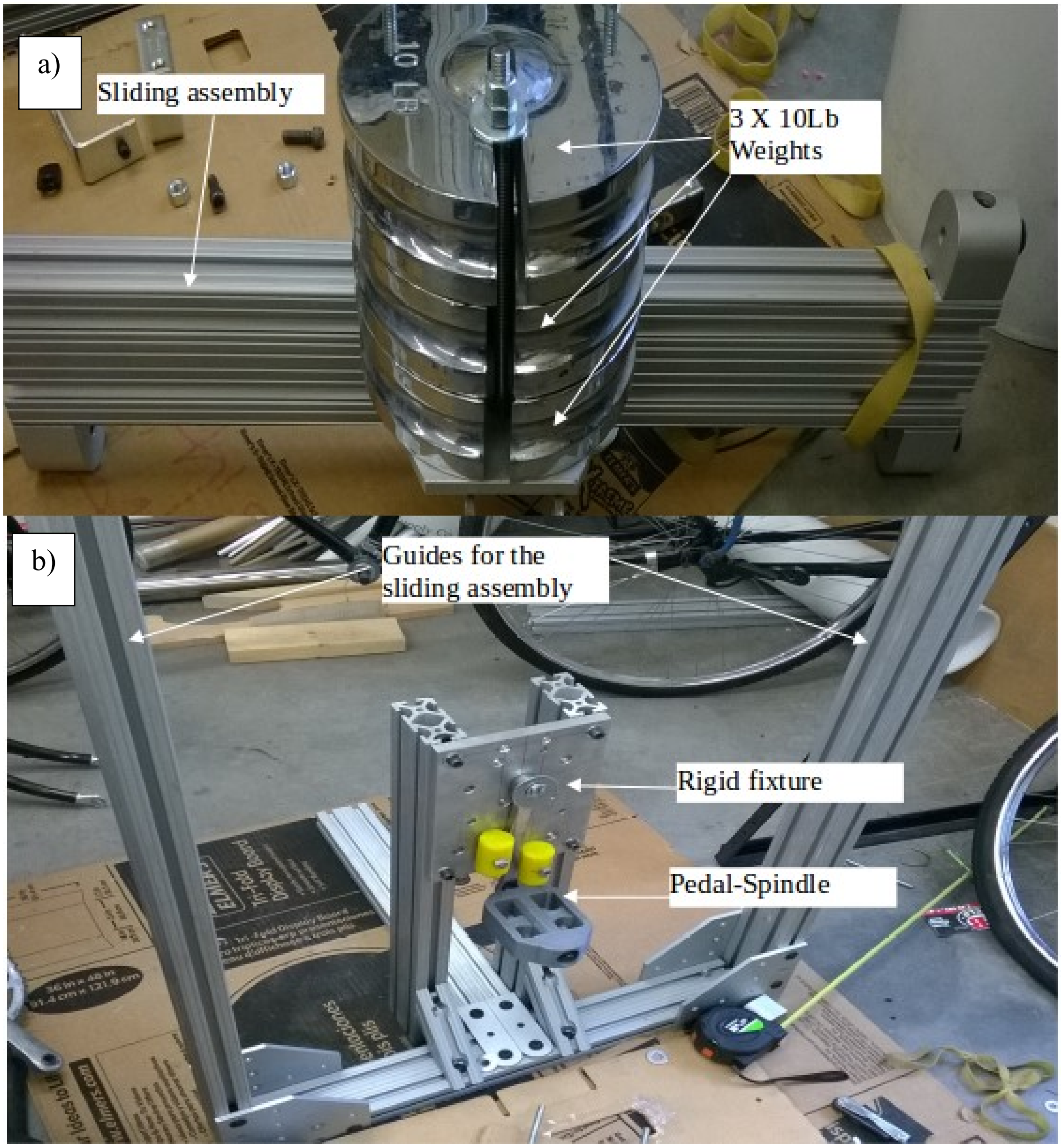

Figure 3-5. Impact test setup.

3.2.5.3. Dynamic durability test

CEN standards require that the spindle be spun at 100 rev/min for a total of 100,000 revolutions. The pedal should have a mass of 65kg suspended by a spring. This test is intended to simulate a real world bicycle with a person standing on the pedals. The test is satisfied if there are no fractures or cracks in the Pedal-Spindle system. The pedal was attached to a bicycle and tested directly. The pedal was tested for about 300,000 revolutions (50 hours over a period of 2 weeks), with approximately 200,000 revolutions while the person's weight was carried by the pedals alone. The weight of the person was 75kg. The cadence fluctuated between 90 and 100 rpm for most of the test duration.

3.3. Results

We conducted the three CEN pedal tests for the 3-D printed pedal: 1) static strength test, 2) impact test, and 3) dynamic durability test. Overall, the CEN pedal tests of the 3-D printed pedal were successful.

3.3.1. Static strength test

Upon completion of the CEN static strength test on the bicycle pedal, no fractures, visible cracks, or distortion of the assembly were observed.

3.3.2. Impact test

Upon completion of the CEN impact test on the bicycle pedal, no fractures were observed. A small visible "dent" was observed at the impact point as can be seen in Figure 3-6.

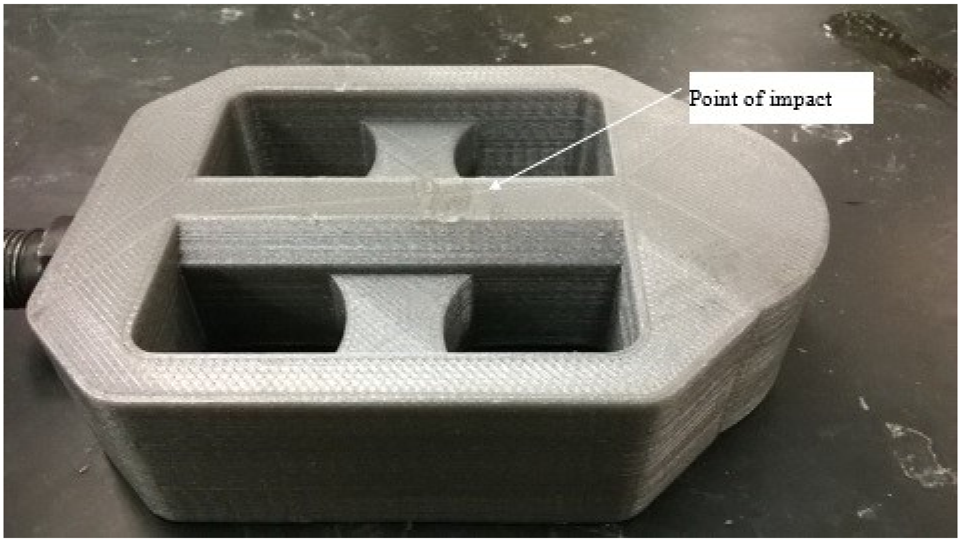

Figure 3-6. Pedal after the impact test.

3.3.3. Dynamic durability test

Upon completion of the CEN dynamic durability test on the bicycle pedal, no fractures or visible cracking were observed on the pedal.

3.4. Discussion

The Stock Black Mamba pedal costs 280 Kenyan Shillings (KES) in Kenya, which is equivalent to US$2.77. This includes the spindle and bearings which have not been printed, due to the high strength required by the spindle and difficulty in manufacturing the bearings. Upon pedal failure, the bearing and spindle are reusable nearly all of the time and it just the pedal itself that fails. The stock pedal weighs 277g (excluding the spindle and bearings). The 3-D printed pedal is intended to be a replacement for the stock pedal, used with the bicycle's original spindle and bearings. A comparison of the cost of material for the 104g tested pedal is shown in Table 3-2.

Table 3-2: Cost of the pedal based on material source.

PLA material source	Cost per kg (US$)	Pedal cost (US$)
Commercial PLA closed source [45]	53.33	6.30
Commercial PLA [37]	24.95	2.90
PLA pellets through recyclebot [46]	<5.00	0.59
Recycled PLA via recyclebot no labor costs [47]	~0.10	0.01

As can be seen in Table 3-2, commercial PLA from proprietary vendors produces a pedal that is more than double the cost of the stock pedal. PLA from open source vendors is about 5% more expensive than the stock pedal. This cost differential could be easily overcome by further refinement of design, but it is clear that the costs of the stock Black Mamba pedals are well below even the cheapest pedals sold in developed economies (e.g., the least expensive pedals in the US market according to Google Shopper on 6.10.2016 was $4.99 for a children's pedal and ranged up to $30.00). However, filament is still sold at a substantial markup, as raw pellets can be purchased for under $5.00 per kg, reducing the cost of the 3-D printed pedal by a factor of five and ten compared to the open source and proprietary filament vendors, respectively. Bicycle shops or other small companies, or even individuals, can purchase a commercial recyclebot (e.g., Filastruder) or build one from freely available plans to produce their own filament. Doing so would drop the price of a printed pedal to nearly one fifth of the current cost of the Black Mamba pedal. Taking it one step further, if waste plastic can be procured (e.g., saving spent food containers like McDonald's orange juice cups that are made of PLA) the price of the pedals falls to a single U.S. cent for the materials cost. PLA is used in only select applications now, but it is becoming a more popular polymer to be used in packaging of all kinds (e.g. Wal-Mart the largest uses it in 100s of millions of containers a year). It should be pointed out that in some locations there are no source of PLA waste, however other polymers can be used in recyclebots and RepRaps, which would need to be tested in future work.

The development of 3-D print shops has been proposed in the industrialized world because distributed manufacturing offers a large potential profit because of reduced manufacturing costs [48]. It is instructive to analyze the potential for such 3-D print shops (perhaps located within a more conventional bicycle shop) in the developing world. If it is assumed that the parts for RepRap and recyclebot can be purchased for $1000, then 1,010 pedals could be manufactured at a cost of materials and equipment of $1 per pedal. As the print time is over

6 hours/pedal, it can be assumed that a print start occurs once at the start of day and once at the end of day results in 505 days of printing. Thus, even for this extremely low-cost part the payback time is less than 1.5 years. As commercial pedals sell for $2.77 there is substantial potential revenue to account for labor and other business expenses as well as healthy profit. Realistically, the recyclebot and RepRap distributed manufacturing system would be used to fabricate far more than a single low-cost product. For example, they could be used to 3-D print a host of replacement parts for small local retailers, not just replacement bicycle parts, but also parts for agricultural implements and water pumps [49], medical and scientific equipment [50,51,52] and home wares [15].

The biggest advantage of this pedal and the distributed manufacturing approach is that it can be printed in remote locations, where transportation costs become a big factor in the overall cost of products. In remote and rural areas, where bicycles may be the most depended upon and subjected to the harshest conditions, access to spare parts is necessary, but expensive. The stretched supply chains in these areas may not be able to adequately keep bicycle parts sufficiently stocked at an affordable price. Items that are stocked are already so expensive at wholesale, that it makes it difficult for small, rural retailers to sufficiently profit from their sale.

The printed pedal is significantly lighter than the stock pedal (104g vs. 277g). Though negligibly more energy efficient, this reduction in weight may prove to be a marketing negative to the developing world consumer. The heavier material and construction of the stock Black Mamba pedal give it the perception of being rugged and reliable to consumers. Though sufficiently strong to surpass any of the CE tests, the printed pedal may be perceived by consumers to be of lower quality, though specific marketing research would be necessary to verify this concern. It should therefore sell at a significantly lower price point than the stock Black Mamba pedal.

Anyone can print the pedal with a basic FFF 3-D printer, basic computer skills and sufficient filament. Local bicycle shops in the developing world can print out pedals, (among other parts) instead of buying them from suppliers. In addition, a 3-D print shop might offer the pedal as one of many varied products. This would save a lot of transportation costs. It would also reduce the storage costs as products do not have to be kept in stock. The local bicycle shops or 3-D print shops can also modify the design easily, enabling them to customize the pedal according to the needs of the community or to provide higher value products to their customers. Consumers can also print the pedal at home, using desktop 3-D printers. This would be economical as well as convenient.

3.5. Conclusions and recommendations

Replacement pedals for a typical developing world bicycle were successfully designed using open source software and manufactured using an open-source 3-D printer. These pedals were tested following the CEN bicycle pedal standards and the results show that the pedals meet the standards and can be used on bicycles. The 3-D printed pedals are significantly lighter than the stock pedals used on the Black Mamba, which provides a potential performance enhancement. The pedals can be made using recycled materials, reducing the material costs, potentially as low as US$.01 in material costs; reducing bicycle costs even for those living in extreme poverty. The pedals can be customized by anyone trained in CAD use, using FreeCAD. These CAD files could be made locally, or more likely from an online downloadable database that is freely available. Other bicycle parts could also be manufactured using 3-D printers by bicycle shops for a better return on investment on the 3-D printer.

There are many other materials available on the market for prosumer FFF 3-D printing. A recent study has already investigated the mechanical properties of RepRap 3-D printed parts using a commercial open-source RepRap for a wide range of materials. Future work could probe the use of these other materials for bicycle components. In addition, with the continued development of novel and affordable 3-D printing technologies, the types of materials that may become common for FFF is expected to grow [53, 54] and involve the use of additives [55] such as strengthening agents to common 3-D printable materials [56, 57]. Other techniques involve treating 3-D printable materials to increase strength [58]. In addition, other components of the bicycle such as handlebars, brake levers, brake pads, handlebar grips, etc. could be designed and tested for use.

Although, tensile strength of many 3-D printing materials are available, these results cannot directly be used for structural analysis. The orientation, infill density, direction of force applied, type of forces, etc. change the strength of the component being analyses. A database of mechanical properties for various combinations of orientations, infill density, and direction/method of forces applied would enable FEA analysis of components would help create better designs and reduce testing time.

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4. Conclusion and Future Work

The studies in this thesis show the mechanical properties of fused filament-based 3-D printed components and the potential for manufacturing these components for functional use.

The first study provides a database of mechanical properties of a wide-range of FFF materials. It also shows that the tensile strength of components printed under similar conditions depends largely on the mass and this can be used for estimating the strength of components. This information can be used as a role of thumb for technical viability with low-cost equipment.

The data in the first study needs further analysis. Some flexible specimens have more than 100% density, as compared to the filament density. This is probably due to the fact that they are flexible, which may have compressed the filament when it was heated and compressed for printing. However, a detailed analysis would be helpful to understand the reasons better.

The second study shows that a bicycle pedal can be manufactured using open source technology. The 3-D printed pedal meets the CEN standards for a racing bicycle. This design and method of fabrication can be used by anyone around the world to 3-D print bicycle pedals. From the first study results it is also possible to predict that a pedal printed similarly will also meet these standards as long as it has a similar mass.

The pedal was tested according the CEN standards. However, the real world pedals may have different requirements in terms of strength. One example for this is that the pedals usually develop cracks at the outer edge which can hit the ground. The CEN standards have no tests for the strength in that edge. Another real world problem that may be encountered is high temperature. Plastic at higher temperatures are generally weaker and the CEN standards require no temperature control over the tests.

This work indicates that functional parts are indeed possible to fabricate using low-cost open source 3-D printers and this work can be continued further. More materials can be included as part of the database for mechanical properties. Other mechanical properties such as bending strength, torsional strength, and compression strength can be tested for the materials providing more variables for structural analysis. There is a potential for investigation into the effect of variables for printing such as orientation, infill density, shell thickness, speed, temperature, room (atmospheric) conditions, etc. A database of several such variables will enable better design of 3-D printed components using design analysis softwares. Slicing softwares such as Cura/Slic3r can be modified to automatically determine the best orientation for printing based on inputs of structural and strength requirements and more advanced versions can also take into account environmental conditions (e.g. humidity)

Another area of future work is the study of recycled materials. The cost of filament is fairly high as compared to the cost of raw materials and recycled plastic will significantly reduce the cost. The use of recycled materials will also be more environmentally friendly. A study on the mechanical properties of recycled materials will be useful. There is potential for study in the deterioration of mechanical properties of materials such as PLA, ABS, etc. after consecutive recycling using different process parameters. These studies will be useful to determine the number of times a given component can be recycled before it loses its function and also provide a guide to the amount of virgin material or additives are necessary to make a functional part from recycled plastic.

Future work can also look into composites of various filaments in a component. Some materials are rigid (e.g. PLA, ABS) and some are flexible (e.g. Ninjaflex). These different materials can be used in different parts of a component to achieve the required strength, flexibility and look.