

Bending Stiffness of Recycled Polylactic Acid in FDM Printing: a Cantilever Beam Deflection Study

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ABSTRACT

This study examines the closed-loop recycling of 3D-printed components that have reached the end of their service life within a student robotics context. While additive manufacturing is naturally material-efficient, many functional parts lose their utility following seasonal competitions, such as the FIRST Tech Challenge (FTC). Polylactic acid (PLA) was selected for this investigation due to its prevalence in educational institutions. To evaluate the feasibility of local material recovery, disposed PLA parts were shredded and re-extruded into filament using a desktop extrusion system, and printed into cantilever beam specimens along with a virgin PLA control group under identical settings. Mechanical integrity was evaluated by dead-weight cantilever deflection testing over five load levels (300-500 g). Recycled PLA specimens demonstrated a mean effective bending modulus of 0.841 GPa – a 31.5% reduction relative to the 1.228 GPa measured for virgin PLA ($t = 21.2$, $df = 37$, $p < 0.001$). This reduction is substantially larger than the changes reported for tensile modulus of recycled PLA in the closely related literature (at most a few percent, and in some 3D-printed process chains a slight increase), which is attributed to the amplified effect of inter-bead bonding defects on structural (bending) stiffness at the low (15%) infill density used for lightweight FTC components. These findings confirm that single-cycle mechanically recycled PLA retains sufficient structural stiffness for non-impact, stiffness-governed robotics applications. However, components subjected to active collisions require further mechanical characterization before recycled material can be broadly recommended. Overall, this work demonstrates a low-cost, low-resource pathway for closing the material loop in educational robotics and reducing reliance on external supplies.

INTRODUCTION

The FIRST Tech Challenge (FTC) is a competitive robotics program in which student teams design, build, and operate robots to compete in seasonal game challenges. The rapid prototyping demand within FTC competitions has made fused deposition modeling (FDM) 3D printing a standard tool across teams worldwide. One of the common materials used in 3D printers today is polylactic acid (PLA), mainly because it is readily available and relatively easy to print. Despite being one of the most convenient materials to use, the competitive nature of the activity results in the creation of large amounts of waste

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PLA. For instance, there are cases where printers fail to work correctly due to errors in slicer settings and in CAD model design, leading to wasted prints that never see action. In addition, once a FTC season concludes, most of the robot parts become useless because of new design specifications in the game rules. The fused deposition modeling (FDM), or fused filament fabrication (FFF), is the most prevalent additive manufacturing method in educational and recreational applications. In FDM a long thermoplastic filament is melted in an extruder and deposited in a layer by layer process on the work platform following the trajectory designed by the software. The layers stick together as they cool down and solidify, eventually creating the three-dimensional object. FDM enables the creation of highly complex objects directly from a digital CAD model, which makes the process especially suitable for rapid prototyping during a design-and-build process. For example, this technique can be very useful in robotics competitions. For different sets of mechanical, thermal and processing properties, various thermoplastic materials are available in filament form depending on the specific application. Acrylonitrile butadiene styrene (ABS) has good impact resistance and higher heat tolerance, but requires high bed temperatures and an enclosed print chamber to prevent warping as it cools. Polyethylene terephthalate glycol (PETG) offers a good balance of strength, layer adhesion and resistance to moisture, and is increasingly used for functional parts. Elastomeric parts can be printed by means of flexibles such as thermoplastic polyurethane (TPU). High-performance material such as nylon and polycarbonate have better mechanical properties but require more precise thermal control and are more difficult to reliably print. PLA, in contrast, has a relatively low glass transition temperature (approximately 55-60 °C) and melting point (approximately 175 °C), meaning that it can be printed at lower nozzle temperatures (typically 190-220 °C) than ABS or nylon, without requiring a heated enclosure. This reduces printer hardware requirements and simplifies the printing process. PLA also exhibits low shrinkage during cooling, which minimizes warping and improves dimensional accuracy on open-frame printers. These characteristics collectively make PLA the dominant material in educational FDM contexts: it is inexpensive, widely available, forgiving of suboptimal print settings, and produces parts with adequate stiffness and surface quality for most prototyping and light-load functional applications.

The current methods for waste management in school robotic environments remain rather haphazard, as components are either thrown away in regular trash or kept indefinitely. None of the two approaches described above appears to be environmentally friendly or financially beneficial. Mechanized recycling by way of shredding end-of-life plastic products and extrusion into a fresh strand of filament seems to represent a promising solution with a minimum level of required equipment, as demonstrated for other thermoplastics such as ABS [1]. Nevertheless, the viability of this technique hinges on the ability to ensure that the filament produced has adequate mechanical qualities.

Proposed Solution

This study proposes a closed-loop recycling approach for PLA waste generated in FTC robotics environments. Instead of discarding failed or obsolete printed parts, the material is mechanically reprocessed into filament suitable for FDM printing. By focusing on the relationship between material reuse and mechanical properties, this study aims to determine whether recycled PLA can serve as a viable

alternative to virgin one. This directly addresses both sustainability concerns and the high material consumption associated with competitive robotics.

LITERATURE REVIEW

PLA in FDM Additive Manufacturing

Polylactic acid (PLA) is a bio-based thermoplastic polyester derived from renewable resources such as corn starch or sugarcane. Its low glass transition temperature (55-60 °C) and melting point (~175 °C) and good printability have made it the dominant material for desktop FDM printing. The mechanical properties of bulk PLA are well characterised: Young's modulus is typically reported in the range 3.0-3.5 GPa and tensile strength in the range 50-65 MPa for injection-moulded specimens [2].

Mechanical properties of FDM-printed PLA parts differ substantially from bulk values, primarily because of the layered microstructure, inter-bead bonding quality, and the proportion of air voids introduced by the chosen infill density and pattern. Chacón et al. [4] investigated the effect of process parameters, including infill density and pattern, on the mechanical properties of FDM-printed PLA. Fernandez-Vicente et al. [5] reported that reducing infill density from 100% to 20% decreased the apparent tensile modulus by more than 50%, from approximately 3.0 GPa to 1.4 GPa. At 15% infill density – as used in the present study – effective bending moduli in the range 0.9-1.3 GPa are therefore consistent with published trends and reflect the dominant influence of infill geometry on structural stiffness rather than intrinsic material properties alone.

Mechanical Degradation of PLA upon Recycling

The mechanical consequences of recycling PLA arise primarily from thermally induced chain scission during melt-reprocessing. Each pass through the extruder barrel exposes the polymer to elevated temperatures (typically 185-210 °C), causing random cleavage of the ester backbone and a reduction in number-average molecular weight (Mn) [6]. Lower Mn reduces the density of entanglements between polymer chains, which in turn reduces tensile strength and ductility while having a comparatively smaller effect on elastic stiffness.

Pillin et al. [6] reported that a single melt-processing cycle reduced elongation at break by approximately 20% and tensile strength by 10-12%, while Young's modulus decreased by only 5-8%. Zhao et al. [7] used gel permeation chromatography to confirm a 12% reduction in Mn after one recycling cycle, correlated with a decrease in elongation at break from 6.5% to approximately 5.2%. Sanchez et al. [8] noted that the magnitude of degradation depends on extrusion temperature and dwell time – processing at the lower end of the recommended temperature range (185-190 °C) minimises chain scission and produces filament closest in properties to the virgin material.

Two closely related studies by the same research group provide directly comparable prior data on recycled-PLA modulus, though neither examined bending stiffness: both report only tensile properties

(ISO 527, extensometer-measured). Cruz et al. [9] re-extruded PLA through five cycles and found the tensile modulus of the resulting filament remained essentially unchanged (3.09-3.56 GPa across cycles, with no consistent downward trend), even as number-average molecular weight fell by 46.9% and melt flow index increased six-fold. Sanchez et al. [8], an expanded journal version of the same underlying study comparing four recycling process chains (injection-moulded reference, extruded feedstock, and printed specimens with and without a reference injection step), found elastic modulus changed by at most 3.7% for injection-moulded material and remained constant for extruded feedstock – and, for 3D-printed specimens specifically, slightly increased with recycling (+4.1% to +4.7% after five cycles), even as tensile strength fell by 38-71% depending on the process chain. This indicates that molecular-weight loss during recycling primarily degrades strength and ductility rather than elastic stiffness, likely because increasing crystallinity and reduced internal void content (from lower melt viscosity) partially compensate for the loss of chain-entanglement density. Anderson [3] similarly found tensile modulus of once-recycled, 100%-infill printed PLA was statistically unchanged (4258 MPa virgin vs. 4032 MPa recycled, a 5.3% difference, $p = 0.054$), despite a significant 10.9% reduction in tensile strength and significantly increased property variability. None of these studies presents a structural bending-stiffness measurement at reduced infill; this gap (recycling-induced degradation well characterized in tension across multiple studies, but not in bending at low infill) is one motivation for the present study.

Cantilever Beam Theory and Low-Resource Mechanical Testing

The cantilever beam is a classical structural configuration whose deflection under a concentrated end load is described by the Euler-Bernoulli beam equation. For a uniform rectangular beam of length l , width b , and thickness h , clamped at one end and subjected to a concentrated load P at the free end, the tip deflection is [10]:

$$\delta_{max} = \frac{Pl^3}{3EI} \quad (1)$$

where E is the Young's modulus of the material and I is the second moment of area of the rectangular cross-section:

$$I = \frac{bh^3}{12} \quad (2)$$

Rearranging for E :

$$E = \frac{Pl^3}{3I\delta} \quad (3)$$

This inverse relationship allows the effective bending modulus to be determined from measurements of applied force and corresponding deflection without strain gauges. Beyond the free-end tip, the deflection at any cross-section at distance x from the fixed support is:

$$y(x) = \frac{Px^2}{6EI} (3l - x) \quad (4)$$

This profile equation describes how deflection accumulates non-linearly along the beam length: cross-sections near the fixed support deflect very little, while deflection grows rapidly towards the free end. The equation is derived by integrating the bending moment distribution $M(x) = P(l - x)$ twice with respect to x , applying the boundary conditions that both deflection and slope are zero at the clamped end ($x = 0$). The slope (or angle of rotation) at the free end is given by:

$$\theta = \frac{Pl^2}{2EI} \quad (5)$$

These equations assume a homogeneous, isotropic, linearly elastic material and small deflections ($\delta/l < 0.1$). Since the layered microstructure means that FDM-printed parts are neither perfectly homogeneous, nor isotropic, any modulus observed from beam deflection tests is thus an effective structural modulus as opposed to a true material constant. Despite this, the cantilever approach has been adopted in educational and low-resource research settings as a practical means of comparing relative stiffness between specimen groups [5], and provides reliable comparative results provided specimen geometry and test conditions are consistent.

METHODOLOGY

Recycled Filament Production

Figure 1 shows the components of the Wellzoom extruder being used for the project. In this study, the Wellzoom Desktop Extrusion Production Line II was used to produce recycled PLA filament. This system is a desktop extrusion unit that integrates an extruder, water cooling system, filament tractor, and winder into a single device.

Prior to loading, PLA waste was reduced to small pieces suitable for extrusion. Particle size consistency is an important factor in achieving stable material feed through the barrel and consistent filament diameter output.

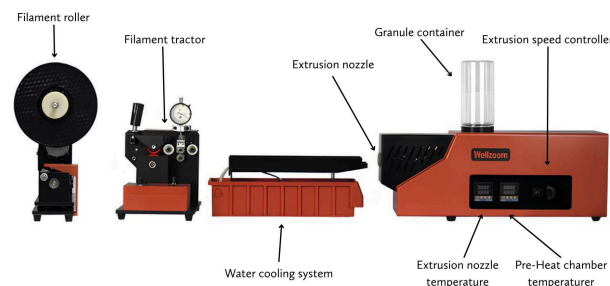


Figure 1: Well Zoom Extruder [11]

The waste material used for the recycled group was sourced exclusively from failed prints and retired FTC robot components originally printed with Bambu PLA Basic – the same commercial filament used for the virgin control group. No other brands or PLA formulations were included in the feedstock, eliminating material provenance as a confounding variable between the two groups.

The waste PLA and resulting recycled filament were not subjected to a drying step prior to extrusion or printing. As PLA is hygroscopic and residual moisture promotes hydrolytic chain scission during melt processing, the measured 31.5% reduction in modulus should be interpreted as an upper bound on the degradation attributable to mechanical recycling alone under controlled (dried) conditions.

The fragmented material was loaded into the granule container, where it was transported by a rotating screw through a heated barrel and forced through a 1.8 mm nozzle. The extruded filament passed through a water bath for cooling, followed by a filament tractor to maintain constant tension, and was finally wound onto a roller, producing filament of approximately $1.75 \text{ mm} \pm 0.05 \text{ mm}$ diameter. The pre-heat chamber temperature was set to 180°C and the extrusion nozzle to 185°C . The selected temperatures were based on the manufacturer recommendations and had mild adjustment through preliminary trials to ensure stable extrusion along with consistent filament quality. As shown in Figure 2, the filament is produced through a continuous extrusion and cooling process, before being wound onto a spool.

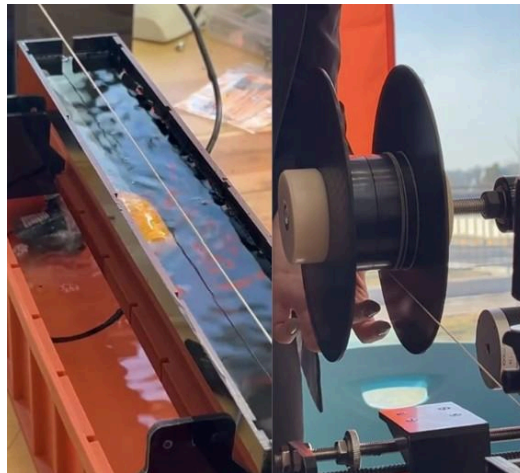


Figure 2: Filament being produced using a desktop extrusion system

The diameter of the recycled filament was dimensionally inspected prior to printing using a digital vernier caliper ($\pm 0.01 \text{ mm}$ resolution) along a 10 m spool at 0.5 m intervals (20 measurement stations). At each station, two orthogonal diameters (dx , dy) were recorded to account for cross-sectional ovality ($N = 40$

data points). The resulting diameter was 1.75 ± 0.04 mm (mean $\pm$ SD, range 1.68-1.82 mm) – closely matching the manufacturer-specified tolerance of the virgin Bambu PLA Basic filament (1.75 ± 0.03 mm) and confirming the recycled filament's suitability for standard 1.75 mm direct-drive FDM extrusion without nozzle clogging.

Specimen Design and Printing

Flat rectangular beam specimens were designed in Autodesk Fusion [12] and exported as STL files for slicing. The nominal dimensions were 200 mm (length) $\times$ 30 mm (width) $\times$ 4 mm (thickness). A circular through-hole of diameter 10 mm was positioned at the free end of each specimen, with the hole centre located 10 mm from the nearest edge, serving as the load application point. A CAD rendering of the specimen geometry is shown in Figure 3.

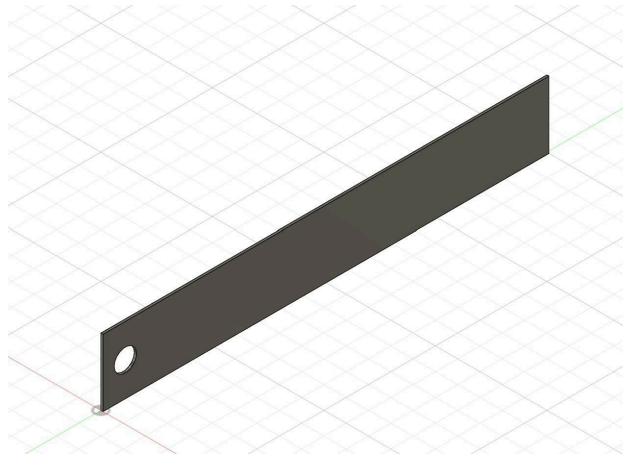


Figure 3: CAD screenshot of specimen geometry from Autodesk Fusion

All specimens were printed on a Bambu Lab A1 FDM printer using the standard Bambu PLA Basic profile with the following settings: nozzle temperature 220 °C, bed temperature 35 °C, layer height 0.2 mm, infill density 15% (gyroid pattern), and print speed 250 mm/s. All models were oriented flat on the build plate (200 $\times$ 30 mm face in the XY-plane, 4 mm thickness along the Z-axis) to align the extruded polymer beads with the principal longitudinal bending stresses. The shell geometry comprised 2 perimeter wall loops (0.84 mm total wall thickness), 4 solid top shell layers (0.8 mm), and 3 solid bottom shell layers (0.6 mm). These process parameters correspond to the default Bambu Studio 'Bambu PLA Basic' preset for the A1 printer rather than settings independently optimized for this study; the 220 °C nozzle and 35 °C bed temperatures reflect Bambu Lab's factory calibration for its PEI-coated plate and all-metal hotend, and the 250 mm/s print speed is within the manufacturer's recommended range (up to 300 mm/s), enabled by the A1's CoreXY motion system. These settings were held identical across both material

groups; a differential interaction between this process window and the recycled filament's lower melt viscosity was not independently isolated and is acknowledged as a limitation. Five specimens were printed from virgin PLA (V1-V5) and five from recycled PLA (R1-R5), for a total of ten specimens. The increased sample size of five per group was chosen to improve the repeatability and statistical reliability of the results. The actual dimensions of each specimen were recorded with a digital calliper before testing; these values were used in all subsequent calculations to account for any printing-induced deviation from nominal geometry. The printed specimens' examples (virgin and recycled) are shown in Figure 4.

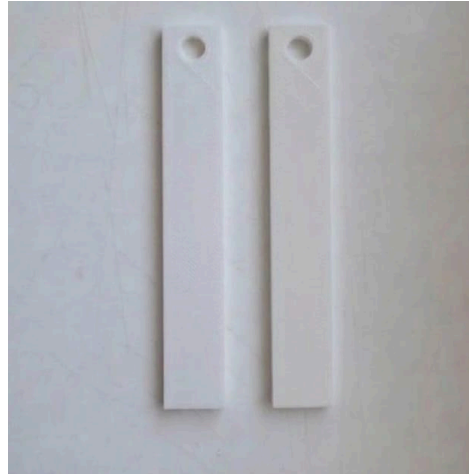


Figure 4: 3D-printed samples made from virgin and recycled PLA

The nominal dimensions and cantilever test geometry for the printed specimens are summarized in Table 1.

Parameter	Value
Total specimen length	200 mm
Specimen width (b)	30 mm
Specimen thickness (h)	4 mm
Load-hole diameter	10 mm
Effective cantilever length (l)	100 mm
Second moment of area (I), nominal	$1.600 \times 10^{-10} \text{ m}^4$

Infill density	15% (gyroid)
Printer	Bambu Lab A1
Specimens per material group	5

Table 1: Nominal specimen dimensions and cantilever test geometry

Note: I above is calculated from nominal specimen dimensions (30×4 mm) and is shown for reference only. All modulus calculations from 'Experimental Young's modulus' onward use each specimen's individually measured cross-section (b, h); the full per-specimen dataset is reported in Appendix A.

Cantilever Beam Deflection Testing

Each specimen was clamped at one end to the edge of a rigid workbench such that the effective cantilever length – measured from the clamping edge to the centre of the load-hole – was 100 mm. The clamping arrangement approximated a fixed-support boundary condition, in which both deflection and slope at the support are taken as zero. A lightweight wire hook was threaded through the free-end hole, and calibrated masses of 300, 350, 400, 450, and 500 g were applied sequentially (corresponding to forces of 2.943, 3.433, 3.924, 4.415, and 4.905 N respectively). After each mass addition, a settling period of 15 seconds was observed before recording the deflection. Deflection at the free end was determined using video analysis in Logger Pro 3.10.1. The experiment was recorded at each load step, and the vertical displacement of the free end was obtained by tracking its position relative to the initial unloaded configuration. Each test was repeated for all five specimens in each group. Mean deflections were computed at each load level for subsequent analysis. After complete load removal, all specimens returned to their original position with no visible permanent deformation, confirming that all measurements remained within the elastic regime. A schematic diagram of the experimental arrangement is shown in Figure 5.

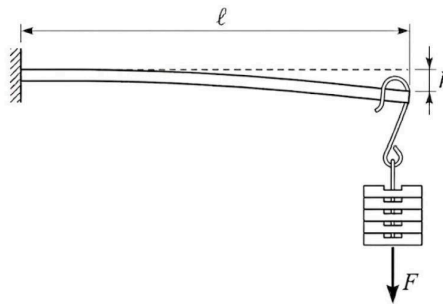


Figure 5: Schematic diagram of cantilever beam test setup

The mass of the loading hook (1.2 g) and of a representative specimen (12.8 ± 0.2 g) were measured directly. The hook contributed 0.24-0.40% to the applied force across the tested load range and is included in the force values used throughout this paper (e.g. 2.955 N at 300 g rather than 2.943 N). Specimen self-weight, treated as a distributed load over the cantilevered span, contributed an estimated 0.04 mm to the tip deflection (0.5-0.8% of the measured deflection at any load level). Both effects are well within the 0.1-0.2 mm resolution of the Logger Pro measurement system; self-weight was not separately corrected for.

Deflection at three additional points along the beam ($x = 25, 50,$ and 75 mm from the clamped support) was measured at the 400 g load step using the same video recordings obtained for the tip-deflection measurement described above. Cross-shaped markers (+) were applied to the specimen surface at these positions with a fine-tip permanent marker (Sharpie) prior to testing, providing trackable reference points for Logger Pro. Tracking was performed independently on all five specimens in each material group (V1-V5, R1-R5), and the resulting deflections were averaged across the five specimens at each x -position, consistent with the $n = 5$ sampling approach used throughout the study ('Specimen design and printing' and 'Measured deflection and load-deflection data', above). These results are presented in 'Consistency of the deflection profile with Euler-Bernoulli theory', below, and the full per-specimen dataset is reported in Appendix B.

The full loading sequence from 300 g to 500 g for a given specimen took approximately 90-120 seconds in total. No deflection drift was observed during the 15-second settling period at any load step.

RESULTS

Measured Deflection and Load-Deflection Data

Table 2 presents the mean measured tip deflections for both material groups across all five load levels. Recycled PLA specimens deflected consistently more than virgin PLA specimens at every load level. The load-deflection relationship was linear for both groups, with R^2 values exceeding 0.999 for the linear trend lines fitted through the origin in GeoGebra, confirming elastic behaviour throughout the tested range.

The $R^2 > 0.999$ reported above reflects a fit to the five load-level group means (Table 2); the zero-intercept constraint further inflates R^2 over a load range as narrow as 300-500 g. Fitting each specimen's own five raw measurements individually (unconstrained about the origin) gives $R^2 \geq 0.9995$ for every specimen in both groups (mean $R^2 = 0.9997$ virgin, 0.9998 recycled), confirming that deflection is highly linear with load within each specimen. Pooling all 25 specimen-load measurements per group into a single unconstrained fit, however, gives $R^2 = 0.926$ (virgin) and $R^2 = 0.993$ (recycled), both with near-zero intercepts (-0.036 mm and -0.025 mm respectively – an order of magnitude smaller than the measurement resolution). The lower pooled R^2 for the virgin group reflects genuine specimen-to-specimen differences in stiffness (see 'Experimental Young's modulus', below) rather than

any non-linearity or measurement noise within a given specimen, and the near-zero intercepts confirm that forcing the fit through the origin does not introduce meaningful bias.

Mass (g)	Force P (N)	Virgin δ (mm)	SD	Recycled δ (mm)	SD	Diff. (%)
300	2.955	5.02	0.29	7.18	0.13	+43.0
350	3.445	5.84	0.32	8.38	0.13	+43.5
400	3.936	6.68	0.37	9.56	0.15	+43.1
450	4.426	7.54	0.42	10.78	0.18	+43.0
500	4.917	8.36	0.45	11.96	0.21	+43.1

Table 2: Mean tip deflection (δ , mm $\pm$ SD) under applied load – virgin and recycled PLA (n = 5 specimens per group per load level). Force P includes the 1.2 g hook mass (see 'Cantilever beam deflection testing', above). “Diff. (%)” is the percentage increase in mean deflection for the recycled group relative to virgin at each load level.

Before computing the effective modulus (below), each individual measurement was checked against the $\delta/l < 0.1$ small-deflection validity criterion stated in 'Cantilever beam theory and low-resource mechanical testing', above. For the virgin group, this criterion was satisfied at every load level (maximum $\delta/l = 0.090$, at 500 g). For the recycled group – which deflects more under identical load owing to its lower stiffness – the criterion was satisfied at 300-400 g but exceeded at 450 g and 500 g for all five specimens ($\delta/l = 0.106$ – 0.130). For a specimen with the group-mean recycled modulus and dimensions, the criterion is calculated to cross $\delta/l = 0.1$ at approximately 414 g. Measurements exceeding the criterion (10 of 25 recycled specimen-load combinations) were retained in the raw dataset (Appendix A) but excluded from the modulus averages reported below.

Experimental Young's Modulus

Table 3 presents the effective Young's modulus, calculated from Equation (3) using each specimen's individually measured cross-section (b, h), averaged across specimens at each load step meeting the validity criterion above. Uncertainty in individual E measurements is dominated by the deflection resolution of the Logger Pro system (0.1-0.2 mm), contributing an estimated 1.8-4.3% combined relative uncertainty per measurement after propagating through the caliper uncertainty in specimen thickness (h, entering as h^3).

Mass (g)	P (N)	Ea Virgin (GPa)	SD	Ea Recycled (GPa)	SD
300	2.955	1.228	0.088	0.841	0.042
350	3.445	1.231	0.083	0.840	0.042
400	3.936	1.229	0.084	0.841	0.041
450	4.426	1.225	0.084	excluded	—
500	4.917	1.227	0.081	excluded	—

Table 3: Effective Young's modulus (GPa, mean $\pm$ SD, n = 5 per row) calculated at each load step meeting the $\delta/l < 0.1$ criterion, using each specimen's own measured cross-section.

The full per-specimen dataset (50 measurements: 5 specimens $\times$ 5 load steps $\times$ 2 groups, with individually measured b, h, and computed I and E for every cell) is reported in Appendix A, directly addressing the request for per-specimen traceability. Group means, computed directly from all individual specimen-load measurements meeting the validity criterion (n = 25 virgin, n = 15 recycled), are $E_{\text{virgin}} = 1.228 \pm 0.015$ GPa and $E_{\text{recycled}} = 0.841 \pm 0.010$ GPa (mean $\pm$ standard error of the mean), a reduction of 31.5 ± 1.2 percentage points (Welch's two-sample t-test: $t = 21.2$, $df = 37$, $p < 0.001$). With n = 5 per group at each load step, the statistical power of any single-load-step comparison is limited; the pooled comparison above, across all qualifying load steps, is more robust.

Consistency of the Deflection Profile with Euler-Bernoulli Theory

The theoretical deflection profile given by Equation (4) was evaluated at $x = 25, 50, 75$, and 100 mm using the group-mean effective modulus ($E_{\text{virgin}} = 1.228$ GPa, $E_{\text{recycled}} = 0.841$ GPa, derived from tip-deflection measurements across all load steps, see 'Experimental Young's modulus', above) and the group-mean second moment of area computed from measured specimen dimensions ($I_{\text{virgin}} = 1.603 \times 10^{-10} \text{ m}^4$, $I_{\text{recycled}} = 1.634 \times 10^{-10} \text{ m}^4$), under a 400 g (3.936 N) load. Because the modulus used here was itself derived from tip-deflection data, this comparison is presented as an internal consistency check between the measured deflection shape and the Euler-Bernoulli prediction, rather than as an independent validation of the model.

x (mm)	y_theor virgin	y_meas virgin ($\pm$ SD)	Dev.	y_theor recycled	y_meas recycled ($\pm$ SD)	Dev.
25	0.57	0.66 ± 0.04	+0.09	0.82	0.83 ± 0.02	+0.01
50	2.08	2.35 ± 0.13	+0.27	2.98	2.95 ± 0.05	-0.03
75	4.21	4.71 ± 0.26	+0.50	6.03	5.92 ± 0.10	-0.10

100	6.65	6.68 ± 0.37	+0.03	9.52	9.56 ± 0.15	+0.04
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Table 4: Theoretical vs. measured deflection profile at $P = 3.936 \text{ N}$ (400 g), $n = 5$ specimens per group per point (Appendix B).

Agreement is close at the tip for both groups ($\leq 0.04 \text{ mm}$), which follows directly from the modulus having been derived from tip-deflection measurements at this and other load steps. At intermediate sections, agreement is good for the recycled group ($\leq 0.10 \text{ mm}$, within measurement resolution) but weaker for the virgin group, with deviation reaching 0.50 mm at $x = 75 \text{ mm}$ – approximately 1.9 standard deviations of the measured value at that point ($SD = 0.26 \text{ mm}$, $n = 5$ specimens). This pattern reinforces that the comparison should be read as an internal consistency check rather than independent model validation, and is particularly notable because the Euler-Bernoulli beam deflection equations assume a homogeneous and isotropic material, which cannot strictly be said of the anisotropic, layered specimens tested here.

DISCUSSION

The main result of this study is that the mean effective bending modulus of single-cycle mechanically recycled PLA printed with 15% infill density is $E_{\text{recycled}} = 0.841 \text{ GPa}$ against $E_{\text{virgin}} = 1.228 \text{ GPa}$ of virgin PLA printed with the same conditions, i.e. a reduction of 31.5%. The result must be interpreted taking into account both material degradation and infill geometry effects.

The effective moduli of both groups are considerably lower than the 3.0-3.5 GPa typically reported for bulk or 100%-infill PLA [2]. This is expected: the apparent structural stiffness at 15% gyroid infill is determined by the infill geometry, not just the intrinsic modulus of the material, because only a small fraction of the cross section is loaded. The virgin PLA modulus of 1.228 GPa falls within the range of 0.9-1.3 GPa as estimated using literature-based infill scaling relationships (tensile infill-sensitivity trends [5] used as a proxy for bending, given both are governed by similar void-content and inter-bead-bonding effects), thus indicating successful setup operation.

The modulus drop of 31.5% due to recycling is substantially higher than the tensile-modulus changes reported in the closely related literature: Anderson [3] found a statistically non-significant ~5% reduction for once-recycled, 100%-infill printed PLA; Cruz et al. [9] and Sanchez et al. [8] – the latter a fuller journal version of the former by the same research group – found tensile modulus of extruded filament and injection-moulded PLA changed by at most a few percent across five recycling cycles, and even slightly increased (+4-5%) for 3D-printed specimens despite tensile strength falling by 38-71%. No directly comparable measurement of bending stiffness at reduced infill was found in any of these studies. This larger than expected reduction is consistent with the low (15%) infill density used in this work. At low infill there are fewer contacts between beads throughout the structure. Thus, the higher void content and the weaker inter-bead bonding of the recycled filament because of chain scission and lower melt

viscosity during re-extrusion have a relatively larger impact on bending stiffness. This is even more so when compared to bulk or fully-dense materials where the applied loads are evenly distributed through the cross-section rather than concentrated at the weak inter-bead interfaces.

The load-deflection response was linear for both groups at all five levels of load ($R^2 > 0.999$), and no residual deformation was observed in any specimen following removal of load. Such observations are consistent with the elastic behaviour observed during the test, which validates both the Euler-Bernoulli formula and the modulus calculation. The computed modulus values were consistent over the load steps (coefficient of variation $< 1\%$ for each group), providing further evidence that the dead-weight cantilever method is reliable under these experimental conditions. Testing five specimens per group mitigated the effect of individual specimen variation and increased the repeatability of mean modulus estimates.

Comparison of the measured deflection profile with the Euler-Bernoulli prediction ('Consistency of the deflection profile with Euler–Bernoulli theory', above) showed close agreement at the tip for both groups (≤ 0.04 mm) and at all intermediate sections for the recycled group (≤ 0.10 mm); for the virgin group, intermediate deviation reached 0.50 mm at $x = 75$ mm. As this comparison uses a modulus derived from the same class of measurement being predicted, it is reported as an internal consistency check rather than independent model validation. This is particularly notable because the Euler-Bernoulli beam deflection equations assume a homogeneous and isotropic material, which cannot strictly be said of the anisotropic, layered specimens tested here.

Practically speaking, a 31.5% decrease in bending modulus implies that, for a rectangular cross-section where $\delta \propto 1/(E h^3)$ at fixed load and length, the required thickness should be increased by approximately 13.4% to keep the same deflection under the same load (to offset the effect of $E = 0.685 E_0$, h must be increased by a factor of $(1/0.685)^{1/3} \approx 1.134$). For robot components used in FTC that usually feature considerable geometrical margins, this change would be easy to accommodate in Autodesk Fusion software.

Several limitations of the study should be discussed. In particular, the clamping method itself introduces the largest systematic source of uncertainty.

Any compliance or rotation of the support under load adds apparent deflection at the tip beyond that produced by pure elastic bending of the beam. Because the effective modulus is calculated from the total measured deflection under the assumption that all of it arises from beam bending ($E \propto 1/\delta$), this effect leads to an underestimation, not an overestimation, of the reported modulus values. This source of error was not independently quantified (e.g., by tracking deflection near the clamp face to separate support rotation from beam bending) and is noted as a limitation. However, since both material groups were tested under an identical clamping arrangement, the comparative conclusion (the relative reduction in modulus between virgin and recycled PLA) remains valid, as any support-compliance bias would affect both groups similarly.

Additionally, the Logger Pro video analysis is non-intuitive and has a limited distance between the camera and the object to allow for greater displacement measurements (the calibration scale) to measure displacement. This issue can be partly alleviated by averaging multiple specimens across load levels, but a contact or laser displacement sensor would ideally produce more accurate results. The 10 mm hole for the load application also eliminates roughly one third of the cross-sectional width of the beam at the loading section – a non-uniformity that therefore lies in contradiction to the assumptions underlying the uniform-beam approximation used by Euler-Bernoulli formulas applied throughout; given that its location coincides with the point of load application rather than within the peak bending moment region, such an effect on reported effective modulus should be small but was not independently quantified. Besides, this experiment considers only a single recycling cycle of the material. Since the polymer continues to degrade with each additional recycling cycle, further experimental data would be needed to understand how the modulus changes over multiple cycles. Lastly, all specimens were 3D-printed with the same infill percentage; no interaction between infill percentage and the modulus reduction due to recycling reported here was investigated in this study.

CONCLUSION

The present work focused on determining the bending stiffness of single-cycle recycled PLA filament compared with virgin PLA by measuring deflection in a cantilever beam test. The beams were designed in Autodesk Fusion and printed using the Bambu Lab A1 printer with an infill percentage of 15%. The deflection was measured using Logger Pro 3.10.1 video analysis software, while the effective Young's modulus was calculated using the inverse Euler-Bernoulli formula, applied individually to each specimen's measured cross-section.

The average effective bending modulus of virgin PLA specimens was 1.228 ± 0.015 GPa ($n = 25$ specimen–load measurements) and that of recycled PLA specimens was 0.841 ± 0.010 GPa ($n = 15$, after excluding measurements exceeding the $\delta/l < 0.1$ small-deflection validity criterion), a reduction of 31.5 ± 1.2 percentage points ($t = 21.2$, $df = 37$, $p < 0.001$). Both groups displayed a linear load–deflection behaviour over the range tested (300–500 g), and for both groups, the measured deflection profile was generally consistent with the Euler–Bernoulli shape (deviations of a few tenths of a millimetre at intermediate sections, and ≤ 0.04 mm at the tip), presented as an internal check on consistency rather than independent validation since the modulus used in these checks was derived from the same tip-deflection dataset. The results indicate that: (1) mechanically recycled PLA after a single cycle shows a significant decrease in bending stiffness when printed at a low (15%) infill density, which is considerably larger than the modulus losses (or slight increases in some process chains) reported in the closely related literature for testing printed, extruded or injection-moulded recycled PLA in tension (Anderson [3]; Cruz et al. [9]; Sanchez et al. [8]), suggesting that the effect is amplified by structural rather than purely material effects; (2) classical beam theory is generally applicable to the bending behavior of FDM printed PLA samples at 15% infill, within the constraints of an internal consistency check; and (3) the proposed cantilever method

is a useful tool for assessing the relative stiffness of material groups in a school environment without the need for specialized laboratory equipment.

The results are specific to the bending stiffness. In competition, FTC robot components also generally see impact and collision loading, where strength and ductility, properties not measured in this study, are likely more important than stiffness alone. The literature reviewed in “Mechanical degradation of PLA upon recycling” suggests these properties degrade more than modulus upon recycling (10–20% vs. 5–8%). Within this explicit scope, mechanical recycling of PLA at 15% infill may be appropriate for low-impact, stiffness-governed FTC components, where the measured reduction in effective modulus can be offset by a modest ($\approx 13\%$) increase in wall thickness. Regardless of whether the PLA is virgin or recycled, load-bearing or impact-prone elements should use a higher infill factor, and recycled material should not be recommended for such applications without additional strength or impact characterization (e.g., tensile or Izod/Charpy testing) in future work. Further research should explore the effect of infill density on modulus reduction during recycling, moduli after multiple recycling cycles and quantification of void content using optical microscopy.

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APPENDIX

Appendix A – Full per-specimen deflection dataset

Group	Spec.	Load(g)	P(N)	b(mm)	h(mm)	I(m ⁴)	δ(mm)	E(GPa) / status
virgin	V1	300	2.955	30.10	4.05	1.666e-10	5.2	1.137
virgin	V1	350	3.445	30.10	4.05	1.666e-10	6.0	1.149

virgin	V1	400	3.936	30.10	4.05	1.666e-1 0	6.9	1.141
virgin	V1	450	4.426	30.10	4.05	1.666e-1 0	7.8	1.135
virgin	V1	500	4.917	30.10	4.05	1.666e-1 0	8.6	1.144
virgin	V2	300	2.955	30.00	3.98	1.576e-1 0	5.4	1.157
virgin	V2	350	3.445	30.00	3.98	1.576e-1 0	6.3	1.157
virgin	V2	400	3.936	30.00	3.98	1.576e-1 0	7.2	1.156
virgin	V2	450	4.426	30.00	3.98	1.576e-1 0	8.1	1.156
virgin	V2	500	4.917	30.00	3.98	1.576e-1 0	9.0	1.155
virgin	V3	300	2.955	29.90	4.02	1.619e-1 0	5.0	1.217
virgin	V3	350	3.445	29.90	4.02	1.619e-1 0	5.8	1.223
virgin	V3	400	3.936	29.90	4.02	1.619e-1 0	6.6	1.228
virgin	V3	450	4.426	29.90	4.02	1.619e-1 0	7.5	1.215
virgin	V3	500	4.917	29.90	4.02	1.619e-1 0	8.3	1.220
virgin	V4	300	2.955	30.00	4.00	1.600e-1 0	4.8	1.282
virgin	V4	350	3.445	30.00	4.00	1.600e-1 0	5.6	1.282
virgin	V4	400	3.936	30.00	4.00	1.600e-1 0	6.4	1.281

virgin	V4	450	4.426	30.00	4.00	1.600e-1 0	7.2	1.281
virgin	V4	500	4.917	30.00	4.00	1.600e-1 0	8.0	1.280
virgin	V5	300	2.955	30.05	3.96	1.555e-1 0	4.7	1.348
virgin	V5	350	3.445	30.05	3.96	1.555e-1 0	5.5	1.343
virgin	V5	400	3.936	30.05	3.96	1.555e-1 0	6.3	1.339
virgin	V5	450	4.426	30.05	3.96	1.555e-1 0	7.1	1.336
virgin	V5	500	4.917	30.05	3.96	1.555e-1 0	7.9	1.334
recycled	R1	300	2.955	29.80	4.08	1.687e-1 0	7.1	0.822
recycled	R1	350	3.445	29.80	4.08	1.687e-1 0	8.3	0.820
recycled	R1	400	3.936	29.80	4.08	1.687e-1 0	9.4	0.827
recycled	R1	450	4.426	29.80	4.08	1.687e-1 0	10.6	excluded ($\delta/l=0.106$)
recycled	R1	500	4.917	29.80	4.08	1.687e-1 0	11.8	excluded ($\delta/l=0.118$)
recycled	R2	300	2.955	29.90	4.04	1.643e-1 0	7.0	0.856
recycled	R2	350	3.445	29.90	4.04	1.643e-1 0	8.2	0.852
recycled	R2	400	3.936	29.90	4.04	1.643e-1 0	9.4	0.849

recycled	R2	450	4.426	29.90	4.04	$1.643e-10$	10.6	excluded ($\delta/l=0.106$)
recycled	R2	500	4.917	29.90	4.04	$1.643e-10$	11.7	excluded ($\delta/l=0.117$)
recycled	R3	300	2.955	29.80	4.12	$1.737e-10$	7.3	0.777
recycled	R3	350	3.445	29.80	4.12	$1.737e-10$	8.5	0.778
recycled	R3	400	3.936	29.80	4.12	$1.737e-10$	9.7	0.779
recycled	R3	450	4.426	29.80	4.12	$1.737e-10$	10.9	excluded ($\delta/l=0.109$)
recycled	R3	500	4.917	29.80	4.12	$1.737e-10$	12.1	excluded ($\delta/l=0.121$)
recycled	R4	300	2.955	30.00	3.98	$1.576e-10$	7.2	0.868
recycled	R4	350	3.445	30.00	3.98	$1.576e-10$	8.4	0.867
recycled	R4	400	3.936	30.00	3.98	$1.576e-10$	9.6	0.867
recycled	R4	450	4.426	30.00	3.98	$1.576e-10$	10.8	excluded ($\delta/l=0.108$)
recycled	R4	500	4.917	30.00	3.98	$1.576e-10$	12.0	excluded ($\delta/l=0.120$)
recycled	R5	300	2.955	30.05	3.94	$1.532e-10$	7.3	0.881
recycled	R5	350	3.445	30.05	3.94	$1.532e-10$	8.5	0.882

recycled	R5	400	3.936	30.05	3.94	1.532e-10	9.7	0.883
recycled	R5	450	4.426	30.05	3.94	1.532e-10	11.0	excluded ($\delta/l=0.110$)
recycled	R5	500	4.917	30.05	3.94	1.532e-10	12.2	excluded ($\delta/l=0.122$)

Appendix B – Per-specimen intermediate deflection points (Table 4 raw data)

Group	Specimen	x=25mm	x=50mm	x=75mm	x=100mm
virgin	V1	0.68	2.43	4.86	6.90
virgin	V2	0.71	2.53	5.07	7.20
virgin	V3	0.65	2.32	4.65	6.60
virgin	V4	0.63	2.25	4.51	6.40
virgin	V5	0.62	2.22	4.44	6.30
recycled	R1	0.81	2.89	5.80	9.40
recycled	R2	0.82	2.91	5.84	9.40
recycled	R3	0.85	3.01	6.03	9.70
recycled	R4	0.83	2.96	5.95	9.60
recycled	R5	0.84	2.98	6.00	9.70