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Tensile Load Capacity of 3D Printed Parts Manufactured using In-House PLA Filament

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Abstract

Fused Deposition Modeling (FDM) is 3D printing technology to manufacture any complex part from a Computer Aided Design (CAD) model. Polylactic acid (PLA) is one of the popular and environment friendly polymer plastic filament used by FDM 3D printer users. Literature review indicates that tensile load capacity of PLA parts is significantly affected by PLA parts. The purpose of this research is to experimentally compare tensile strength of 3D printed parts created using in-house developed PLA with that of commercially available PLA. Therefore, the first step involves manufacturing of in-house PLA filament followed by 3D printing and tensile testing. In this study six different build orientations are considered with three different thicknesses i.e.,1.2 mm, 2.0 mm and 2.8 mm. Tensile tests are performed as per ASTM standards. Results show that in-house manufactured PLA has tensile strength lower than commercial PLA and it varies between 4 to 20% depending on build orientation and thickness of the specimen. All specimens exhibited brittle fracture as there is no evidence of any necking phenomenon during tensile testing. Experimental results show edge orientation has highest tensile load capacity whereas upright-45 has lowest tensile load capacity. Tensile load capacity is affected by three major factors load-layer Angle, number of layer joints resisting load and stair effect.

Keywords: 3D Printing, Fused Deposition Modeling, Build Orientation, PLA, Tensile Strength

1. Introduction

A 3D printing technology to manufacture any complex part from a Computer Aided Design (CAD) model. [1]. It is quickly growing interest in aerospace, automotive, construction, and biological research [2].Fused Deposition Modeling (FDM) is a3D printing technique in which layers of materials arefused together to create parts. Typically, the material is heated and then continuously pushed through the extruder nozzle to fuse layers. The raw material is continuously supplied in the form of filament from the spool [3]. FDM 3D printing adoption is increasing due to open-source low-cost 3D printers made by firms like Ultimaker [4]. Polymer plastics are commonly used filaments which account for 51% of parts manufactured by FDM 3D printing [5, 6]. PLA is one of the popular and environment friendly polymer plastic filament used [7]. PLA is a polymer made of monomer lactic acid.It is biodegradable thermoplastic filament manufactured from Corn starch [8, 9]. PLAfilament has many advantages over other traditional polymer filaments. However, FDM 3D printed PLA parts are brittle [10]. Recently, many researchers have attempted to alter the brittle nature of PLA filament by various methods such as using different raw materials, altering manufacturing processes and using additives in PLA. In research laboratories in-house PLA is manufactured using different techniques [11].A review on FDM 3D printing of polymers indicates thatseveral factors affect the mechanical strength of parts [3, 6, 12-18]. It is observed that part build orientation is one of the factors which significantly affects strength of the FDM 3D printed PLA parts.The build orientation refers to how the printed part is positioned on the build plate. Therefore, in this work in-house PLA filament is manufactured followed by tensile testing under different build orientations. Finally, tensile strength of in-house PLA parts is compared against commercial PLA under different build orientations. Several researchers studied the effect of build orientation on mechanical strength through experimental, analytical and numerical methods. However, next section presents literature review on the experimental studieson tensile testing of FDM 3D printed PLA parts under various build orientation.

2. Literature review

A summary of review of relevant literature is given in Table 1. It includes summary of past experimental studies that considered build orientation, uniaxial tensile test and PLA filament for FDM 3D printing. From the literature review, it is observed that researchers have investigated the effect of build orientation using commercially available standard PLA. Moreover, these studies have included a limited number of build orientations. None of the studies used in-house custom manufactured PLA filament in their research while considering different part build orientation. Therefore, this research work presents a comparison of tensile load capacity of FDM 3D printed parts manufactured using standard and in-house PLA filament for three thicknesses with six build orientations. The build orientations considered in this study are flat, flat-45, edge, edge-45, upright and upright-45.

Table 1 – Summary of past experimental studies

Study by	Orientations considered in the study	Specimen thickness	Concluding remarks
Hanon et al. [19]	Flat, edge and upright orientation.	4.0 mm	Different orientations exhibited variation in tensile strength.
Cerda-Avila et al. [20]	Flat, edge and upright orientation with different % infill.	5.0 mm	Ultimate tensile stress is affected by the infill percentage and build orientation.
Mazurchevici et al. [21]	Flat and edge orientation.	4.0 mm	Tensile strength is better for edge-oriented parts than flat.
Hsueh et al. [22]	Edge, upright and flat with intermediate angles.	6.0 mm	Edge and flat orientations are stronger than upright orientation.
Wang et al. [23]	Edge and upright orientations with intermediate angles.	4.0 mm	Edge orientation is stronger than upright orientation.
Yao et al. and Ye et al. [24, 25]	Edge and upright with intermediate angles.	4.0 mm	Edge orientation improves the tensile strength of PLA.
Giri et al. [26]	Horizontal and vertical orientation (same as flat and upright orientation).	Not available.	Horizontal orientation yielded higher strength than vertical orientation.
Chacón et al. [27]	Flat, edge and upright orientations.	4.0 mm	Edge and flat orientations showed the highest tensile strength while upright orientation resulted in the lowest strength.
Patadiya et al. [28]	X (flat), Y (edge) and Z (upright) orientations.	3.2 mm	Part printed in the X orientation has higher tensile and impact strength over the part printed in the Y and Z direction.
Rodríguez-Panes et al. [29]	Orientation 1 (flat), 2 (edge) and 3 (upright).	3.2 mm	Orientation 1 is stronger than the other two orientations.
MeltemEryildiz [30]	Edge, upright, and flat-0°,45°, 90° angles.	3.5 mm	Build orientation affects the tensile strength of the part.
Hikmat et al. [31]	Flat and edge orientation.	4.0 mm	Infill density and build orientation has a significant effect on tensile strength.
Ramasamy et al. [32]	Orientations with 0, 45, and 90 degrees.	Not available.	The results showed that build orientation affects tensile strength significantly.
Stoica et al. [33]	Horizontal (flat), longitudinal (edge) and transverse (upright) orientation.	Not available.	Horizontal orientation exhibits higher mechanical strength compared to transverse and longitudinal orientation.
Corapi et al. [34]	Horizontal (flat), on-side (edge) and vertical (upright) orientation.	7.0 mm	Horizontal and on-side orientation exhibited higher strength than vertical orientation.

3. Methodology

In this section methodology of research work is presented. The purpose of this research is to compare tensile load capacity of FDM 3D printed in-house manufactured PLA parts experimentally with that of PLA parts manufactured using commercially available PLA under different build orientation. Therefore, the first step involves manufacturing of in-house PLA filament followed by FDM 3D printing and tensile testing.

3.1 In-house manufacturing of PLA

In-house PLA filament is manufactured using PLA granules (pallets). These granules are purchased from Rivika Bio Industries Pvt. Ltd. India [35]. PLA filament manufacturing process is athree-step process as shown in Fig. 1. Initially, granules are heated to

80 °C for about 1 hour to remove moisture from PLA granules. After de-moisturization granules are poured in a hopper to pass through athree-stage melting process. Granules are melted at 180, 190 and 200 degrees at stage 1, stage 2 and stage 3 respectively. Molten PLA is maintained for about 1 hour at each stage for achieving uniformity in the melting furnace. Molten PLA is extruded through a mold of PLA of 1.75 mm diameter to obtain in-house PLA filament. After solidification, the filament is removed from the die and cleaned. The diameter is measured at various locations and diameter accuracy is within ±0.1 mm.

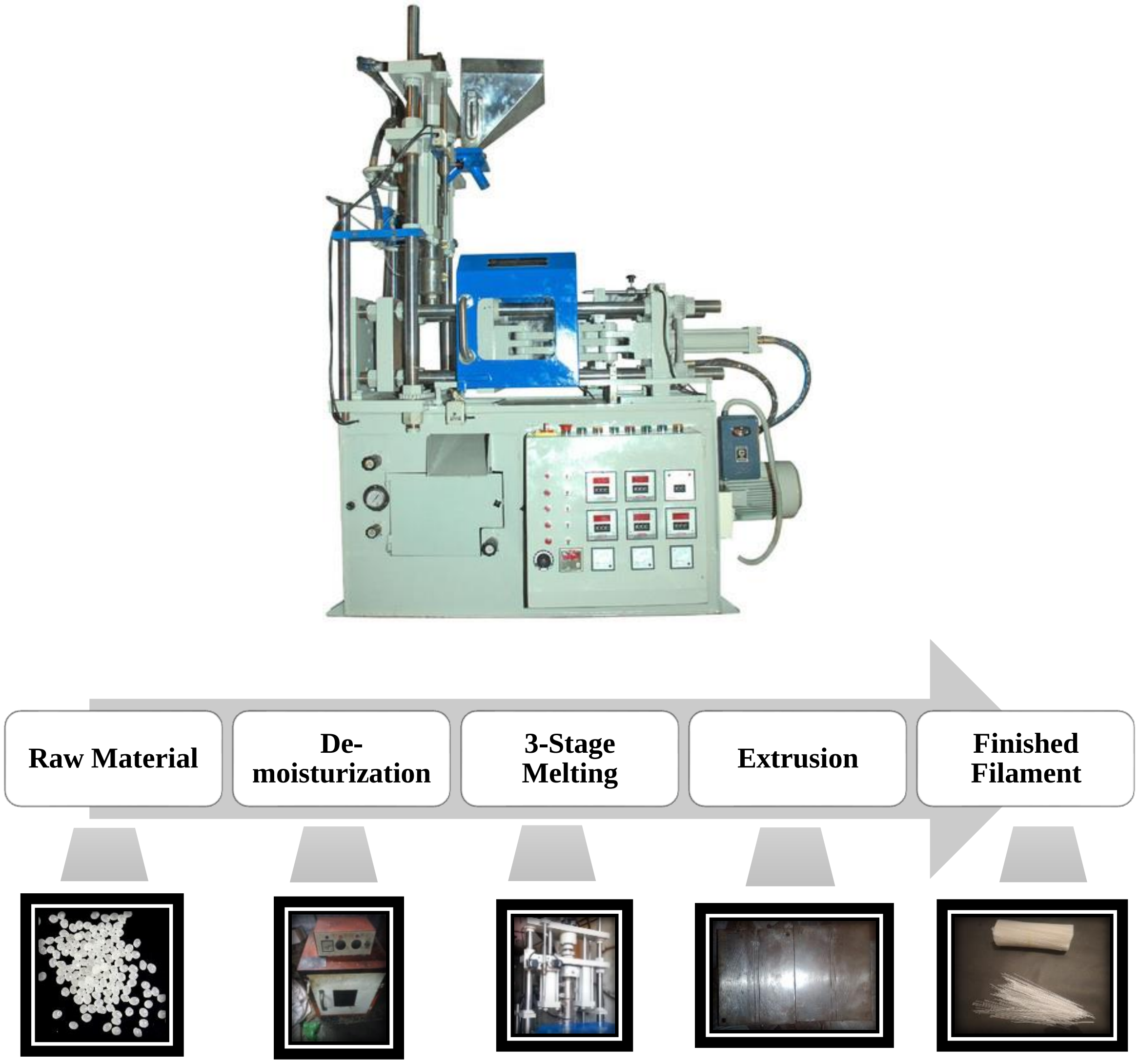
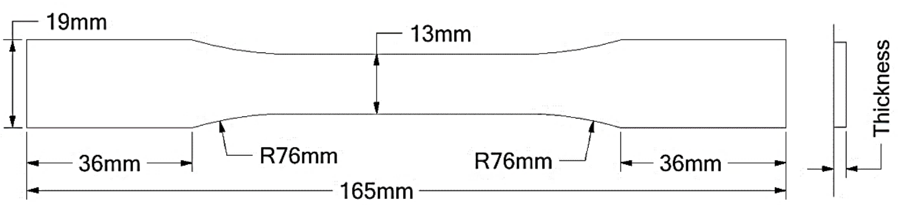


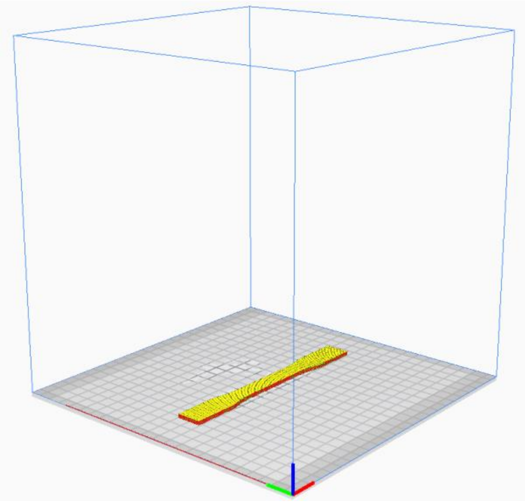
Figure 1 – In-house PLA filament manufacturing process

3.2 CAD modeling of tensile test specimen

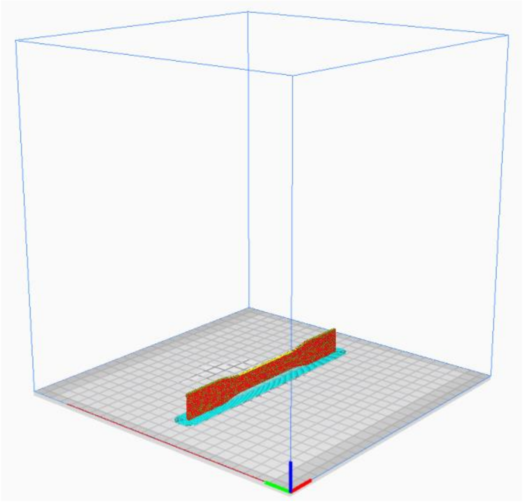
Computer Aided Design (CAD) model of uniaxial tensile test specimen is created as per the ASTM standards [38] (see Fig. 2a.). SolidWorks [36]is used to create CAD model and exported as a Standard Tessellation Language (STL) file. STL is imported in slicing software to create 3D printing file.UltimakerCura [37]is used for slicing part geometry. Tensile test specimens are created in three different thicknesses i.e., 1.2 mm, 2.0 mm and 2.8 mm. Each thickness model is oriented in six different build orientations in slicer software. Fig. 2b to 2g shows six different orientations of tensile test specimens considered in this work. Six build orientations are chosen based on three transition cases of build orientations for tensile test specimen as shown in Table 2.



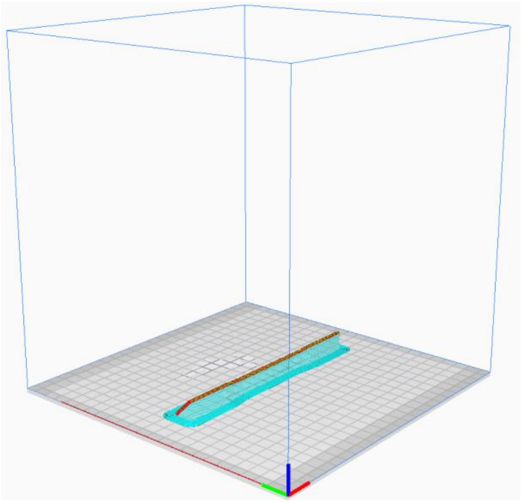
a. CAD model of uniaxial tensile test specimen



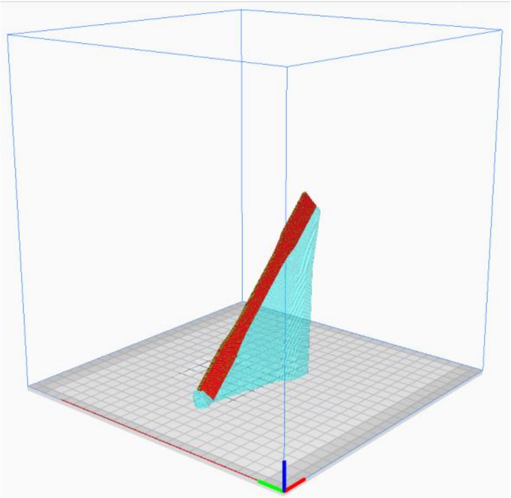
b. Flat Orientation



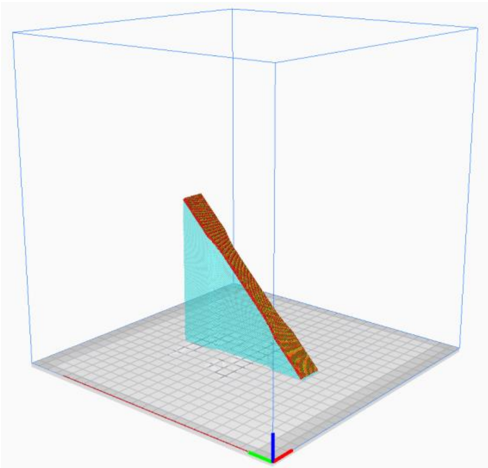
c. Edge Orientation



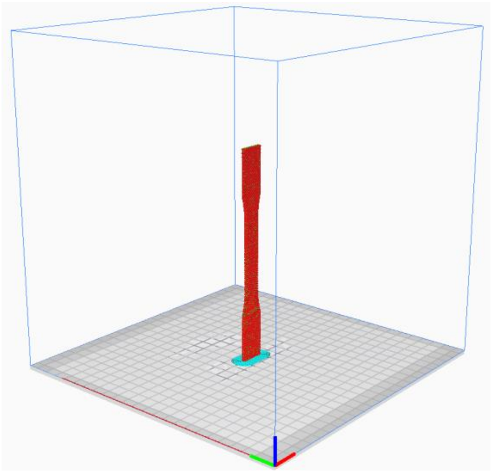
d. Flat-45 Orientation



e. Edge-45 Orientation



f. Upright-45 Orientation

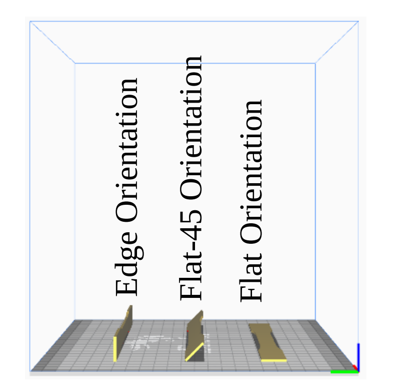


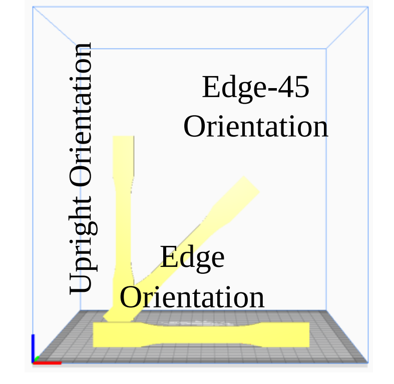
g. Upright Orientation

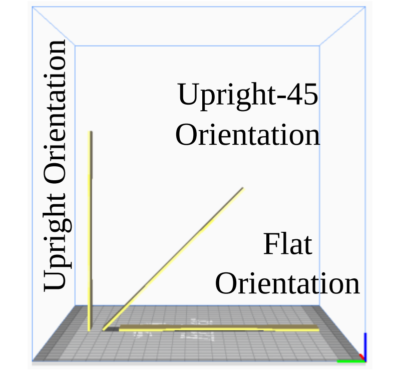
Figure 2 – Uniaxial tensile test specimen with corresponding build orientations in Cura software

Table 2 – Build orientation transition cases

Transition Case 1	Transition Case 2	Transition Case 3
Flat to Edge	Edge to Upright	Upright to Flat



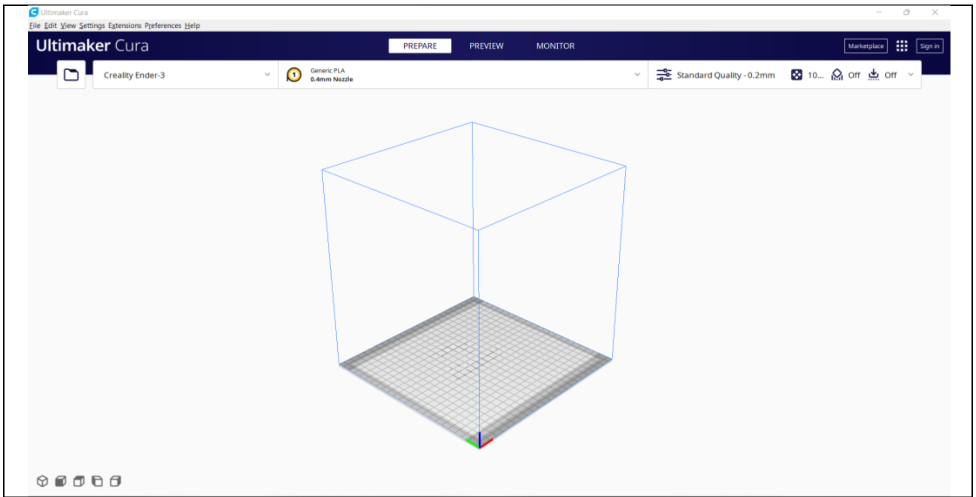




3.3 Slicing of CAD model

Cura software is used for slicing the CAD model of uniaxial tensile test specimen. Slicing is performed for Ender-3. Specifications of Ender-3 are given in the next section. After importing part model in STL format, first step is orientating part in desired build orientation on build plate. Next step is selecting different 3D printing settings given in Table 3. Most of these settings are kept same for all the build orientations. Fig. 2 shows build orientation of tensile test specimen in Cura software for six build orientations considered in this work. Support and build plate adhesion is used wherever required. Brim option is used for build plate adhesion for edge orientation (see Fig. 2c), flat-45 orientation (see Fig. 2d) and upright orientation (see Fig. 2g) as there is not enough area during printing of the first layer. Support is provided for 3D printing of tensile test specimens in flat-45 orientation, edge-45 orientation (see Fig. 2e) and upright-45 orientation (see Fig. 2f). In order to minimize the material used for printing support, support line width of 0.12 mm is used. Line support is used for flat-45 orientation and upright-45 orientation whereas tree support is used for edge-45 orientation as it improves stability of part during 3D printing. 3D printing of specimen with support requires filament 2-4 times more than without support depending on thickness and orientation of specimen.

Table 3 – Cura slicer software settings for Ender-3



Slicer Parameter	Value
Layer Height	0.2 mm
Line Width	0.2 mm
Support Line Width	0.12 mm
Wall Thickness	0.4 mm
Top Thickness	0.4 mm
Bottom Thickness	0.4 mm
Infill	100 %
Infill Pattern	Lines
Infill Line Angle	±45°

Printing Temperature	200 □C
Infill Print Speed	50 mm/s
Wall Print Speed	25 mm/s
Nozzle Diameter	0.4 mm
PLA Filament Diameter	1.75 mm

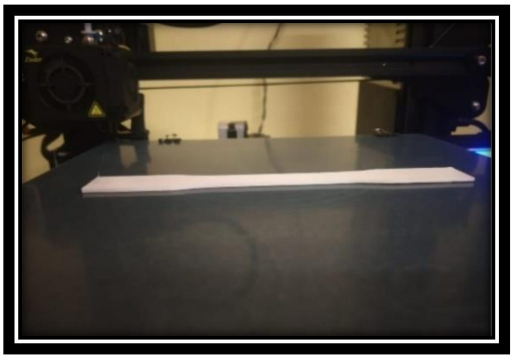
3.4 3D printing of specimen

3D printing of tensile test specimen is carried out using the Ender-3 3D printer. It is FDM based an open-source low-cost 3D printer from Creality [39]. It can 3D print part of maximum size 220 x 220 x 250mm and precision of ±0.1 mm. This 3D printer requires PLA filament of diameter 1.75 mm. Therefore, in-house PLA filament manufactured as described in Section 3.1 can be used with Ender-3. Table 4 shows Ender-3 along with its specifications used in this work.

Table 4 – 3D Printer and its specifications [39]

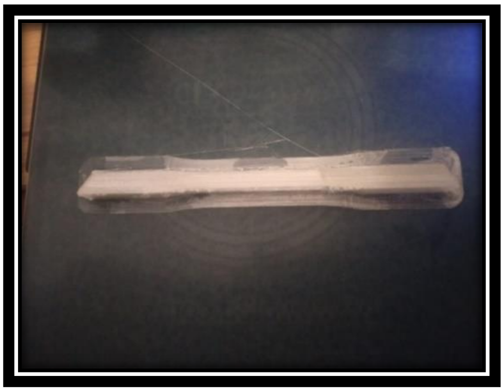
Machine Parameter	Value
Machine Weight	*6.62 Kg*
Machine Size	*440 x 440 x 465 mm*
Power Supply	*Input AC 115V/230V Output DC 24V 270W*
Printing Size	*220 x 220 x 250 mm*
Printing Speed	*≤ 180 mm/s*
Printing Precision	*± 0.1 mm*
Nozzle Diameter	*0.4 mm*
Bed Temperature	*≤ 100 ℃*
Nozzle Temperature	*≤ 270 ℃*

Six build orientation, three thicknesses, two materials and three repetitive tensile test result in 108 specimens. Therefore, total 108 uniaxial tensile test specimens are 3D printed. 54 specimens are 3D printed using in-house PLA filament and 54 specimensare 3D printedusing commercially available PLA. Each thickness orientationis tested 3 times for confirming repeatability. In-house manufactured PLA is white in color whereas commercial PLA filament is gray in color. Literature review reveals that the PLA filament color has no effect on the tensile strength of the 3D printed part [44-45]. Fig. 2 shows 3D printed specimen on the build plate of Ender-3 in six build orientations. Minimum material is required for 3D printing specimen in flat orientation, edge orientation and upright orientation whereas two times, three times and four times material required for 3D printing specimen in flat-45 orientation, upright-45 orientation and edge-45 orientation respectively as support increases amount of filament.After 3D printing tensile test specimen, support material and additional material used for build plate adhesion is cleaned up.

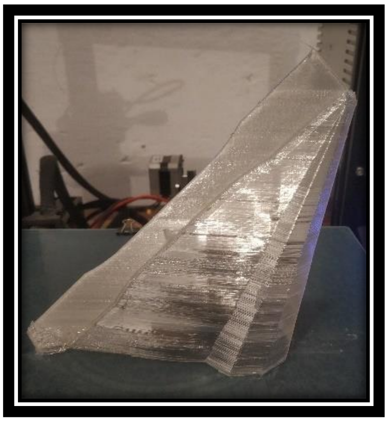


a. Flat orientation

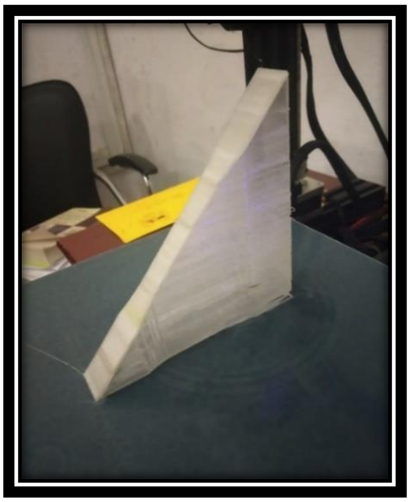
b. Edge orientation



c. Flat-45 orientation



d. Edge-45 orientation



e. Upright-45 orientation

f. Upright orientation

Figure 3 – 3D printed tensile test specimen in respective build orientation on build plate

4. Tensile testing of 3D printed specimen

Computerized universal tensile testing machine (see Table 5) is used to perform tensile tests on 54 specimens manufactured using in-house PLA and 54 specimens manufactured using commercial PLA. Table 5 gives the specifications of computerized universal tensile testing machine used in this work for tensile testing.After cleaning 3D printed tensile test specimen is mounted in the attachmentand strained until fracture. Each specimen is verified for dimensional and weight accuracy before straining to the fracture. The force value collected at the breaking point using strain gauge-based load cells.

Table 5 – Computerized universal tensile testing machine and itsspecifications

Testing Machine	**Machine Parameter**	**Specification Value**
	Machine Type	*Digital*
	Machine Class	*Class-1*
	Machine Size	*700 x 550 x 1800 mm*
	Load Range	*0 to 5000 N*
	Load Resolution	*0.1 N*
	Coverage Factor	*K-2*
	Precision	*±0.5%*
Attachment	Crosshead Stroke	*600 mm*
	Crosshead Speed	*1-500 mm/min*
	Power	220VAC 50/60Hz 1Phase
	Machine Operating Temperature	*23 ℃*
	Machine Standard	*IS1828(1)2015 identical to ISO7500(1)2004*

For each orientation and each thickness, three readings of peak tensile load are recorded to ensure repeatability of the experiments.An average value of three readings is considered for further analysis.Table 6 shows average tensile load for 3D printed specimens manufactured using in-house PLA filament as well as commercial PLA filament.It can be observed that in-house manufactured PLA filament 3D printed part has lower tensile strength than commercial PLA 3D printed part. Variation in tensile load is between 4 to 20% depending on build orientation and thickness of the specimen. The variation in tensile load of in-house PLA and commercial PLA can be attributed to various reasons as listed below:

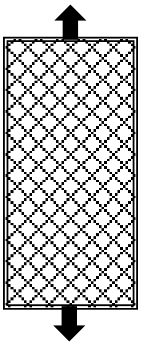
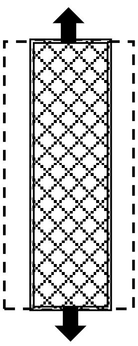
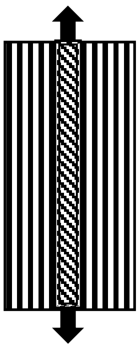
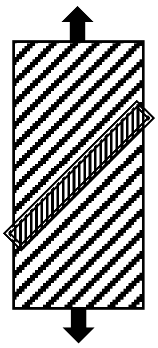
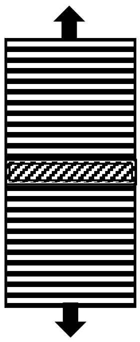
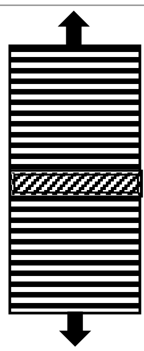
- Variation in raw material properties used for filament manufacturing
- Variation in manufacturing process of in-house and commercial PLA
- Minor variations in tensile test measurement setup
- Minor variations in 3D printing

All specimens fractured without necking indicating brittle nature of 3D printed PLA specimens. Two types of brittle fractures observed i.e. zigzag fracture and straight line fracture. Flat orientation, flat-45 orientation and edge orientations exhibited zigzag fracture due to strong fusion of subsequent layers.Therefore, these build orientations belong strong build orientation group. Edge-45 orientation, upright orientation and upright-45 orientations exhibited straight line fracture due to weak fusion of layers. Therefore, these build orientations belong to weak build orientation group. Similar fracture phenomenon is observed in specimens created using in-house PLA filament as well as commercial PLA filament irrespective of specimen thickness. These observations are in agreement with past studies [22-23]. Eryildiz [30] made similar observations about fracture phenomenon of FDM 3D printed PLA parts.Table 7 shows layer arrangement for six different orientations resulted due to common settings in Curasoftware. Due to this inherent layer arrangement load capacity of specimen varies with build orientation. It can be observed that tensile load value of strong build orientation group is higher than weak build orientation group.

Table 6 – Tensile load of 3D printed part using in-house and commercial PLA filament

Build Orientation	Thickness (mm)	Average Tensile Load (N)		Percentage Variation	Group
		In-house PLA	*Commercial PLA*		
Flat Orientation	1.2	546	626	12.78	**StrongBuild OrientationGroup**
	2.0	926	1076	13.94	
	2.8	1437	1523	05.65	
Flat-45 Orientation	1.2	403	501	19.56	
	2.0	829	963	13.91	
	2.8	1375	1430	03.85	
Edge Orientation	1.2	633	673	05.94	
	2.0	1112	1175	05.36	
	2.8	1640	1759	06.77	
Edge-45 Orientation	1.2	114	129	11.63	**Weak Build Orientation Group**
	2.0	274	303	09.57	
	2.8	450	470	04.26	
Upright Orientation	1.2	129	161	19.88	
	2.0	417	469	11.09	
	2.8	690	753	08.37	
Upright-45Orientation	1.2	94	106	11.32	
	2.0	209	226	07.52	
	2.8	380	394	03.55	

Table 7 – Layer cross section and intralayer arrangement in reduced section

Flat Orientation	**Flat-45 Orientation**	**Edge Orientation**	**Edge-45 Orientation**	**Upright-45 Orientation**	**Upright Orientation**
Alternate layer lines make ±45°angle with the load.	Alternate layer lines make ±45° angle with the load. Majority of layer lines are parallel to the load.	Majority of layer lines are parallel to the load.	Angle between layer plane as well as layer line and loadis45°.	Layer line is ⊥ to load. ∠ layer plane and loadis45°.	Load is ⊥ to the layerplane.
Raster lines makes ±45° with outer wall lines of layer cross-section.					
					
Top view of reduced section which is same ascross-section of layer		Side view of reduced section along with cross-section of layer		Front view of reduced section along with cross-section of layer	
Strong Build Orientation Group			**Weak Build OrientationGroup**		

5. Results and Discussions

This section presents results of tensile loads of FDM 3D printed parts using in-house PLA filament. Fig. 4 shows tensile load for 3D printed parts using in-house PLA and commercial PLA. It is observed that tensile load increases with increase in thickness. This is in agreement with the theory of solid mechanics. It can be seen that edge orientation has highest tensile load carrying capacity whereas upright-45 orientation has lowest tensile load carrying capacity. For in-house PLA filament 3D printed part, maximum tensile load of 1640 N is observed for 2.8 mm thick specimen with edge orientation whereas minimum tensile load of 94 N is observed for 1.2 mm thick specimen with edge-45 orientation.Three transition cases of build orientations for tensile test specimen are highlighted in Fig. 5. It can be seen that when orientation transitions from flat to edge, edge to upright and upright to flat, the tensile load for intermediate orientation decreases from initial orientation and again increases in final orientation. This is attributed to several factors related to reduced section i.e.,gray region of tensile test specimen as given in Table 8.

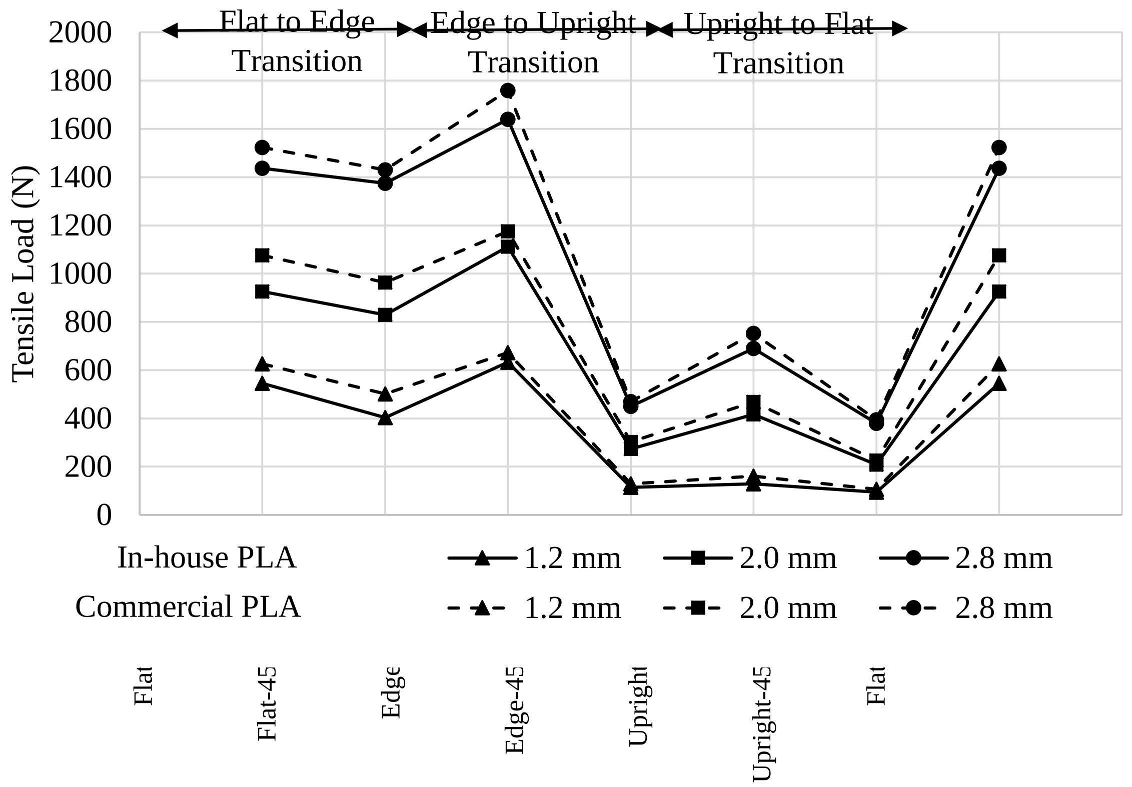


Figure 4–Tensile load vs build orientation for different thickness showing three transition cases of build orientation

Transition case 1 consists of three orientations i.e.flat, flat-45 and edge orientations (see Table 2). In this case edge orientation is the strongest orientation whereas flat-45 orientation is weakest.The tensile load capacity of flat orientation is better than flat-45 orientation but lower than edge orientation. It is normally observed that parts which have maximum built area on build plate are better in quality and strength. In this case, although edge orientation does not have maximum area on the build plate, still edge orientation is stronger orientation than flat orientation. This is due to alarge number of layer joints resisting the load and more than 50% of layer lines make zero-degree angle with load. Although, parameters of edge orientation and flat-45 orientation are similar,but flat-45 orientation is the weakest orientation among these three. This is due to the presence of a stair effect on the width face as shown in Fig. 5a. However, this stair effectdoesn't decrease tensile load capacity significantly as the stair effect is along the length of the specimen.

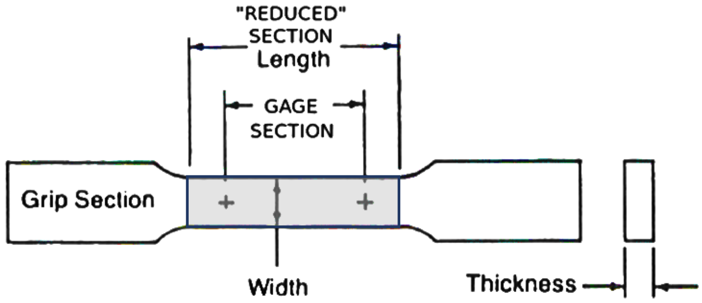
Transition case 2 consists of three orientations i.e., edge, edge-45 and Upright orientations (see Table 2). In this case, edge orientation is the strongest and edge-45 orientation is the weakest. Upright orientation is 30 to 40% stronger than edge-45 depending on the thickness of the specimen. Edge-45 orientation is weakest because of following three factors:

- *Load-Layer Angle:* Angle between load and layer joint is 45° makes it weaker. Table 8 shows the intralayer and load arrangement.
- *No. of Joints Resisting Load:* Although a reduced section is created using 245 layers but only one joint resists the tensile load and weakest joint cracks first.
- *Stair Effect:* Presence of stair effect on thickness face along thickness makes failure prone to mode-I fracture. Fig. 5b shows stair effect during 3D printing of specimen in edge-45 orientation.

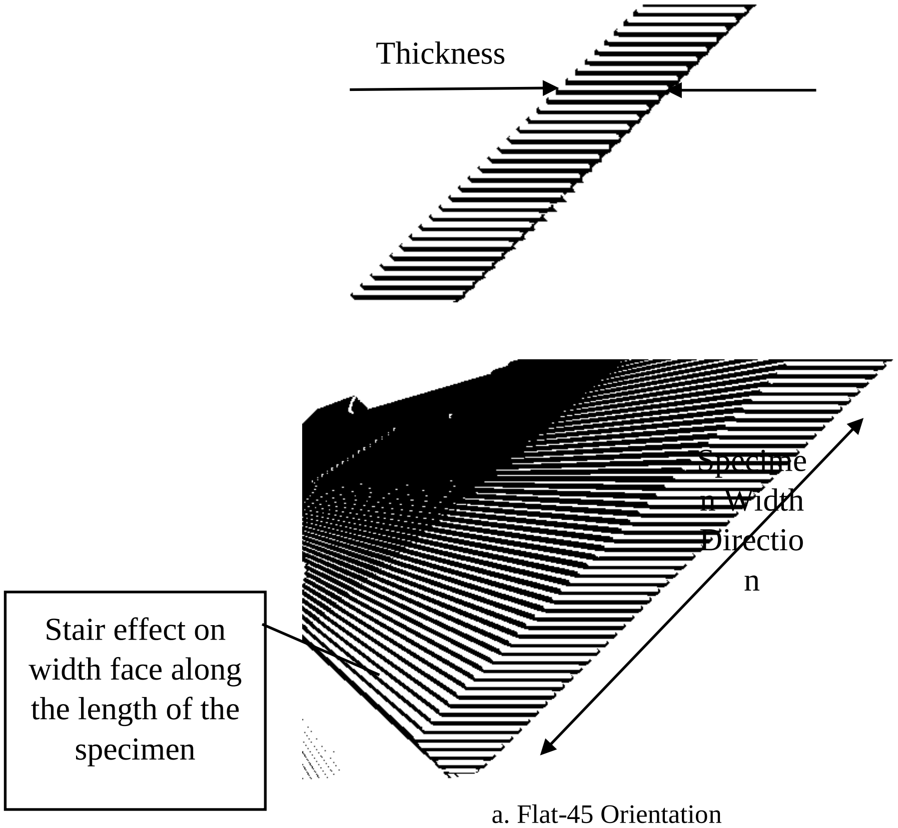
Transition case 3 consists of three orientations i.e., upright orientation, upright-45 orientation and flat orientation (see Table 2). As orientation transitions from upright to flat orientation, the tensile load decreases for upright-45 orientation making it the weakest orientation in this transition case. Upright-45 orientation is weakest because of similar factors applicable to edge-45 orientation.

Fig. 8c shows the stair effect during 3D printing of specimen in upright-45 orientation. It can be seen that the intralayer arrangement makes it the weakest section (see Table 8). Load layer angle is 90° as well as angle between load and layer cross-section is 45°. This load layer arrangement also makes it the weakest section among all orientations.

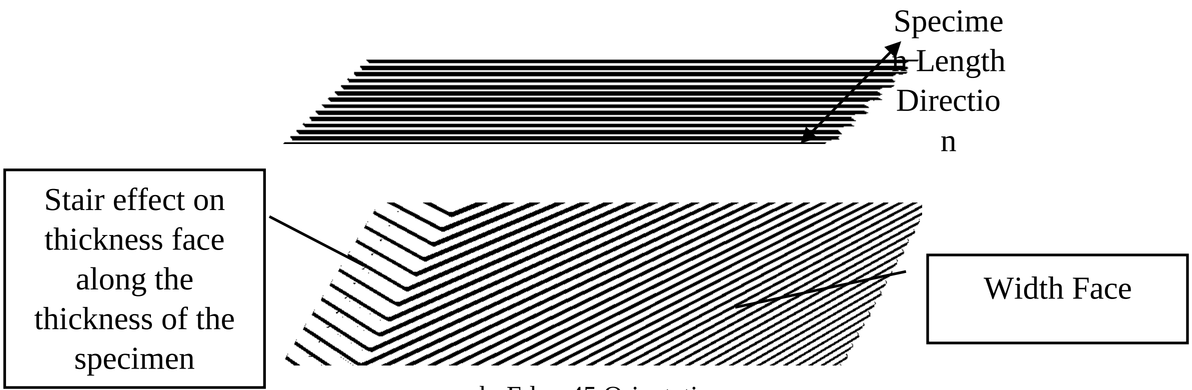
Table 8 – Reduced section parameters of tensile test specimen



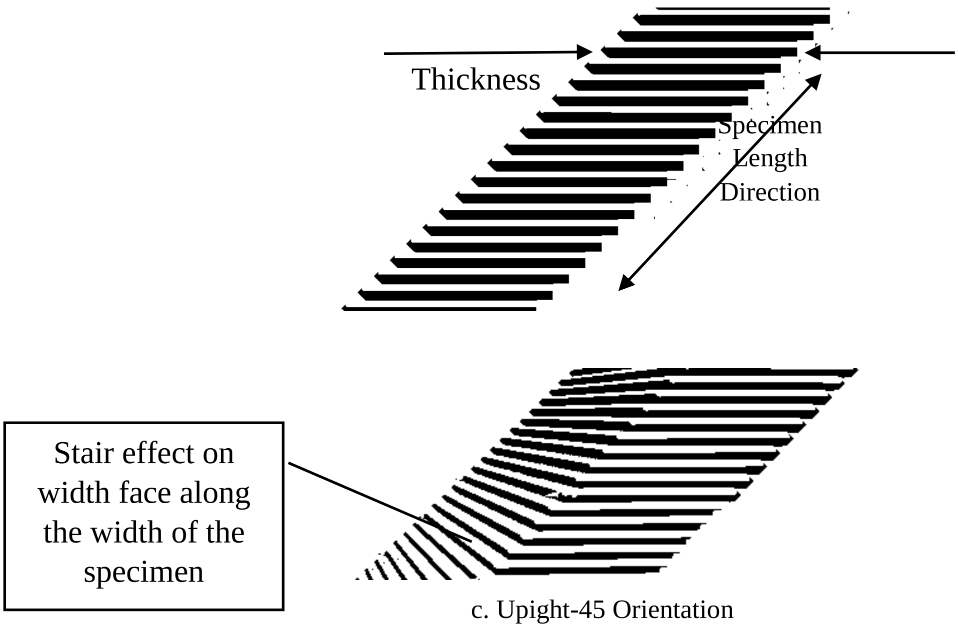
Orientation	Build Angle (Deg.)	Load-Layer Angle (Deg.)	Stair Effect	Length (mm)	Width (mm)	No. Layers	No. Layers Joints Resisting Load	Thickness					
								1.2 mm		2.0 mm		2.8 mm	
								Joint Area (mm^2)	Tensile Load (N)	Joint Area (mm^2)	Tensile Load (N)	Joint Area (mm^2)	Tensile Load (N)
Transition Case 1 – Flat to Edge Transition													
Flat	0	0	No stair effect on any face	57	13	6 - 14	10 - 26	741.0	546	741.0	926	741.0	1437
Flat-45	45	0	Stair effect on width face along length	57	13	48 - 52	94 - 100	62.5	403	115.6	829	168.7	1375
Edge	90	0	No stair effect on any face	57	13	66	130	68.4	633	114.0	1112	159.6	1759
Transition Case 2 – Edge to Upright Transition													
Edge	0	0	No stair effect on any face	57	13	65	130	68.4	633	114.0	1112	159.6	1759
Edge-45	45	45	Stair effect on thickness face along thickness	57	13	245	1	21.3	114	35.2	274	49.5	470
Upright	90	90	No stair effect on any face	57	13	285	1	15.6	161	26.0	417	36.4	753
Transition Case 3 – Upright to Flat Transition													
Upright	90	90	No stair effect on any face	57	13	285	1	15.6	161	26.0	417	36.4	753
Upright-45	45	45	Stair effect on width face along width	57	13	200	1	14.3	129	26.4	209	41.0	394
Flat	90	0	No stair effect on any face	57	13	6 - 14	10 - 26	741	546	741	926	741.0	1437



a. Flat-45 Orientation



b. Edge-45 Orientation



c. Upright-45 Orientation

Figure 5 – Stair Effect

6. Conclusions

In this paper, thein-house PLA manufacturing process is explained and the tensile load capacity of 3D printed PLA specimen is studied experimentally for six different orientations and three different thicknesses. Some of the main conclusions of this work are as given below:

- In-house PLA of 1.75 mm diameter is manufactured using PLA granules (pallets).PLA filament manufacturing process is a three-step processi.e. de-moisturization, melting and extrusion. The PLA filament diameter accuracy is within ±0.1 mm.
- Ender-3,a low cost FDM 3D printer from Crealityis used to 3D print tensile test specimen as per ASTM standards. 3D printed specimen dimensions are within ±0.1 mm accuracy. Moreover, the actual weight of a specimen and weight given by Cura software are in agreement.
- Literature review indicates that the effect of build orientation on tensile load capacity is studied using commercially available PLA. Therefore, this research work presents a tensile load capacity of 3D printed parts manufactured using in-house PLA filament for three thicknesses under six build orientations. The build orientations considered in this study are flat, flat-45, edge, edge-45, upright and upright-45 build orientations.
- All tensile test specimen are FDM3D printed with constant 3D printing parameters except support and build plate adhesion. Flat, edge and upright orientations do not require support whereas flat-45, edge-45 and upright-45 require support. Except flat-45, edge and upright orientationsrequire build plate adhesion whereas flat, edge-45 and upright-45 orientations do not require build plate adhesion.Uniform 3D printing setting in Cura and build orientation results in unique inherent layer arrangement for each build orientation. Due to this unique intralayer arrangement, fracture behavior and load capacity of specimen varies.
- Total 108 specimens are 3D printed. 54 specimens are printed using in-house PLA and 54 specimens are printed in commercially available PLA to compare strength. Tensile test is performed using a computerized universal testing machine which has load range 0.1 N and precision ±0.5%. Each specimen is strained until it initiates a crack and breaks into two pieces. Breaking load is recorded and used for further analysis. The average of three force values is considered for further analysis. It can be observed that in-house manufactured PLA has lower tensile strength than commercial PLA. Variation in tensile load is between 4 to 20% depending on build orientation and thickness of the specimen.
- All specimens exhibited brittle fracture as there is no evidence of any necking phenomenon during tensile testing. Zigzag fracture appears for flat, flat-45 and edge build orientations because of strong fusion of subsequent layers. Straight line fracture appears for edge-45, upright and upright-45 build orientations because of weak fusion of inter layers. Similar fracture phenomenon is observed in specimens created using in-house PLA as well as commercial PLA irrespective of specimen thickness. These observations are in agreement with previous studies.
- It is observed that tensile load increases with increase in thickness. This is in agreement with the theory of solid mechanics. It can be seen that edge orientation has highest tensile load carrying capacity whereas upright-45 orientation has lowest tensile load carrying capacity. Maximum tensile load of 1640 N is observed for 2.8 mm thick specimen 3D printed with edge orientation whereas minimum tensile load of 94 N is observed for 1.2 mm thick specimen printed with edge-45 orientation.
- Three transition cases consist ofthree build orientations each are considered in this work. It can be seen that when orientation transitions from flat to edge, edge to upright and upright to flat, the tensile load for intermediate orientation decreases from initial orientation and again increases in final orientation. This is attributed to several factors related to reduced section.Load-layer angle, no. of layer joints resisting load, joint area and stair effect are major parameters affecting the tensile load capacity of specimen in each orientation.

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