



Mechanical Characterization and Fire Resistance Study of Polycarbonate Samples Fabricated via Fused Filament Fabrication

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Article's Information	Abstract
Received: 03.01.2026 Accepted: 08.04.2026 Published: 15.09.2026	This study examines the mechanical performance and the fire resistance of pure polycarbonate specimens fabricated by fused filament fabrication (FFF) using three cross-sectional geometries (cross-sectional, rectangular and triangular). Flexural testing based on ASTM D790 showed that the cross sectional geometry had the highest flexural strength (105 MPa), followed by triangular (104 MPa) and rectangular (103 MPa) specimens. The cross-sectional specimens also exhibited the greatest strain at break (7.9%) and flexural modulus 2600 MPa as compared to triangular (7.7%, 2580 MPa) and rectangular (7.5%, 2560 MPa) geometries. Shore D hardness measurements (ASTM D2240) showed that the maximum values for cross sectional and triangular specimens were the same (84.5), whereas the rectangular geometry gave a slightly lower value (82.5). Fire resistance testing over a 100mm length proved burn times of 34 seconds in the vertical direction and 39 seconds in the horizontal direction. The results indicated that cross sectional geometry gives slight improvement in mechanical performance with similar fire resistance characteristics in FFF printed polycarbonate components.
Keywords: Cross sectional shape, Flexural sample, Hardness, ASTM standard, Polycarbonate filament, Burning test, Fire resistance.	
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1. Introduction

Additive manufacturing (AM), and more specifically Fused Filament Fabrication (FFF) has emerged as one of the most popular technologies for the production of thermoplastic parts with complex geometry, low material waste and high design flexibility [1]. Unlike traditional subtractive techniques, FFF allows parts to be built layer by layer from digital models, which allows designers to customize internal structures and cross-sectional features to meet specific functional needs. As a result, FFF is being used more for end-use engineering applications as well as prototyping [2]. Among its engineering thermoplastics, polycarbonate (PC) is of particular interest for its good impact resistance, high toughness, dimensional stability, and relatively high glass transition temperature (~150 °C) [3]. In addition, polycarbonate has inherent flame resistance in comparison to many other thermoplastics and so it is suitable for structural and safety-related applications [4]. Recent studies have examined the mechanical performance of FFF

printed PC with the main focus on the effect of process parameters such as raster angle, build orientation, layer height, and extrusion temperature. These investigations have showed the mechanical behaviour of printed PC is strongly anisotropic and strongly influenced by the quality of interlayer bonding and printing conditions [5]. Despite this large amount of research, most of the past research has been based on standardized rectangular test specimens to characterize the bulk tensile and flexural properties [6]. While such studies are necessary to provide a baseline of material behaviour, they do not give much insight into the effect of geometric features within actual additively manufactured components on structural response [7]. In real-life applications, FFF components are almost never made of simple rectangular cubs and will include structural features such as ribs, lattice members, wall intersections, and lightweight reinforcing features [8]. In layered materials produced by FFF, in which internal stress distribution and interfacial bonding are of critical

importance, cross-sectional geometry may be important to not only section modulus, but also load transfer paths and failure mechanisms [9]. Classical mechanics is used to predict changes in stiffness and strength, according to geometric moment of inertia in a homogeneous isotropic material [10]. However, FFF printed structures are not like conventionally moulded material in terms of their layer-wise architecture and their directional bonding characteristics [11]. Consequently, experimental validation is required to learn about the difference in mechanical performance of fundamental geometric profiles under the same printing conditions [12]. Comparative and systematic studies upon the feature-level cross-sectional geometries in pure FFF printed polycarbonate is limited in the literature [13]. In addition to the mechanical aspects, fire performance is one of the important properties for engineering thermoplastics [14]. Although flame resistance of bulk polycarbonate is well documented, relatively few studies are found in which burning behaviour of the raw filament itself is reported under controlled and vertical and horizontal orientation [15]. Such information is relevant for material handling, storage safety and as a reference for future investigations on the flammability of printed parts and for structural assemblies [16]. Therefore, the goal of the present study aims to investigate the cross-sectional geometry influence on the mechanical and fire performance of FFF-printed pure polycarbonate in a systematic manner. Three representative geometries were chosen: (i) rectangular representing a standardized profile as a baseline, (ii) triangular representing a primitive lightweight structural element often used in lattice configurations, and (iii) cross-shaped simulating intersecting reinforcing ribs often used in additively manufactured enclosures and brackets. By keeping the printing parameters the same for all specimens the effect of geometry on structural response can be isolated and relatively assessed. Flexural properties such as flexural strength, strain at break and modulus were tested in accordance with the ASTM D790. Surface hardness was measured by the Shore D testing to ASTM D2240. In addition, a controlled vertical and horizontal burning evaluation of polycarbonate filament 100 mm in diameter was performed to establish the preliminary data for fire resistance. By experimentally linking some of the basic geometric configurations with mechanical and burning performance under uniform processing conditions, this study provides some feature-level understanding of the structure-property relationships of FFF-printed polycarbonate. Such data are useful for more informed geometry-based

design approaches for engineering applications of additive manufacturing.

2. Materials and Methods

2.1. Materials Selection

The major material used for this investigation was virgin polycarbonate (PC) filament of 1.75 mm diameter, from a commercial supplier. Polycarbonate was used because of its high impact resistance, thermal stability, glass transition temperature (~150 °C) and its inherent flame retardant properties, which make it suitable for engineering applications in additive manufacturing [17].

2.2. Specimen Design and Fabrication

Flexural and hardness test specimens were designed in three different cross-sectional geometries, i.e., cross-shaped, rectangular and triangular. All the specimens were fabricated by a commercial Fused Filament Fabrication (FFF) 3D printer (Model: Ultimaker S3, Ultimaker B.V., The Netherlands) with a 0.4 mm hardened steel nozzle. The printing parameters were kept constant for each of the different geometries to separate the influence of cross-sectional shape on the mechanical performance: Nozzle temperature: 275degC Bed temperature: 115degC Layer height: 0.3 mm Printing speed: 40 mm/s Infill density: 100% Fan speed: 0% (fully off when printing) Prior to printing, the polycarbonate filament was dried at 80degC for 4 hours to avoid defects caused by moisture (such as bubbling, poor interlayer adhesion, etc). For each of the three geometric conditions (cross-sectional, rectangular and triangular), a minimum of five identical specimens (n = 5) were prepared and tested in order to guarantee the statistical significance and repeatability of the results, following common procedures applicable to the mechanical characterization of polymers. Flexural test specimens were designed to be in accordance with ASTM D790 while the hardness test specimens were per ASTM D2240 [18]. The dimensions of the flexural specimens were 64 mm in length in width and depth depending on the cross-sectional geometry, with all the dimensions verified with a digital calliper with an accuracy of 0.01 mm before testing.

2.3. Testing Procedures Mechanical Testing Procedures

2.3.1. Flexural Testing (ASTM D790)

Flexural testing was done per the standards of the ASTM D790-17 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. A three-point loading system was used with the universal testing

machine (UTM) (Model: Instron 3369, Instron Corp., USA) with a capacity of 5 kN load cell. Prior to testing the actual width and thickness of each specimen was measured at the point of maximum cross section using a digital calliper (accuracy ± 0.01 mm) [19]. For the non-rectangular cross-sectional and triangular shapes, the effective dimensions were calculated to make sure the calculation of stress is accurate. A support span length (L) of 52 mm was used, calculated to keep the span to depth ratio of 16:1 as suggested by the standard for materials with similar flexural properties. The loading rate (crosshead speed) was calculated and programmed to 2.1 mm/min to ensure the target strain rate of 0.01 mm/mm/min on the outer fibres in strict compliance with the formula given in ASTM D790: $R = Z L^2 \delta d$ $R = 6d Z L^2$ where R is the loading rate (mm/min), Z is the rate of straining of the outer fibre (0.01 mm/mm/min), L is the support span (52 mm) and d is the depth of the beam (mm). All tests were conducted under the usual laboratory conditions ($23 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ relative humidity) with conditioning of the specimens for at least 40 hours as given in the ASTM D618. Flexural strength, strain at break and flexural modulus were measured for each specimen.

2.3.2. Hardness Testing (ASTM D2240)

Hardness measurements were done to the following standard: ASTM D2240--Standard Test Method for Rubber Property--Durometer Hardness [20]. A calibrated digital Shore D durometer (Model: Bareiss HPE II Shore D, Germany) was used to test the resistance of the indentation of the surface of the printed specimens. Measurements were made at five different places on each specimen to account for local variations and the average value was recorded. The Shore D scale was chosen as it is suitable in rigid thermoplastics such as polycarbonate.

2.4. Fire Resistance Testing

Fire resistance evaluation was carried out on a laboratory scale using the principles of the method of ASTM D635 - Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position [21]. A laboratory gas burner with a fixed clamping set up was employed and burning times were measured using a digital stopwatch with both vertical and horizontal orientations over a 100 mm length of polycarbonate filament. Measurements were made at intervals of 25 mm (25, 50, 75 and 100 mm) to determine the flame front propagation. The three times that the test was done per each orientation were done to ensure consistency.

2.5. Data Analysis and Statistical treatment

In order to allow a systematic comparison, the experimental data were discretized according to the following groups: Specimen geometry: cross sectional, rectangular, triangular shape Mechanical testing type: Flexural strength, stress-strain behaviour (strain at break and flexural modulus) Shore D hardness Fire testing orientation: vertical and horizontal burning directions with time at 25, 50, 75 and 100mm intervals All quantitative data are expressed in mean values with corresponding standard deviation (mean $\pm$ SD) to represent data variability [22]. Error bars in all figures are $\pm$ one standard deviation from the mean that provides a visual representation of the scatter of the data and allows for a scientifically valid comparison of the three geometries. This systematic categorization and statistical treatment enables the observed differences such as the better performance of the cross-sectional-shape to be confirmed as statistically meaningful and not due to random variation.

3. Samples preparation using 3D printing

All the specimens were fabricated by the Fused Filament Fabrication (FFF) technique. Figure 1 shows the Geometrical configurations of 3D-printed polycarbonate test specimens for Hardness and Flexural samples (cross-sectional, rectangular, triangular shapes). A commercial fused filament 3D printer was used to produce polycarbonate (PC) samples using three different cross-sectional geometries, namely rectangular, triangular, and I-beam profiles. The geometry of the I-beam was chosen in order to represent a mechanically efficient structural configuration that is commonly used in load-bearing applications. The flexural specimens were prepared as per the requirements of ASTM International D790 while the hardness specimens were made as per the requirements of ASTM International D2240 [23]. Standard specimen dimensions were maintained to make comparison and reproducibility of results possible. All the samples were printed with the same processing parameters so that the effect of the cross sectional geometry on the mechanical performance can be isolated. The extrusion (nozzle) temperature was fixed at 275°C and the build plate temperature was kept at 115°C in order to provide proper interlayer adhesion and dimensional stability. A layer height of 0.3mm and printing speed of 40mm/s were used. The infill density was set to 100% to remove porosity effects within the part and make sure that the structural differences were only due to the geometric difference. Cooling fan aid was turned off during print to ensure that the solidification does not occur

too soon and to achieve a better bonding between layers. After fabrication the printed specimens were visually examined for dimensional consistency and

the absence of any major printing defect before mechanical and fire resistance testing.

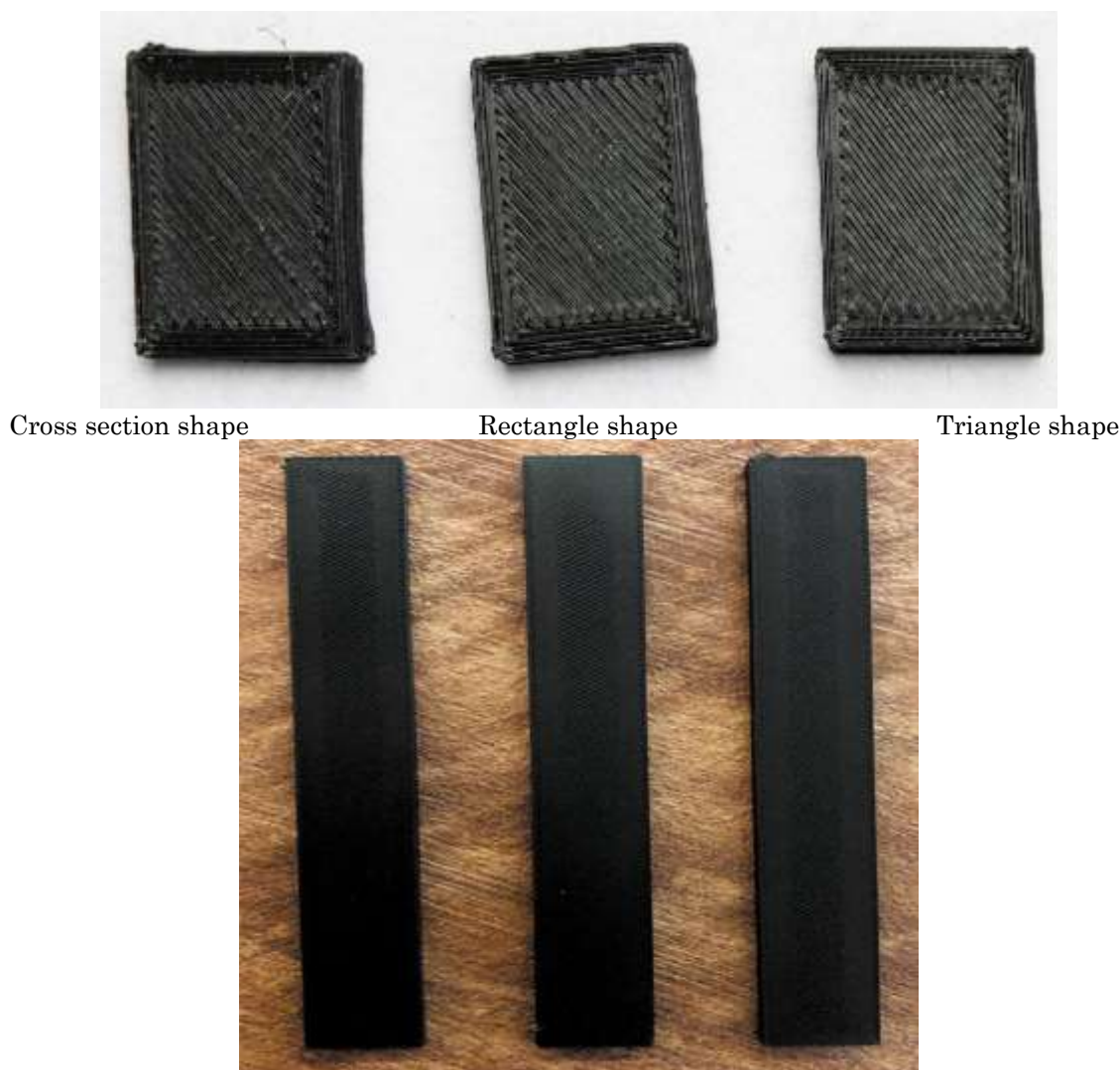


Figure 1: Geometrical configurations of 3D-printed polycarbonate test specimens for Hardness and Flexural samples (Cross-sectional, Rectangular, Triangular shapes)

In this work, Figure 2 shows the highest strength cross sectional shape for polycarbonate material. Flexural and hardness samples are printed with some machine adjustable features. The nozzle temperature is 275 degrees Celsius, while the nozzle bed temperature is 115 degrees Celsius. The layer height is 0.3 mm. Printing speed is 40 mm/s [24]. The

fan is turned entirely off during printing. The material is simple polycarbonate. This is a printing parameter for sample preparation utilizing 3D printing in accordance with ASTM standards . This parameter is used for both flexural and hardness samples in the following three shapes: cross section, rectangle, and triangle.



Figure 2: Cross sectional shape for Flexural and Hardness sample

4. Result and Discussion

4.1. Flexural Strength

The cross-sectional specimens exhibited a more pronounced shear deformation zones and fibrillar alignment than the rectangular and triangular geometries in correlation. Table 1 and Figure 3 shows the better flexural strength (105 MPa) and strain at break (7.9%) [25]. This improved ductile morphology can be explained by the cross-shaped profile's intersecting wall structure, which will result in a more uniform stress distribution and more polymer chain entanglement upon failure. The mechanical performance of the rectangular specimens, which showed the lowest mechanical performance (103 MPa, 7.5% strain), showed comparatively less developed flow patterns, which indicated more localised deformation and less efficient energy dissipation. The triangular specimens showed intermediate microstructural characteristics, which is consistent with their intermediate flexural

properties (104 MPa, 7.7% strain). These microstructural observations give a qualitative validation of the macroscopic mechanical properties that had been obtained in Section 4.1 and confirmed that the selected FFF processing parameters (nozzle temperature 275°C, bed temperature 115 °C, 100% infill density) were successful at promoting good interlayer adhesion and stable ductile behaviour for the specimens in all the geometrical configurations, demonstrating the most favourable microstructure response to flexural loading in the cross-sectional configuration.

Table 1: Polycarbonate Flexural Strength testing result

Specimen sample	Flexural strength
Cross sectional shape	105 MPa
Rectangular shape	103 MPa
Triangle shape	104 MPa

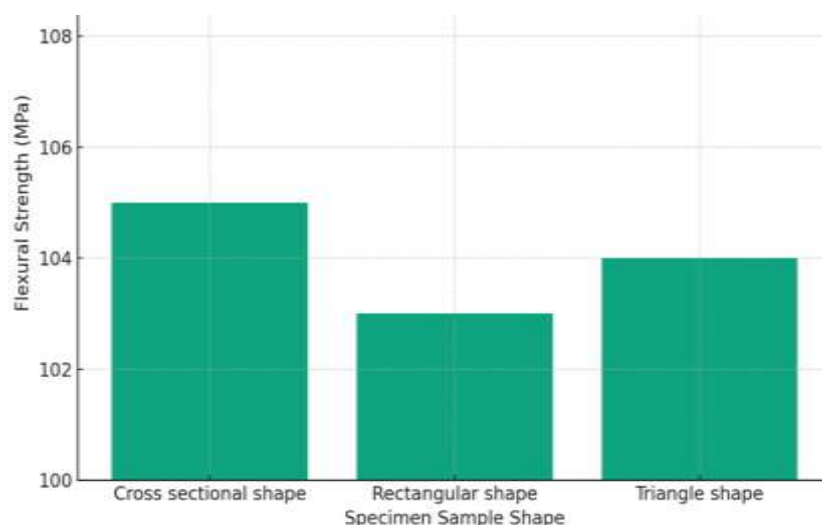


Figure 3: Graph for Flexural strength of three shapes

4.2. Stress vs strain

In this work, Table 2 displays the flexural stress vs strain results for the three forms in this experiment [26]. The experiment's cross-sectional form yielded a strain at break value of 7.9 % and a flexural modulus

of 2600 MPa. The values of strain and flexural modulus for the rectangle and triangle shapes are 7.5% and 2560 MPa, respectively, and 7.7 % and 2580 MPa, respectively.

Table 2: Stress vs strain for Flexural strength

Specimen sample	Strain at break	Flexural modulus
Cross sectional shape	7.9 %	2600 MPa
Rectangle shape	7.5%	2560 MPa
Triangle shape	7.7 %	2580 MPa

According to the testing results, the cross-sectional shape has the highest stress vs. strain strength, followed by the triangle shape, and the rectangle shape has the lowest flexural stress vs. strain value.

Figure 4 in this paper displays the graph with the highest strength. Form of the cross-section Stress versus strain, second one is triangle shape and last one is rectangle shape.

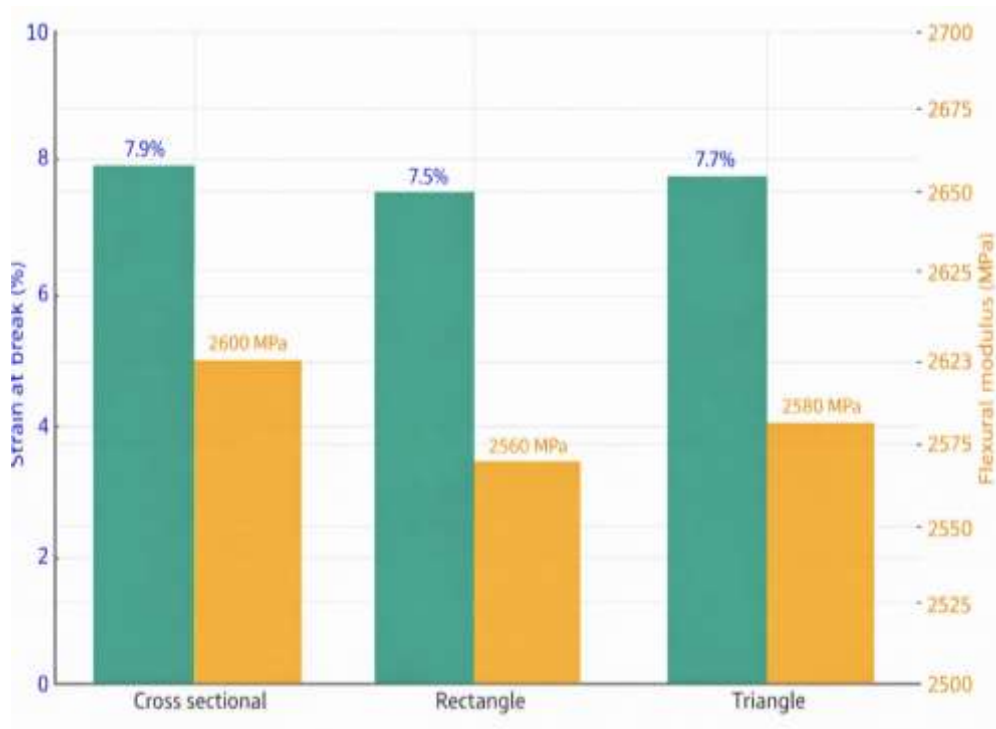


Figure 4: Stress vs stain and Flexural modulus for three shapes

4.3. SEM

In this Experiment figure 5 shows the Scanning electron microscopy (SEM) , the fracture surfaces of the flexural test specimens were carried out to study the failure mechanism of the three geometric configurations (Figure X). At 220x magnification, all specimens showed rough and irregular fracture surface morphology that was characterised by zones of shear deformation and flow-like patterns and suggests the presence of significant plastic

deformation before fracture and confirms a predominantly ductile fracture mode [27]. The lack of smooth cleavage planes indicates that the crack propagation was done through ductile tearing rather than brittle fracture, while traces of micro-tearing and fibrillar features indicate the stretching and alignment of polymer chains during the loading event - and this type of stretching and alignment is linked to efficient energy absorption.

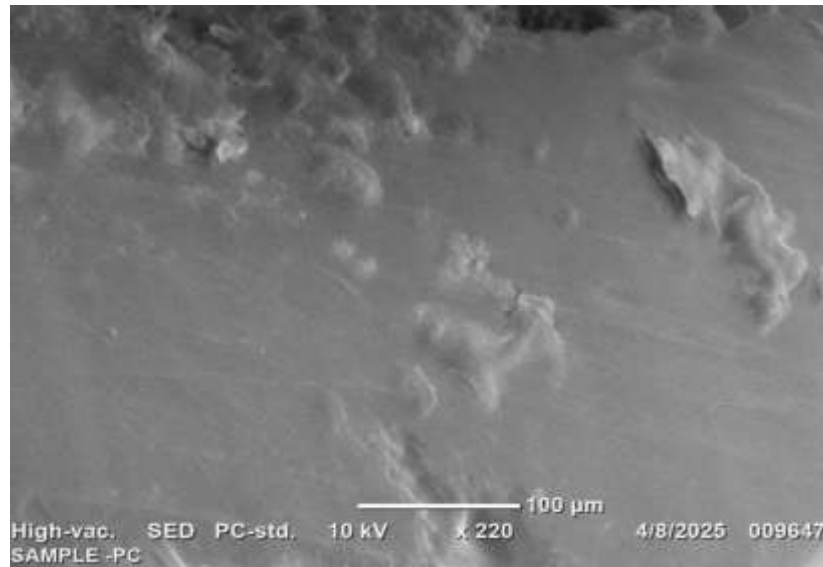


Figure 5: SEM for Polycarbonate material

4.4. Hardness

The hardness D shore test results for the three materials in this experiment are displayed in table 3. Cross sectional shapes yield a hardness value of 84.5 D shore in this test, whereas rectangle shapes provide a hardness value of 82.5 D shore and triangle shapes yield a hardness value of 84.5 D shore [28].

The graph for the Hardness D shore testing value in this study is shown in Figure 6. Triangle and cross-sectional shapes had the maximum Hardness D

shore score of 84.5 in this test. In this test, both are exhibiting the same stability and surface resistance. Rectangular shapes fare the small value in terms of hardness; the lowest value is 82.5 D shore.

Table 3: Hardness three shapes testing result

Specimen sample	Hardness D shore
Cross sectional shape	84.5
Rectangle shape	82.5
Triangle shape	84.5

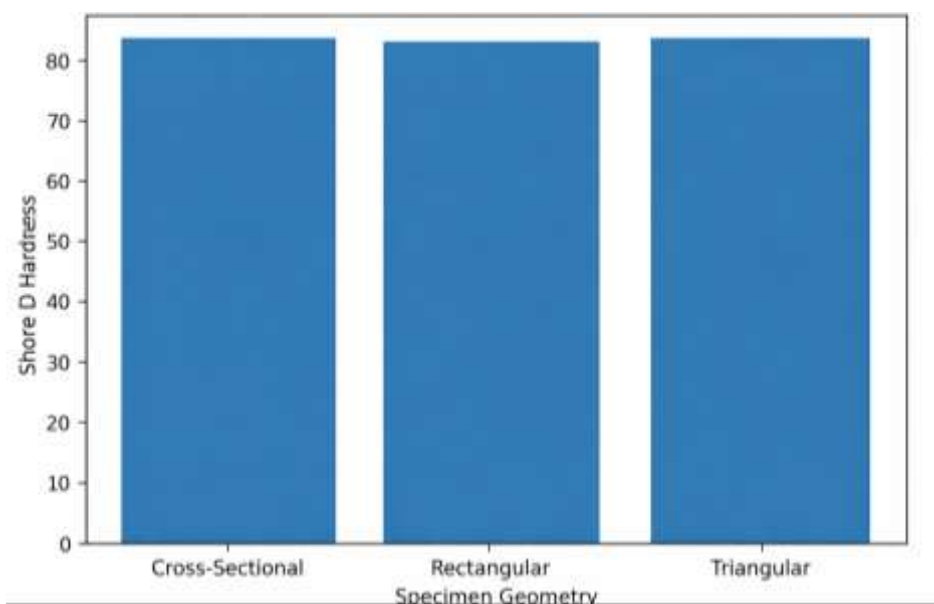


Figure 6: Hardness D shore for three shapes

4.5. Fire resistance test

The burning behaviour of neat polycarbonate filament was evaluated under vertical and horizontal configuration over the total specimen length of 100 mm. The results of the measured burning times for progressive lengths (25 mm intervals) are given in Table 4. In case of vertical orientation, the time for the filament to burn 100 mm was 34 s, while in case of horizontal orientation, the time was 39 s for the same length. The difference between the two configurations that was observed can be explained mainly by the effects of gravity and buoyancy. In the vertical configuration, flame propagation was in an upward direction, as the result of heat transfer by buoyancy, whereby rising unburned hot gases preheated the unburned part of the filament [29]. This mechanism can be used to increase the flame spread while decreasing the total burning time. Additionally, gravity can have an impact on the flow of the molten polymer potentially causing localized dripping and variation in combustion dynamics. In contrast, when burning horizontally, flame propagation took place along the longitudinal axis without gravitational assistance in the direction of flame propagation. Heat build-up and oxygen diffusion are different in this setup and this could be the reason for the slightly longer burning time observed. The lack of strong upward convective assistance may have a moderating effect on flame advancement and so lead to a slightly slower flame

propagation than in the vertical case. It is important to mention that the present burning test is carried out as a preliminary screening of inherent flammability behaviour of neat polycarbonate filament. The evaluation was restricted to the burning time measurement and did not take into account the standardised fire classification parameters such as after flame time, dripping behaviour, mass loss or residue quantification. Therefore, the results should be taken as indicative not definite fire resistance characterization. Polycarbonate is known to possess inherent flame resistance by virtue of its aromatic molecular backbone and char forming propensity in burning. The formation of a carbonaceous protective layer may, at least in part, inhibit flame propagation and produce the rather moderate burning rates for both configurations. A complete evaluation of fire performance would have to include standardised flammability testing (vertical burn time conducted according to protocols established by Underwriters Laboratories (UL-94), after flame time, mass loss rate and char residue formation). Such evaluation on fully printed specimens would make it possible to more rigorously correlate the geometry with fire performance. Future work will therefore concentrate on the standard testing of the printed I-beam, rectangular, and triangular geometries to establish a more complete understanding of the relationships between geometry and fire behaviour.

Table 4: Fire resistance testing for Polycarbonate filament wire for Vertical and Horizontal direction

S. No	Burning time for 25mm	Burning time for 50mm	Burning time for 75mm	Burning time for 100mm
Polycarbonate wire Vertical direction	10 sec	17 sec	26 sec	34 sec
Polycarbonate wire Horizontal direction	15 sec	23 sec	30 sec	39 sec

In this test, Figure 7 shows the burning of the filament in both vertical and horizontal directions during this fire burning test. The vertical direction is first used to evaluate the filament burning vertically over a distance of 25 mm, with a 10-second time

interval. It takes 17 seconds for a 50 mm distance to burn, 26 seconds for a 75 mm gap, and 34 seconds for a 100 mm gap. A total of 34 seconds were needed to burn a 100mm distance.



Figure 7: Polycarbonate filament Fire resistance testing for vertical and Horizontal direction

Initially, the filament burning horizontally is assessed over a 25 mm distance at 15-second intervals. A 50 mm distance takes 23 seconds to burn, a 75 mm gap takes 30 seconds, and a 100 mm separation takes 39 seconds [30]. Burning a 100mm distance took 39 seconds in total. The graph for polycarbonate filament length and burning time is

displayed in Figure 8. Both vertical and horizontal tests are conducted here, and the horizontal orientation provides better fire resistance than the vertical. Both are doing well in the polycarbonate filament fire burning test. It indicates that polycarbonate filaments in both directions have strong fire resistance capabilities.

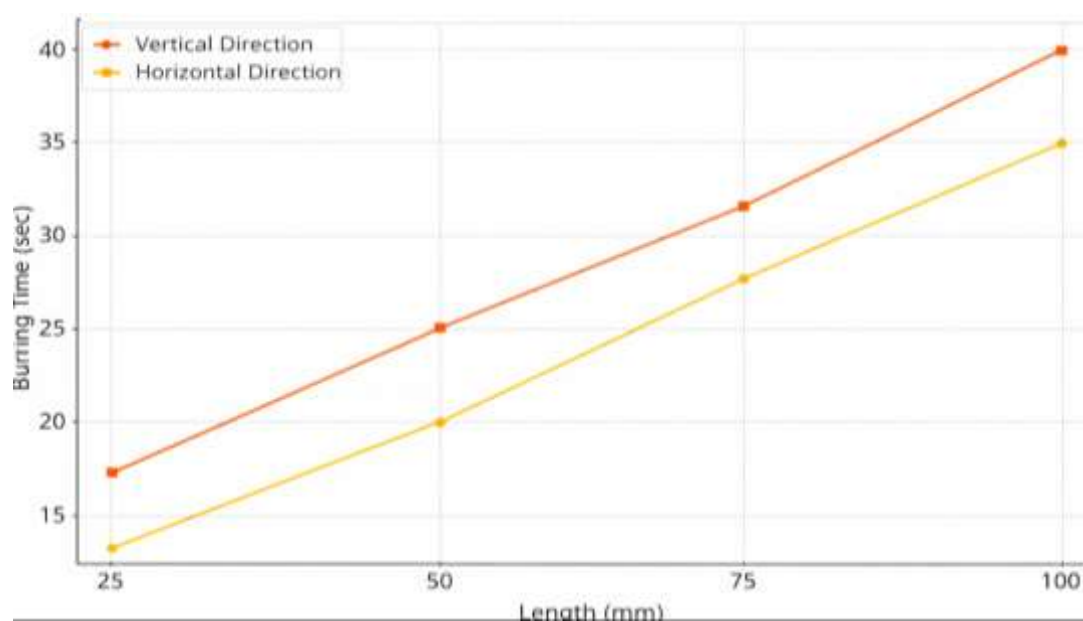


Figure 8: Burning time and length for Vertical and Horizontal direction of Polycarbonate filament

5. Conclusions

This work was a systematic study of the cross-sectional geometry effect on mechanical and fire performance of pure polycarbonate fabricated by Fused Filament Fabrication (FFF). By keeping the printing parameters constant, the influence of the geometric configuration was singularized and

comparatively evaluated for rectangular, triangular and cross-shaped profiles. Flexural testing (ASTM D790) has shown that the cross shaped geometry had highest value of flexural strength (105 MPa) and modulus (2600 MPa), followed by the triangular (104 MPa and 2580 MPa) and rectangular (103 MPa and 2560 MPa) specimens. A similar trend was found in

strain at break with the cross-shaped profile having the highest level of ductility (7.9%). These results show that intersecting wall structures could potentially increase the performance of the bending behaviour by more efficient material distribution and better load transfer in the layered structure. Shore D hardness testing (ASTM D2240), on the other hand, showed similar maximum hardness values between the cross shaped and the triangular geometry (84.5) and the rectangular specimen had a slightly lower value (82.5), indicating that surface resistance has a low sensitivity to geometric variation. Fire resistance assessment of the raw polycarbonate filament showed burn times of 34s (vertical) and 39s (horizontal) over a distance of 100mm, proving the natural flame retardant effect of the material in the conditions tested. Overall, the obtained results give experimentally verified geometry-property correlations for FFF-printed polycarbonate. Although the mechanical difference between geometries is moderate, the results support geometry based design considerations for the purposes of increased structural efficiency in AM components.

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