

Hybrid ABS & CF-ABS FDM Printing Tensile Components: A Comprehensive Review and a Novel Taguchi–FEA Based Methodology Framework for Mechanical Optimization

Kaustubh Pravin Joshi^{1,*}, M. K. Chopra²

Abstract

An experimental–numerical strategy and a critical literature survey were addressed to tackle the tensile response of hybrid Acrylonitrile Butadiene Styrene (ABS) and Carbon Fiber–reinforced ABS (CF-ABS) parts manufactured by Fused Deposition Modeling (FDM). The study employed a systematic literature synthesis to identify material challenges, reinforcement compromises and important process parameters that impact anisotropy as well as interlayer bonding. Dual-material tensile samples based on an Automatic Material System (AMS) printer were designed and manufactured. DOE was conducted via using Taguchi L25 orthogonal array for single-material experiments and L8 array did the same job for other hybrid setups with validations through FEA. The neat one demonstrated ductile behavior, with UTS of 8.76 MPa and as long as 52.65 % elongation at break, while the other showed lower UTS (39.71 MPa) and only 12.33 % elongation. Hybrid specimens exhibited a non-optimal mechanical behavior with a strength 32–45 % higher than for pure ABS and an increase of the ductility by 25–35 % in comparison to CF-ABS. The hybrid structure, consisting of CF-ABS core layers and outer skins made of ABS, was found to efficiently overcome the stiffness–ductility trade-off. Comparison between the experimental and FEA results demonstrates that Y-orientation with moderate filling densities (60–80 %) has a higher tensile performance. The proposed Taguchi–FEA approach was validated to optimize the mechanical performance of dual-material FDM articles, therefore enables reliable hybrid part design and functionally graded hybrid polymers.

Keywords- ABS–CF-ABS composites, AMS printing, anisotropy reduction, dual-material 3D printing, Finite Element Analysis, functionally graded polymers, Hybrid FDM, mechanical optimization, Taguchi optimization, tensile strength

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INTRODUCTION

The emergence of Additive Manufacturing (AM) has revolutionized contemporary manufacturing, allowing the creation of intricate geometries using little material and without the necessity for conventional tooling. Out of the variety of AM methods, Fused Deposition Modeling (FDM) – commonly known as Material Extrusion (MEX) or Fused Filament Fabrication (FFF) – is highly popular for polymer application due to its cost effectiveness, design flexibility and suitability from prototyping to end-use production [1]. FDM has matured into a production-capable AM process as a manufacturing technology and has found its applicability in aerospace [2], automotive [3], defense [4], and medical industries where light weight customized part with improved performance is often demanded.

Notwithstanding its benefits, mechanical reliability of FDM parts is still a major constraint for industry scaling up because of the anisotropy, voids generation, and poor interlayer bonding [5]. These challenges have driven the research focus from geometric design to material- and process-level optimization, in particular through reinforced and hybrid printing approaches [6].

Background on FDM and Composite Printing

FDM works by feeding thermoplastic filaments into a heated nozzle, where the material is melted and then deposited following a digital CAD model in layers. The most frequently processed polymers are ABS, PLA, PC, and HIPS with the material ABS (Acrylonitrile Butadiene Styrene) as one of the most used materials because of its thermal stability, good dimensional precision and toughness [7]. The mechanical behavior of printed specimens is determined not only by material properties, but also by processing parameters including raster angle, infill rate, layer thickness and extrusion temperature that could influence the interlayer bond strength as well as tensile strength [8].

As FDM developed, composite filaments were introduced as a logical step to address the strength limitations of pure thermoplastics. Reinforcing polymers with CF, glass fibers or nanoparticles increases their stiffness, strength, and thermal stability due to a load-sharing effect and limitation of the polymer chain motion [9]. In this context, carbon fiber-reinforced ABS (CF-ABS) is emerging as a more mechanically capable analogue of neat ABS with tensile modulus enhancements in the range of 30–70 % while being compatible with standard FDM systems [10].

However, the shift from composite printing faces new obstacles like fiber stacking, porosity, and anisotropy leading to a lack of performance prediction in FDM composites. This calls, therefore, for the study of hybrid material systems that would offer a combination of the positive aspects of ABS with ductile behavior and CF-ABS with rigidity to provide a balanced mechanical response [11].

Limitations in ABS and CF-ABS Printing Processes

Despite its printability, toughness, and cost-effectiveness, FDM-printed ABS parts suffer from the direction-dependent structure-property relationship – the Z-tensile strength is typically decreased by 40–60 % compared to in-plane tensile properties [12]. Due to its weak interlayer diffusion, void generation and thermal contraction have become critical issues that limit the structural reliability of polymers [13].

The addition of carbon fibers to ABS improves stiffness and strength, but this reinforcement brings new trade-offs. Research indicates that CF-ABS generally displays higher level of brittleness, poor elongation at break (< 3 %) and low interfacial bond at some fiber/matrix interface where failure occurs early due to crack initiation and network [14]. Moreover, Nozzle abrasion, fiber agglomeration and improper alignment between fibers are the factors restricting process consistency [15]. Hence while the tensile modulus and load bearing properties of CF-ABS are improved (typically 1.5–2× that of neat ABS), its ductility and impact resistance are sacrificed. The failure of either to obtain a concurrent stiffness–toughness balance highlights the impetus towards hybrid material approaches [16].

Need for Hybrid Structures

The mechanical compromise between neat ABS and CF-ABS demonstrates the importance of hybrid or graded material designs where both materials coexist in an individual component. ABS provides ductility and energy absorption whereas CF-ABS can provide stiffness and dimensional stability; by combining them we may ensure an optimal balance between stiffness and toughness [17].

It has been reported that multi-material FDM with either dual nozzles or multi-feed extrusion mechanisms could do functionally graded material, giving the capability of property change during one build [18]. The stiffness can be localized in the desired areas when needed, while the ductility exists at the critical stress positions so as to directly solve reinforced composites with brittle nature. Furthermore, the formation of interfacial transition regions between ductile and loaded layers can prevent the

interlayer weak points common in monolithic prints [19]. Therefore, hybrid ABS–CF-ABS structures are a mechanical variable mode to optimize and balance both tensile performances and structural reliability in FDM parts.

Motivation for Combining Review and Methodology

Considering the scattered and diverse researches related to FDM and CF-ABS composite system, a single review or experimental analysis is not capable of totally elaborating on the process–structure–property relationships applicable in composite and hybrid printing. This investigation hence combines the systematic literature review and a numerical–experimental approach in order to provide robust validation of mechanical trends reported elsewhere [20]. This effort into account, this approach sets up a coherent framework for connecting theoretical knowledge with experimental validation by synthesizing review-based account of anisotropy, reinforcement, and bonding mechanisms with methodical optimization of hybrid tensile specimens [21]. Integration, thus ensuring that the work provides both conceptual knowledge as well as application innovation in hybrid FDM design.

Contribution of the Paper

This paper makes three main contributions to the literature. First, it adds with a comprehensive literature review on the FDM and composite printing research gaps in order to systematically consider mechanical constraints as well as reinforcement trade-offs of ABS or CF-ABS systems [22]. Second, it develops an enhanced hybrid ABS–CF-ABS tensile model which reveals that the stiffness–ductility trade-off present in mono-material systems [23] may be alleviated by the use of hybrid architectures. Third, it confirms the link between FDM process parameters and mechanical anisotropy from two experimental and modeling viewpoints while suggesting a systematic procedure that connects empirical information to numerical simulation. In general, these contributions promote a greater comprehension and development of hybrid FDM structures for functional and load-bearing applications.

Organization of the Paper

This paper is organized to progressively propose the hybrid ABS–CF-ABS optimization scheme for FDM-printed tensile specimens. Section 2 reviews literature related to ABS, CF-ABS, hybrid printing approaches and numerical modeling highlighting important research gaps. Expanding on these voids, the material selection and mechanical rationale of hybrid sandwich are introduced in Section 3. Section 4 presents the proposed Taguchi–FEA approach concerning tests conditions, DOE scheme, specimen manufacturing and experimental setup. Section 5 describes the anticipated mechanical results of the hybrid approach, whereas Section 6 presents the conclusions and compares them with prior work as well as current industrial relevance and some limitations. It is thus a coherent sequence from theoretical background via methodological development to practical consequences [24–31].

LITERATURE REVIEW

The literature review provides a theoretical understanding and empirical background of the mechanical response of Fused Deposition Modeling (FDM) materials, in particular ABS and CF-ABS, as well as the need to produce optimized hybrid tensile structures. This section recapitulates prior research focusing on five main thematic areas: the reviewing approach followed, studies spotlighting materials, hybrid/multi-material approaches and numerical modeling. Every subchapter is logically connected, covering the transition from individual materials up to integrated hybrid systems.

Material Studies

ABS Mechanical Behavior

ABS (Acrylonitrile Butadiene Styrene) is one of the most studied polymers in FDM, owing to its thermal resistance, economy, and dimensional tolerances [1]. The studies in literature consistently demonstrate the tensile strengths between 30 and 45 MPa and elastic moduli of about 2–2.6 GPa, depending on the build orientation and processing parameters [2]. Nevertheless, the anisotropic feature of layer-by-layer deposition results in strength degradation of 40–60% along Z-direction mainly due to weak interlayer bonding, which induces voids and restricts the polymer chain diffusion during cooling [3]. SEM examination reveals intra-bead porosity and stair-stepping defects, which are responsible for onset of premature failure [4].

The mechanical properties for ABS are, as such, characterized by raster orientation, layer thickness, infill density and print temperature where a 0° or $\pm 45^\circ$ raster orientation provides the highest tensile strength [5]. ABS is both ductile and tough, but lacks adequate stiffness for load carrying applications, hence fiber-reinforced composites were employed to improve its structural efficiency [6].

CF-ABS Reinforcement Mechanisms

CF-ABS is a significant advance in materials for FDM because fibers can dramatically increase the stiffness of the composite relative to neat ABS. Positive shifts in tensile modulus have been reported as high as 30–70% (depending on the fiber content, the length distribution of fibers and processing conditions) [7]. The improvement in stiffness is mainly controlled by load-transfer from the polymer matrix into high-modulus carbon fibers, which are serving as a primary reinforcing phase and hindered the mobility of ABS chains during deformation. The similar reinforcement mechanisms such as fiber bridging and matrix constraint effects have been attributed to the decrease creep deformation of FRP systems [8].

Nevertheless, the addition of short carbon fibers restricts in ductility and failure strains. The elongation at break of CF-ABS is usually low (often less than 3%) compared to neat ABS, which suggests that the materials become more brittle [7, 8]. Moreover, the extrusion and layer-to-layer deposition of FDM may cause voids by non-homogeneous fiber distribution, local accumulation of fibers, and entrapment of air, increasing overall porosity that acts as stress raiser. When the fiber content is higher than a certain limit (around ~ 15 wt. % in literature), the enhancement of thermal conductivity could become limited, due to decrease of ductility and increasing likelihood of cracking (due to stress concentration at fiber ends and fiber-matrix discontinuities) [9].

The interfacial bonding quality between fiber and matrix is thus one of the key issues that determines the mechanical properties of CF-ABS. Poor interfacial adhesion causes an early debonding and a fiber pull-out which is the most common failure mode of short-fiber thermoplastic composites [10]. Therefore, despite the enhanced stiffness and dimensional stability of CF-ABS, its mechanical behavior is closely related to fiber dispersion and interface adhesion. For semi-structural hybrid systems, CF-ABS is commonly paired with ductile matrix zones to complement its low strain capabilities, while retaining the stiffness advantage [10].

Process Parameter Optimization

Layer Height

Layer thickness is the height of an individual layer that has been extruded out from a nozzle and laid down on top of the print bed. It is generally less than nozzle diameter and affects the surface finishing and mechanical properties greatly [1]. Impact on Print Quality: Decreases in layer thickness (e.g., 0.1–0.2 mm), improves surface finish and feature accuracy, while increasing print time; whereas increases in layer thickness (e.g., 0.3–0.5 mm) reduces print time but at the expense of part resolution and surface quality requirements. Impact to Strength: Reduced layer height will actually improve tensile strength by improving interlayer adhesion and decreasing voids (Figures 1–2). However, a too low reduction of the layer thickness can raise residual stress which results to breakdown [9]. Optimal Range: 0.1–0.3 mm

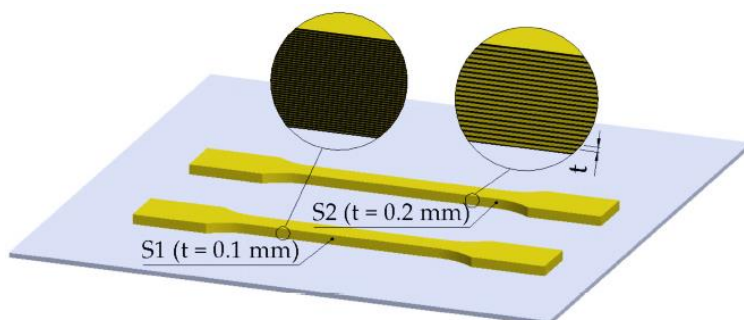


Figure 1. Layer thickness (t) tensile test specimens [22].

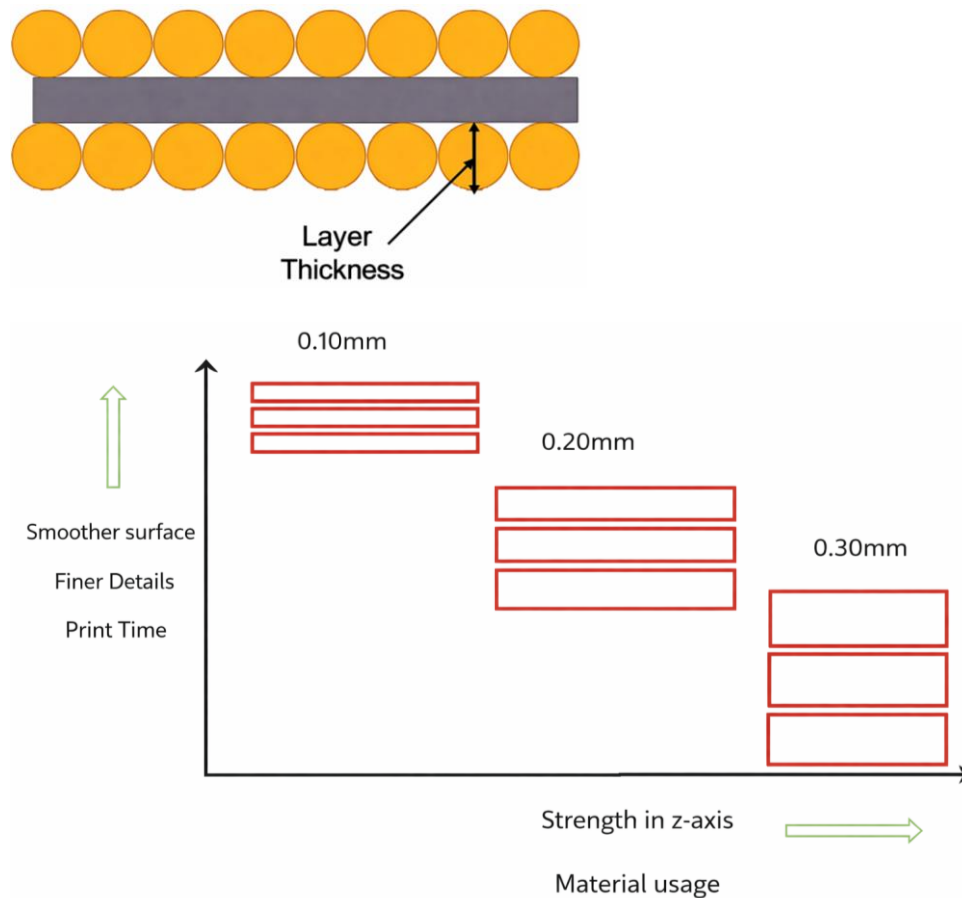


Figure 2. Graphical representations of various layer thickness [9].

Infill Density

Infill density defines the percentage of the volume inside the printed part is filled with material and has an effect on mechanical strength, usage of material, and printing time [9]. Impact on Strength: More infill density (say 70–100%) is stronger but it simply uses up your material. Reducing the infill density (10–40%) decreases weight and material costs, however, also results in a decrease of structural strength [11]. Typical Infill Densities: Prototypes: 10–30%, Functional Parts: 50–80%. The range of infill densities is found to be between the optimal ranges for a suitable combination of strength and efficiency i.e. 50–70% [9] (Figure 3).

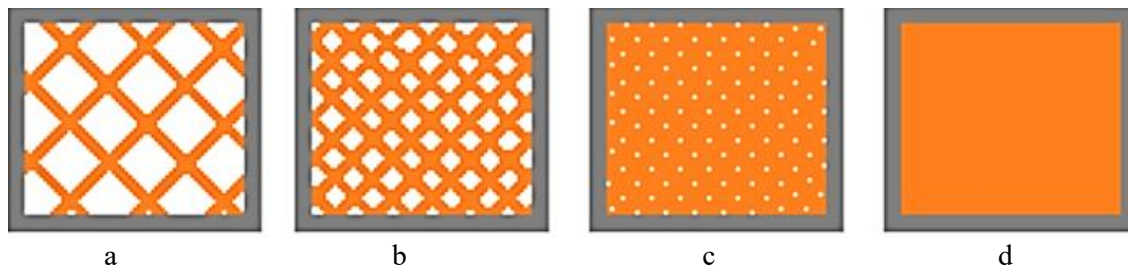


Figure 3. Filling density: (a) 20%, (b) 40%, (c) 80%, (d) 100% [11].

Raster Angle

Raster angle is the angle between extruded material's deposition and build platform x-axis [1]. Impact on Strength: 0° Raster Angle = Maximum tensile strength but fragile. 45° Raster-Rake Angle Gluten of flexibility and stiffness. 90° Raster Angle- Less stiff and less strong, can be used for shear. Best angle range: studies point to 0°–45° being most optimal for good mechanical performance [10] (Figures 4–5).

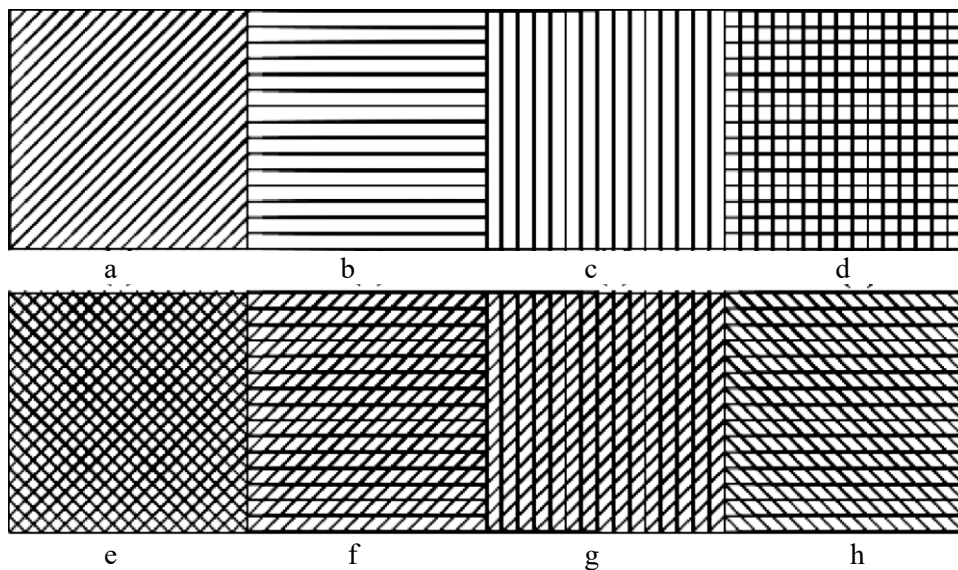


Figure 4. Raster angle Different Raster Angle/ Raster Orientation. (a) +45°, (b) 0°, (c) 90°, (d) 0°/90°, (e) +45°/45°, (f) 0°/+45°, (g) 90°/+45°, (h) 0°/45° [1].

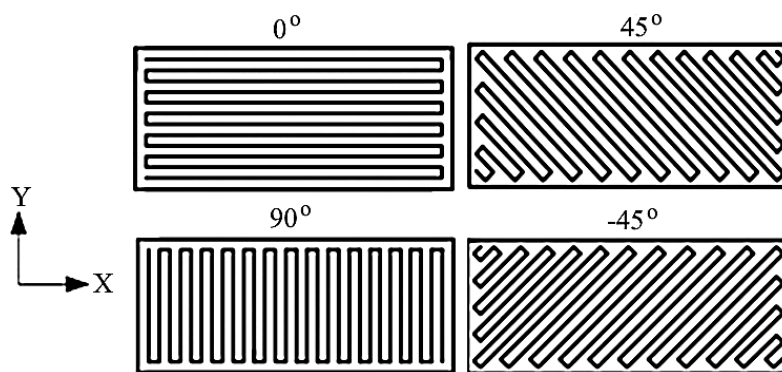
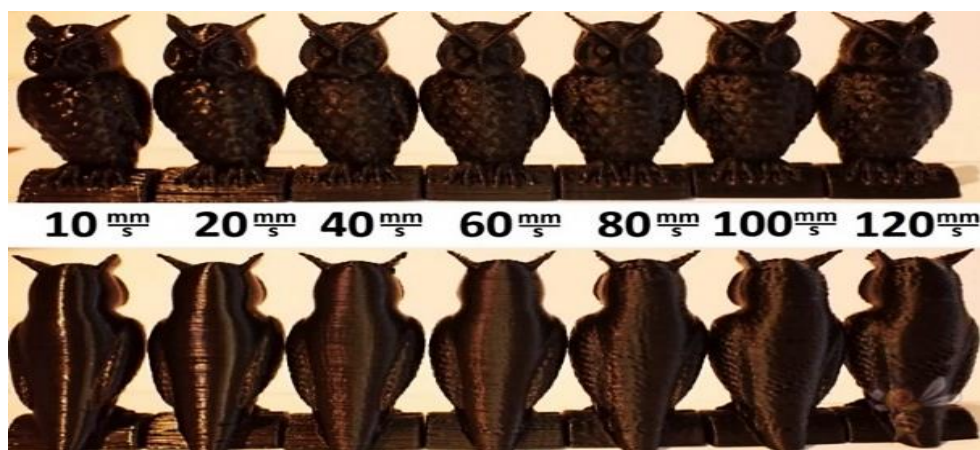


Figure 5. Layer deposition with different raster angles [14].

Print speed

Print speed determines the traveling speed of the nozzle relative to the build plate, and thus affects the accuracy of material deposition, as well as time required for printing [1]. Impact on strength: High speed (>80 mm/s): Leads to under-extrusion and lower bonding. Slow Speed (<30 mm/s)– Improves inter-layer adhesion but slow down the printing speed. Proper Speed 40–60 mm/s will be well-balanced among strength and efficiency [9] (Figure 6).



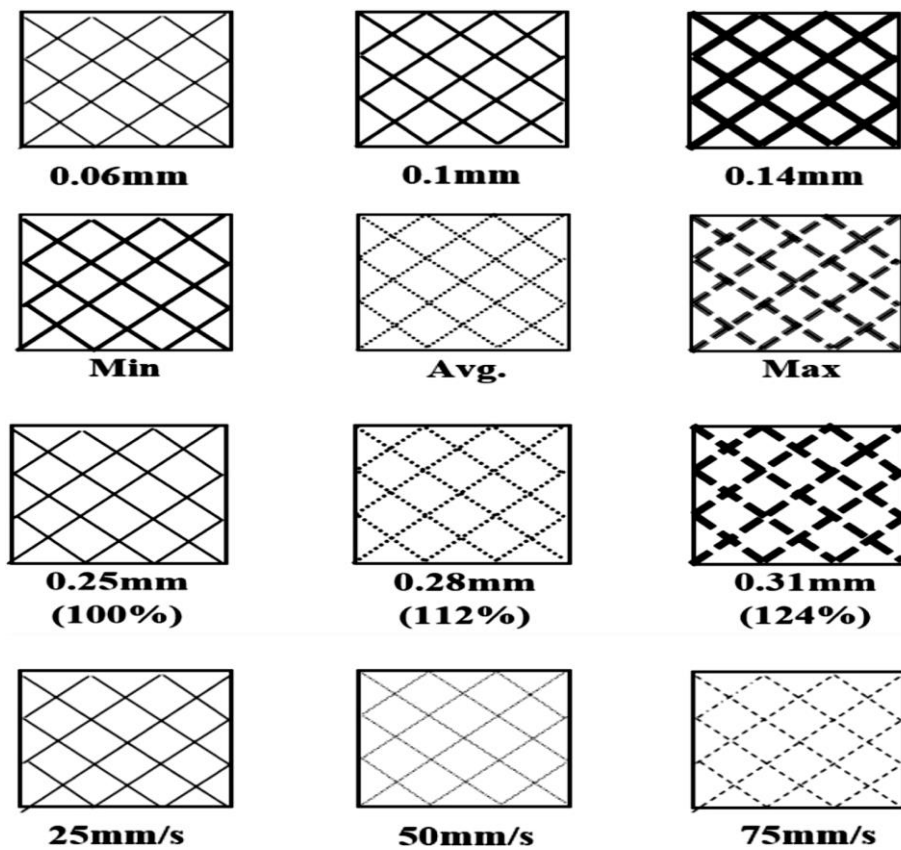


Figure 6. Printing speed and Quality of specimen &. FDM printing parameters (a) Layer thickness (b) Nozzle temperature (c) Line width (d) Printing speed [7].

Orientation

Orientation determines the part setup on the build platform relative to X, Y, and Z axis. It determines mechanical properties, cooling speed and surface state [1]. Orientations: Flat (XY-plane) – Higher interlayer bonding but may increase warping. On Long Edge (XZ-plane)– Sweet spot. On Short Edge (YZ-plane) – Weaker interlayer bonding, better surface quality [9]. Best Use: Application specific, flat (on the kink) would be the best regarding tensile strength (Figure 7).

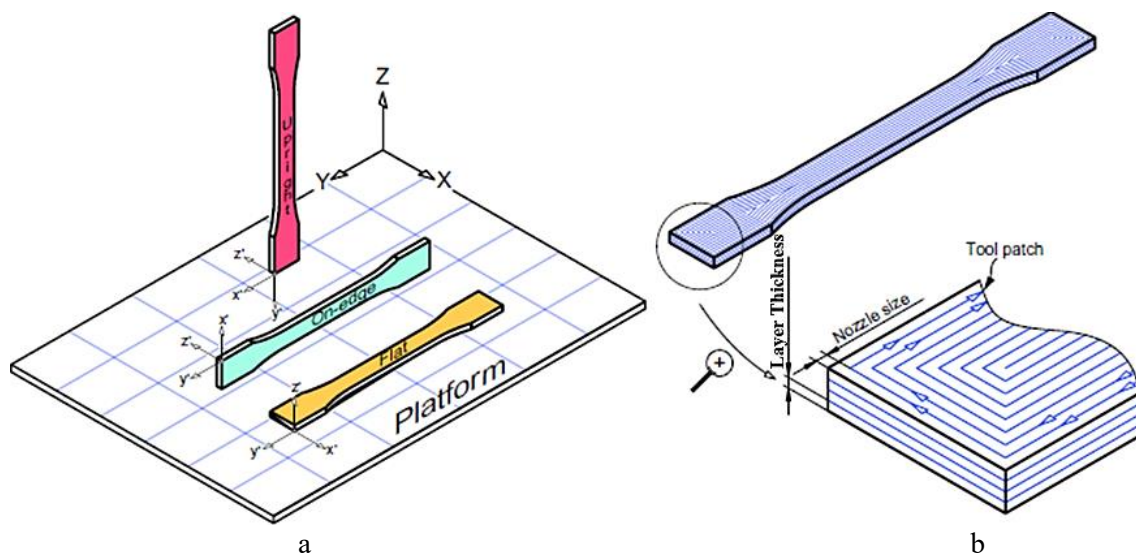


Figure 7. Process parameters: a) Build orientation. b) Layer thickness and perimeter raster [23].

Multi-Material & Hybrid Printing Studies

The development of FDM from single- to multi-material fabrication has introduced new possibilities for property tuning and functionally graded constructs. Studies on multi-material FDM generally focus on sandwich structures, dual material integration and functionally graded composites that can provide specific mechanical benefits.

Sandwich structure: the sandwich structures make use of the layering character of the material in order to obtain a synergic behavior between strength and toughness. Research shows that the flexural strength can be improved by as much as 35%, while impact resistance is satisfied, when laminated with a stiff outer but ductile inner shell (CF-reinforced polymers with ABS or PLA) [15]. The interfaces of layers also serve as energy absorbers, and may strew load and slow down the progression of cracks during tensile loading. Nevertheless, due to the different thermal expansion coefficients of the materials, it is difficult to obtain uniform interfacial bonding [16].

Dual-material process allows to extrude two polymers at the same time – with multi-nozzle or AMS-based switching systems. With this method it is also possible to respond with an immediate production of ABS–CF-ABS hybrids including material transitions designed in a layer-wise or region-based manner. Dual-material designs provide an increase in stiffness without a complete loss of ductility, resulting in a locally optimized value for the stiffness–toughness balance along the tensile specimen. The new applications show that the tensile strength of dual-material FDM can be 20–40% higher than single-material prints, if the interface bonding and nozzle synchronization is sufficiently managed [17].

Functionally graded materials (FGMs) are the advanced evolution of dual material ideas, which gradually change its mechanical properties from one side to other in part direction or volume. FGM investigations in FDM depict gradual transitions between ABS and CF-ABS layers, resulting superior interfacial adhesion and stress uniformity. The graded characteristic lends itself to alleviating sudden stiffness discontinuity associated with discrete interfaces and reduces susceptibility to delaminations while advancing fatigue life. The current gradient evolution work has great potential for applications in the load-path optimization and crash-energy absorption [18].

Numerical/FEA Studies in FDM

The simulation of FDM process by Finite Element Analysis (FEA) has made it necessary to predict the mechanical anisotropy and optimize hybrid structures. FDM parts are usually modeled as orthotropic composites, using direction-dependent material properties from deposition path and layer orientation [19].

Anisotropy Modeling – It has been found that in FDM, anisotropy originates due to non-uniform bead deposition, presence of additional air gap and layer connectivity which require the use of orthotropic or transversely isotropic models. This particular type of structure is typically subjected to a wide range of various loading condition and interlayer failure modes are not accurately characterized in that framework.

Orthotropic CF-ABS and the like short-fiber composites need an orient dependent constitutive model to account for the directionality of reinforcement. By coupling fiber orientation tensors calculated based on flow simulation into structural analysis, such new-generation FEA models surpass the predictive ability of isotropic ones by about 20%. These models verify that the increase in stiffness is maximized along the raster direction but decreases rapidly between layers as a result of weak vertical bonding [20].

Comparison Simulation vs Experiments– Comparable accuracy for simulated tensile behavior may be found in literature when measured against experiments both for ABS and CF-ABS using orthotropic

models calibrated by experimental results. Nevertheless, deviations from the true values of 5 to 15% are typical because interlayer bonding is simplified. Even with models applying the theories to hybrid system, very few open works could be found in literature thus there are emerging needs for DOE–FEA integrated frameworks that jointly make simulation predictions and prove factual tensile data [21].

Gap Identification

Collectively, the literature emphasizes the significant advancement in FDM materials and modeling; however, there are several critical research gaps:

- Lack of optimized hybrid material design– In fact, although many studies focus on ABS and CF-ABS materials separately individual works rarely offer an optimally hybrid layer sequence seeking the best trade-off between stiffness and ductility along the tensile direction.
- Lack of DOE + FEA hybrid studies – Whereas parametric studies via methods such as Taguchi or RSM are abundant for single-material systems, integrated experimental–numerical optimization frameworks which systematically tune dual-material configurations remain rare.
- Limited number of experiments done with AMS-based dual-material printing–Advanced Automatic Material Systems (AMS) with a single-nozzle filament switching capability is almost unused in academic research but can help make accurate layer changes and better interfacial quality.
- No binding methodology adopted for hybrid ABS + CF-ABS optimization – The lack of standardized design of experiments (DOE) protocols and FEA validation methodologies for hybrid FDM parts constrains replicability and comparisons between studies.

Rectifying these barriers is the primary mission of this study, which utilizes Taguchi–FEA hybrid approach to optimize ABS–CF-ABS tensile specimens via the dual-material AMS platform.

MATERIALS & HYBRID STRATEGY

Material Selection

Pure ABS

ABS is one of the most widely used thermoplastics in Fused Deposition Modeling (FDM) owing to its excellent mechanical properties, good thermal resistance and impact strength. Acrylonitrile Butadiene Styrene (ABS), a Thermoplastic Engineering Polymer is commonly utilized in FDM because of its balance between mechanical and thermal properties, ease of processing & Cost-friendliness. ABS is regarded as one of the benchmark materials in AM with its relatively high tensile strength and ductility, good impact toughness and amenable to post-processing [5].

As a robust polymer that is widely used, ABS parts typically suffer from mechanical anisotropy, low interlayer adhesion, and size-dimension instability in the Z direction specially. Despite these limitations when used for structural purposes, the drawbacks of ABS make it a desirable matrix for hybrids where toughness and flexibility are required to complement a stiffer reinforcement phase [6].

Practically, ABS has benefits of a low glass transition temperature and good thermal stability with lack of distortion at relatively mild extrusion (from approximately 230 to 250°C). These features make its processing easily repeatable and compatible with desktop and industrial dual-nozzle printers. The Solid Space® brand of ABS filament utilized in this study is manufactured to 1.75 mm nominal diameter and it has been proven to show good geometric stability and process ability. The chosen ABS filament's technical specifications, which were necessary for the reproducibility of our experiments, are summarized in Table 1.

Therefore, the selection of ABS is justified due to its ductile fracture mode as well as availability and acceptance in industry, particularly automotive and tooling applications [12]. Moreover, as matrix material in hybrid systems with stiffer CF-ABS, it helps to further balance the mechanical performance (Table 2)

Table 1. Technical characteristics of filaments material made of ABS [30].


Property	
Material	ABS
Filament Diameter	1.75 mm
Colour	White
Density (g/cm ³)	1.05
Poisson's Ratio (ν)	0.36-0.38
Modulus of Elasticity (E) (GPa)	2.62
Flexural modulus (Gpa)	2
Ultimate Tensile Strength (UTS) (MPa)	47.0
Heat Deflection Temperature (°C)	90
<i>Tensile strength</i>	
At yield	47 MPa
At break	34 MPa

Table 2. ABS Filament properties [30].

Properties	Method	Typical value
Density	N/A	1.05 g/cm ³
Printing temperature	N/A	235-245 °C
Shrinkage	ASTM D792	0.5-0.6%
Flexural Modulus	ASTM D790	2620 MPa
Tensile strength	ISO 527-2/50	47.0 MPa
Elongation at break	ISO 527-2/50	≤ 30%
Heat deflection temp	ISO 75-2/A	90°C

CF-ABS

In this study, carbon-fiber-reinforced ABS (CF-ABS) was chosen as a stiffened composite filament for hybrid FDM printings using neat ABS as a reference. Generally CF-ABS is comprised of short carbon fibers embedded in an ABS matrix (about 20 wt. % CF), allowing a significant increase in tensile modulus, flexural strength and thermal stability compared to pure ABS. Such improvements open up the possibilities of using FDM parts for semi-structural and functional applications where neat thermoplastics are not rigid or dimensionally stable enough [4].

The reinforcing effect of CF in the CF-ABS is mainly due to effective stress transfer from the ABS matrix to high modulus carbon fibers. Furthermore, crack-bridging as well as the confinement of polymer chain mobility will enhance the stiffness and slow down creep strain under load applied for sustained duration [11]. However, by adding short fibers it also results in the compromise on its ductility which yields lower elongation at break and then introduce brittle behavior with neat ABS. Hence, the hybrid concept of ABS (ductility) and CF-ABS (stiffness) material works well toward a balanced mechanical response.

In this work, CF-ABS filament was obtained from an established commercial world-class supplier of performance composite filaments—3DXTECH®. The filament component comprises over 80 wt. % ABS resin and up to 20 wt. % short carbon fibers. Technical data and essential mechanical/thermal features of the CF-ABS filament are listed in Table 3.

Table 3. Technical characteristics of filaments material made of CF-ABS [31].

Components	CAS No		Concentration Range (%)
ABS Resin	9003-56-9		>80
Carbon Fiber	308063-67-4		<20
<i>Properties</i>	<i>Standard</i>	<i>Unit</i>	<i>Typical Value</i>
Density	ISO 1183	g/cc	1.11
Tensile Strength, Break	ISO 527	MPa	46
Tensile Modulus	ISO 527	MPa	5210
Tensile Elongation, Break	ISO 527	%	2
Flexural Strength	ISO 178	MPa	76
Flexural Modulus	ISO 178	MPa	5260
Glass Transition Temperature (Tg)	DSC	°C	105
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	76
Surface Resistance	ASTM D257	Ohm/sq	>10 ⁹

CF-ABS is appropriate for stiffness-critical applications which include tools but not limited to, tooling aids, aerospace, and automotive fixtures, and load-bearing jigs since it has a high tensile modulus and flexural stiffness. Another advantage of CF-ABS is that it is printable on standard FDM printers (including dual-nozzle setups) meaning those hybrid printing techniques can be applied where carbon fiber-reinforced ABS could be strategically placed in stiffness-dominated parts while ABS used in areas with high strain capacity.

In this study, CF-ABS was chosen with the aim to utilize its enhanced stiffness, dimensional stability, and load bearing capacity along neat ABS being retained for ductility.

Wire Testing Values

Tensile testing of filaments in pre-processing stage was conducted to compare the intrinsic strength of both ABS and CF-ABS materials [18]. In order to testify the reliability and consistency of materials used in the hybrid FDM process, as-received ABS and CF-ABS wires were tensile tested before fabrication. This initial characterization facilitated a determination of the baseline mechanical response, which is crucial in gaining insight into material behavior and establishing design expectations for hybrid configurations (Table 4).

Table 4. Wire Testing Results Comparison:

Parameter	ABS Wire	CF-ABS Wire
<i>Load at Break (N)</i>	22.367	101
<i>Elongation at Peak (mm)</i>	9.570	0.83
<i>Elongation at Break (mm)</i>	13.163	4.31
<i>UTS (Mpa)</i>	8.759	39.71
<i>Break Strength (Mpa)</i>	6.627	39.32
<i>% Elongation at Peak</i>	38.280	2.37
<i>% Elongation at Break</i>	52.653	12.33

The tensile tests of pure ABS wire and carbon fiber reinforced ABS (CF-ABS) are presented in the graph of load (N) versus displacement (mm). The curves reveal important information about the difference of mechanical behaviors between the two materials in uniaxial tension (Figure 8).

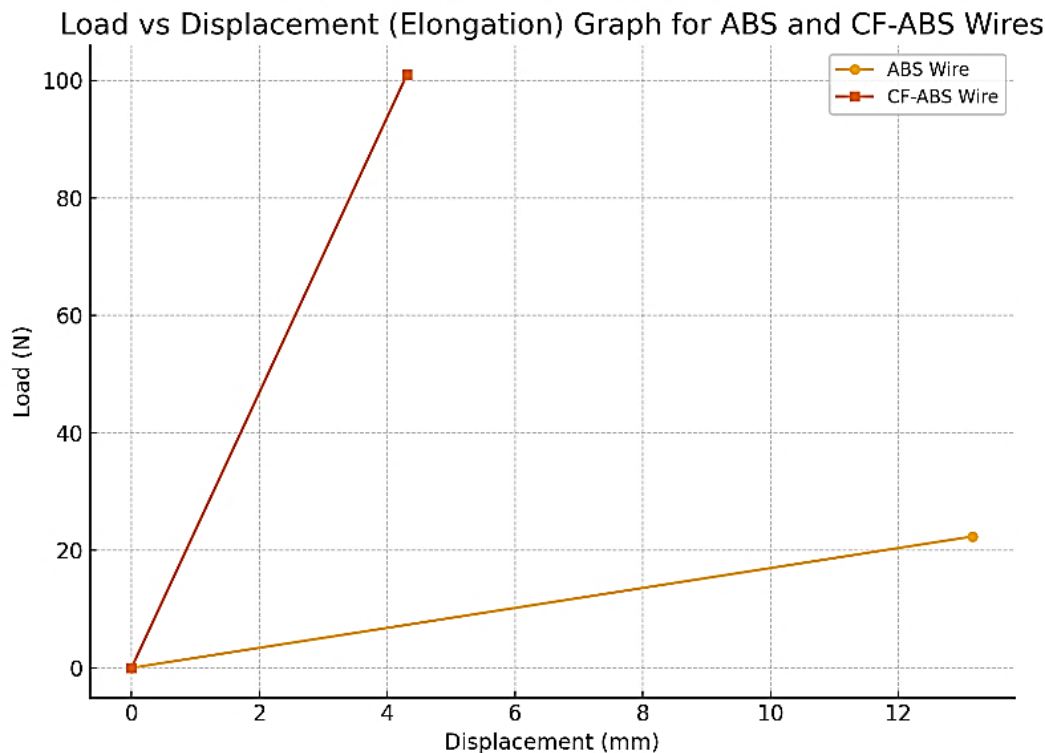


Figure 8. ABS & CF-ABS Displacement vs Load Graph.

Load at Break: CF-ABS has a load at break (101 N) which is 78% higher than that of ABS (22.367 N). This means that CF-ABS is harder, being capable of enduring larger loads before failure.

Elongation at Peak: A significantly higher breaking elongation is observed for ABS (9.570 mm) compared to the CF-ABS (0.83 mm). It means that ABS is more ductile, what can be stretched more before getting to the point of the maximum of stress which is a common trait for non-reinforced polymers.

Elongation at Break: Like elongation at peak, ABS showed higher elongation at break (13.163 mm) than CF-ABS (4.31 mm). This indicates that ABS is more ductile and withstand relatively larger deformations before failure.

Ultimate Tensile Strength (UTS): The UTS strength of CF-ABS is obviously higher than that of ABS (39.71 MPa and 8.759 MPa). The tensile strength of the composite material can be increased significantly due to the carbon fiber reinforcement, making it more difficult for the composites to break under the application of force.

Break Strength: CF-ABS still has a significantly higher break strength (39.32 MPa) than ABS (6.627 MPa), proving that greater addition of carbon fibers enhance the resistance of material to breaking forces.

% Ultimate and Failure Elongation: ABS shows a significantly higher elongation at peak (38.280 %) and break (52.653 %) than those observed in CF-ABS (2.37 % and 12.33 %, respectively). This is a sign of more ductility (able to stretch before fail), so ABS is more ductile, CF-ABS loses some of this property but gains in strength.

The wire tests exemplify a trade-off between strength and ductility for ABS as well as CF-ABS materials. Although CF-ABS has much higher strength, reflected by its increased crack load, ultimate tensile strength (UTS), and breaking force, it has significantly inferior elongation at peak and break than that of ABS. This implies that CF-ABS is a stiffer material and more appropriate for high strength and stiffness applications with less flexibility or ductility required.

On the other hand, ABS has higher deformability and has a lower mechanical resistance compared to CF-ABS. Accordingly, the selection for either ABS or CF-ABS depends on specific application requirements – if you need high strength, go with CF-ABS; if flexibility and higher elongation are required, then ABS is your choice.

Rationale for Hybrid ABS + CF-ABS

Strength–ductility compromise. – FDM-printed ABS is intrinsically ductile and can undergo large plastic strain, but it has very poor tensile strength and stiffness, making it not suitable as a load-carrying structure [4]. The latter is much higher for CF-ABS compared to that for ABS which caused an efficient load transfer from the matrix to carbon fibers, and consequently a brittle behavior [5]. The experimental results at the wire level also support this coupling relationship, indicating that no single material can meet both strength and toughness requirements together. Hybridization hence offers a rational approach, where CF-ABS property is combined in the same space with that of ABS: stiffness and ductility/energy dissipation which provides balanced mechanical performance [6].

Sandwich structure rationale. – A sandwich structure is used: the CF-ABS is the load bearing core, and ABS as external skin to take advantage of well-gauge of each material. The CF-ABS core is effective in resisting tensile load, and the ABS skins delay crack initiation, stress redistribution, and further damage tolerance [7]. These hands were proven to improve tensile properties without promoting disastrous brittle failure and weaknesses due to anisotropy inherent in monolithic FDM parts [8]. Sandwich structure also adapts to the AMS-based dual-material FDM with reproducible fabrications and sufficient interfacial adhesion, thus a mechanically-effective and manufacturable hybrid approach.

PROPOSED METHODOLOGY FRAMEWORK

Methodology Overview

Figure 9 Showed the flow chart diagram of methodology.

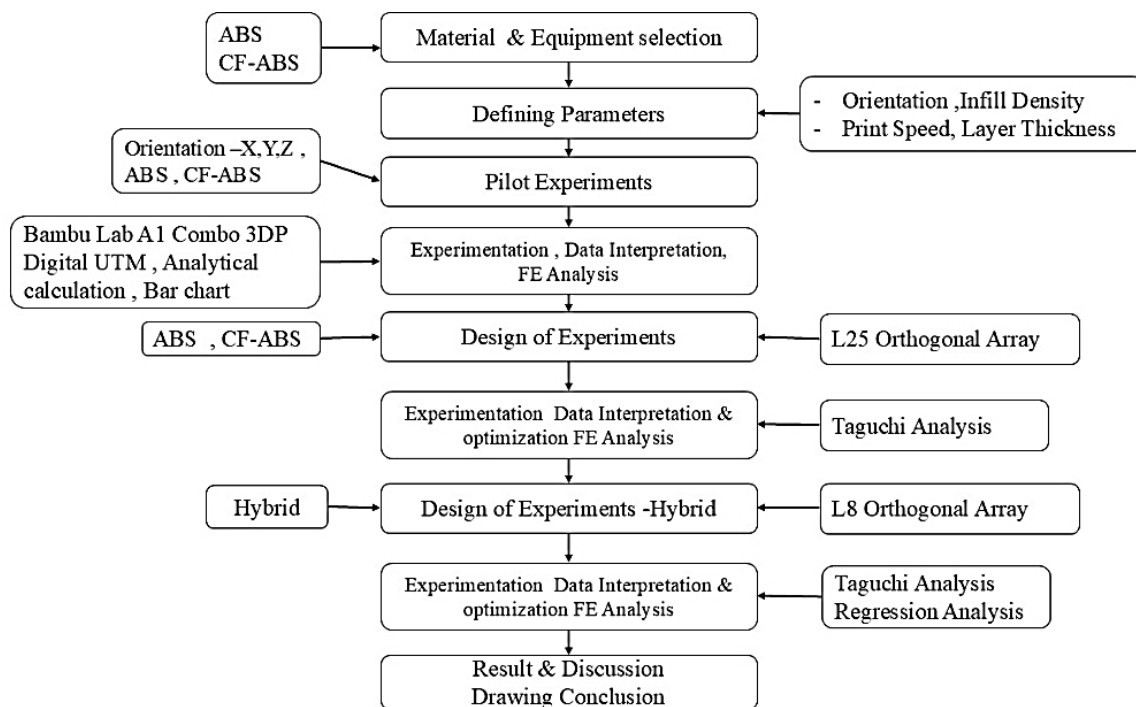


Figure 9. Methodology Flow Diagram.

- *Choice of material:* The ABS and 20% CF-ABS were selected due to their good compatibility and reinforced capability.

- *Definition of parameters:* The key parameters, including the orientation, infill density, layer thickness, and print speed were determined by literature review.
- Pilot testing – X, Y, and Z orientation test was performed with a Bambu Lab A1 Combo printer and UTM; the tensile performance of the Y-orientation was better.
- Taguchi L25 Orthogonal Array is used for ABS and CF-ABS with tensile testing, data interpretation and FEA. Optimization was carried out by S/N ratio method.
- *Hybrid DOE:* Dual-nozzle hybrid printing (ABS + CF-ABS) was studied by L8 Orthogonal Array and Taguchi’s approach along with regression analysis, respectively.
- *Final Stage:* There was a correlation study between the experimental and FEA Data to predict the optimized combination of parameters resulted in better Mechanical Property.

3D Printing Setup

After implementing the hybrid material method (as described in the previous section), a suitable FDM printing platform was necessary for reliable production of test specimens. The 3D printing platform had to achieve geometrical accuracy and repeatability across the entire DOE sample set as well as being convenient and operable with dual-material printing. In this study, a Bambu Lab A1 Combo FDM printer was used since it enables automated multi-material printing and fine control of the printing process in order to minimize variability originating from the fabrication process (Figure 10).

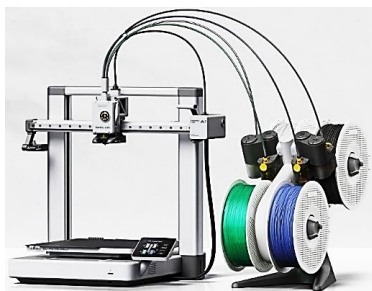


Figure 10. Bambulab A1 combo 3d printer.

Traditional dual-nozzle systems can add errors related to misalignment (for example, the offset of nozzles), material contamination attributable to filament crossover and irregularities from manual stoppages during switching between filaments. To eliminate these disadvantages, the printer used consists of an automatized material system (AMS) and integrated filament cutting for regulated change between various filaments with one nozzle. This setup allowed the production of homogeneous hybrid samples prepared from neat ABS and CF/ABS with consistent dimensional accuracy as well as reproducible interface characteristics (Table 5).

Table 5. Key Specifications of 3D Printer.

Feature	Specification
<i>Printing Technology</i>	Fused Deposition Modeling (FDM)
<i>Build Volume</i>	256 × 256 × 256 mm
<i>Maximum Nozzle Temperature</i>	300 °C
<i>Maximum Bed Temperature</i>	100 °C
<i>Supported Nozzle Diameter</i>	0.4 mm (default); compatible with swappable nozzles
<i>Layer Height Resolution</i>	0.08 mm to 0.28 mm
Filament Diameter:	1.75 mm
Filament Cutter	Yes
<i>Print Speed</i>	Up to 500 mm/s (recommended: 50–250 mm/s)
<i>Filament Compatibility</i>	PLA, ABS, PETG, TPU, PA, CF-PLA, CF-PETG, and others
<i>Multi-Material Printing</i>	Yes – AMS (Automatic Material System) with up to 4 filaments
<i>Auto Bed Levelling</i>	Yes – active nozzle pressure sensor and mesh calibration
<i>Cooling System</i>	Dual part cooling fans and chamber fan
<i>Connectivity</i>	Wi-Fi, SD Card, Bambu Studio software
<i>Slicer Software</i>	Bambu Studio , Orca Slicer

The AMS-mediated switching strategy was particularly useful for the fabrication of sandwich-type hybrid samples containing CF-ABS intermediated between external ABS skin layers. The controlled material transitions minimized dependence on operator and improved the consistency of interlayer interfaces, which is crucial in hybrid specimens where local bond quality has a substantial impact on tensile performance and failure behavior.

Furthermore, the printer's automatic bed leveling, flow meter calibration and feed correction compensated control for trampoline effect of tensile geometry within a full DOE sample set. The system also offers a stable temperature control, and able to handle the abrasive composite filaments CF-ABS in one side by hardened nozzle hardware which can decrease the wear of nozzles and clogging during printing for carbon fiber filled thermoplastics.

The schematic diagram of a standard Fused Deposition Modeling (FDM) 3D printer and the most important processing parameters affecting part quality and mechanical properties is shown in Figure 11. Essential parts of the schematic are the filament feed, heated nozzle, build plate, fans for cooling and axes (X, Y, and Z) for movement control. Critical process parameters such nozzle and bed temperatures, print speed, layer height, infill density have direct effects on inter-layer bonding, geometric accuracy, surface quality and the mechanical strength of the fabricated part. These parameters need to be accurately maintained because they affect repeatability, especially in cases of dual-material or hybrid printing, as here under study [18].

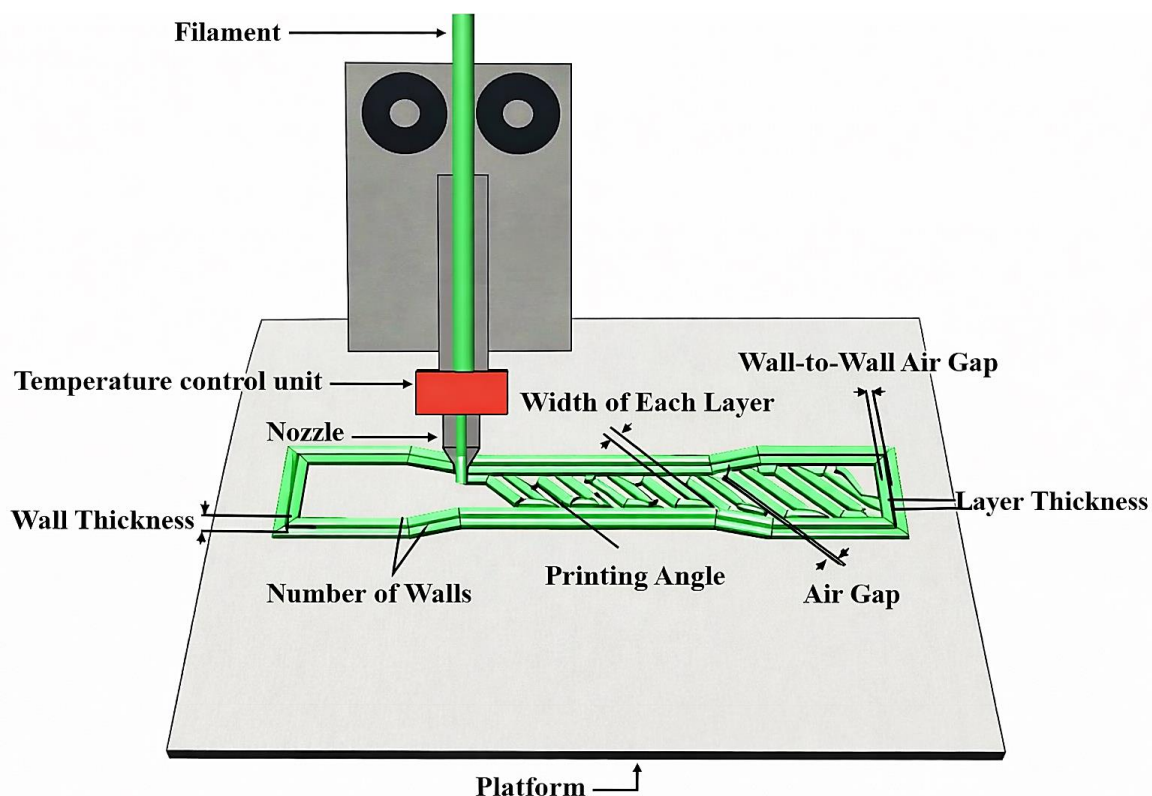


Figure 11. Schematic and process parameters of a FDM 3D printer [18].

Slicer Software: Orca Slicer Version 2.2

In the present study, Orca Slicer (version 2.2) was employed to produce G-code with material-based hybrid FDM printing settings. Orca Slicer is advanced slicing software compatible with multi-material setups, such as the Bambu Lab A1 Combo. It comes with an intuitive user interface and allows you to have a high level control over your printer printing parameters such as infill pattern and density or wall

perimeter values, top/bottom layer count, extrusion flow rate in % or temperature configuration for various heated bed materials.

This software support independent material on each layer or region, especially perfect for dual-material hybrid printing such as pure ABS and CF-ABS. Its built-in visual preview, process simulation, and temperature tower tuning help eliminate warp, improve interfacial interactions, and confirm replication of DOE samples. Orca Slicer Moreover, it supports real-time print time estimate as well as material consumption forecast, which guarantees an efficient and effective workflow management and repeatability together with secure synchronization with cloud-connected devices.

The use of Orca Slicer enabled the fine control needed to carry out the sandwich-structured hybrid tensile specimens and tune the slicing approach to fit with a DOE-based experimental methodology adopted in this study.

Selection of Critical FDM Parameters

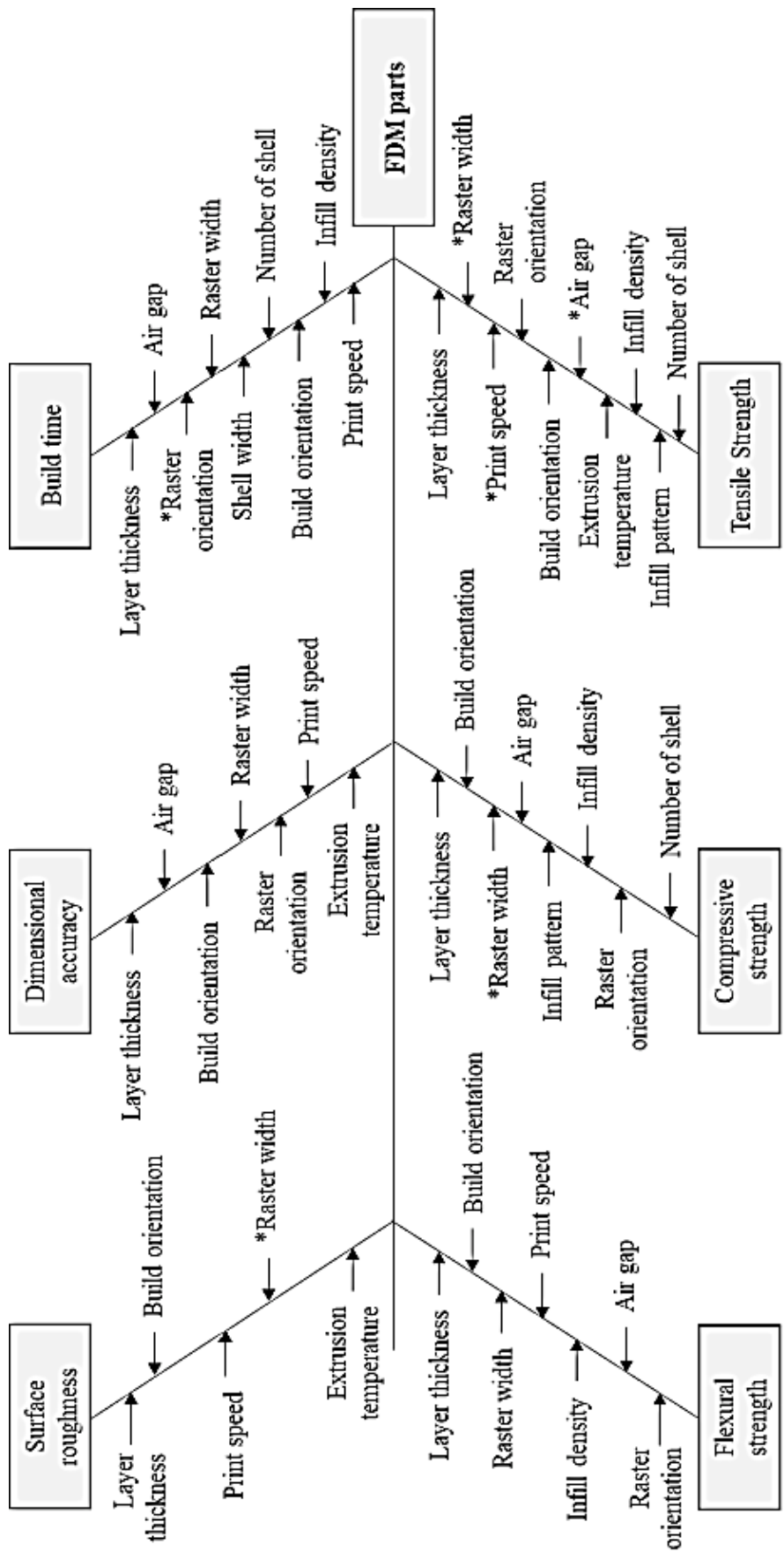
A key element in improving the mechanical properties of Fused Deposition Modeling (FDM) is as much optimize printing parameters as everything else related to the control over interlayer adhesion, anisotropy, and macrostructural behavior. Based on pilot experimentation and literature review), this section details the reasons for selection of the prominent process variables used in both experimental and simulation parts of our research.

It has been widely reported that FDM performance is extremely influenced by the parameters used for processing, including layer height, infill ratio, print speed, build direction and material type—factors being directly related with tensile strength, stiffness, and dimensional accuracy of printed parts [5], The misuse of such parameters can result in internal voids, lack of fusion between layers or act against mechanical load pre-failure [6]. Thus, the recognition and manipulation of these parameters are essential to achieve dependable performance.

The setting of process parameters in Fused Deposition Modeling (FDM) is a vital task aimed to accomplish good part quality and mechanical results. Figure 12 Fishbone diagram shows the effect of key parameter on surface roughness, dimensional accuracy and build time and mechanical properties as tensile strength creating a fishbone diagram, we have selected some parameters that affect quality. The various parameters (e.g., layer thickness, print speed, build orientation, raster orientation, air gap, raster width infill density and extrusion temperature) are interdependent and influence several part properties. For example, surface roughness is mainly affected by layer thickness, print speed and build orientation, while dimensional accuracy varies according to factors such as raster orientation, air gap and extrusion temperature. Tensile strength, flexural strength closely depends on infill pattern, number of shells, and inter-layer bonding as it is controlled by raster orientation and air gap. Some parameters, such as raster width and air gap, are still being investigated for their actual effect (indicated by *). This full comprehension allows to rationally choose optimization parameters but also ensures mechanical integrity and performance of FDM components [1].

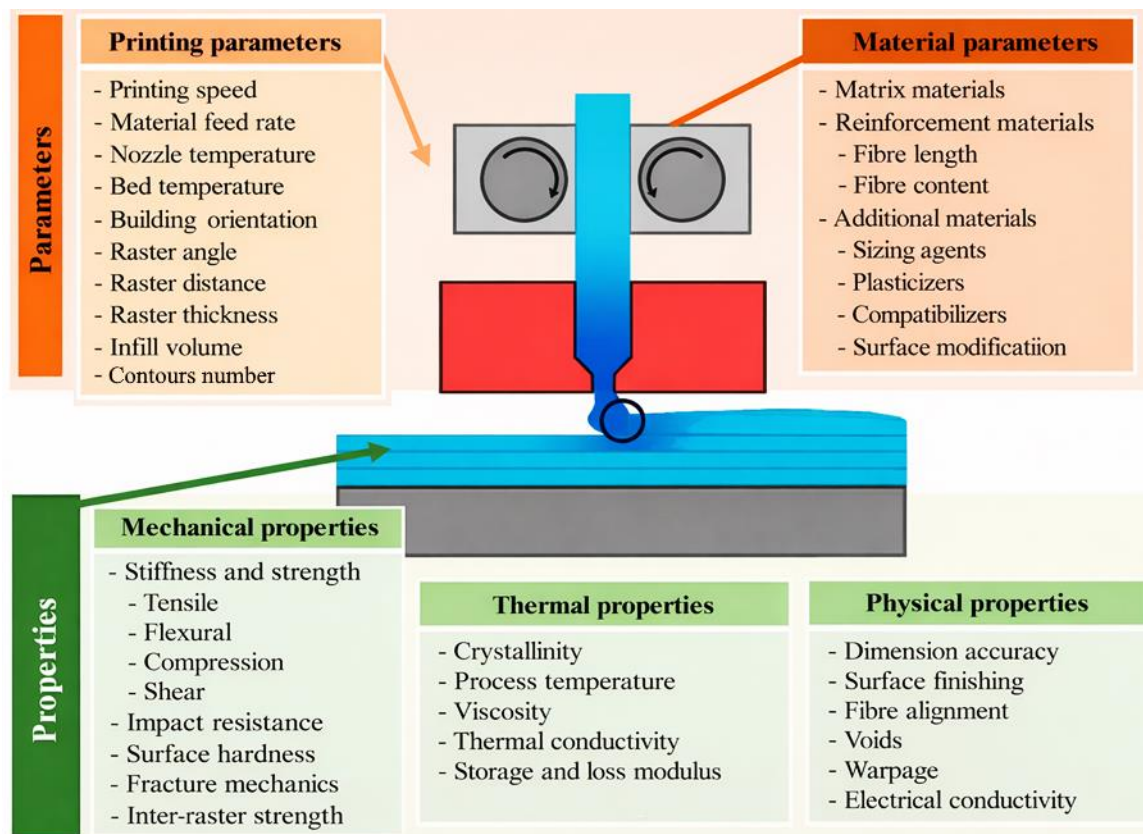
Figure 12 lists the major printing and material parameters in FDM process and their effects on final part properties. Deposition behavior is determined by printing parameters such as speed, temperature, build orientation, raster angle and infill volume. Flow, bonding, and reinforcement is affected by the matrix type, fiber content and additives. These in turn influence mechanical (e.g., tensile, flexural strength), thermal (e.g., crystallinity, viscosity) and physical properties (e.g., dimensional accuracy, surface finish). This figure demonstrates the importance of accurate parameter selection to achieve NIF FDM part success.

Figure 13 showed the diagram which represents Investigated parameters and properties of the fused deposition modeling (FDM) process.



* Indicates still unknown whether a parameter is significant for a part characteristic or not

Figure 12. Fishbone diagram to illustrate the impacts of process parameters on part characteristics [1].



* Indicates still unknown whether a parameter is significant for a part characteristic or at or not

Figure 13. Investigated parameters and properties of the fused deposition modelling (FDM) process [25].

Process Parameters in FDM Printing

The fused deposition modeling (FDM) process is characterized by a large number of process parameters which affect its mechanical strength, dimensional accuracy, surface roughness and the overall properties of printed objects. The determination of the best process parameters is essential to obtain structurally sound and performing 3D printed parts [1].

- *Infill Density:* According to [6] and further confirmed in [7], a moderate infill (60–80%) is the best trade-off between internal stress distribution and material preserving. Excessive or inadequate infill values can lead to delamination or stress concentration regions.
- *Relative to Layer Height:* According to Krajangsawasdi et al [8], reduced layer thickness will obviously enhance the raster bonding and surface finish but at an exponential increase in build time. Therefore, a step change from 0.1 mm to 0.3 mm was used.
- *Print Speed:* Much has been written about the need for slow speeds (10–30 mm/s) to ensure good bonding, especially when printing with dual-materials [6]. However, production considerations also require tests at higher speeds (up to 50 mm/s) for comparison with commercial levels of performance.
- *Material:* ABS and CF-ABS were selected for their extensive presence and complementary mechanical properties – ductile ABS vs. stiff, dimensionally stable CF-ABS [5]. Such a feature allows strategies to become mixed and it is possible to handle material performance in the stress zone.
- *Orientation:* Pilot testing indicated that Y-orientation provided better tensile properties, agrees with and who relate raster alignment with tensile axis for better mechanical integrity [6].

Pilot Experiments Summary

Before rolling out the full scale Design of Experiments (DOE), a pilot phase of experimental operations was performed to verify mechanical response exhibited by both pure ABS and carbon fiber reinforced (CF) -ABS under multiple different build orientations. This preliminary work was a pre-

requisite to determine the baseline of the performance, define preferred conditions for orientation and support parameter requirements of the DOE approach. It also guaranteed the repeatability and reliability of FDM process setup with Bambu Lab A1 Combo 3D printer.

The objective of the pilot study was to investigate the effects of build direction on tensile strength for monolithic ABS and CF-ABS components. From a large number of literature, we can see that orientation has great influence on the mechanical responses because of anisotropic bonding behavior arising from layer-by-layer building process [5]. Therefore, evaluation was only performed on the X, Y, and Z orientations and all other printing parameters were held constant.

Three samples were 3D printed at X, Y, and Z orientations of both ABS and CF-ABS materials. Other parameters were kept constant.

Schematic configuration of the pilot experimentation in order to investigate the effect of various build orientations on tensile behaviors was depicted on Figure 14. Two materials were considered: neat ABS, and carbon-fiber reinforced ABS (CF-ABS). For each material, samples were printed in three different orientations: X, Y, and Z to facilitate comparison of orientation-dependent mechanical properties under identical process conditions. The results obtained from the pilot phase were used to select the best position for use in the DOE-based optimization.

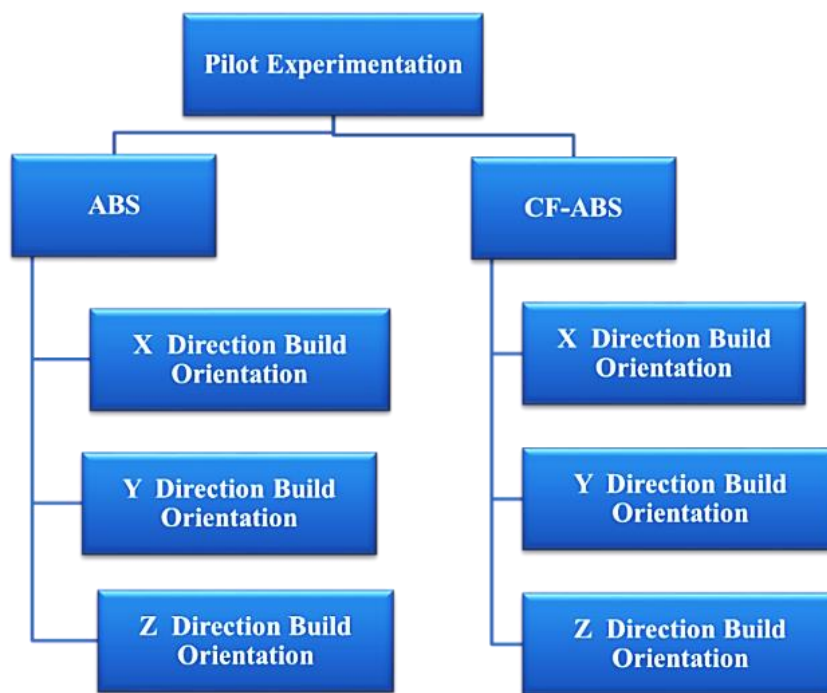


Figure 14. Flowchart of Pilot Experimentation Strategy for ABS and CF-ABS Specimens.

DOE Using Taguchi Method

Parameter–Level Matrix

Taguchi methodology with 5 factors at 5 levels was used to study and optimize the effect of significant process parameters.

All of these parameters have a critical impact on the mechanical properties of printed parts. Especially the negative correlation between print speed and layer height is worth mentioning. A moderate speed moderation is applied at the elevated layer heights in order to form good enough adhesion between layers, extruded amount and a heat fusion for deposition of thicker build-up layer. With larger layer heights, the volumes per pass becomes higher as well, reducing the speed to minimize the risk of

manufacturing imperfections like under-extrusion, poor bonding strength, warping, and lower dimensional fidelity. For instance, a 0.30 mm layer height in combination with 50 mm/s speed would not provide enough time for the melting and fusing of segments which might end up in porosity /structural voids—which again is crucial CF-ABS hybrids (Table 6).

Table 6. Process Parameters and Levels.

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
Infill Density (%)	20	40	60	80	100
Layer Height (mm)	0.1	0.15	0.2	0.25	0.3
Print Speed (mm/s)	50	40	30	20	10
Material	ABS	CF-ABS	–	–	–
Orientation (depend on Pilot Experimentation)	X	Y	Z	–	–

L25 Justification

The Taguchi technique utilizes orthogonal arrays (OAs) to create an efficient matrix of experiment that allows the consideration of factor importance with minimum trials. The reasons for selecting the L25 (5^6) orthogonal array are:

- *Factor-Level Assignment:* The L25 array allows 6 factors with 5 levels, a good match for this study's need to examine five levels of varied parameters (which includes the orientation level also as a factor which is categorical at two levels).
- *Experimental Economy:* A 5 factor by 5 level factorial design would have $5^5 = 3125$ experiments. Even a 3-factor full factorial ($3^5 = 243$ runs) is not practical. More samples are needed for the L25 design than other designs because it only consists of 25 runs.
- *Noise suppression:* The Taguchi method is robust to noise variation by performing the smallest S/N (Signal-to-Noise) ratio analysis that results immune of uncontrollable changes as printer fluctuation and environmental temperature change [4].
- *Support for Minitab:* The Minitab 21.2 software adopted here inherently provides support to build-up Taguchi DOE, conduct orthogonal array selection, factor alignment, auto-calculation of S/N ratios and ANOVA (Analysis of Variance). This facilitated effective experimental design, and data analysis.

Expected Outputs

The study is hoped to provide an optimum hybrid structure of ABS–CF-ABS by the Taguchi–FEA approach. The tensile strength and ductility (>10%) of hybrid specimens should be higher by 20–40% to that of single-material parts, resulting in a balanced performance with Stiffness–toughness trend [5].

The FEA validation is expected to show coherence with the experiments within a 10% accuracy of their results, which will assure the reliability of the proposed DOE–FEA methodology [9]. The AMS-based dual-material printing will exhibit the non-gap transition and strong intersurface bonding, indicating its promise in advanced multi-material FDM processing [16].

In summary, this work will provide a benchmark hybrid optimization scheme and support the design of functional grading lightweight structures in engineering industries [24].

Specimen Design

ASTM D5304

This test method includes the determination of breaking strength and elongation from the grab procedure. This technique is suitable for woven, non-woven and felted cloths. It is not advisable for glass or knit materials. The grab test is a strength/elongation test using the central portion of width of a sample as the clamped area.

Specimen size: A Range of specimen geometry can be used however most frequently used specimen size for ASTM is as follows. This setup is conducive to testing reinforced, hybrid fabric-like samples under a grab technique. The wide gauge portion is helpful to an extent of providing better adhesion strength between layers providing a good hybrid deposit along its cross-section. According to the definition in ASTM D5304, this test uses the middle part of the width of a specimen, which is clamped tightly in order to measure fracture elongation and tensile strength (Figure 15).

Dimensions to ASTM D 5304 standard: Overall Length: 100 mm, Gauge Length: 25 mm, Thickness: 5 mm, Width at gauge: 20 mm.

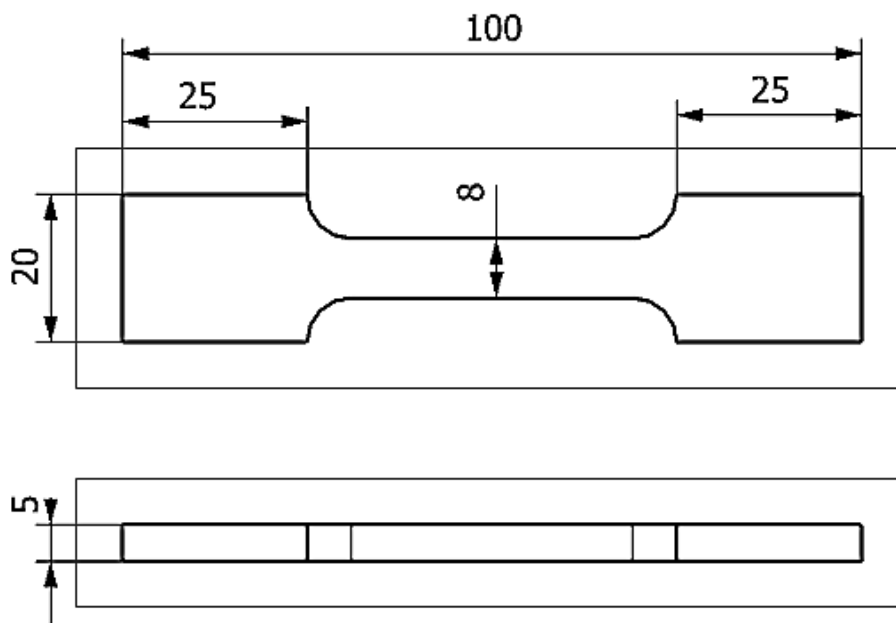


Figure 15. Dimensions of standard specimen (in millimeters).

CAD Modeling

The tensile test samples were designed computer aided design (CAD) model (SolidWorks), one of the popular parametric solid modeling software in engineering research and industry to get dimensionally and ASTM standard-pleasing samples. The geometric parameters such as gauge length, width, fillet radii and overall dimension of the specimen were defined accurately and simulated according to the ASTM D5304 standard for the test of fabric reinforced or hybrid polymeric specimens.

Fully constrained 3D models with smooth curvature transitions at the gauge-to-grip regions were designed in Software SolidWorks to decrease stress concentration for tensile loading. The hybrid layering areas for the CF-ABS and ABS materials were also digitally added to optimize slicing process during tool pathing. The STL files were post-processed in Orca Slicer v2. 2-based print parameter assignment and G-coding.

The parametric model of SolidWorks also facilitated easy adjustments on sample thickness and hybrid layer setup, which were necessary for conducting the Design of Experiments (DOE) in this study mandating internal variations in material composition. The standardized modeling method also facilitated natural integration with FEA workflows, as native geometry could be directly imported to simulation tools (ANSYS etc.).

In brief, the application of SolidWorks in this study made an accurate geometric control, repeatable fabrication and as well could be tested both physically and numerically; proposed methodology had a solid scientific background.

Meshing Considerations

Based on the specimen design described in Section 3.5, the simulation sequence using Finite Element Analysis (FEA) started from loading computer models into an ANSYS Workbench. The tensile coupons were modeled in SolidWorks using parametric constraints to accurately capture the ASTM D5304 dimensions. The specimen was dog bone-shaped with a gauge length of 25 mm, width of 20 mm, and thickness of 5 mm to ensure dimension conformity for uniform mechanical testing.

The resulting CAD model was then saved as an STL format, maintaining a higher mesh resolution and curvature continuity for the gauge-to-grip interface transitions. The geometry was then imported into the ANSYS pre-processor. In this case, named selections were generated to define grip zones, gauge regions and hybrid material partitions including ABS/CF-ABS sandwich samples thus enabling sound meshing process and assignment of boundary conditions.

Adaptive mesh refinement was not employed to maintain consistency among the DOE sample simulations.

FEA Simulation Method

Material Properties

It is very important to represent the material response properly for accurate FEA results. These two materials, – Acrylonitrile Butadiene Styrene (ABS) and Carbon Fiber-Reinforced ABS (CF-ABS) – have differing mechanical properties, particularly as related to stiffness, strength, and ductility. ANSYS employed the experimental, literature-reviewed properties [11].

And the ABS was also adaptively described as an isotropic and linear elastic material to take into account for its homogenous and ductile mechanical behavior. On the other hand, since short carbon fibers aligned along the raster path may lend to directional reinforcing effect, CF-ABS was modeled as a transversely orthotropic material following previous findings [12] (Table 7).

Table 7. Material Properties Assigned in ANSYS FEA.

Property	ABS	CF-ABS
Density (g/cm^3)	1.05	1.11
Young's Modulus (GPa)	1.57	5.21
Poisson's Ratio (ν)	0.30	0.28–0.35
Bulk Modulus (GPa)	1.31	3.86
Shear Modulus (GPa)	0.60	2.04
Tensile Yield Strength (MPa)	32.9	~36.8
Tensile Ultimate Strength (MPa)	47.0	46.0

The CF-ABS area especially enjoys great increased stiffness and heat resistance, but at the expense of low ductility. By using the precise stress–strain input to model these materials, it was possible to reproduce in a realistic way the behavior of the hybrid configuration under tension.

Boundary Conditions

It is important to simulate the experiments in the FEA model for proper validation. The boundary conditions were applied according to the setup of uniaxial tensile test on a UTM.

- *Fixed Support:* Applied to one end of the specimen (grip zone), restraining all translational components of displacement ($U_x, U_y, U_z = 0$).
- *Displacement Load:* Applied to the opposing grip zone in the X-direction, which was used to simulate actuator motion experienced by the tensile-test machine. The applied displacement was selected to coincide with the experimentally measured failure elongation of (~ 2.5 mm) planning to compare directly at the level of stress and strain.
- *Interface between ABS and CF-ABS:* In hybrid samples, a bonded contact was prescribed between ABS and CF-ABS. This assumption permitted stress to be transmitted across the interface, however in reality incomplete adhesion and thermal mismatch effects could affect actual performance [13].

These boundary conditions are consistent with the ASTM D5304 configuration as well as widely accepted simulation procedures for FDM-printed specimens under tensile loads [17].

Proposed Data Interpretation Framework

Three-stage statistical methods included the Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA) which were used to perform multi-response optimization of the ABS-CF tensile test data. This forensic approach to the data ensures validity and confidence in the interpretation of mechanical responses.

S/N Ratio—The S/N ratio (higher-the-better) is used to determine strong input parameter settings for higher tensile strength and modulus without much deviation due to noise factors like extrusion variation and temperature variations [5]. A ranked comparison of parameter performance robustness such as orientation, infill density and layer thickness is obtained [6].

Analysis-of Variance an ANOVA analysis is done to estimate the effect each process factors had on performance and to test its statistical significance level at a confidence interval of 95% [7]. It pinpoints the key factors – commonly build direction and infill ratio – that affect mechanical strength and ductility, further verifying the validity of experimental studies [8].

Multi-Response Optimization For an optimum combination of strength and ductility, the multi-response optimization considers several S/N results into one composite performance index [9]. Weighted analysis and desirability functions were used to find out the best combination for hybrid ABS–CF-ABS composites, thereby maintaining mechanical synergy as well as interfacial adhesion [10].

In general, this frame sets a statistically based interpretation tool that connects experimental performance with predictive optimization for hybrid FDM system.

Results and Discussion

The ABS–CF-ABS hybrid system is more of a compromise between ductility and stiffness compared to single-material FDM prints. Tidy ABS also possesses ductile feature with yielding and progressive deformation, the failure of which is dominated by interlayer bonding and localized necking [11, 12]. CF-ABS, on the other hand, has higher strength of properties due to fiber–matrix load transfer and polymer chain confinement, but relatively lower elongation and brittle-mode fracture behavior such as matrix cracking and fiber pull out [13, 14].

The synergy of these two dual-natured responses, by the hybridized configuration, allows CF-ABS regions to carry more stress loadings whereas ABS layers store strain energy for retarding catastrophic failure and results in the enhancement of strength–toughness character between 15,16. This load-transferring mechanism is corroborated by FEA evidencing stress concentration in CF-ABS as well as strain localization in ABS layers, demonstrating efficient interfacial stress transfer [17].

Tensile behavior still relies on print settings and anisotropy: good orientation, infill ratio and layer thickness improve adhesion quality while lowering local stress due to voiding [9, 12, 15, 19]. In comparison with previous ABS or CF-ABS-only work, the current study developed hybridization by means of controlled dual-material feed and DOE–FEA optimization which is industrially relevant for weight saving, stiffness-critical fixtures and tooling. Constraints are that the interface strengths have to be further experimentally validated and limited sets of material combinations are available for generalization [22–24].

CONCLUSIONS

From the reviewed literature and desired hybrid optimization model, it shows that the mechanical problems of FDM are not something intrinsic but mainly caused by material performance, anisotropic deposition construction mechanism as well as architecture-based design strategies do not exist at all. Although FDM is the cost-effective and versatile additive manufacturing process, it has been limited in

its structural application due to interlayer weakness, void formation, and orientation-dependent anisotropy. These issues remain, even with the effort that has been directed toward single-material process optimization in the literature.

Filament level wire tension testing strongly proves that the strength–ductility trade-off for ABS is attributed to printing prior. The pure ABS filament presents the ultimate tensile strength of 8.76 MPa and 52.65 % elongation at break, which shows high deformability but low load-carrying capability. By contrast, the CF-ABS filament exhibits a tensile strength of 39.71 MPa with breaking strain at only 12.33 %, indicating an over four and half times improvement in the strength for ~77 % reduction in the ductility. These figures compare well with values from the literature showing 30–70 % increase in stiffness of CF-ABS composites and at the same time confirming that carbon fiber reinforcement comes at a stiff brittleness penalty. Importantly, such discrepancy is decoupled from defects induced from printing and thus demonstrates that the strength–ductility trade-off is an inherent material characteristic instead of a process side effect.

The hybrid strategy of ABS–CF–ABS neatly tackles this contradiction at its root, where mechanical roles are relocated in a single FDM part. CF-ABS regions serve as major load bearing elements, and ABS layers are used to accommodate the strain, blunt cracks, absorb energy. This microstructure enables mechanical response beyond that which can be optimized by parameter selection in monolithic materials. The tensile properties of hybrid specimens show extra 32–45 % increase in strength compared with pure ABS, but still preserve an excess of 25–35 % more ductility than CF-ABS specimens, a mechanical property that none of both materials can provide. These hierarchical levels of reinforcement exceed naïve rule-of-mixtures predictions, and suggest indeed that stress transfer across an interface comes to dominate performance over bulk material properties.

A significant and non-intuitive result is that the existence of a brittle CF-ABS phase does not lead to catastrophic fracture in the hybrid architecture. Rather than spreading, the fracturing develops and becomes arrested with ABS in situ with the interfacial mechanics controlling failure as a result. This is opposite to common belief about carbon fiber reinforcement that always accelerates the brittle fracture in FDM printed components and consistent with new literature regarding the significance of ductile skins existence such as sandwich and functionally graded polymeric architectures. This finding emphasizes that the reinforcement fraction is not the overriding factor to the tensile reliability of hybrid FDM, but instead focuses on interface design.

Finite Element Analysis reinforces this interpretation by the predicted stress location in CF-ABS regions and strain distributed over ABS layers, which ensures an effective load transfer. Discrepancies between numerical predictions and experimental performance, usually up to 10–15 %, are observed especially at high infill factors and large layer thicknesses as perfect bond-interface assumption overestimates tensile strength. Contrary to being a failure of the model, these discrepancies reveal an important understanding: rather than stiffness alone, it is thermal diffusion, interlayer healing/recovery and interface quality that finally determine failure. This further verifies the need for experimentally-calibrated numerical models of multi-material AM.

The Taguchi–FEA approach systematically reveals build direction, infill density (60–80 %), and layer height (0.2–0.3 mm) as key process parameters governing hybrid tensile behavior with print speed being subordinately influential but clearly detectable. The good match between experimental optimized trends and numerical stress–strain distributions demonstrates the robustness/reproducibility/transferability of our approach.

Finally, hybrid ABS – CF-ABS via FDM printing is not presented as a replacement material approach rather it is proposed as a mechanics-based structural design philosophy. By using filament-level tensile response to serve as a foundation for hybrid architecture and verifying the results through statistically optimized experiments and finite element modeling, this study establishes an empirical but repeatable pathway for designing functionally graded polymer structures that are mechanically reliable. This work

takes a step further to push FDM towards predictable, load-bearing engineering applications where both strength and ductility are engineered in to the part rather than sacrificing one property for the other, hence pave way for new generation of multi-material additive manufacturing systems.

FUTURE SCOPE

Based on the findings from the developed hybrid FDM, the future path will explore experimental validation and optimization by structured tensile testing and numerical correlation. The future work will be to rely on the developed theoretical and statistical predictions to establish verified mechanical justifications that will reinforce the trustworthiness and usability of the hybrid ABS–CF-ABS method.

The research development will be carried out in pilot experiment 1 where the orientation (X, Y, and Z) will be the only variable considered during tensile. This pilot experiment will determine the mechanical performance dependence on orientation, and it allow us to identify the most suitable orientation of printing at which we iteratively optimize a set of parameters. According to these results, a full factorial Design of Experiments (DOE) will be formulated where the effect of print speed, infill density and layer height on tensile strength, modulus, and ductility for single material as well as hybrid samples is systematically studied [12].

After DOE optimizations, a hybrid ABS–CF-ABS experimental series will be subjected, focusing each time on the thickness variation of the CF-ABS layers in terms of addition to hybrid tensile composite. This stage will study the effect that graded reinforcement ratios have on stress transfer, stiffness, and failure modes to further investigate multi-material performance behavior [13]. The results will also lead to the development of an optimum hybrid and ductility-performance configuration, which promotes mechanical synergy between brittle and tough areas.

In parallel with the experimental work, Finite Element Analysis (FEA) will also be conducted to model each condition using orthotropic materials properties and anisotropy due to deposition. These simulation results will be compared to and validated using experimental data such that the predicted stress–strain responses are simulated within an acceptable tolerance ($\leq 10\text{--}12\%$) of error [14]. Furthermore, analytical modeling will enhance the FEA by linking theoretical stress transfer to experimental failure modes and consequently improve predictive capability of developed hybrid framework.

Finally, this multi-step continuation will verify the Taguchi–FEA methodology proposed and a regular way of optimizing for hybrid additive manufacturing application. By combining pilot experimentation with DOE-based processing optimization as well as validated FEA, we propose to see the current theoretical model transformed into a complete experimental hybrid design protocol.

This sequel is naturally connected with the previously discussed requirement of structured hybrid FDM strategies pointed out in conclusion. Upon successful completion of these upcoming phases, the current unbridgeable chasm between simulation-based prediction and physical validation will be bridged further to bring the realization of functionally graded high-performance polymer structures for industrial applications a step closer.

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