

University of Wales Trinity Saint David School of
Engineering



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

*Investigation & Modelling of 3D-Printed (FDM) ABS
Anisotropy as a Laminated Composite
ACMA6013, Dissertation Report*

Sean Mee

2218461

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1 Abstract

This dissertation investigates the mechanical anisotropy of polymers manufactured via Fused Deposition Modelling (FDM). It specifically focuses on Acrylonitrile Butadiene Styrene (ABS) within an industrial context. As 3D printing transitions from rapid prototyping to end-use applications, an advanced understanding of interlaminar structures created by the layup FDM process is crucial for wider adoption.

The limitations of traditional Finite Element Analysis (FEA) are explored, which oversimplifies FDM materials as orthotropic. To address this, the project compared predictive computational models against experimental data obtained through ISO 527-2 tensile testing. Specimens were analysed across three distinct orientations: out-of-plane (Z-axis), perpendicular (0-90°), and at the 'bias' (45°). Significant findings include mechanical inconsistencies; bias-oriented samples exhibited the highest performance, with an Ultimate Tensile Strength (UTS) of 32.3 MPa and a Young's Modulus of 2.26 GPa. Conversely, out-of-plane properties were substantially lower (19.2 MPa UTS) than the value the manufacturer provides. The study further demonstrates that traditional FEA models can produce strain discrepancies up to 2.6 times the actual experienced values, making them unreliable for predicting precise mechanical behaviour.

To improve predictive accuracy, the project implemented a modified analytical model based on the Halpin-Tsai equation. When informed by experimental data regarding interlaminar bond strength, this model replicated material behaviour more accurately than standard FEA or manufacturer data. In order to contextualise these findings, an industrial case study of an AGV bump-stop illustrates the practical application of these findings, concluding that designers must optimise infill orientation to maximise impact resistance and cost-justification in end-use components. Furthermore, these inconsistencies must be taken into account when using 3D printed components in rapid prototyping for production components manufactured with more traditional methods.

2 Introduction

2.1 Project Overview

Additive manufacturing is increasingly used within Bisley for a wide variety of applications, providing a valuable tool during product development and product updates. The continued reduction of the technology's cost has led to its adoption in a wider range of applications (Unionfab 2024). Research into the mechanical properties of additive materials is essential to ensure that components manufactured using these processes align with Bisley's reputation for producing robust products intended for heavy engineering environments. By understanding how printed materials respond to stress and wear, designers can effectively employ custom hardware that couldn't be otherwise offered due to lead times, order quantities and tooling costs.

The critical importance of material science in this area is highlighted by specific polymers such as ABS, which is already utilised in on-site jigs, retrofitting equipment and one-off mock-up products. Leveraging 3D printing in these areas allows Bisley to present completed mock-up products with parts which would otherwise be constrained by plastic components already stocked, due to MOQ's (minimum order quantities). The growing demand for tailor-made workspace solutions necessitates a design toolkit that can accommodate unique project requirements and ways of dealing with novel component sizes and specialised internal fittings. Methodologies such as Fused Deposition Modelling (FDM) enable high customisation, reducing both time and costs inherent in conventional manufacturing processes to explore successive design iterations (Zalewska et al, 2025).

When applied to 3D printing, an advanced understanding of the mechanical limits of these plastics is critical so that the longevity of the final product isn't compromised. As 3D printing moves into end-use applications, understanding the mechanical properties of printed materials is critical because the layup process creates a weakened structure between layers. Controlled studies on extrusion-based printing show z-direction strength reductions relative to the in-plane directions.

This project aims to investigate how polymers manufactured using additive filament deposition methods (FDM) behave under stress, and how these characteristics influence engineering designs that employ the technique, often in rapid prototyping during product development. Rapid prototyping through additive manufacturing significantly advances the design and creation of complex structures across various engineering fields. This research provides a deeper understanding of these mechanical inconsistencies and develops design principles to accommodate them.

2.2 Aim & Objectives

This project furthers the understanding of how polymers manufactured using additive filament deposition methods behave under stress, and how this impacts designs which employ rapid prototyping. To achieve this, the following objectives outline how the project intended to answer this question.

2.2.1 Objective 1

To understand the elastic and shear stress properties in FDM polymers. Polymers formed by additive manufacturing in ideal conditions behave differently from those formed by subtractive techniques (Rossetos et al, 2024).

- Objective 1.1: Collect test data from both additively and subtractively processed specimens.
- Objective 1.2: Apply suitable stress analysis models to the results, using both computational and mathematical approaches.
- Objective 1.3: Analyse how these models fail to account for the types of stress anisotropy introduced by filament deposition processes.
- Objective 1.4: Where possible, explore whether models for complex stress in solid materials can be adapted to predict anisotropic behaviour.

2.2.2 Objective 2

To understand how adverse conditions exacerbate the additively manufactured structure. This objective explores why rapid prototyped parts might not be a good analogue for their final production counterparts when considering component life span.

- Objective 2.1: Test samples subjected to environmental degradation (e.g., UV exposure, salt spray) and collect comparative data alongside new components.
- Objective 2.2: Analyse these results in the context of the computational and mathematical models applied in Aim 1.
- Objective 2.3: Develop an understanding of the limitations of these models with respect to the specific materials used and their degradation over time.

2.2.3 Objective 3

To apply the learnings from Aims 1 and 2 to broader design principles, considering the limitations of prototyping with additive manufacturing techniques, and how engineering designs may need to accommodate differences compared to production methods such as injection moulding.

- Objective 3.1: Explore a case study where additive techniques were used to prototype a component that was ultimately manufactured using a different method, such as injection moulding.
- Objective 3.2: Analyse how this influenced the design, and whether the anisotropic nature of the test components affected the final product.
- Objective 3.3: Discuss how additive manufacturing can be more effectively applied to prototyping for mass-produced components.

2.3 Project Timeline

The project was predicted to follow the timeline outlined in Figure 1. This timeline reflects the expectations at the outset of the project. The chart concludes at week 21, which marks the deadline for the final report submission (highlighted in red). The work for Objective 1 and Objective 2 involves similar processes: analysing the collected information and applying it to theoretical models, and is the focus of the project through its first half.

Objective 3 may be extended or compressed depending on the workload from Objectives 1 and 2, which are expected to be the primary focus of this project. Exploring a case study is important to help contextualise the theoretical work by comparing to an industry example, selected according to the results and conclusions drawn from the earlier sections.

Individual Project Plan

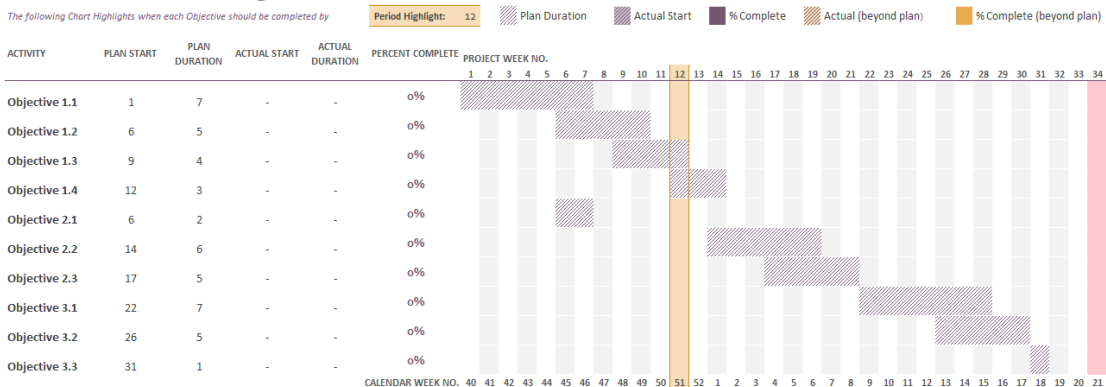


Figure 1 Gantt Chart of Planned Timeline at the Outset of the Project

The allotted time in Figure 1 reflects the expected work content and approximately how much of the report would consequently address each objective. Objective 2 has the fewest total weeks given over to it and is expected to be addressed alongside objective 1 throughout the report.

3 Literature Review

The review explores the mechanics of load transfer within 3D-printed laminate structures, how to address the anisotropic nature of FDM components, and briefly explores how ABS is tested for strength and corrosion. Anisotropic materials exhibit differing properties dependent upon which direction they are loaded or measured in; additionally, these properties don't conform to three perpendicular directions, X, Y and Z. Central to this is the understanding that stress is primarily guided by shear stress at the interlaminar interfaces between deposited layers, which is a critical factor for analysing stresses in the out-of-plane axis.

The anisotropic characteristics arising from the layer-by-layer fabrication technique often led to inconsistencies in elastic properties. Printed structures can deviate from those of traditionally processed materials. Rossetos et al (2024) indicated that the elastic properties of such materials can actually be an improvement over commonly manufactured parts.

The transfer of loads within a 3D printed component laminate structure is guided by shear stress in the interlaminar interface between each deposited layer (Viet & Kuo, 2012). The efficiency of these interfaces is crucial in understanding stresses in the 3rd axis. A mathematical model has previously been developed by Zaki et al (2017) to understand stress between composite laminate materials, validated by FEA, a 3-layer aluminium laminate. The modelling principles used could be applicable in understanding the behaviour of laminated layers in a 3D printed component. There is a wide variety of methods to model the behaviour of FDM materials, but FEA modelling is widespread and is often considered effective for this purpose (Zheng et al, 2021).

3.1 Material Manufacture Information

This section aims to address general information around filament deposition to contextualise objectives 1 & 2. Filament deposition is a process in which a material, commonly polymers, is layered in successive profiles to form a complete structure. As shown in Figure 2, each layer is created by extruding a semi-liquid polymer along a pre-defined profile on a build platform. As each layer is completed, the platform is lowered in the 'Z' or out-of-plane direction, so that the following layer can be created. The properties of the component created through this lay-up process are dependent on how well each layer bonds to the previously deposited layer. The temperatures this filament is heated to, the speed at which the head travels, and the height of each layer all have an impact on the strength of the material structure created (Vaezi & Chua, 2011).

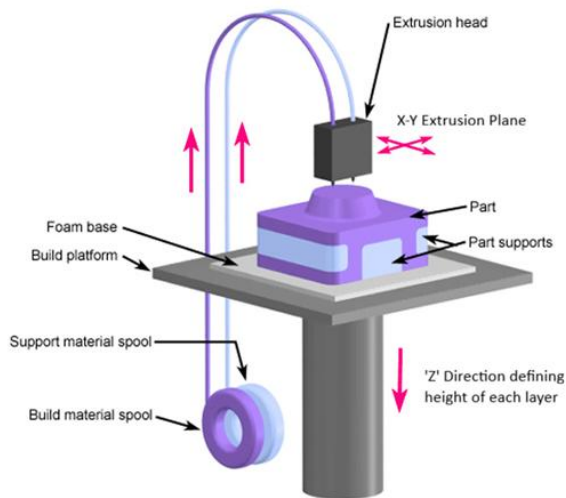


Figure 2 Diagram of a typical FDM 3D printing Process (Gloria 2025)

As shown in Figure 3, the manufacture of ABS filament, which is used to create the billet samples for tensile testing, only provides information on tensile and bending orthotropic stress. The values provided for the X-Y directions are similar to those of Tymrak et.al. (2014), who demonstrated slightly lower values of 28.5MPa in the X-Y direction. However, this casts doubt on the stated values for the z-direction of 28+/- 2MPa in Figure 3, which seems extremely high for inter-layer tensile strength.

• Properties

Bambu Lab has tested the differing aspects in the performance of ABS material, including physical, mechanical, and chemical properties. Typical values are listed as followed:

Physical Properties		
Subjects	Testing Methods	Data
Density	ISO 1183	1.05 g/cm ³
Melt Index	260 °C, 2.16 kg	34.2 ± 3.8 g/10 min
Melting Temperature	DSC, 10 °C/min	200 °C
Glass Transition Temperature	DSC, 10 °C/min	N/A
Crystallization Temperature	DSC, 10 °C/min	N/A
Vicar Softening Temperature	ISO 306, GB/T 1633	94 °C
Heat Deflection Temperature	ISO 75 1.8 MPa	84 °C
Heat Deflection Temperature	ISO 75 0.45 MPa	87 °C
Saturated Water Absorption Rate	25 °C, 55% RH	0.65%

Mechanical Properties		
Subjects	Testing Methods	Data
Young's Modulus (X-Y)	ISO 527, GB/T 1040	2200 ± 190 MPa
Young's Modulus (Z)	ISO 527, GB/T 1040	1960 ± 110 MPa
Tensile Strength (X-Y)	ISO 527, GB/T 1040	33 ± 3 MPa
Tensile Strength (Z)	ISO 527, GB/T 1040	28 ± 2 MPa
Breaking Elongation Rate (X-Y)	ISO 527, GB/T 1040	10.5 ± 1.0 %
Breaking Elongation Rate (Z)	ISO 527, GB/T 1040	4.7 ± 0.8 %
Bending Modulus (X-Y)	ISO 178, GB/T 9341	1880 ± 110 MPa
Bending Modulus (Z)	ISO 178, GB/T 9341	1590 ± 100 MPa
Bending Strength (X-Y)	ISO 178, GB/T 9341	62 ± 4 MPa
Bending Strength (Z)	ISO 178, GB/T 9341	39 ± 4 MPa
Impact Strength (X-Y)	ISO 179, GB/T 1043	39.3 ± 3.6 kJ/m ² ; 21.5 ± 2.2 kJ/m ² (notched)
Impact Strength (Z)	ISO 179, GB/T 1043	7.4 ± 1.2 kJ/m ²

Figure 3 Image of Material Datasheet from Manufacturer (BambuLabs 2025)

Using the values provided by Bambu Labs, an FE model could be used to predict the maximum strain at the point of failure for the test piece based on the manufacturer's information. However, a single value for the X-Y directions doesn't incorporate findings from (Tymrak et.al., 2014) in Table 1, which demonstrate possible differences in strength based on the layup pattern. This paper found that +45°/-45° orientation is stronger (29.5 MPa) than 0°/90° (27.7 MPa). This correlates with findings by Ravikumar et al. (2023) in the next section.

Table 3
Average tensile strength, strain at tensile strength and elastic modulus for RepRap printed components.

	Specimens tested	Specimens considered	Average tensile strength (MPa)	Average strain at tensile strength (mm/mm)	Average elastic modulus (MPa)
ABS					
0.4 mm Layer height	30	24	28.2	0.0197	1875
0.3 mm Layer height	40	39	27.6	0.0231	1736
0.2 mm Layer height	40	35	29.7	0.0201	1839
0/90 Orientation	60	52	27.7	0.0192	1867
+ 45/-45 Orientation	50	46	29.5	0.0233	1739
Total	110	98	28.5	0.0212	1807
PLA					
0.4 mm Layer height	30	17	54.9	0.0194	3286
0.3 mm Layer height	40	31	48.5	0.0171	3340
0.2 mm Layer height	20	18	60.4	0.0196	3480
0/90 Orientation	50	27	54.9	0.0188	3336
+ 45/-45 Orientation	40	39	52.3	0.0181	3384
Total	90	66	56.6	0.0193	3368

Table 1 Results Table Tymrak et.al. (2014) of 3D printed ABS Material Properties

3.2 Material Theory

3.2.1 Tensile-Stress Loading

When modelling 3D printed materials, and more specifically FDM material, it's common to assume that this group of materials are orthotropic in order to simplify the process of computational modelling (Song et al, 2017). Modelling materials in this way lends itself to FEA modelling, which may explain why many studies choose to use this approach for its ease of implementation and approximate accuracy. However, there are inherent shortcomings of these assumptions. As outlined by Ravikumar et al. (2023) and explored in this section, there is good justification that 3D printed materials are anisotropic, which means they have distinct properties which don't follow three perpendicular directions. Traditional FEA models are often optimised to map properties on the X, Y and Z coordinate systems in all digital 3D objects.

The strength of printed components is known to be impacted by the loading direction in the X-Y plane against the layer orientation. Ravikumar et al. (2023) found that in the 0-90° plane, the tensile strength was lower than in the 45-45° plane, as only half the layers are strained by the loading. This could be explained by how the deposition strands share a load. At 90-0°, the 0° strands are subject to all the stress under a given load. However, like with composites, those perpendicular to or at 90° cannot take the strain in the grain direction. Instead, the stress is applied to layer bonds. Figure 4 shows a diagram of these cross-sections.

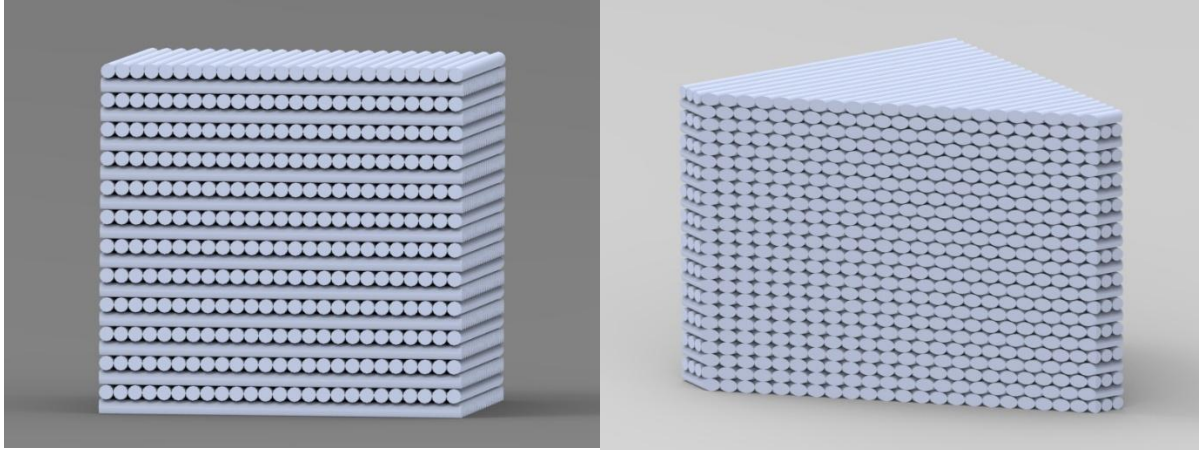


Figure 4a, b Cross-sections of modelled filament layup, perpendicular(a) and 45° (b)

At 45°, each strand can take $1/\sin(45^\circ)$ (~71%) of the strain, but unlike when the strands are parallel or perpendicular, the total grain-direction strain is only 50% (half of the layers are at 100% utility). This is potentially complicated by the efficiency of the bond strength, as at 0%, the total strength might reflect 50% and 0.71%, and at 100%, the material would just be isotropic.

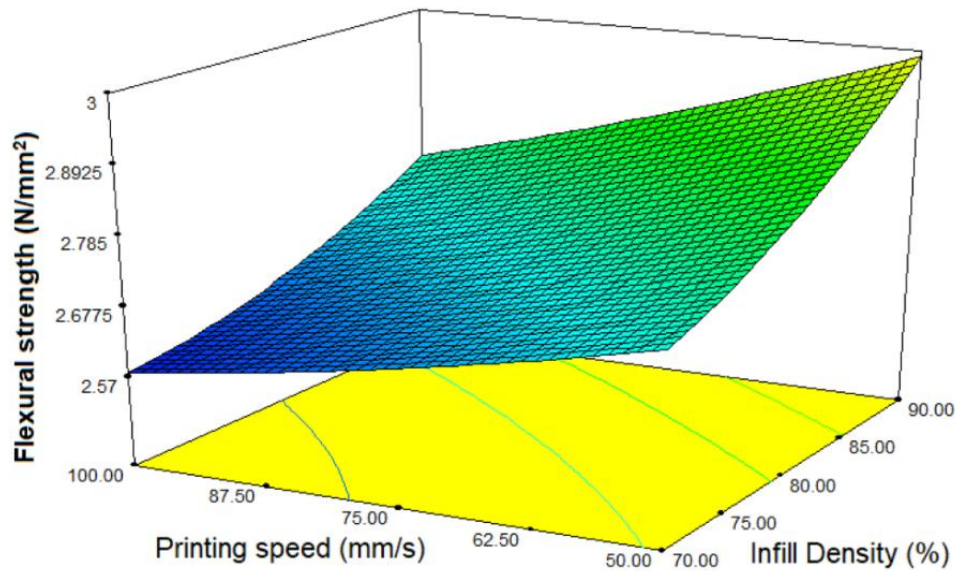


Figure 5 Ternary plot of speed & density's impact on flexural strength (Ravikumar et al., 2023)

Shown in Figure 5, the relationship between infill density and flexural strength. This relationship is a product of additional material being present in the structure of the component. Unexpectedly, there is also a negative relationship with printing speed. This is corroborated by other research, which agrees that slower printing speeds improve strength (Vaezi & Chua, 2011) (Kumar, Teraiya & Potdar, 2022). However, this relationship can be expected to have upper and lower limits, where manufacturing conditions such as temperature become dominant constraints. The limits of this appear to be, from the

aforementioned papers, determined experimentally for a given manufacturing method and material. The relationship of speed may need to be considered as a variable in the properties of the individual material fibres. These relationships need to be considered and controlled when designing tests for other variables. This research highlights a clear conflict between BambuLabs and existing research, which is crucial to resolve to improve current modelling techniques.

The concept of 'warp' (fibres running parallel to a fabric's length) and 'weft' (fibres that interlace with the warp) is foundational in woven fabrics and consequently composite materials. The interaction of such fibres is known to be anisotropic. According to Pan et al (2015), loading composites at a 45° 'bias' angle often results in reduced tensile strength compared to on-axis loading (0° or 90°) due to the non-optimal alignment of load-bearing fibre, where no individual fibre is loaded at both ends, the material has significantly lower strengths and can be expressed as a function of θ . Furthermore, while some reinforcement fibres may exhibit increased strain to failure when loaded at a bias (Godara & Raabe, 2007), the overall mechanical performance suffers from decreased stiffness and ultimate tensile strength when tested relative to the main fibre directions. From this, it might be expected that composites with perpendicular fibres might be weaker along the 'bias' direction, which is contradictory to studies looking at FDM materials such as that from Ravikumar et al. (2023). Improving the methods of modelling FDM materials may be able to borrow from modelling methods used in woven materials, such as those by Scelzo, Backer & Boyce (1994), but re-modelling them to imitate the reverse behaviour.

3.2.2 Shear-Stress Loading

The FDM process involves the melting and extruding of filament materials through a nozzle onto material of a different temperature, which inherently weakens them to shear forces acting at the boundary. These forces are influenced by the properties of the polymer materials used, and the quality of the bond between these layers influenced by many factors.

The nozzle temperature significantly affects the viscosity of polymers during extrusion, consequently influencing interlayer adhesion. Higher temperatures can enhance polymer flow and diffusion between layers, improving the bond strength (Xu et al, 2020). However, excessive temperatures may lead to material degradation. Elevated ambient temperatures can help manage the thermal gradient between layers, facilitating better bonds at the molecular level (Woodruff & Wang, 2020).

When optimising printing parameters, thinner layers generally result in improved shear resistance properties due to improved inter-layer bonding (Custodio et al, 2024). The layer height needs to be balanced with the in-plane strength of the material, which has the reverse relationship as shown in Figure 6, which gains strength with greater layer heights (BambuLabs 2025).

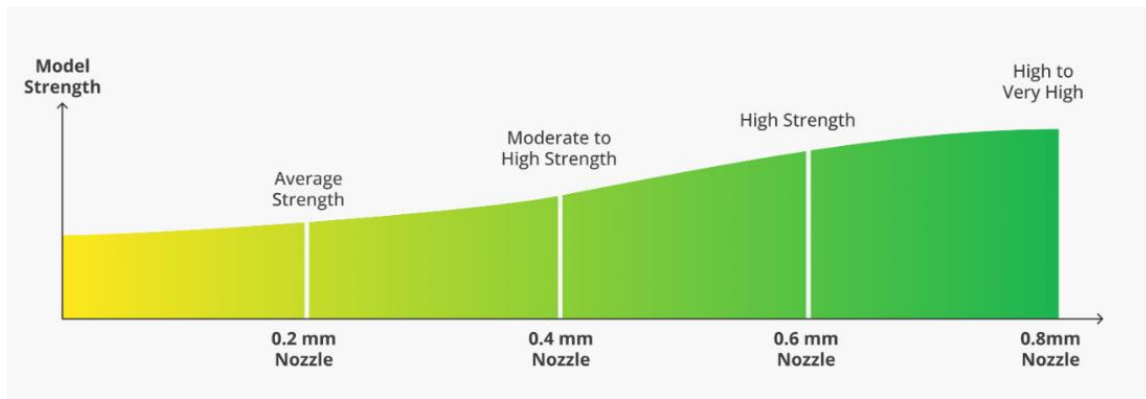


Figure 6 Dimensionless graph of layer height vs strength (BambuLabs 2025)

Predicting shear stress in 3D printed material is complex due to filament deposition, and failure often initiates at the weak interfaces between printed layers. Nazemzadeh et al. (2021) utilised FE techniques in conjunction with Cohesive Zone Modelling (CZM) to evaluate the bond strength in 3D printed polylactic acid (PLA). This method examines the inter-layer behaviour under various loading conditions, providing insights into how shear yield conditions can differ based on the material properties of the printed parts.

Wang et.al. (2023) present a method for solving shear stress within FDM materials. This was done using an Iosipescu Shear (IS) Test, involving a V-notched beam to produce a nearly constant shear stress distribution at the vertical centre of the specimen. Using an FEA model to identify the stress within the component, the actual point of failure can be assessed when this FEA model predicts in-plane shear stress (τ_{xy}) at the centre of the part that exceeds the material's interlayer shear strength (τ_i). Additionally, Zhang et al. (2015) developed an analytical model to evaluate shear and peel stresses in adhesive layers bonded to various substrates. This model doesn't directly apply FDM materials, but the principles might be relevant for conditions specific to 3D printed polymers and provide a basis for understanding shear stress behaviour.

This section focused on addressing objectives 1.4 and 1.2, exploring how tensile and shear stress are modelled, indirectly in fibrous materials, and directly in other 3D printed setups. This research shows a wide range of possibilities, from no impact to a positive or negative one. The best model to approach the problem can be drawn from these, based on lab results.

3.3 Analytical Models

The exploration of analytical models is essential because traditional Finite Element Analysis (FEA), while widespread and easy to implement, often relies on oversimplified assumptions that fail to capture the complexities of 3D-printed materials as discussed. The project applies analytical models to evaluate properties outside the standard orthotropic directions and explore how varying loading angles (such as the 45° bias) help to resolve conflicts between manufacturer claims, FEA models and

actual research findings. Identifying the framework best-suited for this type of material is the foundation to complete objective 1.2.

3.3.1 Halpin-Tsai

The Halpin-Tsai equation is a semi-empirical model for predicting the mechanical properties of composite materials, particularly between filler and polymer matrix materials. The model is set up to model the behaviour of composites based on the shape, orientation and elastic properties of the matrix and fibres which make up the material (Fuchs et.al., 2006). Like most equations expressing composite materials, it is reliant upon the volume fractions of the two materials in the cross-section perpendicular to loading (Molajavadi & Garmabi, 2011). The model employs a 'reinforcement factor' (ξ) and aids in providing insights into the elastic properties of hybrid materials in lay-up configurations (Yun et al., 2023). The application for specific circumstances can be established through experimentation and/or the type of loading the material is undergoing (Zhou et.al., 2024); for circular fibres, it is often expressed as $\xi = 2L/D$, where L is the average length of the fibres, and D is the fibre's diameter (Tóth & Virág, 2025).

$$\frac{P}{P_m} = \frac{1 + \xi \zeta V_f}{1 - \eta V_f} \quad \text{with} \quad \eta = \frac{P_f / P_m - 1}{P_f / P_m + \zeta}$$

Equation 1 Halpin-Tsai General Expression (Budarapu et.al., 2019)

The equation offers a simplification which removes the need to carry out more experimentally difficult studies to measure the Poisson's ratio and shear modulus of new materials, but assumes there are no additional stresses arising from a mismatch in the Poisson's ratio between the fibre and matrix (Beckett et al., 2024). In the context of applying this methodology to an FDM material of a single material type, this is actually an advantage, as no mismatch exists in this material type (There is only one material type in a pure ABS FDM layup). The key disadvantage of the Halpin–Tsai model is that it only considers the properties of the fibre and matrix, ignoring the forces at the interface between materials (Zhou et.al., 2024). This concurs with the research by Beckett et al. (2024), as stresses arising from a difference in the contraction/expansion rate of materials would be focused at material interfaces. Additionally, variation in the distribution of fillers within the matrix is an assumption that may not always hold true in practical scenarios. Discrepancies can arise when assessing materials with irregular filler configurations (Georgantzinis et al., 2021)

3.3.2 Mori-Tanaka

An alternative model that can predict properties of materials based on different mechanisms and assumptions is the Mori-Tanaka method. It's a mean-field micromechanical approach to analyse the mechanical behaviour of composite materials. This method considers the stress surrounding a single inclusion within a composite matrix (Othman et al., 2022). The Mori-Tanaka method better accounts

for the interactions between inclusions than the Halpin-Tsai model, which typically assumes the independence of the reinforcing inclusion (Kundalwal, 2017). The method is built upon eigenstrain theory and relates the average stress in the fibre to the stress in the matrix through the 'strain concentration tensor' (B). The governing equation of the Mori-Tanaka method is used to determine the overall effective stiffness tensor of a composite material. It relates the stiffness of the matrix (C_m) and the fibre (C_f) based on the fibre volume fraction (V_f) and a specific concentration tensor (Raju, Hiremath, Mahapatra, 2018) as shown in Equation 2.

$$C = C_m + V_f(C_f - C_m)B$$

Equation 2 General Expression of Mori-Tanaka equation (Raju et.al., 2018)

While this method addresses a shortcoming of the Halpin-Tsai approach by accounting for interactions at the interfaces within composite materials, it is not directly applicable to simple FDM materials. In this case, the properties of the interfacial regions would effectively need to be treated as the 'matrix' properties. If the Halpin-Tsai formulation does not adequately represent the performance of FDM materials, this method may nonetheless be worth exploring as a means of investigating potential mechanical interactions between layers that are otherwise overlooked.

3.4 Testing Standards

In order to effectively complete objective 1.1, a consistent and effective methodology needs to be adopted for the collection of data. ISO 527 recommends using one of two standard testing billets, one of which is shown in Figure 7. This drawing is an ISO 527-compliant piece from which test billets can be modelled after. ISO 527-2 is applicable in determining the tensile properties of plastic materials, which can be used to encompass those produced from additive manufacturing processes. This standard has been used elsewhere to examine anisotropy in 3D printed components due to factors like air gaps and stress concentrations within the printed structures (Bembenek et al., 2022). Neivock et al. (2023) also utilised ISO 527 to examine the effect of geometry in testing 3D printed parts for tensile strength, along with other properties. This study emphasises that different geometrical configurations markedly impact the properties of components created through fused deposition modelling (FDM).

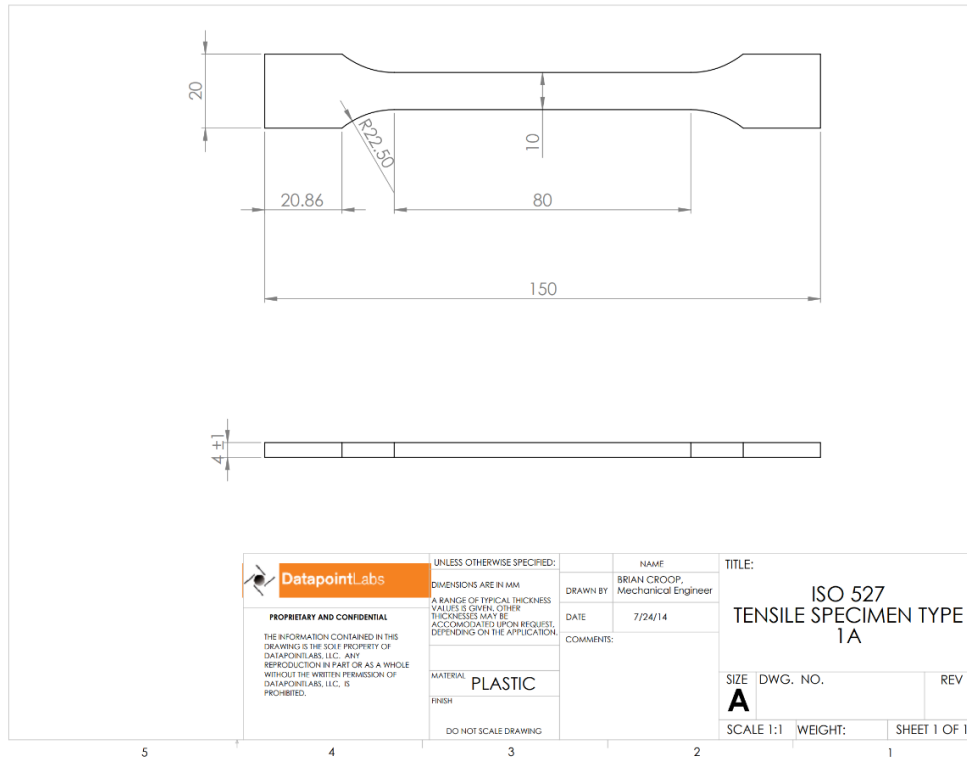


Figure 7 Engineering drawing of ISO 527 compliant test billet (Applus 2025)

Based on ISO 527-2, standardised specimen geometries, in this case a Type 1A (dog-bone shape) should be used, such as in Figure 7 (Chansamai et al., 2023). Type 1A bars are intended for 'quasi-static' tests (Applus 2025) in which the test is conducted slow enough that the plastic deformation doesn't create internal changes, and each instant can be considered as a traditional static-loading scenario. In order to achieve this, the test could be carried out at a low, steady strain rate. Typical strain rates range from 1-50mm/min (Vanaei et al., 2022). The lower end of this range is preferred in this experimentation to guarantee the validity of the results.

After the tensile test, many experiments conduct examination of the fracture surfaces using digital microscopy or scanning electron microscopy (SEM) in order to evaluate specific failure modes and origins of stress fractures (Vanaei et al., 2022) (Gonabadi et al., 2020). While the data is extremely helpful, its collection is constrained by the types of equipment available and the time constraints of this project. For this reason, electron microscopy is an unrealistic data collection method.

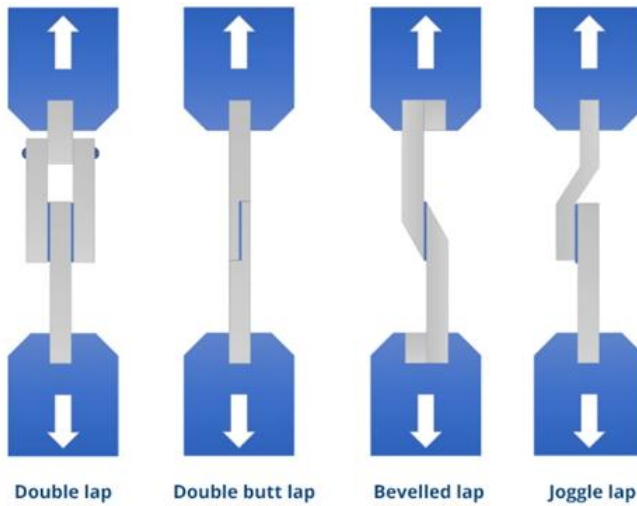


Figure 8 Various billet designs used to test material shear (Viet and Kuo, 2011)

In Addition to the type 1A billet, there are other designs of billet, intended to concentrate the stress in specific locations. Figure 8 shows various common configurations used to test shear stress, in which the billet is intentionally weakest at the overlapping section of the material. The design of samples can also create a combined load of shear and tensile stress (Dorogoy et al, 2015), dependent on the type of stress being studied. In the context of analysing the behaviour of filament bond strength in filament deposition material types, isolating shear stress between layers provides an interesting second view of the out-of-plane bond properties. The billet types in Figure 8 can be trialled with the use of FEA to identify which structure has the highest probability of creating the conditions for failure through delamination of filament layers.

4 Testing Prediction

4.1 FEA Orthotropic Modelling

To evaluate how the manufacturer states 3D printed ABS material behaves under load, and compare that to actual conditions, an FE model, shown in Figures 10 and 11, was created with the lowest tolerance values provided from the manufacturer's data sheet (Figure 3) for both the X-Y and Z orthotropic directions. An FEA model was chosen as a suitable computational model for objective 1.2 because it's a widely applied approach across many industries. These Von-Mises stress and strain values represent the worst-case scenario based on the tolerances provided by the manufacturer. This FEA was carried out with a 1mm nominal mesh size, which is sufficient to capture the behaviour of a component with a simple geometry. This is corroborated by the fact that the stress concentrations are gradual, and none are focused in individual or small clusters of cells.

As seen in Figure 10(a) and Figure 11(a), the greatest stresses within the component are predicted to be at the end of the filleted corners towards the neck of the test billet. Figure 10 shows the billet X-Y loaded to 2235N, which is a sufficient load for the maximum Von-Mises stress to exceed 30MPa (the lowest strength within Bambu-Labs' tolerance). At this load, the neck of the component would be expected to deform approximately 10mm (9.94mm). The maximum value of strain is 12 (no units), but this is local to the maximum point of stress, and when such a component is tested, a rate of strain is applied, not a rate of stress. As such, the approximate maximum strain could be expected to be less than 12 (no units).

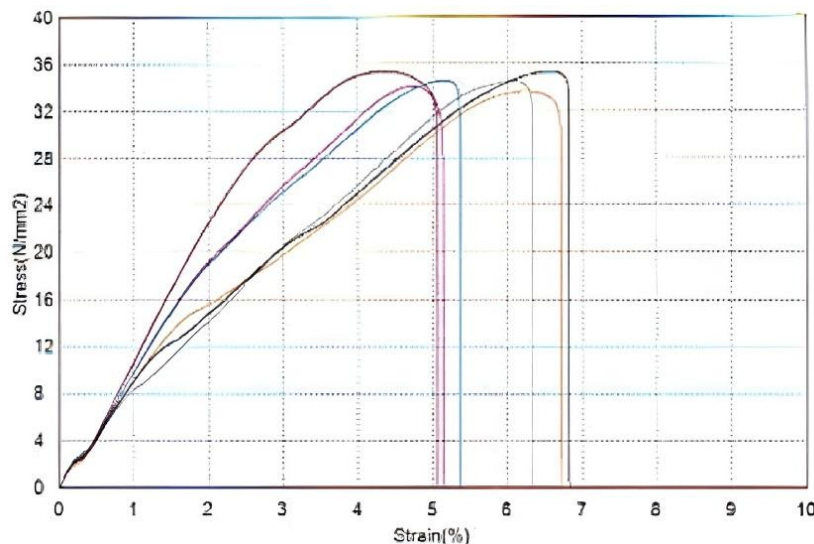


Figure 9 Stress-strain graph of ABS material (Irawan et.al., 2020)

There may be some inaccuracy in these exact strain values, as the ABS considered by the FEA model was assumed to experience only elastic deformation up until the point at which the stress exceeded the threshold. This strain of 6.67% can be considered approximately reliable in comparison with other similar materials, as tested by Irawan et.al. (2020) and shown in Figure 9, which have a similar ultimate strain percentage.

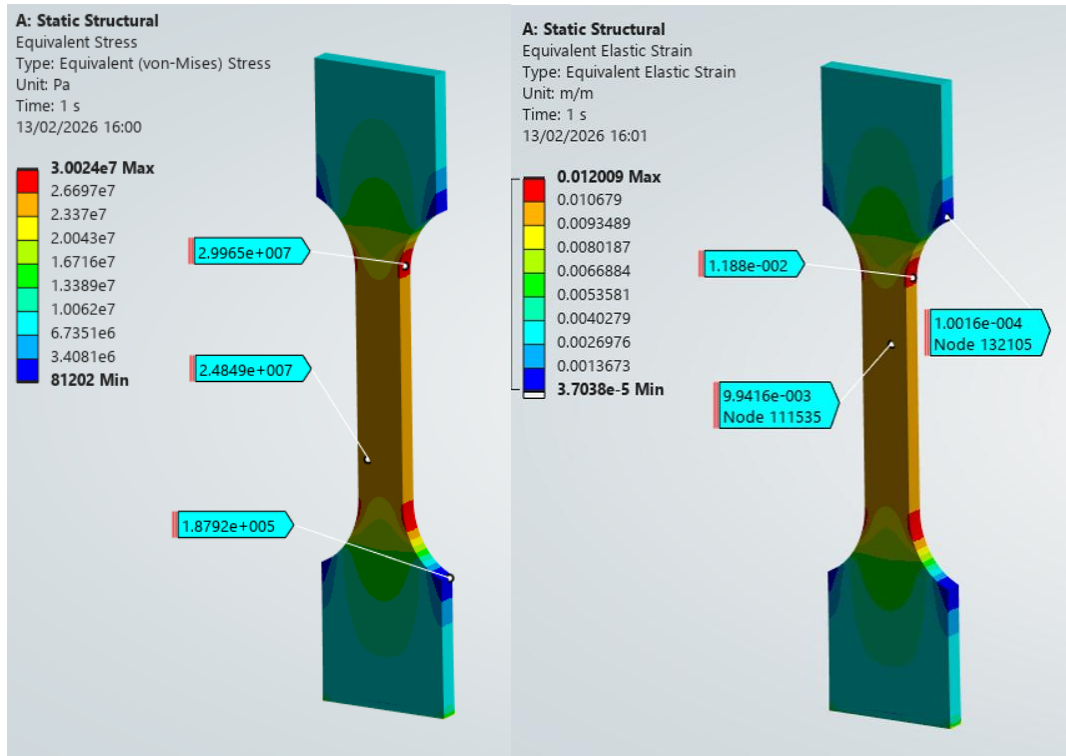


Figure 10a, b Von-Mises stress & strain from FEA model for X-Y printed billet

Figure 11 shows the result of the same process, but in the out-of-plane properties of the ABS between the deposited layers. This was achieved by applying 1940N to the structure, which fulfilled the low-bound tolerance of the UTS for this direction (26MPa). The stress was again concentrated in the same areas. In this case, it could be expected that Figure 11(b) and the strain value of 10.4 (no units) are unreliable due to the structure of the material. As the material is reliant entirely on the strength of the bonds between these layers, less elastic behaviour might be expected in this case.

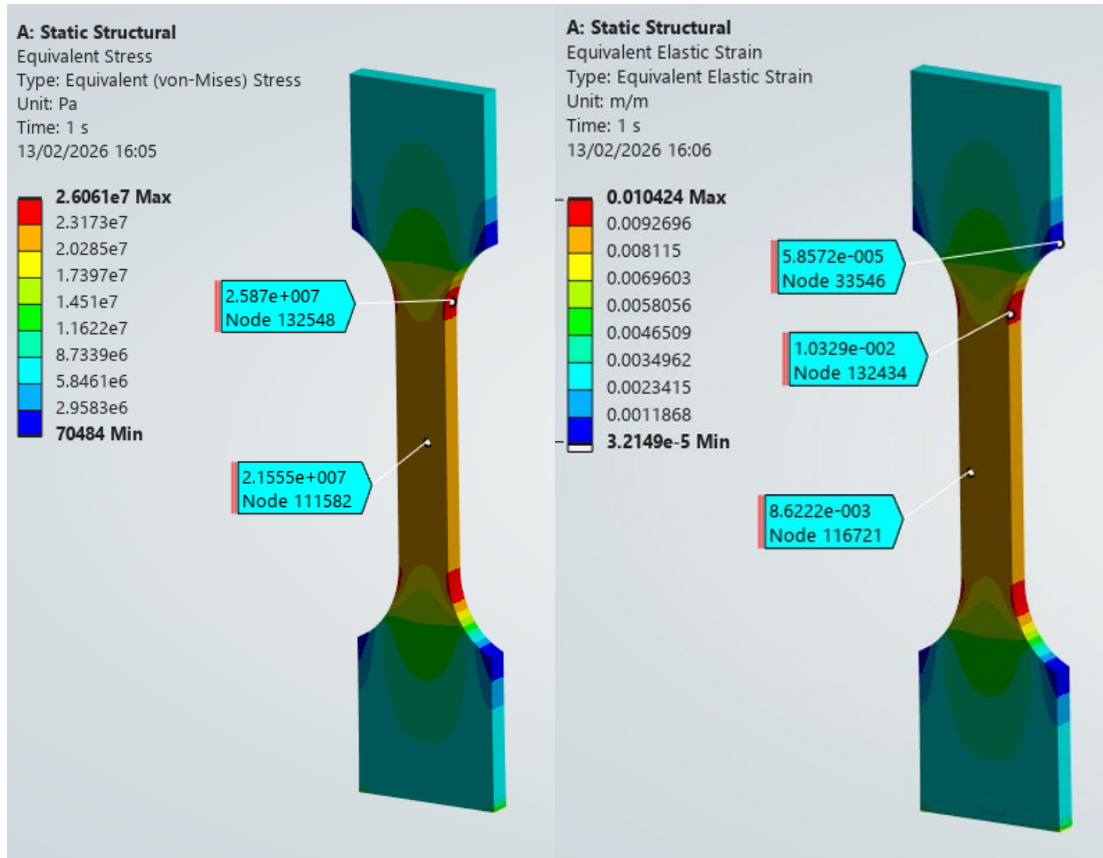


Figure 11a, b Von-Mises stress & strain from FEA model for Z-printed billet

4.2 Shear Failure Confirmation using FEA

Figure 12 shows a different design of billet, based on Figure 8. This FEA aimed to corroborate the fact that this design would fail due to shear at the interface between two filament layers. Due to the lack of information on shear behaviour provided by Bambu-Labs, the loading here was set to 3KN as a general value. The purpose was therefore to see where the peak stress would appear within the model, and not the force or strain required to cause this breakage. The stress (Von-Mises) is concentrated around the faces of the double and single sheets, at 31.13MPa in Figure 12(a). The peak 51.1MPa load was at the perfectly rigid face at the bottom of the model, which is a loading which won't be seen in actual test conditions. This false stress peak was also true for the maximum shear stress (Figure 12(b)).

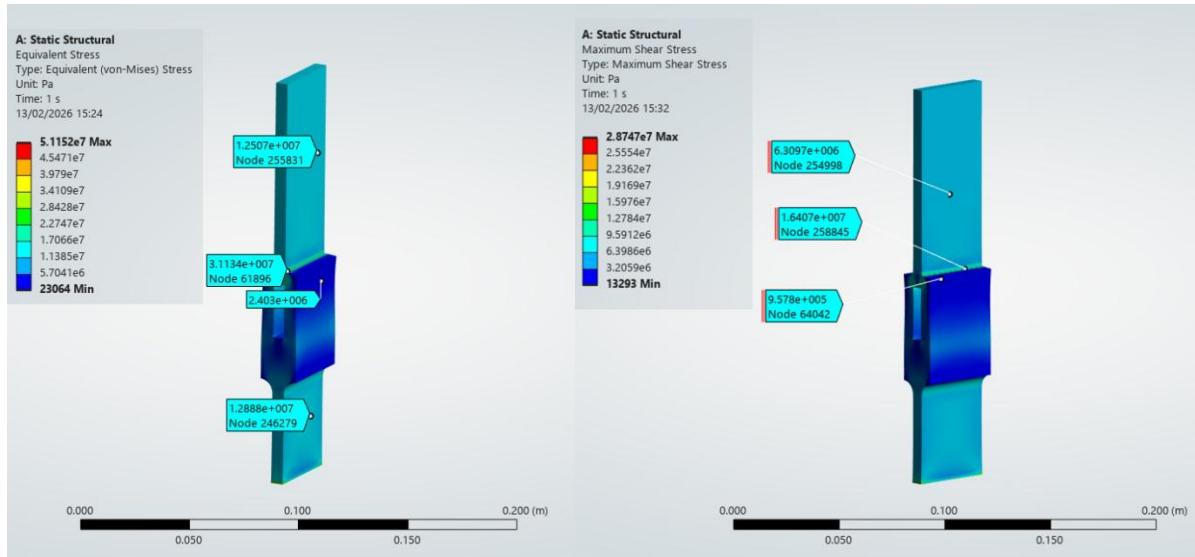


Figure 12a, b Maximum shear & Von-Mises stress in shear-failure designed billet

4.3 Analytical Models

Figure 13 shows the results of an application of the Halpin-Tsai equation to predict the tensile strength of a sample in the X-Y planes; the code used to create these can be found in the appendix. This model was created to explore the possibility that the properties within the printing plane aren't uniform, as discussed by Ravikumar et.al. (2023), amongst others previously.

```

Command Window

Actual_Tensile_45 =

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Actual_Tensile_Perp =

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>> Press [Ctrl] + [Shift] + [P] to generate code with Copilot

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Figure 13 Anisotropic MATLAB model through application of Halpin -Tsai Equation

To model this, Equation 1 was used to implement a Halpin-Tsai style model within MATLAB, using the properties provided by Bambu Labs. The modified expression is shown in Equation 3. The Halpin-Tsai is built on the combination of a fibre and matrix material property, and takes into account the length of the fibres being loaded.

$$\sigma = \sigma_z \cdot \frac{1 + \xi \cdot n \cdot V_{xy}}{1 - n \cdot V_{xy}}$$

where:

$$n = \frac{\sigma_z / \sigma_{xy} - 1}{\sigma_z / \sigma_{xy} + \xi}$$

and:

$$\xi = 2 \frac{L_f}{\varnothing_f}$$

Equation 3 Modified Halpin-Tsai equation for ABS FDM material

In this case, there aren't two materials, but there are two material properties, and so the 'matrix' property was substituted for the out-of-plane property, and the fibre property was the general property of the material, in this case ABS. The strength of the matrix is heavily linked to the strength of the interface in traditional composite materials (Zhang et.al., 2020), especially at higher loads. The out-of-plane strength of an FDM material is a direct measure of the bond strength of that technique; in the load case where the material is loaded out of the print plane, the force is spread across a 100% bonded cross-section, giving a second property.

Using these assumptions, the Halpin-Tsai equation was implemented, with the cross-section proportion being 100% fibre for the 45° loading, and 50% at the perpendicular load cross-section, as depicted in Figure 11(b). The key assumption in mapping the Halpin-Tsai to this model is that the fibres running 90° to the stress perform the same as the perpendicular fibre bonds. At the 45° loading condition depicted in Figure 11(a), the fibre length is the hypotenuse of the billet's width, which is 21.2mm in this case. In the perpendicular case, the fibre length is equal to the length of the billet, which is 180mm.

5 Experimentation

5.1 Planning

To ensure results are comparable to established engineering data, the experimentation adheres to ISO 527-2, which is the recognised standard for determining the tensile properties of plastics, including those produced via additive manufacturing. This ISO standard utilises Type 1A specimen geometry. Figures 14 and 15 show engineering drawings which comply with the Type 1A design as explored in section 2.5.

As these components have varying properties based on temperature, printing speed and out-of-plane height, etc. The recommended settings from BambuLabs were applied to all printed components used in any testing. Table 2 shows these settings as reflected in the documentation for BambuLabs ABS (BambuLabs 2025). Using consistent settings throughout testing guarantees that each set of results is as comparable as possible. The objective of testing was to build a model which better predicts the behaviour of these types of materials. Altering these parameters changes the material properties of the extruded filament, which would be a part of the model's inputs and so ultimately outside the scope of this project. The settings chosen are those recommended for ABS in the P1S printer variant, which is an enclosed printer which comes with a pre-installed carbon filter. This is a requirement for ABS printing, as the polymer produces VOC's (Volatile Organic Compounds) when heated, and so open printers aren't recommended for this type of material.

Property	Recommended Value
Filament Diameter	1.75mm
Nozzle Print Temperature	270°C
Build Platform Temperature	90°C
Initial Layer Traverse Speed	50mm/s
Outer Wall Speed	200mm/s
Inner Walls Speed	300mm/s
Layer 'Z' Height	0.2mm
Nozzle Diameter	0.4mm

Table 2 BambuLabs print settings for ABS on a P1S series printer (BambuLabs 2025)

These specimens were tested with various internal configurations, but have the same external shape and ABS material supplied by Bambu Labs. These controls exist to compare how the lay-up of the filament deposition (FD) alone, as they would influence the behaviour of a component, despite having the same material geometry and property as predicted by the material supplier. The two drawings in

These UTS tests are dependent on being conducted under quasi-static conditions (Vanaei et al., 2022). To achieve this, the material is put under a low rate of strain at 10mm/min for all materials. Several of each sample type, meaning various lay-up orientations, are used to understand out-of-plane (Z-axis), perpendicular-parallel and bias (45°) load conditions. The test billets feature a constant infill-density of 100% within these various layup orientations, and printing speed set to the manufacturer's recommended values (BambuLabs 2025) of 50mm/s for the initial layer, and 250mm/s for the interlayers.



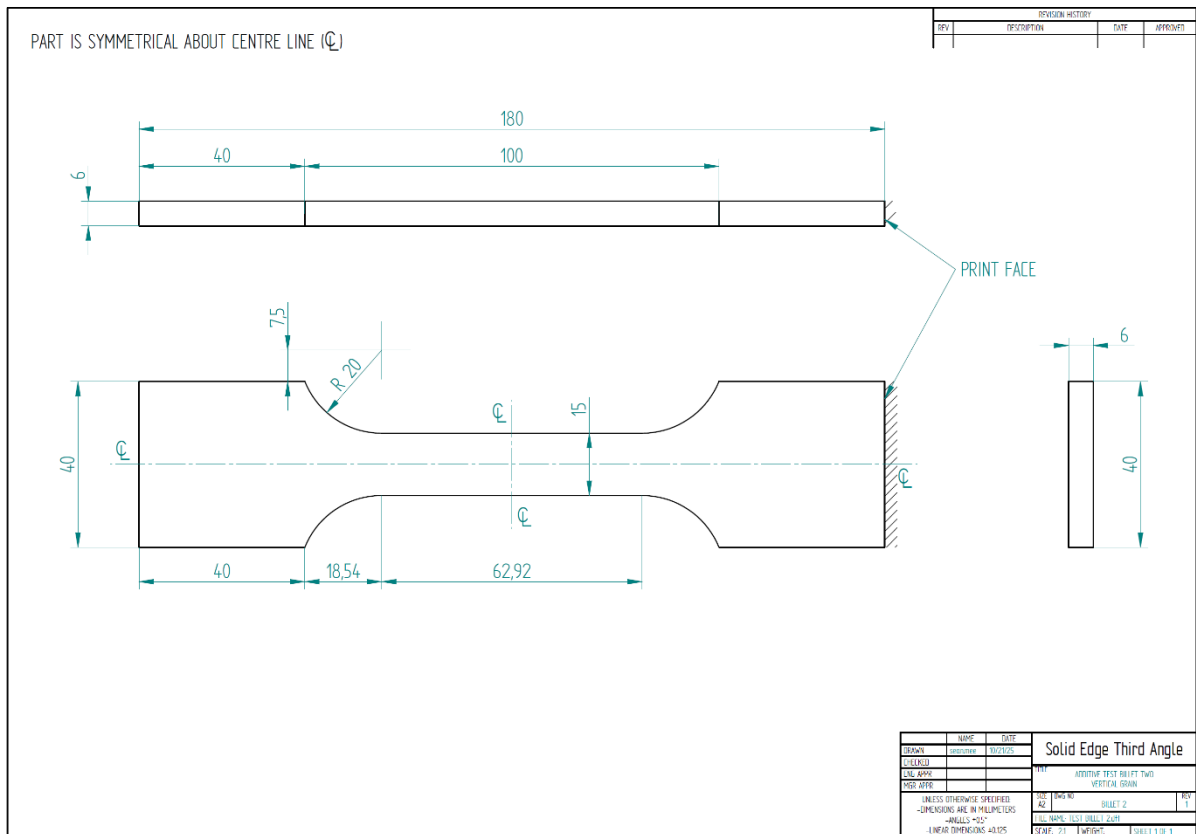


Figure 15 Engineering drawing of test billet for out-of-plane tensile tests

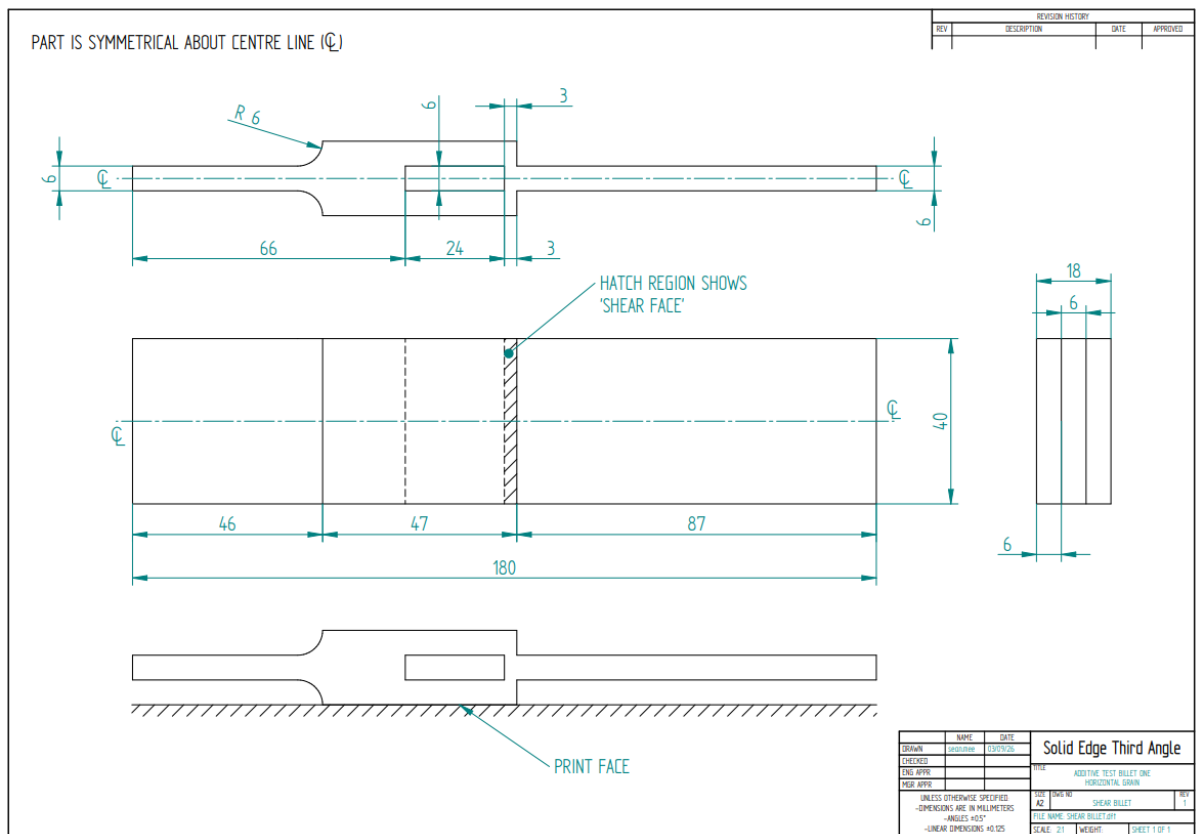


Figure 16 Engineering drawing of test billet for in-plane shear stress tests

As shown in Figure 16, the shear test billet was manufactured with each layer parallel to the length of the component, as with Figure 14. Due to its geometry, this creates surface finish defects along the face overhanging the print face/bed, where the material must be supported. This isn't crucial to the function of the test, but it's a key variation between this and the other billets. The 'neck' at which the component fails is a surface within the geometry of the component, highlighted in Figure 16. As dimensioned, the total area of both of these faces is equal to the cross-sectional area of the component. To the left of this area, a larger cross-sectional area is left to ensure the location of the material failure.

The shear billet wasn't manufactured in the end, as it was decided that shear testing would be moved to future work. The results from the tensile tests required more analysis and time to model than expected.

5.2 Results

The results discussed in this section focus on the data collected for objective 1.1.

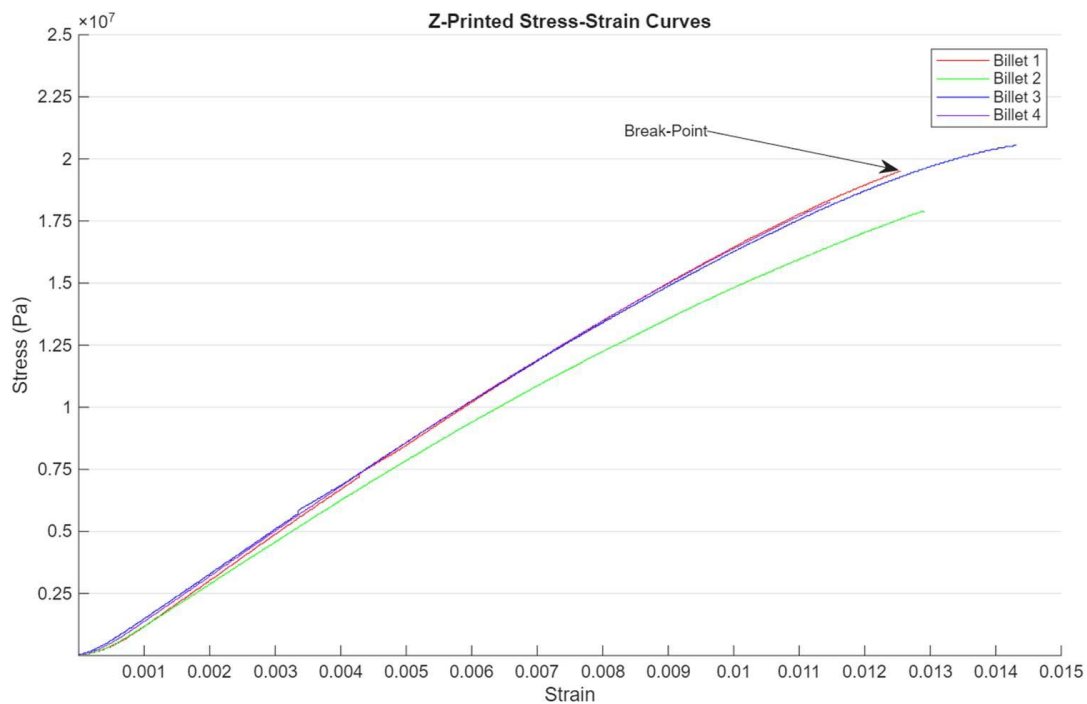


Figure 17 Stress-strain curve for out-of-plane UTS test

Figure 17 shows the stress-strain curves for the samples printed with the Z-direction aligned with the stress through the material. This set of samples has the widest variation in ultimate failure loads, with a median of 19.2MPa $\pm$ 7.09%, and a mean of 19.05MPa. This large error range is something the literature didn't discuss and could be due to weaknesses within specific layers during the printing process. Additionally, the Young's Modulus of these samples varied within a standard deviation of 79.33MPa and an average of 1.71GPa (1.68GPa $\pm$ 5.20%). This result was influenced by Billet 2, which is an outlier, in green. With this sample removed, the range is much tighter at $\pm$ 1.59%. This

indicates a defect with this particular sample. The fact that there was a defective component within such a small sample indicates that guaranteeing that every one of the deposited layers' bonds is a major factor in FDM strength. Dust, moisture or other factors could have caused this defect. Large design tolerances in out-of-plane strength might be a design consideration without an NDT process in place to guarantee material quality.

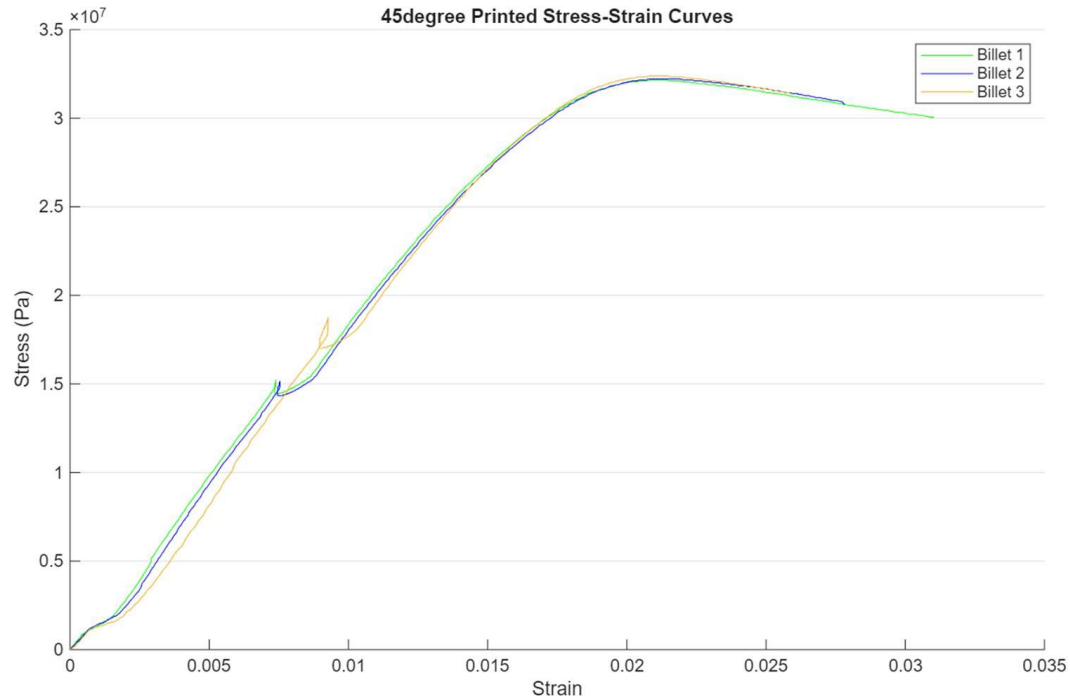


Figure 18 Stress-strain curve for 45° fibre orientation under UTS test

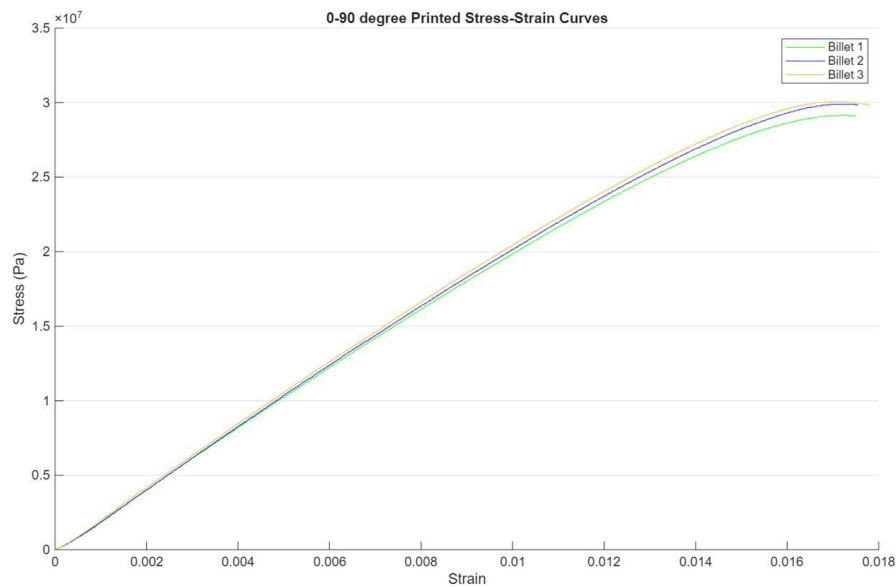


Figure 19 Stress-strain curve for perpendicular fibre orientation under UTS test

Figure 19 shows a stress-strain curve for filament lamination perpendicular to the direction of stress. The Young's modulus of this sample set is 1.98GPa with a standard deviation of 34.31 MPa. The limit of proportionality occurs around 25MPa, or when the strain is approximately 0.013. This occurs early for billet 1, suggesting a problem with the testing conditions or a defect with the sample.

Figure 18 shows the same information as Figure 19, but at 45 degrees to the loaded direction. This data set has a systematic error due to the addition of an extensometer, similar to that shown in Figure 21, which must be removed partway through the experiment to prevent damage when the sample breaks. Removing this measurement equipment causes the error between the strain values of 0.0075 and 0.01. When the stress is 'against the bias' in this manner, the ABS exhibits an average Young's modulus of 2.27 GPa; although an improvement upon perpendicular loading, it provides more unreliable results and corresponds with similar testing on FDM components with a large standard deviation of 135.44MPa.

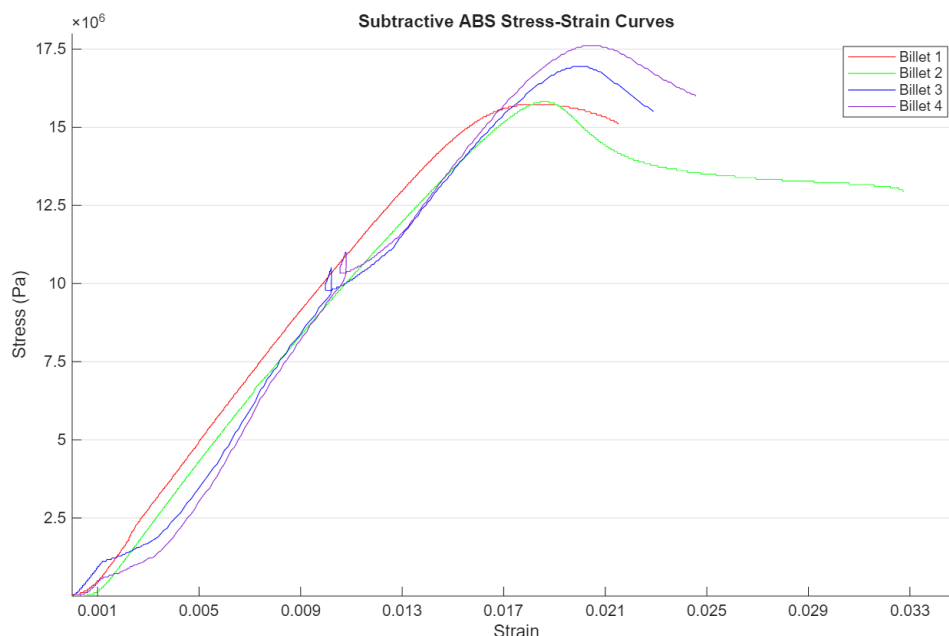


Figure 20 Stress-strain curve for solid ABS under UTS test

As a control to compare these results to, a series of ABS billets was tested using a subtractive water-jet cutting manufacturing process. The ABS sheet material these billets were cut from was 3mm in thickness due to constraints in procurement, compared to the 6mm thickness as per Figures 14 & 15, which produced a roughly halved UTS as shown in Figure 20. Additionally, the ABS used in this test is necessarily from a different supplier. Due to these constraints, this figure cannot be used to directly compare UTS or Young's Modulus values. Yet, from the profiles of this test, it can be concluded that only ABS loaded at the bias has the same necking and plastic deformation region as moulded ABS. The out-of-plane and perpendicular billets had sudden failures directly after reaching their UTS.

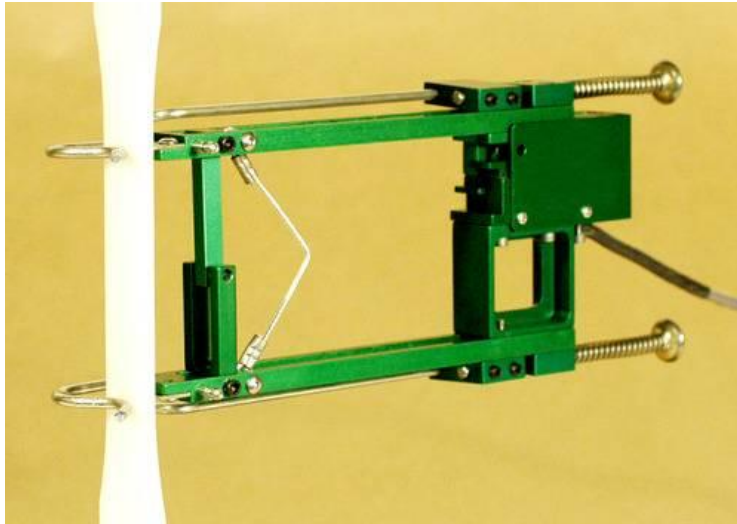


Figure 21 Image of the type of extensometer used during testing (United Testing Systems 2019)

Value	Tolerance		Source	max	min
Force (N)	Limits	-0.72% - 0.04%	Testing Equipment Calibration	<i>As Measured</i> +	<i>As Measured</i> -
Area (mm ²)	+/-	0.0156	Drawing	90.0156	89.9844
∂L (mm)	+/-	0.01%	Testing Equipment Calibration	<i>As Measured</i> +	<i>As Measured</i> -
L (mm)	+/-	0.125	Drawing	180.125	179.875

Table 3 Tolerances of measuring equipment used (Adkin & Willet, 2022)

Table 3 contains the tolerances for all variables measured to find Young's modulus (and therefore UTS) values. Some of these tolerances are from (Adkin & Willet, 2022), which is the calibration certificate for the universal testing machine from which these readings were taken. The force on this machine is biased to over-read the actual value applied to the specimen; the actual force value is - 0.38% that measured by the machine (tested at 5KN). This was measured within 0.34%, providing the overall limits for force values given in Table 3. The geometric tolerances are derived from Figures 5 & 6.

These values were considered when calculating the overall tolerances seen in Tables 4 & 5. Compared to the variation of results, the measurement equipment and geometric manufacturing tolerances have a negligible effect on the overall outcome. To do this, the following equations were applied to each set of experiments. For example, the maximum UTS out-of-plane value was calculated using Equation 4a. By taking the force applied to Billet 3, using the upper -0.04% tolerance, and applying the minimum geometric area value as above, the highest possible true value of out-of-plane UTS can be found.

$$\sigma_{max} = \frac{F_{max}}{A_{min}}$$

$$\sigma_{min} = \frac{F_{min}}{A_{max}}$$

$$E_{max} = \frac{F_{max} \cdot L_{max}}{A_{min} \cdot \delta L_{min}}$$

$$E_{min} = \frac{F_{min} \cdot L_{min}}{A_{max} \cdot \delta L_{max}}$$

Equation 4a, b, c & d Expressions for upper and lower limits of UTS and Young's modulus

Type of Loading Young's Modulus	Median	Error (+/-)	Mean	Standard Deviation
Out of Plane	1.68 GPa	5.20 %	1.71 GPa	79.33 MPa
Perpendicular	1.99 GPa	1.49 %	1.98 GPa	34.31 MPa
Along Bias	2.26 GPa	5.98 %	2.27 GPa	135.44 MPa

Table 4 Table of Young's Modulus results for FDM ABS materials tested

Type of Loading UTS	Median	Error (+/-)	Mean	Standard Deviation
Out of Plane	19.2 MPa	7.09 %	19.05 MPa	1.21 MPa
Perpendicular	29.6 MPa	1.50 %	29.70 MPa	0.47 MPa
Along Bias	32.3 MPa	0.34 %	31.29 MPa	1.94 MPa

Table 5 Table of UTS values for FDM ABS materials tested

The results within Tables 4 & 5, compared to Figures 10 & 11, show that the predictions for the UTS in the FEA models were closer in the perpendicular/parallel to the fibre direction. Interestingly, the bias direction was within the tolerance given by Bambu Labs, and the perpendicular direction wasn't (as stated in Figure 3). This could suggest that the values provided for this material have been tested in this favourable direction, which is also supported by the Young's Modulus values, which are again within tolerance in the bias and out of tolerance when the stress is perpendicular. More significantly is how far from the manufacturer's tolerance the out-of-plane maximum load is. As suggested with the Billet 2 in this set of tests, this could be a systemic failure in the manufacturing of this sample set, or overly optimistic reporting by the manufacturer.



Figure 22 Image of a fracture in an out-of-plane billet sample

Figure 22 shows a break in a sample produced in the out-of-plane layer orientation, which corresponds with Billet 1 in Figure 17. The material in this position demonstrates a clean break, and the position of the fracture corresponds with the FEA model, where the stress is concentrated at the end of the fillet. As can be seen in Figure 23, the break is between two filament layers. The discolouration shows how the delamination began in one corner, and the two layers 'peeled' away from each other as the strain increased. Figure 17 shows that this peeling effect occurs extremely quickly, due to the fact that the gradient doesn't change much before the point of failure. This can also be explained by the application of $\sigma = F/A$. Once the corner of the material delaminates, the area on which the force is acting begins shrinking, causing a sudden and rapid increase of stress at this layer boundary, leading to a sudden failure. The early failure of the filament perpendicular to the direction of stress could also account for the brittle failure of the $90^\circ - 0^\circ$ billet. Once the perpendicular fibres delaminate, the stress is suddenly concentrated in 50% of the surface area, causing a runaway failure instead of the traditional 'plastic' deformation usual with this type of material.



Figure 23 Image of out-of-plane fracture section

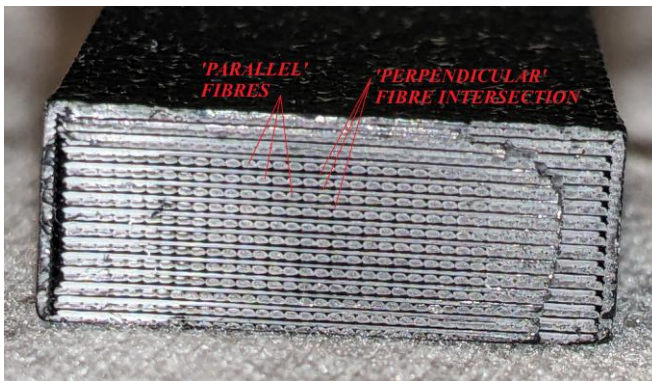


Figure 24 Image of perpendicular fracture section



Figure 25 Image of 'bias' fracture section

Similar to Figure 23, Figures 24 & 25 show the cross-section of failure for Billets 1 for both perpendicular and Bias loading samples, corresponding to Figures 18 and 19. These break patterns were typical for all samples tested in each category. The broken structure of the perpendicularly loaded material (Figure 24) was similar to that of the out-of-plane material in that the fracture was square and had discolouration on one side. This suggests that the mechanism of failure was similar. Figure 19 corroborates this result, with the behaviour displaying brittle behaviour. This type of break pattern could be due to the horizontal filament strains behaving exactly the same as the out-of-plane filament strands. These inter-filament bonds break around 19.2MPa, precipitating a fracture in the layers perpendicular to the direction of loading. In addition to the fact that the bonds between filament layers aren't as efficient due to temperature differences, the circular packing of the filaments means

the entire available volume isn't utilised by the material. By giving Gemini (Google's LLM) a portion of the clearer middle section of this image, the ratio of light to dark pixels is estimated to be approximately 3:2, which would translate to an effective volume fraction of approximately 60%. As all the X-Y samples are created with the same packing method, it can be said that this is a general shortcoming of this manufacturing method.

In Figure 25, the fracture isn't all perpendicular to the tensile stress direction. The material failure is actually perpendicular to the direction of filament infill. This leads to a random break pattern along the 45° strands. Between the different tests, the exact locations of these peaks didn't have a clear pattern, but this could be due to a relatively small sample size. In these samples, as previously explored, the billet had a well-defined plastic/necking region of deformation. The infill region has pulled away from the printed 'walls' which are printed entirely in the direction of the perpendicular stress. The perpendicular billet had some of this deformation, and the out-of-plane billet had none. It can be inferred that a lot of the Poisson's effect experienced during the plastic region occurred due to the 'bias', and the fracture is across the 'main zone', as occurs in fabrics such as that in Figure 26.

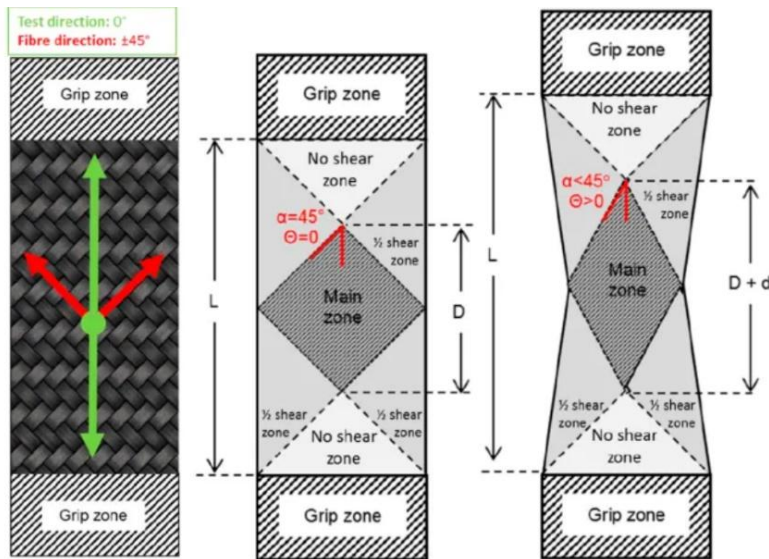


Figure 26 Fabric bias deformation due to movement within the weave (Martin et.al., 2022)

6 Informed Modelling Methods

6.1 FEA Modelling

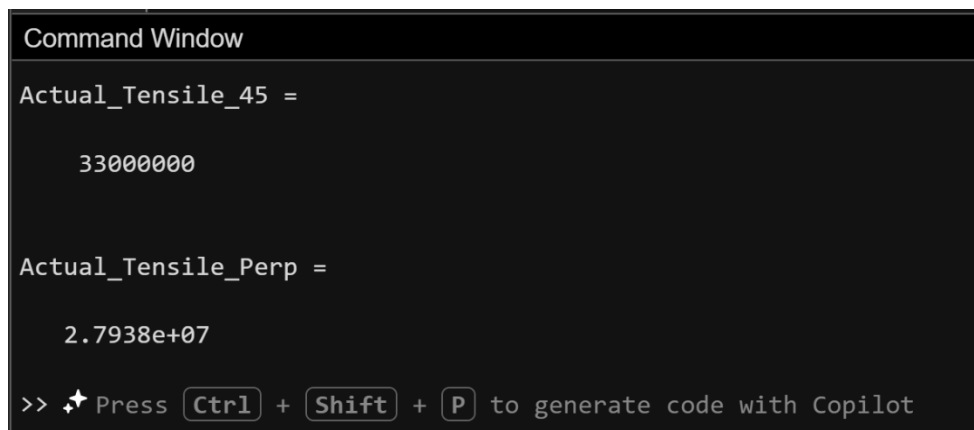
Looking at these results, it is clear that the FEA modelling approach cannot be relied upon. Relying on the traditional method of modelling FDM materials as symmetric around the X-Y plane is flawed, and the results directly conflict with the idea that FEA is an effective tool for dealing with these material types, as stated by Zheng et al (2021). In the perpendicular filament direction, the FEA model shown in Figures 10 & 11 has a discrepancy of as much as 2.6 times the strain proposed by this model (12mm proposed by the FEA model against 31mm experienced along the 'bias' of the test material in the most extreme case). Additionally, while the FEA model expected an ultimate tensile strength of 30MPa, the material could consistently perform around 7.5% better in this direction.

While for general-purpose prediction of material failure, the finite element method could be considered reliable, the extreme discrepancy of strain and therefore Young's Modulus means the technique cannot be relied upon to predict deformation or the specific mechanical behaviour of a component.

6.2 Analytical Modelling

6.2.1 X-Y Plane

Figures 27 & 28 show the implementation of Equation 3 using the data collected by experimental means. The 'matrix' property applied in this model is the z-axis values measured. This value is the actual property of the material bonds. It's shown in this MATLAB model that the Halpin-Tsai equation provides an accurate value for material bonding and replicates the experimental data more accurately than either the analytical or FEA methods used to predict the behaviour of the material.



```
Command Window

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Actual_Tensile_Perp =

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>> ✨ Press [Ctrl] + [Shift] + [P] to generate code with Copilot
```

Figure 27 Halpin-Tsai Implementation based on results UTS

```
Command Window

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Actual_youngM_Perp =

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>> ✨ Press Ctrl + Shift + P to generate code with Copilot
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Figure 28 Halpin-Tsai Implementation based on results of Young's Modulus

Part of this will be due to the contradictory information relating to layer bonding from BambuLabs. This method represents a significant improvement in accuracy by mapping each distinct property direction; there are areas where this basic application of the Halpin-Tsai doesn't exactly replicate the results.

- The value for the properties along the bias, although more accurate, still has a degree of systematic error. This could be from several factors, including a fundamental limitation with the Halpin-Tsai Equation as applied in this context, or an additional variable not accounted for here.
- This application only models the X-Y stresses within specific loading orientations.

To model stresses in the entire X-Y plane, these discrete directions, shown in Figure 29, need to be expressed as part of a function dependent on any possible angle. This has been achieved by applying a method based on the rule of mixtures Wen, M. et.al. (2020) in order to create an expression for combining distinct properties.

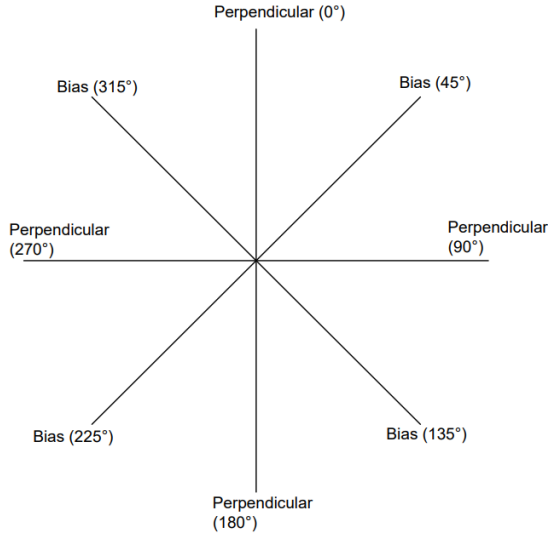


Figure 29 Distinct Material Property vectors governed by the Halpin-Tsai equation

In a standard application of trigonometry, a property, often a length or force, is applied to a sine or cosine wave to express its component strength as applied to a given direction. Along with the typical application in combining vectors, Ren et.al. (2010) used a trigonometric function to combine properties of a fibre-matrix composite. In this application, the frequency at which the strength cycles from full strength to no effect back to full strength is doubled at 45° sections, not 90°. Additionally, the sin/cosine waves must be displaced vertically, so that they are between the maximum value and the x-axis, since no negative value can be expressed for a value of UTS. Two of these waves must be added together, 180° out of phase with each other, each multiplied by a respective directional property.

Equation 5 shows an expression used to create Figures 30 & 31 for UTS at angle Θ . This expression is identical for Young's modulus and the UTS and meets the previously outlined requirements for such a formula. The resulting combined waveform (in green) requires future work in order to test the interim values between each 45° and confirm this modelling theory at interim angles.

$$P_{\theta} = \frac{P_b \cdot -\cos(4\theta) + P_b}{2} + \frac{P_p \cdot \cos(4\theta) + P_p}{2}$$

where P is the property being combined (σ stress or E Young's Modulus)

and b and p is represents that property along the bias or perpendicular directions

Equation 5 Derived expression for a property 'P' at angle theta for in-plane properties

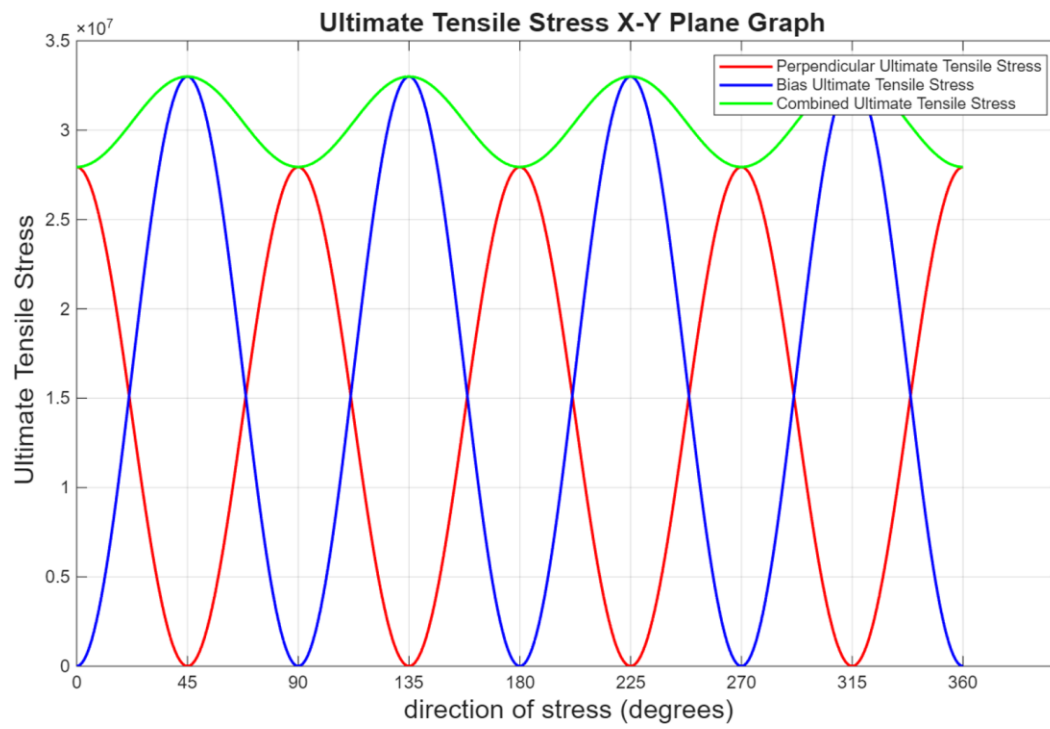


Figure 30 Graph of UTS in-plane at angle theta

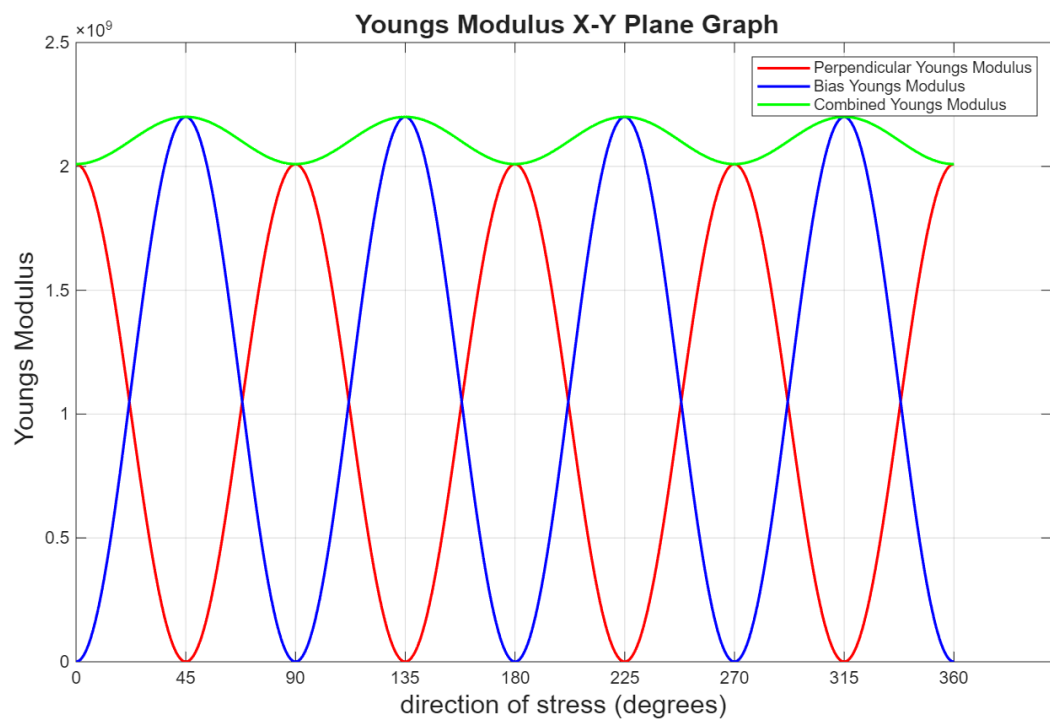


Figure 31 Graph of Young's Modulus in-plane at angle theta

$$P_{\alpha\gamma} = \frac{P_{xy} \cdot \cos(2\gamma) + P_{xy}}{2} + \frac{P_z \cdot -\cos(2\gamma) + P_z}{2}$$

where

$$P_{xy} = \left(\frac{-P_b \cdot \cos(4\alpha) + P_b}{2} + \frac{P_p \cdot \cos(4\alpha) + P_p}{2} \right)$$

α is the $X-Y$ Plane angle, and γ is the out-of-plane angle

P_z is the out of plane property

Equation 6 Expression for 'P' at angles alpha and gamma (in-plane direction & incline)

Equation 6 is an expression containing the third out-of-plane property. This is a direct substitution of Equation 4, with a known X-Y property and a halved cosine wave frequency. This complete expression allows any direction within the material to be substituted. As this is compounding the same function, the accuracy of this is increasingly uncertain, and is a key component of any future work on this topic.

7 Case Study

This section focuses on objective 3 exclusively in order to contextualise the results discussed in section 5 and modelled in section 6.

7.1 Background and Business Case

FDM additive manufacturing techniques have been applied in a widening variety of applications in recent years for both maintenance and production. Understanding how the material behaves under stress is a crucial part of applying this manufacturing technique in industry.

Figure 32 shows an AGV (Autonomous Guided Vehicle) which is deployed within Bisley. These move palletised finished goods from the end of production lines to a goods-out storeroom, ready to be picked when they are shipped as part of an order. These offer an automated alternative to forklifts and facilitate the movement of product along a path which is too long and complex to have a direct roller/conveyor belt connection.



Figure 32 Image of AGV (Autonomously Guided Vehicle) used in Bisley

At each corner, this design of AGV has a 'bump-stop' attached to a spring-loaded hinge and sensor. If the AGV were to make contact with an object placed within its pre-programmed path, this physical component acts in tandem with motion sensors to halt the AGV and alert an operator of an error. In this role, these bumpers are exposed to ensure nothing else on the machine contacts the surroundings first, and are partially sacrificial so that nothing more critical is damaged. Figure 33 is an engineering drawing of this component.

As per Table 6, an approximate price per part via additive manufacturing is around £12.08. In order to fit each component, an AGV would need to experience downtime, being replaced by an operator with a forklift. Additionally, a member of staff from maintenance would need to spend half a day completing the work on the AGV. If each of these employees costs the business £25/hr, including national insurance, benefits, etc. Refitting this component costs £200.00 in labour (one half day), or £400/day of downtime.

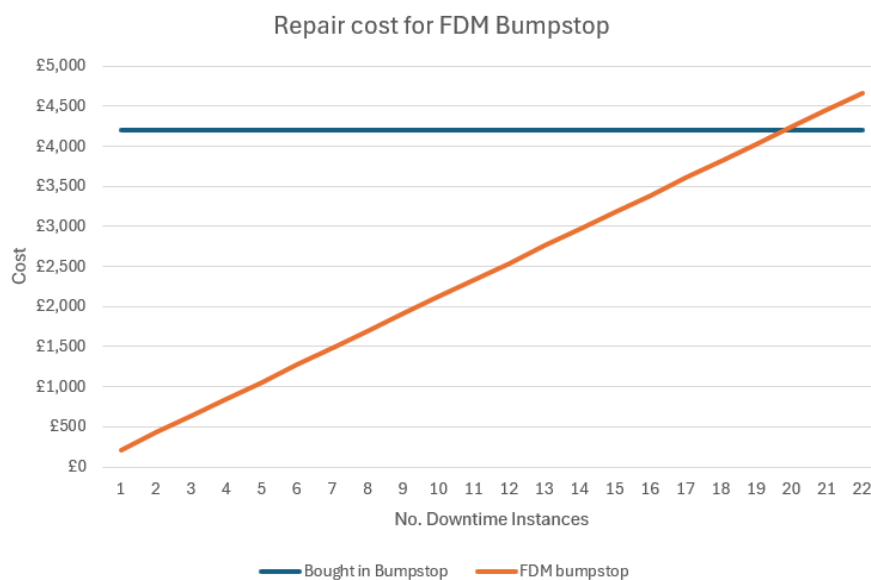


Figure 34 Repair cost for the bump-stop over the number of failures

Using these values in Figure 34, it's shown that a 3D printed bump-stop would need to be 20x less effective (experience material failure 20x more often) to justify buying an external component. This does not take into account possible damage to the AGV due to reduced performance, or failure to deliver product to the customer should a forklift or driver not be available to replace the AGV. The cost per unit for the 3D printed component is mostly the labour cost of fitting ($£200 + £12.08 = £212.08$).

7.2 Current Material Manufacturing Design

The bump-stop was manufactured with the standard filament direction assigned by the slicing software Bambu Studio. As seen in Figure 35, this was 3° from parallel/perpendicular to the front sloped edge and biased against the leading square edge.

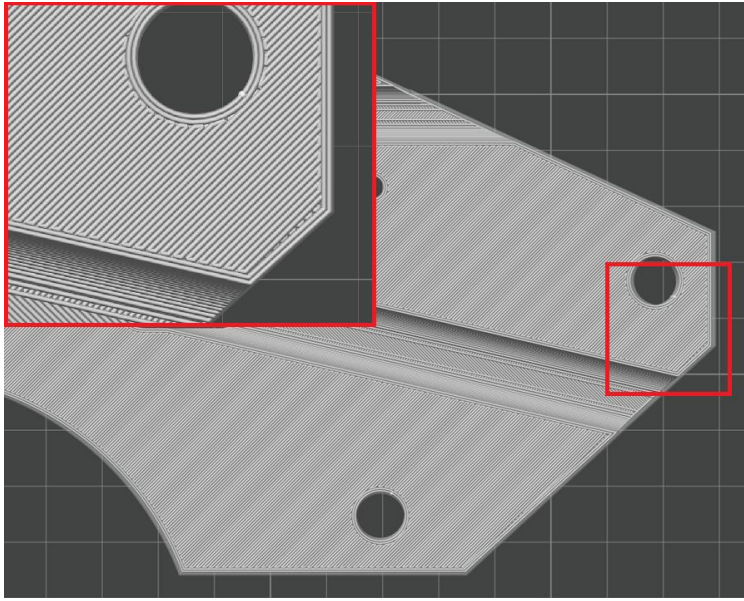
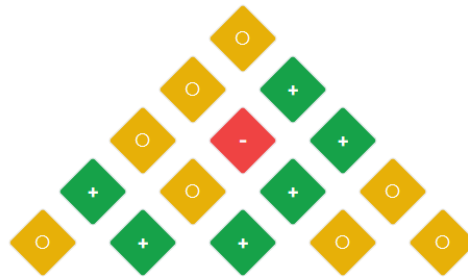


Figure 35 Image of current FDM layering within the 'bump-stop' component

This component is expected to take repeated impacts around this corner, with the front sloped edge facing out from the corner of the AGV. The original design utilised a solid nylon extrusion, and any replacement would need to be highly impact-resistant. Calculated from Figures 18 & 19, the strain energy per mm^3 of FDM polymers is much higher in the bias direction before the point of elastic failure (approximately $0.206\text{mJ}/\text{mm}^3$ along the bias vs $0.169\text{mJ}/\text{mm}^3$ perpendicular to the fibres) due to the higher gradient and greater elastic strain limit. The strain energy per unit volume is crucial to a material's impact resistance (Tan et al., 2025); this indicates that optimising the filament orientation in components that are expected to experience repeated impacts is crucial to optimising an FDM material.



Customer Requirements (WHATs)	Grain Direction	Time to Manufacture	Strain Energy/Unit Vol	Material Selection	Infill Density	Grain Size	Importance
HOWs (Technical Requirements)	(deg from Bias)	(days)	(J/mm ³)	(Nylon, TPU, ABS etc)	(%)	(mm)	
Direction of Improvement		↓	↑		↑	↑	
Impact Resistance	9	1	9	9	9	3	5
Access to Replacements		9		1	1	1	4
Cost of Replacements		3	1	3	3	1	3
Corrosion Resistance				9	1	3	2
Technical Priority Weight	45	50	48	76	60	28	

Figure 36 QFD (Quality Function Deployment) of bump-stop requirements

The bump-stop has four requirements: impact resistance, access to replacements, the cost of replacements and corrosion resistance. These requirements are mediated by the interactions of various technical requirements, and not all requirements are necessarily influenced by the design changes previously mentioned. The interactions between these variables and the technical requirements which influence them are mapped in Figure 36 in a QFD (Quality function Deployment).

The time to manufacture has a lower priority than infill density, due to the ease and low cost of stocking replacements, and is the only technical requirement with a negative correlation. This translates to extending print times in order to achieve higher-density components at maximum infill. Material selection is set by the best impact resistance material available (TPU 95), and since it has no negative correlations, this requirement can be effectively eliminated.

After these selections, the most important consideration is the strain-energy absorption and grain direction. Grain-direction is an independent variable, only linked in any way to strength, in this case, impact resistance and strain energy absorption. From this, it can be seen there's no disadvantage in optimising the grain direction 45° against the expected direction of impact. Future work within the company should focus on optimising the filament direction in this and similar parts to be maximally efficient. Different areas of the component may be printed in different orientations, effectively creating two or more 'grains', each optimised to strengthen different faces.

8 Outcome

8.1 Future Work

Throughout the course of this project, several areas were identified as requiring future work. Many of these areas are points which have arisen due to the research which has been completed, or work which would require extended time on this project to complete, which was originally part of the objectives.

UV exposure and the embrittling of ABS as the main mode of corrosion can lead to a drastic reduction in tensile strength (Niu et al., 2021). The impact of this behaviour upon a filament deposition structure could vary for many reasons. Air gaps within the structure could make such material more translucent to UV light, maybe leading to an increased rate of penetration and corrosion throughout the centre of the material. Additionally, the embrittling of the material might impact the weakened inter-filament layers more than solid material, impacting the types of behaviour the material exhibits. To identify such effects, if any, samples would need to be subject to controlled artificial UV ageing to quantify the exact amount of degradation, matching closely the conditions used by a previous study of 'pure' ABS of the same type or manufacture. 1.75mm filament cut from a spool of Bambu Labs ABS could be tested, providing an identical control. This problem wasn't explored within this project due to the time constraints of the project, and a greater proportion of the project was allocated to the analysis of the initial results due to the unexpected behaviour of the material.

A 'warp' and 'weft' parallel from woven fabrics is applied in this research to attempt to understand the anisotropy of FDM components due to some similarities previously discussed, where loading at a 45° bias can result in a reduction in Young's Modulus, because no individual fibre is loaded at both ends, allowing the superstructure to exhibit extreme elasticity. However, also because of this indirect loading, woven materials are generally considered weaker along the bias (Godara & 9 Raabe, 2007) (Pan et al., 2015). It is possible that the difference in layered material vs a woven fibre, or the use of many layers, not one set of fibres in each direction, is causing a behaviour contrary to that hypothesised. To assess the accuracy of warp-weft theory for FDM components, a high-speed camera could capture the mechanism of deformation. Additionally, future testing should measure Poisson's ratio perpendicular and biased loading to quantitatively confirm this behaviour.

In Figures 23 & 24, there is evidence of layer 'peeling' where failure begins concentrated in one area, as previously discussed. In future testing, high-speed footage should also be used to investigate this type of failure in greater detail. Being able to record the moment of failure might provide qualitative data to corroborate or invalidate any understanding decided upon through measurements. Evidence should be sought to link the behaviour of this to work by Martin et.al. (2022).

When modelling these behaviours, the Halpin-Tsai method was applied for previously discussed reasons. The Mori-Tanaka method should also be attempted, and the differences in analytical

prediction should be cross-compared in order to highlight the areas where the Halpin-Tsai method isn't suitable. This approach better accounts for mechanical interactions between inclusions (layers/strands) than Halpin-Tsai (Kundalwal, 2017) and might help explain materials where an additive is already present, such as glass-fibre filaments for high-stress applications. In addition, it's important to look at the influence of infill densities upon this type of analytical model. In most FDM techniques, infill patterns of various types are applied to reduce print time and material use (Fernández-Vicente et al., 2016) while maintaining material strength. Various geometric options are available with a wide range of software packages. A large body of research already exists (Agrawal et.al., 2023) (Jagadeesh et al., 2025) exploring the effects of infill patterns on UTS, and this research can be incorporated into this modelling technique.

When combining the distinct Halpin-Tsai properties, a cosine and -cosine wave form was applied. This has approximated the interim angles outside of those tested. However, no attempt was made to verify this technique for combining material properties, and this method is a very simplistic way of combining directionally proportional variables. Further work will definitely be required to refine this mathematical model and match it to experimental data.

Finally, all the results collected and consequently modelled in this project have been dependent upon the manufacturer's recommended printing speed, temperature etc. These variables aren't in any way reflected in the analytical approach taken. Future work should explore the extent of these settings and to adjust the model accordingly. It's not known how Bambu Labs came to their recommended values, and modelling the behaviour of each independently might yield a more scientific and more effective set of parameters.

8.2 Conclusions

This project has advanced the understanding of how Fused Deposition Modelling (FDM) polymers behave under stress, highlighting the anisotropic nature of these materials and the inherent limitations of traditional modelling techniques. The research demonstrated that while additive manufacturing offers high customisation and cost-efficiency, its mechanical inconsistencies—particularly the weakened structure between layers—require specific design principles and informed modelling to ensure components are fit for purpose.

Individual Project Plan

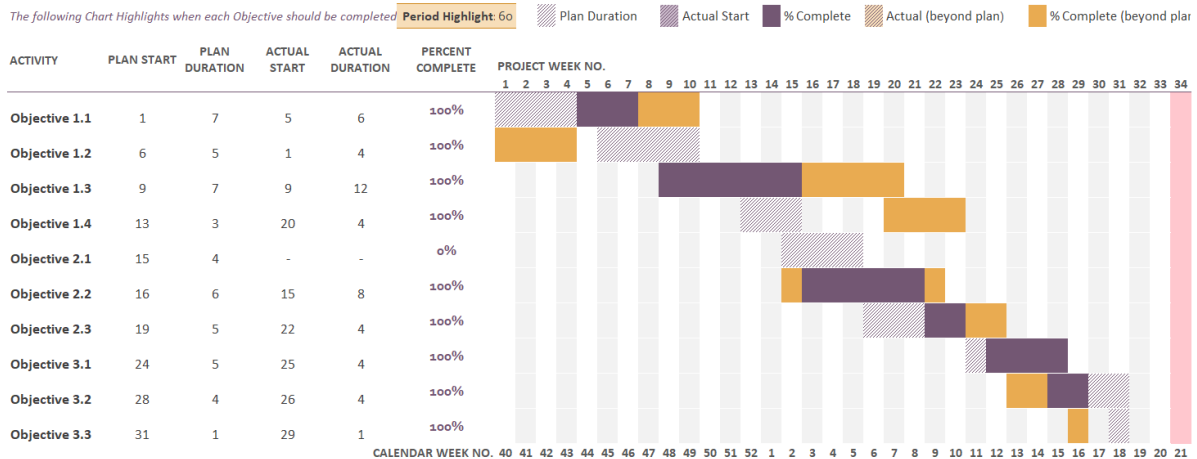


Figure 37 Final Gantt chart of the project timeline

The first objective focused on understanding elastic and shear stress properties through data collection and analysis. The project collected comparative data, showing that Bias (45°) loading yielded a higher Young's Modulus (2.26 GPa) and Ultimate Tensile Strength (32.3 MPa) compared to perpendicular or out-of-plane loading. This finding was backed up by literature, which found similar results in 3D printed materials. As in Figure 37, this was actually completed after objective 1.2, as it proved more informative to compare a predictive model based on the academic literature, finding that traditional Finite Element Analysis (FEA), which assumes orthotropic symmetry, is flawed for FDM material types.

As the project developed, it became evident that analysing the limitations of these models and exploring how other models might address this became the focus of the project. To this end, the timeline for objectives 1.3 and 2.2 was completed in parallel, one influencing the other, and the total time to finish this stage consumed much of the overall project time. The project implemented an analytical approach using the Halpin-Tsai equation. When informed by experimental data on interlaminar bond strength, this model replicated material behaviour more accurately than standard FEA or manufacturer data.

Objective 2.1 aimed to explore how adverse conditions like UV radiation and saltwater exacerbate structural weaknesses. Although some initial research confirmed that UV exposure significantly weakens the chemical bonds in ABS polymers, the changing nature of the project didn't ultimately leave time to explore this with experimental data, as noted in future work. Future research should focus on experimental UV ageing tests to quantify the exact rate of corrosion in layered structures. Comparative testing between solid ABS and 3D-printed material needs to be carried out, or other research exploring this area should be integrated into this project's learnings.

The final objective was to apply these findings to broader design principles through an industrial case study. As initially outlined, the timeline for these objectives was informed by when other elements of the project were completed. This ultimately led to a slightly shorter segment than initially planned. The case study of an AGV bump-stop demonstrated that FDM components are a highly viable alternative to machined parts. It was found that a 3D-printed part would need to be 20 times less effective than the original, provided various previously stated assumptions, to lose its cost-justification, given the massive price discrepancy between production methods. The project identified that for impact-prone components, designers must optimise filament orientation towards the bias direction to maximise impact resistance and UTS.

In order to make this research available to the relevant parties, a copy of this paper was shared within Bisley for this information to be applied in relevant future work. Additionally, a condensed copy of the testing and modelling sections was sent to contact@bambulab.com as a query about how they came to the values presented within their materials datasheet via my UWTSD email address.

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10 Appendix

10.1 MATLAB code used to calculate Figure 13:

```
clc % - clear command window
clear all %- removes all commands in current matlab code
close all % - closes all figures
% 6mm high
% 0.2mm layers
% bottom layers = 3, top = 5
% 0.2*8= 1.6
% 6-1.6 = 4.4
% 3.8/6 = 63.33%
function Pc = Halpin(Vf,Pm,Pf,Dia,fL)
    % Pc = property of the overall Composite
    % Pm / Pf = property of the matrix / fibre
    % Vf = volume fraction of 'fibre'
    % fL = fibre Length
    c = 2*(fL/Dia); % reinforcement geometry aspect ratio
    n = ((Pf/Pm)-1)/((Pf/Pm)+c);
    Pc = Pm*((1+c*n*Vf)/(1-n*Vf));
end
function Direction_Graph(Perp_Value,deg45_Value,Label)
    X = 0:360;

    Y1 = (Perp_Value*cosd(4*X)+Perp_Value)/2;%+Perp_Value
    Y2 = (deg45_Value*-cosd(4*X)+deg45_Value)/2;%+deg45_Value
    YT = Y1 + Y2;

    % Plotting the sine and cosine functions
    figure;

    plot(X, Y1, 'r', 'DisplayName', strcat('Perpendicular',Label));
    hold on;
    plot(X, Y2, 'b', 'DisplayName', strcat('Bias',Label));
    hold on;
    plot(X, YT, 'g', 'DisplayName', strcat('Combined',Label));
    xlabel('direction of stress (degrees)');
    ylabel(Label);
    title(strcat(Label, ' X-Y Plane Graph'));
    xticks(0:45:360)
    legend show;
    grid on;

end
XYTensile = 33*10^6;
ZTensile = 19.2*10^6;
%ZTensile = 28*10^6;
Dia = 0.2*10^-3;
Actual_Tensile_45 = Halpin(1,ZTensile,XYTensile,Dia,21.2*10^-3)
Actual_Tensile_Perp = Halpin(0.6333,ZTensile,XYTensile,Dia,180*10^-3)
XY_youngM = 2.2*10^9; % given material prop for ABS
Z_youngM = 1.68*10^9; % measured out of plane young-mod
Actual_youngM_45 = Halpin(1,Z_youngM,XY_youngM,Dia,21.2*10^-3)
Actual_youngM_Perp = Halpin(0.6333,Z_youngM,XY_youngM,Dia,180*10^-3)

% 0.7 because you have 45deg un-avoidable due to top&bottom layers
```

% 45 deg fibres are shorter, only running left-right

Direction_Graph(Actual_Tensile_Perp,Actual_Tensile_45,' Ultimate Tensile Stress')
Direction_Graph(Actual_youngM_Perp,Actual_youngM_45,' Youngs Modulus')

10.2 MATLAB code used to generate Figures 17-20:

clc % - clear command window

clear all % - removes all commands in current matlab code

close all % - closes all figures

%This programme is dependant on the excel sheets in the test1 folder

%dont delete these!!

function PrintData = ZPRINT_IMPORT(Range)

% Set up the Import Options and import the data

opts = spreadsheetImportOptions("NumVariables", 2);

% Specify sheet and range

opts.Sheet = "Average";

opts.DataRange = Range;

% Specify column names and types

opts.VariableTypes = ["double", "double"];

% Import the data

PrintData = readmatrix("C:\Users\sean.mee\OneDrive - Bisley Office Furniture
Ltd\Documents\UWTSD Yr 4\Dissertation\Sean Mee Test1\Z-Print Data.xlsx", opts, "UseExcel", false);

% Clear temporary variables

clear opts

end

function PrintData = PRINT0_90_IMPORT(Range)

% Set up the Import Options and import the data

opts = spreadsheetImportOptions("NumVariables", 2);

% Specify sheet and range

opts.Sheet = "Plotting";

opts.DataRange = Range;

% Specify column names and types

opts.VariableTypes = ["double", "double"];

% Import the data

PrintData = readmatrix("C:\Users\sean.mee\OneDrive - Bisley Office Furniture
Ltd\Documents\UWTSD Yr 4\Dissertation\Sean Mee Test1\0-90 Print Data.xlsx", opts, "UseExcel", false);

% Clear temporary variables

clear opts

end

function PrintData = PRINT45_IMPORT(Range)

% Set up the Import Options and import the data

opts = spreadsheetImportOptions("NumVariables", 2);

% Specify sheet and range

opts.Sheet = "Plotting";

opts.DataRange = Range;

% Specify column names and types

opts.VariableTypes = ["double", "double"];

% Import the data

PrintData = readmatrix("C:\Users\sean.mee\OneDrive - Bisley Office Furniture
Ltd\Documents\UWTSD Yr 4\Dissertation\Sean Mee Test1\45 Print Data.xlsx", opts, "UseExcel", false);

```

    % Clear temporary variables
    clear opts
end

function variation = Percent_Variation(list)
    CNTR_VALUE = (max(list)+min(list))/2;
    variation = ((CNTR_VALUE - min(list)) / CNTR_VALUE) * 100;
    variation = string(round(CNTR_VALUE))+ " +/- " +string(variation)+ " %";

end

%% Z-PRINT STRESS-STRAIN CURVE GRAPH

Range1 = "C6:D908"; %FIRST TEST STRESS-STRAIN
Range2 = "H6:I929"; %SECOND TEST STRESS-STRAIN
Range3 = "M6:N1035"; %THIRD TEST STRESS-STRAIN
Range4 = "R6:S826"; %FOURTH TEST STRESS-STRAIN

figure;
hold on; % Keep the current plot
ZPrint1 = ZPRINT_IMPORT(Range1);
plot(ZPrint1(:,1),ZPrint1(:,2), 'r')
% young's mod of line 2
EZPrint1 = (ZPrint1(300,2)-ZPrint1(400,2)) / (ZPrint1(300,1)-ZPrint1(400,1));

ZPrint2 = ZPRINT_IMPORT(Range2);
plot(ZPrint2(:,1),ZPrint2(:,2), 'g')
% young's mod of line 2
EZPrint2 = (ZPrint2(300,2)-ZPrint2(400,2)) / (ZPrint2(300,1)-ZPrint2(400,1));

ZPrint3 = ZPRINT_IMPORT(Range3);
plot(ZPrint3(:,1), ZPrint3(:,2), 'b')
% young's mod of line 2
EZPrint3 = (ZPrint3(300,2)-ZPrint3(400,2)) / (ZPrint3(300,1)-ZPrint3(400,1));

ZPrint4 = ZPRINT_IMPORT(Range4);
plot(ZPrint4(:,1), ZPrint4(:,2))
% young's mod of line 2
EZPrint4 = (ZPrint4(300,2)-ZPrint4(400,2)) / (ZPrint4(300,1)-ZPrint4(400,1));

hold off;

xticks(0.001:0.001:0.02)
yticks(0.25*10^7:0.25*10^7:2.5*10^7)
xlabel('Strain');
ylabel('Stress (Pa)');
title('Z-Printed Stress-Strain Curves');
legend('Billet 1', 'Billet 2', 'Billet 3', 'Billet 4');

%% Z-PRINT FORCE-EXTENSION CURVE GRAPH

Range1 = "A6:B908"; %FIRST TEST STRESS-STRAIN
Range2 = "F6:G929"; %SECOND TEST STRESS-STRAIN
Range3 = "K6:L1035"; %THIRD TEST STRESS-STRAIN
Range4 = "P6:Q826"; %FOURTH TEST STRESS-STRAIN

```

```

figure;
hold on; % Keep the current plot
ZPrint1 = ZPRINT_IMPORT(Range1);
plot(ZPrint1(:,2),ZPrint1(:,1), 'r')

ZPrint2 = ZPRINT_IMPORT(Range2);
plot(ZPrint2(:,2),ZPrint2(:,1), 'g')

ZPrint3 = ZPRINT_IMPORT(Range3);
plot(ZPrint3(:,2), ZPrint3(:,1), 'b')

ZPrint4 = ZPRINT_IMPORT(Range4);
plot(ZPrint4(:,2), ZPrint4(:,1))

hold off;

xticks(0.1:0.1:2)
yticks(200:200:10000)
xlabel('Extension (mm)');
ylabel('Load (N)');
title('Z-Printed Force-Extension Curves');
legend('Billet 1', 'Billet 2', 'Billet 3', 'Billet 4');

%% 45deg-PRINT STRESS-STRAIN CURVE GRAPH

Range1 = "C4:D2504"; %FIRST TEST STRESS-STRAIN
Range2 = "H4:I1350"; %SECOND TEST STRESS-STRAIN
Range3 = "M4:N1330"; %THIRD TEST STRESS-STRAIN
Range4 = "R4:S1237"; %FOURTH TEST STRESS-STRAIN

figure;
hold on; % Keep the current plot
%ZPrint1 = PRINT45_IMPORT(Range1);
%plot(ZPrint1(:,1),ZPrint1(:,2), 'r')

ZPrint2 = PRINT45_IMPORT(Range2);
plot(ZPrint2(:,1),ZPrint2(:,2), 'g')
% young's mod of line 2
E45deg2 = (ZPrint2(170,2)-ZPrint2(200,2)) / (ZPrint2(170,1)-ZPrint2(200,1));

ZPrint3 = PRINT45_IMPORT(Range3);
plot(ZPrint3(:,1), ZPrint3(:,2), 'b')
% young's mod of line 2
E45deg3 = (ZPrint3(170,2)-ZPrint3(200,2)) / (ZPrint3(170,1)-ZPrint3(200,1));

ZPrint4 = PRINT45_IMPORT(Range4);
plot(ZPrint4(:,1), ZPrint4(:,2))
% young's mod of line 2
E45deg4 = (ZPrint4(170,2)-ZPrint4(200,2)) / (ZPrint4(170,1)-ZPrint4(200,1));
hold off;

%xticks(0.001:0.001:0.02)
%yticks(0.25*10^7:0.25*10^7:2.5*10^7)
xlabel('Strain');
ylabel('Stress (Pa)');
title('45degree Printed Stress-Strain Curves');

```

```

legend('Billet 1', 'Billet 2', 'Billet 3');

%% 0-90deg-PRINT STRESS-STRAIN CURVE GRAPH
% y = mx+c
% m = dy/dx

Range2 = "C4:D1255"; %FIRST TEST STRESS-STRAIN
Range3 = "H4:I1258"; %SECOND TEST STRESS-STRAIN
Range4 = "M4:N1278"; %THIRD TEST STRESS-STRAIN

figure;
hold on; % Keep the current plot

Print90deg_2 = PRINT0_90_IMPORT(Range2);
plot(Print90deg_2(:,1),Print90deg_2(:,2), 'g')
% young's mod of line 2
E90deg_2 = (Print90deg_2(500,2)-Print90deg_2(520,2)) / (Print90deg_2(500,1)-Print90deg_2(520,1));

Print90deg_3 = PRINT0_90_IMPORT(Range3);
plot(Print90deg_3(:,1), Print90deg_3(:,2), 'b')
% young's mod of line 2
E90deg_3 = (Print90deg_3(500,2)-Print90deg_3(520,2)) / (Print90deg_3(500,1)-Print90deg_3(520,1));

Print90deg_4 = PRINT0_90_IMPORT(Range4);
plot(Print90deg_4(:,1), Print90deg_4(:,2))
% young's mod of line 2
E90deg_4 = (Print90deg_4(500,2)-Print90deg_4(520,2)) / (Print90deg_4(500,1)-Print90deg_4(520,1));

hold off;

%xticks(0.001:0.001:0.02)
%yticks(0.25*10^7:0.25*10^7:2.5*10^7)
xlabel('Strain');
ylabel('Stress (Pa)');
title('0-90 degree Printed Stress-Strain Curves');
legend('Billet 1', 'Billet 2', 'Billet 3', 'Billet 4');

%Print all youngs modulus
fprintf('45deg youngs mod:\n%g GPa\n%g GPa\n%g GPa\n',E45deg2*10^-9,E45deg3*10^-9,E45deg4*10^-9)
fprintf('0-90deg youngs mod:\n%g GPa\n%g GPa\n%g GPa\n',E90deg_2*10^-9,E90deg_3*10^-9,E90deg_4*10^-9)
fprintf('Z youngs mod:\n%g GPa\n%g GPa\n%g GPa\n%g GPa\n',EZPrint1*10^-9,EZPrint2*10^-9,EZPrint3*10^-9,EZPrint4*10^-9)

%% using to find variations

EZ = [EZPrint1,EZPrint2,EZPrint3,EZPrint4];
E45 = [E45deg2,E45deg3,E45deg4];
EPerp = [E90deg_2,E90deg_3,E90deg_4];
% median and bounds

Z_BREAKPOINTS = [ZPrint2(end,2),ZPrint2(end,2),ZPrint3(end,2),ZPrint4(end,2)];

```

```
%Bias_BREAKPOINTS = [max(ZPrint2(:,2)),max(ZPrint3(:,2)),max(ZPrint4(:,2))];
%Perp_BREAKPOINTS = [max(Print90deg_2(:,2)),max(Print90deg_3(:,2)),max(Print90deg_4(:,2))];

disp('Percent_Variation(Z_BREAKPOINTS)')
Percent_Variation(Z_BREAKPOINTS)
```

10.3 Environmental Effects and Corrosion

The following research was carried out for objective 2, but as discussed in the future work section, the required testing wasn't followed through on.

Acrylonitrile-butadiene-styrene (ABS) is a widely used thermoplastic. Like many materials used in additive manufacturing, it's vulnerable to environmental degradation from factors such as ultraviolet (UV) radiation and saltwater exposure. UV is well known to cause a decline in mechanical strength, particularly tensile strength. Virgin ABS subjected to artificial UV ageing at 50°C - 60°C show significant reductions in tensile strength, with measured values decreasing to approximately 29.44 MPa after 15 days of exposure (Kuram et al., 2025) for solid ABS. This degradation is characterised by 'yellowing' of the material, and only happens in the presence of oxygen, sped up at shorter wavelengths of UV light (Santos et al., 2010).

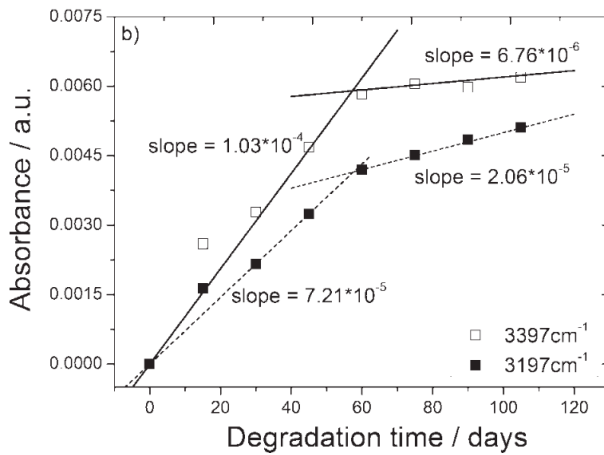


Figure 38 Degradation of moulded ABS exposed to UV light over time (Santos et al., 2010)

UV exposure significantly affects chemical bonds in a polymer matrix, which is seen in Figure 38. This could have a particularly pronounced effect on adhesion between printed layers, which already have poor bonding due to the temperature difference during deposition. This can lead to up to an 85% reduction in tensile strength in the out-of-plane direction (Niu et al., 2021). This research forms the basis for designing experiments that address objective 2.