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Structural Optimization of FDM-Processed ASA Polymer Frames through Acetone Solvent Welding, Variable Infill Strategy, and Layer Orientation: Experimental Validation via Quadcopter Flight Testing

Sunny Nanade[1,*], Zarvan Movdawalla[2]

Abstract

Acrylonitrile styrene acrylate (ASA) is an amorphous terpolymer with superior UV resistance compared to acrylonitrile butadiene styrene (ABS), as its acrylate rubber phase lacks photodegradation-prone carbon–carbon double bonds. This study proposes acetone solvent welding as a polymer joining method to produce monolithic structures from FDM-processed ASA components, addressing three processing challenges: achieving structural continuity through polymer chain interdiffusion at solvent-wetted interfaces, correcting thermal warping via post-print geometric correction during welding, and optimizing infill density distribution for maximum strength-to-weight ratio. Two iterative frame designs were fabricated and tested using quadcopter flight testing as a structural loading platform. Frame 1 (450 g) employed solid (100%) infill landing gears with conventional infill elsewhere, while Frame 2 (443 g) used a strategic variable infill strategy (60–20%) with key layer orientation to exploit FDM polymer anisotropy. A novel warping correction method was developed: acetone-softened ASA components were clamped against a flat granite surface plate during solvent evaporation, achieving geometric correction as polymer chains interdiffused across bond interfaces. Frame 1 failed structurally within 10 flights, while Frame 2 completed 40+ flights with no structural degradation, no acetone joint separation, and motor mount coplanarity within 0.1 mm tolerance. Despite a 1.5% weight reduction, the optimized design achieved approximately four times greater operational life, demonstrating that polymer volume fraction distribution and layer orientation optimization are superior to uniform high-density infill. These findings provide reproducible guidelines for solvent-welded ASA polymer structures and an effective warping-reduction process without heated build chambers.

Keywords: ASA polymer, solvent welding, acetone bonding, polymer chain interdiffusion, variable infill, fused deposition modeling, thermoplastic processing, anisotropic polymer properties, warping mitigation

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INTRODUCTION

Fused deposition modeling (FDM) is a polymer processing method that uses melt extrusion to form complex three-dimensional structures using thermoplastic filaments quickly [1, 9]. The polymer chemistry, processing parameters and part geometry, such as infill density, orientation of layers and after-treatment of the part, such as solvent bonding, all interact in a complex fashion to dictate the mechanical properties of FDM-processed parts [5, 9, 12]. These process-property correlations need to be comprehended and optimized to increase the applications of FDM polymers in structural applications.

When using outdoor structural applications, the type of material should consider the ultraviolet (UV) photodegradation, which constrains the usefulness of several popular thermoplastics.

Structural optimization in additive manufacturing refers to the systematic improvement of part geometry, material distribution, and processing parameters to maximize mechanical performance while minimizing material usage and weight [14, 15]. Unlike conventional subtractive manufacturing, FDM enables the production of complex internal geometries that can be tailored to meet specific loading conditions. This encompasses topology optimization, where material is distributed according to stress paths, as well as process parameter optimization including layer height, raster angle, and nozzle temperature settings that directly influence the mechanical response of printed components [16, 18]. Recent studies have demonstrated that integrating computational optimization with experimental validation can significantly enhance the structural efficiency of FDM-processed polymer parts [14, 17].

Polymer Joining Methods for FDM Structures

Mechanical Fastening: When connections are done with bolts, the structure can be taken to pieces and replace components, although it brings out stress concentrations at the fastener holes (stress concentration factor K t = 2 -3), introduces parasitic weight due to metal hardware, and results in joint compliance that decreases structural rigidity [5, 13].

The paper explores solvent welding of acetone in the formation of monolithic ASA polymer structures to eliminate weight and stress concentration of fasteners and structural continuity is made possible by interdiffusion of polymer chains at the molecular level.

Thermal Warping in ASA Polymer Processing

ASA has a high level of thermal shrinkage between melt processing temperature (245–250°C) to ambient conditions. The high coefficient of thermal expansion and the large temperature differential create internal residual stresses that manifest as part warping, particularly in large components where asymmetric cooling gradients develop. Traditional mitigation strategies include heated build chambers (50–70°C) and elevated bed temperatures (90–110°C), which add equipment complexity and cost [3].

Another method of processing polymers is provided in the paper where geometric correction of distorted parts of the process of acetone bonding is used. Using this to take advantage of temporary plasticity of acetone-softened ASA polymer, warped parts are clamped to a flat reference surface during curing in the solvent to allow relaxation of residual stress and geometric correction without the use of heated build chambers.

FDM-printed polymer frames commonly exhibit several categories of defects that compromise structural integrity. These include inter-layer delamination due to insufficient polymer chain diffusion across layer interfaces, voids and porosity stemming from incomplete raster fill and air entrapment between adjacent deposited filaments, and dimensional inaccuracies resulting from thermal shrinkage during cooling [15, 16]. Surface roughness inherent to the staircase effect of layered deposition introduces stress concentration sites that can serve as crack initiation points under dynamic loading [18]. Additionally, moisture absorption in hygroscopic polymers and UV-induced degradation in outdoor applications further compromise the mechanical performance of FDM frames. Understanding and mitigating these defects through process parameter optimization is essential for producing reliable structural components [14, 16].

Anisotropic Mechanical Properties in FDM Polymers

FDM-processed polymers exhibit directionally dependent mechanical properties due to the layer-by-layer melt deposition process. Tensile strength parallel to printed layers typically exceeds perpendicular (inter-layer) strength by 30–50% in amorphous thermoplastics, a consequence of limited polymer chain reptation and entanglement across layer interfaces compared to full chain mobility within deposited tracks [6, 7]. This anisotropy is a fundamental characteristic of the FDM polymer processing technique and must be considered in structural design.

Strategic part orientation during FDM processing enables alignment of the stronger in-plane direction with primary loading conditions. Additionally, infill density critically affects effective polymer properties: prior studies demonstrate that infill density and print strategy substantially influence the stiffness and strength of FDM polymer parts [6, 7, 9]. Weight reduction together with optimization of strength may be achieved with variable infill strategies; the density of the polymer should be lower in the non-stress parts but higher in the areas of stress-concentration.

Topology-based infill strategies represent an advanced approach to structural optimization in FDM processing, wherein the internal fill pattern is designed to align with principal stress trajectories rather than using uniform density distributions [14, 17]. By concentrating polymer material along primary load paths and reducing infill in low-stress regions, topology-optimized structures achieve superior stiffness-to-weight ratios compared to conventional uniform infill approaches. Finite element analysis methods have been employed to validate the mechanical performance of such optimized structures under complex loading conditions [15]. Furthermore, topology-based infill can improve the energy absorption capacity and impact resistance of FDM polymer frames by directing deformation through programmed failure zones, thereby preventing catastrophic structural failure [16, 17].

Research Objectives

This study aims to:

1. Determine acetone solvent welding capability of monolithic ASA polymer structure fabrication and bond integrity under operation dynamic loading.
2. Design and establish a viable after print warping correction method that takes advantage of the acetone induced plasticity of polymer during bonding.
3. Investigate variable infill density optimization for polymer volume fraction distribution in load-bearing FDM structures
4. Evaluate the effect of FDM layer orientation on impact resistance of anisotropic ASA polymer components
5. Provide comparative performance data between optimized and non-optimized ASA polymer structural designs

MATERIALS AND METHODS

ASA Polymer Properties

All frames were fabricated using commercial ASA thermoplastic filament. ASA (acrylonitrile styrene acrylate) is an amorphous terpolymer consisting of a styrene-acrylonitrile (SAN) continuous matrix phase with dispersed acrylate rubber particles [2]. The following properties are relevant to structural polymer applications:

- *Tensile strength:* 40–50 MPa (bulk polymer, injection molded)
- *Flexural modulus:* 2.0–2.5 GPa
- *Glass transition temperature ():* 100°C
- *Density:* 1.05–1.07 g/cm (approximately 16% lower than PET-G by volume)
- *UV resistance:* 10 superior to ABS due to acrylate rubber phase [2]
- *Acetone solubility:* Amorphous SAN matrix dissolves in acetone, enabling solvent welding
- *Moisture sensitivity:* Moderate hygroscopic behavior (filament dried at 80°C for 4 hours before processing)

The acrylate rubber phase provides impact energy absorption through stress whitening and craze formation mechanisms, while the glassy SAN matrix contributes structural rigidity and chemical resistance [2, 3]. ASA's higher compared to PET-G (100°C vs 80–85°C) provides improved thermal stability for applications where motor heating may elevate local temperatures.

Table 1. FDM manufacturing parameters for ASA frame fabrication.

Parameter	Value
Layer height	0.2-0.25 mm
Nozzle temperature	245-250°C
Bed temperature	100-105°C
Print speed	50 mm/s
Infill pattern	Grid/Rectilinear
Wall lines (perimeters)	3
Top/bottom layers	4
Cooling fan	Minimal (10-20%)

Table 2. Variable infill density distribution.

Component	Frame 1 (WF)	Frame 2 (BF)
Arms	20-30%	60%
Landing gears	100% Solid	60% (truss only)
Body panels	20-30%	20%
Total weight	450 g	443 g
Weight difference	—	-7 g (-1.5%)

Frame Design

The quadcopter frame followed standard X-configuration architecture with 450 mm motor-to-motor diagonal spacing. It consisted of a modular design of arms, central body plate, and landing gear separately printed. The constraint in the volume of the printer builds necessitated this modularity, and allowed optimisation of the components independently.

The major design considerations were:

1. Integrated motor mounts in arm assemblies
2. Central electronics bay with ventilation channels
3. Truss-structure landing gears (Frame 2 optimization)
4. Mounting provisions for 12-inch propellers and AS2317 brushless motors
5. PIXHAWK 6C flight controller mounting with vibration isolation
6. Raspberry Pi single-board computer housing with cooling airflow

Manufacturing Parameters

Aion Mk3 FDM 3D printer was used in manufacturing of all the components. The generic ASA processing parameters of slicer software were used. Table 1 is a summary of the manufacturing parameters.

Variable Infill Strategy

Two frame iterations were made using alternative infill strategies in order to explore the effects of optimization. Table 2 will describe the distribution of the infill density in each frame.

- *Frame 1 (White Frame - WF):* Inflammable landing gears constructed using the material of 100 per cent. solid infill to enhance maximum impact resistance. The bodies and arms were of regular density of infill.
- *Frame 2 (Blue Frame - BF):* he causes of 60% infill to Arms was because of high bending loads during flight. Landing gears used the design of truss structure with 60 percent infill containing the load-bearing truss structural members; hollow areas contained 20 percent infill. Body panels utilized 20 per cent infill as low stress parts. This strategic material placement realized 7g weight loss coupled with the focus of strength on vital load routes.

Layer Orientation Strategy

When landing, components of landing gear undergo an impact loading at right angles to the longitudinal axis of the thickness. In order to take advantage of the anisotropic strength of FDM components, the landing gears were printed flat on the build plate with the lines of the layers running cross-grain. This arrangement aligns the stronger in-plane direction with the strongest impact forces so as to maximize impact resistance [6].

Conversely, the printing of arms was done vertically so that the layers were oriented along the longitudinal axis to offer the highest stiffness to the bending forces of the propeller thrusts. The acetonic bonding reaction is a crucial novelty in this research, as it allows a monolithic structure to be formed and structural geometric distortion due to thermal warping is also corrected.

Acetone Fusion Welding Process

Components in print were washed off to get any surface contamination or support material. Mating surfaces were checked on the accuracy of dimensions and the degree of warping.

- *Surface preparation:* Printed parts were washed so as to eliminate any surface dirt or remnants. Mating surfaces were checked in terms of dimensional accuracy and warping of magnitude.
- *Two-stage acetone application:* The acetone usage was a bi-method procedure of the perfect dissolution of polymer:
  - *Method 1:* Heavy Initial Application: Acetone was applied using the finger (with the assistance of protective nitrile gloves) in order to form a thick layer of the solvent on the surfaces of mating. The original use was good surface dissolution of polymer.
  - *Method 2:* Comprehensive Coverage: Acetone was applied with a brush to all bond surfaces to have even penetration of the solvent and full coverage.

Warping Mitigation During Bonding

The non-planar components that were produced by ASA thermal warping during printing were especially apparent in large parts like landing gears and body plates. Conventional methods demand that the process of warping is removed by utilizing heated chambers. In this study, a different approach was formulated; that is, to correct the warping in the bonding process.

Procedure

1. Components were placed on a flat plate of granite which was to be used as geometric reference immediately after the application of acetone.
2. The micrometer verification was used to check parts to get proper spacing and orientation.
3. On top of the assembly some heavy weights of steel (about 5–10 kg altogether) were put.
4. The assembly was left undisturbed to allow the evaporation of all the acetone (4–6 hours at least).
5. Mechanism: Gravity acting together with a force of weight and polymer of acetone softened allowed overcoming residual stresses of warping. Conformity of parts to the geometry of the flat reference surface happened as acetone evaporated and the polymer solidified instead of their original deformed shape.

Critical Importance

In the case of UAV it is the motor mount coplanarity that has a direct impact on the flight stability. The misalignment introduced in the warping leads to the unevenly distributed thrust and instability in the control process. The surface plate bonding technique also attained motor mount coplanarity at the level of measurement (±0.1 mm) [8].

The alignment of surface plates is documented in Figure 1 and weight application in Figure 2 when curing is taking place.

Figure 1 documents the surface plate alignment process, while Figure 2 shows weight application during curing.

Figure 1. Parts positioned on flat reference surface during acetone bonding. Micrometer verification ensures geometric accuracy despite ASA thermal warping.


Figure 2. Masses that are added to the acetone evaporation in order to counter thermal warping forces and to ensure that the surface is flat during interdiffusion of the polymer chains. Curing time: 4–6 hours minimum.

Testing Protocol

These two frames were both tested in the air. The procedures involved in testing included:
1. Hover stability test at altitude of 2m.
1. Performing controlled maneuvers of takeoffs and landings.
2. Forward, lateral and combined translation.
3. Altitude hold performance assessment.
4. Cases of emergency landings (battery simulation of drained batteries)

The duration of flight, structural integrity and impact events during testing were recorded. None of the pre-flight destructive testing or formal mechanical characterization were carried out; all the performance data are based on operational use.

RESULTS

Frame 1 (WF) Performance

Frame 1 (White Frame) had good starting flight characteristics in the form of an excellent hover and control. Table 3 summarizes the completed frame specifications and the performance.

The plane had a successful flight of nine journeys. On the tenth of flights, a power malfunction in the battery system led to premature loss of power, leading to a hard landing with an estimated landing velocity of 2–3 m/s. This effect led to structural failure. Failure analysis indicated that there were damages at major joints. The failure location is recorded in Figure 3.

Discussion

The 100 percent infilled solid landing gears introduced a lot of weight (when compared to Frame 2 optimization) but there was no equivalent strength advantage in the limited critical failure points. The extra 7 grams of mass decreased the flight endurance and solid infill did not protect the structural failure during hard landing. This implies that homogenous high-density infill is inefficient material utilization.

Frame 2 (BF) Performance - Optimized Design

Frame 2 (Blue Frame) had design optimizations through Frame 1 performance analysis. The idea of variable infill strategy, landing gears as truss structures and optimization of layer orientation were put in place. Table 4 gives a performance summary.

Table 3. Frame 1 (White Frame) performance summary.

Parameter	Value
Total Mass	450 g
Landing Gear Design	100% solid infill
Arms Infill	20-30%
Successful Flights	10 flights
Cumulative Flight Time	100–120 minutes (est.)
Failure Event	Flight 10 (approx.)
Failure Cause	Hard landing (battery issue)
Failure Mode	Structural damage
Status	Non-operational

Figure 3. Structure frame 1 (White Frame) structural failure after hard landing on flight 10. The use of solid infill landing gears (100% infill) did not provide any benefit in terms of weight increase and reduction in critical load paths.

Frame 2 has already made more than 40 successful flights and has had a number of landing impacts of similar or more severity than the one that killed Frame 1. No structural degradation, crack initiation or separation of joints have been noticed.

Simultaneous reduction in weight and improvement of performance were realised with the variable of infill strategy. Weapons with 60 percent infill showed no bending and deformation with flight loads. The structure of landing gears truss with selective 60% infill in load bearing members gave sufficient impact resistance and minimized unnecessary weight as compared to Frame 1 which had solid infill structure. Figure 4 illustrates the Frame 2 weight reading which has been completed, and Figure 5 records the performance of operation. Figure 6 presents a flight test montage demonstrating Frame 2 operational performance across various test programs, and Figure 7 shows the flight sequence during one of the test sessions including takeoff, hover, and maneuver, with no visible deformation or joint separation observed in the solvent-welded ASA polymer structure.

Table 4. Frame 2 (Blue Frame) performance summary.

Parameter	Value
Total Mass	443 g
Weight vs Frame 1	-7 g (-1.5%)
Landing Gear Design	Truss structure, 60% infill
Arms Infill	60%
Body Infill	20%
Successful Flights	40+ flights (ongoing)
Cumulative Flight Time	400-500+ minutes (est.)
Impact Events	Multiple hard landings survived
Structural Failures	0
Status	Fully operational

Figure 4. Total assembly weight Frame 2 (Blue Frame): 443 grams. Variable infill strategy (60% arms/landing gears, 20% body) had 7g reduction in weight over Frame 1 whilst still being structurally intact after 40+ flights.

Figure 5. Frame 2 when it is at flight. Flown successfully 40+ times with no structural failures and showed variable infill, layer orientation and acetone bonding strategies to be effective.

Figure 6. Flight test montage put together of various test programs demonstrating Frame 2 (Blue Frame) operational performance. The sustained structural integrity of acetone-welded ASA polymer joints through repeated dynamic loading is confirmed by sequential frames taken out of flight videos.

Table 5. Comparative performance: Frame 1 vs Frame 2.

Parameter	**Frame 1 (WF)**	**Frame 2 (BF)**
Weight	450 g	443 g
Landing gear infill	100% solid	60% (truss)
Arms infill	20-30%	60%
Body infill	20-30%	20%
Successful flights	10	40+
Flight time	100-120 min	400-500+ min
Structural failures	1 (catastrophic)	0
Operational life	—	4× longer
Weight efficiency	Poor	Excellent

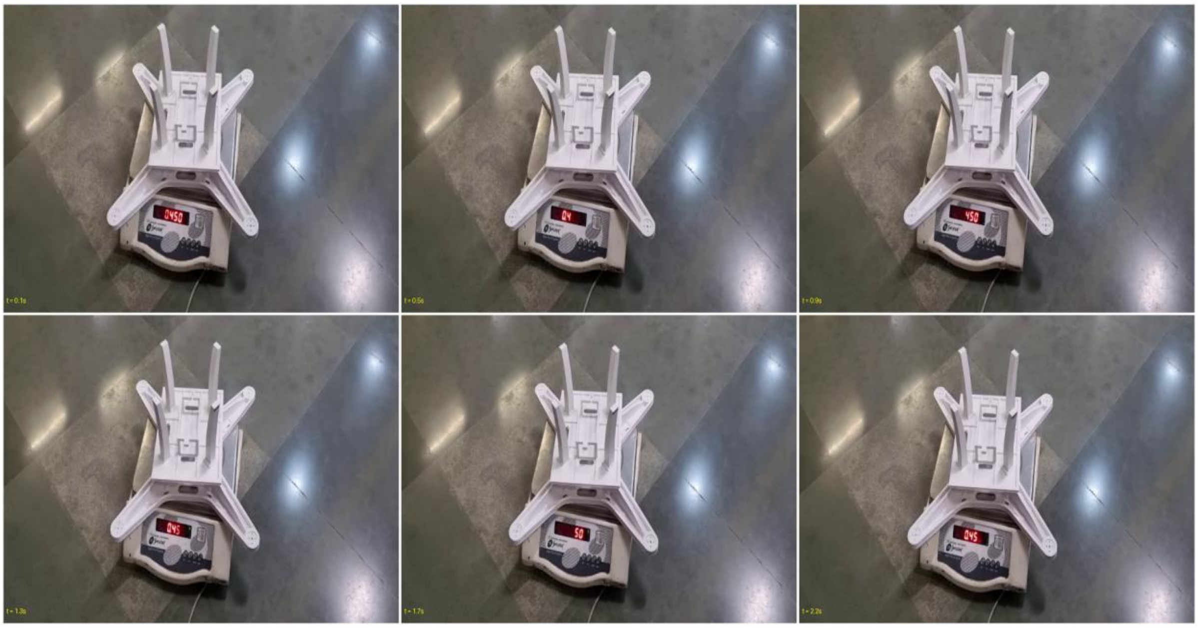

Figure 7. Flight sequence in one of the test sessions including takeoff, hover and maneuver. No visible deformation or joint separation observed in the solvent-welded ASA polymer structure during dynamic loading.

Comparative Performance Analysis

Table 5 presents side-by-side comparison of Frame 1 and Frame 2 performance metrics.

Key findings from comparative analysis:

- Frame 2 achieved 1.5% weight reduction (7g) through optimized design
- Operational life increased fourfold (10 flights to 40+ flights)
- Cumulative flight time increased approximately fourfold
- Variable infill demonstrated superiority over uniform solid infill
- Strategic material placement (60% in arms/landing gears) provided adequate strength
- No acetone bond failures observed in either frame
- Warping mitigation strategy successfully produced dimensionally accurate assemblies

Acetone Bonding Quality

Both frames had no acetone bond failure in testing. The visual inspection of the two frames after they had been flown showed no cracks, delamination or separation at bonded interfaces. The monolithic structure behaviour ensured effective polymer chain interdiffusion across the bond lines.

The surface plate bonding method was able to overcome the problem of geometric distortion due to thermal warping. Motor mount coplanarity measurements (through dial indicator) were found to be within the error of ±0.1 mm which is in tandem with flight stability requirements. The added weight application technique and flat reference surface technique were found to be effective in the process of creating accuracy in the assembling of the non-planar printed parts.

DISCUSSION

Solvent Bonding Mechanism and Polymer Chain Interdiffusion

At the surface the amorphous SAN matrix phase of ASA polymer will be dissolved in acetone forming a mobile polymer-solvent solution at the interface. The mechanism of dissolution is as follows: acetone molecules enter between the chains of polymer, conquering secondary intermolecular forces (van der Waals and dipole-dipole interactions) and raising the mobility of the chain segments

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[4]. When two acetone-treated ASA surfaces come into contact, polymer chains on both sides of the interface undergo interdiffusion at the interface by reptation dynamics the tube-like diffusion model of the movement of polymer chains in entangled systems [4].

The volume fraction of polymer at the interfacial zone also increases with time as acetone evaporates during 4–6 hours curing process. The density of the chain entanglement increases until the material is no longer a polymer solution, and still has molecular connectivity across the initial interface. The bond region produced is not discrete, the polymer structure changes gradually between the different components.

This cohesive bonding at the molecular level is completely different to the adhesive joining which consists of the foreign material filling the gap between the surfaces of the polymer. Literature claims bond strengths of 60 and 85 percent of bulk ASA polymer of properly done joints solvent weld bond strength, where an order of magnitude higher than that of typical adhesive bond strength, is needed [4]. The fact that there were no bond failures in this experiment even after several high-energy landing impacts, proves that acetone solvent welding is effective in structure application of ASA polymer.

Indeed, as was previously shown in a study by the current authors [13], 3D-printed polymers (structures) were tested as robotic chassis components, showing the wide range of application of FDM-processed polymers in the structural implementation of a variety of application areas.

Post-Print Warping Correction via Solvent-Induced Polymer Plasticity

The large coefficient of thermal expansion in ASA cause residual stresses when cooling down to ambient temperature after melt processing temperature (around 245–250 oC). Non-uniform shrinkage (geometric distortion), which is caused by asymmetric cooling gradients in parts that are large in FDM, is evident as geometric distortion. This is solved using conventional methods in which polymer processing is done using heated chambers (50-70 oC ambient temperature) and high bed temperature (100–110 oC). Heated chambers however, increase cost and complexity of equipment.

This work proves the existence of another paradigm accept warping in the FDM processing and fix geometry in the post-print solvent bonding. The softened polymer in the bonding zone using acetone offers a window of chain mobility on which stresses remaining in the residual can be relieved with the help of external force (gravity and weights applied). The geometric reference of the flat granite surface plate is to guarantee that the corrected parts are true to design as opposed to their distorted as-printed geometry..

Polymer Science Basis: Acetone uptake within the amorphous ASA matrix decreases the effective glass transition temperature of the surface layers and transiently transforms the solid glassy polymer into a rubbery polymer with much improved chain segment mobility [4]. When the polymer is under applied loading, it experiences viscoelastic deformation and the remaining thermal stresses are removed. The acetone is desorbed, and Tg picks up, and the polymer hardens in the geometricalally corrected form.

Variable Infill as Polymer Volume Fraction Optimization

The principle of structural optimization consists of the idea that one should locate material based on the location of stress. Homogenous infill density is an inefficient use of polymer: the areas in which stress is low have surplus polymer volume and the areas in which stress is high may not be sufficiently reinforced [6, 7, 9].

The variable infill strategy of Frame 2 is a spatial polymer volume fraction optimization. Compression of the arms to high bending loads was infilled 60 percent, which gave sufficient effective stiffness by polymer content in the cross-section. Infill was also done to landing gear truss members subject to concentrated impact loads, at 60%. In low-stress areas, body panels used little 20% infill minimizing the polymer mass where structural demand is minimal [6].

The strategic polymer distribution minimized the overall weight of the frame by 7 g and increased the overall lifespan of the opera four times. On the other hand, the solid landing gears (100% infill) in Frame 1 are a waste of polymer material: the extra weight did not increase the endurance of flight, but instead it did not diminish the structural integrity. The failure mode in Frame 1 indicates that the uniformity of polymer volume concentration fails to overcome the geometric discontinuity stress concentrations - reinforcement of the important load paths is more effective than blanket density enhancements [7].

FDM Polymer Anisotropy and Layer Orientation Strategy

FDM-processed polymers exhibit anisotropic mechanical properties due to the layer-by-layer melt deposition process. Tensile strength parallel to layer planes exceeds perpendicular (inter-layer) strength by 30–50% in amorphous thermoplastics such as ASA [6, 7, 10]. This anisotropy arises from limited polymer chain reptation across layer interfaces during the brief thermal contact period between deposited beads, compared to full chain entanglement within deposited tracks where chains remain in the melt state longer.

Frame 2 landing gears were printed flat on the build plate, orienting deposited layers across the thickness direction. Impact forces during landing act perpendicular to the landing gear thickness, thus loading primarily in the strong in-plane direction of the FDM polymer laminate rather than the weak inter-layer direction. This orientation strategy aligns polymer chain continuity with the primary loading direction. The success of Frame 2 in surviving multiple hard landings—compared to Frame 1's failure—partially attributes to this layer orientation optimization. Quantification of the anisotropic strength benefit via controlled mechanical testing of differently oriented ASA specimens is recommended for future work.

Monolithic Polymer Structure Benefits

The solvent-welded ASA frames are monolithic polymer structures that do not have distinct molecular load paths and a discontinuity at a joint. This offers a number of benefits as compared to polymer assemblies joined mechanically:

Elimination of Stress Concentrations: Stress concentrations of bolt holes are localized with local intensification factors of 213× [5, 13]. In monolithic polymer structures, there are no fastener holes, so the loads are distributed in polymer chain networks.

- *Weight reduction:* Metal (M3 bolts, nuts, washers) fasteners add 1525 g to the normal assemblies. The presence of acetone bonding completely removes this parasitic non polymer mass.
- *Structural rigidity:* Joint Compliance Connections in bolted polymer connections permits microscopic relative motion between components, and decreases the overall stiffness of the structure. Polymer structures are monolithic and therefore do not have joint compliance, which offers higher rigidity [5].
- *Trade-off:* Permanent assembly eliminates the ability to replace components, as it cannot be disassembled. Damaged areas need a complete replacement of structure and not a replacement of parts. This trade-off is reasonable in the cases where the structural reliability is of paramount significance.

ASA Polymer Selection: Comparative Thermoplastic Analysis

ASA selection features give certain benefits of polymer properties in structural outdoor:

- *UV photostability:* The acrylate rubber phase does not have carbon/carbon double bonds that the butadiene rubber phase of ABS has. These bifunctional bonds can be used as chromophores in radical chain reactions with UV-initiation causing chain scission and crosslinking the main photodegradation processes of ABS. They are not found in ASA which gives them about ten times better weathering resistance [2, 3].
- *Thermal properties:* ASA's of 100°C exceeds that of PET-G (80–85°C) and PLA (55–65°C), providing improved dimensional stability at elevated operating temperatures.

- *Mechanical properties:* Higher flexural modulus (2.0–2.5 GPa) compared to PET-G (2.0 GPa) improves structural stiffness critical for dynamic loading applications.
- *Solvent weldability:* The amorphous SAN matrix phase dissolves in common organic solvents (acetone, MEK), enabling molecular-level polymer joining impossible with semi-crystalline or cross-linked polymers [4].
- *Cost:* ASA filament costs approximately $30–35/kg compared to PET-G's $25–32/kg, representing a modest premium for substantially improved outdoor durability.

Design Guidelines for FDM-Processed Polymer Structures

The findings of this research and the guidelines to be followed in the design of structural FDM polymer are as follows:

1. *Variable polymer volume fraction:* Match infill density to local stress distribution. High-stress regions require 50–60% infill; low-stress regions can use 20% for polymer mass savings [6, 7].
2. *Layer orientation:* Exploit FDM polymer anisotropy by orienting parts to align the stronger in-plane direction with primary loading. Avoid loading perpendicular to layer interfaces [7, 10].
3. *Solvent bonding:* For amorphous thermoplastics, solvent welding provides superior structural continuity compared to mechanical fastening through polymer chain interdiffusion [4].
4. *Warping correction:* Post-print geometric correction via solvent-induced polymer plasticity can substitute for heated build chamber requirements in high-shrinkage polymers.
5. *Polymer selection:* Match thermoplastic properties to application environment—UV exposure, operating temperature range, impact loading requirements, and solvent compatibility for joining [2, 11].

Limitations

This research paper has a number of limitations that need to be noted:

- *Sample size:* Two frames only under test. Uncharacterized statistical variation in material properties, print quality and loading scenarios. More samples needed to come up with strong conclusions.
- *Quantitative mechanical testing:* No formal tensile test, flexural test or impact test. Directly not measured strength. Performance evaluation depends solely on the use in real service as opposed to laboratory experimentation.
- *Environmental control:* Frames so that days were printed with what might have been different conditions (ambient temperature, moisture content of filaments, adhesion of the bed). Process variables that are not under systematic control or record.
- *Load measurement:* Impact Forces in landings were estimated and not being measured through instrumentation. The real loading magnitude is unclear.
- *Long-term durability:* Frame 2 has been in operation about 2-3 months. Prolonged durability such as UV decadence, thermal cycling and fatigue that are yet to be evaluated. Outdoor exposure on a multi-year basis in order to have full weatherability assessment..
- *Bonding process standardization:* Not fully quantified: Acetone application technique (amount, duration, coverage). Process is manipulated by operator skill as opposed to parameters.

Future Work

Various research directions may be the continuation of this work:

1. *Quantitative testing on bond strengths:* Lap shear, peel and tensile tests of acetone welded specimens to determine design allowables.
2. *Optimization parameter of acetone application:* The solvent concentration, application method and cure time were varied systematically.
3. *Variable infill, Finite element analysis:* Optimization of infill distribution with prediction.
4. *Long term UV testing:* 6-12 months outward weathering, where mechanical property testing is done periodically.

5. *Alternative solvent systems:* MEK, dichloroethane and cyclohexane as an alternative solvent in ASA bonding.
6. *Automated bonding process:* Development of consistent acetone application to manufacturing.
7. *Topology optimization:* Computational design of variable density pattern of infills of stress fields.
8. *Comparative benchmarking:* Performance comparison to the performance of carbon fiber composite and aluminum frames.
9. Other thermoplastics Extension to ABS, polycarbonate and Nylon solvent bonding.
10. *Hybrid structures:* Acetone bonded and mechanical held joints used together to achieve the optimum assemblies.

CONCLUSIONS

This investigation proves that the option of acetone solvent welding is feasible as one of the polymer joining methods to join the monolithic ASA frames with utilised variable infill density and layout of layers. Key findings include:

1. Via acetone solvent welding, monolithic structures of ASA polymer were successfully prepared by interfacial chain interdiffusion, and none of the structures were broken by 40+ flights under dynamic loading.
2. Accurate assembly (within +0.1 mm coplanarity) of thermally warped ASA prints using a novel process called post-print warping correction, which takes advantage of the acetone-induced plasticity of polymers in the presence of a flat reference surface during the curing process was realized, and this technique does not require heated build chambers.
3. Reduction in weight (1.5%), through variable infill optimization (60 percent in high-stress arms/landing gears, 20 percent in low-stress body panels) was obtained with polymer volume fraction concentrated in load-bearing directions.
4. The optimized design was found to have four times higher operational life (40+ flights vs 10+ flights) at 7 g lighter than unstrategic polymer placement, and so it was established that high-density infill that is distributed uniformly is not as effective as strategic polymer distribution.
5. Solid 100% infill landing gears (Frame 1) were of no benefit compared to 60% infill truss structure (Frame 2), which is ineffective use of polymer.
6. The use of Layer orientation strategy (printing landing gears in a flat manner to align solid in-plane polymer direction with impact loads) enhanced crash survivability.
7. Monolithic polymer structures welded with solvents created no concentrations of stress, and no parasitic metal mass, and enhanced the structural rigidity.

Recommendations for FDM-Processed ASA Polymer Structures:

- Variable infill density is used to optimize spatial polymer volume fraction based on the distribution of stress.
- High stress polymer components (arms, landing gear load paths) 60% minimum infill.
- Minimise infill to one-fifth of low-stress zones in optimisation of mass polymer.
- While orient FDM components take advantage of anisotropic polymer behavior, strong in-plane direction is oriented so as to be aligned with primary loading.
- Use surface plate + weight correction method of post-print warping when bonding acetone solvent.
- Mechanical fastening should be replaced with acetone solvent welding of amorphous thermoplastic structural joints.
- Minimum cure time of full solvent desorption and reconsolidation of polymers should be 4-6 hours.
- ASA polymer has good viability in structural out-of-door use with good FDM processing plan and solvent bonding method. The price (cost) of about 30–35 dollars per unit structure and the manufacturing time of 24–30 hours printing and 4–6 hours bonding/ assembly make it cost-effective in offering polymer processing solutions to research platforms, student competitions and low volume structural uses.

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