



# Error as Form: Exploring the Aesthetic and Structural Potential of Deformation in Digital Fabrication

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## Abstract

**Background** While digital fabrication primarily focuses on precise replication, its potential for sculptural exploration through deformations remains largely underexplored. Recent studies suggest embracing technical glitches as creative elements, and this study builds upon that perspective. Introducing the Error-Driven Design Fabrication Workflow, this research integrates deformations as an active component of the design process rather than unintended flaws.

**Methods** To explore intentional deformations in 3D printing, this study examined three key variables: structural instability due to gravity, retraction effects, and curvature-induced deformation. The digital model was systematically adjusted, followed by an iterative printing process to observe and analyze the resulting deformation patterns. Rather than treating these distortions as mere errors, the study implemented an iterative reverse modeling feedback workflow, reframing unintended deviations as sculptural elements within the design process.

**Results** The experimental analysis reveals that deformations emerging during fabrication broaden the scope of sculptural exploration. Gravity-induced instability generates collapse patterns, introducing new possibilities for form development. Retraction effects disrupt filament connectivity, resulting in intricate, web-like textures that can be utilized as surface design elements. Increased curvature leads to layering instability, shaping distinct geometric patterns and influencing overall structural articulation.

**Conclusions** By shifting the perception of deformations from errors to design tools, this study presents an alternative fabrication approach that prioritizes sculptural exploration over rigid precision. Through iterative feedback, deformations are incorporated into the design process to expand formal possibilities. Future research will focus on real-time feedback integration and extend this approach across varied materials and fabrication techniques.

**Keywords** Error-driven Design, Digital Fabrication, Generative Deformation, Computational Workflow

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## 1. Introduction

Digital fabrication has focused on precision and repeatability, yet the sculptural potential of fabrication-induced deformations remains largely unexplored. Traditional computer-aided design (CAD) and computer-aided manufacturing (CAM) systems have prioritized efficiency and precision, often focusing on optimized production over creative inquiry (Cardoso Llach, 2015). Despite their advantages, these tools have limitations in capturing informal and subjective design elements in the creative process (Bazjanac, 1975).

Digital design often operates on a deterministic logic that prioritizes physical accuracy and total control, thereby relegating material responsiveness and contingency to a secondary role in the creative process.

In 3D printing, deviations such as retraction marks or sagging are usually minimized as flaws, although they can also generate sculptural possibilities. In this study, error is defined not as a malfunction but as a deliberate departure from standard production norms. Even predictable deviations—such as gravitational sagging—are reinterpreted here as productive catalysts intentionally integrated into the design process. Unlike precision-focused approaches, this study proposes the Error-Driven Design Process, which integrates deformations into sculptural exploration.

The Error-Driven Design Process treats deformation not as a defect but as an essential dialogue between digital intent and material behavior. Through iterative feedback, these deviations are refined into new sculptural forms.

This study focuses on three key research directions.

- 1) **Intentional Error Design:** In Geometric Processing, design parameters (thickness, spacing, curvature) are adjusted to induce controlled deformations.
- 2) **Exploring Output Discrepancies:** In Fabrication, deformations are recorded and analyzed as sculptural opportunities.
- 3) **Iterative Feedback through Reverse Modeling:** Deformation data is reverse modeled into digital parameters to generate new iterations.

Through this iterative process, the study moves beyond the precision-driven CAD-CAM paradigm, proposing a design methodology that employs deformations as creative tools. By reconsidering the discrepancies between digital modeling and material output, this study explores fabrication inconsistencies as sculptural experimentation to expand formal possibilities.

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## 2. Related Work

### 2. 1. Theoretical Perspectives on Error in Design

In the process of design and making, *error* is often understood not as a failure, but as a moment where material agency and designer intention intersect—a point that reveals the creative potential inherent in digital fabrication. Rather than treating error as a flaw to be corrected, this perspective considers it a productive force that can shape design outcomes in unexpected ways.






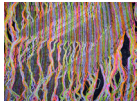
Through his notion of the anti-aesthetic, Hal Foster (1983) challenges traditional ideas of beauty, favoring process and experiment over polished perfection. The glitch, described by Rosa Menkman (2011) as both destructive and generative, emerges as a rupture that opens space for new forms to take shape—an error that becomes a vital means of generating artistic meaning.

Drawing from new materialist thought, Jane Bennett (2010) reminds us that materials possess their own agency, refusing to simply yield to human intention and sometimes intervening or even transforming a designer’s plans. Tim Ingold (2013) also suggests that making is not a one-way act of imposition but an ongoing dialogue between human intention and the flows of materials and forces. These ideas resonate in the discourse of post-digital fabrication, which calls for a renewed appreciation of error, uncertainty, and the unruly nature of materials—an invitation to embrace the imperfect as part of the creative process.

## 2. 2. Comparative Case Analysis of Error Engagement

Depending on how the concept of error is framed, this section analyzes selected cases of creative work. Two criteria guide this analysis: (1) whether the error emerged naturally, and (2) to what extent the creator controlled or adjusted that error. These criteria distinguish between approaches that embrace error as a chance occurrence and those that structure it as a deliberate design variable. Table 1 classifies six cases based on the way error intervenes in the creative process. Each case illustrates how error is harnessed within the act of making, serving as a foundation for situating this study within its broader context.

Table 1 Design Cases Classified by Error Involvement

Error Mode	Title/Creator	Image	Contribution
Natural Indeterminacy	Spider, Web Pavilion/ Tomas Saraceno		Explores spatial complexity through emergent patterns.
Systemic Glitch Aesthetic	The Glitch Moment/ Rosa Menkman		Frames encoding errors and system crashes as rupture aesthetics.
Material Destruction as Form	Smoke Series/ Maarten Baas		Converts destructive burning into a finishing technique.
Embraced Misprinting	3D Ceramic Printing/ Alterfact Studio		Uses printing failure and collapse to justify unique sculptural forms.
Controlled Deviation	FreeD/ Zoran & Paradiso (MIT)		Balances human control and automated constraints in shaping outcomes.
Randomized code injection	Glitch Knitting/ Open Source		Introduces code-level randomness to visualize algorithmic instability in generative textile forms.

The four cases at the top of the table (Saraceno, Menkman, Baas, and Alterfact) align with an approach that accepts error as an external factor or chance occurrence, interpreting it as an aesthetic or conceptual resource. These creators reveal errors in its raw form or incorporate traces of destruction and instability into their work.

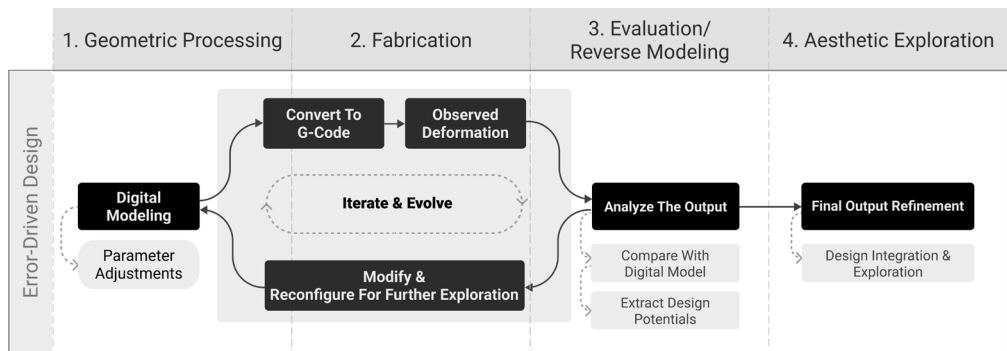
By contrast, the two cases at the bottom (FreeD and Glitch Knitting) engage with error through detection or code-level modulation. They seek to tightly control the production process by limiting the scope of error or by deliberately inserting it, treating error as a repeatable and calculable element. While earlier studies have often focused on embracing error as an outcome or transforming unintended variations into aesthetic effects, attempts to partially control errors such as in FreeD and Glitch Knitting—have remained relatively limited. This study builds on those precedents yet also seeks to explore ways of configuring error as a repeatable condition, integrating it more deliberately into the design process.

### 3. Proposed Error-driven design Workflow

#### 3.1. Error-driven design Workflow

This study proposes an Error-Driven Workflow that considers deformations occurring during the digital fabrication process not as mere errors but as elements for exploring new forms. Unlike conventional CAD-CAM methods, it views errors as factors that expand sculptural possibilities. In other words, it embraces the uncertainties and deformations arising during fabrication and uses them as tools for design exploration.

The proposed workflow, as shown in Figure 1, consists of four main phases, each forming a nonlinear iterative process so that fabrication functions as a system that accounts for material responses rather than mere execution.



**Figure 1** Error-Driven Design Process: An Iterative Feedback Loop Incorporating Reverse Modeling in Digital Fabrication

#### Phase1) Geometric Processing

Design variables are adjusted to anticipate deformations, generating a parametric model in Grasshopper. A controlled deformation factor is introduced to guide experimental exploration.

### Phase2) Fabrication

The digital model is translated into G-code, with printing conditions set to induce specific deformations. Support structures are omitted, allowing material responses to shape the outcome. Iterative experiments adjust parameters to amplify deformations or explore new forms.

### Phase3) Evaluation and Reverse Modeling

The printed result is compared to the digital model to interpret sculptural meaning. Scanning and measurement convert physical deviations into digital data, which are reintegrated as design variables—such as material response, structure, or texture—turning deformation into a design tool.

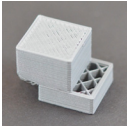


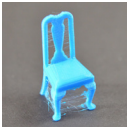
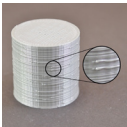

### Phase4) Aesthetic Exploration

Iterative experiments analyze printed patterns to explore sculptural potential. Reverse Modeling integrates deformed forms into the design, enabling further manipulation for expanded formal exploration. Finally, the design applicability of deformations is evaluated, incorporating them as generative tools for form development.

## 3. 2. 3D Printing Errors and Experimental Variables

Various types of errors can occur in the 3D printing process. Based on previous research and case analysis, 3D printing errors have been broadly categorized into two groups, as shown in Table 2.

Table 2 Classification of 3D Printing Errors (Adapted from Simplify3D, n.d.)

Category	Error Type / Description	Image
Uncontrollable Errors (Caused by hardware issues; requires maintenance or part replacement)	1) Layer Shift Misalignment due to sudden movement or external impact.	
	2) Under-Extrusion Gaps between layers due to insufficient extrusion.	
	3) Belt Misalignment Deformation caused by a loose or misaligned belt.	
Controllable Formative Errors (Can be resolved by adjusting print conditions and settings)	1) Stringing or Oozing Thin filament residue due to excessive extrusion.	
	2) Blobs and Zits Surface protrusions when extrusion starts/stops.	
	3) Small Features Not Printed Structures smaller than the nozzle failing to print.	

This study examines three deformation factors—independent of hardware issues—through experimental analysis, adjusting design and printing parameters as outlined in Table 3.

Table 3 Experimental Variables and Design Considerations

Variable	Definition	Adjustment Method
Gravity-Induced Instability	Deformation/collapse increases as thickness decreases..	Adjust thickness – test specific range.
Retraction by Spacing	Filament retraction occurs with wider spacing.	Adjust spacing – test gap variation.
Curvature-Induced Deformation	Adhesion fails when amplitude exceeds a threshold.	Adjust amplitude – vary values.

### 3. 3. Evaluation Criteria for Aesthetic Utility

To make the assessment of deformation outcomes transparent and repeatable, this study adopts a theory-grounded rubric for aesthetic utility—the degree to which an induced deformation both (a) enriches perceptual qualities and (b) remains compatible with functional or structural intent. Table 4 summarises the three sub-criteria and the 0–5 scale used in this rubric.

Table 4 Aesthetic Utility Evaluation Rubric

Criterion	Scale (0 – 5)	Operational description
Visual coherence	0 = fragmented · 5 = highly unified	Consistency of proportion, rhythm, and overall legibility after deformation.
Perceived novelty	0 = mundane · 5 = highly original	Extent to which the form elicits surprise or freshness relative to conventional prints.
Structural integration	0 = mundane · 5 = highly original	Degree to which the deformation maintains or enhances load-bearing, assembly, or ergonomic requirements.

The three criteria are adapted from established discussions of unity–novelty balance and functional fit in product-aesthetics research (Hekkert, 2006; Veryzer & Hutchinson, 1998). In the exploratory phase reported here, scores were assigned internally by the authors to guide iterative tuning of print variables. A comprehensive expert-panel validation and inter-rater reliability analysis is planned for future work.

By specifying measurable sub-criteria and a common scale, the rubric constrains purely subjective judgements and provides a reproducible framework for comparing alternative parameter sets in subsequent studies.

## 4. Workflow Implementation

### 4. 1. Geometric Processing

In the first phase, a parametric digital model is created in Grasshopper, adjusting experimental variables to induce deformations. Figure 2 shows the Grasshopper node structure used in the experiment.



To directly observe deformations, the Convert to G-code step is executed without support structures, ensuring that the printed object relies solely on its inherent structural stability. This setup allows deformations to emerge naturally through variable adjustments rather than being artificially constrained. Once printing is complete, the deformations are documented and analyzed in the Evaluation phase. The model is then modified and reconfigured to amplify specific patterns or generate new forms, followed by renewed digital modeling. Through these iterations, the deformation characteristics are systematically explored, enhancing their sculptural potential.

By continuously cycling between Fabrication, Geometric Processing, and Evaluation, this methodology transforms unpredictable deformations into deliberate opportunities for sculptural exploration.

### **4. 3. Evaluation and Reverse Modeling**

This section evaluates the outcomes of the three primary experimental variables—thickness (structural stability under gravitational influence), spacing (filament retraction effects), and curvature (amplitude-induced deformation). Using a reverse modeling methodology, each variable was incrementally adjusted based on prior observations to achieve an optimal balance between structural integrity and aesthetic potential.

The evaluation process consists of:

- 1) Independent analysis of each variable to understand its influence on material behavior.
- 2) A comparative selection matrix to synthesize results and determine the most viable parametric conditions.


#### **4. 3. 1. Structural Instability by Gravity**

This experiment analyzes structural collapse and deformation under gravity, examining the potential of controlled deformations as sculptural elements. As shown in Figure 4, thickness was systematically varied at specific intervals to observe deformation patterns and structural limitations, with the goal of identifying an optimal thickness that balances stability and sculptural expressiveness.


Variation	Thickness (mm)	Structural Stability	Deformation Patterns	Aesthetic Utility
GR_T1	1.5mm	Stable	No deformation	Low
GR_T2	1.25mm	Moderate	Minor distortion	Medium
GR_T3	1.0mm	Collapsed	Uncontrolled failure	Not usable
GR_T4	1.1mm	Partial collapse	Unstable pattern	Limited use
GR_T5	1.15mm	Borderline stability	Localized deformation	Medium
GR_T6	1.2mm	Stable	Controlled deformation	High

**Digital Modeling**



**Physical Outcome**



GR\_T1
GR\_T2
GR\_T3
GR\_T4
GR\_T5
GR\_T6

**GR\_T** (Gravity-induced Retraction\_Thickness Variation)  
**Structural Stability** (Indicates whether the structure maintained its form without collapse)  
**Aesthetic Utility** (Evaluates how useful the resulting patterns are for artistic purposes)

**Figure 4** Transformation of Structural Stability with Thickness Variation

The experiment showed that when thickness was reduced below 1.0mm (GR\_T3), structural collapse occurred, compromising practicality. In contrast, GR\_T6 (6.0mm) and GR\_T2 (2.0mm) maintained stability while forming distinct sculptural patterns (Figure 4). Though both conditions provided similar stability, their pattern formation differed. GR\_T6 created sharp deformation patterns, allowing for intricate expression, while GR\_T2 exhibited minimal deformation but a uniform and refined pattern.

This suggests design applicability, providing criteria for selecting the appropriate thickness based on design objectives.

Meanwhile, GR\_T1 (1.5mm) demonstrated high stability but lacked deformation, making it inconsistent with sculptural goals. This indicates that a stability-focused approach may limit sculptural diversity.

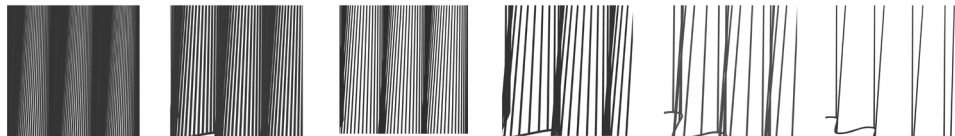
In conclusion, GR\_T2 (2.0mm) and GR\_T6 (6.0mm) balanced stability and sculptural potential, with their pattern differences suggesting diverse possibilities in sculptural design. These findings serve as a valuable reference for future design applications.

### 4. 3. 2. Retraction by Spacing

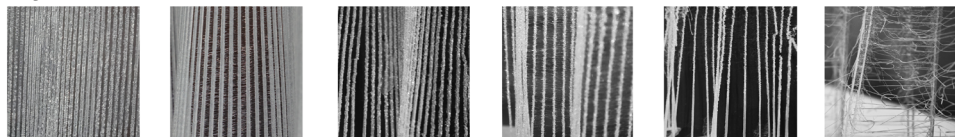
The experiment examines how filament spacing affects retraction patterns and sculptural properties, exploring their design potential. As shown in Figure 5, spacing was systematically adjusted to observe pattern formation and texture characteristics.

Variation	Spacing (mm)	Pattern Density	Formation Characteristics	Aesthetic Utility
RT_S1	1mm	Very High	Dense chaotic webbing	Surface texture possible
RT_S2	1.5mm	Very High	Irregular filaments	Surface texture possible
RT_S3	2mm	High	Fine web-like structures	Suitable for porous textures
RT_S4	3mm	High	Chaotic, semi-linear patterns	Rough texture applications
RT_S5	5mm	High	Unstable filament networks	Improved texture control
RT_S6	15mm	High	Irregular, semi-connected webbing	Improved texture control
RT_S7	18mm	Medium-High	Fine, interconnected filaments	Suitable for delicate designs
RT_S8	25mm	Medium	Semi-linear, controlled texture	Balanced texture utility
RT_S9	29mm	Medium	Organic filament alignment	Useful for organic connections
RT_S10	46mm	Medium-Low	Thin, linear filament structures	Semi-transparent layers
RT_S11	90mm	Low	Sparse, long filaments	Layered structure utility
RT_S12	200mm	Low	Weak, directional alignment	Limited usability
RT_S13	500mm	Very Low	Nearly disconnected filaments	Structurally unstable

#### Digital Modeling



#### Physical Outcome



RT\_S2

RT\_S3

RT\_S5

RT\_S8

RT\_S11

RT\_S13

RT\_S (Retraction Test\_Spacing Variation)

**Pattern Density** (Indicates the concentration of filament structures in the output (e.g., High, Medium, Low))

**Formation Characteristics** (Describes the shape, structure, and distribution of filament patterns)

**Aesthetic Utility** (Evaluates how suitable the pattern is for artistic and design applications)

Figure 5 Transformation of Retraction Patterns with Spacing Variation

Retraction-induced web-like patterns were observed across all spacing conditions. At 1-2mm, dense patterns formed, resembling a continuous membrane, making the printed object appear flexible and elastic, suggesting potential for sculptural texture applications. As spacing increased, patterns became more fragmented and irregular. In RT\_S6(15mm) and RT\_S7(18mm), patterns appeared irregular, resembling unintended errors, yet these irregularities indicated potential for organic and natural textures. At 90mm or wider, pattern density decreased, and strands aligned linearly, exhibiting transparent layer-like characteristics.

Notably, in RT\_S12(200mm) and RT\_S13(500mm), weakly connected and directional structures emerged, suggesting potential applications in delicate sculptural elements and semi-transparent layering.

Narrower spacing resulted in denser and more flexible textures, whereas wider spacing produced weaker and more simplified structures.

These findings suggest that retraction patterns are not merely printing errors but can

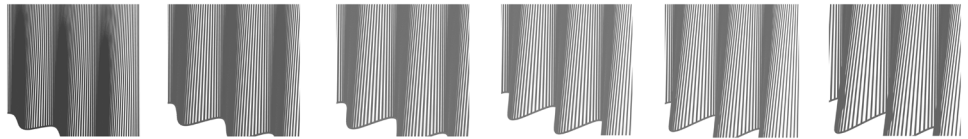
function as sculptural elements depending on spacing conditions. By adjusting spacing parameters according to design objectives, retraction patterns can be intentionally incorporated into sculptural design.

### 4. 3. 3. Curvature-Induced Deformation

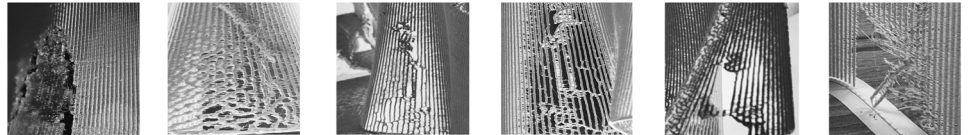
The relationship between curvature and deformation patterns was examined, focusing on its sculptural potential. As shown in Figure 6, Amplitude values were varied from 20 to 80, allowing an analysis of how curvature at specific points generates distinct textures.

Variation	Amplitude (mm)	Pattern Formation	Structural Stability	Aesthetic Utility
CU_A1	20mm	Minimal deformation	Highly stable	Low
CU_A2	30mm	Moderate wrinkling	Stable	Medium
CU_A3	40mm	Balanced wrinkling	Strong balance	High
CU_A4	50mm	Slight irregularity	Moderate stability	High
CU_A5	60mm	Excessive wrinkling	Weak balance	Limited usability
CU_A6	70mm	Severe distortion	Weak	Low
CU_A7	80mm	Over-deformed	Structurally unstable	Not usable

#### Digital Modeling



#### Physical Outcome



CU\_A1

CU\_A2

CU\_A3

CU\_A4

CU\_A6

CU\_A7

CU\_A (Curvature Test\_Amplitude Variation)

**Pattern Formation** (The type of surface deformation caused by curvature changes)

**Structural Stability** (Indicates whether the structure maintained its form without excessive distortion)

**Aesthetic Utility** (Evaluates how suitable the pattern is for artistic and design applications)

Figure 6 Transformation of Curvature-Induced Deformations with Amplitude Variation

At Amplitude values of 20–30 (CU\_C1, CU\_C2), the prints maintained structural stability, while distinct textures emerged at curvature points. These textures exhibited delicate patterns unattainable through digital modeling, making them particularly effective for sculptural applications. Additionally, flat areas retained their original form, allowing for localized deformation to introduce unique design elements. As Amplitude increased to 40–60 (CU\_C3, CU\_C5), curvature effects became more pronounced, producing stronger textures between curved sections. However, these textures often appeared overly exaggerated or irregular, reducing their practical usability in sculptural design. At Amplitude values of 70–80 (CU\_C6, CU\_C7), excessive curvature compromised structural integrity, leading to form

collapse. Under these conditions, textures became unstable and unbalanced, significantly limiting their applicability in sculptural contexts.

The findings indicate that Amplitude values between 20 and 30 (CU\_C1, CU\_C2) yielded the most effective balance of stability and textural refinement. In particular, CU\_C1 (20) and CU\_C2 (30) preserved structural integrity while generating intricate textures with high sculptural potential. In contrast, Amplitude values above 40 resulted in excessive deformation or structural failure, making them unsuitable for controlled sculptural applications.

#### 4. 4. Aesthetic Exploration

The final stage of this study explores new sculptural possibilities by combining the results from the thickness, spacing, and curvature experiments. Based on the findings from Section 4.3, three variable combinations were selected to produce physical prints, extending beyond experimental analysis to investigate design applications.

As summarized in Figure 7, these combinations were chosen to balance structural stability, sculptural applicability, and controllability. Each combination exhibits distinct characteristics suited to different design objectives.

Aesthetic Exploration Matrix				
Combination Parameters	Structural Stability	Aesthetic Utility	Controllability	Key Features
GR_T1 + RT_S13 + CU_A2	Low	High	Medium	Organic and irregular patterns, delicate textures.
GR_T3 + RT_S2 + CU_A1	High	High	Medium	Dense textures with crystal-like surface qualities.
GR_T6 + RT_S1 + CU_A2	Medium-High	High	High	Balanced stability and refined details with high overall completion.

Figure 7 Aesthetic Exploration Matrix

##### 4. 4. 1. Combination 1 (GR\_T1 + RT\_S13 + CU\_A2)

Designed to emphasize organic and irregular patterns with delicate and fragile textures. While structural stability is relatively low, the result (Figure 8) features intricate, thread-like formations that enhance aesthetic value. This combination is suitable for artistic and experimental applications where visual complexity is prioritized over structural rigidity.



Figure 8 3D-printed structure of Combination 1

#### 4. 4. 2. Combination 2 (GR\_T3 + RT\_S2 + CU\_A1)

This setup generates a dense, crystalline texture, maximizing sculptural aesthetics. While its structural stability was moderate, the unique surface texture created dynamic interactions with light and shadow, producing sculptural expressions well-suited for artistic applications (Figure 9).

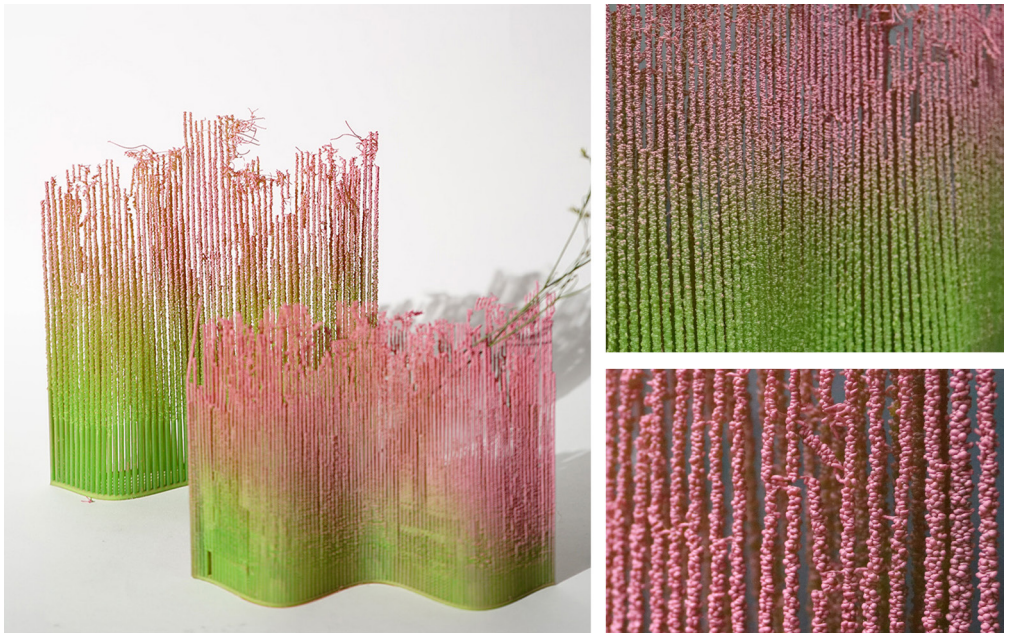


Figure 9 3D-printed structure of Combination 2

#### 4. 4. 3. Combination 3 (GR\_T6 + RT\_S1 + CU\_A2)

Achieving the best balance between stability, sculptural value, and controllability. The resulting print (Figure 10) combined refined patterns with smooth transitions, integrating structural and decorative elements, making it ideal for high-precision design applications.



Figure 10 3D-printed structure of Combination 3

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## 5. Conclusion and Discussion

This study explored the potential of utilizing deformation as a sculptural element within the framework of the Error-Driven Design Process. By manipulating three key variables—thickness, filament spacing, and curvature—the experiments demonstrated that deformations caused during the fabrication process can serve as intentional design features rather than mere anomalies.

The results showed that structural collapse due to gravitational instability occurred below a certain threshold of thickness, while repetitive and organic patterns emerged under specific conditions. Filament retraction affected the density and texture of surfaces, and curvature-induced deformations created distinct surface patterns within a usable range, though excessive curvature decreased print stability.

Beyond single-variable tests, combinations of variables enabled more complex sculptural exploration. Patterns generated from these combinations were analyzed according to three criteria: structural stability, applicability to sculptural design, and controllability. Some combinations yielded stable yet organic textures, while others enhanced surface articulation and expressive potential.

Reverse modeling was also employed to reinterpret deformation not as a byproduct but

as an integral part of the design process. This method enabled the generation of forms unattainable through conventional modeling approaches, allowing unpredictable outcomes to be reintroduced into the design workflow.

By critically addressing the deterministic logic of precision-focused digital design, this study offers an alternative framework that embraces uncertainty and deformation as essential components of creative form-making.

These findings suggest that as digital fabrication technologies continue to prioritize precision and repeatability, there is value in reframing error and deformation as opportunities for creative experimentation. The proposed approach demonstrates that digital fabrication can extend beyond replication toward sculptural inquiry through the intentional integration of error.

However, the experiments in this study were limited to Fused Deposition Modeling (FDM) and specific printing conditions. The deformation characteristics observed may vary significantly across other fabrication methods such as Stereolithography (SLA) or Selective Laser Sintering (SLS). Future research should explore alternative techniques to expand the scope of sculptural approaches and investigate new material interactions.

Additionally, while this study focused on three selected printing parameters, further investigation into factors such as nozzle diameter, filament material, layer speed, and printer type would help build a more comprehensive understanding of deformation phenomena. Continued research in this area will contribute to developing a systematic methodology for incorporating deformation as a controllable and repeatable element within design workflows.

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