

# Research on the Influence of Concrete Strength Discreteness on Structural Reliability by 3D Printing

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## Abstract

3D-printed concrete is revolutionizing the construction industry through its mold-free manufacturing and high design flexibility. However, its performance variability-caused by factors like manufacturing processes, material properties, and environmental conditions-often leads to structural weaknesses, anisotropic behavior, and unconventional failure modes. While existing research employs discrete medium simulations, quantifying the impact of multi-source variability on structural reliability remains a critical challenge. To address this, this study establishes an analytical framework of "multi-source etiology-reliability impact," aiming to uncover underlying mechanisms. The findings will provide theoretical foundations for developing probabilistic design and code systems for 3D-printed concrete structures.

## Keywords

3D Printed Concrete; Multi-source Genesis; Discreteness; Reliability.

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## 1. Introduction

In the context of intelligent and sustainable development in the construction industry, 3D-printed concrete (3DPC) technology has emerged as a promising new development opportunity. However, its structural reliability is subject to complex influences from multiple factors including temperature, rheological properties, and pore gas. As illustrated in Figure 1, discrete factors such as printing paths, interlayer interfaces, and material property fluctuations exert more significant and multifaceted impacts on reliability. This indicates that traditional structural design theories based on homogeneous materials, which fail to adequately account for these inherent discrete characteristics, will fundamentally challenge structural reliability and directly compromise safety margins.

While current domestic and international research has improved printing performance through material modification and process optimization [1], and explored material-level enhancements and phenomenon recognition via multiple approaches, there remains insufficient in-depth discussion on how strength variability affects overall structural design theory and reliability assessment. Existing studies predominantly focus on improving single performance indicators, lacking systematic analysis of variability sources and comprehensive evaluation criteria that holistically assess the impact of variability on structural safety.

This study systematically investigates the multi-source causes of 3DPC strength discreteness and analyzes its impact mechanisms on structural reliability. Based on the multidimensional influencing factors revealed in the analysis, we propose a comprehensive evaluation framework. This framework not only facilitates the engineering application of 3DPC technology but also establishes a theoretical foundation for reliability design, thereby addressing the current gap in discrete evaluation standards.



complexly, Wu Xikai et al. noted that requirements for rheological parameters during pumping, extrusion, and construction phases often differ or even conflict, creating "temporal heterogeneity" as a key challenge in process control [6]. To mitigate these temporal fluctuations, researchers employed response surface methodology for multi-objective optimization, identifying the optimal mix ratio parameters (liquid-solid ratio 0.482, cement-sand ratio 0.675, water-cement ratio 0.344) to improve slurry rheology and extend open time to 30 minutes, providing an effective approach to stabilize rheological properties at the source [7].

In summary, the combined effects of raw materials, mix proportions, process parameters, and environmental conditions result in spatial-temporal variability of 3D-printed concrete's rheological properties. The uneven rheological behavior observed during the initial printing phase constitutes a primary source of subsequent macroscopic property dispersion. Fluctuations in rheological parameters directly influence extrusion flow and deposition stability, thereby altering strip morphology, deposition patterns, and interlayer contact efficiency. These factors lead to uneven interlayer pore distribution and differential bonding strength, providing direct evidence for analyzing interlayer performance and pore structure variability.

### 2.2.2 Interfaces and Porous Bubble in Materials

Through microscopic analysis, scholars including Zhu Chao revealed that the discrete distribution of interlayer and interstrip interface pores/micro-cracks is the fundamental cause of macroscopic mechanical anisotropy, particularly the weakest FZ direction and performance dispersion, attributing this to differences in microscopic defect spatial configurations determined by printing processes [8]. Researchers led by Cui Hongzhi demonstrated through discrete element simulations that interlayer and interstrip interfaces form pores and micro-cracks due to hydration time differences, resulting in significant reduction of bonding strength. They confirmed that interlayer bonding strength is a critical attribute determining the overall performance of components [9]. Macroscopic experiments conducted by Cai Jianguo confirmed that discrete fluctuations in interfacial microparameters directly cause macroscopic strength dispersion and performance degradation. Specifically, they proposed that this dispersion manifests as the highest compressive strength in the X printing direction, while the Y and Z directions exhibit strength values of approximately 90% and 93% of the X direction, respectively [10].

The variability of interfacial pores and defects directly results from fluctuations in material properties and multiple stages of the printing process. Researchers including Shi Qingxuan have demonstrated that material rheological parameters influenced by temperature and other factors lead to discrete variations in component stability and maximum print height. Mismatched flow rate and speed during extrusion can cause dimensional variations in the extruded strip, further resulting in discrete geometric dimensions and interlayer contact surfaces [11]. Sun Xiaoyan and colleagues noted that the cross-sectional shape of extruded strips undergoes random changes due to fluctuations in material and process conditions, leading to uneven distribution of interlayer pores and effective contact areas, thereby causing discreteness [12]. Xu Hui et al. pointed out that nozzle diameter and shape affect extrusion stability, with wear or adhesion causing performance discreteness over time. The layer height must match the material's rheological properties, as fluctuations in layer height caused by uneven base layers can lead to uneven compaction force, resulting in discreteness in bonding strength. [13] Unreasonable spiral blade design may induce material "slipping" and "segregation", resulting in uneven distribution of extrudates in aggregate size, moisture content and density—a primary cause of mechanical and durability performance variability [14]. Path angle or curvature changes can cause differential extrusion and accumulation behaviors, creating systematic defects influenced by material state that lead to strength performance dispersion across component locations [15] Ma Zongfang et al. demonstrated that start-stop operations generate material accumulation nodules, whose dimensions and impact range are affected by extrusion pressure, material viscosity and other random factors, thereby exacerbating performance dispersion [16]. Shi Qingxuan et al. found that nozzle height fluctuations significantly impact compaction efficiency, causing uneven interlayer porosity with a

greater adverse effect on compressive strength than flow velocity, constituting a key source of performance variability [17].

The performance variability and anisotropy of 3D-printed concrete originate from the random distribution of interlayer interface pores and micro-defects. Process disturbances such as material rheological fluctuations, extrusion, layer height variations, path variations, and nozzle conditions lead to uneven strip formation and inconsistent compaction effects. These factors result in heterogeneous pore formation, uneven contact areas, and inconsistent compaction forces at the interface, ultimately causing discrete bonding strength. This manifests as macroscopic strength variations and anisotropy, which fundamentally represents the cumulative effect of process fluctuations at the interface scale.

### 2.2.3 Additional Discreteness

The inherent discreteness also impacts flowability, thereby affecting reliability. Scholars including Cui Ziheng have identified that 3D-printed concrete, lacking formwork protection and exposed immediately after printing, faces challenges in early curing and rapid moisture evaporation. These factors significantly increase its shrinkage cracking risk compared to traditional concrete, though optimized curing can mitigate these issues [18]. Research by Liu Qiaoling et al. demonstrates that moderate water-reducing agent addition reduces yield stress and improves extrusibility, while retarders regulate setting time and influence paste viscosity and yield stress, enabling 3D-printed mortar to achieve rheological properties tailored to printing requirements [19].

In conclusion, factors such as admixtures and non-uniform curing environments introduce additional mechanical and performance variability into 3D-printed concrete components, which significantly impact structural reliability and long-term performance stability.

## 3. Influence Mechanism of Multi-source Discreteness on Structural Reliability

### 3.1 Mechanism of Reliability Influenced by Rheological Properties

The rheological properties of materials are the core intrinsic factors ensuring structural stability and shape accuracy in 3D printing. Research by Wu Xikai et al. demonstrates that insufficient static yield stress development over time directly leads to interlayer slippage, global buckling, and even collapse in printed structures during subsequent construction, which constitutes the direct cause of structural failure [6]. Meanwhile, Ma Yapeng et al. systematically enhanced the slurry's thixotropy, dynamic yield stress, and plastic viscosity through thixotropic agent incorporation, significantly improving its buildability. This is specifically manifested in higher height retention rates and reduced expansion rates of printed strips, directly ensuring geometric precision and dimensional stability during component stacking [20]. Zhang Xinying et al. found that the static yield stress ( $\tau_0$ ) and thixotropy index of materials determine their deformation resistance. Randomly low  $\tau_0$  values may cause instantaneous reliability failure during construction phases, while slow thixotropic recovery reduces the mean interlayer tensile strength ( $\mu$ ), affecting long-term reliability [5]. Therefore, ensuring materials possess sufficient yield stress and appropriate plastic viscosity forms the foundation for resisting deformation, achieving high-precision printing, and preventing structural failures.

The quality control of the printing process is a critical external factor in converting rheological properties into high-quality components, with the core objective being stable and uniform material extrusion. Experiments by Han Yixuan et al. demonstrated that employing advanced control strategies (e.g., PSO-PID) tailored to material characteristics can enhance extrusion uniformity, yielding high-quality printed parts free from obvious defects. Conversely, improper control may introduce defects such as voids, cracks, and weak interlayer bonding, compromising the forming accuracy and mechanical properties of the components [21]. This directly proves that extrusion uniformity directly ensures the forming accuracy and mechanical performance of printed components, thereby fundamentally improving structural reliability.

Rheological properties are pivotal to the reliability of 3D-printed concrete structures. Sufficient yield stress and appropriate plastic viscosity ensure structural deformation resistance and construction

stability. Precise rheological control guarantees uniform material extrusion, preventing defects like voids and cracks. Ultimately, the forming accuracy and dense microstructure determine the mechanical properties and durability of components. The reliability fundamentally stems from precise rheological material control and its synergistic interaction with printing processes.

### 3.2 Mechanism of Interlayer Interface Influence on Reliability

Chen Zhaohui et al. demonstrated through triaxial compression tests and numerical analysis that the material exhibits weakest strength under interlayer interface loading (Z-direction), with anisotropic shear modulus and Poisson's ratio. This results in significant differences between the structural deformation response under seismic or wind loads and that predicted by traditional homogeneous models, indicating a high failure risk in the computational model [22].

Studies by Shi Qingxuan et al. demonstrate that the printing interval creates a "dry-wet" mechanical weak interface, whose bonding strength is significantly lower than the matrix. This results in cracks preferentially initiating and propagating along this weak interface, leading to a marked reduction in splitting tensile strength [17]. During printing, free water in the upper slurry is forced to the lower surface, forming an interlayer "water film" that prevents direct contact between cement particles. This effectively adds a lubricant layer between layers, severely reducing interlayer friction and chemical adhesion [23]. Rui Luo et al. pointed out that the interlayer interval time is a random variable, causing the interface strength to be discrete. Printing intensity is high during the "healing period" but extremely low during the "decline period." This strength dispersion caused by temporal randomness means the overall structural reliability depends on the weakest layer. This is the fundamental reason why 3D-printed concrete has lower reliability than traditional cast concrete [24].

In structural column compression tests conducted by Ge Jie et al., interlayer interfaces caused the load-bearing capacity of 3D-printed columns to decrease by 10%-20% compared to conventional reinforced concrete columns. During failure, significant interlayer slip and increased deflection were observed, exhibiting brittle failure characteristics [25]. Studies indicate that the "cold joints" formed during printing processes reduce interfacial strength to merely 50%-85% of the matrix, leading to crack propagation along these weak interfaces. This often triggers brittle delamination failure at loads far below design specifications, determining the ultimate failure mode [26]. Additionally, altered interfacial slip and energy dissipation mechanisms play a role. Wang Hailong et al. noted that weak interlayer interfaces cannot effectively dissipate energy under dynamic loads, making them prone to direct slip. This reduces structural ductility and toughness, thereby increasing failure probability under accidental loads [27].

The interlayer interface is a critical factor determining the reliability of 3D-printed concrete structures. Its impact mechanisms include: strength degradation, performance variability, inadequate deformation and energy dissipation capacity, reduced load-bearing capacity, interlayer water film formation, and uneven time distribution. Consequently, the presence of interlayer interfaces is the fundamental reason for the lower reliability of 3D-printed concrete structures compared to traditional cast-in-place structures. Controlling interface quality is therefore the core approach to enhancing their engineering applicability.

### 3.3 Mechanism of Porosity Affecting Reliability

Zhu Chao et al. noted that mismatched slurry rheology with extrusion speed or poor strip overlap can create V-shaped cavities or "lychee-like" voids between strips and within layered bands, directly reducing the concrete's solid surface area for compressive resistance and leading to nominal strength reduction [8]. Sun Xiaoyan et al. pointed out that the pores generated by printing are not spherical but irregularly elongated or sharply angular. These sharp pore edges generate extremely high local stresses under load, becoming crack initiation points that accelerate material failure [12].

Wang Hailong et al. discovered that interlayer and interstrip interconnected pores form preferential diffusion pathways for corrosive media such as CO<sub>2</sub> and chloride ions. The diffusion rate of CO<sub>2</sub> at the interlayer interface is significantly faster than that in the matrix, leading to the "uncarbonized

island" phenomenon and anisotropic carbonation resistance (with deepest carbonation along the Z-axis), which directly reduces the long-term reliability of structures under service conditions [28]. Other studies indicate that pores (particularly interconnected pores) severely attenuate ultrasonic energy, resulting in reduced detection amplitude and wave velocity. This acoustic attenuation makes it difficult for non-destructive testing to accurately assess internal damage, potentially concealing safety hazards and leading to overly optimistic reliability evaluation results[29]. Liu Chao et al. pointed out that porosity directly reduces the material's macroscopic elastic modulus and peak stress. In numerical models, porosity is converted into a damage variable, causing the steeper descent phase of the constitutive curve, accelerating the loss of load-bearing capacity, and reducing structural redundancy [30].

Scholars including Shi Qingxuan have demonstrated that the stability of extrusion flow and velocity directly determines the geometric dimensional consistency of components, specifically the coefficient of variation (Cv). When extrusion flow and moving speed are mismatched, component dimensions fluctuate randomly, leading to stress concentration or load-bearing capacity dispersion, which directly reduces the structural reliability index  $\beta$ . Research by Xu Hui et al. indicates that improper printing paths introduce geometric uncertainties. Inappropriate layer height-to-spacing ratios may trigger "cantilever beam effects" or "local buckling," causing brittle geometric instability before material strength is reached. Additionally, path curvature variations result in material redistribution, making component load-bearing capacity a function of path changes, significantly increasing design uncertainty and failure risks [11].

Research by Ma Zongfang et al. demonstrates that process variations (including start-stop cycles and height fluctuations) generate random defects at predetermined structural positions. The material bulges (with random dimensions) caused by start-stop operations, combined with compaction degree variations due to height fluctuations, result in interlayer strength exhibiting a random field distribution. According to the weakest link theory, structural failure invariably originates from these "worst points," where reliability is governed by these random defects rather than average strength. [16].

The nozzle diameter directly impacts print continuity and material uniformity by controlling aggregate clogging randomness and shear-induced segregation, serving as a critical process parameter for component reliability. Xu Hui et al. found that a small nozzle diameter-to-aggregate maximum particle size (D/dmax) ratio increases the likelihood of clogging, leading to print interruptions and macroscopic defects that drastically reduce local reliability. Meanwhile, high shear stress exacerbates slurry-aggregate segregation, causing uneven extrudate composition and weakened interlayer bonding strength, ultimately compromising overall reliability [13].

Peng Zhi's research demonstrates that improper nozzle blade design induces material flow instability and segregation, resulting in uneven residence time and the formation of hard lumps and micro-cracks. The extrusion strip exhibits a component gradient (slurry above, bone below), creating weak interfacial contact between aggregates in the interlayer. This inherent non-uniformity exacerbates interlayer performance variability and compromises long-term component reliability [14].

The mechanism of the influence of voids on the reliability of 3D printed concrete structures is mainly reflected in reducing the macro mechanical properties, accelerating the deterioration of durability, affecting the detection accuracy and hiding the hidden safety risks, which collectively weaken the overall reliability of 3D printed concrete structures. Controlling the morphology, distribution and connectivity of voids is the key to improving its performance and service safety.

## 4. Summary and Outlook

### 4.1 Summary

This study systematically investigates the transmission mechanism between "rheological properties, interlayer interface/pore structure, performance variability, and structural reliability" in 3D-printed concrete. The core findings reveal that material rheology serves as the primary factor influencing interlayer bonding quality and pore structure statistics, which significantly exacerbates macroscopic

performance variability and ultimately determines the structural service reliability. The key research conclusions are summarized as follows: Rheological properties modulate interlayer porosity statistics, thereby affecting structural reliability. Current design codes fail to ensure the safety of 3D porous concrete (3DPC) structures by neglecting this mechanism.

## 4.2 Outlook

To address these challenges and promote the safe, reliable, and standardized application of 3D-printed concrete technology, future research and practice should focus on the following directions: (1) Establish dynamic control standards for 3D printing processes and product quality based on statistical indicators such as coefficient of variation, providing direct evidence for process stability evaluation and reliability quantification control; (2) Develop dynamic structural reliability assessment and prediction methods that integrate time-varying performance degradation, load uncertainty, and random initial defects; (3) Actively advance the standardization process from traditional single "performance indicator" acceptance criteria to a dual-core indicator system encompassing both performance and reliability, laying theoretical and data foundations for updating core design specifications.

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