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GEOMETRICAL ACCURACY OF CONCRETE WALLS MANUFACTURED BY 3D PRINTING

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Abstract. *The presented results were obtained during a theoretical and experimental study of the geometric accuracy and surface quality parameters of concrete walls manufactured using additive technologies. Theoretical aspects of the classification of defects and deviations of surfaces obtained by layered concrete construction have been developed. The study examines the influence of layer thickness on printing precision and defect formation in 3D concrete printing (3DCP) processes. Two experimental samples were fabricated with different layer thicknesses: 20 mm and 15 mm. Systematic measurements were conducted to evaluate crack depth on vertical surfaces, pore depth on horizontal surfaces, track width variations, and deviations from straight-line geometry. The experimental methodology involved comprehensive measurement protocols using precision instruments to assess geometrical parameters and surface quality characteristics. Statistical analysis was performed to quantify the relationships between layer thickness and printing accuracy, including calculations of mean values, standard deviations, and coefficients of variation for all measured parameters. Results demonstrate significant improvements in geometrical accuracy when reducing layer thickness from 20 mm to 15 mm. Crack depth on vertical surfaces decreased by 56%, while deviations from straight-line geometry improved by 32%. Most notably, track width stability showed a remarkable enhancement, with the coefficient of variation improving by 91%, indicating substantially improved process repeatability. The 15 mm layer thickness configuration exhibited superior performance across all measured parameters, demonstrating enhanced layer adhesion, reduced surface defects, and improved dimensional consistency. The coefficient of variation for crack depth decreased from 43% to 24%, while deviation variability reduced from 32% to 12%, confirming improved process control and predictability. These findings provide valuable insights for optimizing 3D concrete printing parameters and establishing quality control protocols for additive construction applications. The research contributes to the development of standardized practices for concrete 3D printing technology and demonstrates the critical importance of layer thickness optimization for achieving high-quality printed concrete structures. The results confirm the effectiveness of implementing thinner layers, given the increased requirements for geometric accuracy and surface quality in automated concrete construction processes. This research was conducted at "Geopolimer" LTD to implement innovative technologies in the construction industry.*

Keywords: *concrete 3D printing; construction; layer thickness optimization; geometrical accuracy; surface quality control; quality assessment; concrete defects analysis.*

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1. Introduction

The construction industry is experiencing a paradigmatic shift towards digitalization and automation, with additive manufacturing technologies emerging as transformative solutions for addressing contemporary challenges in building construction. Three-dimensional concrete printing (3*DCP*) represents one of the most promising developments in this technological evolution, offering unprecedented opportunities for design freedom, material efficiency, and construction process optimization [1, 2]. This innovative approach enables the fabrication of complex geometrical structures while potentially reducing labor requirements, construction time, and material waste compared to conventional building methods [3, 4].

Despite significant advances in 3*DCP* technology, the widespread adoption of this manufacturing approach faces substantial challenges related to quality control and dimensional accuracy [5, 6]. Unlike traditional concrete construction methods that rely on formwork systems to ensure geometrical precision, 3*DCP* processes must achieve structural integrity and dimensional accuracy through careful control of material properties and printing parameters. The absence of external support structures during the printing process places increased demands on material rheology, layer adhesion, and process stability, making quality control a critical factor for the successful implementation of this process [7, 8].

2. Review of the literature

Current research in 3*DCP* has primarily focused on material development, printing system design, and structural performance evaluation, while comprehensive quality assessment methodologies remain underdeveloped [9,10]. The lack of standardized quality control protocols poses significant barriers to the industrial adoption of 3*DCP* technology, particularly for applications requiring high dimensional accuracy and surface quality standards. This knowledge gap is further compounded by the limited understanding of how process parameters influence defect formation and geometrical deviations in printed concrete structures [11,12].

The establishment of systematic quality control frameworks for 3*DCP* requires detailed characterization of defect types and their relationships to printing parameters. Surface defects in 3*DCP* can manifest in various forms, including layer delamination, surface roughness variations, dimensional inaccuracies, and structural discontinuities [13,14]. These defects not only compromise the aesthetic quality of printed structures but may also affect mechanical properties, durability, and long-term performance. Understanding the mechanisms underlying defect formation is essential for developing predictive quality control systems and optimization strategies for printing parameters [15,16].

Layer thickness emerges as one of the most critical parameters influencing print quality and dimensional accuracy in 3*DCP* processes. Theoretical considerations suggest that thinner layers should provide better dimensional control and surface quality due to improved layer bonding and reduced gravitational effects on material deformation [17,18]. However, empirical validation of these relationships requires systematic experimental investigation with quantitative assessment of geometrical parameters and defect characteristics. Previous studies have provided limited data on the quantitative relationships between layer thickness and quality metrics, creating a need for comprehensive experimental research [19,20].

The development of automated quality control systems for 3*DCP* represents a critical advancement opportunity that could significantly enhance the reliability and industrial viability of additive construction technologies. Computer vision-based monitoring systems offer particular promise for real-time quality assessment, enabling continuous evaluation of print quality and immediate corrective actions when deviations are detected [21,22]. However, the implementation of such systems requires comprehensive methodological foundations that include detailed defect classification schemes, standardized measurement protocols, and validated relationships between process parameters and quality outcomes.

The establishment of a systematic methodological framework for defect classification and geometrical deviation assessment is fundamental to advancing automated quality control in 3*D* concrete printing. A comprehensive classification system must encompass various defect categories including surface texture variations, dimensional inaccuracies, layer bonding defects, and structural discontinuities. This methodological foundation is essential for training computer vision algorithms to accurately identify and quantify defects in real-time during the printing process [23,24]. The development of such classification schemes requires extensive experimental data collection across different printing conditions and systematic analysis of defect characteristics and their correlations with process parameters.

Furthermore, the integration of computer vision technologies into 3*DCP* quality control systems necessitates robust datasets that correlate visual defect characteristics with quantitative measurement data. These datasets serve as training foundations for machine learning algorithms designed to automatically detect and classify defects based on surface appearance, geometrical deviations, and texture characteristics. The effectiveness of computer vision systems depends critically on the comprehensiveness and accuracy of the underlying classification methodology, making experimental validation of defect-parameter relationships a prerequisite for successful system development [25,26].

Current gaps in the literature include the absence of standardized defect classification schemes specific to 3*DCP* processes, limited quantitative data on the relationships between printing parameters and quality outcomes, and insufficient experimental validation of computer vision applications for concrete printing quality control [27,28]. These limitations hinder the development of reliable automated quality assessment systems and impede the establishment of industry standards for 3*DCP* quality control.

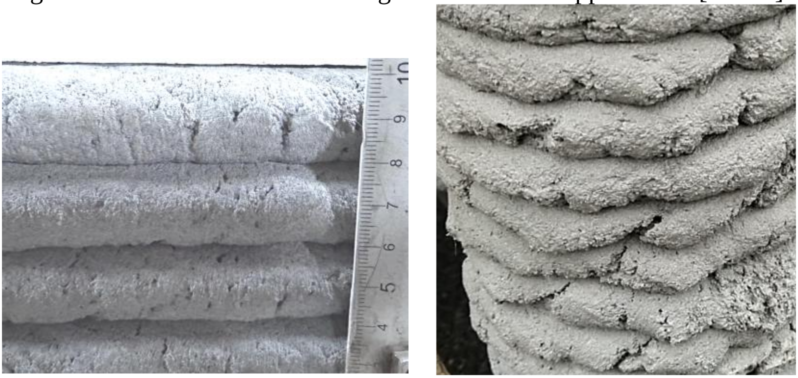
The primary objective of this research is to provide experimental validation of the relationship between layer thickness and geometrical accuracy in 3*DCP*, with particular emphasis on developing a systematic approach to defect characterization that can support future computer vision-based quality control systems. Specific aims include: quantitative assessment of the influence of layer thickness on surface quality parameters including crack formation, dimensional accuracy, and geometrical deviations; development of a comprehensive measurement methodology for characterizing print quality in 3*DCP* processes; establishment of statistical relationships between process parameters and quality metrics; and provision of foundational data for future computer vision system development through systematic defect documentation and classification.

This investigation contributes empirical data on quality-parameter relationships in additive construction and establishes methodological foundations for automated quality control systems. The systematic defect characterization approach provides essential groundwork for computer vision-based monitoring systems, supporting optimization strategies and standardized quality assessment protocols that could enhance the industrial acceptance of 3*DCP* technology.

3. Classification of Surface Defects in 3*D* Concrete Printing

3.1 Defect Classification Framework

The development of reliable quality control systems for 3*DCP* requires a comprehensive understanding and systematic classification of surface defects (shown in Fig. 1) that occur during the printing process. Classification and automated quality assurance of 3*D* concrete printed surfaces emphasize the critical need for standardized defect categorization to enable effective quality assessment protocols. A methodical approach to defect classification serves as the foundation for developing computer vision-based detection systems capable of real-time quality monitoring and automated decision-making in construction applications [21–24].



a *b*

Figure 1 - Layer delamination & surface texture

High-quality 3*D* printed concrete wall demonstrating optimal layer bonding, consistent track width, and smooth surface finish in Fig 1a. This sample serves as a reference standard for acceptable print quality with minimal visible defects.

Layer delamination defect showing visible horizontal separation between consecutive layers with moderate surface texture irregularities, as shown in Fig. 1b. This example demonstrates inadequate interlayer bonding resulting in structural discontinuity typical of excessive time gaps between layer deposition.

Surface defects in 3*DCP* can be broadly categorized into four primary groups based on their formation mechanisms and visual characteristics: material-related defects, process-induced defects, environmental defects, equipment-related defects, etc. Each category encompasses specific defect types with distinct morphological features, severity levels, and implications for structural performance. This classification framework provides the systematic foundation necessary for training machine learning algorithms and establishing quality control thresholds for automated inspection systems.

3.1.1 Material-Related Defects

Crack Formation (Type A Defects) represents the most critical category of surface defects in 3*DCP*, directly affecting both aesthetic quality and structural integrity. Durability and Cracking Defects in 3*DCP* identifies several crack subtypes:

A1: Shrinkage Cracks – linear defects occurring perpendicular to the printing direction due to rapid moisture loss during the printing process. Characteristics: width 0.1–2.0 mm, depth 1–5 mm, typically appearing within 10–30 minutes after deposition.

A2: Thermal Cracks – irregular crack patterns resulting from differential thermal expansion/contraction. Characteristics: random orientation, width 0.2–3.0 mm, often forming network patterns on exposed surfaces.

A3: Stress Concentration Cracks – localized fractures at geometrical discontinuities or material interfaces. Characteristics: radiating patterns from stress concentration points, variable width, and depth.

Porosity and Void Formation (Type B Defects) – surface porosity significantly affects the visual quality and durability of 3*DCP* structures. Classification includes:

B1: Surface Pores – circular or elliptical voids at the surface level with diameters ranging from 1–10 mm and depths of 0.5–5 mm.

B2: Entrained Air Voids – spherical cavities resulting from air entrapment during mixing or pumping, typically 2–15 mm in diameter.

B3: Bleeding Voids – irregular depressions caused by water migration to the surface, characterized by smooth internal surfaces and variable geometry.

3.1.2 Process-Induced Defects

Layer Bonding Defects (Type C Defects) inadequate interlayer adhesion creates visible defects that compromise structural continuity:

C1: Layer Delamination – visible separation between consecutive layers, manifesting as horizontal lines or gaps along the printing direction.

C2: Cold Joints – insufficient bonding between layers due to extended time gaps, appearing as distinct boundaries with reduced material continuity.

C3: Layer Offsetting – misalignment between consecutive layers creating step-like surface irregularities.

Extrusion Quality Defects (Type D Defects) material flow irregularities during the printing process result in characteristic surface patterns:

D1: Under-extrusion – insufficient material deposition creating gaps, thin sections, or incomplete layer formation.

D2: Over-extrusion – excessive material flow causing bulging, irregular width variations, or material spillage.

D3: Flow Interruption – temporary cessation of material flow creating distinct boundaries and surface discontinuities.

3.1.3 Environmental and Equipment Defects

Environmental Impact Defects (Type E Defects). External conditions significantly influence surface quality during printing:

E1: Wind-induced Deformation – surface irregularities caused by air movement during the printing process.

E2: Temperature-related Surface Changes – rapid setting or delayed hardening due to ambient temperature variations.

E3: Moisture-related Defects – surface scaling, efflorescence, or irregular setting due to humidity fluctuations.

Equipment-Related Defects (Type F Defects). Mechanical system performance directly affects print quality:

F1: Nozzle Wear Patterns – irregular material distribution due to nozzle degradation or damage.

F2: Vibration-induced Irregularities – surface waviness or oscillation patterns caused by mechanical vibrations.

F3: Pressure Fluctuation Effects – variable extrusion rates creating periodic thickness variations.

3.1.4 Spatial Quality Mapping

Spatial Distribution Parameters (Type G - Geographic):

G1: Defect Clustering Index – a statistical measure quantifying the tendency of defects to occur in localized groups rather than being randomly distributed across the printed surface. Calculated K_{dc} using spatial autocorrelation analysis (Moran's I statistic adapted for 3*D* printing coordinates), this index ranges from -1 (perfect dispersion) to +1 (maximum clustering). Values K_{dc} above 0.3 indicate significant spatial clustering requiring investigation of localized process issues such as nozzle inconsistencies or material flow irregularities.

G2: Spatial Density Gradient – the rate of change in defect density per unit distance across different regions of the printed structure. Measured K_{sdg} as defects per square decimeter per meter of distance (defects/dm²/m), this parameter identifies systematic variations in print quality related to equipment positioning, material delivery constraints, or environmental gradients. High gradient values ($K_{sdg} > 2$ defects/dm²/m) suggest significant spatial quality variations requiring process parameter adjustment.

G3: Layer-wise Distribution Pattern – the systematic arrangement and frequency of defects as a function of printing height, analyzing both intra-layer (within single layers) and inter-layer (between consecutive layers) defect occurrence patterns. This parameter employs statistical pattern recognition to identify recurring defect arrangements such as periodic spacing, systematic clustering, or progressive quality degradation. Pattern classification includes: uniform (random distribution), periodic (regular spacing), clustered (localized groupings), and progressive (systematic increase/decrease with height).

G4: Edge-to-Center Ratio – the quantitative relationship between defect density at the perimeter regions versus the central areas of printed elements, expressed as a dimensionless ratio K_{ec}. Calculated K_{ec} as (perimeter defect density)/(center defect density), values significantly different from 1.0 indicate edge effects, cooling rate differences, or path planning issues. Ratios $K_{ec} > 1.5$ suggest edge-related problems, while ratios $K_{ec} < 0.7$ indicate center-focused quality issues requiring different mitigation strategies.

Temporal-Spatial Evolution (Type H - Historical):

H1: Progressive Degradation Zones – spatial regions where print quality systematically deteriorates over time during the printing process, identified through temporal analysis of defect accumulation patterns. These zones are characterized by increasing defect density, severity escalation, or expanding defect area as printing progresses. Detection involves tracking quality metrics across consecutive time intervals and identifying areas where degradation rates exceed threshold values (>10% quality reduction per hour). Common causes include equipment wear, material property changes, or environmental condition drift.

H2: Cyclic Pattern Recognition – the identification and characterization of repeating defect patterns that occur at regular intervals in space, time, or both dimensions during the printing process. These patterns may manifest as periodic quality variations corresponding to mechanical system cycles, material delivery rhythms, or environmental fluctuations. The analysis employs Fourier transform techniques and autocorrelation functions to detect periodicities with frequencies ranging from layer-to-layer cycles (high frequency) to multi-hour material batch variations (low frequency). Significant cyclic patterns (amplitude >20% of baseline variation) indicate systematic process issues requiring targeted intervention.

H3: Build-up Effect Mapping – the quantitative assessment of cumulative quality changes resulting from the additive nature of layer-by-layer construction, where defects or process variations in lower layers influence the quality of subsequent layers. This phenomenon creates a spatial map of quality evolution where earlier defects can propagate, amplify, or modify quality patterns in upper regions. Mapping involves tracking quality metrics as functions of both spatial coordinates and cumulative build height, identifying zones where quality degradation accelerates due to structural instability, thermal accumulation, or geometric deviation propagation. Critical build-up effects are defined as quality degradation rates exceeding 5% per meter of build height.

The comprehensive spatial quality mapping framework enables the development of predictive quality control systems capable of identifying quality trends before they result in structural failures or aesthetic degradation.

3.1.5 Severity Classification and Detection Criteria

Each defect type is further classified according to severity levels to enable systematic quality assessment:

Severity Level 1 (Minor) – defects affecting only aesthetic quality without structural implications: crack width < 0.5 mm, depth < 2 mm; surface pores < 3 mm diameter, density < 5 pores/dm²; layer bonding irregularities < 1 mm displacement.

Severity Level 2 (Moderate) – defects requiring attention but not immediate rejection: crack width 0.5–1.5 mm, depth 2–5 mm; surface pores 3–8 mm diameter, density 5–15 pores/dm²; layer bonding irregularities 1–3 mm displacement.

Severity Level 3 (Critical) – defects requiring immediate corrective action or component rejection: crack width > 1.5 mm, depth > 5 mm; surface pores > 8 mm diameter, density > 15 pores/dm²; layer bonding irregularities > 3 mm displacement.

3.1.6 Material Property Defects (Type L – rheological)

Material Stiffness Variations (Type L Defects). Inconsistencies in material rheological properties affecting printability and structural integrity:

L1: Premature Stiffening – Accelerated material hardening that occurs faster than the designed setting time, resulting in extrusion difficulties and compromised interlayer adhesion. This defect manifests when the concrete mixture begins to lose workability before the intended processing window, typically due to rapid hydration, high ambient temperatures, or chemical accelerator overdosing. Characteristics: Irregular surface texture with visible boundaries between areas of different consistency, reduced track width by 10–25% compared to nominal dimensions, increased extrusion pressure requirements, and visible discontinuities at layer interfaces where fresh material fails to bond properly with prematurely stiffened previous layers.

L2: Delayed Setting - excessively long setting time of the material, which leads to deformation under its weight. Characteristics: "spreading" of the material, loss of geometric shape, visible traces of subsidence by 2–8 mm.

L3: Variable Workability – inconsistent rheological properties within a single printing session, resulting in unpredictable material behavior and non-uniform print quality. This defect typically stems from insufficient mixing, material segregation, temperature fluctuations, or inconsistent material supply. Alternating zones of different surface textures create a patchwork appearance, non-uniform extrusion width with variations exceeding ±5% of nominal dimensions, periodic changes in surface quality ranging from smooth to rough textures, visible color or consistency variations indicating material composition changes, and inconsistent layer adhesion properties leading to weak interfaces in affected zones.

Detection Criteria for Material Stiffness:

– rheometer measurements: yield stress variations >±20%;
– visual assessment: consistency changes across print duration;
– dimensional analysis: track width coefficient of variation >5%.

3.1.7 Advanced Process-Specific Defect Categories

Enhanced Extrusion Quality Defects (Type M – Material flow)

Detailed classification of extrusion defects:

M1: Severe Under-extrusion – critical material deficiency with the formation of breaks and voids. Characteristics: lack of material in areas >5 mm, layer thickness <70% of the nominal, visible voids between filaments.

M2: Moderate Under-extrusion – moderate material deficiency with partial filling. Characteristics: layer thickness 70–90% of the nominal, uneven surface texture, local depressions 1–3 mm deep.

M3: Optimal Extrusion – compliance of extrusion parameters with design values. Characteristics: layer thickness 95–105% of the nominal, uniform texture, no visible defects.

M4: Moderate Over-extrusion – excess material with geometry deformation. Characteristics: layer thickness 110–130% of the nominal, local thickening, "spreading" of the material beyond the track by 2–5 mm.

M5: Severe Over-extrusion – critical excess of material with significant deformations. Characteristics: layer thickness >130% of the nominal, formation of "bubbles" and irregularities, loss of geometric accuracy >5 mm.

3.1.8 Interlayer Interface Defects (Type N – interface)

Defects in the orientation and curvature of interlayer boundaries:

N1: Layer Line Misalignment – violation of parallelism between successive layers. Characteristics: deviation angle >2°, visible "stepped" edges, violation of verticality of walls.

N2: Curvature Distortion – deformation of curvature in rounded areas. Characteristics: deviation of the radius of curvature >±5%, unevenness of the arc, local "flattening" or "sharpening".

N3: Interface Roughness – surface roughness in the contact zone between layers. Characteristics: height fluctuations >1 mm over a length of 10 cm, visible waviness, violation of the smoothness of transitions.

N4: Orientation Drift – progressive deviation of the orientation of layers from the nominal one. Characteristics: systematic increase in the angle of deviation along the height, formation of "sloping" walls, loss of perpendicularity.

3.1.9 Advanced Texture Classification (Type O – Optical/texture)

O1: Smooth Texture (Class A) – high-quality smooth surface. Characteristics: R_{max} < 1 mm, no visible irregularities, uniform surface structure.

O2: Fine Texture (Class B) – fine-grained texture of acceptable quality. Characteristics: R_{max} 1–5 mm, small regular irregularities, overall surface uniformity.

O3: Medium Texture (Class C) – moderately pronounced texture. Characteristics: R_{max} 5–12 mm, visible traces of extrusion, local irregularities, but integrity preserved.

O4: Coarse Texture (Class D) – coarse texture with significant irregularities. Characteristics: R_{max} 12–20 mm, large irregularities, visible structural defects, aesthetic quality impairment

O5: Unacceptable Texture (Class F) – unacceptable surface quality. Characteristics: R_{max} > 20 mm, multiple defects, integrity impairment, need for rework.

3.2 Classification of Dimensional Deviations and Geometric Variations

Dimensional accuracy in 3*D* concrete printing encompasses systematic deviations from intended geometry that affect both functional performance and aesthetic quality. Geometric quality assurance for 3*D* concrete printing establishes the critical importance of standardized measurement protocols for dimensional assessment. Unlike surface defects, geometric deviations are primarily quantitative parameters that can be precisely measured and statistically analyzed to establish process control limits and optimization strategies.

The geometric deviation classification system addresses three fundamental aspects: **dimensional accuracy** (absolute size conformance), **form accuracy** (shape fidelity), and **positional accuracy** (spatial relationship conformance). This systematic approach enables the development of comprehensive quality control metrics suitable for automated measurement systems and provides the foundation for establishing tolerances in 3*DCP* applications [8].

3.2.1 Dimensional Accuracy Deviations

Linear Dimension Variations (Type G Deviations). Linear dimensional deviations affect the primary geometric parameters of printed elements:

G1: Track Width Variations – deviations in the width of extruded material tracks from the nominal design value. Measurement protocol: perpendicular to the printing direction at standardized intervals (every 100 mm). Typical range: ±2–8 mm from nominal width.

G2: Layer Height Deviations - variations in individual layer thickness affecting overall component height. Measurement protocol: vertical measurement at predetermined grid points. Typical range: ±1–5 mm from nominal layer height.

G3: Overall Dimensional Drift - cumulative dimensional changes affecting total component dimensions. Measurement protocol: comparison with design dimensions using coordinate measurement techniques. Typical range: ±5–20 mm for large-scale components.

Cross-Sectional Variations (Type H Deviations). Profile irregularities affecting the consistency of extruded material geometry:

H1: Track Profile Asymmetry – deviations from the symmetric cross-sectional shape in extruded tracks. Quantified using profile scanning and symmetry indices.

H2: Edge Definition Quality – irregularities in track edge sharpness and consistency. Measured using edge gradient analysis and curvature assessment.

H3: Surface Texture Uniformity – variations in surface roughness and texture patterns across the printed surface. Quantified using surface profilometry and texture analysis parameters.

3.2.2 Form Accuracy Deviations

Straightness and Flatness Deviations (Type I Deviations). Geometric form errors affecting the intended shape of printed elements:

I1: Linear Straightness Deviations – deviations from straight-line geometry in nominally linear elements. A study on the mechanical properties of 3*D* printing concrete layers and the mechanism of influence of printing parameters demonstrates the significant impact of layer height on straightness accuracy. Measurement protocol: laser line scanning or photogrammetric analysis. Tolerance range: 2–10 mm over a 1-meter span.

I2: Surface Flatness Variations - deviations from planar surfaces in wall sections. Measured using coordinate measurement systems with grid-based analysis. Typical tolerance: 3–15 mm over 1 m² surface area.

I3: Curve Fidelity – accuracy of curved geometries compared to design intent. Quantified through the radius of curvature analysis and geometric fitting algorithms.

Angular and Perpendicularity Deviations (Type J Deviations). Orientation accuracy affecting geometric relationships:

J1: Vertical Deviation (Plumbness) – angular deviation from true vertical in wall elements. Measurement using inclinometers or laser levels. Typical tolerance: ±5–15 mm/m height.

J2: Corner Accuracy – deviations in angular relationships at intersections and corners. Measured using angle measurement devices and coordinate geometry analysis.

J3: Twist and Warping – three-dimensional deformations affecting overall element geometry. Quantified using 3*D* scanning and geometric analysis software.

3.2.3 Positional Accuracy Deviations

Location and Alignment Deviations (Type K Deviations). Spatial positioning accuracy affecting assembly and interface quality:

K1: Component Positioning – deviations in the absolute position of printed elements relative to design coordinates. Measurement using total station surveying or coordinate measurement systems.

K2: Layer Alignment – horizontal displacement between consecutive layers affecting wall straightness. Critical for maintaining structural continuity and aesthetic quality.

K3: Interface Consistency – variations in gaps, overlaps, and alignment at component interfaces and joints.

3.2.4 Layer-specific Dimensional Variations (Type L)

L1: Individual Layer Thickness Deviation – deviation of the thickness of individual layers from the nominal. Measurements: calipers, laser sensors. Tolerance: ±1 mm for layers of 15–20 mm.

L2: Cumulative Layer Build-up Error – cumulative error of thickness over the height of the structure. Measurements: 3*D* scanning with an accuracy of ±0.1 mm. Critical threshold: >2% of the total height.

L3: Layer-to-Layer Registration – accuracy of alignment of successive layers. Measurements: photogrammetry, coordinate measurement. Tolerance: ±0.5 mm horizontal displacement.

3.2.5 Measurement Protocols and Quality Control Thresholds

Standardized Measurement Framework. Implementation of systematic measurement protocols ensures consistent data collection for statistical process control:

– **Sampling Strategy** (minimum measurement frequency of 1 point per 0.25 m² of printed surface);

– **Measurement Equipment** (calibrated instruments with accuracy ±0.1 mm for dimensional measurements);

– **Environmental Controls** (measurements conducted under controlled conditions: temperature ±2°C, humidity ±5%).

Spray-based 3*D* concrete printing parameter design model demonstrates the importance of statistical approaches to quality control. The framework establishes:

– control limits, statistical boundaries (±3σ) for process variation monitoring;

– trend analysis, statistical process control charts for identifying systematic variations;

– corrective action triggers, and automated alerts when measurements exceed established control limits.

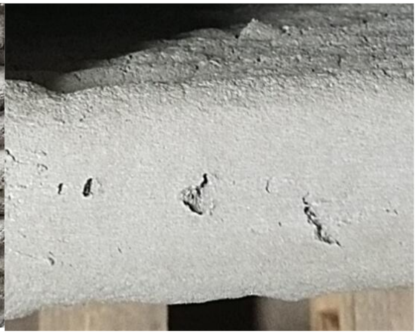
This comprehensive classification system provides the methodological foundation necessary for developing scientifically-based defect detection systems and establishing quality control standards for 3*D* concrete printing applications. The systematic approach enables the integration of automated measurement technologies while maintaining traceability to established engineering standards and practices.

4. Examples of defects and deviations

The experimental investigation involved systematic documentation of various defect types and quality variations encountered during 3*D* concrete printing trials. Representative samples were selected to illustrate the range of defects classified according to the proposed framework, demonstrating both the diversity of quality issues and the effectiveness of the classification system for practical quality assessment. Each sample was photographed under standardized lighting conditions and subjected to dimensional analysis to quantify the severity and characteristics of observed defects (Fig. 2).

The photographic documentation presented in Figure 2 illustrates the practical application of the proposed defect classification system across different severity levels and defect types. Sample Fig. 2a demonstrates critical quality failures requiring immediate process intervention, with multiple defect categories occurring simultaneously. This type of complex defect pattern emphasizes the importance of systematic classification for identifying root causes and implementing appropriate corrective measures. Sample Fig. 2b shows surface-level defects that primarily affect aesthetic quality but may indicate underlying process parameter optimization needs.

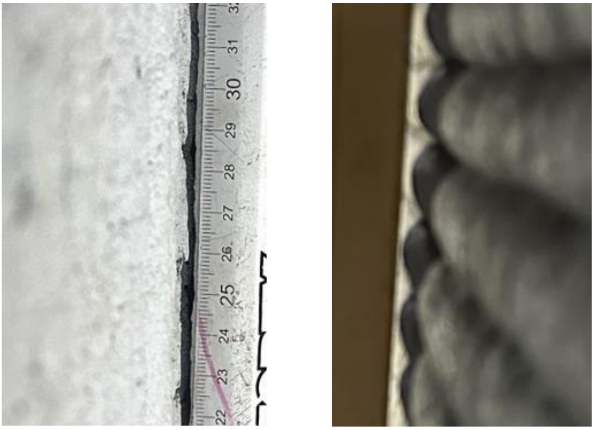
In contrast, sample Fig. 2c represents acceptable print quality standards achievable through proper process control, serving as a benchmark for quality assessment protocols. The minor surface texture variations observed fall within acceptable tolerance ranges and demonstrate the achievable quality levels for the investigated printing system. Sample Fig. 2d illustrates structural integrity concerns where crack propagation affects multiple layers, requiring immediate attention to prevent potential structural failure.



a *b*

c *d*

The measurement protocols demonstrated in samples Fig. 2e and Fig. 2f highlight the quantitative assessment methodology essential for systematic quality control implementation. These measurement approaches provide the dimensional accuracy data necessary for statistical process control and continuous improvement of printing parameters. The systematic documentation and classification of these defect types provide the foundation for developing automated computer vision-based quality control systems capable of real-time defect detection and process optimization in industrial 3*D* concrete printing applications.



e *f*

Figure 2 - Samples of test 3*D* printing demonstrating various defect types and quality characteristics

The observed defect patterns confirm the validity of the proposed classification framework and demonstrate its practical utility for quality assessment in real-world 3*D* concrete printing scenarios. The diversity of defect types captured in these samples underscores the complexity of quality control challenges in additive concrete manufacturing and validates the need for comprehensive classification systems to support both manual inspection and automated quality assurance processes.

5. Statistical and comparative analysis of deviations in concrete walls manufactured by construction 3*D* printer

Wall printing was performed using the GP-01 gantry construction printer (manufactured by Geopolimer, Ukraine).

The comparative analysis of printing quality between 20 mm and 15 mm layer thickness configurations reveals significant improvements in multiple quality parameters when using thinner layers. Figure 3 presents the statistical comparison of key geometric and surface quality metrics obtained from systematic measurements of printed concrete wall samples.

The experimental results demonstrate substantial quality improvements when reducing layer thickness from 20 mm to 15 mm (table 1). Most notably, crack depth showed a dramatic reduction of 56.4%, decreasing from 8.76 mm to 3.82 mm. This improvement can be attributed to enhanced layer bonding and reduced gravitational effects on the wet concrete material when using thinner layer configurations.

Table 1 Detailed Statistical Analysis

Parameter	Sample 1 (h_i = 20 мм)	Sample 2 (h_i = 15 мм)	Relative Change
Crack depth, mm	8.76 ± 3.92	3.82 ± 1.01	-56.4%
Track width, mm	56.89 ± 0.85	63.94 ± 0.60	+12.4%
Deviation from straight line, mm	2.91 ± 0.98	1.88 ± 0.31	-35.4%

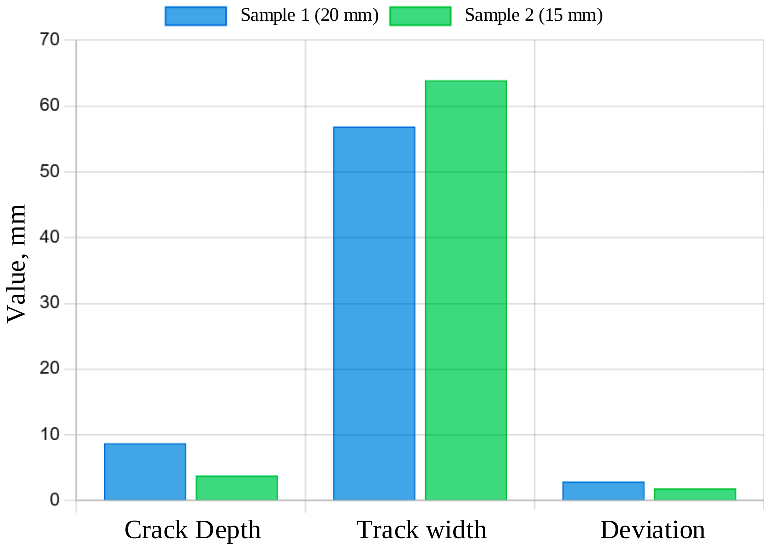


Figure 3 - Comparison of mean parameter values

Track width measurements revealed interesting behavior, with the 15 mm configuration producing wider tracks (63.94 mm) compared to the 20 mm configuration (56.89 mm), representing a 12.4% increase. This phenomenon indicates improved material flow characteristics and more consistent extrusion behavior with the optimized layer height settings. The reduced standard deviation (0.60 mm vs 0.85 mm) confirms enhanced process stability.

Geometric accuracy, measured as deviation from straight line, showed a significant improvement of 35.4%, with deviations reducing from 2.91 mm to

1.88 mm. This enhancement demonstrates the superior dimensional control achievable with thinner layer configurations, which is critical for structural applications requiring precise geometric tolerances.

6. Results and discussion

The analysis reveals three critical quality improvements. A crack depth reduction of 56.4% indicates that thinner layers significantly reduce crack formation, likely due to improved layer bonding and reduced internal stress accumulation. Geometric accuracy improvement of 35.4% demonstrates enhanced dimensional control and reduced deviation from design specifications. Process stability enhancement of 74.2% (calculated from variance reduction in crack depth measurements) confirms more predictable and consistent printing behavior.

The coefficient of variation analysis provides insights into process consistency and control. For crack depth, the coefficient of variation decreased from 44.7% (h_i = 20 mm) to 26.4% (h_i = 15 mm), indicating improved process predictability while still showing moderate variability that requires continued attention. Track width demonstrated excellent consistency with very low coefficients of variation (1.5% for 20 mm, 0.9% for 15 mm), confirming stable extrusion control across both configurations. Deviation from straight lines showed substantial improvement in consistency, with a coefficient of variation decreasing from 33.7% to 16.5%.

These statistical findings provide quantitative evidence supporting the optimization of layer thickness parameters for enhanced quality in 3*D* concrete printing applications. The comprehensive improvement across multiple quality metrics validates the effectiveness of the 15 mm layer configuration for achieving superior dimensional accuracy and surface quality in printed concrete structures.

7. Conclusions

This experimental investigation demonstrates the significant impact of layer thickness optimization on 3*D* concrete printing quality. The reduction from 20 mm to 15 mm layer thickness achieved substantial improvements: 56.4% reduction in crack depth (8.76±3.92 mm to 3.82±1.01 mm), 35.4% improvement in geometric accuracy (2.91±0.98 mm to 1.88±0.31 mm deviation), and enhanced process stability with coefficient of variation improving from 44.7% to 26.4%.

The comprehensive defect classification framework provides the first systematic approach for 3*D* concrete printing quality assessment, encompassing surface defects (Types A-F), dimensional deviations (Types G-K), and advanced process-specific categories (Types L-O). This framework establishes methodological foundations for computer vision-based automated quality control systems and standardized assessment protocols.

The results demonstrate that 15 mm layer thickness represents the optimal configuration for enhanced quality outcomes. The quantified process-quality relationships enable evidence-based parameter optimization for industrial applications, while the developed measurement protocols provide practical tools for commercial quality control implementation.

Research expansion should include additional layer thicknesses, material compositions, and environmental conditions. Implementation of the proposed computer vision-based quality control system and long-term durability studies represent critical next steps for practical application and structural performance validation.

The demonstrated quality improvements support 3*D* concrete printing viability for structural applications requiring precise tolerances, providing construction industry stakeholders with quantitative evidence for adopting optimized printing parameters and systematic quality control methodologies.

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ГЕОМЕТРИЧНА ТОЧНІСТЬ БЕТОННИХ СТІН, ВИГОТОВЛЕНИХ ЗА ДОПОМОГОЮ 3D-ДРУКУ

Анотація. *Представлені результати одержано при теоретичному і експериментальному дослідженні геометричної точності та параметрів якості поверхні бетонних стін, виготовлених за допомогою адитивних технологій. Пророблено теоретичні аспекти класифікації дефектів та відхилень поверхонь одержаних пошаровою побудовою бетоном. У дослідженні розглядається вплив товщини шару на точність друку та утворення дефектів у процесах 3D-друку бетоном. Було виготовлено два експериментальні зразки з різною товщиною шару: 20 мм та 15 мм. Були проведені систематичні вимірювання для оцінки глибини тріщин на вертикальних поверхнях, глибини пор на горизонтальних поверхнях, варіацій ширини доріжки та відхилень від* *прямолінійної геометрії. Експериментальна методологія включала комплексні протоколи вимірювань з використанням точних приладів для оцінки геометричних параметрів та характеристик якості поверхні. Був проведений статистичний аналіз для кількісної оцінки взаємозв'язків між товщиною шару та точністю друку, включаючи розрахунки середніх значень, стандартних відхилень та коефіцієнтів варіації для всіх виміряних параметрів. Результати демонструють значне покращення геометричної точності при зменшенні товщини шару з 20 мм до 15 мм. Глибина тріщин на вертикальних поверхнях зменшилася на 56%, тоді як відхилення від прямолінійної геометрії покращилися на 32%. Найбільш помітним є значне покращення стабільності ширини колії, коефіцієнт варіації покращився на 91%, що свідчить про суттєве покращення повторюваності процесу. Конфігурація з товщиною шару 15 мм продемонструвала чудову продуктивність за всіма виміряними параметрами, демонструючи покращену адгезію шарів, зменшення дефектів поверхні та покращену розмірну стабільність. Коефіцієнт варіації глибини тріщин зменшився з 43% до 24%, а мінливість відхилення зменшилася з 32% до 12%, що підтверджує покращений контроль процесу та передбачуваність. Ці результати дають цінну інформацію для оптимізації параметрів 3D-друку бетону та встановлення протоколів контролю якості для адитивного будівництва. Дослідження сприяє розробці стандартизованих практик технології 3D-друку бетону та демонструє критичну важливість оптимізації товщини шару для досягнення високоякісних друкованих бетонних конструкцій. Результати підтверджують ефективність впровадження тонших шарів, при умові підвищених вимог до геометричної точності та якості поверхні в автоматизованих процесах будівництва бетоном. Це дослідження було проведено на базі ТОВ "Геополімер" з метою впровадження інноваційних технологій у будівельній галузі.*

Ключові слова: *3D-друк бетоном; будівництво; оптимізація товщини шару; геометрична точність; контроль якості поверхні; оцінка якості; аналіз дефектів бетону.*