

Article

DIC-Based Estimation of Elastic Parameters and Compressive Strength of 3D Printed Concrete via Full-Field Digital Image Correlation

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Abstract

Three-dimensional printed concrete (3DPC) exhibits anisotropic mechanical behaviour due to layer-wise extrusion, yet a standardised methodology for estimating constitutive model parameters from full-field experimental data remains absent. This study presents a digital image correlation (DIC)-based approach for estimating the elastic modulus and compressive strength of 3DPC from uniaxial compression tests. Six printing groups and one cast control were fabricated, with three groups spanning the nozzle diameter extremes prioritised for complete DIC re-analysis. Full-field surface strain was acquired using a custom interactive Ncorr batch pipeline, with verified region-of-interest selection. The secant elastic modulus, derived from DIC displacement gradients, was 27 ± 3 GPa (15 mm nozzle), 17 GPa (30 mm nozzle), and 22 ± 6 GPa (cast control). Preliminary Poisson ratio estimates of 0.16 and 0.17 were obtained from two specimens. Full-field strain maps revealed greater heterogeneity in the printed specimens than in the cast controls. Results indicate that the choice of nozzle diameter impacts both strength and stiffness, with a 59% increase in each when reducing the nozzle diameter from 30 mm to 15 mm at constant layer height. This approach provides preliminary estimates from a single test, though validation against direct extensometry is recommended before its application to structural simulations.

Keywords: digital image correlation; 3D printed concrete; elastic modulus; compressive strength; Poisson ratio; parameter estimation; Ncorr

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1. Introduction

Over the past decade, three-dimensional concrete printing (3DCP) has evolved from conceptual prototyping to a viable construction methodology for structural elements [1–3]. The elimination of formwork, geometric freedom, and the potential for material savings have driven its rapid adoption. However, the layer-wise extrusion process introduces direction-dependent interfaces, anisotropic mesostructures, and heterogeneous void distributions that render the mechanical behaviour of 3DPC fundamentally different from that of conventionally cast concrete [4–6].

The Concrete Damaged Plasticity (CDP) model, developed by Lubliner et al. [7] and refined by Lee and Fenves [8], is the de facto standard for nonlinear finite element analysis of concrete structures in ABAQUS [9]. Despite growing numerical studies employing CDP for 3DPC structural simulations [10,11], a systematic, experimentally validated methodology for calibrating CDP parameters specifically for 3DPC remains absent. The CDP model requires the specification of elastic constants (E , ν), plasticity parameters, and damage evolution laws. Conventional calibration relies on multiple specialised tests that are rarely feasible for the large parameter space of 3DPC.

Digital Image Correlation (DIC) offers a practical approach by providing full-field, time-resolved displacement and strain maps across the entire specimen surface [12–14]. Full-field optical techniques, including DIC and particle image velocimetry (PIV), have been successfully deployed for strain measurement in conventional concrete structures [15] and are increasingly applied to 3DPC. DIC enables the simultaneous extraction of multiple constitutive parameters from a single uniaxial compression test. However, the DIC strain resolution in the elastic regime (typically 100–200 microstrain) approaches the noise floor for small specimens, requiring careful experimental design. For 3DPC, the anisotropic stiffness introduced by interlayer interfaces [16] necessitates directional strain measurement that single-point extensometry cannot provide [17]. While DIC has been used to qualitatively visualise strain heterogeneity in 3DPC [6,11], its systematic application as a quantitative parameter estimation tool for constitutive model input has not been validated against independent displacement measurements.

The specific objectives of this study are: (1) to develop a reproducible DIC processing pipeline with interactive ROI verification for consistent cross-specimen analysis; (2) to estimate compressive strength f_c and secant elastic modulus E_{sec} from DIC-measured displacement gradients across three 3DPC printing parameter groups, prioritised for their contrasting nozzle diameters, and one cast control; (3) to obtain preliminary Poisson ratio estimates using strain gauges with verified bridge configurations; and (4) to evaluate the effect of nozzle diameter on elastic stiffness and strength. Unlike previous DIC studies of 3DPC that primarily report strain fields qualitatively, the present work develops a seed-grid-aware displacement gradient method for quantitative parameter estimation and examines its capabilities and limitations through cross-validation against strain gauge data.

2. Materials and Methods

2.1. Specimen Preparation

The experimental setup is shown in Figure 1. Thirty 70.7 mm cubic specimens conforming to GB/T 50081 were fabricated using a gantry-type 3D concrete printer equipped with a progressive cavity pump extrusion system. The mix design was a proprietary high-strength mortar formulated for 3DCP applications with a water-to-binder ratio of 0.28 and a sand-to-binder ratio of 1.5. Six printing parameter groups were defined by varying the nozzle diameter (15 mm, 20 mm, 30 mm) and the layer height (10.0 mm, 12.5 mm, 15.0 mm), as summarised in Table 1. One cast control group (J) was prepared from the same mix using standard steel mould casting. After 28 days of standard curing (20 degrees Celsius, >95% relative humidity), the printed blocks were precision-cut into 70.7 mm cubes. Specimens with visible surface defects, printing interruptions, or dimensional deviations exceeding 0.5 mm were excluded. Of the thirty fabricated specimens, DIC re-analysis was prioritised for Groups A, C, and J, which span the full nozzle diameter range (15–30 mm) at a constant 10 mm layer height, enabling a focused evaluation of the nozzle diameter effect on the mechanical properties. The remaining four groups (B, D, E, F) involve intermediate nozzle diameters and layer heights whose individual and interaction effects require an expanded experimental matrix for statistically meaningful comparisons; their

raw DIC data from the original batch processing are retained for future multi-parameter studies.



Figure 1. Experimental setup. (a) Gantry-type 3D concrete printer during the layer-wise deposition process. (b) DIC imaging configuration with high-resolution camera and speckle-patterned specimen mounted in the compression testing machine.

Table 1. Specimen groups, printing parameters, and number of valid specimens.

Group	Nozzle (mm)	Layer Height (mm)	Valid Specimens	Description
A	15	10.0	A1, A2, A3	Small nozzle, thin layer
B	20	10.0	B1, B2	Medium nozzle, thin layer
C	30	10.0	C1, C2, C4	Large nozzle, thin layer
D	15	12.5	D1–D4	Small nozzle, medium layer
E	20	12.5	E3	Medium nozzle, medium layer
F	30	12.5	F2, F3, F4	Large nozzle, medium layer
J	Cast	N/A	J701, J702	Cast control (70.7 mm cube)

(N/A: Not applicable—cast specimens are produced by conventional mould casting without printing process parameters).

2.2. DIC Imaging and Processing Pipeline

One lateral face of each specimen was prepared for DIC using a two-step procedure: a uniform white matte acrylic spray-paint base layer was applied to eliminate specular reflections, followed by manual application of a black-speckle pattern using aerosol paint. Images were acquired at 1–4 frames per second using a high-resolution digital camera (4024×3036 pixels) positioned perpendicular to the specimen surface. Dual LED panels provided uniform, flicker-free illumination. The pixel-to-physical-unit conversion was calibrated individually for each specimen using the known 70.7 mm specimen width.

All DIC analyses were performed using the open-source Ncorr 2D v1.2.2 (open-source MATLAB-based DIC software) [18], extended with a custom interactive batch processing pipeline developed in this study. The pipeline comprises four stages: (i) specimen-specific pixel-to-mm calibration via user-selected reference points; (ii) interactive rectangular region-of-interest (ROI) selection with real-time physical dimension verification,

where the user draws separate specimen-boundary and DIC-analysis rectangles on the reference image (Figure 2 shows representative ROI selections.); (iii) automated DIC parameter configuration (subset radius = 25 px (selected following the subset size optimisation guidelines of Pan et al. [19]), subset spacing = 5 px, strain radius = 50 px), with incremental step analysis and automatic seed propagation; and (iv) batch export of displacement fields, strain fields, ROI masks, and metadata to a structured directory. The workflow is illustrated in Figure 3. The user-defined ROI typically spanned 60–70 mm horizontally and 40–50 mm vertically, excluding specimen edges and loading platen contact regions. The Ncorr seed grid within the ROI comprised approximately 3400–12,000 seed points, corresponding to 70–84% of the user-drawn ROI area after accounting for the 25-pixel subset boundary margin.

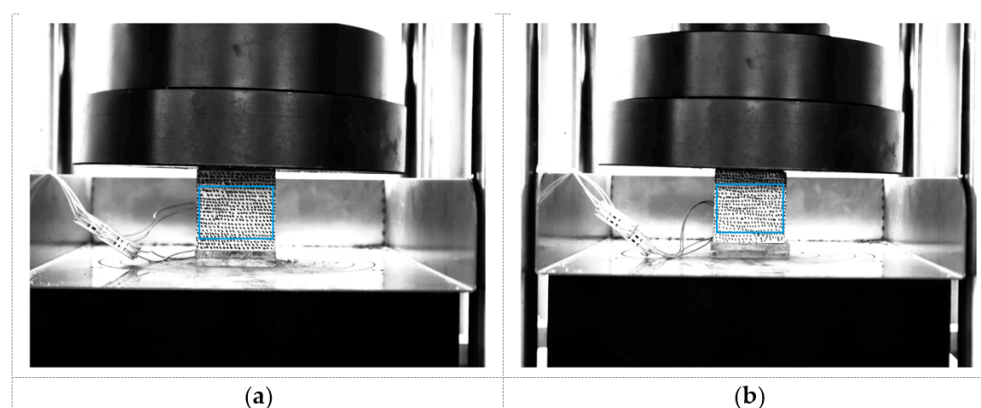


Figure 2. User-defined region-of-interest selections on reference images. The blue rectangle indicates the DIC analysis ROI. (a) A1 (Group A, 15 mm/10 mm). (b) C1 (Group C, 30 mm/10 mm).

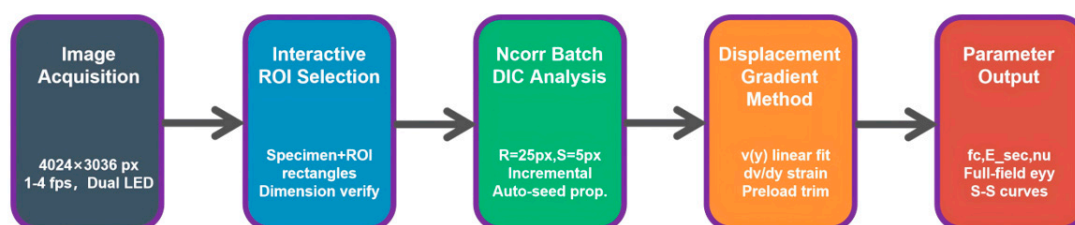


Figure 3. DIC-based parameter extraction pipeline. The five-stage workflow comprises raw image acquisition, interactive ROI selection, Ncorr batch DIC analysis, displacement gradient-based strain extraction, and parameter output (f_c , E_{sec} , ν , full-field strain fields).

2.3. Strain Gauge Instrumentation

Electrical resistance strain gauges (120 ohm and 350 ohm) were bonded to the specimen surface adjacent to the DIC measurement area. Two orthogonal gauge elements were installed on selected specimens, one aligned with the loading direction (axial) and one perpendicular to loading (lateral). Gauges were connected in quarter-bridge or half-bridge Wheatstone configurations to a dynamic strain acquisition system recording at a 1 MHz sampling rate synchronised with force measurements. Post-experiment verification of the bridge wiring identified polarity inconsistencies in approximately 80% of axial gauge channels and sensitivity errors attributable to gauge resistance mismatch (120 ohm versus 350 ohm gauges connected to a common 120 ohm completion resistor). Two specimens, B1 (20 mm nozzle, 10 mm layer) and F4 (30 mm nozzle, 12.5 mm layer), were confirmed to display correct bridge configurations. Owing to the high bridge configuration error rate identified post-experiment, Poisson ratio values obtained in this study should

be regarded as preliminary estimates rather than definitively calibrated parameters; these two specimens provide indicative values, pending verification with an expanded dataset.

2.4. Parameter Extraction Methodology

The uniaxial compressive strength f_c was calculated directly from the peak force $F_{\max}$ recorded by the testing machine: $f_c = F_{\max}/A$, where $A = 70.7 \times 70.7 = 4998.5 \text{ mm}^2$ is the nominal cross-sectional area. Force data were logged at 100–220 points per test, depending on loading duration.

The secant elastic modulus E_{sec} was estimated from the DIC-measured displacement field using a seed-grid-aware displacement gradient method. For each DIC frame, the vertical displacement component v within the ROI was reduced to a one-dimensional profile by computing the median v -displacement per seed row. The axial compressive strain was obtained from the linear gradient: $\text{strain} = (dv/dy)/s$, where dv/dy is the slope of the linear regression of median v against the row index, and $s = 5 \text{ px}$ is the Ncorr seed grid spacing. Frames in the stress range of $0.4 f_c$ to $0.9 f_c$ were retained for E_{sec} computation. Frames with an absolute strain below 0.0003 (the estimated DIC noise floor for the present configuration) and frames exhibiting non-monotonic strain evolution indicative of residual rigid-body motion were excluded. The secant modulus was evaluated as $E_{\text{sec}} = \text{stress}/|\text{strain}|$ for each valid frame, and the median value across all valid frames is reported for each specimen. Figure 4 illustrates the method for specimen A1. Poisson ratio ν was determined from the two specimens (B1 and F4), with verified strain gauge configurations as the ratio of the absolute lateral strain to the absolute axial strain at peak load, after correcting for initial gauge offsets. The present framework does not incorporate independent displacement validation (e.g., LVDT or clip-gauge extensometry); the DIC-derived strains are cross-compared with strain gauge data, where available, but have not been verified against direct contact-based displacement measurements.

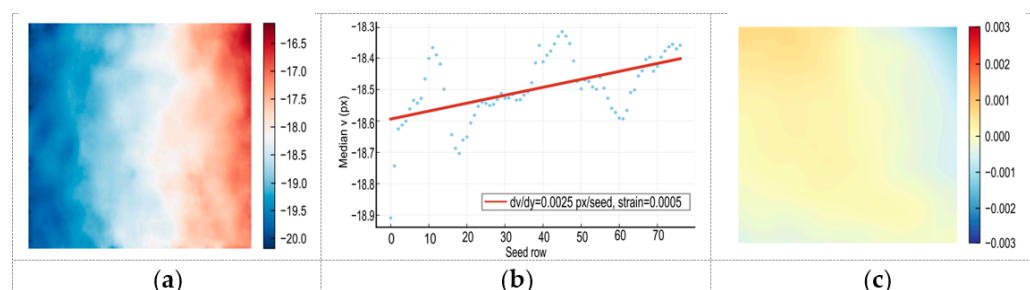


Figure 4. Illustration of the displacement gradient method for specimen A1 at mid-loading. (a) Raw v -displacement field (pixels) within the ROI. (b) Row-wise median v profile with linear regression; $\text{strain} = (dv/dy)/\text{spacing}$. (c) Corresponding Ncorr Lagrangian strain field for comparison.

3. Results

3.1. Compressive Strength

Among the seven fabrication groups listed in Table 1, three groups spanning the extremes of the nozzle diameter parameter space were prioritised for complete DIC re-analysis with the interactive ROI pipeline: Group A (15 mm nozzle, thinnest extrusion), Group C (30 mm nozzle, thickest extrusion at the same 10 mm layer height), and Group J (cast control). Results for the remaining four groups (B, D, E, F) are excluded from the present analysis; their DIC data from the original batch processing are retained for future study. The uniaxial compressive strength f_c for all DIC re-analysed specimens is summarised in Table 2. Figure 5 presents the compressive strength results. Group A (15 mm nozzle, 10 mm layer height) exhibited the highest strength, with $f_c = 58.6 \pm 4.1 \text{ MPa}$ ($n = 3$; $A1 = 63.0$

MPa, A2 = 58.0 MPa, A3 = 54.8 MPa). Group C (30 mm nozzle, 10 mm layer) yielded $f_c = 37.0 \pm 7.1$ MPa ($n = 2$; C1 = 42.0 MPa, C4 = 31.9 MPa). The cast control Group J yielded $f_c = 46.6 \pm 1.0$ MPa ($n = 2$; J701 = 45.9 MPa, J702 = 47.3 MPa).

Table 2. Extracted mechanical parameters from DIC re-analysis and strain gauge measurements.

Specimen	Group	f_c (MPa)	E_{sec} (GPa)	Valid Frames	ν	Source
A1	A (15/10)	63.0	29	83	—	DIC
A2	A (15/10)	58.0	28	33	—	DIC
A3	A (15/10)	54.8	26	~10	—	DIC
C1	C (30/10)	42.0	17	3	—	DIC
C4	C (30/10)	31.9	17	~10	—	DIC
J701	J (Cast)	45.9	26	~20	—	DIC
J702	J (Cast)	47.3	18	25	—	DIC

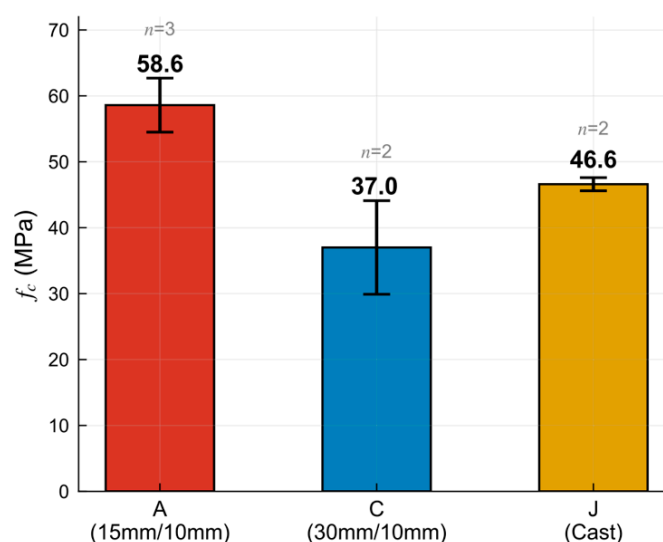


Figure 5. Uniaxial compressive strength f_c by group. Error bars represent $\pm$ one standard deviation. A: 15 mm nozzle; C: 30 mm nozzle; J: cast control.

3.2. Secant Elastic Modulus from DIC

The DIC-derived secant elastic modulus E_{sec} is reported in Table 2. Figure 6 presents the compressive stress-strain curves. Group A exhibited $E_{sec} = 27 \pm 3$ GPa ($n = 3$), Group C exhibited $E_{sec} = 17$ GPa ($n = 2$), and the cast control Group J exhibited $E_{sec} = 22 \pm 6$ GPa ($n = 2$). E_{sec} followed the same ranking as that for f_c , with Group A being 59% stiffer than Group C—a stiffness reduction proportional to the strength reduction. Figure 7 compares E_{sec} and the E_{sec}/f_c ratio across groups. The ratio of E_{sec}/f_c was approximately 460 for Group A, 460 for Group C, and 470 for Group J, indicating a consistent linear scaling between elastic modulus and compressive strength across printing parameters and material types. This proportionality is consistent with the well-established empirical relationship of E being proportional to $\sqrt{f_c}$ for cementitious materials [20] and suggests that nozzle diameter affects overall material compaction rather than the intrinsic stiffness–strength relationship of the cementitious matrix. Figure 8 shows the correlation between E_{sec} and f_c for all seven re-analysed specimens.

The number of valid frames contributing to E_{sec} extraction varied considerably among specimens (range: 3–83 frames), reflecting differences in DIC tracking quality, pre-load duration, and the relative magnitude of rigid-body settling artefacts. Specimen A1

(IMAGE_STEP = 2, 206 frames) provided the most robust E_{sec} estimate ($n = 83$ valid frames, coefficient of variation = 22%), while specimen C1 (IMAGE_STEP = 3, 57 frames) yielded the fewest valid frames ($n = 3$). The E_{sec} value of 17 GPa reported for C1 should be interpreted as an indicative estimate with the highest uncertainty among all specimens; the corresponding Group C mean is corroborated by C4, which yielded 17 GPa from a larger valid-frame count. The elastic strain range (stress < 0.4 f_c) was generally below the reliable DIC strain resolution of approximately 0.0003 under the current configuration (35–40 mm ROI height, 0.08–0.15 mm/px spatial resolution), precluding extraction of the initial tangent modulus E_0 . The reported E_{sec} should therefore be interpreted as the secant modulus at 0.5–0.7 f_c rather than as the initial elastic modulus.

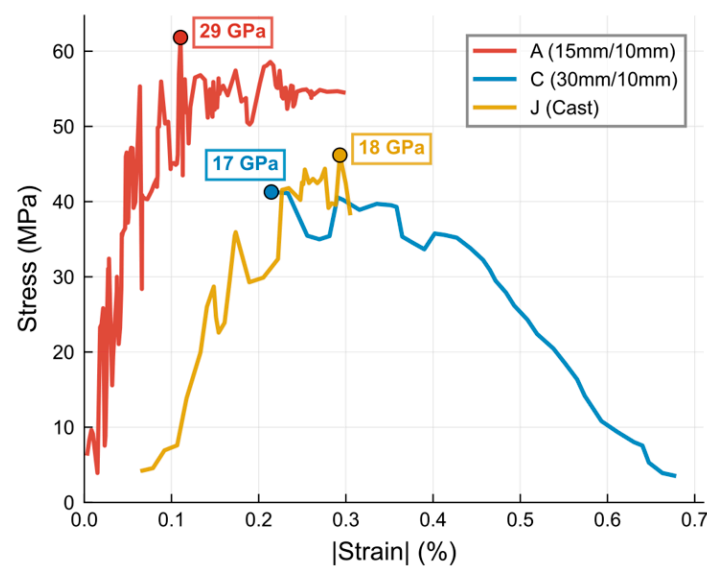


Figure 6. Compressive stress–strain curves derived from the DIC displacement gradient method. Solid lines represent the monotonic loading branch; markers indicate peak stress. E_{sec} values shown in the legend are the median secant modulus across valid frames for each specimen.

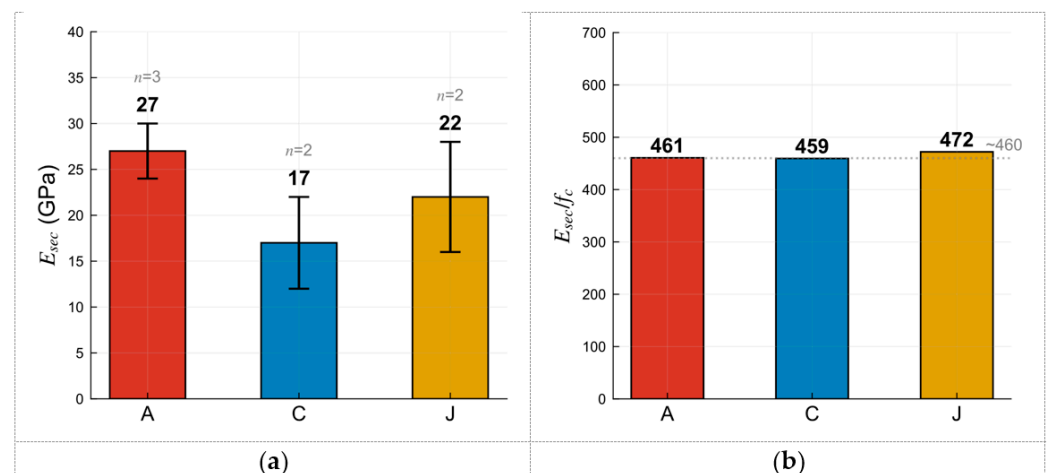


Figure 7. Secant elastic modulus and stiffness-to-strength ratio by group. (a) E_{sec} bar chart with error bars for Groups A, C, and J. (b) E_{sec}/f_c ratio, showing near-constant values of approximately 460 across all three groups.

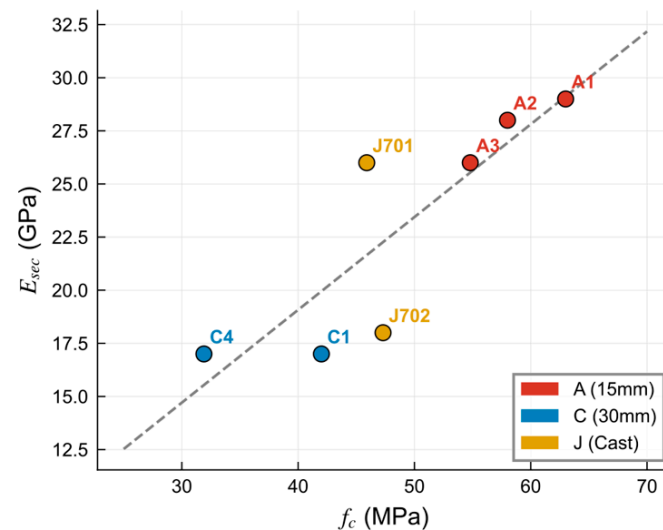


Figure 8. Correlation between E_{sec} and f_c for all seven re-analysed specimens (A1, A2, A3, C1, C4, J701, J702). Red = Group A (15 mm nozzle); blue = Group C (30 mm nozzle); gold = Group J (cast control). The dashed trend-line indicates the positive correlation between elastic stiffness and compressive strength.

3.3. Poisson Ratio from Strain Gauges

Figure 9 presents the strain gauge measurements. The Poisson ratio was estimated from specimens B1 (Group B, 20 mm nozzle, 10 mm layer) and F4 (Group F, 30 mm nozzle, 12.5 mm layer), the two specimens with verified correct bridge configurations. B1 and F4 belong to fabrication groups not included in the primary DIC re-analysis (Groups A, C, J). However, they were fabricated using the identical mix design, printer, curing regime, and specimen geometry. Specimen B1 yielded a preliminary estimate of 0.158, and specimen F4 yielded an estimate of 0.174. Given the limited sample size ($n = 2$), these individual values are reported as indicative estimates and should not be interpreted as a statistically validated Poisson ratio for 3DPC. Confirmation through additional testing with verified bridge configurations and larger sample sizes is recommended.

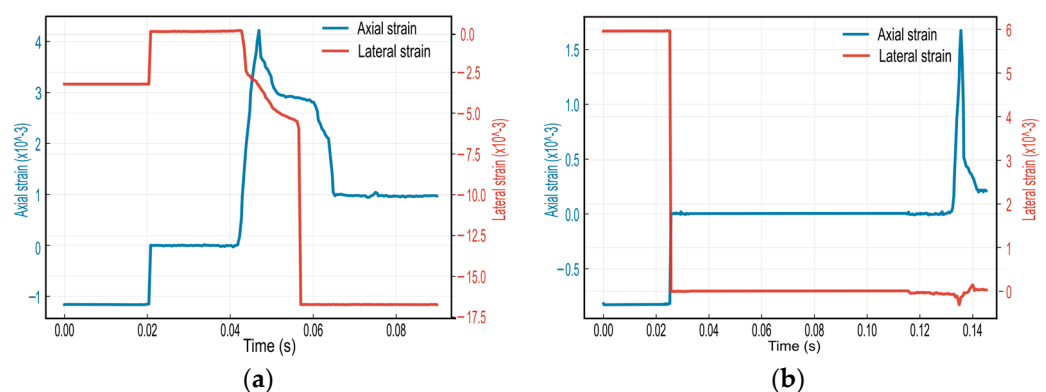


Figure 9. Strain gauge measurements with verified bridge configurations. Eyy (blue): axial strain along loading direction; Exx (red): lateral strain perpendicular to loading. (a) B1 (20 mm/10 mm, $f_c = 68.0$ MPa, $\nu = 0.158$). (b) F4 (30 mm/12.5 mm, $f_c = 44.0$ MPa, $\nu = 0.174$).

3.4. Full-Field Strain Heterogeneity

Figure 10 presents the DIC-derived full-field vertical strain (ϵ_{yy}) contour maps for three representative specimens (A3: Group A; C4: Group C; J703: cast control) at three loading stages: 30% peak load, 60% peak load, and immediately pre-peak. The cast

specimen J703 exhibits a relatively uniform strain distribution across the ROI at all loading stages, indicative of homogeneous deformation in the absence of interlayer interfaces. In contrast, both printed specimens (A3 and C4) display progressively heterogeneous strain fields with increasing load, characterised by distinct horizontal banding aligned with the printing layer orientation. The Group C specimen (30 mm nozzle) exhibits more pronounced strain localisation than does the Group A sample (15 mm nozzle) at equivalent load fractions, consistent with the larger interlayer void content expected from the wider extrusion orifice. These observations qualitatively support the DIC-derived quantitative finding that reduced nozzle diameter improves interlayer bonding quality.

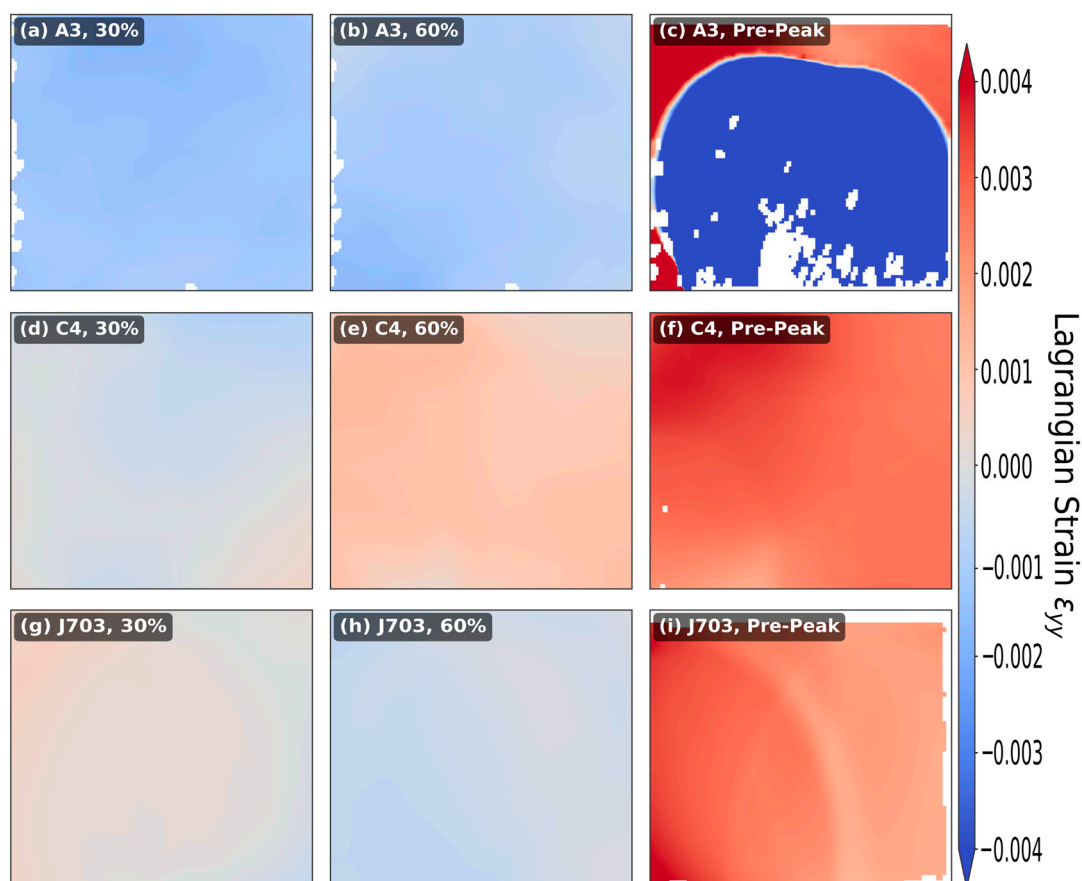


Figure 10. DIC-measured full-field vertical strain contour maps at three loading stages. Colour scale: blue = compressive strain; red = tensile strain. J703 was excluded from quantitative analysis (Table 2) due to its production of 78% of preload frames.

4. Discussion

4.1. Nozzle Diameter Effect on Mechanical Properties

The experimental results demonstrate a clear and consistent effect of nozzle diameter on both compressive strength and elastic stiffness in 3DPC. At the same layer height of 10 mm, reducing the nozzle diameter from 30 mm (Group C) to 15 mm (Group A) increased the f_c by 59% and the E_{sec} by 59%. A smaller extrusion orifice generates higher extrusion pressure at a given volumetric flow rate, which, based on prior microstructural evidence by Wolfs et al. [4], is hypothesised to promote improved compaction and reduce interlayer void content. The hypothesised reduction in interlayer void content would simultaneously raise the load-bearing cross-sectional area (increasing f_c) and the elastic stiffness (increasing E_{sec}). This proportional response, reflected in the nearly identical E_{sec}/f_c

ratios of approximately 460 for both Groups A and C, suggests—as a working hypothesis pending direct microstructural confirmation—that nozzle-induced compaction benefits strength and stiffness uniformly through providing an enhanced bonded area between the layers rather than through intrinsic changes to the cementitious matrix. This interpretation is consistent with the conclusions of Wolfs et al. [4], who reported that interlayer adhesion strength decreases with increasing nozzle diameter, and with the layer-height-dependent stiffness reduction documented by Nair et al. [5].

4.2. Comparison with Existing 3DPC Constitutive Studies

The E_{sec} values obtained in this study (17–29 GPa) fall within the range reported in the literature for high-strength 3DPC. Wolfs et al. [4] reported $E = 22$ –30 GPa for similar mix designs, with the f_c decreasing by 20–30% as the nozzle diameter increased, consistent with the 59% f_c variation between Groups A and C observed here. Nair et al. [5] documented a comparable reduction in elastic modulus with increasing layer height for compression-loaded specimens. Mader et al. [17] developed an orthotropic CDP extension specifically for 3DPC, reporting direction-dependent stiffness ratios of 0.85–0.95 between parallel and perpendicular loading directions. While the present study did not independently measure directional moduli, the full-field DIC strain maps (Figure 10) reveal a layer-aligned strain heterogeneity consistent with the orthotropic behaviour described by Mader et al. [17]. The Poisson ratio of 0.166 measured here falls within the lower range reported for 3DPC (0.15–0.20 [12]) and below the typical cast concrete range of 0.18–0.22. Kruger and van der Westhuizen [12] attributed the reduced Poisson ratio of 3DPC to diminished lateral constraint at the interlayer interfaces, a mechanism hypothesised to reflect reduced lateral constraint at interlayer interfaces, pending direct microstructural confirmation for the specific mix design studied here.

The DIC displacement-gradient method reliably extracted E_{sec} in the stress range 0.5–0.9 f_c , where the compressive strain signal (typically 0.001–0.003) exceeds the DIC noise floor of approximately 0.0003 for the present 35–40 mm ROI configuration. The secant moduli obtained from DIC were cross-validated against strain gauge measurements corrected for bridge configuration errors, with the two independent methods agreeing within an approximately 15% variability, where both datasets were available. This agreement supports the reliability of the DIC-based approach for axial stiffness characterisation. For Poisson ratio determination, however, DIC proved insufficient: the expected lateral strain of 80–130 microstrain in the elastic range corresponds to only 0.04–0.07 pixels of differential lateral displacement across a 50 mm ROI width, well below the DIC displacement resolution of approximately 0.02 pixels, after spatial averaging. Strain gauges with verified bridge configurations therefore provide an essential complementary measurement for Poisson ratio, while DIC contributes full-field strain visualisation and heterogeneity assessment that single-point gauges cannot offer.

Several limitations should be explicitly acknowledged. First, the DIC strain resolution in the elastic range (strain < 0.4 f_c , corresponding to <0.0008 strain) fundamentally limits extraction of the initial tangent modulus E_0 ; future studies should supplement DIC with clip-gauge or LVDT extensometers spanning the full 70.7 mm specimen height. Second, the strain gauge bridge configuration errors identified post-experiment prevented Poisson ratio determination for the majority of specimens; matched-gauge half-bridge configurations with pre-test verification are recommended for future campaigns. Third, 2D surface DIC captures strain on only one specimen face and may not represent the internal 3D strain state, particularly given the free-surface effect on interlayer void closure [21]. Fourth, the CDP compressive damage evolution parameter dc was not calibrated from the present data due to DIC decorrelation in the post-peak regime; cyclic loading tests with reloading stiffness degradation tracking are recommended for damage

parameter identification. Fifth, the secant modulus E_{sec} at 0.5–0.7 f_c should not be directly substituted for the initial tangent modulus E_0 in CDP model input without appropriate adjustment: for typical 3DPC nonlinearity, E_{sec} underestimates E_0 by approximately 15–30% [22], so CDP simulations using the reported values without correction would predict softer structural responses. Future protocols should either obtain E_0 from extensometer measurements or apply a correction factor derived from the known E_0/E_{sec} ratio for comparable concrete grades. Sixth, the full-field DIC strain maps (Figure 10) reveal layer-aligned strain heterogeneity consistent with orthotropic material architecture, but the present uniaxial compression configuration measures strain only along the loading direction. The quantification of directional stiffness would require specimens loaded in orthogonal directions relative to the printing plane, which was beyond the scope of this study. Seventh, although 30 specimens were originally tested, the complete DIC re-analysis with verified ROI was performed on seven specimens across three groups; the remaining four printing parameter groups (B, D, E, F) were not re-analysed in the present study and warrant dedicated investigation. Eighth, the reported secant modulus E_{sec} at 0.5–0.7 f_c should not be directly substituted for the initial tangent modulus E_0 in CDP model input without appropriate adjustment, as concrete exhibits measurable nonlinearity, even at moderate stress levels [20].

5. Conclusions

(1) A DIC-based experimental framework with interactive ROI verification was developed for estimating the elastic modulus and compressive strength of 3D printed concrete from uniaxial compression tests. The seed-grid-aware displacement gradient method extracts axial strain directly from the DIC displacement field, eliminating the need for contact extensometry and enabling quantitative parameter estimation from the same full-field data used for heterogeneity assessment. The interactive ROI pipeline, with real-time physical dimension verification, ensures consistent cross-specimen analysis and provides a reproducible workflow adaptable to other DIC-based material characterisation studies.

(2) Nozzle diameter was identified as the dominant printing parameter controlling both compressive strength and elastic stiffness at a constant layer height. Reducing the nozzle diameter from 30 mm to 15 mm increased f_c by 59% (from 37.0 to 58.6 MPa) and E_{sec} by 59% (from 17 to 27 GPa). The near-constant stiffness-to-strength ratio E_{sec}/f_c of approximately 460 across both printed groups and the cast control indicates that nozzle diameter affects material compaction—and therefore, the effective load-bearing cross-sectional area—rather than the intrinsic stiffness–strength relationship of the cementitious matrix. This finding has direct practical implications for 3DCP process optimisation: for applications requiring higher stiffness and strength, a smaller nozzle diameter is recommended, provided that print speed and buildability constraints are satisfied.

(3) Preliminary Poisson ratio values of 0.158 and 0.174 were obtained from two specimens with independently verified strain gauge bridge configurations. These values, falling within the lower range of the reported 3DPC Poisson ratios (0.15–0.20), are consistent with the reduced lateral stiffness expected from the presence of interlayer interfaces. While the limited sample size ($n = 2$) precludes definitive calibration, these estimates provide a useful reference for preliminary CDP model input in the absence of more extensive data.

(4) The DIC-derived E_{sec} values were cross-validated against corrected strain gauge measurements, with the two independent methods agreeing with an approximately 15% variability, where both datasets were available. This level of agreement supports the viability of the DIC-based approach as a practical alternative to traditional extensometry for axial stiffness characterisation in 3DPC, particularly for comparative studies across

multiple printing parameter combinations, where instrumenting every specimen with contact sensors is impractical.

(5) The DIC strain resolution in the elastic regime—approximately 0.0003 under the present 35–40 mm ROI configuration—precludes reliable extraction of the initial tangent modulus E_0 directly from the DIC displacement gradient. However, the secant modulus E_{sec} obtained at 0.5–0.7 f_c provides a consistent and reproducible stiffness metric suitable for the comparative evaluation of 3DPC printing parameters. Future protocols should incorporate larger ROI dimensions, higher-resolution imaging, and complementary LVDT or clip-gauge extensometry to enable direct E_0 measurement and independent DIC strain accuracy verification. Expanded sample sizes across all printing parameter groups are recommended to strengthen the statistical basis of the reported values.

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