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Shrinkage characterization and compensation for 3DPC

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Abstract

3D concrete printing is an additive manufacturing process in which elongated beads are assembled in layers to form 3D parts. In cementitious materials, water evaporation as well as the setting of the material results in a volumetric shrinkage of the printed structures. This imposed shrinkage strain, commonly referred to as *eigenstrain*, is the source of residual progressive stress evolution within the printed parts. Consequently, the accumulation of stress during fabrication and drying may induce cracks, buckling, and surface defects in the final product. Evaluating and modeling the effect of shrinkage on the printed beads is therefore essential to optimize the machine path and process parameters in order to mitigate such issues and guarantee the integrity of the printed parts. In particular, this paper focuses on the development of a compensation strategy such that the final geometry correctly approximates the target geometry.

The proposed approach relies on the experimental characterization of the displacement field and hence the total strain by using Digital Image Correlation performed on in-situ imaging of the process. The history of the eigenstrain strain (i.e., shrinkage) has been measured on flat rectangular thin-walled walls, and then used in a mechanical model as an imposed strain. Resulting geometrical distortions have been validated against experiments. On this basis, a simple compensation strategy is proposed consisting in correcting the initial machine path by the opposite of the computed distortions when the structure is subjected to shrinkage. Several examples on various part geometries are presented and discussed.

A fast one-dimensional mechanical model named QuadWire proposed recently is being used for numerical simulations, as the final objective is to create large database to train neural network algorithms in order to apply this compensation strategy in real-time during the printing process.

Keywords: Additive manufacturing ; Plastic Shrinkage ; In-Situ Digital Image Correlation ; QuadWire model

1. Introduction

3D concrete printing (3DCP) offers design flexibility, allowing for the manufacturing of complex and unique structures. Various geometries can be designed to optimize mechanical performance, residual stresses, or the amount of material used. To ensure the buildability of the parts, a rapid setting of the concrete is necessary. The setting of concrete is coupled with pore water evaporation causing a negative pore pressure resulting in significant shrinkage deformation. This phenomenon is amplified in 3DCP due to the fast setting and the absence of large aggregates that hinder the shrinkage [1]. It is essential to consider shrinkage from the early stages of design in concrete 3D printing as it may cause surface defects, cracks, and even geometrical and structural failures, thereby endangering the safety and durability of printed components. Hence a significant number of studies investigated parameters that influence shrinkage, such as environmental conditions [2], and curing methods [3]. Monitoring and experimental quantification of shrinkage have also been studied extensively [4].

This work aims to propose a strategy for geometric compensation of shrinkage to obtain a desired geometry. To do so, an experimental study is first conducted to characterize the shrinkage during printing and at an early age after printing. Fabrication sessions are monitored and analyzed through Digital Image Correlation (DIC) in order to directly estimate the eigenstrain corresponding to shrinkage, which in turn is used in a fast one-dimensional mechanical model [5, 6] to compute the mechanical response of the structure. DIC measurements are also used to validate the numerical model by comparing displacement fields. Finally, a simple compensation method is proposed to minimize the distance between target and final geometries. To do so, the displacement induced when the material undergoes shrinkage (i.e. eigenstrain) is computed for the structure obtained with the initial machine path. Then the corrected machine path consist in subtracting this displacement to the initial machine path. This technique is applied on four different structures : two are thin walls with free edges and two are closed structure.

2. Experimental studies

This section presents the experimental investigations that have been performed in order to estimate the shrinkage strain history of a 3D printed concrete formulation.

For the two presented experimental campaigns, the water to powder mass ratio is equal to 0.1. A phosphonates base superplasticizer is added with 0.5% mass ratio to reach an initial yield stress of approximately 150 Pa. The mixing process is performed on the mixing unit of an XtreeE printing cell. The aluminum sulfate-based accelerator Floquat ASL is added through the XTree printing head via a dosing micro-pump at a dosage of 4 mL.kg^{-1} to obtain a satisfying build-up rate. Fabrication of is achieved in the layer pressing regime with a 16 mm diameter nozzle and 8 mm layer height. The print head is assembled on an ABB IRB 6620 6-axis robot arm which is programmed to follow the print path at a feed rate of 100 mm.s^{-1} .

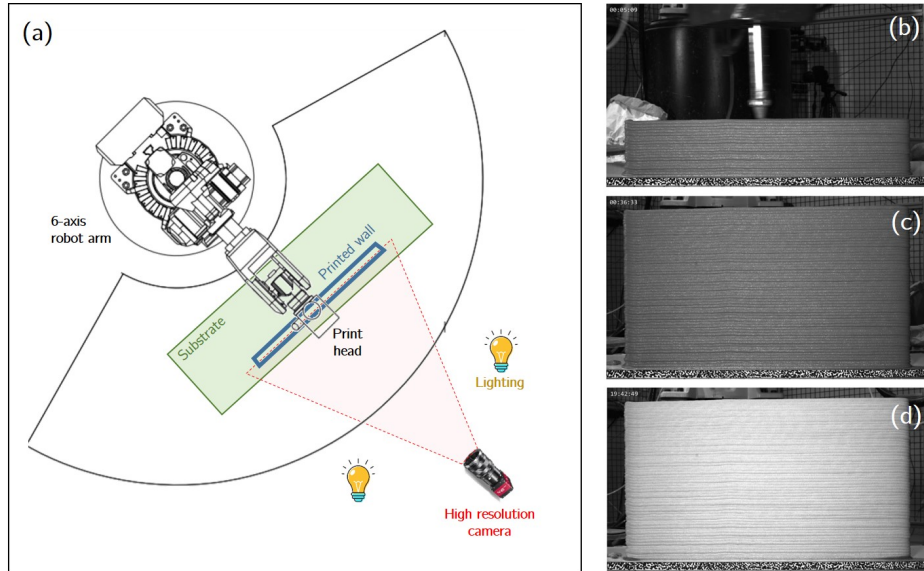


Figure 1: Experimental setup for the determination of the shrinkage strain history on a flat wall. Scheme of the setup (a) and sample images acquired (b) during fabrication, (c) 20 minutes and (d) 20 hours after the end of the fabrication.

2.1. Edge-free flat wall

In order to characterize the shrinkage strain history $\varepsilon^{\text{sh}}(t)$ of the chosen concrete formulation, a double-sided flat wall of $L \times H = 0.8 \text{ m} \times 0.45 \text{ m}$ has been fabricated using a continuous path. This way, the process parameters (e.g. inter-layer time, layer pressing) can be considered constant during printing. The wall is printed on a substrate that is stiffened in order to prevent bending caused by the weight of the concrete. In addition, the top surface of the substrate is oil-coated in order to lower the friction coefficient so that the wall boundaries can be considered free of stresses. The printing process takes around 13 minutes.

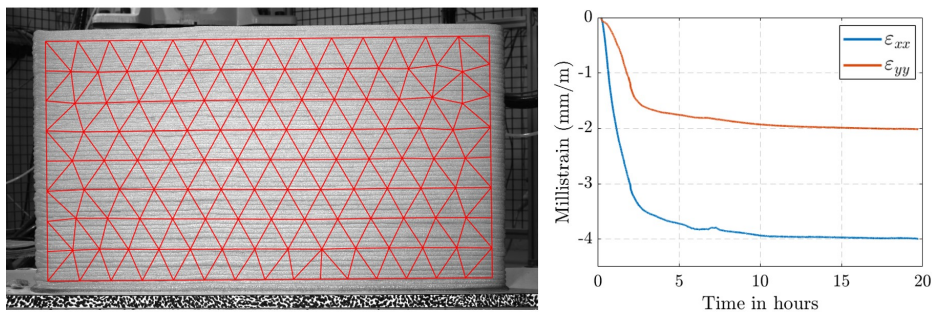


Figure 2: Shrinkage strain estimation. Left: mesh defining the region of interest for performing Digital Image Correlation. Right: estimated strain history in milli-strains after printing.

A scheme of the experimental setup is presented in Fig. 1a. The specimen fabrication and shrinkage is captured with a single high-resolution Allied Vision Prosilica GT 5400 camera equipped with a Sony IMX387 image sensor (max. 16.8 mega pixels at 7 frames per second), facing the printed wall at a distance of approximately 2 m that allows to maximize the sensor coverage with the chosen 85 mm Zeiss lens. Two 50 W LED spotlights are added to the setup to provide constant lighting during the overall experiment duration. A variable frame rate is chosen in order to sample the changing dynamics: 1 second by frame (FPS^{-1}) during the print, then 5 FPS^{-1} the first two hours, then 30 FPS^{-1} until the end; resulting in a sequence of approximately 5000 images covering the first 20 hours of the specimen life. Three representative images of the sequence are shown in Fig. 1(b-d).

To derive the shrinkage strain history from the acquired sequence of images, the displacement and hence the total strain of the entire structure is estimated by Global Digital Image Correlation (gDIC) techniques. A triangular mesh is defined on the wall surface that corresponds to the Region of Interest (ROI, see left part of Fig. 2). The end of printing is used as the reference configuration to compute the displacement of the mesh nodes by minimization of the gray level difference in between successive images as performed in [7]. The rough surface of fresh concrete provides enough gray level contrast to obtain accurate measurements. The measured total strain is composed of shrinkage strain and elastic strain. A homogeneous structure with free boundary conditions should be considered to reduce as much as possible the formation of elastic strains to directly identify shrinkage. This is reasonably well verified considering that fabrication took only 13 minutes while shrinkage time scale is several hours, and oil has been used to minimize friction. As shown on the right side of Fig. 2, it should be noted that the two estimated in-plane components of the deformation are not equal, the horizontal strain ε_{xx} having approximately twice the magnitude of the vertical strain ε_{yy} . This shrinkage strain anisotropy is attributed here to the highly oriented nature of the deposition process (print vs. build directions) that is the result of both layer pressing (initial compressive vertical stress) and bead extrusion (that can result in initial tensile stresses). Such stresses are mostly aligned with the vertical direction and correspond to elastic strains that should not be taken into account to estimate shrinkage. Therefore, only the total strain along the horizontal direction ε_{xx} is used to identify the shrinkage strain.

In addition, two regimes of strain *rate* (evolution of strains with time) can be identified in Fig. 2. In the initial 2-3 hours following printing, the strain rate is elevated, before gradually slowing down and reaching a plateau after 15 hours. This second phase is also characterized by a drastic change of the specimen texture, from a reflective surface to a diffusive surface that is attributed to water loss. Overall, 90% of the shrinkage strain occurs within the 5 first hours of the sample's lifespan.

2.2. Clamped curved wall

A second experimental study is performed on a curved wall, with initial radius of curvature $R_0 = 725$ mm, continued with columns in order to constrain the displacement at its ends (see Fig. 3). The deformation of the structure is estimated here using an Optitrack Motion Capture system equipped with 4 cameras. At the end of the 75

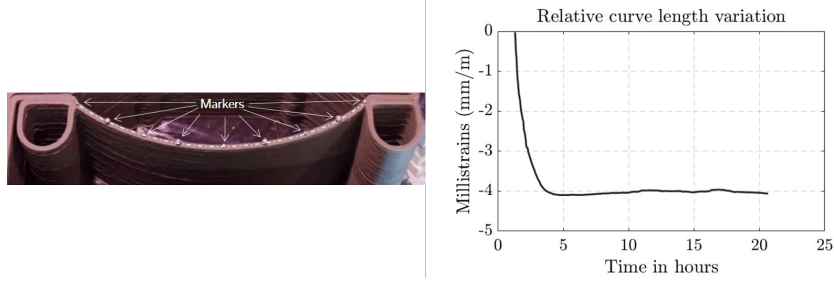


Figure 3: Shrinkage behavior of a curved wall with constrained boundary conditions.

minutes-long print, 9 infrared reflective spherical markers are placed along the top edge of the curved wall and tracked during the following 20 hours. Due to the boundary conditions created by the two columns, the horizontal shrinkage strain ε_{xx} causes a variation of the overall wall *arc length* that can be estimated from the marker positions as a function of time. The resulting history of the arc length variation (relative to its initial value) is shown in Fig. 3. It is in good agreement with the horizontal strain history ε_{xx} identified on the free flat wall shown in Fig. 2. The stabilized arc deformation is estimated to -4 mm.m^{-1} at the end of the experiment, resulting in an ultimate wall deflection of 4.74 mm (total displacement of the apex point of the arc).

3. Numerical simulations

3.1. QuadWire model

The QuadWire model is a one-dimensional model immersed in \mathbb{R}^3 . It's a multi-particular model, meaning that each material point \mathbf{x} is described by four distinct particles that can move independently in the three-dimensional space. Fig. 4 presents the QuadWire model geometry and 3D representation of a material element. This construction leads to a semi-discrete model : continuous in its tangential direction and discrete in its section. All numerical simulations will be carried out using the QuadWire model. For more details, readers are referred to [5] as well as the GitHub repository [6].

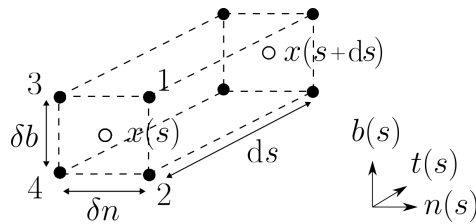


Figure 4: 3D representation of a material element of the 1D QuadWire model. Two consecutive material point $\mathbf{x}(s)$ and $\mathbf{x}(s + ds)$ are presented with their four attached particles. The local frame is $(\mathbf{t}(s), \mathbf{n}(s), \mathbf{b}(s))$ where s is the curvilinear abscissa.

3.2. Validation on the curved wall

The apex deflection of the clamped curved wall study presented in section 2.2 is first used to validate the numerical model. To this aim, an isotropic strain of $\epsilon^{\text{sh}} = -4.10^{-3}\mathbf{1}$ is imposed in the model, corresponding to the final value of the horizontal shrinkage strain estimated on the free flat wall in section 2.1. Fig. 5 displays the geometry and the numerical deflection obtained using the QuadWire model using 80 nodes uniformly distributed along the length of the wire. The maximum apex displacement is $\delta = 4.71$ mm, that is in good agreement with the experimental value of $\delta_{\text{exp}} = 4.74$ mm.

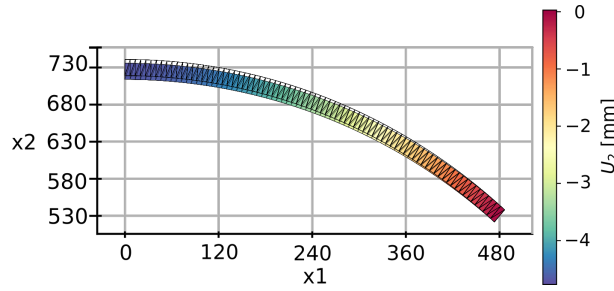


Figure 5: Numerical results of the shrinkage simulation using the QuadWire model in the horizontal plane. The initial mesh is in black while the deformed wall is in color. The colorbar indicates the displacement in millimeters along the x_2 direction, i.e. the deflection of the wall.

A mesh refinement study was carried out, maintaining a uniform mesh along the length of the element. It showed that the numerical deflection converges towards a result with 1% of error with the experimental measurement.

3.3. Compensation strategy

3.3.1. Strategy

The shrinkage strain, measured through DIC in section 2.1, is imposed as an eigenstrain in the QuadWire finite element method solver. The objective of the presented compensation strategy is to minimize the distance between the targeted geometry denoted by $\mathbf{X}_{\text{target}}$ and the deformed corrected geometry obtained after shrinkage denoted by $\mathbf{X}_{\text{cor}}^{\text{def}}$. To do so, a first computation is performed where the target geometry is deformed due to shrinkage leading to an intermediate deformed geometry denoted by $\mathbf{X}_{\text{target}}^{\text{def}}$. The distortion $\Delta\mathbf{X} = \mathbf{X}_{\text{target}}^{\text{def}} - \mathbf{X}_{\text{target}}$ is used as a correction to obtain the corrected printing path (i.e., undeformed) denoted by $\mathbf{X}_{\text{cor}} = \mathbf{X}_{\text{target}} - \Delta\mathbf{X}$.

The indicator used in order to evaluate the performance of the compensation strategy is \mathbf{Q}_c the local quality of performance and is given by $\mathbf{Q}_c = 1 - (\Delta\mathbf{X}_{\text{cor}}/\Delta\mathbf{X})$, where $\Delta\mathbf{X}_{\text{cor}} = \mathbf{X}_{\text{cor}}^{\text{def}} - \mathbf{X}_{\text{target}}$. If \mathbf{Q}_c is close to 1 the compensation strategy worked.

3.3.2. Case studies

Four structures are presented to evaluate the quality of the proposed trajectory correction strategy. Two structures are open walls (straight and sinusoidal), while

the other two are closed (round-based cylinder and square-based cylinder). Table 1 presents the geometric parameters used for the simulations, where L is the length of the structures with open paths or a quarter of the length for closed paths, H is the total height, nLayers is the number of layers and nNodes is the number of nodes per layer for the numerical discretization.

Table 1: Parameters used in the simulation.

L [m]	H [cm]	δn [mm]	δb [mm]	nLayers [#]	nNodes [#]
1	50	20	10	50	200

Fig. 6 and Fig. 7 depict the geometry of the four structures under study. The colormap used is based on the quality coefficient of the compensation strategy Q_c .

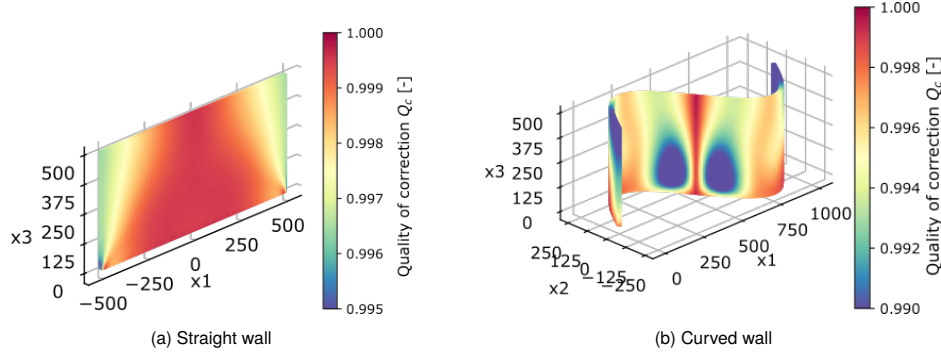


Figure 6: Numerical results of the compensation method on the straight wall (left) and the curved wall (right). The color-map indicates quality of performance of the compensation strategy Q_c . Axis units are in millimeters.

Firstly, the initial geometrical distortion $\Delta \mathbf{X}$ for all geometries is in between 2 and 5 mm while the corrected geometrical distortion $\Delta \mathbf{X}_{cor}$ is in between 10 and 30 μm , which demonstrates high efficiency of the proposed correction strategy. Secondly, the regions experiencing the most significant deformations are the upper layers, which is consistent with experimental observations. These regions also coincide with regions where the proposed compensation exhibits its lowest efficiency. But considering the minimum quality coefficient being 0.95 for all the tested examples, one can conclude that the compensation strategy, despite its simplicity, gives excellent results in counteracting the geometric distortion induced by concrete shrinkage.

4. Conclusion and perspectives

This study was dedicated to the experimental estimation of the shrinkage strain history of 3D printed concrete structures with the aim to predict the induced structural distortions via an original numerical model. This model was validated on a curved wall

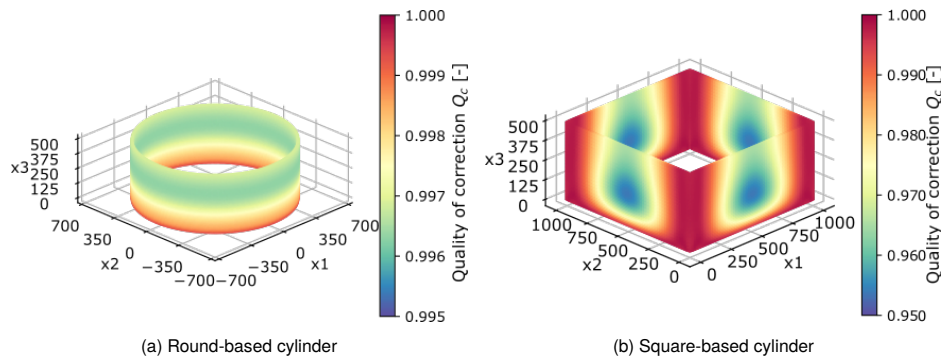


Figure 7: Numerical results of the compensation method on closed structures of perimeter $4L$: round-based cylinder of perimeter (left) and square-based cylinder (right). The color-map indicates quality of performance of the compensation strategy Q_c . Axis units are in millimeters.

shape with constrained edges, showing excellent agreement between the distortions estimated experimentally and predicted numerically. A compensation method was proposed to minimize the geometrical distortions: namely, the distance between the target geometry and the real geometry deformed because of shrinkage. To do so, the predicted structural distortions due to shrinkage strains are used to modify the printing path. It was shown, for simple geometries, that the proposed approach decreases the geometrical distortions by several orders of magnitudes. Finally, the experimentation shows that shrinkage occurs well before the hydration peak of mortar. Hence, it can be deduced that the shrinkage primarily results from the drying of the mortar and thus depends on environmental conditions such as temperature and relative humidity. The integration of the poro-mechanical coupling in the QuadWire model could be the topic of future research.

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