

Modelling orthotropic behaviour in robotic 3D printing of cementitious matrices with natural fibres and metallic reinforcement: a digital twin approach

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ABSTRACT

Robotic 3D printing with cementitious materials is reshaping construction by enabling geometrically complex and resource-efficient structures. Yet, the lack of robust analytical frameworks for validating the print quality and behaviours of fibre-reinforced composites continues to constrain the broader use of this technology in the construction industry. This study proposes a digital twin (DT)-based methodology for the post-production assessment of cementitious elements reinforced with natural and metallic fibres. By comparing photogrammetric point clouds of printed components to their original toolpath-derived meshes, one implements a geometry-based DT workflow that captures deviations, anisotropy, and layer-wise inconsistencies between layers that occur during fabrication. This process enables the qualitative and quantitative evaluation of geometric conformance and deformation. It provides critical insights into how reinforcement strategies affect material deposition, layer morphology, and build stability. The digital analyses highlight the influence of fibre content, reinforcement type, and rheological behaviour on the orthotropic performance of 3D printed elements. The core contribution lies in demonstrating how DT tools rooted in geometric fidelity and mesh-to-cloud comparisons can inform adaptive design, improve quality control, and support the development of performance-based standards for additive manufacturing in architecture and construction. This research advocates the integration of DT feedback loops into the 3D concrete printing pipeline, reinforcing the role of digital verification in advancing reliable and sustainable construction technologies.

KEYWORDS: Digital Twin, Fibres, Reinforcement, Robotic Additive Manufacturing (AM).

1.- INTRODUÇÃO

Robotic 3D concrete printing (3DCP) is a technology that is set to transform the construction industry through its material efficiency, the complexity of its geometries, and the reduction in formwork required. Nevertheless, ensuring dimensional accuracy and

structural reliability, particularly in reinforced cementitious elements, remains a critical challenge.

Digital twin (DT) methodologies, though well-established in the aerospace and manufacturing sectors, have not yet been widely adopted in construction-scale additive manufacturing. By comparing as-built point clouds to design meshes, they enable detailed assessment of deformation, anisotropy (material directionality), and print fidelity.

The utilisation of natural fibres (NF), such as sisal (SF) and coconut coir (CF), in conjunction with metallic reinforcements, such as embedded screws, has been posited as a potential solution to enhance mechanical and rheological performance. However, these materials may disrupt material flow and introduce geometric instability and introduce geometric instability during the printing process.

The present study proposes a DT framework for the evaluation of the geometric and orthotropic behaviour of fibre and screw-reinforced 3D-printed mortar elements. The objective of this research is to enhance quality control, guide adaptive fabrication strategies, and contribute to more sustainable and precise construction workflows.

2.- MATERIALS AND METHODS

2.1.- Production of prototypes

A pre-mixed commercial mortar from Weber, Saint Gobain (3D 160-1) was utilised as the foundation for the 3D printing trials. This mixture conforms to the EN 206 standard [1] and has been meticulously formulated for 3D printing applications. The mortar formulation is characterised by a maximum aggregate size of 1 mm, with the incorporation of short polypropylene fibres measuring less than 5 mm. The mortar has been enriched with NF, namely SF and CF. SF are a by-product of industrial tapestry production. The extraction of CF is derived from the coconut husk. It is important to note that these fibres have not undergone any post-treatment modifications. (Table 7).

Table 16. Summary of mortar and fibres properties

Mortar Weber 3D 160-1			
Binder	OPC CEM		
Additives	Limestone, PP < 5 mm	Compressive class	C50/60
Aggregates	Dmax. < 1 mm	Flow value	
Spec. density	2200 kg/m ³	Haegermann cone	140 mm
Sisal fibres			
Density	1.4 g/cm ³	Tensile strength	400 - 700 MPa
Length/width	1 - 500 mm / 0.1 – 0.4 mm	Elastic modulus	9 - 38 GPa
Coconut fibres (coir)			
Density	1.4 g/cm ³	Tensile strength	70 - 106 MPa
Length/width	1 - 4 mm / 0.1 – 0.5 mm	Elastic modulus	3 - 6 GPa

The constituent proportions of fibres, water, and pre-dosed mortar for each fibre-reinforced batch were carefully measured. The mixtures were produced using a Controls Group 65-L0502 bench mixer, with each batch yielding a total volume of 4 litres. The mixing process began with the dry blending of fibres with the pre-dosed mortar. Subsequently, water was added to the mixer, followed by the gradual incorporation of the fibre-mortar blend over a span of approximately two minutes, while mixing at a low speed (120 RPM). The mixture was then homogenised at 285 RPM for a further five minutes.

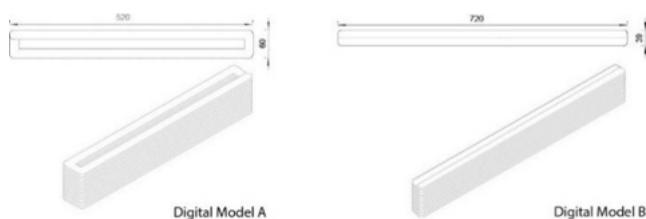


Figure 13. Geometrical and dimensional variation among digital models A (left) and B (right)

Table 17. Summary of mixtures

Prototype	Designation	Digital model	Water	Reinforcement
P1	Ref	A	11% Mortar	--
P2	Screw	A	11% Mortar	Wood screws
P3	Sisal 0.40	A	12% Mortar	0.40% Sisal by weight of mortar
P4	Coconut 0.13	B	12% Mortar	0.13% Coconut by weight of mortar
P5	Coconut 0.40	B	12% Mortar	0.40% Coconut by weight of mortar

Five mixes were created, each corresponding to one of the five prototypes. The reference prototype was composed solely of mortar, with a water content of 11% by mass of anhydrous mortar (Ref). Where half of the prototype comprised 4 x 60 mm galvanised steel wood screws. Furthermore, three additional prototypes were fabricated, incorporating SF and CF, at a mass percentage of 0.4% of anhydrous mortar. Each prototype comprised 16 layers, with a thickness and width of 6 mm and 20 mm, respectively. The robotic arm's forward speed was operated at 0.15 m/s. The extrudability of each mixture was assessed, and a series of tests were conducted to correct for the presence of water in mixtures with NF. This established the water content that ensured the maintenance of these printing parameters (see Table 2). The prototypes were divided into two dimensional and geometrically distinct Digital Models A and B (Figure 13). Prototypes 1, 2 and 3 had an overall length of 520 mm and featured a central gap in the design (Digital model A). Prototypes 4 and 5 had a monolithic geometry without central gap with total length of 720 mm (Digital model B).

After the production of the five prototypes (P1, P2, P3, P4 and P5), they were maintained within a laboratory environment for a period of 365 days.

2.2.- Digital Twin

The geometric conformance (print quality and geometric accuracy) analysis of the 3D-printed prototypes was performed by comparing photogrammetric point clouds with the mesh models of the original designs. These meshes were generated using Rhinoceros' Shrinkwrap algorithm applied to the swept sections of the toolpaths created in Grasshopper (Rhinoceros plug-in) for fabrication. The cross-sectional geometry was assumed to follow an oblong profile, as suggested in prior literature [2; 3] for layer-pressing 3DCP.

The point-cloud models of the specimens were scaled using ground control points positioned during the survey around the specimens. The survey was conducted with a Nikon ZF6II camera equipped with a 24-70 mm f/2.8 lens set to 24 mm with a fixed aperture. Prototypes P1 to P5, required 88, 89, 79, 226, and 65 photos respectively. All photosets were aligned in Agisoft Metashape Pro 2.2 (generates 3D spatial data from digital images) to obtain the SfM models and dense point clouds. The sparse clouds were optimized up to ± 0.30 RMS of reprojection error. The table on which the specimens were placed served as a reference for aligning the models to the XY plane. The registration of the point cloud with the as-designed mesh is obtained using the Iterative Closest Point (ICP) algorithm, constraining scale transformations, translations in the Z axis, and rotations in X and Y axes. This ensures an optimal alignment of the models.

3.- RESULTS

3.1.- Qualitative analysis

Signed distance maps from CloudCompare (3D Point cloud/mesh processing software) showing the elevation deformation on **Figure 14** (side view) of five 3D-printed prototypes: reference (top left), SF (top right), metallic screw reinforcement (bottom left), and 0.13% and 0.40% CF (bottom right). Distances are calculated from the point cloud to the reference mesh (DT), with colour gradients representing deviations in millimetres, i.e., error. Green zones indicate minimal deviation; red and blue denote over and under extrusion respectively.

Reference: Shows moderate deviations at the base and right edge, with visible blue and red patches indicating under and over extrusion. The absence of reinforcement leads to flow inconsistencies and limited interlayer bonding (likely led to a mix with reduced cohesion and increased flow, contributing to surface instability and settling effects during the build), characteristic of low-viscosity mixes.

Screw Reinforcement: This prototype displays highly localized geometric disruptions, particularly concentrated around the zones of screw placement. The deformation pattern shows that the screws interfere with the extrusion path, especially near the top-right corner, where irregularities are more pronounced. These artifacts indicate that the embedded screws act as physical obstructions, disrupting the intended material flow, altering

compaction, and inducing vertical displacement. Such mechanical interference compromises the continuity of the printed layers and highlights the need for more integrated reinforcement strategies in additive manufacturing workflows [4].

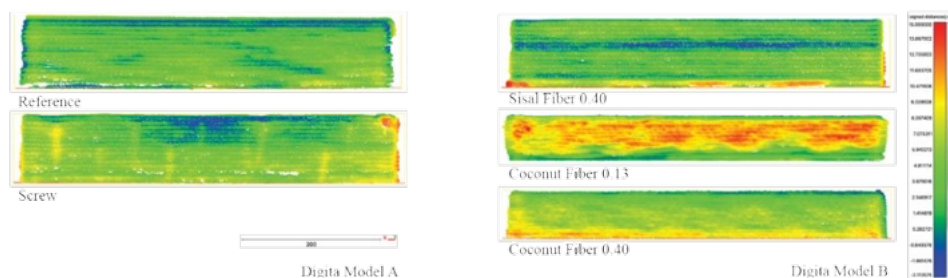


Figure 14: Comparison of elevation deviations in 3DCP elements with varying reinforcement strategies

SF 0.40: This prototype demonstrates one of the most stable and uniform deposition profiles among the tested configurations. The elevation closely aligns with the reference mesh across the entire surface, showing minimal signs of over-deposition, slumping, or layer distortion. Such geometric fidelity reflects a well-balanced rheological behaviour, likely attributed to the stiffening and bridging effects of sisal fibres. These fibres enhance thixotropy and interlayer cohesion. As a result, they promote better shape retention and reduce deformation during printing. This is mainly due to their high tensile strength and mechanical stiffness [5].

CF 0.13: This prototype exhibits the highest geometric deviation among all configurations. The signed distance map reveals extensive over-deposition concentrated in the mid-height layers, forming longitudinal ridges. The low dosage of CF, combined with their relatively low stiffness and water absorption capacity, likely resulted in a highly fluid mix with limited shape stability. This rheological imbalance may have caused the extruded material to slump or flow beyond the intended profile, especially before setting. The findings highlight the importance of optimizing fibre content for stability and consistency during printing [6-10].

CF 0.40: Although less uniform than the SF-reinforced prototype, this sample exhibits a relatively consistent elevation profile, particularly across the middle section. Minor deviations are observed at the base and bottom right, where slight over-deposition occurs. These distortions may be attributed to the lower elastic modulus and bonding capacity of CF compared to SF, resulting in reduced structural restraint and dimensional control during setting. The soft and flexible nature of coconut fibres allows greater movement within the fresh mortar. This effect is amplified at higher fibre contents, potentially compromising shape stability [6-10].

Additional levels of digital analysis are added, with great potential in the context of the DT. **Figure 15** illustrates, as an example, the analysis of Prototype 4 (CF 0.13) from five different perspectives. On the left side (A) displays a cross-sectional comparison between

the as-built point cloud (black outline) and the target design mesh (red profile). The contours reveal pronounced sidewall deviations and minor top-surface deformation, potentially caused by nozzle lift or over-deposition. Image (B), illustrates evenly spaced horizontal slices along the Z-axis, enabling localized layer-by-layer assessment. Variability in edge sharpness and symmetry suggests mechanical disturbances or inconsistent rheology during printing. The Axon cloud analysis (C) shows that displacements are mainly concentrated along the longitudinal side walls of the CF-reinforced concrete prototype, as indicated by warmer colour gradients (yellow to red). Conversely, the top and bottom faces display minimal deformation (cooler colours), suggesting higher dimensional stability. This distribution likely results from the anisotropic mechanical behaviour of the CF and boundary condition effects, indicating that reinforcement predominantly affects the vertical plane. On the right side (D) shows the plan view of the top layer, where lateral irregularities are most visible. Terminal regions of the extrusion present bulging, likely linked to material buildup or deceleration artifacts. Finally, on the right (E), provides a composite 3D view of the layered contours, with each line representing a horizontal cross-section. The stratification reflects build progression and highlights cumulative geometric drift over height.

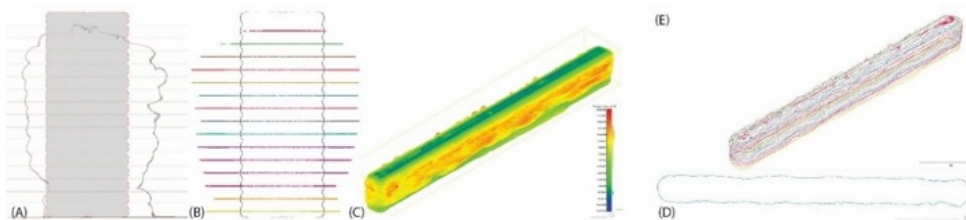


Figure 15. Qualitative analysis of prototype 4: cross-sectional comparison (A/B), axon cloud analysis (C), top layer plan view (D) and composite 3D layered contours (E)

3.2.- Quantitative analysis

It is also possible to statistically model the performance of the prototypes by determining the displacements of the various points on them. As illustrated on the left side of **Figure 16**, the distribution of the displacements of all the prototypes is presented. The x-axis indicates the displacements i.e. error, whilst the y-axis indicates the frequency of the data. On the right side. In the same figure, on the right-hand side, we report the mean and standard deviation (SD) for each prototype. It is evident that the reference, screw and SF 0.40 (P1, P2 and P3) demonstrate a distribution that is analogous to the normal distribution. The mean of the distribution is marginally positive, though negligible, with a value of less than 3 mm. The SD are equivalent to the averages and can thus be considered acceptable. Furthermore, the superior performance of Screw and SF 0.40 is clear, as evidenced by the lower statistical data when compared to the reference.

An analysis of the CF prototypes (P4 and P5) reveals a distinct difference in the data. The prototypes in question have been found to demonstrate high average displacements. However, the most salient point is that the standard deviation of the CF 0.13 is commensurate with the mean. This outcome demonstrates the inefficiency of the prototype,

attributable to the inadequate incorporation of fibres, as previously referenced. In this regard, it is noteworthy that this prototype is the only one to exhibit bimodal behaviour, as evidenced by the presence of two peaks in different locations: one on the positive axis at approximately 12 mm, and the other on the negative axis near -10 mm. The CF 0.40 prototype demonstrated a tendency to conform more closely to the reference, albeit with more pronounced errors.

This analysis clearly demonstrates that it demonstrates the efficacy of statistical decomposition in facilitating the derivation of conclusions that are in alignment with the qualitative analysis. Alternatively, a subjective assessment can be obtained through the utilisation of previously established data. The system can also be systematised or automated for the purpose of quality control in the context of prototype production, whether this takes place during or after the production process. It is also possible to establish different tolerances, depending on whether the displacements are positive or negative.

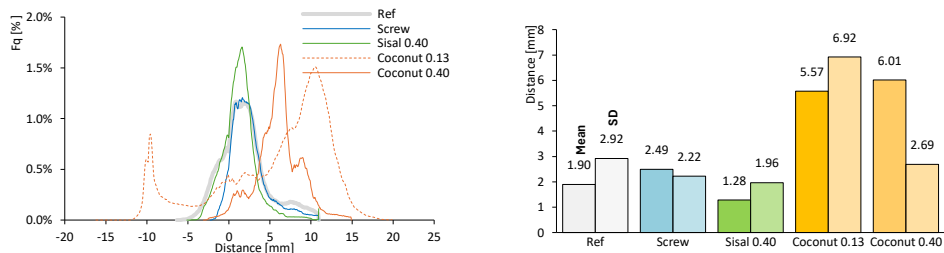


Figure 16. Distribution of prototype displacements: frequency (left) and mean with standard deviation (SD) (right)

4.- CONCLUSIONS

This study demonstrates the critical role of DT frameworks in advancing the precision, reliability, and adaptability of 3DCP workflows.

- Through high-resolution geometric analyses – such as signed distance mapping, cross-sectional comparison, and layer-wise contour evaluation - one systematically assessed the effects of different reinforcement strategies, including NF and metallic elements, on the dimensional fidelity of printed components. The results confirm that material behaviour, particularly rheological properties influenced by reinforcement type and dosage, significantly impacts the geometric outcomes of additive manufacturing.
- The integration of DT enables not only detailed post-fabrication assessment but also establishes a foundation for predictive modelling and real-time feedback control. By identifying deviations, i.e., error, early and correlating them with material-process interactions, this approach offers a pathway to optimize print parameters, improve structural performance, and minimize waste.
- Digital twin technologies offer excellent potential for the construction industry by enabling real-time or post-printing quality control. Their capacity to generate closed feedback loops between design and fabrication supports adaptive optimisation and more reliable, data-driven manufacturing workflows.

- In conclusion, the use of DT methodologies in 3DCP holds transformative potential, particularly when paired with hybrid reinforcement systems. It facilitates a shift toward closed-loop, data-informed manufacturing processes capable of delivering high-performance, geometrically accurate, and sustainable concrete components. Future work should extend this methodology toward automated correction protocols and deeper integration with AI-driven adaptive fabrication systems.

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