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Structural behavior of 3D printed load bearing elements

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Abstract. 3D Printing technology is rapidly reshaping the construction industry as an innovative and sustainable building solution. Printing elements with structural and load bearing functions, using concrete material is among the considered solutions.

The present study aims to demonstrate the ability of using 3D printed elements as fully structural. A comprehensive experimental program has been implemented to demonstrate this structural capability for 3D Printed element as the technology is presently outside construction codes. The program compares, in the same production and curing conditions, the mechanical behavior of cast in molds material, 3D printed material, and the associated l performance of structural elements at real scale. The material used was a one-component (1k) ink.

Reliable correlations between material scales and large-scale elements can be established. However, a larger design safety margin than stated in the codes for conventionally cast concrete needs to be considered presently.

Keywords: 3DP Structural elements; Load bearing/structural; Concrete; Fiber reinforced concrete; mechanical performance.

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1 Introduction

3D Concrete Printing (3DCP) is a promising technology, enabling design flexibility and optimization, a more efficient use of resources (material savings, reduced wastes), lower embodied carbon, faster construction, enhanced reliability and working conditions to answer the shortage of skilled labor. Nowadays, 3DCP technology is still facing challenges for its full integration, especially in the absence of appropriate standards and guidelines that regulate its implementation and ensure the execution of safe and high-end quality products. Important efforts are being made to develop appropriate building codes and standards (e.g., ISO/ASTM. RILEM). Alongside, experimental studies are done to draw rational recommendations on its use. The specificities of 3D printing process, from its intrinsic anisotropy due to layering, to the absence of vibration while placing, and the unprotected curing conditions in the absence of formworks, open the question of the overall structural behavior.

Several studies addressed the use of 3D printed elements as structural components, e.g., floor slabs [1], girders [2], cantilevers [3], etc. However, most studies investigated the structural capacity of 3D printed wall elements equivalent to Concrete Masonry Units systems and with different infill patterns [4] [5].

Hence, the objective of this study is to assess the mechanical performance of 3D Printed Concrete elements compared to their cast counterparts and to structural elements at scale 1.

2 Materials and methods

2.1 Concrete Mix composition

The concrete ink used for this experimental campaign is made by mixing on site, using a batch mixer, a micro-mortar (TectorPrint 804 from Holcim) with local “wet” (at their moisture content) aggregates made of limestone-type and maximum size below 8 mm, water, a liquid admixture and synthetic macro-fibers. The TectorPrint 804 is based on CEM VI cement (low carbon binder), various admixtures to manage open time, buildability and setting time, and a < 10% of micro-sand (finer than 0.6mmEfficient Water to Cement ratio is 0.43, aggregates. A specific quality procedure was developed to ensure consistent production, by following up the yield stress increase with time.

2.2 Printing method

All elements were printed with a gantry frame printer inside a closed hall. All prints were done under similar conditions to usual 3D Printing jobsite operating environments, to be representative of in situ conditions. Hence, the ambient temperature was varying between 20°C - 30°C, time interval between two successive layers was close to 10 min with a printing speed up to 25 cm/s, and the relative humidity was kept above 80% at least during the first 24h after printing. The printed elements for material

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characterization consisted of 2 adjacent layers, printed next to each other. Each layer is 8 cm wide and 2 cm thick, resulting in a 16 cm wide section. In parallel, cast samples were produced under the same curing conditions, and from the same batch of concrete, then demolded after 24 hours. Large scale elements for structural tests were made of a single layer, 8 cm wide.

2.3 Material characterization

An illustration of the sampling plan for the material characterization of 3D Printed concrete is shown in Fig. 1.

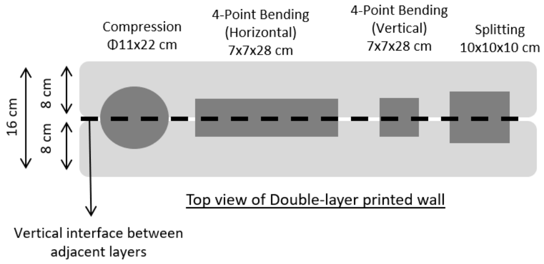

Figure 1: Illustration of the Sampling plan.

Most samples were tested at 7 and 28 days. A minimum of 6 samples was considered for each test. Loading configurations are shown in Fig. 2 and detailed hereafter.

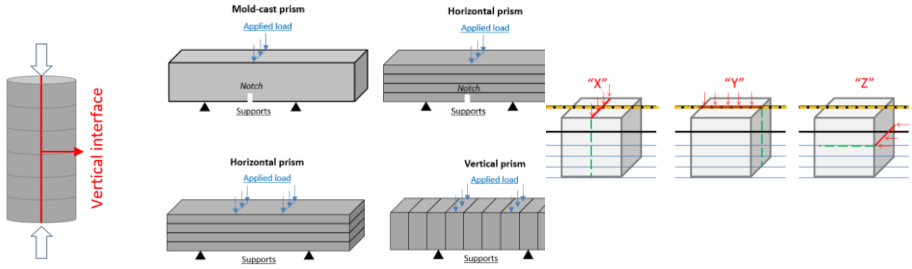

Figure 2: Testing configurations: (i) compression and E-modulus on the left, (ii) 3-point and 4-point bending on the middle, respectively top and bottom, (iii) splitting on the right.

The compression and E-modulus tests were run according to the EN 12390-3 and EN 12390-13 standards respectively, using 11x22 cm cylinders cored in the middle of the printed element. The applied load was perpendicular to the printed layers.

Flexural tests were conducted according to EN 12390- 5 using 7x7x28 cm cut prisms.

- 3-point bending tests were conducted on horizontally cut prisms from the 3D printed elements and on cast counterparts to measure the ductility provided by the fibers and

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assess the impact of printing on the fibers orientation. A notch-configuration was used for better control of the crack propagation.

- 4-point bending tests were conducted on prisms cut vertically and horizontally in printed elements, to characterize respectively the bond strength between superposed layers and the strength of the bulk material.

Splitting tests were run according to EN 12390-6 using 10x10x10 cm cubes cut from the 3D printed elements, to evaluate the joint between layers, in comparison to the flexural results.

2.4 Samples for structural Characterization

Large printed elements were tested in bending and compression, on samples aged between 30 and 35 days, with 3 samples for each configuration. 3-point bending strength was measured on 8 cm thick and 1.7 x 0.5 m large elements, with a distance between supports of 1.5 m and a loading rate of 2 kN/s, applied parallel or perpendicular to the printed layers (Fig. 3). Samples with and without macro-fibers for ductility were tested. The compression test was done on 8 cm thick and 2.4x0.76 m elements, with a loading rate of 0.004 mm/s (Fig. 3). The load was applied perpendicularly to the printed layers, and only fiber reinforced concrete panels were tested.

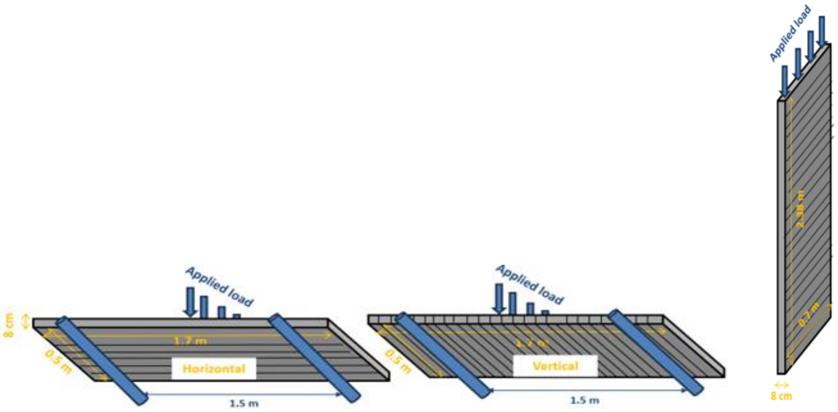

Figure 2:3-Point Bending (left) and compression (right) test on large scale 3D Printed concrete elements in different directions.

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3 Results

3.1 Material Characterization

Compression and E-modulus measurements

Table. 1 shows the density, compressive strength, and E-modulus of printed and cast specimens.

Table 1: average compressive strength, E-modulus, and density (standard deviations between brackets)

	Printed samples		Cast samples	
	7 days	28 days	7 days	28 days
Density (kg/m^3)	2225.0 *(6.0)*	2225.0 *(3.0)*	2238 *(5.0)*	2238.0 *(3.0)*
Compressive strength (MPa)	36.1 *(1.1)*	46.6 *(1.1)*	41.5 *(0.5)*	60.0 *(1.3)*
E-modulus (GPa)	-	28.0 *(0.7)*	-	31.4 *(0.5)*

Strength of printed samples (compression and E-modulus) is lower than cast ones (reduction from ~10 to 20%). This is in the range reported in the literature, from 15% [6] to 40% for compressive strength and around 50% for E-modulus [4]. Table 1 shows that the difference of density between cast and printed samples is minimal, similar findings reported by Wolfs et al. [7]. This does not fully explain the strength reduction (Bolomey's equation predicts only a ~3 MPa compressive strength reduction at 28 days), yet it can be mainly attributed to the lack of vibration. Curing from the lateral surfaces seems also to be ruled out as specific care on hygrometry was brought during the first 24 hours (RH > 80%). However, rapid moisture loss and drying of layer interface while printing was mentioned by several authors and could also have an influence [7]. Besides, the effect of core drilling on the specimens further contributes to the strength reduction. Thus, the strength reduction between printed and cast specimens results from the combination of all these factors, adding on top the influence of 3D printing.

Flexural tests

The 3-point and 4-point bending results are shown in table 2.

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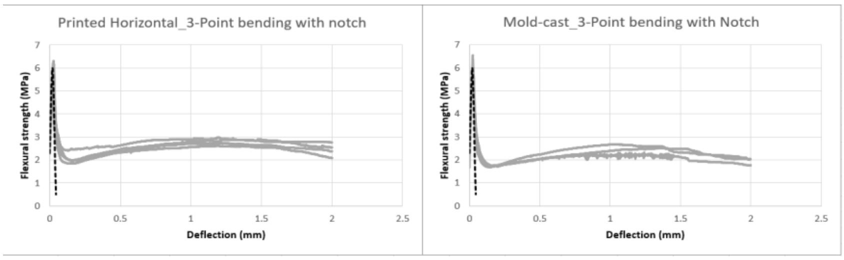
Table 2: 3-point and 4-Point Bending results

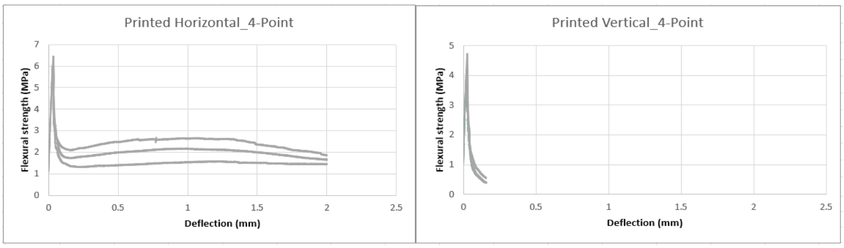
	Printed samples				Cast samples	
	7 days		28 days		7 days	28 days
	Vertical	Horizontal	Vertical	Horizontal		
3-Point (MPa)	-	-	-	5.9 *(0.4)*	-	6.2 *(0.4)*
4-Point (MPa)	3.4 *(0.3)*	5.6 *(0.5)*	4.5 *(0.5)*	6.3 *(0.4)*	4.6 *(0.4)*	-
4-Point **with CJ** (MPa)	4.3 *(0.3)*	-	4.5 *(0.4)*	-	-	-

Graphs 1 and 2 show the load vs deflection of printed and cast samples when tested under 3-point bending. Note that dashed-gray curves are used as reference for plain concrete, whereas full lines correspond to the fiber-reinforced concrete. 3-point being results show that macro fibers allow to develop ductile behavior, with the same performance for 3D printed horizontal prisms as mold-casted references.



Graphs 1 & 2: Load vs. deflection under 3-Point bending.

4-point bending results are now considered (table 2, graphs 3 and 4). Flexural strength at 28 days in the vertical direction is 28% lower than in the horizontal direction. The interface between superposed layers is therefore weaker than the bulk material, as the failure in vertical elements has always happened between layers. Besides, samples tested in the vertical direction have no ductility (brittle failure) compared to those tested in the horizontal direction. Last, fibers follow the printing direction, and they have no doweling effect between superposed layers.



Graphs 3 & 4: Load vs. deflection under 4-point bending.

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Splitting tests

All splitting results are shown in table 3. The printed layer itself or bulk concrete was assessed through loading in the “X” direction as presented in Fig. 2. The interface between superposed layers was assessed through the “Z” direction, and the vertical interface between adjacent layers was assessed through the “Y” direction. As a result, it was found that all tensile splitting results were homogeneous and coherent with the flexural bending results. Nevertheless, the vertical interface between adjacent layers seems not to be as strong as a homogeneous layer.

Table 3: Splitting strength results.

Printed				Casted	
"X"	"Y"		“Z”	7 days	28 days
28 days	7 days	28 days	28 days		
4.6 *(0.5)*	3.6 *(0.6)*	3.7 *(0.8)*	3.4 *(0.9)*	3.9 *(0.5)*	4.3 *(0.2)*

3.2 Structural Characterization

Compression / Buckling

The measured thickness of the tested specimen was equal to 9 cm. The tests were intentionally stopped when a local failure at the head of the wall was observed as can be seen in Fig. 3. The Average Load bearing capacity of the 3 tested walls was equal to 983.5 kN equivalent to 14.4 MPa and 1294 kN/ml. The prediction of the critical linear buckling load according to the Eurocode based Euler analytical approach would have given 29146 kN/ml which is equivalent to 324 MPa (227 MPa considering the effect of geometric defects up to 30% reduction in the load, in the form of additional eccentricity of the load). This stress value is much higher than the intrinsic compressive strength of the printed concrete material which is 46.6 MPa on average. This means that a compressive failure would precede a buckling failure in this case. However, in this study, the local failure was noticed at 14.4 MPa. We recommend for safety reasons to consider a safety factor coefficient of 2.0 instead of 1.5 (as given bythe EC2) on the compressive strength when designing printed sections under compressive stress. It is also important to note that in most mid-rise buildings the acting ULS normal load on walls rarely exceeds 5 MPa which means that from a mechanical point of view a 9 cm thick wall should be enough.

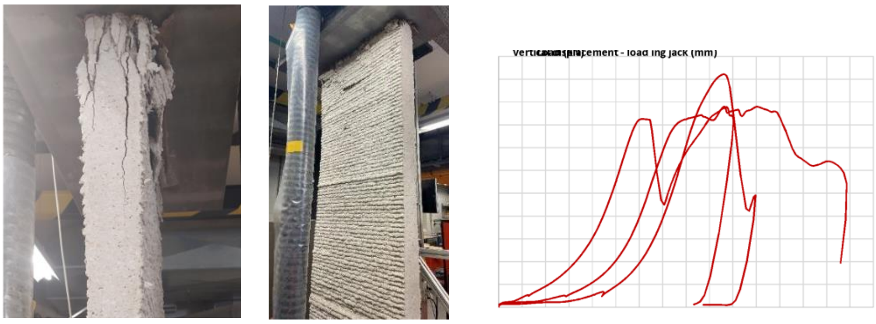

Figure 3: Compression test on scale 1 3D Printed panel with fibers.

Bending

Graph 5 shows the individual curves of the 3-Point bending results on large scale elements. The effective thickness of the panels was equal to 9 cm. Comparing the results of both loading configurations, Horizontal vs Vertical, the average load bearing capacity of the horizontal walls was around 6.5 kN. However, the average strength achieved in the vertical direction was equal to only 1.8 kN. It should be noted that an analytical estimation of the breaking load, considering a flexural tensile strength of 6.3 MPa or 4.5 MPa (load perpendicular to layers or parallel) based on the experimental 4-point bending tests at the material scale, and assuming a linear elastic stress distribution in the section, would have given 6.0 kN and 4.3 kN respectively. The expected value of 6.0 kN for the horizontal configuration (when the load is perpendicular to the layers) is very close to what was observed experimentally, i.e. 6.5 kN. However, for the vertical panels, the expected value of 4.3 kN was well beyond what was obtained experimentally, i.e. only 1.8 kN. These results show that the difference between vertical and horizontal samples is more pronounced at scale 1 compared to small scale samples. Herein, the strength attained by the vertical samples is only 28% of the strength of horizontal ones. The failure occurs due to loss of adhesion between the layers. Therefore, special care should be taken in the structural design when the load is parallel to the layers. This should be less critical in building applications where the walls only support load essentially in one direction between 2 columns, without or with a vertical load due to the floor. Comparing the results of fiber reinforced samples with those without fibers when tested in the horizontal direction, it is observed that the addition of fibers does not increase the peak load, but on the other hand brings ductility to the overall behavior of the structure which is often desired in ULS conditions (Ultimate Limit State). We can note an average residual resistance of approximately 50 % of the peak load (i.e. 3.3 kN), which is coherent with the fraction of the residual stress at material scale, and this resistance is maintained up to relatively high deflection levels compared to the span of the element, i.e., approximately 10 mm of deflection (L /150).

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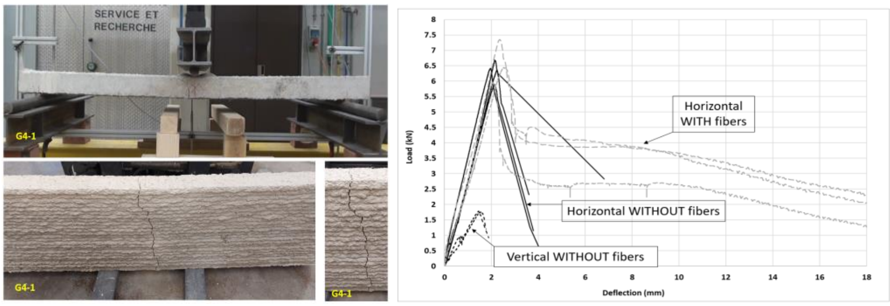

Graph 5: Load vs. deflection of scale 1 specimens tested in the horizontal and vertical directions under 3-Point bending.

4 Conclusion

The key conclusions of the present experimental study can be summarized as follow:

- 3D printed concrete has a lower compressive strength and E-modulus compared to cast concrete.
- 3D Printed concrete has the same flexure strength as cast concrete when tested in the horizontal direction. However, a slight reduction is found between superposed layers of around 30%.
- At scale 1, the load at failure is not equivalent to what is predicted at material scale. Therefore, specific safety coefficients for 3D printed structures must be defined.
- It is believed that thicker layers might improve the bending strength in the vertical direction of 3D printed walls at scale 1.

5 References

1. Joris Burger, Tobias Huber, Ena Lloret-Fritschi, Jaime Mata-Falcon, Fabio Gramazio, and Matthias Kohler, “Design and fabrication of optimised ribbed concrete floor slabs using large scale 3D printed formwork,” *Automation in Construction*, vol. 144, p. 104599, 2022, doi: https://doi.org/10.1016/j.autcon.2022.104599.
2. Gieljan Vantyghem, Wouter De Corte, Emad Shakour, and Oded Amir, “3D printing of a post-tensioned concrete girder designed by topology optimization,” vol. 112, p. 103084, 2020, doi: https://doi.org/10.1016/j.autcon.2020.103084.
3. Paul Carneau, Romain Mesnil, Nicolas Roussel, and Olivier Baverel, “Additive manufacturing of cantilever - From masonry to concrete 3D printing,” *Automation in Construction*, vol. 116, p. 103184, 2020, doi: https://doi.org/10.1016/j.autcon.2020.103184.
4. M. V. G. Silveira, J. S. Wagner, M. Khanverdi, and S. Das, “Structural performance of large-scale 3D-printed walls subjected to axial compression load,” *Can. J. Civ. Eng.*, p. cjce-2023-0395, Feb. 2024, doi: 10.1139/cjce-2023-0395.
5. Xiaoyu Han, Jiachuan Yan, Mingjian Liu, Liang Huo, and Junlin Li, “Experimental study on large-scale 3D printed concrete walls under axial compression,” *Automation in Construction*, vol. 133, p. 103993, 2022, doi: https://doi.org/10.1016/j.autcon.2021.103993.

6. S. Yu, M. Xia, J. Sanjayan, L. Yang, J. Xiao, and H. Du, “Microstructural characterization of 3D printed concrete,” *Journal of Building Engineering*, vol. 44, p. 102948, Dec. 2021, doi: 10.1016/j.jobe.2021.102948.
7. R. J. M. Wolfs, F. P. Bos, and T. A. M. Salet, “Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion,” *Cement and Concrete Research*, vol. 119, pp. 132–140, May 2019, doi: 10.1016/j.cemconres.2019.02.017.