3D Concrete Printing – from Mechanical Properties to Structural Analysis

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Abstract. Facing growing problems such as rising prices and shortage of skilled workers, additive manufacturing with concrete offers a promising solution for the construction industry. Increasing productivity through automated processes and reducing environmental impact by exploiting the novel geometric freedom as well as the use of sustainable printing materials are just some of the many advantages of the new construction technology. In order to establish concrete printing as a construction method for larger-scale structures, extensive research is required. From a structural engineering perspective, the basic printing methods, extrusion and particle bed, each with or without reinforcing elements, lead to structural behavior that differs from conventional structural concrete as their layer-by-layer production results in anisotropic material characteristics. While the focus of international research is mainly on mastering the printing process and the fresh or hardened concrete properties on small specimens, this study aims to propose a verification method for printed structural members that are primarily loaded by compressive forces. Recent studies on printed unreinforced large-sized structural members are evaluated and design concepts based on current standardization for unreinforced concrete and masonry walls are compared. Based on the results, their application for printed wall segments for the verification of load-bearing capacity is discussed to initiate standardization.

Keywords: 3D-Printing · Additive Manufacturing · Structural Design · Load-Bearing Behavior · Dimensioning

1 Introduction

Recent developments in additive manufacturing with concrete offer new opportunities for the construction industry and demand new designs for structural elements. Advantages of this technology include increased geometric freedom, reduced formwork and labor requirements, and faster building times. While extrusion printing of concrete has already been used to manufacture the first houses around the world, much of the ongoing research is focused on determining the mechanical properties of small-scale printed concrete elements. Further research is needed to establish concrete printing as a viable building method, particularly in terms of dimensioning and verification approaches to support the approval process. The research project "Innovative use of 3D printing technology in

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building practice using regionally available mineral resources and technology-adapted structures" (INNOBAU 3D) investigates additive manufacturing (AM) with concrete at Munich University of Applied Sciences (HM) together with the industrial partners PERI for extrusion printing and Fit AG for particle bed printing. With its interdisciplinary approach, it aims to develop new printing materials with regionally available recycled coarse aggregates, to optimize the tensile load-bearing capacity of the printing materials and to address the aforementioned issues by deriving possible dimensioning approaches from experiments carried out on small- and large-scale specimens. This article intervenes here and provides an overview of the current research on material characterization for structural analysis and discusses existing standardization approaches to derive design rules for 3D printed structures.

2 State of the Art

2.1 Characteristics of Printing Material

Previous research on extrusion printing with concrete has focused on the influence of process parameters or the effect of mix formulation and admixtures on the properties of the fresh mix or hardened components [1–3]. The horizontal joints of the printing process were identified as a significant parameter of hardened concrete properties at an early stage of the research, and the scientific community has made efforts to establish a meaningful experimental program covering all possible combinations of joint orientation and loading direction [4, 5]. A common feature of most publications is that predominantly small specimens, in particular mortar prisms and their fracture halves as proposed by DIN EN 196-1, are used to investigate the mechanical hardened concrete properties [6, 7]. Since an important aspect in the development of extrusion printing is the complex material development of a printable mixture and most printing mortars still work with comparatively small maximum grain size, the choice of this small specimen shape is evident. Yet, the transferability of the obtained values for applications in building practice is questionable since their usual dimensions exceed those of the mortar prisms significantly and prism dimensions are not necessarily in correlation with layer thickness.

While the influences of specimen size and shape are well-known for conventional concrete and empirical relationships have been derived from reliable data sets [8, 9], these relationships have not yet been sufficiently investigated for additive manufacturing processes and are likely to differ with variating parameters (e.g., grain size, layer thickness, printing nozzle, open layer time, …). Numerous publications on the mechanical properties of printed concrete show that the strength values, in particular the flexural tensile strength, decrease with increasing specimen size and highlight the need to perform large-scale component tests if the strength values obtained are to be transferred to load-bearing structural elements in real projects [10]. Both aspects, directionality and scaling effects, are also main issues addressed in an ongoing interlaboratory study of the technical committee *Assessment of Additively Manufactured Concrete Materials and Structures* (ADC) of RILEM [11]. Amongst numerous laboratories worldwide, HM is participating in this study to collect test data on the mechanical properties of printed concrete.

2.2 Additive Manufacturing in the Construction Industry

As clearly shown in [12], large-format printing with concrete is increasing significantly worldwide. The design and approval approach differ for those projects depending on the place of execution and the function to be assumed by the respective component: from furniture over lost formwork to support for slabs only geometrical requirements were fulfilled or full-scale testing was performed. Even though researchers are working intensively to integrate reinforcement into additive manufacturing with concrete [13, 14], the status in practice is different: the printed walls or columns are predominantly unreinforced elements.

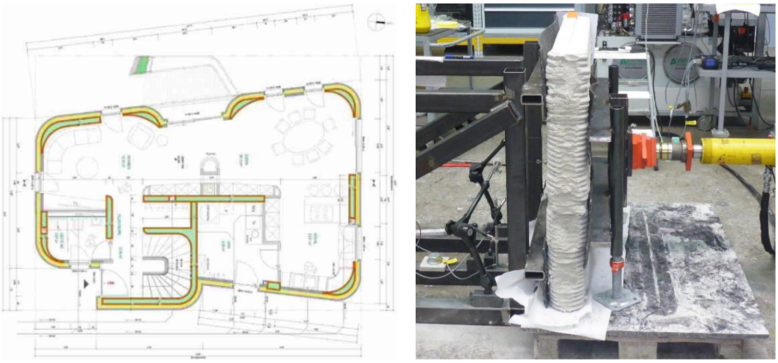

Fig. 1. Floor Plan of 3D printed house in Beckum [10] and large-scale testing [Documents provided by PERI]

In Germany, PERI 3D Construction GmbH, among others, is strongly involved in the development of 3D printing with concrete as an alternative to conventional construction methods. In 2020 the first house was printed in Beckum, where all vertical elements contain printed parts. However, the load transfer of vertical loads and the lateral bracing are ensured by unreinforced cores made of in-situ concrete, where printed strands served as lost formwork. For approval, several small- and large-scale tests were carried out in close coordination between the designer and the approving authority, which are summarized in [10, 15]. These allowed to derive the necessary design values of the material strength for the verification of the load-bearing capacity according to DIN EN 1996-3. The floor plan of Beckum representing the different existing wall types as well as one of the performed large-scale experiments for obtaining flexural strength values are represented in Fig. 1.

3 Small-Scale Testing

To evaluate the material parameters of wall elements printed by PERI, experimental investigations on small-scale specimens were conducted in the laboratory of the Munich University of Applied Sciences. Based on those results and derived conclusions on the material behavior, comparisons to other common construction forms - unreinforced concrete and masonry - are drawn on material parameters as well as their dimensioning approach. Deduced differences and similarities show the possible way forward to future design and dimensioning methods.

3.1 Experimental Set-Up

To determine the material properties, small-sized test specimens were cut from wall elements provided by PERI and used to characterize the mechanical properties of the hardened concrete. Wall elements from two different mixes were available: Mix A with a maximum grain size of 2 mm and Mix B with a maximum grain size of 4 mm. The printed strands are about 6 cm wide and 2 cm high. After printing, the specimens are kept protected from environmental exposition either at PERI for several months (Mix A) or on the building site (Mix B) for two weeks. On arrival at the university, the wall elements are stored under constant conditions (approx. 20 °C and 65% relative humidity) until testing. A few days before the execution of the experiments, the specimens are obtained by sawing (prisms) or core drilling (cylinders); the end faces of the cylinders are additionally ground to ensure plane-parallel load application.

The test program covered 3-point bending tensile tests on mortar prisms (40 mm × 40 mm × 160 mm) in accordance with DIN EN 196-1, compression tests on the resulting fracture halves of the previously tested prisms, and additional compression tests on small-sized cylinders (∅/h = 60 mm/120 mm). As the wall elements of Mix A contained curved and straight sections, the experimental program was extended to take into account this variation for the cylindrical specimens.

In all tests performed, the specimens were loaded in different directions in reference to the orientation of the printing layers. This allows to assess the influence of the layer boundaries and their bond strength on the load-bearing capacity of the section and whether orthotropic material models are required to describe the structural behavior. For clearly referencing the different directions the denomination proposed by [4] is used, where u represents the printing direction of the nozzles, v the direction perpendicular to u in the ground plan and w the vertical axis. For the experiments on flexural behavior, the nomenclature consists of two letters, the first indicating the loading direction and the last the orientation of the longitudinal axis of the tested prism. Fig. 2a reflects the chosen nomenclature.

3.2 Results

Figure 2b and Fig. 3 show the experimental results via boxplots, reflecting the individual data points and the arithmetic mean. While the influence of the direction is evident in the results of the flexural tensile test ($f_{y,v.u}(MixB) \approx 1,99 \times f_{y,u.w}(MixB)$, this effect is less pronounced for the compressive strengths ($f_{c,u}(MixA) \approx 1,37 \times f_{c,w}(MixA)$.

Furthermore, the compressive strength obtained with cylindric samples is significantly lower than the one of the fracture halves for Mix B. A longer specimen length compared to the maximum dimension in the thickness direction negatively affects the compressive strengths. This effect, well known from conventionally cast concrete, is caused by restrained deformation in transverse direction. While in the case of the prism-halves, a favorably acting three-dimensional stress state prevails almost over the entire

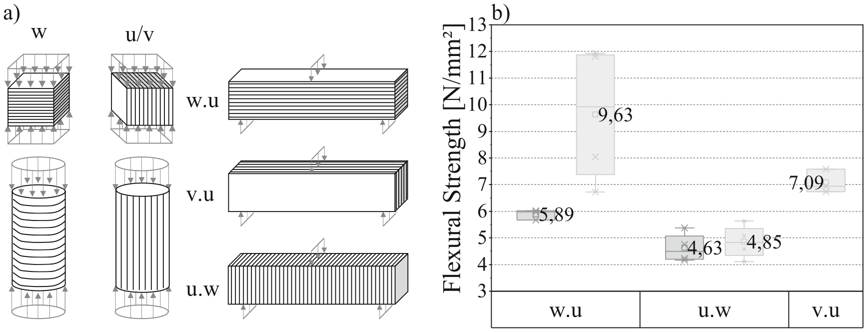

Fig. 2. a. Nomenclature of loading directions [4], b. Flexural strength in 3-point-bending

height due to the friction on the load introduction plates, this is hardly effective anymore in the case of the cylinder specimens in the middle of the height and the specimen fails at lower loads.

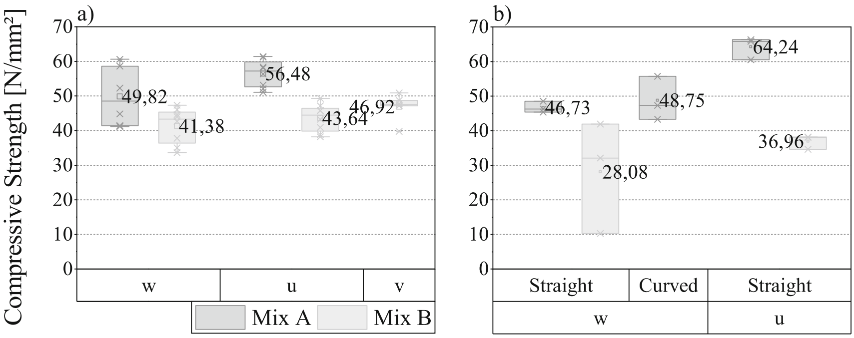

Fig. 3. a. Compressive strength on prism-halves, b. Compressive strength on cylinders

These results confirm previously published results on material behavior of extrusion-printed specimens. An anisotropic behavior is caused by the layering and needs to be considered in the structural analysis, especially when applying bending moments leading to tension perpendicular to the orientation of the layers.

4 Dimensioning Approaches in Existing Codes

For structural elements, the dimensioning approach in existing codes usually consists of two basics: obtaining material parameters based on experiments and a verification concept depending on the actions to be transmitted. For the first part, the literature review and own experimental results show that for additively manufactured elements an anisotropic material behavior must be considered and that obtaining the strength parameters only on small-sized specimens such as mortar prisms does not represent the construction reality in an appropriate way. For the latter one, it is crucial to differentiate between the different loading situations. A simple approach to enable load bearing in printed structures is to omit the poured concrete cores and assign the transfer of vertical loading to the printed wall segments, combined with horizontal efforts due to wind loads or lateral bracing. One of the resulting loading situations, on which the focus will be set here, is therefore a compression member with additional bending from lateral load or eccentricity, covered in the standardization for masonry (DIN EN 1996-3) and for concrete (DIN EN 1992-1-1) with simplified design approaches.

4.1 Material Parameters and Geometrical Constraints

Comparing printed walls to either masonry structures or conventional unreinforced concrete walls reveals some clear differences: while masonry is composed of two different materials, bricks and mortar, the latter is made of fresh concrete, a mixture of aggregates, cement, and other additives. At the component level, this material can be considered homogeneous. The material is poured into a formwork, and compacted, resulting at best in no horizontal joints within a wall height. Printed walls, on the other hand, lie between these two scenarios: the material is similarly uniform as for the conventional concrete wall, but the manufacturing process results in at least horizontal joints at a much smaller distance than in masonry. In most printing processes, the small nozzle sizes also result in a vertical joint between adjacent strands to achieve a reasonable wall thickness (s. Fig. 4). Whilst for concrete the compressive strength is obtained by testing cylinders (∅/h = 150 mm/300 mm) or cubes (d = 150 mm) following DIN EN 206, the standard for masonry offers an experimental setup in DIN EN 1052-1 considering the different joints as represented by Fig. 5. The specimen sizes depend on the actual size of the bricks used to ensure that at least one vertical joint in each horizontal layer and four horizontal joints are tested.

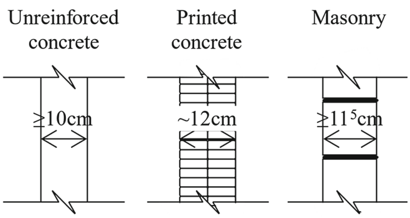

Fig. 4. Different construction principles with minimal dimensions

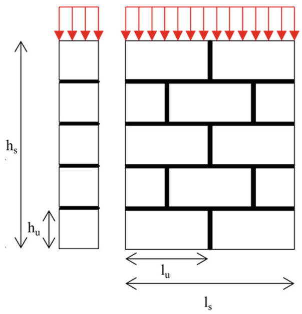

Fig. 5. Experimental setup for compressive strength on masonry wall segments [DIN EN 1052-1]

Regarding the prerequisites for the application of the simplified verification methods, it is notable that in both codes, minimum dimensions of the wall thickness are required as represented in Fig. 4. For precast concrete walls these are 10 cm, while poured in situ walls are starting from 12 cm width; for load-bearing interior walls of masonry 11^5 cm and for exterior walls without further restrictions even 17[5] cm are the required minimum. The printed inner shell of the building in Beckum with a wall thickness of 2 × 6 cm = 12 cm thus lies in an appropriate range.

4.2 Verification Concepts of Existing Standards

The existing standards for masonry DIN EN 1996-3 and concrete DIN EN 1992-1-1 offer simplified verification concepts for walls primarily subjected to normal forces. In both simplified design methods, the ultimate load - defined by the compressive strength multiplied by the cross-sectional area - is reduced by considering load eccentricities (eccentric support of slabs, rotation angle of slabs, or horizontal loads) and the sensitivity of the walls regarding buckling via a reduction coefficient Φ (s. Eq. (1.1) and (2.1)). For the comparison of the design concepts, the following assumptions are made:

– The floor slabs are supported on the printed wall elements over their entire *width (a* $= t = h_w =$ *12 cm).*
– Any occurring slab rotation is not introduced into the supporting walls by constructive measures e.g., an elastic inlay.
– The analysis is carried out for a wall with sufficiently large normal force, not for attics.
– Simplifying the support situation, the wall is to be considered as supported only on its top and bottom.

The main equations governing the two approaches are represented in Table 1 supplemented by a list of abbreviations in Table 2.

Table 1. Governing equations for the simplified verification of compression members

Masonry – DIN°EN°1996-3 + NA		Concrete – DIN°EN°1992-1-1 + NA	
$N_{Rd} = \Phi\, t\, f_d$	(1.1)	$N_{Rd} = \Phi\, h_w\, f_{cd,pl}$	(2.1)
$\Phi = \min\{\Phi_1; \Phi_2)$	(1.2)	Φ	(2.2)
$\Phi_1 (f_k \geq 1{,}8\, N/mm^2)$	(1.3)	$= 1{,}14\,(1 - 2\ e_{tot}/h_w) - 0{,}02\, l_0/h_w$	
$= (1{,}6 - l_f/6)\ a/t\ \leq 0{,}9\ a/t$		$\leq\ 1 - 2\ e_{tot}/h_w$	
$\Phi_2 = 0{,}85\ a/t - 0{,}0011\ (h_{ef}/t)^2$	(1.4)	$e_{tot} = e_0 + e_i + e_\varphi$	(2.3)
		$e_0 =\ M_0/N_0$	(2.4)
		$e_i = l_0/400$	(2.5)
		e_φ *may be neglected*	
$h_{ef} = \rho_2\, h$	(1.5)	$l_0 = \beta\, l_w$	(2.6)
with $\rho_2 = 0{,}75$ for $t \leq 175mm$		with $\beta = 1{,}0$ for two-sided support	

These two concepts were applied as a case study to the wall section of the Beckum project [10, 15], and several key differences were identified. Whereas the dimensioning approach of the concrete wall addresses horizontal loads through a linear load eccentricity e_0, the reduction factor for masonry walls does not take any horizontal loading into account. Here, additional conditions such as a minimal wall thickness - depending on the magnitude of the horizontal efforts, the compressive strength, and the resulting normal force (s. DIN EN 1996-3 Eq. 4.2) - and a minimal acting normal force (s. DIN EN 1996-3 NA.4) ensure that the cross-section remains compressed.

Table 2. List of abbreviations

Masonry – DIN°EN°1996-3 + NA		Concrete – DIN°EN°1992-1-1 + NA	
t	wall thickness	h_w	overall thickness of the cross-section
a	slab support depth	e_{tot}	overall eccentricity
l_f	span of the adjacent floor slab	e_0	load eccentricity (Th. I. O), see 5.8.8.2 (2)
Φ_1	Reduction Factor for eccentricity	e_i	unwanted additional load eccentricity due to geometrical imperfections, see 5.2
Φ_2	Reduction Factor for buckling	e_φ	eccentricity due to creep
h_{ef}	buckling length	l_0	buckling length
f_d	design-value of compressive strength for masonry	$f_{cd,pl}$	design-value of compressive strength for unreinforced concrete

The second major difference is the way how the standards address the slenderness and therefore resulting buckling sensitivity of the wall, essentially determined by the buckling length to be applied. To obtain the latter the national annex for masonry structures allows the reduction of the internal height by a factor of 0,75 for wall thicknesses below 17[5] cm, while the buckling length for an unreinforced concrete wall supported on the bottom and top is set to be equal to the internal height.

The diagram in Fig. 6 reflects the resulting reduction factor for different slenderness ratios according to the standards while completely omitting eccentricity ($\Phi_1 = 1$ and $e_0 = 0$). It shows that the admissible normal forces are reduced in a less pronounced way according to DIN EN 1992-1-1 than following the design approach for masonry (s. DIN°EN°1996-3). Considering the load eccentricity e_0 due to wind loads, this observation is no longer accurate and the reduction factor for concrete walls can drop to values lower than 10% for unfavorable ratios of large moments to small normal forces. This significantly low value questions the practicality of the simplified method, as it does not result in economic cross-sections.

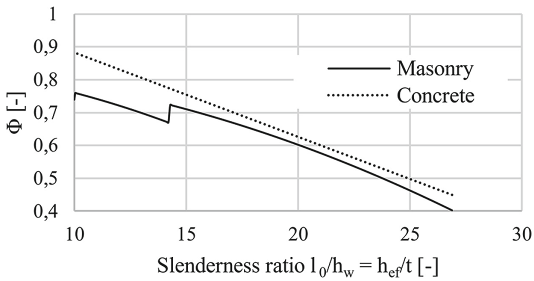

Fig. 6. Reduction factor over slenderness ratio

5 Transferability of the Design Approach to Printed Walls and Outlook

The present work offers a first approach to verify the load-bearing capacity of unreinforced printed structural elements predominantly subjected to normal forces. Transferring the observations made on the simplified design approaches to extrusion-printed walls offers the advantage that the verification is facilitated by only referring to compressive strength values in vertical direction. Thus, it is not necessary to analyze the flexural strength covering all possible combinations of loading vs. layer orientation. Nevertheless, one needs to question which approach to choose for handling horizontal efforts because the one proposed in DIN EN 1992-1-1 tends to have quite unfavorable reduction factors for high horizontal forces combined with low vertical loading.

Furthermore, to obtain reliable material parameters and establish a suitable experimental program extensive studies are required on specimens of different sizes. Based on those empiric data a convergence study can be performed to identify the minimal required sizing for appropriate specimens. The resulting sizes depend on the material (e.g., maximum grain size) and the process parameters (e.g., printing width and height), but also on the governing loads (compression or bending) in the section.

To make 3D printing even more competitive as a manufacturing method in the future, it is a promising approach to transfer load-bearing functions to the printed wall elements to eliminate the need for in-situ concrete supplements in vertical elements. To develop a proper verification concept and thus facilitate the approval process large-scale experimental investigation will be carried out. It will be investigated which of the two presented concepts offers a sufficient level of safety for different boundary conditions (such as different loadings) without leading to uneconomical solutions. This aspect will not only be considered for straight wall elements, but also for curved ones, knowing that the additional geometric stiffness will have a favorable effect on the transfer of horizontal loads and the risk of buckling. Thus, one of the great advantages of 3D printing, the geometrical freedom, is taken into account and advantageously considered in design rules. Another aspect, that will be addressed by future research is the integration of reinforcement to expand the possibilities of 3D printing in the construction industry and offer dimensioning approaches for those reinforcement strategies.

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