3D Concrete Printing on Site: A Novel Way of Building Houses?

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Abstract. As a result of the constantly increasing world population and its purchasing power, it becomes more and more clear that raw materials are finite and the capacity of the earth to renew the stock of raw materials is almost exceeded. This is also important for construction industry as half of the extracted materials and about one third of the water consumption is absorbed by this sector. During the last years, a lot of progress has been made in creating more energy efficient buildings, but unfortunately, construction represents at this moment still 40% of the energy demand in Europe and 36% of the total CO_2 emission [1]. However, the construction sector offers significant potential to handle these struggles and a possible solution to improve the sustainability is through automated construction by for example 3D printing the structural components. This new way of manufacturing has the advantage that there is no need for energy demanding and expensive molding, there is a larger freedom of form and there is the opportunity to use the material in a more eco-friendly way since it is only used where necessary. However, before acceptance of this technique on the construction site, it is necessary to compare the structural behavior of printed and cast specimens. For that reason, two wall types were tested on their compressive strength and also two types of reinforcement above a window opening were investigated through 3-point bending tests. These results showed that, in general, the mechanical performance of the suggested wall types is greater than that of traditional walls consisting of brickwork. This, in combination with the lack of molding and the higher construction speed, can accelerate the application of 3D printing on site.

Keywords: 3D printing on site · Construction · Mechanical performance

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1 Introduction

The development of digital construction processes for the production of concrete components and structures directly on the construction site is a decisive step towards the introduction of the "industry 4.0" concept into the construction industry. The technological and economic potentials (accelerated construction time, lack of formwork, reduced construction cost, etc.) of digital concrete construction have now been recognized by many industrial stakeholders and the extend of innovation in this field is increasing month by month.

Most current applications of 3DCP are driven by original architectural and design concepts, which require novel production techniques. However, considering today's mainstream demands with respect to architecture and structural design, high geometrical complexity is not the main priority of the construction industry and more attention should be paid to real-scale, mainstream applications.

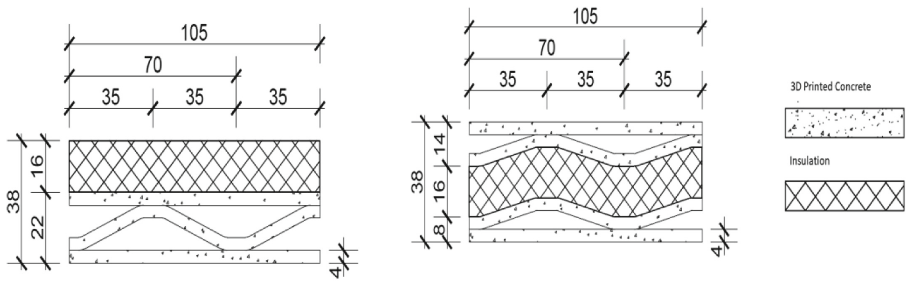
Before full acceptation of this technique on the construction site, it is necessary to compare the behavior of printed and traditional fabricated structural elements. For that reason, two different wall types (i.e. structural wall and isolated wall) were tested on their compressive strength and also two different types of reinforcement (i.e. reinforcement bars and a reinforcement mesh) above a window opening were compared through 3-point bending tests. These results showed that, in general, the mechanical performance of the suggested wall types is higher compared with a traditional wall consisting of brickwork. This in combination with the lack of molding and the higher construction speed, can accelerate the application of 3D printing on site.

2 Materials and Methods

2.1 Mix Composition and Print Process

The material used for this research (Weber 145-1) has been developed by Saint-Gobain Weber Beamix. To fulfill all the requirements [2] with regard to printing, the material consists out of Portland Cement (CEM I 52.5 R), a siliceous aggregate, limestone fillers, rheology modifying agents and a small amount of polypropylene fibers to reduce the crack formation [3]. The water-to-dry mortar ratio used in this research equals 0.15. The structural components were printed by using a 4-degree of freedom gantry robot (BOD2), developed and designed by the company 3D Printhüset (Copenhagen). During this research, a rectangular nozzle ($40 \times 15\ mm^2$), equipped with side towels and grooves, was used. The layer height and applied printing speed equal 15 mm and 150 mm/s.

Within the scope of this research, two essential structural components (i.e. wall and window lintel) were tested in order to make the comparison with traditional constructions. The first test series consists out of two different wall types. More specifically, a structural and an insulated wall type were tested and the geometry of both elements is represented in Fig. 1(a, b). The height of the specimens equals in both cases 66 cm. In the second test series, two alternatives to reinforce the window lintel were tested. More specifically, reinforcement bars (Ø 10 mm) were integrated above the window opening in the first test setup, while the second alternative was the integration of a small reinforcing mesh (MURFOR Compact E, Bekaert). Both types of reinforcement were integrated manually during printing and the geometry of these elements is given in Fig. 2.



(a) (b)

Fig. 1. Top view of the different wall types: (a) structural wall and (b) insulated wall (dimensions in [cm])

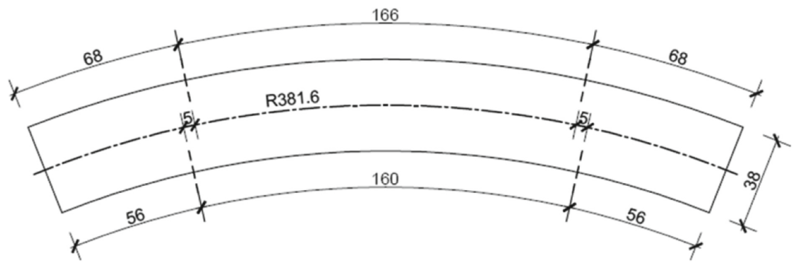


Fig. 2. Top view of the printed specimens, fabricated to investigate two reinforcement alternatives above a window opening (dimensions in [cm])

2.2 Compressive Strength

The mechanical performance of both, the structural and insulated wall, was tested by means of a compression test. The compressive strength f_c [kN/m^2] (Eq. (1)) was measured for two specimens loaded perpendicular to their print direction during a load controlled test at a rate of 1 kN/s. To obtain representative results, the evenness of the top and bottom surface plays an important role and, therefore, both surfaces were smoothened before testing and a hardboard was used during the compression test to ensure a uniform distribution of the load.

$$f_c[KN/m^2] = \frac{F}{A} \quad (1)$$

Within this formula F [kN] is the failure load and A [m^2] is the actual area of the printed specimen on which the load is acting.

2.3 3-Point Bending Test

The failure load F_t [kN] of the printed elements with reinforcement was measured by performing a 3-point bending test (Fig. 2). During this test, the load was applied by using a hydraulic jack (10 ton Amsler jack), placed centrally on an I-profile. The loading speed for both test specimens was equal to 1 kN/s. In addition to the breaking load, the vertical displacement at 6 different positions was measured by using Linear Variable Differential Transformers (LVDT's) (Fig. 3).

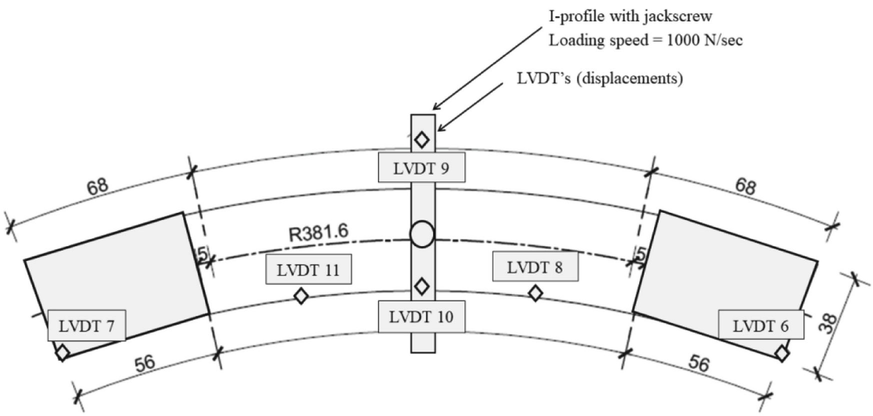


Fig. 3. Top view of the of the test setup, including the LVDT positions (dimensions in [cm])

3 Results and Discussion

3.1 Compressive Strength

Table 1 represents the failure load of the different wall types measured during the compression test. Based on this, one can conclude that the compressive strength of both wall types is by approximation the same. In case of a traditional wall, built up from building bricks (288 × 188 × 138 mm), the compressive strength equals approximately 20 MPa [4]. Comparing the latter with the results mentioned in Table 1, one can conclude that the mechanical performance of the printed specimens is much better compared to the traditional construction way. As the height/width ratio is kept similar for both wall types, the failure mechanism during the compression test is the same (Fig. 4).

Table 1. Failure load of the different wall types measured during compression test

		Structural wall		Insulated wall	
F	[N]	2012370	2126700	2711500	3324250
A	[mm^2]	66000	53000	86000	98000
f_c	[N/mm^2]	30.49	40.13	31.53	33.73
$f_{c,mean}$	[N/mm^2]	35.31		32.63	

(a) (b)

Fig. 4. Failure mechanism in case of (a) structural wall and (b) insulated wall type

3.2 3-Point Bending Test

Table 2 represents the failure load of the different wall types and the corresponding displacement measured during the 3-point bending test. One can conclude that the addition of a reinforcement bar resulted in a higher failure load compared with the introduction of a reinforcement mesh, which is also represented in the load-displacement curves of both reinforcement alternatives (Fig. 5). Comparing these results with a traditional lintel, placed above a window opening, which has a failure load of approximately 25 kN [5], the results are higher for both. Figure 6 gives an overview of the specimens after failure.

Table 2. Failure load measured in case of two alternatives for window lintels (i.e. reinforcement bars and mesh)

		Reinforcement bars	Reinforcement mesh
F_t	[kN]	65.62	33.74
LVDT 6	[mm]	16.96	9.25
LVDT 7	[mm]	12.30	7.62
LVDT 8	[mm]	−6.69	−11.24
LVDT 9	[mm]	−13.12	−16.07
LVDT 10	[mm]	−11.63	−17.83
LVDT 11	[mm]	−6.49	−12.29

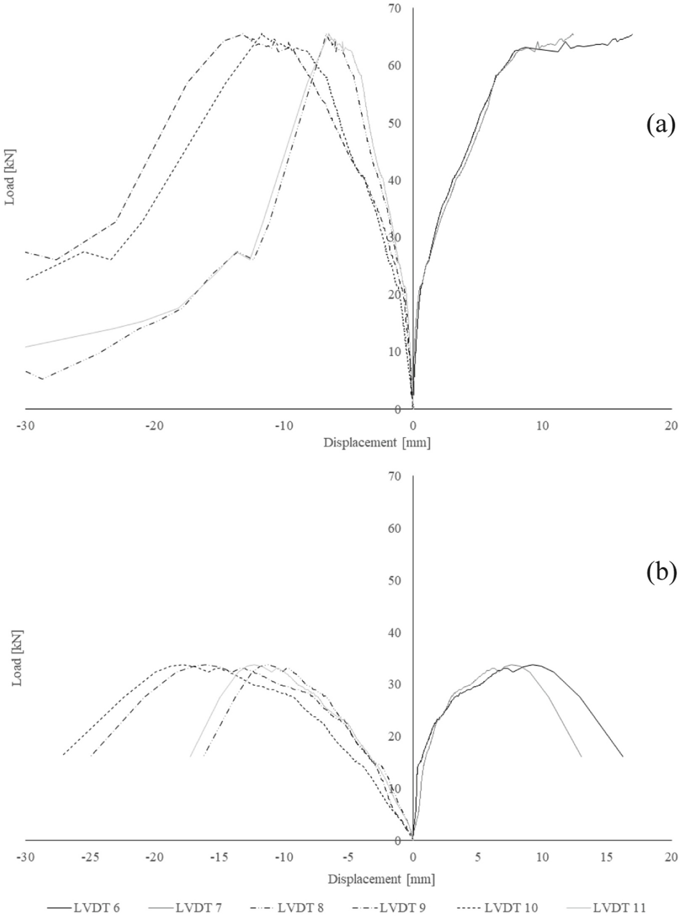


Fig. 5. Load-displacement curves for two reinforcement alternatives: (a) rebars and (b) reinforcement mesh

(a) (b)

Fig. 6. Failure mechanism for two alternatives: (a) the introduction of rebars and (b) reinforcement mesh

4 Conclusions

Within the scope of this research, printed alternatives for two constructive aspects (i.e. traditional masonry and the introduction of a lintel above window openings) of a traditional house are investigated. The following conclusions could be drawn:

- The mechanical performance of the structural and insulated wall type, measured by means of a compression test, do not differ in a significant way;
- The compressive strength is for both wall types higher than the compressive strength of a wall erected by means of traditional masonry;
- The load at failure of the lintel alternatives is in both cases higher than the traditional one;
- The addition of reinforcement bars results in the best option in case of printing window openings.

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