Composite concrete columns of 3DP concrete and self-compacting concrete subjected to normal force

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Abstract. Conventional concrete columns are cast in forms made of steel or wood. The work of erecting and dismantling the formwork is time-consuming and laborious. Steel forms can be used several times but wood forms are usually only used once or a small number of times but in both cases additional materials are necessary for completing the columns. By using 3D Printed Concrete (3DPC) as lost forms, the work can be more efficient. If composite action between the form and the concrete core can be reached, also material savings with connected reductions in CO_2 emissions can be achieved by combining a high performance concrete form with a concrete core of moderate strength. The process can be even more efficient by using Self Compacting Concrete (SCC) in the core.

One BSc and one MSc thesis project on small specimens of this type has been conducted with promising result at KTH. That led to the successful application of a larger experimental program containing both load tests and tests on durability. This paper focuses on four composite and two homogeneous SCC beams that were produced and subjected to normal force up to failure. The specimens were 3 m long and had a circular cross section with a diameter = 0,3 m. The composite columns reached failure loads that corresponded well to the ones of the homogeneous columns. After the loading tests, the bond between the form and the core was tested using pull-off tests of cores drilled from the columns in areas without failure zones. The average bond strength value was 1,75 MPa which is in the same range as frequent values in laboratory tests of bond between concrete and concrete and an additional indication of composite actions.

Keywords: 3DPC, Bond Strength, Composite Columns, Load Tests, SCC.

1 Introduction

1.1 The Problem and Its Possible Solution

Columns constitute one of the major structural members and are often the ones that carry the vertical load in buildings and bridges. Since the column is mainly compressed, concrete is very competitive for columns. Concrete columns are cast in forms of steel or wood. Erecting and dismantling the forms is time-consuming, laborious and thus also expensive. Steel forms can be used several times but wood forms rarely more than once or twice. The use of forms leads to additional materials, costs and CO_2 emissions. By using 3D Printed Concrete (3DPC) as lost forms, savings would be possible regarding labour, cost, CO_2 emissions, and time. If composite action between the 3DPC form and the cast concrete inside the form can be shown and guaranteed, the total amount of concrete can be reduced.

Currently, 3DPC mixes contains a high amount of cement due to a limited maximum aggregate size. If the 3DPC form could provide a dense and durable shell to the interior reinforced concrete core, it would be possible to reduce the cement content in the concrete core and, hence, make it possible to reach a total cement content that is less than the one in a corresponding homogeneous concrete column.

1.2 Previous Research

3DPC columns have been treated by architects or researchers in architecture to make other shapes than vertical columns with circular or rectangular cross sections possible [1, 2, 3]. Zhu et al. [4] studied short (h = 600 mm) composite concrete columns consisting of a lost 3DPC form and conventionally cast concrete. They concluded that the composite columns were able to carry loads of the same magnitude as monolithic columns cast with the same concrete as the core in the composite ones.

Chen et al. [5] investigated also short (h = 630 mm) composite concrete columns. In contrast to the study cited above, they studied columns with square shaped cross sections instead of circular ones. Their results were less promising. The obtained failure load did not reach the load-carrying capacity for a composite column working monolithically. However, for the best specimens, the failure load exceeded the load-carrying capacity of the conventionally cast concrete core inside the lost 3DPC form.

Raza et al. [6] produced precast concrete columns in segments, where each segment was made by a lost 3DPC form. They studied two columns of this type for seismic load and reached promising results.

The technology to produce composite columns is not new. Concrete cores cast in steel pipes have been and are still used. In Sweden, Grauers [7] tested composite columns of that type. She noticed that the bond between steel and concrete was decisive for the structural performance. If only the steel pipe was loaded in the case without bond, the column behaved as a hollow steel column without any contribution from the concrete.

1.3 Aims and Limitations

The main aim of the current project was to determine the load-carrying capacity of composite concrete columns consisting of a lost 3DPC form and a Self Compacting Concrete (SCC) core and compare the obtained values with corresponding ones developed by homogeneous SCC columns of equal size and strength. A second aim was to study if a loading surface limited to the size of the core would lead to any differences between the composite column and a homogeneous one.

The tests were limited to four composite and two homogeneous columns, all with equal dimensions and cast with just one concrete mix for the SCC and just one for the 3DPC. The slenderness (measured as height H divided by diameter Φ) was limited to $H/\Phi = 3{,}0/0{,}3 = 10$ eliminating any risk of buckling. The columns were reinforced but due to practical reasons the reinforcement amount was less than stipulated by Eurocode 2 [8].

2 Pilot Studies at KTH

2.1 First BSc Thesis

The first pilot test was conducted during spring 2021 at KTH Royal Institute of Technology in co-operation with the companies ConcretePrint (providing the printer and 3DPC mix) and Betongindustri (providing the concrete) [9-11]. The tests consisted of four wall elements with the dimensions $L \times b \times H = 1{,}0 \times 0{,}3 \times 1{,}08$ m^3 with thickness t = 50 mm of the lost 3DPC form. Two lost forms were filled with conventional concrete and two were filled with SCC. The casting results were satisfactory and after the tests an average bond strength = 0,86 MPa between the concrete and the 3DPC was determined through pull-off tests on cores taken from the specimens.

2.2 Second BSc Thesis

The second pilot test was conducted during autumn 2021 with the same parties involved as in the first one [10-12]. This time, four cylindrical columns with height H = 2,4 m, diameter Φ = 0,5 m and a form thickness t = 50 mm were cast. The aim was to see if it was possible to print lost forms with the height of 2,4 m and fill them with SCC without leading to collapse or leakage due to the formwork pressure when casting the SCC. The aim was fulfilled. The formwork pressure was close to fully hydrostatic pressure but in a cylindrical form with such a small diameter, the ring force causing tensile stresses is so small that these are far below the concrete tensile strength [10].

The night after the SCC casting (Dec. 17), the temperature dropped 10 degrees to -5,8°C during 18 hours. That led to cracking of the 3DPC form. The lesson learned is that temperature differences between the hardened 3DPC form and the new-cast concrete core have to be considered, especially during wintertime.

3 Column Tests

3.1 Test Specimens

The tests specimens consisted of six cylindrical columns with height H = 3,0 m and diameter Φ = 0,3 m. Two of the columns were cast in cardboard forms solely with SCC while the other four consisted of lost 3DPC forms with a thickness t = 40 mm and a core of SCC (Fig. 1a). The lost forms were printed by the company Concrete-

Print on August 23, 2023. SCC was placed by the ready mix concrete company Betongindustri in the forms on September 22, 2023. These operations were both carried out in Tumba, 25 km south of Stockholm City. On October 24, the columns were transported to Borås (410 km south of Stockholm) for loading tests.

Each column was reinforced with four vertical Φ8 mm bara and 10 Φ5 mm rings with a spacing of 320 mm. The vertical reinforcement exceeded the minimum reinforcement according to Eurocode 2 [8] while the ring reinforcement was spaced less densely than required due to practical reasons (too narrow space inside the forms).

Of both the concrete for 3DP and the SCC, standard cylindrical test specimens with h = 300 mm and Φ = 150 mm were cast for measuring compressive strength f_{cc} and modulus of elasticity E_c. Please, not that the test specimens made of the concrete for 3DP were cast and not printed. The way to produce the specimens will of course influence the strength but it is still interesting to know the strength of the material itself also for a concrete that is printed and not cast.

(a) (b)

Fig. 1. (a) Four 3DPC forms and one cardboard form ready to be filled with SCC. (b) Column V after failure.

3.2 Concrete Mixes

The constituents for the concrete mixes used are shown in Table 1. The anticipated 28-day compressive strength of the concrete for 3DP and SCC was 40 and 35 MPa, respectively.

Table 1. Concrete mixes. Values in kg/m³.

	Mix for 3DPC	Mix for SCC
Cement	625	325
Limestone filler		83
Water	312	195
Gravel 0-4 mm	1350	
Gravel 0-8 mm		1032
Gravel 8-16 mm		785
Air entraining agent	1,35	
Superplasticizer	X	4,45
Accelerator	X	
Other chemicals	X	
Total	2288	2324
w/c	0,50	0,60

Note: X = amount is a trade secret.

3.3 Loading

The loading tests of the columns were conducted between October 31 and November 3, 2023, at the RISE laboratory in Borås. The age of the 3DPC forms and the SCC was 69-72 days and 39-42 days, respectively. The columns were tested vertically and the boundary conditions could be regarded as simple supports at both top and bottom.

One variable in the loading tests was the size of the loading area at the top of the column. A load covering the entire circular cross section was compared with a load covering only a centrally placed part of the cross section (cf. Sections 1.2-1.3). In the latter case, the loaded area was a circle with the diameter 200 mm aiming at just covering the SCC core in the tests on composite columns.

The load was applied until failure in 350 kN steps. Every step started with a successive load increase with a velocity of 150 kN/min. After each load increase, the load was kept constant during 2 minutes. Load, deformation and strain in two reinforcement bars were registered continuously.

4 Results

4.1 Compressive Strength

The average concrete compressive strength of the SCC was 36,7 MPa at 28 days and 43,8 MPa at 41 days (i.e., at the age of loading tests). The average concrete compressive strength of the concrete for 3DP was 37,3; 49,5 and 56,3 MPa at 28, 29 and 69-70 days, respectively. The reason for the low values at 28 days has not been found. 49,5 MPa is closer to the anticipated value for a concrete with $w/c = 0{,}5$ and also in relationship to the value at 70 days. The modulus of elasticity of the SCC and the concrete for 3DP was 31,8 (at 28 days) and 32,2 GPa (at 29 days), respectively.

4.2 Ultimate Loads

The obtained ultimate loads (Fig. 1b) varied between 1370 and 2529 kN (Table 2). The difference in ultimate load was not between composite and homogeneous columns but between columns loaded with a large and small loading surface. The columns where the entire cross section was loaded failed at loads between 2074 and 2529 kN. The columns where only an inner part of the cross section was loaded failed at substantially lower loads (between 1370 and 1411 kN, or 60 % of the average of the other three columns).

The most likely reason to the difference between these two groups of columns is eccentricity. An eccentricity of 24 mm would theoretically reduce the failure load with 40 % [13]. At the loading tests, all possible efforts were made to minimize the eccentricity, but some deviations are inevitable. The strains were measured in two opposing reinforcement bars and trials were made to estimate the eccentricity from the measured strain values. Values between 5 and 20 mm were determined but no indication of higher values in the columns with lower ultimate loads could be found.

The simplest way to estimate the load-carrying capacity of a column is to multiply the cross-section area with the compressive strength. In our case, the calculated failure load would be somewhere between 3000 and 3500 kN [13]. One possible explanation to the difference is the mentioned eccentricity. Another possible explanation is that the strength of the SCC in the columns was less that the strength of the small cast cylinders used for the compressive strength tests. Filling a 3 m high and reinforced form with a diameter limited to 0,3 m is not that easy and may have resulted in a strength not fully equalling the one obtained from the compressive strength tests.

Table 2. Ultimate loads, deformations & failure types.

Column No.	Type	Diameter of loading area (mm)	Min. circumference (mm)	Ultimate load (kN)	Deformation at ult. load (mm)	Failure location
I	Composite	300	990	2240	6,8	Top
II	Composite	200	1005	1410	3,1	Top
III	Composite	200	1005	1411	4,6	Top
IV	Composite	300	970	2529	8,2	Bottom
V	Homogenous	300	945	2074	14,7	Bottom
VI	Homogenous	200	945	1370	4,3	Top

4.3 Bond Strength

After the loading tests, the bond strength was evaluated though pull-off tests on cores drilled from undamaged zones of the tested columns. Twelve cores were taken. The average failure stress was 1,75 MPa which is in vicinity of what could be anticipated in the laboratory and higher than the values obtained in the pilot studies at KTH. In five cases, the failure mode was at least 50 % in the interface between the two concrete parts. The average strength of these cases was 1,54 MPa, which also exceeds the recommended threshold value of 1,0 MPa.

5 Concluding Remarks

Based on the conducted loading tests on the composite columns and corresponding homogeneous ones, the following conclusions can be drawn:

1. Composite concrete columns consisting of a lost 3DPC form and a SCC core are able to carry equal compressive forces as corresponding homogeneous SCC ones.
2. The bond strength between the two different concrete parts is sufficient to develop monolithic action. This was shown at the loading tests where only the SCC core was loaded.
3. The bond strength between the lost 3DPC form and the SCC was measured to 1,75 MPa, substantially exceeding the value of 1 MPa that is often used as a limit value for composite action.
4. The technology with lost 3DPC forms filled with SCC is promising and more tests are needed. If it can be shown that the 3DPC form has superior durability, the SCC can be made with reduced cement content resulting in total cement and CO_2 emissions reductions. Tests on the durability are currently performed at KTH and will be reported elsewhere later this year.

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