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Form Pressure in Composite Columns of 3DPC and SCC

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ABSTRACT
Self-compacting concrete (SCC) and 3D printed concrete (3DPC) are two exciting technologies with potential to increase both the productivity and the working environment in the concrete industry. Permanent 3DPC formwork filled with SCC constitutes an interesting alternative for columns. The goal is to create a composite column with complete bond between the form and the core. Laboratory studies on composite columns of this type have been conducted at KTH investigating form pressure, load-carrying capacity, and durability. This paper is focusing on the form pressure that has been an issue ever since SCC was developed in Japan in the early 1990s because of the flowing nature of this concrete type. Two tests series have been performed. In the first one, two 2.4 m high composite columns with radius R = 0.25 m were tested. The casting rate was 2.6 m/h and resulted in a form pressure approaching full hydrostatic pressure but no form failures or any leakage arose. In the second test series, four composite columns with height h = 3.0 m and R = 0.15 m were cast at a casting rate r = 1 m/h. The form pressure was close to the one calculated with Gardner's model. No failures, cracks or leakage occurred. The results are promising but tests on columns with larger dimensions would be of even larger interest.

Key words: Composite concrete columns, SCC, 3DCP, form pressure, measurements.

1. INTRODUCTION

Formwork constitutes a laborious moment during both formwork construction and removal. If wooden formwork is used, it can rarely be used more than two or three times, which also leads to both economic and environmental costs. A new idea to produce concrete columns is to use 3D printed concrete (3DPC) to produce permanent formwork and fill it with conventional or self-compacting concrete (SCC). This technology has been investigated by, e.g., Zhu et al. [1], Chen et al. [2] and Raza et al. [3]. At KTH, we have carried out experimental research on 3DPC column forms filled with SCC since 2021 [4-7].

Both 3DPC and SCC are fairly new technologies and have potential to improve the productivity in the construction industry substantially. SCC has several advantages, e.g., eliminated vibration, improved working environment, and ease to fill also forms with large amount of reinforcement. The drawbacks are higher material cost than conventional concrete and vulnerability for disturbances that may appear during transport from the ready mix concrete plant to the construction site and weather conditions at the site. The market share of SCC is much higher for precast concrete than for concrete cast-in-place since the precast concrete factory fully controls the entire process [8].

There are several advantages with 3DPC:

1. An automatic printing process leading to improved productivity.
2. A process moving heavy working moments from the workers to the robot leading to an improved working environment.
3. Possibilities to make concrete structures where "form follows force" and thus a material optimization.
4. New architectural expressions.
5. Fewer construction errors and less material waste.

The problems the 3DPC industry has to solve deal with (i) reinforcement placing, (ii) the current high cement content in the concrete mix (due to printing nozzles limiting the maximum aggregate size), (iii) the interface between the printed layers, and (iv) the striped expression made by the layers.

The aim of the tests at KTH was to investigate the possibilities to produce composite columns of 3DPC and SCC, their load-carrying capacity, the bond between 3DPC form and the SCC core, and the durability of the composite column. This paper focuses on form pressure which is an important part of the production phase. Results and conclusions regarding load-carrying capacity, bond, and durability have been published in the references [4-7].

2. THEORY

2.1 Calculation of form pressure

An important aspect to consider when using 3DCP forms is the form pressure. If the casting rate is high, the form pressure will be close to hydrostatic pressure. If using SCC, which has high flowability, the probability of hydrostatic pressure increases. The form pressure may, however, be lower than hydrostatic pressure due to both thixotropy and structural build-up [9].

The hydrostatic pressure of SCC can be estimated with the following equation:

$$p = \rho g h \tag{1}$$

where, ρ is the density of the liquid, g is the gravity constant (g = 9.81 m/s^2), and h is height of the form (or distance to the top level of the latest concrete lift). For concrete, the dead weight is frequently expressed as γ given by the product $\gamma = \rho g$. A frequent value for concrete is $\gamma = 24$ kN/m^3 = 0.024 MN/m^3. Concrete mixes with high water content will have a lower dead weight and mixes with heavy aggregates a higher one.

In a cylindrical container with radius R, an interior pressure p will give a circumferential or ring force F (expressed in N/m) that can be determined by the following equation:

$$F = pR \tag{2}$$

The ring force is a tensile force that in turn will give tensile stresses σ_t in the circumferential direction. If the cylinder has a constant thickness t, the maximum tensile stress can be determined with the following equation:

$$\sigma_t = F/t = pR/t = \gamma hR/t \tag{3}$$

For a cylindrical concrete form with $R = 0.15$ m, $t = 0.04$ m, and $h = 3.0$ m, full hydraulic pressure will lead to a tensile stress $\sigma_t = 0.27$ MPa which is much less than an anticipated value of the tensile concrete strength ≈ 2 MPa. In theory, we may give such a column a height $h = \sigma_t \cdot t/(\gamma \cdot R) = 2 \cdot 0.04/(0.024 \cdot 0.15) = 22.2$ m before it reaches its tensile strength.

The problem will be much more severe in real bridge columns that may have a diameter exceeding 1 m. It ought to be mentioned that it is more difficult to estimate the form pressure in other types of forms, e.g., rectangular ones. The determination of stresses in the corners can hardly be made by hand-calculations. The multi-axle stress state implies that the strength may differ from the uniaxial strength that is measured on test samples in the laboratory and defines the strength values tabled in the codes. The multiaxial stress state and the size effect lead to increased complexity that leads to problems that preferably are analysed by advanced FEM programs.

The concern of high tensile stresses due to form pressure is sometimes exaggerated. If we analyse Eq. 3, we see that all variables (γ, h, R, and t) have the same importance. A small radius is as important as a large thickness. In order to show this, the author made a simple test with a liquid-filled paper tube or cylinder (Figure 1). The paper cylinder had the dimensions $R = 12$ mm, $t = 0.093$ mm and $h = 290$ mm. A coloured liquid (wine) was used to improve the contrast between liquid and paper. The value of γ for wine $\gamma = 9.8$ kN/m^3. The tensile stress $\sigma_t = \gamma hR/t = 9.8 \cdot 0.29 \cdot 0.012/(0.093 \cdot 10^{-3}) = 367$ kPa which slightly exceeds the tensile strength of paper (≈ 200 to 300 kPa). However, as seen in Figure 1, the paper cylinder was able to carry this form pressure without collapsing.

 

Figure 1 – Column tests with paper cylinder, before (left) and after filling with wine.

2.2 Form pressure by SCC

General

The liquid properties of fresh SCC have since its origin in the early 1990s caused concern regarding form pressure. A liquid with the density 2.4 times higher than water may constitute high hydrostatic pressure in wall and column forms. However, extensive experimental research has shown that the form pressure in many cases is substantially lower than full hydrostatic pressure if the casting rate is not too high. The reason is a combination of thixotropy and structural build-up. In the Nordic countries, Peter Billberg's research on form pressure generated by SCC [9] is a large source of information.

In 2012, very interesting field tests were conducted at the Swedish Cement & Concrete Research in Stockholm [10]. During four days, a total of eight walls with the height either 4.2 or 6.6 m were cast and instrumented. A number of international researchers participated in the project and eight different calculations methods for form pressure were evaluated through comparisons with the measurements. One of these methods was the one developed by Gardner et al. [11]. It is also one of the simplest and most practical ones. In Sweden, it has been used to compare measurements on a Swedish wall at the Härnösand prison [12]. Gardner's method is summarized in the next subsection.

Gardner's method [11,13]

A key parameter is the slump flow *SF* of the SCC. By measuring the slump flow at different times after casting, a time t_0 representing zero slump can be estimated.

$$t_0 = t_{400} \cdot \frac{SF_\mathrm{i}}{SF_\mathrm{i}-400} \tag{4}$$

where, SF_i is initial slump flow and t_{400} is time at which SF is 400 mm.

In the latest version of his model, Gardner [13] based it on a parameter t_E instead of t_0. He defined t_E as the setting time. t_E seems, however, to have the same meaning as t_0.

The form pressure $p = p(t)$ is calculated as:

$$p(t) = \begin{cases} \gamma r \cdot \left(t - \frac{t^2}{t_E}\right); t < t_E/2 \\ \gamma r \cdot \frac{t_E}{4} = p_{\max}; t \geq t_E/2 \end{cases} \tag{5}$$

where, r is casting rate (measured in m/h). If the time $t_h = h/r$ to fill a form with height h is less than $t_E/2$, the maximum pressure is limited to:

$$p_{\max} = \gamma r \cdot \left(t_h - \frac{{t_h}^2}{t_E}\right) \tag{6}$$

The maximum pressure will never exceed full hydrostatic pressure, i.e., $p_{\max} \leq \gamma h = \gamma r t_h$.

Example
Let us consider an example with a cylindrical column form with height $h = 3.0$ m and radius $R = 0.15$ m. Let us further assume that $t_E = 3.5$ h. We investigate form pressure for two different casting rates; $r = 1$ m/h and $r = 3$ m/h. The maximum form pressure according to Eq. 5 is 21 and 63 kPa, respectively. The development of form pressure for this example is shown in Figure 2. Full hydrostatic pressure is in both cases 72 kPa. The influence of a slow casting rate is obvious.

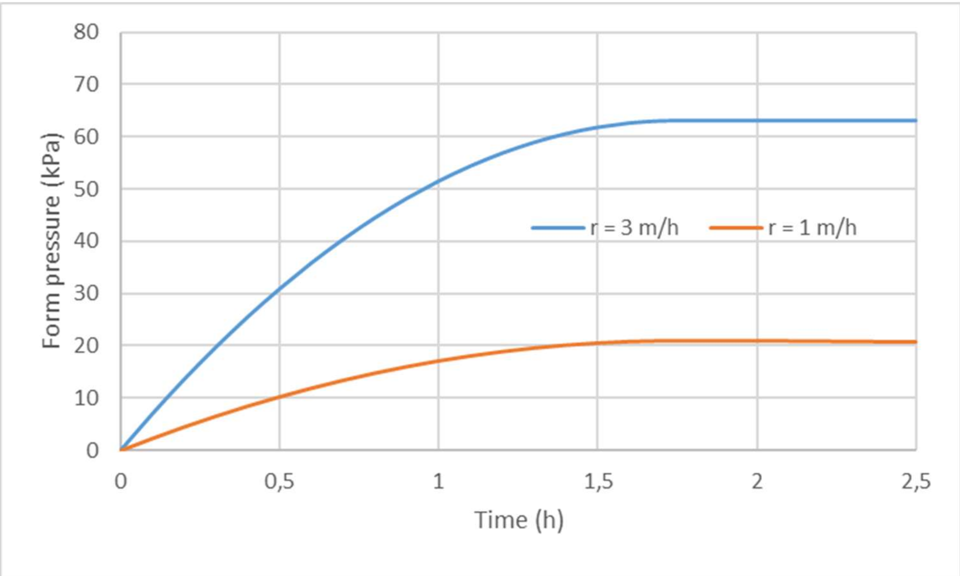

Figure 2 – Development of form pressure for the example with a 3 m high column form. The setting time $t_E = 3.5$ h.

The time to fill the form is $t_h = 3$ h and $t_h = 1$ h, respectively. In the latter case, $t_h < t_E/2 = 1.75$ h. If considering Eq. 6, the maximum form pressure ought to be 51 kPa. However, a model is just a model and not a true mirror of the reality. Consequently, we do not know if 51 or 63 kPa is closest to the real form pressure for our case.

According to Eq. 6, the setting time t_E has a major influence on the form pressure. Using the same indata as the example above, we may study the form pressure for different values of t_E. The more rapidly the SCC stiffens, the shorter t_E and the lower the form pressure (Figure 3).

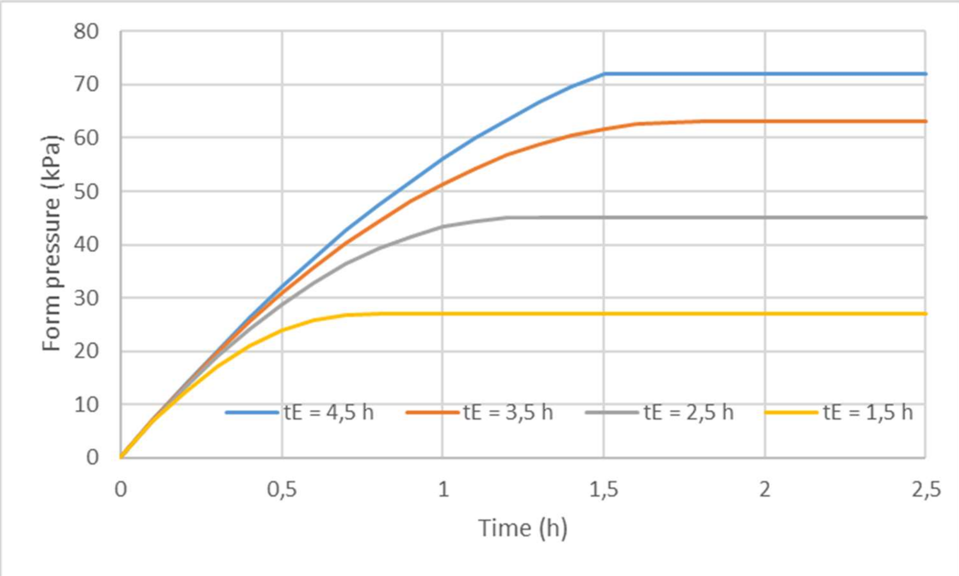

Figure 3 – Development of form pressure for the example with a 3 m high column form for different setting times t_E. The casting rate r = 3 m/h.

3. TESTS ON COMPOSITE 3DPC AND SCC COLUMNS

3.1 Pressure sensors

As mentioned above, the laboratory studies contained two test series. The same type of pressure sensors were used in both test series; PREMO Concrete Pressure Monitoring sensors from Vema Venturi AB [14]. From this instruction document [14], the following description is citied:

> The PREMO Concrete Pressure Sensor is a measuring sensor with a pressure-sensitive membrane. The membrane is filled with a liquid that transfers the mechanical pressure from fresh concrete to a pressure transducer. The pressure transducer generates a digital output signal that is sent to the data acquisition system. The concrete pressure sensor is designed to be attached to the concrete formwork.

The sensor weighs 0.86 kg and has a 50 mm diameter. In the first test series, 150 mm diameter holes were drilled in the 3DPC form to install the sensors that were centrally placed in a 150 mm large circular wooden plate filling the hole. Details are described in Shabo & Hossein [15]. In the second test series, the form pressure was measured in a wooden form placed beside the 3DPC forms and cast at the very same time. The installation of the sensors could be made fully according to the instructions. In both cases, Heidelberg Materials Betong Sverige provided the sensors and assisted with the installation.

3.2 First test series

Description of the tests
The tests were conducted during the autumn 2021 at Betongindustri's ready mix concrete plant in Tumba 25 km south of Stockholm. The tests were documented by the B.Sc. students Ilana Shabo and Jaweed Hosseini at KTH [15].

The tests consisted originally of four composite columns with circular cross section. The forms were made of 3DPC and would later be filled with SCC. The measures of the specimens were height h = 2430 mm, radius R = 250 mm, and 3DPC thickness t = 50 mm (Figure 4). One of the printed forms collapsed during the printing process. The remaining parts of the project were limited to these three specimens. The various steps are summarized in Table 1. The concrete mixes used for the 3DPC and SCC are given in Table 2. As shown, the *w/c* ratio was slightly lower in the 3DPC forms (0.50) than in the SCC core (0.63). The compressive strength of the two concrete mixes was not measured but the *w/c* ratios indicate values around 40 and 50 MPa for the SCC and 3DPC, respectively.

Figure 4 – 3D printed concrete columns in the B.Sc. project during autumn 2021. Photo: T. v. Haslingen.

Table 1 – The test steps with dates and age data [15]

Step No.	Description	Date	Age of form (days)	Age of interior concrete (days)
1	Printing of all forms	Nov. 5, 2021	0	
2	Installation of form pressure gauges	Dec 17, 2021	42	
3	Casting of the two cores with SCC	Dec. 21, 2021	46	0

Table 2 – Material data [15]

	3DPC		SCC
Unit volume (m^3)	0.040	1.0	1.0
Cement (kg)	25	625	315
Limestone filler (kg)			105
Water (kg)	12.5	312	197
Sand 0-4 mm (kg)	59	1475	
Gravel 0-8 mm (%)			60
Gravel 8-16 mm (%)			40
Superplasticizer	X	X	X
Accelerator	X	X	
Other chemicals	X	X	
w/c	0.50	0,50	0.63

Note X indicates presence.
The 3DPC mix was based on a 40 litre volume, the columns for 1 m^3 is a magnification.

Test results

The focus of these tests was the production stage and the form pressure. Form pressure gauges were installed in two of the forms (A and B) at two different levels, both close to the bottom (150 mm above) and at mid-height (= 1.15 m from the bottom). Furthermore, slump-flow tests were carried out both immediately after pouring and after 45 minutes. Two immediate tests gave values of 560 and 620 mm. The values after 45 minutes were 560 and 580 mm. These values indicated that there was not any structural build-up during the first 45 minutes after pouring. The 2.4 m high columns were cast in two lifts in 56 minutes, i.e., the average casting rate was r = 2.6 m/h (Figure 5). Consequently, hydrostatic pressure could be anticipated.

The maximum form pressure at the bottom of columns A and B were measured to 50.8 and 49.6 kPa, respectively. The concrete height above these locations was 2.43 – 0.15 = 2.28 m. This corresponds to a hydrostatic pressure equal to 54.7 kPa (Eq. 1). Consequently, the measured form pressure was close to hydrostatic (90-93%). At the high level, a maximum form pressure = 32 kPa was measured. It is somewhat higher than hydrostatic pressure, which theoretically is impossible. One reason for this difference is likely to be measuring error in the form pressure gauges. Another possible explanation is that the real level of the gauge could differ from the intended distance given in the table. A third possibility is a discrepancy between anticipated dead weight (24 kN/m^3) and the real one (that unfortunately was not measured).

Table 3 – Calculated and measured form pressure [4]

Column	Sensor location in the column	Distance below top surface (m)	Hydrostatic pressure (kPa)	Measured pressure (kPa)	Ratio between measured and calculated pressure (%)	Comment
A	Low	2.28	54.7	50.8	93	No cracks, no leakage
B	Low	2.28	54.7	49.6	91	
A	High	1.28	30.7	32.3	105	
B	High	1,28	30.7	32.2	105	

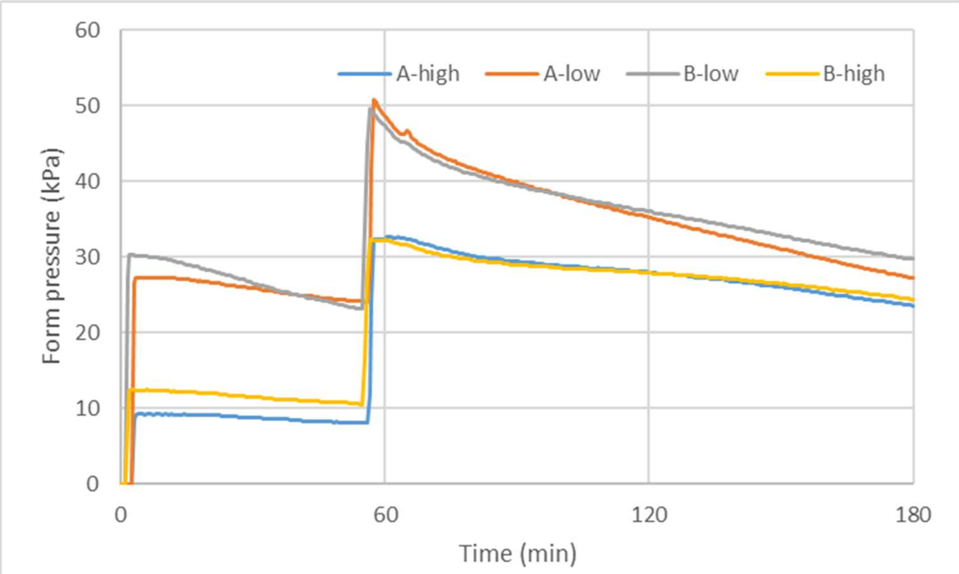

Figure 5 – Measured form pressure in the first test series.

The shape of the curves indicates that the degree of thixotropy and structural build-up is fairly low. This behaviour corresponds well with the measured small decrease in measured slump flow described above.

No cracks or leakage were observed during the casting of the SCC or afterwards. By using Eq. 3, a maximum tensile stress $\sigma_t = 24 \cdot 2.43 \cdot 0.25/0.05 = 292$ kPa can be calculated. It is considerably lower than the estimated tensile strength of the 3DPC form. The lack of distresses is not surprising.

3.3 Second test series

Description of the tests

The second test series was a part of a larger research project focusing on the load-carrying capacity of composite concrete columns consisting of 3DPC forms and SCC. The production of the columns was carried out in August (forms) and in September 2023 (SCC) in Tumba, i.e., at the same location as the first test series. This entire research project is described in detail in the test report [6]. The test steps included in the tests on form pressure are summarized in Table 4.

The tests consisted of four composite columns and two homogeneous ones [6]. The form pressure was not measured in the columns. The reason was that the reinforced composite column was too narrow for instrumentation. Instead, the form pressure was measured in an additional, unreinforced wooden form that was cast with the same SCC, the same procedures and at the same time as the test specimens (Figure 6). This form was also 3 m high but had a square cross section with a side length of 0.3 m. The material utilized was of the same type as the one that is used for conventional wooden formwork (plywood).

Table 4 – The test steps with dates and age data [6]

Step No.	Description	Date	Age of form (days)	Age of interior concrete (days)
1	Printing of all forms	Aug. 23, 2023	0	
2	Installation of reinforcement	Sept. 2023	~ 21	
3	Installation of form pressure gauges	Sept. 2023	~ 28	
4	Casting of SCC in the forms	Sept. 22, 2023	30	0

Figure 6 – 3DPC forms and cardboard form before casting the SCC. Please, note the wooden form to the very left of the photo. It was instrumented for measuring form pressure.

The concrete mixes used for the 3DPC forms and the SCC are shown in Table 5. At 29 days, the 3DPC had a compressive strength of 49.5 MPa. The 28-day compressive strength of SCC was 36.7 MPa. The density of fresh concrete was unfortunately not measured but the density of the SCC cylinders used for compressive testing was 2390 kg/m^3 [6].

Table 5 – Mix proportions of 3DPC and SCC [6]

	3DPC kg/m^3	SCC kg/m^3
Cement (CEM I[1])	625	
Cement (CEM II/A-LL[2])		325
Limestone filler		83
Water	312	195
Gravel (0-4 mm)	1350	
Gravel (0-8 mm)		1032
Gravel (8-16 mm)		685
Air entrainment agent	1.25	
Superplasticizer	> 0[3]	4,45
Accelerator	> 0[3]	
Other chemicals	> 0[3]	
Sum	2288	2324
w/c	0.5	0.6

Notes. [1] 95% Portland Cement. [2] >80% Portland Cement & <20% Limestone filler.
[3] Substance and volume are business secrets.

Test results

The casting speed was fairly low, r = 1 m/h (3 m in 3 hours, Table 7). That meant that the casting was made in three lifts with three different SCC batches but with the same recipe. The slump-flow was measured directly after casting and after 1 and 2 hours (Table 6). Values of 670-700 mm were recorded. After 1 and 2 hours, the slump-flow was reduced to 70 and 40%, respectively.

Table 6 – Measured slump-flow (mm) [6]

	SCC to lift 1	SCC to lift 2	SCC to lift 3
Instantaneous	670	670	700
After 1 h	400	550	-
After 2 h	200	320	-

The measured form pressure is shown in Figure 7 and Table 7. Not surprisingly, the instantaneous form pressure was equal to the hydrostatic one (around 20 kPa). After 1 hour, the form pressure had lowered significantly. This behaviour is repeated after every lift.

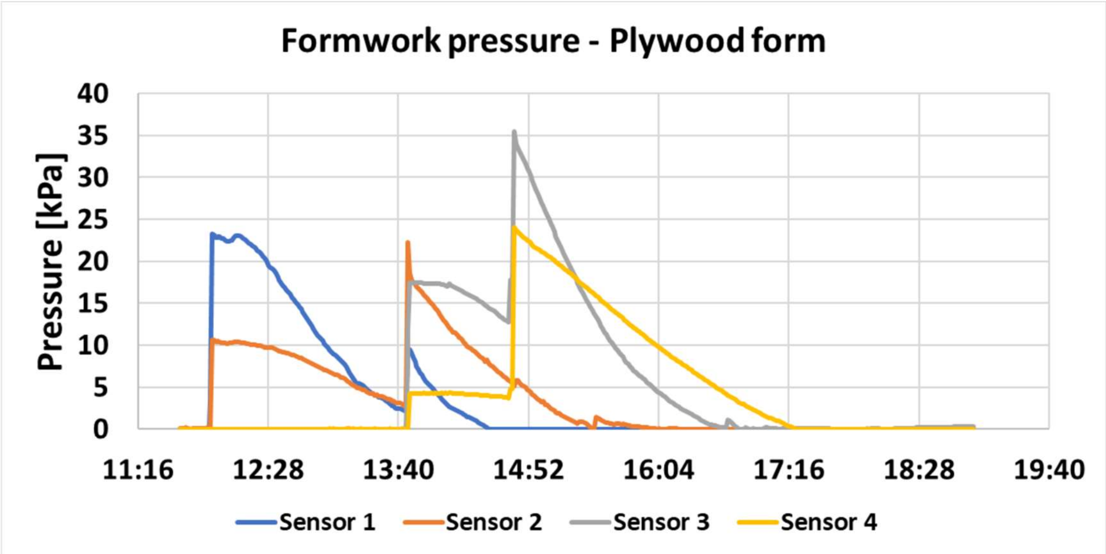

Figure 7 – Measured form pressure in the second test series [6].

Table 7 – Comparison between measured form pressure and hydrostatic pressure immediately after the casting of a lift [6]

		Lift 1			Lift 2			Lift 3		
Casting height (m)		1.0			2.0			3.0		
Time of day		11.40 a.m.			1.40 p.m.			2.40 p.m.		
Time after start (min)		0			120			180		
Sensor No	Level (m)	Hydro-static pressure (kPa)	Measured pressure (kPa)	Measured / hydraulic (%)	Hydro-static pressure (kPa)	Measured pressure (kPa)	Measured / hydraulic (%)	Hydro-static pressure (kPa)	Measured pressure (kPa)	Measured / hydraulic (%)
1	0.15	20.4	23	113	44.4	10	51	68.4	0	0
2	0.80	4.8	10	208	28.8	23	80	52.8	6	11
3	1.45	–	–		13.2	18	136	37.2	36	97
4	2.10	–	–		–	–		21.6	24	111

4. DISCUSSION

The form pressure of SCC is dependent on a number of factors. The most important ones are the density of the concrete ρ, the height of the casting h, the casting rate r, and the properties of the fresh concrete.

In the first test series, a fairly high casting rate (r = 2.6 m/h) was used. It resulted in measured form pressures above 90% of full hydrostatic pressure. A measure of the change in fresh SCC properties is the change in slump flow with time. The *SF* changed from an average of 590 to 570 mm during 45 minutes. Determining Gardner's time t_{400} [11] to estimate at which time the *SF* would approach 400 mm through an extrapolation leads to a very high value (t_{400} = 10 h) that suits the comparison between theory and measurement but is practically unrealistic. During the 56 minutes needed to reach the top of the 2.4 m high columns, we can assume that the contributions from both thixotropy and structural build-up were negligible.

The casting rate was considerably lower (r = 1 m/h) in the second test series. In this case, the slump flow dropped significantly with time, from an average of 670 mm at start to 480 mm after 1 h. Through interpolation, we obtain t_{400} = 1.4 h. By using Eq. 4, we arrive at t_0 = 3.5 h. Setting $t_E = t_0$ = 3.5 h, we are back to the indata of the example in Section 2.2. The maximum calculated form pressure at the bottom of the 3 m high columns is 21 MPa that is reached after 1.5 h. The lowest sensor was located 0.15 m above the bottom. However, since it took 3 h to fill the form completely, the form pressure also at 0.15 m from the bottom will reach 21 MPa, but first at 1.15 h after the casting start. These calculations are based on a continuous casting with a smooth casting rate.

In reality, the casting rate was not smooth. Instead, the columns were filled in three rapid lifts at 0, 2, and 3 h. As shown in Figure 7, the form pressure increases rapidly after a concrete lift but diminishes successively and substantially thereafter. The maximum form pressure at the sensor closest to the bottom was 23 kPa. The value is slightly higher than both the calculated one and hydrostatic pressure immediately after the first lift ($p = 24\cdot(1 - 0.15) = 20.4$ kPa). The reason is probably a deviation between intended and real level of the pressure gauge.

It is interesting to note that the casting of the second lift indeed leads to an increase of the form pressure in the lowest sensor, but that its magnitude never exceeds the one measured immediately after the first lift. Similar behaviour was registered also for the other sensors.

These tests maybe criticized for the absence of measurements on the density of the fresh concrete and accurate measurement on the real locations of the pressure sensors. The pressure sensors could also have been tested prior to the casting of SCC by filling the forms with water. However, it is always easy to be wise after the event. It ought to be stated that the main aim of the test series was not form pressure. The aim of the first test series was to test if it was possible to produce composite columns of this type 2.4 m high. The main aim of the second test series was to test the load-carrying capacity of the composite columns. Measurements on form pressure constituted a secondary aim, but the results are still considered interesting and are consequently reported here.

Full hydrostatic pressure in a 3DPC form with the dimensions corresponding to the tests (h = 3.0 m, R = 0.15 m, and t = 0.04 m) would lead to a tensile stress σ_t = 0.27 MPa which is substantially lower than a default value of the concrete tensile strength f_{ct} = 2 MPa. This means that the parameter values used in the tests series were far from causing failure and leakage. As a rule of thumb, we may limit the product hR to hR = 3 m^2 for 3DPC forms with a thickness t = 40 to 50 mm, if the casting rate is so high that it will cause hydrostatic pressure. Reducing the casting rate to 1 m/h, will lower the maximum form pressure substantially.

5. CONCLUDING REMARKS

Composite columns of 3DPC forms and SCC cores constitute an interesting alternative with potential to increase the productivity in the concrete industry by eliminating the construction and the removal of the formwork and simplify the casting operations while improving the working environment. Casting SCC in vertical forms may cause high form pressure close to full hydrostatic pressure. Two test series with composite columns have been carried out at KTH in order to study form pressure, load-carrying capacity and durability. This paper is focusing on form pressure. The main conclusions are the following:

- 2.4 m high composite columns of 3DPC forms and SCC cores with radius R = 250 mm were able to resist a form pressure approaching full hydrostatic pressure. The same positive result was obtained for composite columns with height h = 3 m and radius R = 150 mm but a less challenging casting rate (r = 1 m/h instead of 2.6 m/h).
- No cracking, leakage or other type of damage occurred in any of the totally six composite columns in the first and second test series.
- Calculated tensile stresses in the 3DPC forms were considerably lower than the estimated concrete tensile strength.
- If permanent 3DPC formwork would be used for higher and/or coarser concrete columns, tensile stresses close to or exceeding the concrete tensile strength would develop, at least at high casting rates. Calculations show that the product hR ought to be limited to hR = 3 m^2 in cases with high casting rates.
- Gardner's calculation method [11] seems to be able to predict the form pressure with decent accuracy.
- It would be interesting to conduct field tests with composite columns of this type but with larger dimensions and thus being more challenging to follow.

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