Numerical Modelling of Concrete Pressure on Vertical Formworks

Kanishka Bhattacharya [*1]; Bjoern Freund [*2]; Tilo Proske [*2]; Ashok D. Pandey[*1]; Saptarshi K. Lahiri [*1]; Ashok Sinha [*1]; Vishnu K. Busetty [*1] and Ravi C. IVP [*1]

**1 Department of Earthquake Engineering, Indian Institute of Technology Roorkee, Roorkee, 247667, INDIA*

**2 Institut fuer Massivbau, Technische Universitaet Darmstadt, Germany*

Abstract

Recent times have seen an advent in the use of high workability concretes as they can be placed with no or minimum vibration, and they provide better surface finishes. There is a lack of information on the resulting formwork pressure distributions during the construction phase, as the provisions of the present standards do not contain pressure values for new age concretes like Self Compacting Concrete etc. In order to assess these pressures, a numerical model has been developed which considers the time dependent material behaviour of concrete and the interaction between fresh concrete and the formwork. Parametric studies carried out for the estimation of formwork pressures for vertical walls of varying widths and heights cast with different types of concrete at different rates, indicate a good correlation with pressures obtained from performed experiments. Furthermore, the model results were compared with values from the German code, DIN 18218, and it is established that the provisions of the code are on the conservative side.

KEY WORDS: Formwork; Finite Element Model; Lateral pressure; Computer Simulation

1. Introduction

Formworks are a temporary structural system constructed to provide support and give shape to fresh concrete while it sets. With concrete becoming the preferred medium for construction, there is a need for a safe and quality formwork system which is economical as well. Construction of the formwork system is the single most expensive step in the entire construction process with expenditures ranging from 40% to 60% (Hanna and Senouci 1997) of the entire concrete constructional work. Previously the formworks were designed for a concrete pressure close to the hydrostatic value. In small scale projects this would not be too big an issue as this overestimation in pressure would not be too uneconomical. Now with project sizes being much larger than they were a few decades before, assumption of hydrostatic formwork pressures result in huge increase in expenditure. While an overestimation of pressure results in the cost of project shooting up, an underestimation can lead to hazards and loss of life.

The last few decades have seen an emergence of research on formwork pressures. Gardner (1980) and Hurd (2002) developed empirical formulas for the estimation of formwork pressures from experimental data. Vanhove's (2004) and Proske's (2007) work which established a numerical model based on Janssen's Silo Theory indicates the need to consider the friction between the formwork surface and the fresh concrete (Silo Effect), as this is seen to reduce the lateral pressures significantly. Experiments by the above authors as well as ones performed by Khayat (2005) have verified that when concrete is allowed to rest, it flocculates and there is a structural build-up which increases its shear strength and reduces the formwork pressures. A few codes (ACI guide to formwork for concrete, CIRIA report 108 and DIN 18218) towards the estimation of formwork pressures have been published. Although these codes are in the right direction they do not cater to all types of concretes.

A 2 dimensional finite element model, which is based on the assumptions of Proske (2007), has been developed using ANSYS 14.0 to estimate the formwork pressure distributions. The model can properly simulate the casting process, as time dependent hardening properties of concrete have been considered. Furthermore, to incorporate the reduction in formwork pressures due to the Silo Effect, the friction between the formwork surface and the concrete, and the friction between the reinforcement and the concrete has been considered. The different material properties and parameters used are from Freund (2014).

2. Numerical Model

2.1 General description of the 2D model

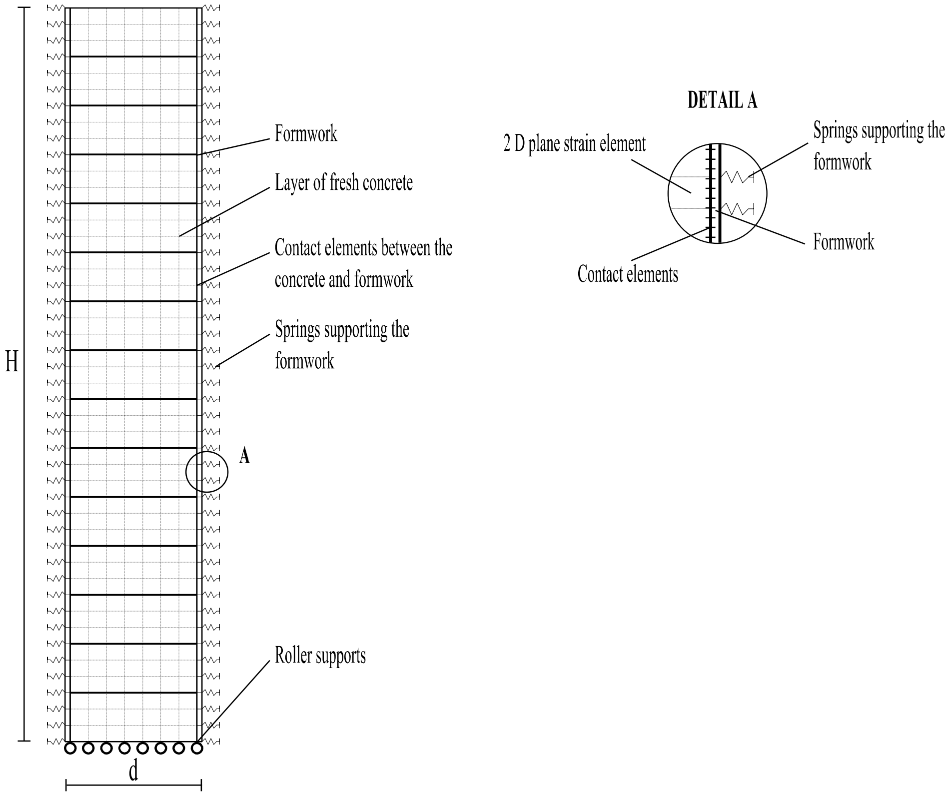


Figure 1: 2D Finite element model

The model is a 2D plane strain model. The concrete has been cast in 15 blocks and it is possible to assign a different material property to each block. To simulate the casting process, the bottommost block has the material properties corresponding to time at the end of casting, while the top block has the material properties corresponding to time zero. Thus the resulting pressure distribution obtained corresponds to the time at which the wall has just been completely cast. It is relevant to investigate the pressures at the end of casting, as prior to that the concrete hasn't reached its full height so the pressures will be less. Investigating pressures anytime after the casting is complete will also provide lower pressure values as the concrete has had time to set and harden.

To model the concrete and the formwork, Plane 82 elements have been used with quadratic interpolation functions. To model the contact between the concrete and the formwork a contact - target pair has been created with the formwork being the target surface and the concrete being the contact surface. TARGE169 and CONTA172 have been used for this purpose. A high stiffness has been assigned in the direction transverse to the formwork to prevent penetration between the concrete and the formwork elements. The contact – target pair can also simulate the friction between the concrete and the formwork surface.

The formwork is 3cm thick with the modulus of elasticity, $E = 1\times10^{10}\,\mathrm{N/m^2}$ and the Poisson's ratio, $\nu = 0.2$ (Proske 2007). Parameter tests have shown that the variation in these values have a negligible effect on the formwork pressures obtained from the FEM model.

To model the stiffness of the formwork system, springs have been provided to restrain the formwork in the x direction. IS 456 – 2000 has specified the maximum allowable deviation of cross sectional dimensions of concrete structural elements as 10mm. A stiffness of $20\times10^6\,\mathrm{N/m}$ per m length of formwork height keeps the maximum deflection below the prescribed limit for a hydrostatic pressure distribution. Furthermore, as shown in Figure 1, the bottom of the model has been restrained for movement in the y direction with the provision of roller supports.

2.2 Material properties of fresh concrete

Concrete when fresh has the properties of a fluid and when set behaves like a solid. So the concrete has been modelled as an elasto – plastic material with the transition from elastic to plastic state defined by the Drucker Prager Yield Criteria. It is assumed that the material is elastic – rigid plastic.

The Drucker Prager yield function is given by;

$$f(I_1, J_2) \equiv \alpha I_1 + \sqrt{J_2} - k = 0 \quad (1)$$

where, α and k depend on the material properties and, I_1 and J_2 are the first invariant of the stress and the second invariant of the deviatoric stress respectively.

Comparing the Drucker Prager yield surface with the Mohr Coulomb yield surface gives the values of α and k in the terms of the cohesion c and the angle of internal friction φ as;

$$\alpha = \frac{2\sin\varphi}{\sqrt{3}(3-\sin\varphi)} \quad (2)$$

$$k = \frac{6c\sin\varphi}{\sqrt{3}(3-\sin\varphi)} \quad (3)$$

Concrete has a non-associated flow rule. The angle of dilatancy for the plasticfication criteria has been taken as half the angle of internal friction. Variation of the angle of dilatancy from a value of zero to a value equal to the angle of internal friction gives a negligible change in results. Furthermore, the concrete has been assumed to be cohesionless, which yields conservative results.

For obtaining φ, the angle of internal friction of concrete and μ, the coefficient of friction between the concrete and the formwork surface, an experimental setup (Figure 2) developed by Graubner and Proske (2005A) was used. From this device μ is obtained directly, along with the ratio of the lateral pressure to the vertical pressure λ (from which φ is derived), for different concrete types.

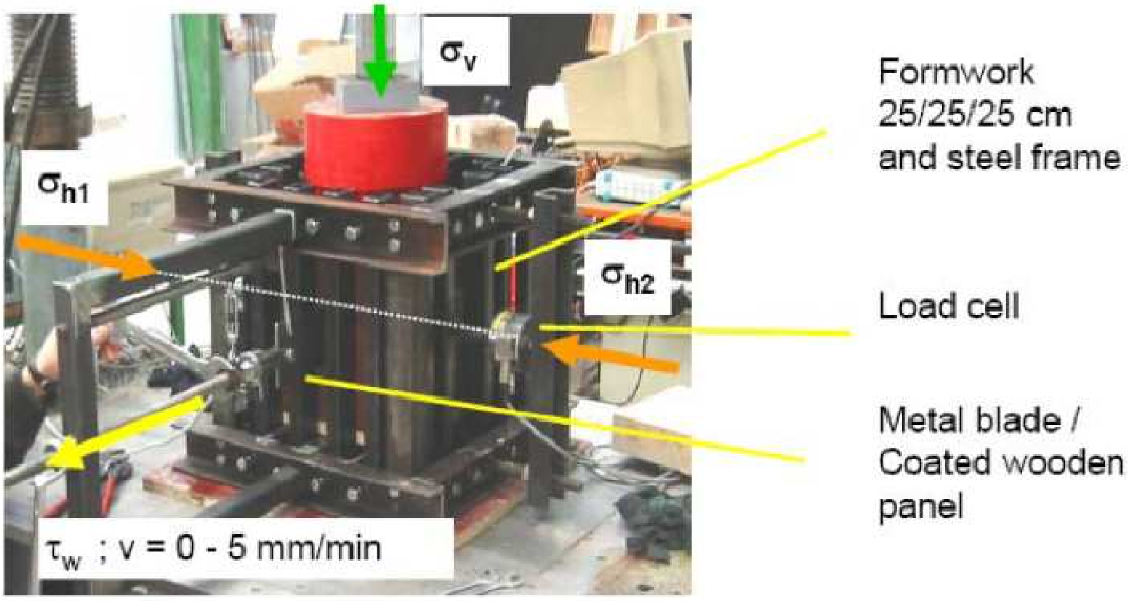


Figure 2: Experimental setup to evaluate model parameters (Graubner and Proske 2005A)

Both μ and λ are time dependent functions. At the time of placement of concrete $\mu = 0$, and it increases as the concrete hardens. The value of λ is initially equal to 1, because when the concrete is in its fluid state the lateral pressure is equal to the overburden pressure. As the concrete hardens, the value of λ reduces to a theoretical value of 0 at the final setting time of concrete. Thus, the functions λ and μ have been normalized for different types of concrete by expressing them in terms of a relative time t/t_E, where t is the time after the concrete has been placed and t_E is the final setting time of concrete. To obtain the value of μ in reinforced concrete, steel bars were placed in the setup.

The angle of internal friction for the fresh concrete was obtained from λ by using the relation for active earth pressure.

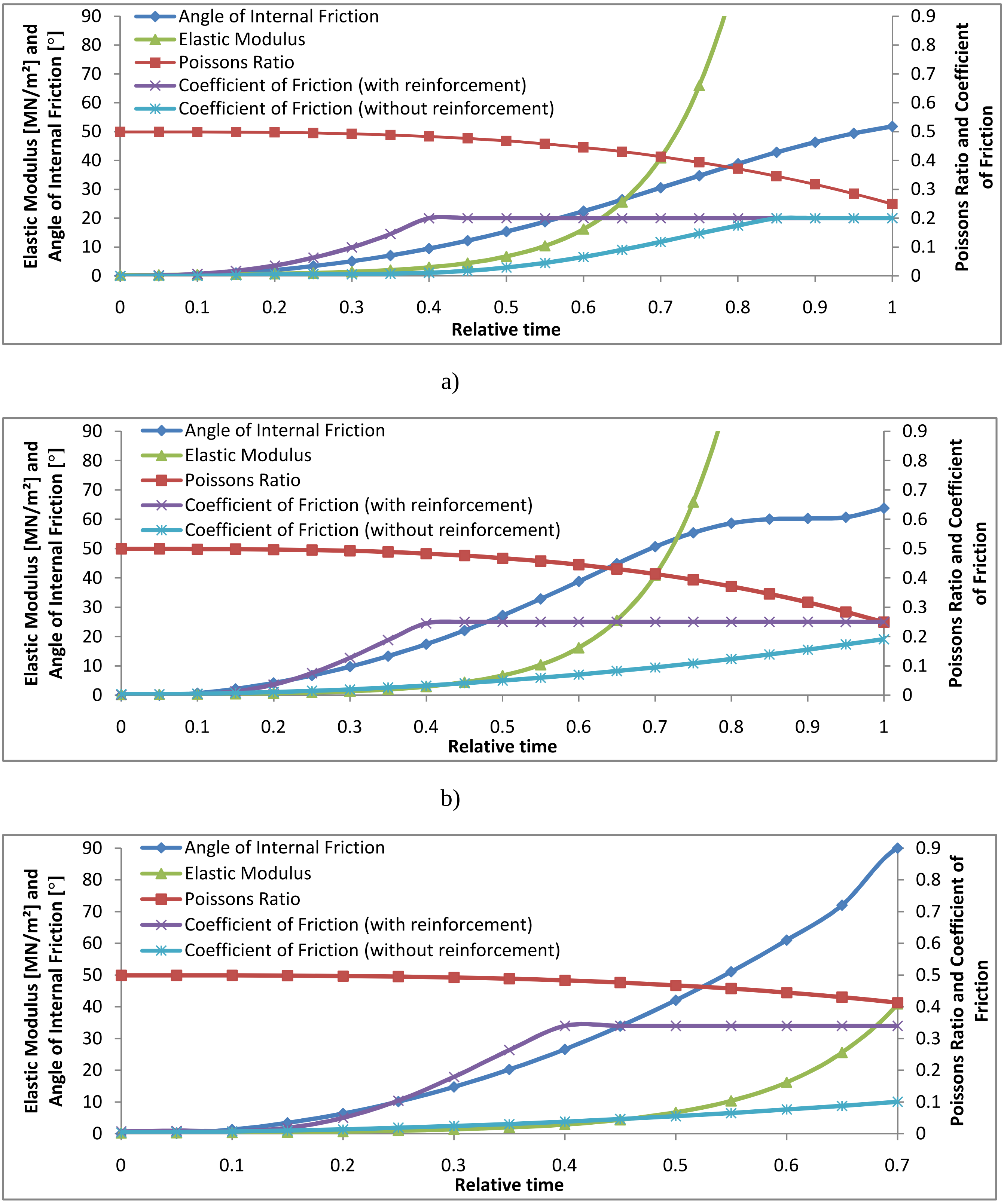
$$\lambda = \left(\tan\left(\frac{\pi}{4} - \frac{\phi}{2} \right) \right)^2 \tag{4}$$

The values of the Poisson’s ratio and the modulus of elasticity taken from Proske (2007) are;

$$\nu = 0.499 - 0.25 \left(t/t_E \right)^3 \tag{5}$$

$$E = 0.25 e^{\left(5\, t/t_E \right)^{1.3}} \times 10^6 \ \mathrm{N/m^2} \tag{6}$$

Figures 3a), b) and c) show the plots of the different material parameters used for three different concrete types F5, F6 and SCC. German codes specify concrete consistency classes from F1 to F6 and SCC, where F5, F6 and SCC are high workability concretes which are being increasingly used nowadays.



a)

b)

c)

Figure 3: Plot of material parameters with respect to relative time for a) SCC b) F6 and c) F5 (Freund 2014)

3. Comparison with experimental results

To verify the adequacy of the model, the numerical results were compared with experimental results obtained from tests. A total of 13 tests were performed at TU Darmstadt (Germany) in 2012 and 2013, on a vertical formwork system. Concretes of types F5, F6 and SCC with different setting times were pumped from the top at varying casting rates. The height of the formwork was either 3.5m or 2.5m and the width of the wall (i.e. the distance between the two formworks) was either 0.1m or 0.2m. The formwork thickness was 3cm. The parameters of the test are presented in Table 1.

Table 1: Parameters of the tests (Freund 2013)

Test No.	Consistency Class	Presence of Rein.	Width of wall	Density	Setting time of concrete	Casting Rate	Height of wall
[-]	[-]	[-]	[m]	$[kg/m^3]$	[h]	[m/h]	[m]
1	F6	Yes	0.2	2330	9.76	2.33	3.5
2	F5	Yes	0.2	2320	11.74	2.28	3.5
3	F6	Yes	0.2	2300	8.80	1.22	3.5
4	F6	Yes	0.2	2310	6.63	4.22	3.5
5	SCC	Yes	0.2	2300	9.00	2.26	3.5
6	F5	Yes	0.2	2340	10.75	2.26	3.5
7	F5	No	0.2	2320	10.96	2.28	3.5
8	F5	Yes	0.1	2300	9.33	2.28	3.5
9	F5	Yes	0.1	2340	11.20	4.04	3.5
10	F5	No	0.1	2320	10.41	2.06	3.5
11	SCC	Yes	0.1	2330	16.20	2.26	3.5
12	F6	Yes	0.2	2360	11.81	2.42	2.5
13	F5	Yes	0.2	2340	12.17	2.28	3.5

Table 2 shows the comparison between the experimental results and the results obtained from the finite element model for the maximum pressure at the end of casting. The relative times at the end of casting give an indication of the formwork pressures, as with all things kept same, higher the relative time at the end of casting, more hardened is the concrete and thus lower is the lateral pressure.

Table 2: Comparison of model and experimental results

Test No.	Consistency Class	Relative Time at end of casting	Experimental Results	Model Results	Ratio
[-]	[-]	[-]	[kPa]	[kPa]	[-]
(a)	(b)	(c)	(d)	(e)	(d)/(e)
1	F6	0.15	48	65	0.74
2	F5	0.13	47.5	66	0.72
3	F6	0.33	33	29	1.14
4	F6	0.13	58	70	0.83
5	SCC	0.17	62	60	1.03
6	F5	0.14	61	64	0.95
7	F5	0.14	57.5	67	0.86
8	F5	0.16	31.5	40	0.79
9	F5	0.08	40	66	0.61
10	F5	0.16	55	55	1.00
11	SCC	0.10	59.5	67.5	0.88
12	F6	0.09	44.5	54	0.82
13	F5	0.13	42.5	67	0.63

% Deviation from the test results	Legend
0-20	🟩
21-40	🟨

From Table 2 it is evident that there is a good correlation between the experimental results and the results from the model for Self Compacting Concrete. This is because a large number of tests were performed to arrive at the material parameters for SCC.

From the relative times of test 5 and test 11 (both conducted with SCC on a 3.5m high wall) it is evident that at the end of casting, the concrete in test 11 has had less time to build its shear strength than the concrete in test 5. Even so, as the width of the wall in test 11 is half the width of the wall in test 5, the experimental results show that the maximum pressure in test 11 is less than that in test 5 (this is because the Silo Effect reduces, i.e. lateral pressure increases as the width of the wall increases). But the model results are contradictory to the experimental ones, i.e. the results from the model show that pressure in test 11 is more than the pressure in test 5. So, perhaps the reduction in pressure due to the reduction in width (Silo Effect) cannot be accurately simulated by the model.

In test 6, a large internal vibrator was used. Consequently the experimental results are high. So, a comparison with the model results should not be made as the model does not incorporate the use of a vibrator.

Tests 2, 8, 9 and 13 which have low relative times at the end of casting, do not show a good correlation of the experimental results with the model results. This might mean that the material properties assumed for F5 for low relative times are not accurate and further tests should be performed to accurately estimate the material parameters. But at the same time, tests 7 and 10, which have been conducted with F5 without reinforcement, show a good correlation. Also apart from test 1, all the experiments performed with F6 show a maximum formwork pressure close to the model results. Thus the material parameters for F6 and for F5 without reinforcement are seemingly accurate.

4. Parametric Study

The parametric studies have been conducted on a vertical formwork system as shown in Figure 1. The variation of the maximum formwork pressure has been investigated for the following parameters.

1. The type of concrete being cast
2. The width of the wall, d
3. The casting rate, R
4. The height of the wall being cast, H

4.1 Comparison between different concrete types

For a wall of height 10 meters, width 0.4 meters, a casting rate of 2m/h, the maximum formwork pressures were compared for different concrete types as shown in Figure 4.

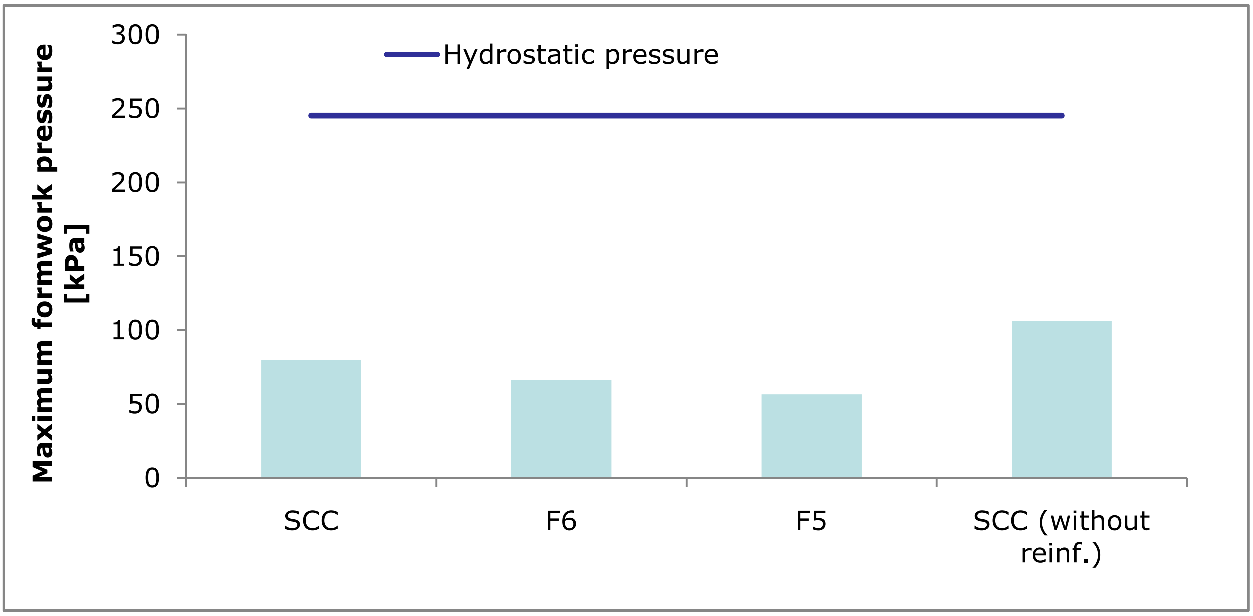


Figure 4: Maximum formwork pressures for different types of concrete

As the slump height (which can be related to the fluidity of the concrete) of SCC is greater than that of F6 which in turn is greater than that of F5, the pressures too increase from F5 to F6 to SCC.

As casting without reinforcement will reduce the friction between the concrete and the reinforcement, the lateral pressures will be higher as is verified from the Figure 4.

4.2 Comparison of maximum formwork pressures for different wall widths

For a wall of height 10 meters, cast with SCC at a rate of 2m/h, the maximum formwork pressures have been plotted for different wall widths.

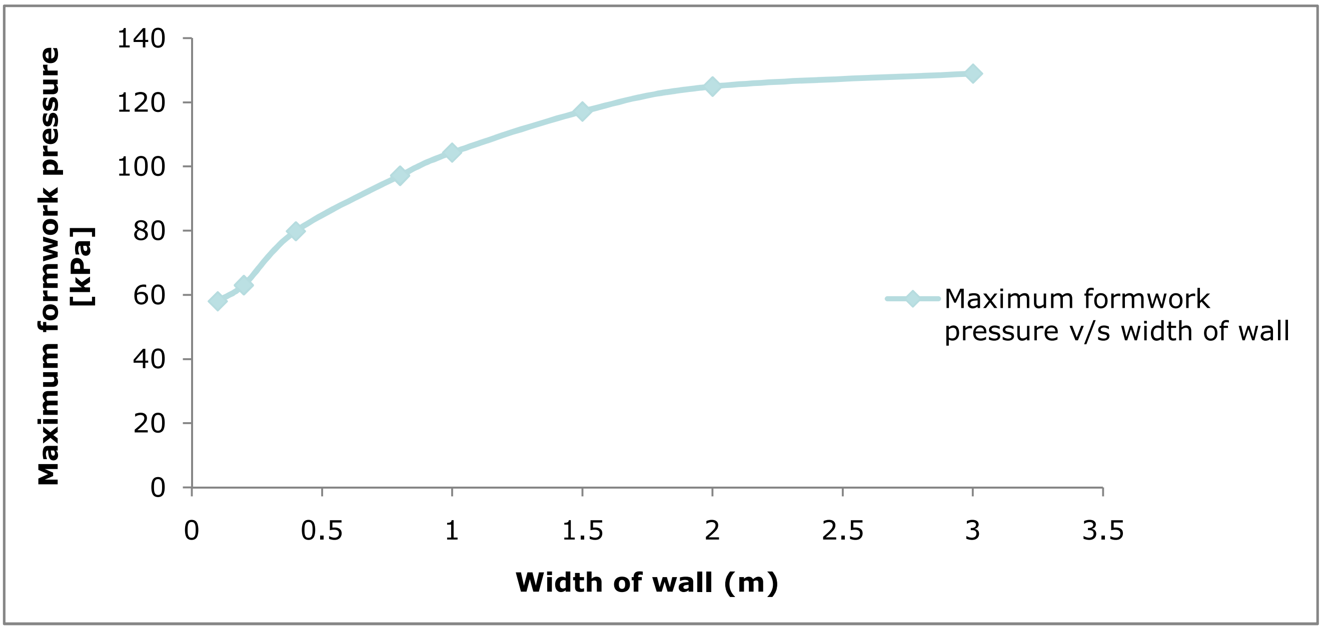


Figure 5: Plot of maximum formwork pressure versus width of wall

As is evident from the Figure 5, the maximum formwork pressure attains saturation as the width of the wall increases. This is because with increasing wall width the Silo effect diminishes.

4.3 Comparison of maximum formwork pressures for different rates of casting

For a wall of height 10m, width of 0.4m and cast with SCC, the maximum formwork pressures at the end of casting, increases with increasing casting rate till it reaches the hydrostatic value (Figure 6). This is because as the rate of casting increases, the time taken to complete the casting reduces and as a result the concrete does not get enough time to set and build its shear strength. Therefore the lateral pressure also increases.

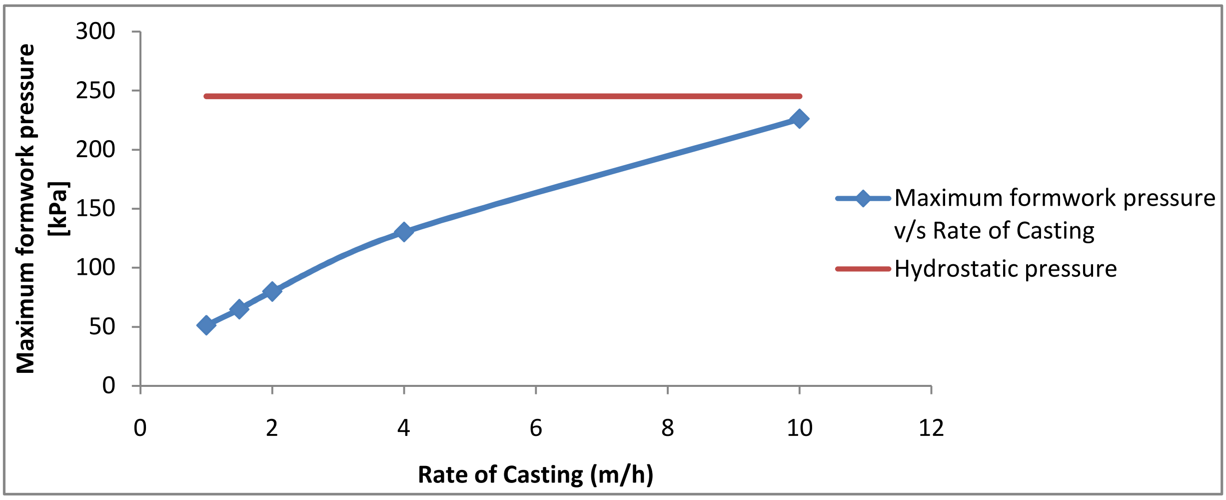


Figure 6: Plot of maximum formwork pressure versus rate of casting

4.4 Comparison of maximum formwork pressures for different wall heights

For a wall 0.4m wide, cast with SCC at a rate of 2m/h, the maximum formwork pressures have been compared for wall heights of 5m, 10m and 15m.

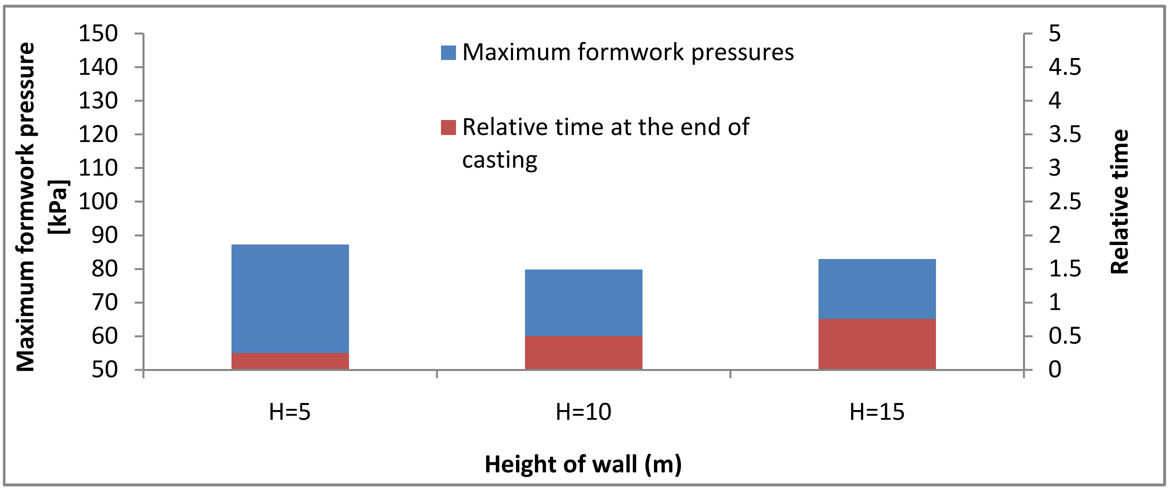


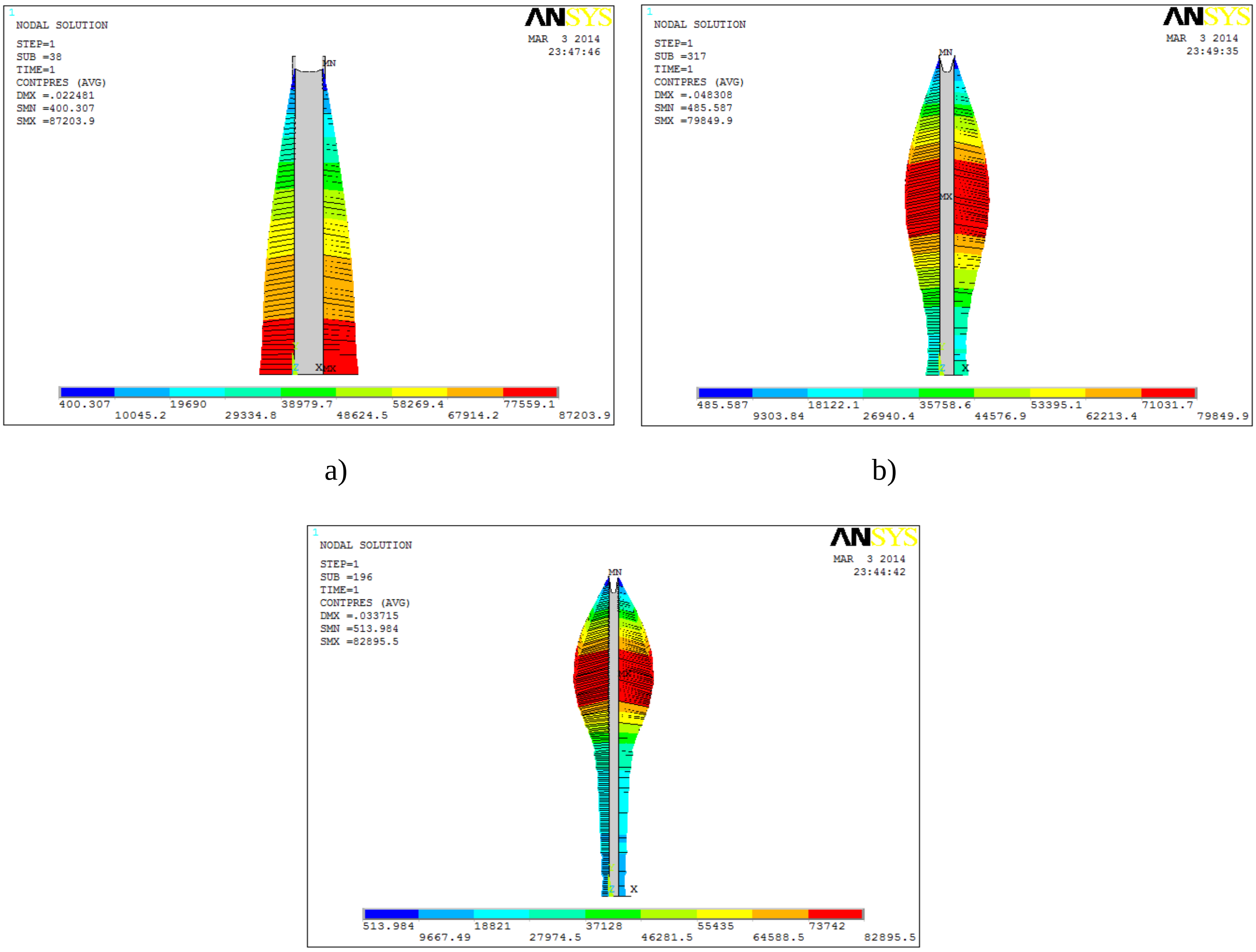
Figure 7: Maximum formwork pressures for different wall heights

It is evident from Figures 7 and 8, that for a height of wall 10m or 15m, the maximum formwork pressures obtained at the end of casting are less than that of a wall of height 5m.

This can be explained by the fact that the relative time at the end of casting increases with increasing wall height, since a higher wall takes more to be cast. As the relative time increases the concrete block hardens and thus reduces the lateral formwork pressure.

As a consequence, codes like the DIN 18218 do not take the height of the wall being cast as a variable for the maximum formwork pressure.

From Figure 8 b) and 8 c) it is evident that the concrete at the lower regions of the wall has had time to set and as a result the lateral pressures on the formworks are lower than the pressures at the top of the wall, where the concrete is still fresh.



a)

b)

c)

Figure 8: Distribution of pressures along the formwork height for a) 5m, b) 10m, and c) 15m

5. Comparison with code

Comparisons of the model results and the results from DIN 18218 have been presented in this section. The concrete used is Self Compacting Concrete and three formwork heights 5m, 10m and 15m have been considered for investigation. The casting rate assumed is 2m/h. The other available codes could not be compared as they do not have formwork pressure distributions for SCC.

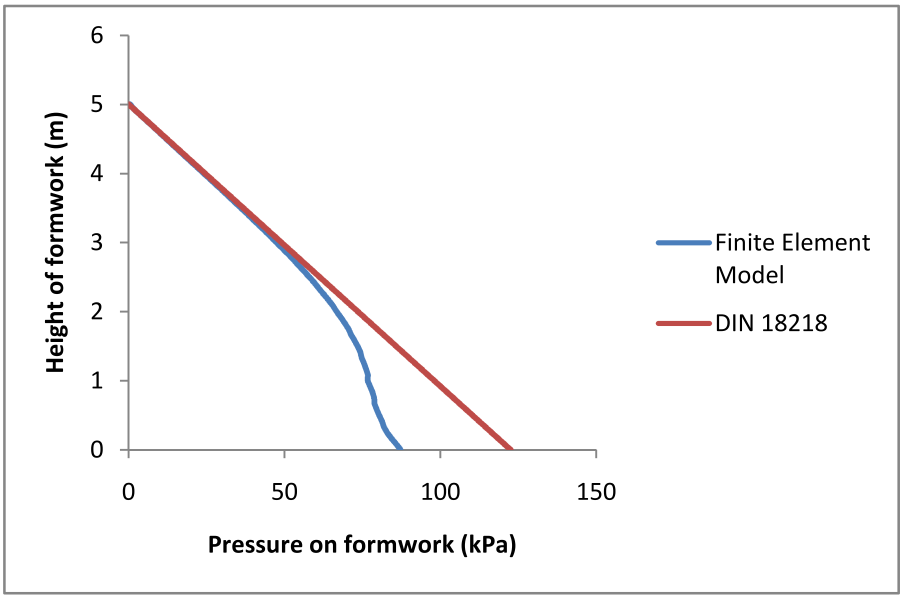


Figure 9: Distribution of the pressure along the formwork of height 5m from the FEM model and from DIN 18218

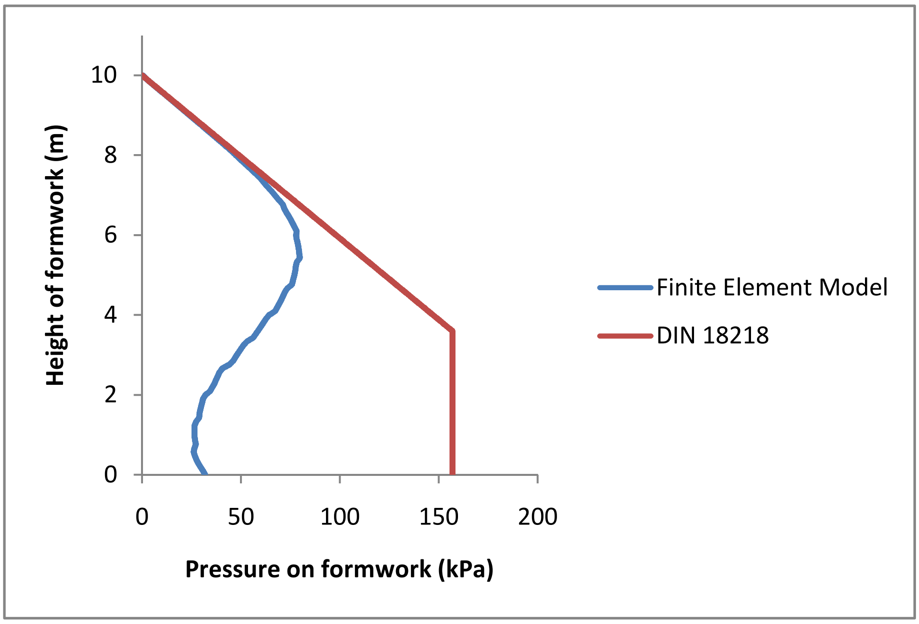


Figure 10: Distribution of the pressure along the formwork of height 10m from the FEM model and from DIN 18218

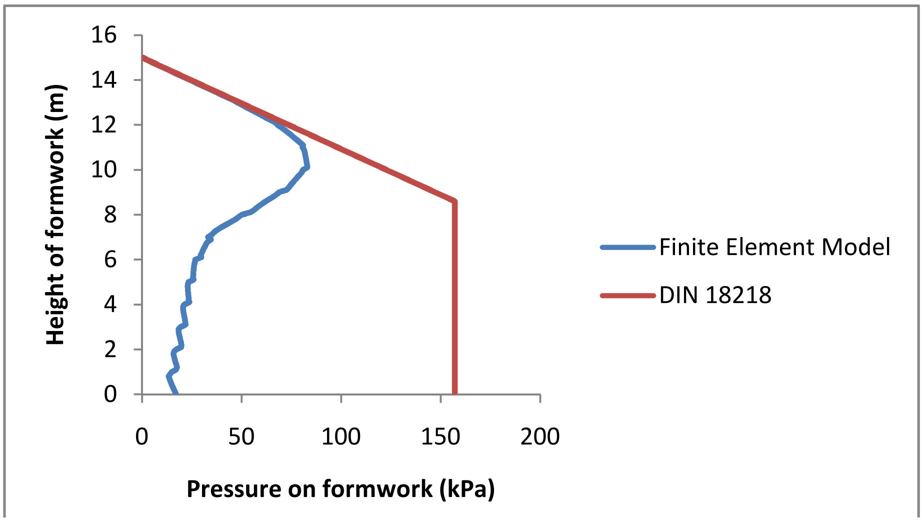


Figure 11: Distribution of the pressure along the formwork of height 15m from the FEM model and from DIN 18218

It is evident from Figures 9, 10 and 11 that for a height of 5m the maximum formwork pressure obtained from the model is close to the value obtained from DIN 18218. But for a height of 10m and 15m the maximum formwork pressure is almost half the value obtained from DIN 18218.

6. Conclusions

The study shows the advantages of using a finite element model to estimate the formwork pressures and can be extended to formworks of different shapes and sizes.

1. It is evident that the consideration of the hardening process of concrete and the friction between the concrete and the formwork surface as well as the concrete and the reinforcement plays a major role in the reduction of the formwork pressures.
2. Comparison with the test results show that the material parameters chosen for Self Compacting Concrete are most accurate of the three concrete types investigated. Further experiments need to be conducted for the different concrete types.
3. The parameters influencing the formwork pressure distribution are the width of the wall, the rate of casting and the type of concrete.

   There is a negligible difference in the maximum formwork pressures for short and long formworks. This is attributed to the fact that tall formworks take more time to be cast, and as a result, the concrete hardens thereby reducing the lateral formwork pressure.

   DIN 18218 recognises this fact and thus the values for maximum formwork pressures provided are independent of the height of the formwork.
4. Comparison of the model results and the results from DIN 18218 shows that for tall formworks the codal values are almost twice the values obtained from the model.

7. References

1. American Concrete Institute (2004). *Guide to Formwork for Concrete ACI 347R-94*. Farmington Hills: ACI Committee 347.

2. Clear, C.A., & Harrison, T.A. (1985). *Concrete Pressure on Formwork, Research Report No.108*. London: Construction Industry Research and Information Association.

3. DIN 18218 (1980). *Frishbeton auf lautrechte (Pressure of Fresh Concrete on Vertical Formwork)*. Berlin: DIN.

4. Freund, B. (2013). Großversuche zur Untersuchung des Frischbetondrucks bei geneigten Schalungssystemen. In Tagungsband der 1. Jahrestagung des Deutschen Ausschusses für Stahlbeton. Bochum.

5. Freund, B. (2014). Materialparameter fuer Parameterstudie. Darmstadt. In Press.

6. Gardner, N. J. (1980, July). Pressure of concrete against formwork. In *ACI Journal Proceedings* (Vol. 77, No. 4). ACI.

7. Graubner, C. – A. and Proske, T. (2005A). Formwork Pressure: A New Concept for the Calculation. In S.P. Shah (Ed.), *Proceedings of the 2nd North American conference on the Design and Use of Self – Consolidating Concrete (SCC 2005) and the 4th International RILEM Symposium on Self – Consolidating Concrete*. Chicago, 2005A, pp. 605 – 613.

8. Hanna, A. S., & Senouci, A. B. (1997). Material cost minimization of concrete wall forms. *Building and environment*, *32*(1), 57-67.

9. Hurd, M. K. (2002). Putting the pressure on formwork. *Concrete international*, *24*(10).

10. Standard, I. (2000). Plain and reinforced concrete code of practice IS 456: 2000. *Bureau of Indian Standards*.

11. Jansen, H. A. (1985). Versuche ueber Getreidedruck in Silozellen. *Zeitschrift*, *506,* 39.

12. Khayat, K. H., & Assaad, J. (2005). Use of rheological properties of SCC to predict formwork pressure. *Proceedings of SCC*, 671-677.

13. Proske, T. (2007). *Frischbetondruck bei Verwendung von selbstverdichtendem Beton: ein wirklichkeitsnahes Modell zur Bestimmung der Einwirkungen auf Schalung und Rüstung*. Inst. für Massivbau.

14. Vanhove, Y., Djelal, C., & Magnin, A. (2004). Prediction of the lateral pressure exerted by self-compacting concrete on formwork. *Magazine of Concrete Research*, *56*(1), 55-62.