Materials and Structures (2014) 47:1099–1113
DOI 10.1617/s11527-014-0274-y

ORIGINAL ARTICLE

Form pressure generated by fresh concrete: a review about practice in formwork design

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Received: 19 December 2013 / Accepted: 4 March 2014 / Published online: 20 March 2014

Abstract In this paper, several current industrial practices in formwork design are presented focusing on the normative calculation of the form pressure. Most of the current Standards are devoting for the design of the formwork for the normal vibrated concrete. Currently, the Standards are being updated to include provisions for the newly adapted concrete, such as the flowable concrete and self-consolidating concrete. However, the experience with these methods is still limited. The available methods for calculating the formwork pressure for the flowable concrete and SCC are based on measuring the shear strength of concrete using different concepts, such as the setting time of concrete or the structural build-up at rest. More field work is necessary to validate and provide the confidence to the available methods for the formwork pressure calculation. With this information the regulations could be improved to ensure a more economic formwork design. The paper was discussed within the RILEM TC 233-FPC "Form pressure generated by fresh concrete".

Keywords Form pressure · Formwork design · Self-consolidating concrete · Shear strength · Setting time · Structural build-up · Thixotropy

List of symbols
Notations in brackets for USA (Chap. 4) and Canada (Chap. 5)

a	Spread in the flow-table test (mm)
b, d	Formwork dimensions (m)
g	Gravity constant (m/s^2)
h	Distance from the concrete level to a certain location (m)
h_E	Distance from the concrete level to the location where the concrete has achieved the final setting (m)
h_S	Hydrostatic height corresponding to the maximum pressure (m)
H (h)	Height of the casting section (m)
s	Slump (mm)
T	Concrete temperature (°C)
t_E	Final setting time of the concrete (h)
v (R)	Mean placing rate (m/h)
V	Variation coefficient (–)

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γ_c (w)	Specific concrete weight ($\gamma_c = \rho_c \times g$ = density of the fresh concrete $\times$ gravity) (kN/m^3)
γ_F	Partial safety factor on the load (–)
γ_g	Global safety factor (–)
ρ_c	Concrete density (g/cm^3)
σ_h	Horizontal (lateral) pressure of fresh concrete (kN/m^2)
$\sigma_{hk,max}$ (P_{max})	Maximum characteristic lateral pressure of fresh concrete (kN/m^2)

1 Introduction

Formwork should be designed for the ultimate as well as the serviceability limit states. Different loads, such as wind, equipment/construction loads, snow, dead loads, live loads and the lateral pressure of concrete have to be considered. The system stability and member buckling should also be investigated [1].

In this paper, several current industrial practices in formwork design are presented focusing on the normative calculation of the form pressure. The design of the formwork takes into account the service loads or loads magnified by a safety factor. The bearing capacity of the formwork has to be calculated according to the materials used and the existing design concept. It should be noted that the calculation of the loads as well as the bearing capacity of the formwork should be based on the same design concept.

2 Review of normative calculation of the form pressure: worldwide

The following documents are considered to be the most widely used regulations for the calculation of form pressure published by national standardization institutes and scientific committees [2, 3]:

- ACI 347-04: Guide to Formwork for Concrete. American Concrete Institute, 2004 [1].
- CAN/CSA S269.3: Concrete formwork, 1992.
- CIB-CEB-FIP 27-98-83: Manuel de Technologie “Coffrage”, 1977 [4].
- CIRIA-Report Nr. 108: Concrete Pressure on Formwork. Construction Industry Research and Information Association, London, 1985 [5].
- DIN 18218:1980-09 Frischbetondruck auf Lotrechte Schalungen (Pressure of Fresh Concrete on Vertical Formwork). Berlin, 1980 [6].
- IS 14687:1999: Guidelines for falsework for concrete Structures, New Delhi, 1999 [7].
- JGJ 162-2008: Technical code for safety of forms in construction, People’s Republic of China, 2008 [8].
- NF P93-350: Équipment de Chantier—Branches industrialisées pour ouvrages en béton. 1995 [9].
- TGL 33421/01: Betonbau, Schalverfahren, Standschalungen, 1977 [10].

These documents, as well as other well-known design models [11, 12], consider only concrete with ordinary consistency. Specific regulations for highly workable concrete and self- consolidating/compacting concrete (SCC) are not included in the standards. In this case, only hydrostatic pressure should be assumed for the design of the formwork. To achieve a more economic formwork design, a number of research efforts have been made to investigate form pressure characteristics exerted by highly flowable concrete, including SCC [13–17]. These approaches take into consideration a number of concrete flow characteristics, including thixotropy, loss of slump flow, and initial setting time. More recently, the German Standard DIN 18218:2010-01 “Pressure of Fresh Concrete on Vertical Formwork” was modified to include some of these findings [18].

3 Formwork design in Europe

3.1 Overview

The general design of formwork for concrete structures in the European Union is regulated in EN 12812:2008 “Falsework—Performance Requirements and General Design” based on EN 13670:2011 “Execution of Concrete Structures” (Fig. 1). The EN 12812:2008 standard was formulated by the European Committee for Standardization (CEN/TC 53 “Temporary works equipment”).

The CEN/TC 53 Committee identified the existing normative regulations in Europe addressing form pressure and accepted the following three documents for the design of formwork according to EN 12812:2008

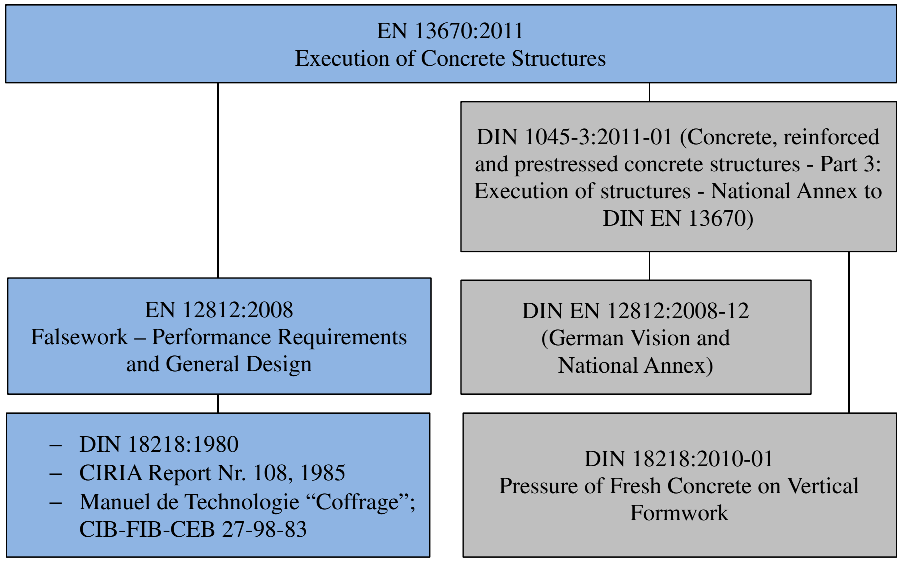

Fig. 1 European regulations for the design of formwork and implementation of DIN 18218:2010-01 (German standard)

[3]. However, national specifications often refer only to a single document.

- DIN 18218: Frischbetondruck auf lotrechte Schalungen (Pressure of Fresh Concrete on Vertical Formwork). Berlin, 1980.
- CIB-CEB-FIP 27-98-83: Manuel de Technologie, Coffrage. 1977.
- CIRIA-Report Nr. 108: Concrete Pressure on Formwork. Construction Industry Research and Information Association, London, 1985.

If the CIRIA-Report or CIB-CEB-FIP-Bulletin is used for the formwork design for the highly workable concrete or SCC, hydrostatic form pressure over the total formwork height must be assumed. The reason is that the development of these empirical concepts was not based on such highly workable concrete.

As a result of the developments in concrete technology and construction processes in the last 20 years, the approaches of the DIN 18218:1980-09, CIB-CEB-FIP-Bulletin and CIRIA-Report do not describe the form pressure sufficiently in all cases. Furthermore, a reliable design for the serviceability limit state, such as limitation of the deformation is to question.

The German standard DIN 18218 [18] was improved by the DIN-Committee NA 005-07-11 AA and issued in 2010. As shown in Fig. 1, DIN 18218:2010-01 [18] is connected to EN 12812:2008 and the National Annex DIN 1045-3:2011-01 and includes explicit design approaches for highly workable concrete and SCC.

3.2 Loads for the design of formwork

During its application, the formwork must withstand various loads. Detailed information about loads which has to be considered in the design is, for example, provided in EN 12812:2008. The standard distinguishes between direct and indirect actions.

Direct actions according to EN 12812:2008 are permanent loads—self-weight for example—as well as variable vertical actions like the concrete weight (to consider with a specific weight including reinforcement of 25 kN/m^3), live load allowance (at least 0.75 kN/m^2), snow and ice. Where in situ concrete is to be placed, an additional vertical live load allowance over a square area of 3×3 m^2 has to be applied. This additional load shall be 10 % of self-weight of the concrete. However the minimum load is limited to 0.75 kN/m^2 and the maximum load to 1.75 kN/m^3. Regarding the calculation of the lateral pressure on formwork, EN 12812:2008 refers to the DIN 18218, CIB-CEB-FIP 27-98-83 and CIRIA-Report Nr. 108 (see Chaps. 3.1, 3.3 and 6).

Horizontal loads should be assumed for imperfections of the construction, wind and earthquake if necessary. Indirect actions according to EN 12812:2008 are based on temperature, settlement or deformations as a result of prestressing.

Also the required load combinations and the partial safety factors are defined in EN 12812:2008. For the calculation of the design values the partial safety factor for permanent actions is $\gamma_F = 1.35$ and for other

Table 1 Consistency class of concrete according to DIN 1045-2:2008-08, DIN EN 206-1:2001-07 and EN 206-9:2010

Consistency class according to DIN 1045-2 and DIN EN 206-1:2001-07

Consistency class	Flow (a) DIN EN 12350-5 (cm)	Slump-flow (sf) DIN EN 12350-8 (cm)	
F1	≤34		Stiff
F2	35–41		Plastic
F3	42–48		Soft
F4	49–55		Very soft
F5	56–62	~55	Flowable
F6	63–69[a]	~60[b]	Very flowable
SCC	≥70	≥65[c]	Self-compacting

[a] According to DIN 1045-2 the concrete is still classified as conventional vibrated concrete

[b] According to EN 206-9 this concrete is already a self-compacting concrete (consistency class SF1) with a slump-flow between 550 and 650 mm

[c] According to EN 206-9 this concrete is a self-compacting concrete (consistency class SF2 or SF3) with a slump-flow between 660 and 750 mm or 760 and 850 mm respectively

actions $\gamma_F = 1.50$. For steel and aluminium elements, the partial safety factors for the material resistance is $\gamma_M = 1.1$ for formwork.

3.3 Lateral pressure of concrete according to DIN 18218:2010-01

Highly workable concrete with consistency class F5, F6 and SCC are now included in the new regulations. The simplified concept for the realistic and reliable calculation of the pressure on formwork is based on several experimental and theoretical studies [2, 19]. The background of the standard is explained in details in [13]. Several equations for the lateral formwork pressure are listed in DIN 18218:2010-01, one for each consistence class according to DIN EN 206-1 and DIN 1045-2 (Table 1).

For the design of the formwork, the bilinear pressure distribution is employed, as shown in Fig. 2. Accordingly, the pressure of fresh concrete is hydrostatic until the maximum characteristic pressure $\sigma_{hk,max}$ and the respective height h_s is reached. Subsequently, the lateral pressure is constant in the remaining section of height $h_E = v \times t_E$ (v: is the casting rate and t_E is the initial setting time of concrete). If the concrete has an age $\geq t_E$, no lateral pressure would be considered anymore. This simplified distribution has the advantage of applying the maximum pressure over a long formwork height. In reality, the position of the maximum pressure of fresh concrete (h_{max}) is influenced by a number of parameters, like formwork stiffness or early shrinkage, which make it difficult to predict exactly. Below the location of h_{max}, a significantly lower pressure than $\sigma_{hk,max}$ will occur. However, for the design of formwork the "safe" bilinear distribution is advantageous, considering the three variables: the setting time (t_E), the casting rate (v), and the height h_E (Fig. 2). Hydrostatic pressure is assumed up to h_s to take into consideration the uncertainties from the discontinuous casting rate or any vibration.

The design of formwork and falsework has to fulfill the requirements for safety and reliability of the construction. According to the semi-probabilistic safety concept, the design value of the pressure of fresh concrete (σ_{hd}) can be calculated from Eq. (1). The characteristic lateral pressure value (σ_{hk}) must be multiplied by the partial safety coefficient (γ_F), as follows.

$$\sigma_{hd} = \sigma_{hk} \cdot \gamma_F \quad (1)$$

The σ_{hk} and the γ_F take into account the variation in the model parameters (for example, the casting rate, v) and uncertainties of the calculation model. The γ_F on the load in the ultimate limit state = 1.5 based on the accepted failure probability of the formwork with $p_f = 10^{-4}$.

For the calculation of the maximum characteristic pressure, the equations in Table 2 are to be applied. It is shown that DIN 18218:2010-01 considers the casting rate (v), the specific concrete weight (γ_c) as well as the stiffening and setting of concrete through the *K1* coefficient. The coefficient *K1* depends on the setting time of concrete (t_E) as shown in Table 3 for concrete of various consistency classes.

The setting time (t_E) is based on the Vicat-penetration test for mortar according to DIN EN 480-2:2006-11 and is equal to the initial setting time of mortar extracted from concrete, according to ASTM C403/C403 M-05. A more practical alternative is the setting time $t_{E,KB}$ according to the Setting-bag test for concrete in DIN 18218:2010-01. The final-setting state occurs when the concrete is penetrable by thumb less than 1.0 mm (with a force of approximately 50 N), corresponding to a compressive strength lower

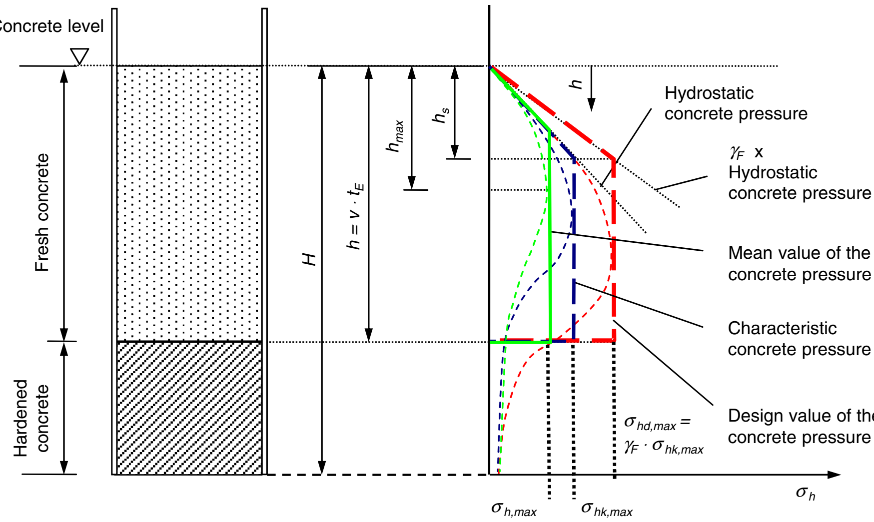

Fig. 2 Distribution of the lateral pressure of fresh concrete on formwork according to DIN 18218:2010-01

Table 2 Characteristic values for the maximum lateral form pressure (placement from the top)

Consistency class	Maximum lateral form pressure, $\sigma_{hk,max}$ (kN/m^2)
F1	$((5 \cdot v + 21) \cdot K1 \geq 25) \cdot K2$
F2	$((10 \cdot v + 19) \cdot K1 \geq 25) \cdot K2$
F3	$((14 \cdot v + 18) \cdot K1 \geq 25) \cdot K2$
F4	$((17 \cdot v + 17) \cdot K1 \geq 25) \cdot K2$
F5	$(25 + 30 \cdot v \cdot K1 \geq 30) \cdot K2$
F6[a]	$(25 + 38 \cdot v \cdot K1 \geq 30) \cdot K2$
SCC	$(25 + 33 \cdot v \cdot K1 \geq 30) \cdot K2$

with *v* Placing rate (m/h). *K1* Coefficient for the stiffening and setting according to Table 3. *K2* Factor for the specific weight $K2 = \gamma_c/25$ kN/m^3

[a] The design pressure for consistency F6 is higher compared to SCC because of the dynamic impact as a result of vibration which is still required according to DIN 1045-2

than 50 kPa. The correlation between $t_{E,KB}$ and t_E is given by Eq. (2).

$$t_E \approx 1.25 \cdot t_{E,KB} \tag{2}$$

To determine the final setting time t_E, the test should be conducted on the same mix design as that expected in the field. The temperature of the concrete sample must not exceed the expected concrete temperature on the construction site. Otherwise an increase of the design pressure by correction factors provided in DIN 18218:2010-01 is necessary.

Compared to the pressure for concrete with consistency classes F1 to F4, the pressure for highly flowable concrete is considerably higher. In addition to the different rheological behaviour connected with the development of the inner friction, the higher sensitivity of the concrete and the consideration of higher uncertainties are responsible for this difference. Furthermore, the characteristic values for the consistence F6 are higher than for SCC because of the significant influence of mechanical compaction on the formwork pressure.

As an example, the maximum pressure ($\sigma_{hk,max}$) according to DIN 18218:2010-01 [18] is plotted in Fig. 3 against the mean casting rate. The final setting time (t_E) in this example is 5 h, $\gamma_c = 25$ kN/m^3, and the concrete is placed from the top. The absolute minimum pressure is defined as 30 kN/m^2 for the highly workable concrete.

If SCC is placed from below by pumping, the design pressure of fresh concrete must be assumed fully hydrostatic and multiplied by $\gamma_F = 1.5$, according to DIN 18218:2010-01. Large scale conducted with SCC [19] showed values similar to the hydrostatic pressure if the concrete was pumped from below. In these tests the casting rate was 2 m/h and the setting time of the SCC approx. 9 h.

4 Formwork design in the United States of America according to ACI 347-04

4.1 General

The American Concrete Institute (ACI) Committee 347 (2004) (ACI 347-04) "Formwork for Concrete"

Table 3 Stiffening and setting parameter *K1*

Consistency class	Coefficient *K1*			
	General equation for setting time (t_E)[b]	Setting time $t_E = 5$ h	Setting time $t_E = 10$ h	Setting time $t_E = 20$ h
F1[a]	$1 + 0.03 \times (t_E - 5)$	1.0	1.15[c]	1.45
F2[a]	$1 + 0.053 \times (t_E - 5)$		1.25	1.80
F3[a]	$1 + 0.077 \times (t_E - 5)$		1.40	2.15
F4[a]	$1 + 0.14 \times (t_E - 5)$		1.70	3.10
F5, F6, SCC	$t_E/5.0$		2.00	4.00

[a] Maximum height of concrete $H = 10$ m

[b] Valid for 5 h $\leq t_E \leq$ 20 h; t_E in h

[c] Example for the calculation of *K1* (when $t_E = 10$ h) $= 1 + 0.03 \times (10 - 5) = 1.15$

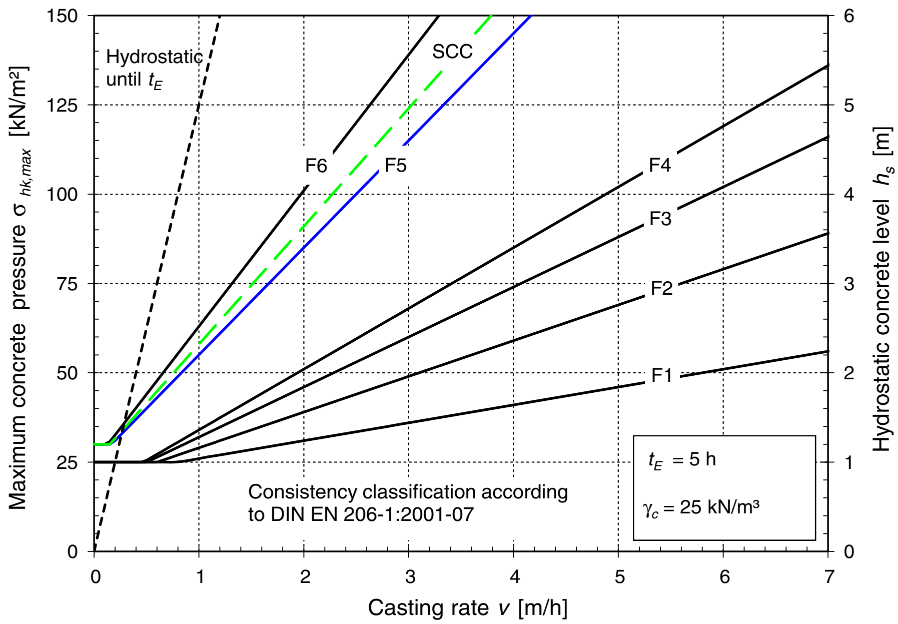

Fig. 3 Maximum lateral pressure of fresh concrete $\sigma_{hk,max}$ according to DIN 18218:2010-01, setting time of the concrete 5 h

proposed that the lateral pressure diagram of concrete is assumed to be trapezoidal in shape, as shown in Fig. 4. The diagram is presumed to be a triangular distribution from the upper free surface of the casting down to some limiting depth, beyond which the value of pressure reached is considered constant until the bottom of the formwork. The significant variables considered in the ACI recommendations are the rate and method of placement, consistency of concrete, coarse aggregate concentration, aggregate nominal size, concrete temperature, smoothness and permeability of the formwork material, size and shape of the formwork, consolidation method, pore-water pressure, content and type of cement, as well as the depth of the concrete placement, or concrete head.

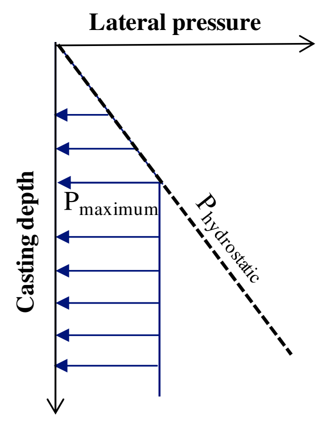

Fig. 4 Lateral pressure diagram for concrete

4.2 Vertical loads

Vertical loads consist of dead and live loads. The weight of formwork plus the weight of the reinforcement and freshly placed concrete is dead load. The live load includes the weight of the workers, equipment, material storage, runways, and impact.

Vertical loads assumed for shoring and re-shoring design for multi-storey construction should include all loads transmitted from the floors above as dictated by the proposed construction schedule.

The formwork should be designed for a live load of not less than 2.4 kPa of horizontal projection. When motorized carts are used, the live load should not be less than 3.6 kPa. The design load for combined dead and live loads should not be less than 4.8 or 6.0 kPa if motorized carts are used.

4.3 Horizontal loads

Braces and shores should be designed to resist all horizontal loads, such as wind, cable tensions, inclined supports, dumping of concrete, and starting and stopping of equipment. Wind loads on enclosures or other wind breaks attached to the formwork should be considered in addition to these loads.

For building construction, the assumed value of horizontal load due to wind, dumping of concrete, inclined placement of concrete, and equipment acting in any direction at each floor line should be not less than 1.5 kPa of floor edge or 2 % of total dead load on the form distributed as a uniform load per linear meter of slab edge, whichever greater.

Wall form bracing should be designed to meet the minimum wind load requirements of the local building code ANSI/SEI/ASCE-7 with adjustment for shorter recurrence interval as provided in SEI/ASCE 37. For wall forms exposed to the elements, the minimum wind design load should be not less than 0.72 kPa. Bracing for wall forms should be designed for a horizontal load of at least 1.5 kPa of wall length, applied at the top.

Wall forms of unusual height or exposure should be given special consideration.

4.4 Lateral pressure of concrete

Unless the conditions discussed below for the wall and column elements are met, formwork should be designed for the lateral pressure of the newly placed concrete given in Eq. (3):

Table 4 Unit weight coefficient C_w

Density of concrete (kg/m^3)	C_w
<2,240	$C_w = 0.5\,[1 + w/2{,}320\ \text{kg/m}^3]$ but not less than 0.80
2,240–2,400	$C_w = 1.0$
>2,400	$C_w = w/2{,}320\ \text{kg/m}^3$

$$P = \rho g h\ (\text{kPa}) \tag{3}$$

where; P Lateral pressure (kPa); ρ Density of concrete (kg/m^3); g Gravitational constant (9.81 m/s^2); and h Depth of fluid or plastic concrete from top of placement to point of consideration in formwork (m).

The set characteristics of a mixture should be understood, and using the rate of placement, the level of fluid concrete can be determined. For columns or other forms that can be filled rapidly before stiffening of the concrete takes place, h should be taken as the full height of the form or the distance between horizontal construction joints when more than one placement of concrete is to be made. When working with mixtures using newly introduced admixtures that increase set time or increase slump characteristics, such as SCC, Eq. (3) should be used until the effect on formwork pressure is understood by measurements.

For concrete having a slump of 175 mm or less and placed with normal internal vibration to a depth of 1.2 m or less, formwork can be designed for a lateral pressure (kPa); R = rate of placement (m/h); T = temperature of concrete during placing (°C); C_w = unit weight coefficient per Table 4; C_c = chemistry coefficient per Table 5.

4.4.1 For columns

The columns are defined as vertical elements with no plan dimension exceeding 2 m.

$$P_{max} = C_w C_c \left[7.2 + \frac{785\,R}{T + 17.8}\right] \tag{4}$$

with a minimum of 30 C_w kPa, but in no case greater than $\rho g h$.

4.4.2 For walls

The walls are defined as vertical elements with at least one plan dimension greater than 2 m.

Table 5 Chemistry coefficient C_c

Cement type or blend	C_c
Type I, II, III (currently Type GU, MS, and MH) without retarders[a]	1.0
Type I, II, III (currently Type GU, MS, and MH) with retarders[a]	1.2
Other types or blends containing less than 70 % slag or 40 % fly ash without retarder[a]	1.2
Other types or blends containing less than 70 % slag or 40 % fly ash with retarder[a]	1.4
Blends containing more than 70 % slag or 40 % fly ash	1.4

[a] Retarders include any admixture, such as a retarder, retarder water reducer, retarding midrange water-reducing admixture, or high-range water-reducing admixture (superplasticizer), that delays setting of concrete

For the walls of a rate of placement of less than 2.1 m/h and a placement height not exceeding 4.2 m;

$$P_{max} = C_w C_c \left[7.2 + \frac{785\,R}{T + 17.8}\right] \quad (5)$$

with a minimum of 30 C_w kPa, but in no case greater than ρgh.

For walls with a placement rate less than 2.1 m/h where placement height exceeds 4.2 m, and for all walls with a placement rate of 2.1–4.5 m/h;

$$P_{max} = C_w C_c \left[7.2 + \frac{1156}{T + 17.8} + \frac{244\,R}{T + 17.8}\right] \quad (6)$$

with a minimum of 30 C_w kPa, but in no case greater than ρgh.

4.4.3 Important notes

(1) Alternatively, a method based on appropriate experimental data can be used to determine the lateral pressure used for form design.

(2) If concrete is pumped from the base of the formwork, the formwork should be designed for the full hydrostatic head of concrete ρgh plus a minimum allowance of 25 % for pump surge pressure. In certain instances, pressures can be as high as the face pressure of the pump piston.

(3) Caution is necessary and additional allowance for pressure should be considered when using external vibration or concrete made with shrinkage compensating or expansive cements. Pressures in excess of the equivalent hydrostatic head can occur.

4.5 New ACI 347 provisions for SCC formwork pressure

In 2012, the ACI 347 committee started to include new provisions and recommendations for casting SCC by considering the rate of concrete placement relative to the rate of development of concrete stiffness/strength. The considered method has to include a measure of the stiffening characteristics of the SCC and should be capable of being easily checked on site using on-site measurements. Three different methods of estimating lateral pressure for non-vibrated SCC, meeting this requirement, have been proposed, as detailed below [14, 15, 17].

In the method proposed by Gardner et al. [14], the time for the slump flow to drop to 400 mm was chosen as the material parameter characterizing the concrete. A simple equation is used to describe the lateral pressure development with time—the equation cannot be used for times greater than that required to achieve P_{max}. The time to reach zero slump flow (t_0) (not a physically measurable phenomena), is defined as:

$$t_0 = t_{400}[\text{initial slump flow}/(\text{initial slump flow} - 400\text{ mm})] \quad (7)$$

The limiting value for lateral pressure of SCC (P_{max}) (kPa) corresponding to the time (t) after start of placement can be determined as follows:

$$\text{when } t < t_0\; P_{max} = wR\left(t - \frac{t^2}{2t_0}\right) \quad (8)$$

$$\text{when } t \geq t_0\; P_{max} = wRt_0/2 \quad (9)$$

$$\text{Except that when } t_h < t_0\; P_{max} = wR\left(t_h - \frac{t_h^2}{2t_0}\right) \quad (10)$$

but in no case greater than wh where

h	Height of placement (m)
p_{max}	Limiting lateral pressure (kPa)
R	Rate of placement (m/h)
t_{400}	Time for slump flow to drop to 400 mm (h)
t_h	h/R (h)
w	Unit weight of concrete (kN/m^3)

In the method proposed by Khayat and Omran [15] the on-site shear strength of SCC is measured by either the portable vane (PV) test [20] or the inclined plane (IP) test [21]. The static yield strengths $PV\tau_{0res@15\ min}$ and $IP\tau_{0res@15\ min}$ (Pa) from the two tests, respectively, are measured after 15 min of rest and reflect the structural build-up of concrete at rest. These values are used to calculate the limiting pressure value (P_{max}) with the pressure envelope being hydrostatic from the free surface to P_{max}. In Eqs. (11, 12), the $PV\tau_{0res@15\ min}$ and $IP\tau_{0res@15\ min}$ values are determined at a concrete temperature of 22 °C, and the concrete temperature parameter (T) accounts for the actual concrete temperature at the time of casting. Equations (13, 14) do not include a temperature parameter since the $PV\tau_{0res@15\ min}$ and $IP\tau_{0res@15min}$ values are determined at the expected concrete temperature (T_i).

$$P_{max} = \frac{wh}{100}\left[112.5 - 3.8h + 0.6R - 0.6T_i + 10D_{min} - 0.021\,PV\tau_{0rest@15min@Ti=22\,°C}\right] \times f_{MSA} \times f_{WP} \quad (11)$$

$$P_{max} = \frac{wh}{100}\left[112.0 - 3.83h + 0.6R - 0.6T_i + 10D_{min} - 0.023\,IP\tau_{0rest@15\,min@Ti=22°C}\right] \times f_{MSA} \times f_{WP} \quad (12)$$

$$P_{max} = \frac{wh}{100}\left[98 - 3.82h + 0.63R + 11D_{min} - 0.021\,PV\tau_{0rest@15\,min@Ti}\right] \times f_{MSA} \times f_{WP} \quad (13)$$

$$P_{max} = \frac{wh}{100}\left[98.4 - 3.80h + 0.60R + 11D_{min} - 0.0227\,IP\tau_{0rest@15min@Ti}\right] \times f_{MSA} \times f_{WP} \quad (14)$$

but in no case greater than *wh* where

h	Height of placement (m)
P_{max}	Limiting lateral pressure (kPa)
D_{min}	Equivalent to the minimum formwork dimension (d). For $0.2 < d < 0.5$ m, use $D_{min} = d$, For $0.5 < d < 1.0$ m, use $D_{min} = 0.5$ m
f_{MSA}	Factor for maximum aggregate size (MSA). For low thixotropic SCC ($PV\tau_{0\ rest@15min@22\ °C} \le 700$ Pa) with MSA = 10 mm, use $1.0 \le f_{MSA} \le 1.10$ for $4 \le H \le 13$ m. For SCC of various thixotropic levels with MSA of 14 and 19 mm, $f_{MSA} = 1.0$ for any H
f_{WP}	Factor to account for delay between successive lifts and varies linearly with the SCC thixotropy: $f_{WP} = 1.0$ for *continuous casting* for any SCC thixotropic levels. $f_{WP} = 1.0$–0.85 for placement *interrupted with a 30-min* waiting period in the middle of casting for very low to highly thixotropic SCC ($PV\tau_{0rest@15min@Ti=22\ °C} = 50$–$1{,}000$ Pa), respectively
T_i	Concrete temperature (°C)
R	Rate of placement (m/h)
W	Unit weight of concrete (kN/m^3)
$PV\tau_{0rest@15min@Ti=22\ °C}$	Static yield strength after 15 min of rest for concrete tested at 22 °C measured using PV test (Pa)
$IP\tau_{0rest@15min@Ti=22\ °C}$	Static yield strength after 15 min of rest for concrete tested at 22 °C measured using IP test (Pa)
$PV\tau_{0rest@15min@Ti}$	Static yield stress after 15 min of rest for concrete tested at the actual concrete temperature (T_i) obtained using the PV test (Pa)
$IP\tau_{0rest@15min@Ti}$	Static yield stress after 15 min of rest for concrete tested at the actual concrete temperature (T_i) obtained using the IP test (Pa)

The method available from DIN 18218 [17] uses a pressure envelope that is hydrostatic from the free surface to a limiting value. The limiting formwork pressures, including SCC and vibrated, high slump concrete, are given in terms of the concrete consistency (DIN 12350-5). For SCC, the limiting pressure (P_{max}) can be calculated from the following equation which requires the 10 MPa Vicat setting time on the sieved mortar using 1.13 mm diameter Vicat needle for a penetration of 2.5 mm. Alternatively, DIN 18218(2010) allows the setting bag test to determine the setting time for SCC.

$$P_{max} = (1.0\,m + 0.26\,Rt_E)w > 30 \text{ kPa} \qquad (15)$$

but in no case greater than wh where, P_{max} Limiting lateral pressure (kPa); R Mean rate of placement (m/h); t_E Setting time for concrete (using 1.13 mm diameter Vicat needle at 10 MPa for a penetration of 2.5 mm) (h); w Unit weight of concrete (kN/m^3).

Experience with these methods is presently somewhat limited. Thus, evaluation of estimated pressure on the basis of more than one method is advisable until satisfactory performance is confirmed for the range of parameters associated with the project.

If SCC is vibrated the pressure should hydrostatic. Site conditions that can transmit vibrations to the freshly-placed concrete as this can cause it to lose its internal structure and re-liquefy. Heavy equipment operating close to the forms, or continued work on the forms, will transmit vibration. Dropping concrete from the pump hose or placing bucket will also agitate the in-place concrete. Concrete pumped into the bottom of a form will always create pressures higher than full liquid head.

5 Formwork design in Canada according to CSA S269.3-1992

In current CSA Standards, there are two document: CSA S269.3 for “Concrete formwork” and CSA S269.1 for “Falsework for construction purposes”.

5.1 Vertical and horizontal loads

Formwork shall be assumed to be subject to vertical loads specified in CSA Standards S269.1 and CAN/CSA-S269.2. Furthermore, formwork exposed to wind pressures shall be designed to resist the following lateral forces:

(a) wind pressures based on those listed by the National Building Code of Canada, using 1 in 10 probability with a gust factor of 2 and a minimum wind pressure of 0.8 kPa; and
(b) any reasonably anticipated lateral loads which may be applied to the formwork structure including forces imposed by powered equipment.

5.2 Concrete pressures[1]

5.2.1 *Pumped concrete*

Form design pressure shall be:

(a) increased by at least 25 % where concrete is to be placed by pumping from the top of the form; and
(b) the hydrostatic pressure plus the anticipated pressure at the pump less minimum expected line and head losses where concrete is to be placed from the bottom of the form, but not less than hydrostatic.

5.2.2 *Columns*

Unless the rate of placement can be controlled to a design specified rate, column forms shall be designed for full hydrostatic pressure.

5.2.3 *Walls*

Wall formwork for internally vibrated concrete using Type 10 or Type 30 cements (similar to ASTM 150 Type I and Type III cements) and maximum 100 mm slump shall be designed for:

(a) full hydrostatic pressure for forms up to 1.3 m in height;
(b) pressures in Table 6 for forms higher than 1.3 m; and
(c) Pressures derived with the following formula [instead of those in (a) and (b)], in special situations where all the parameters are known in advance [22]:

[1] The load information in the following is intended for use with working stress design standards. When limit states design procedures are used, these loads must be taken as specified live loads and factored in accordance with the requirements of the applicable Standards.

Table 6 Recommended concrete pressures for wall form design

Rate of placement (m/h)	Limiting lateral pressure (kPa)[a]					
	Concrete temperature (°C)					
	5	10	15	20	25	30
1.0[(1)]	69	58	50	48	48	48[b]
1.5[(1)]	74	62	54	48	48	48
2.0[(1)]	79	66	57	51	48	48
2.5[(1)]	85	71	61	54	48	48
3.0[(1)]	90	75	65	57	51	48
3.5[(2)]	128	106	91	80	71	65
4.0[(2)]	144[c]	120	103	90	81	73
4.5[(2)]		134	115	101	90	81
5.0[(2)]		144	127	111	99	89
5.5[(2)]			139	121	108	98
6.0[(2)]				132	117	106

This table shall not be used for the design of slip forms

[a] The limiting lateral pressure shall not exceed the hydrostatic pressure

[b] Minimum limiting pressure = 48 kPa

[c] Maximum limiting pressure = 144 kPa

[(1)] Use of ACI 1978 wall equation used up to 3 m/h rate of concrete rise

[(2)] Use of ACI column formula

$$P_{\max} = \left[(24 \times hi) + \left(\frac{d}{40}\right) + \left(\frac{400 \times R^{1/2}}{18+T}\left(\frac{100}{100-F}\right)\right) + \frac{\text{slump}}{10}\right] \text{kPa}$$
$$P_{\max} < (24 \times h)\,\text{kPa} \quad (16)$$

where $P_{\max}$ Limiting pressure (kPa); hi Depth of immersion of vibrator, minimum = 1 (m); d Minimum dimension of form (mm); R Rate of placement (m/h); T Concrete temperature (°C); F Fly ash or slag content of the concrete as percentage of the total cementitious material; Slump: Slump of concrete after application of superplasticizer, if used (mm); h Height of pour (m).

5.3 Admixtures and supplementary cementing materials

The use of admixtures and supplementary cementing materials may modify the setting time of the concrete. This shall be considered when calculating design pressure less than full fluid pressure. Notes in Table 6:

(1) Pressures are calculated from ACI Standard 347-78 wall formula for $R \leq 3$ m/h [Eq. (17) that is similar to Eq. (6) without including the C_w and C_c coefficients].

$$p = 7.2 + \frac{1156\,R}{T + 17.8} + \frac{244\,R}{T + 17.8} \quad (17)$$

(2) Pressures are calculated from ACI Standard 347-78 column formula $R > 3$ m/h [Eq. (18) that is similar to Eq. (5) without including the C_w and C_c coefficients]

$$p = 7.2 + \frac{785\,R}{T + 17.8} \quad (18)$$

where R Rate of placement (m/h); T Concrete temperature (°C).

5.4 The new CSA document CSA S 269-2012 for SCC

The work started on May 2011 aiming at updating the old CSA Standards. The target is to gather both the “Concrete formwork, CSA S269.3” and “Falsework for construction purposes, CSA S269.1” Standards in one document and also include the new concretes existing in the market such as the flowable concrete and SCC. The available draft is named “CSA S 269-2012”.

The new document “CSA S 269-2012” considered the same provisions and language described by the ACI 347-12 (Sect. 4.5) for determining the formwork pressure of SCC. The three methods for determining the SCC formwork pressure are also considered in these CSA Standards [14, 15, 17].

6 Comparison of the normative calculation concepts (maximum unfactored service loads)

In this section, the form pressures of the most important normative concepts are compared. In order to compare the regulations of different normative design concepts, the specific safety concept must be considered. Considering a specific formwork, the permissible characteristic form pressure (σ_{hk}), i.e. the load effect (E_k), based on the global safety concept depends on the material strength (R_d) and the global

Table 7 Comparison of the normative concepts (unfactored service loads)

Approach	$\sigma_{hk,max,2}$ (kN/m^2), parameters and limits	
DIN 18218: 2010-01	Equals $\sigma_{hk,max,2}$ in Tables 2 and 3	
ACI 347-04 (2004)—(USA)	$t_v \leq 1.2$ m, $s \leq 17.5$ cm,	
	C_w = unit weight coefficient (Table 4).	
	C_c = Chemistry coefficient (Table 5).	
	Eqs. (4 and 5)	For columns (largest width of the cross section <2 m),
		For walls if $v \leq 2.1$ m/h and $H \leq 4.2$ m
	Eq. (6)	For walls if $v \leq 2.1$ m/h and $H > 4.2$ m, and
		For walls if $2.1 < v \leq 4.2$ m/h
CIB-CEB-FIP-Bulletin (1977)	$s \leq 10$ cm	
	No additives or admixtures which affect the stiffening are allowed.	
	10 kN/m^2 should be added when the concrete is discharged freely from a height of 2 m or more.	
	Stiffening criterion $\sigma_{hk,max,2} = (24 \cdot v \cdot K + 5) \cdot \frac{\gamma_c}{24}$	K values according to Table 8
	Effect of arching $\leq (15 + 100 \cdot b + 3 \cdot v) \cdot \frac{\gamma_c}{24}$	For $b \leq 0.50$ m (lowest width of the cross section) and $s \leq 80$ mm
CIRIA Research Report No. 108 (1985)—(GB)	$\sigma_{hk,max,2} = \gamma_c \cdot (C_1 \cdot \sqrt{v} + C_2 \cdot K_T \cdot \sqrt{H - C_1 \cdot \sqrt{[]v}})$	$5 \leq T \leq 30$ °C
		C_1 = Coefficient depending on the size and shape of the formwork
		(=1.0 for walls, 1.5 for columns)
		C_2 = Coefficient depending on the constituent materials of the concrete (0.3 to 0.6)
		K_T = Temperature coefficient $K_T = (36/(T+16))^2$
JGJ 162 (2008)—(China)	$\sigma_{hk,max,2} = 0.22 \cdot \gamma_c \cdot t_0 \cdot \beta_1 \cdot \beta_2 \cdot \sqrt{v}$	t_0 = Setting time or temperature coefficient $t_0 = 200/(T + 15)$
		β_1 = Coefficient depending on the use of retarding additives (=1.0 without additives, 1.2 with additives)
		β_2 = Coefficient depending on the slump (0.85 for $s < 30$ mm, 1.0 for s = 50–90 mm, 1.15 for s = 110–150 mm)

safety factor (γ_g). The higher the safety factor, the lower the normative characteristic pressure.

$$E_d = E_k \cdot \gamma_g \leq R_d \tag{19}$$

If the partial safety concept is used, the partial safety factors on the load (γ_F) and the material (γ_M) control the permissible characteristic values of the form pressure (σ_{hk}).

$$E_d = E_k \cdot \gamma_F \leq R_k/\gamma_M = R_d \tag{20}$$

However, the design values as well as the characteristic values of the normative concept are not exactly comparable. Regardless of these possible differences, throughout this paper the characteristic unfactored values of the form pressure (σ_{hk}), i.e. the load effect (E_k) are used.

According to all standards, the maximum characteristic form pressure ($\sigma_{hk,max}$) is the minimum of two limit values, the hydrostatic concrete pressure and a second limit which considers primarily the inner friction of the material and the stiffening of the concrete during the concrete placing. For the second limit, the normative approaches are significantly different from each other. The reason is that the concepts are mostly empirical, based on full-scale experimental tests.

$$\sigma_{hk,max} = \min \left| \begin{matrix} \sigma_{hk,max,1} \\ \sigma_{hk,max,2} \end{matrix} \right| \begin{matrix} \text{Hydrostatic limit} \\ \text{Second limit} \end{matrix} \quad [\mathrm{kN/m^2}] \tag{21}$$

with $\sigma_{hk,\ max,\ 1} = \gamma_c \cdot H$, and $\sigma_{hk,\ max,\ 2}$ according to Table 7 for the various normative concepts.

The maximum characteristic form pressure versus casting rate is shown in Fig. 5 assuming an example with 10 m formwork height of the casting section. The number of normative parameters, such as concrete

Table 8 *K*-values according to CIB-CEB-FIP-Bulletin (1977)

Slump, *s* (mm)	Concrete temperature, *T* (°C)		
	5	15	25
25	*K* = 1.45	0.80	0.45
50	1.90	1.10	0.60
75	2.35	1.35	0.75
100	2.75	1.60	0.90

temperature, additives and setting time remain constant. In addition, the hydrostatic pressure in sections with a concrete age less than 5 h (setting time) is shown. It should be noted that at a casting rate lower than 1 m/h, the form pressure according to ACI and CIRIA is much higher than the values according to CIB-CEB-FIP, JGJ 162 and DIN 18218. For a casting rate of 2 m/h, all concepts show similar design loads. Only the value of DIN 18218 is significantly lower for the consistency class F4. At high casting rates the form pressure according to CIRIA, JGJ 162 and DIN 18218 is comparably low. Further analyses revealed that the formwork pressure according to the Indian standard IS 14687 is equal to the regulations of the former East German standard TGL 33421/01. However, by considering the presented boundary conditions in Fig. 5 the formwork pressure will be similar to that of JGJ 162.

7 Responsibility and risk regarding the calculated pressure load

According to different national regulations—like the European Product Safety Law or that of the U.S.—the manufacturer of every product is responsible for the safe use of his product. In the case of formwork the requirements like the load capacity depending on the maximum lateral formwork pressure have to be taken into account, while calculating the formwork construction.

The producer or the rental company of the formwork shall give the customer an assembly instruction of the used system. This document comprises at least safety guidelines, details on the standard configuration and intended use, as well as the system description.

The contractor is responsible for drawing up a comprehensive risk assessment and a set of installation instructions. The latter is not usually identical to the assembly instructions.

The functional instructions (standard configuration) contained in the assembly instructions are to be complied with as stated. Enhancements, deviations or changes represent a potential risk and therefore require separate verification (with the help of a risk assessment) or a set of installation instructions which comply with the relevant laws, standards and safety regulations. The same applies in those cases where

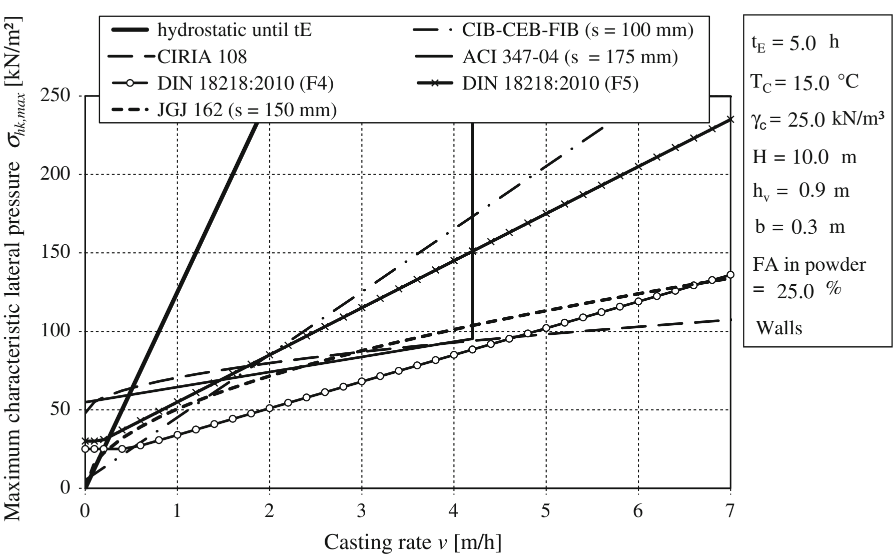

Fig. 5 Maximum characteristic (unfactored) pressure according to CIRIA Research Report 108 (1985), CIB-CEB-FIB-Bulletin (1977), ACI 347-04 (2004), JGJ 162 (2008) and DIN 18218 (2010)

formwork and/or falsework components are provided by the contractor [23].

The contractor or formwork customer at the construction site has to ensure the stability of the formwork and falsework constructions as well as the structure during all stages of construction. Therefore the process of placing the concrete is the critical aspect in respect to the formwork. Here exists the risk like undocumented properties of the fresh concrete, the customer needs for the pouring process. It is fact, that in many countries the supplier of the concrete does not give sufficient information about the concrete characteristics (e. g. the final setting time), which is necessary to calculate the pressure of fresh concrete on the formwork depending on the placing rate (e. g. according to DIN 18218). Therefore a monitoring of the formwork pressure will be helpful, especially if highly workable concretes like SCC are used and the design load is below the hydrostatic pressure value.

8 Conclusions

Most of the current Standards are devoting for the design of the formwork for the normal vibrated concrete. Currently, the Standards are being updated to include provisions for the newly adapted concrete, such as the flowable concrete and self-consolidating concrete. The German Standard DIN 18218:2010-01 is the first Standard to include the formwork pressure for SCC and flowable concrete. However, the updated versions of the other Standards and guidelines such as the ACI-347 and CSA S 269 include methods for casting formwork with flowable concrete and SCC, the experience with these methods is still limited. The available methods for calculating the formwork pressure for the flowable concrete and SCC are based on measuring the shear strength of concrete using different concepts, such as the setting time of concrete or the structural build-up at rest (thixotropy). More field work is necessary to validate and provide the confidence to the available methods for the formwork pressure calculation. With this information the regulations could be improved to ensure a more economic formwork design.

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