International *fib* Symposium on Conceptual Design of Structures

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An alternative method for calculating concrete design compressive strength, f_{cd}

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What motivated this research ?

- ***fib*** Model Code 2020, to promote **sustainability**, allows different ages of control of concrete compressive strength (f_{ck});
- To calculate f_{cd}, only two values of α_{cc} are possible (0.85 and 1.00) based on the control age of f_{ck};
- On MC2020 are models that represent the development ($\beta_{cc}(t)$) and reduction ($\beta_{c,sus}(t, t_0)$) of concrete compressive strength;
- What is the impact of the product $\beta_{cc}(t)$ * $\beta_{c,sus}(t, t_0)$, both which are functions on time t, on the design compressive strength of concrete f_{cd} ?

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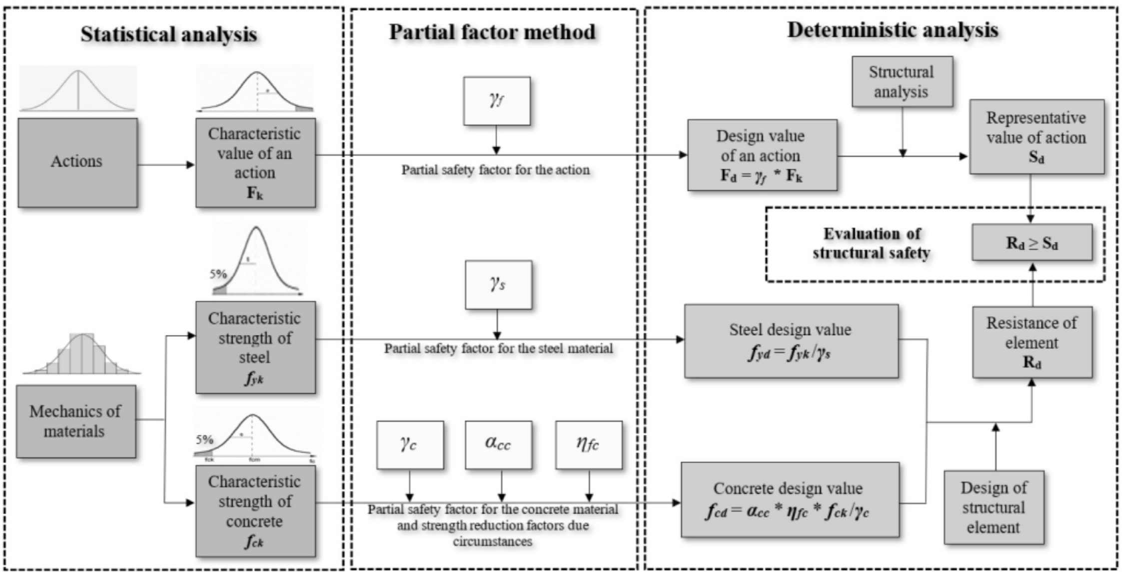

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Design compressive strength of concrete (f_{cd})

- f_{cd} is used in the design of **compressed regions** → available, safe and **minimum** strength for its service life (> 50 years);
- MC2020 specifies the design compressive strength as:

$$f_{cd} = \alpha_{cc} * \eta_{fc} * f_{ck}/\gamma_c;$$

- f_{cd} → design compressive strength;
- f_{ck} → characteristic compressive strength;
- γ_c → partial safety factor for concrete → **equals 1.5** for transient and persistent situations;
- α_{cc} → coefficient for **long-term effects** on compressive strength and unfavorable **effects from the load**;
- η_{fc} → reduction factor for increased **brittleness of high strength concrete**:

$$\eta_{fc} = \left(\frac{40}{f_{ck}}\right)^{1/3} \leq 1.0$$

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Influences between potential strength (f_{ck}) and actual in situ strength ($f_{c,ais}$)

- Actual in situ strength ($f_{c,ais}$) differs from the strength in the standard specimen (f_{ck}) due several reasons:

a) Real structure have very different procedures versus standard specimen test → γ_c ;

b) In structure $f_{c,ais}$ is needed for the service life versus one date for specimen standard → γ_c ;

c) Structure loaded versus unloaded testing specimen → α_{cc} ;

d) Specimen tested under controlled conditions in a rapid test (<5 minutes) → α_{cc} ;

✓ Concrete strength determined in the standard specimen (f_{ck}) represents the **potential** strength of concrete, what means, in real structure, for the same date, concrete strength is lower.

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Partial safe factor for concrete (γ_c)

- Cremonini found out that actual in situ strength ($f_{c,ais}$), from extracted cores, is **20% to 30%** lower than standard specimen (f_{ck}) at 28 days of age;
- γ_c value of 1.5, from MC2010 → $\gamma_{m,c}$ * $\gamma_{Rd1,c}$ * $\gamma_{Rd1,c}$ = **1.39** * 1.05 * 1.05 ≈ 1.5;
- To calculate f_{cd}, it **is still necessary** to consider the effects of sustained loads ($\beta_{c,sus}(t, t_0)$) and strength development over time ($\beta_{cc}(t)$);
- The safety verification **must** take account the differences between actual in situ strength ($f_{c,ais}$) and standard specimen (f_{ck}).

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Development of strength with time (β_{cc}(t))

- Compressive strength of concrete **develops over time** from the chemical reactions of water with cement;
- MC2020 specifies this **development** of strength with time by the expression:

$$\beta_{cc}(t) = \frac{f_{cm}(t)}{f_{cm}} = e^{\left\{s_c\left[1-\left(\frac{t_{ref}}{t}\right)^{0.5}\right]\left(\frac{28}{t_{ref}}\right)^{0.5}\right\}}$$

- $\beta_{cc}(t)$ → coefficient that describes the ratio of strength development with time;
- $f_{cm}(t)$ → mean compressive strength in an age t in days;
- f_{cm} → mean compressive strength at a specified reference age t_{ref} in days;
- t → age of concrete in days;
- t_{ref} → age of concrete at which its strength determined in days;
- s_c → coefficient which depends on the strength development class of concrete, $0.1 \le s_c \le 0.6$

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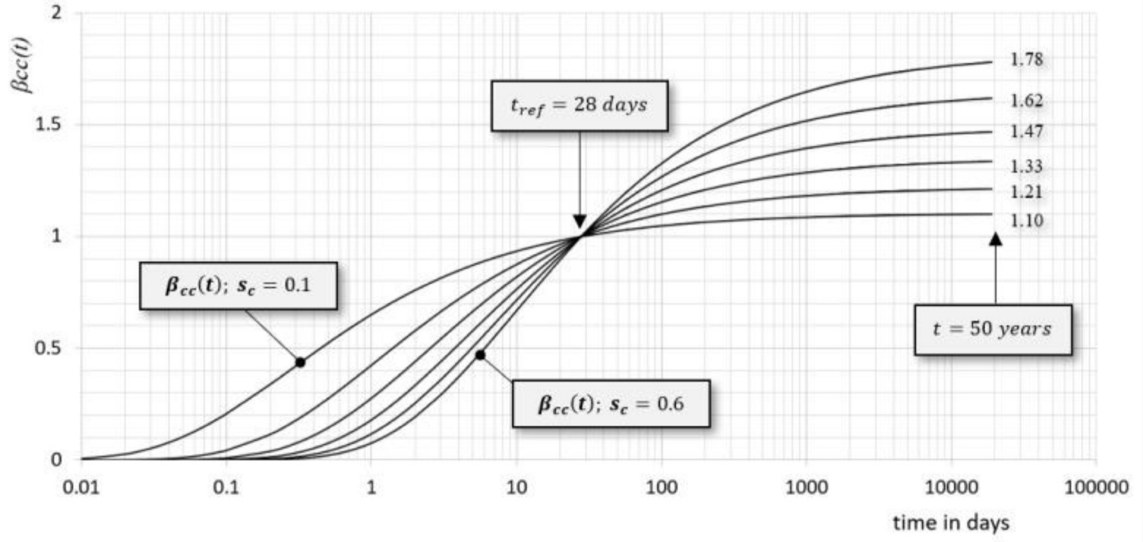
Development of strength with time ($\beta_{cc}(t)$)

Concrete strength, f_{ck} [MPa]	s_C		
	Class CR	Class CN	Class CS
$f_{ck} \leq 35$	0.3	0.5	0.6
$35 < f_{ck} < 60$	0.2	0.4	0.5
$f_{ck} \geq 60$	0.1	0.3	0.4

- Class CR → Rapid strength development class of concrete;
- Class CN → Normal strength development class of concrete;
- Class CS → Slow strength development class of concrete.

Development of strength with time ($\beta_{cc}(t)$)



Reduction of strength under sustained loads ($\boldsymbol{\beta_{c,sus}(t, t_0)}$)

- Rüsch found out in his study that results from **long-duration loads were lower** than specimens from rapid tests;
- MC2020 specifies this **reduction** of strength with time by the expression:

$$\beta_{c,sus}(t,t_0) = \beta_{t0}(t_0) + [1 - \beta_{t0}(t_0)]\left[1 + 10^4\,\frac{(t-t_0)}{t_0}\right]^{-0.1}$$

- $\boldsymbol{\beta_{c,sus}(t, t_0)}$ → coefficient that describes decrease of strength with time under high sustained load;
- $\boldsymbol{\beta_{t0}(t_0)}$ → parameter which considers the maturity of concrete at loading. Calculated as:

$$\boldsymbol{\beta_{t0}(t_0)} = 0.64 + 0.01 * \ln(\boldsymbol{t_0})$$

- $\boldsymbol{t_0}$ → age of concrete at loading in days, valid for t0 ≥ 7 days;
- $\boldsymbol{t - t_0}$ → time under high sustained loads in days, 0.015 days (20 min) ≤ $\boldsymbol{t - t_0}$ ≤ 3650 days (10 years);
- **Note**: the expression is valid for $\boldsymbol{t - t_0}$ above 3650 days, but its value is fixed to 3650 days.

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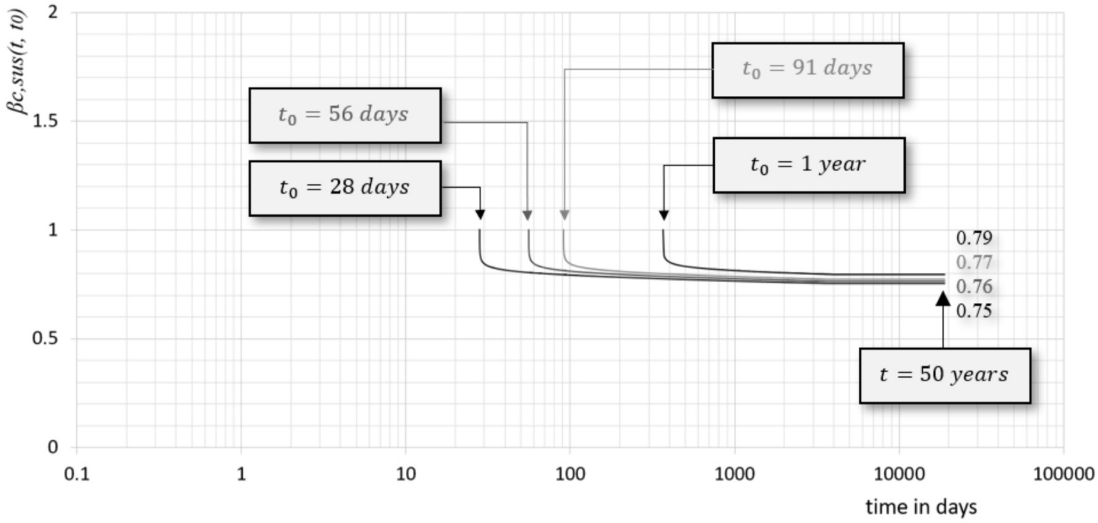
Reduction of strength under sustained loads ($\boldsymbol{\beta_{c,sus}(t, t_0)}$)



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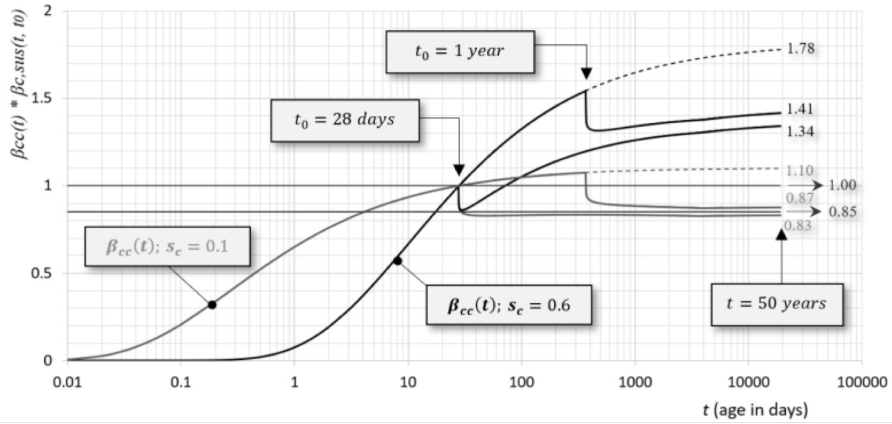
Long term effects on compressive strength (α_{cc})

- The analysis of concrete strength development combines opposite effects using the product $\boldsymbol{\beta_{cc}(t)}$ * $\boldsymbol{\beta_{c,sus}(t, t_0)}$ as follow:



- The product $\boldsymbol{\beta_{cc}(t)}$ * $\boldsymbol{\beta_{c,sus}(t, t_0)}$ represents the definition of $\boldsymbol{\alpha_{cc}}$, but assumes variable values, not the fixed values of 0.85 or 1.0.

Authors proposal for calculating α_{cc} and f_{cd}

- Considering:

a) The first **loads are applied to a structure months after** the reference date t_{ref};

b) The strength of concrete **develops due continuous hydration** of the cement.

- Authors proposal:

$$\boldsymbol{\alpha_{cc}} = \min_{t}[\boldsymbol{\beta_{cc}(t)} * \boldsymbol{\beta_{c,sus}(t, t_0)}]$$

Table 1 Minimum values of α_{cc} for t_{ref} = 28 days, t_0 varying from 28 days to 365 days, and for different concrete classes characterized by s_c.

t_0 [days]	s_c					
	0.1	0.2	0.3	0.4	0.5	0.6
28	0.83	0.84	0.85	0.85	0.86	0.86
56	0.84	0.89	0.92	0.96	0.99	1.02
91	0.85	0.91	0.96	1.01	1.06	1.12
365	0.87	0.95	1.04	1.13	1.22	1.31

Authors proposal for calculating α_{cc} and f_{cd}

- The concrete design strength would be calculated as:

$$f_{cd} = \alpha_{cc} * \eta_{fc} * f_{ck}/\gamma_C = \min_t \left[\beta_{cc}(t) * \beta_{c,sus}(t, t_0)\right] * \eta_{fc} * f_{ck}/\gamma_C$$

- The product of $\beta_{cc}(t)$ * $\beta_{c,sus}(t, t_0)$ does **not always** have its minimum value at 50 years of age;
- In most cases this product can reach minimum values **shortly after** the application of the elevated load.

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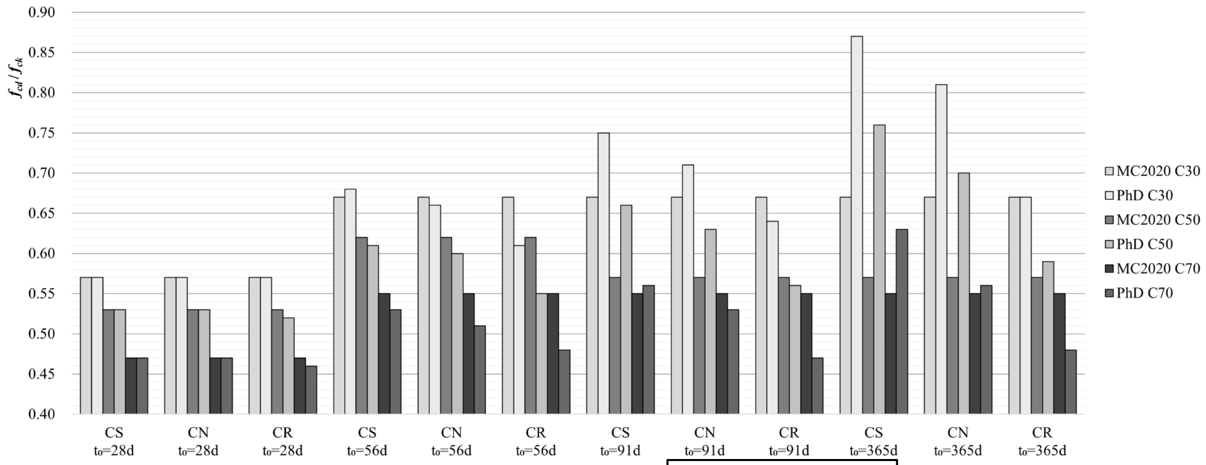
Comparison between results on *fib* and PhD method of f_{cd} calculation



Concrete compressive design strength f_{cd}/f_{ck} for t_{ref} = 28 days.

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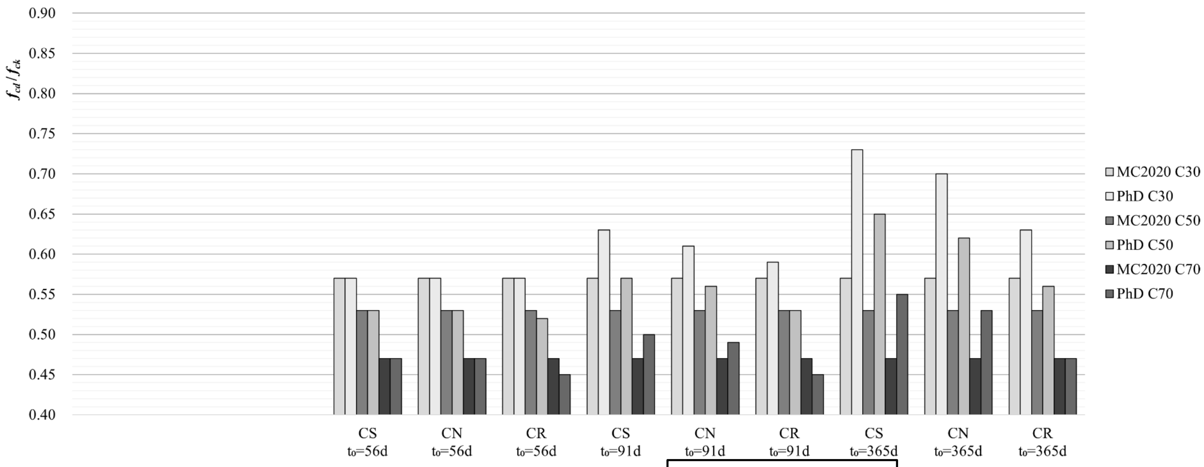
Comparison between results on *fib* and PhD method of f_{cd} calculation



Concrete compressive design strength f_{cd} / f_{ck} for t_{ref} = 56 days.

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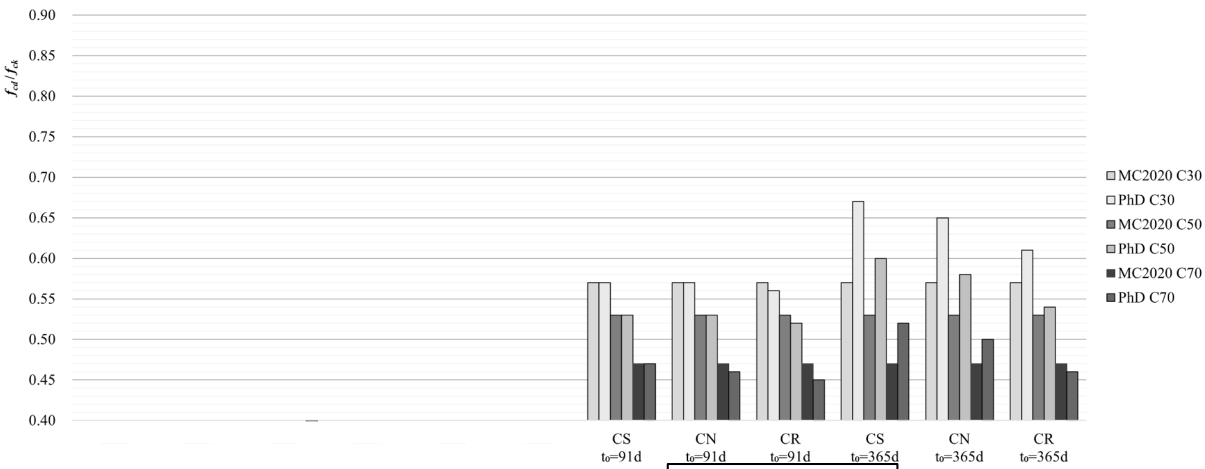
Comparison between results on *fib* and PhD method of f_{cd} calculation



Concrete compressive design strength f_{cd} / f_{ck} for t_{ref} = 91 days.

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Conclusions

- ***fib*** Model Code 2020, MC2020, specifies the value of α_{cc} either 0.85 or 1.00, empirical coefficients, however, they are **both fixed coefficients**;
- f_{cd} values of **0.47*f_{ck} to 0.67*f_{ck}** were obtained using the values of α_{cc} prescribed in MC2020;
- The authors, proposes a **novel methodology** for determining the design compressive strength f_{cd};
- The methodology utilizes **established models** that account for the development ($\beta_{cc}(t)$) and reduction ($\beta_{c,sus}(t, t_0)$) of compressive strength of concrete;
- f_{cd} values of **0.45*f_{ck} to 0.87*f_{ck}** were obtained using the proposed methodology;
- The proposed methodology offers a more accurate and potentially more **economical** and **sustainable** analysis, without compromising design safety.

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Conclusions

- Two examples:
- Short Column l_e = 2.88m with N_{Sd} = 5600 kN of compression and moments M_{xSd} = M_{ySd} = 168 kN.m;

Concrete Class	Cement Class	t_{ref}	t_0	Model	α_{cc}	f_{cd}/f_{ck}	Short Column		
							Dimensions	Total steel	Emission
C30	CS	56 days	365 days	MC2020	0.85	0.57	530mm x 530mm	**130 kg**	**283 kg $CO_{2eq.}$**
				PhD					
C70	CR	28 days	91 days	MC2020	1.00	0.55	380mm x 380mm	**100 kg**	**302 kg $CO_{2eq.}$**
				PhD					

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Thank You

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