Reinforced Concrete Columns with High-Strength Concrete and Steel Reinforcement, Part 1

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ACI Fall 2012 Convention
October 21 – 24, Toronto, ON

ACI WEB SESSIONS

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ACI WEB SESSIONS

Examination of Stress Block Parameters for High-Strength Concrete in the Context of ACI 318 Code

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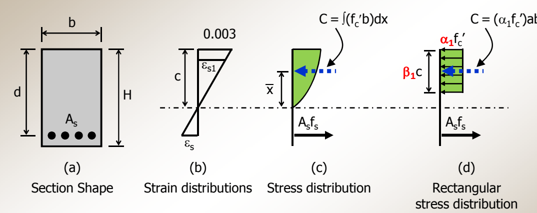
Concrete Rectangular Stress Block



ACI 318 concrete stress block

α_1 = 0.85

β_1 = 0.85-0.05/1000×(f_c'-4000); 0.85≥β_1≥0.65

ACI 318-11 Provisions Related to Concrete Stress Block Parameter(s)

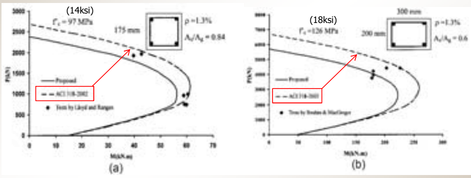
	α_1	β_1
CHAPTER 10. FLEXURE AND AXIAL LOADS		
10.2 – Design assumptions	10.2.7 – Equivalent rectangular concrete stress distribution	10.2.7 – Equivalent rectangular concrete stress distribution
10.3 – General principles and requirements	10.3.6 – Design axial strength ϕP_n of compression members $\phi P_{n,max} = 0.85\phi[\mathbf{0.85}f_c'(A_g - A_{st}) + f_y A_{st}]$ $\phi P_{n,max} = 0.80\phi[\mathbf{0.85}f_c'(A_g - A_{st}) + f_y A_{st}]$	
10.14 – Bearing strength	10.14.1 – Design bearing strength of concrete shall not exceed $\phi(\mathbf{0.85}f_c' A_1)$.	
CHAPTER 18. PRESTRESSED CONCRETE		
18.7 – Flexural strength		18.7.2(a) For members with bonded tendons $f_{ps} = f_{pu}\left\{1 - \frac{\gamma_p}{\boldsymbol{\beta_1}}\left[\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}(\omega - \omega')\right]\right\}$

ACI 318-11 Provisions Related to Concrete Stress Block Parameter(s)

	α_1	β_1
CHAPTER 22. STRUCTURAL PLAIN CONCRETE		
22.5 – Strength design	22.5.1 – Design of cross sections $M_n = \mathbf{0.85}f_c' S_m$ if compression controls, where S_m is the corresponding elastic section modulus.	
APPENDIX A. STRUT-AND-TIE MODELS		
A.3 – Strength of struts	A.3.2 – The effective compressive strength of the concrete in a strut $f_{ce} = \mathbf{0.85}\beta_s f_c'$	
A.5 – Strength of nodal zones	A.5.2 – The calculated effective compressive stress on a face of a nodal zone due to the strut-and-tie forces $f_{ce} = \mathbf{0.85}\beta_n f_c'$	

ACI 318 Concrete Stress Block for HSC

- Many test results indicated that the ACI 318 concrete stress block tend to overpredict the axial and flexural strength of high-strength concrete (HSC) columns.



- Ozbakkaloglu and Saatcioglu (2004) -

- Little guideline has been provided for the concrete strength which the ACI 318 concrete stress block should be avoided.

Issues on Various Concrete Stress Blocks

- Various expressions of concrete stress block have been proposed. But their performance is not fully studied.
- The impact of the change of stress block on other design provisions in ACI 318 has not been examined.

Concrete Stress Blocks: Codes

ACI 318 (2011)	$\alpha_1 = 0.85$ $\beta_1 = 0.85 - 0.05/1{,}000\times(f_c' - 4{,}000)$ $0.85 \ge \beta_1 \ge 0.65$
CSA A23.3 (2004)	$\alpha_1 = 0.85 - 0.010/1{,}000\times f_c'$ $\alpha_1 \ge 0.67$ $\beta_1 = 0.97 - 0.017/1{,}000\times f_c'$ $\beta_1 \ge 0.67$
NZS 3101 (2006) (or Li et al. (1994))	$\alpha_1 = 0.85 - 0.028/1{,}000\times(f_c' - 8{,}000)$ $0.85 \ge \alpha_1 \ge 0.75$ $\beta_1 = 0.85 - 0.05/1{,}000\times(f_c' - 4{,}000)$ $0.85 \ge \beta_1 \ge 0.65$

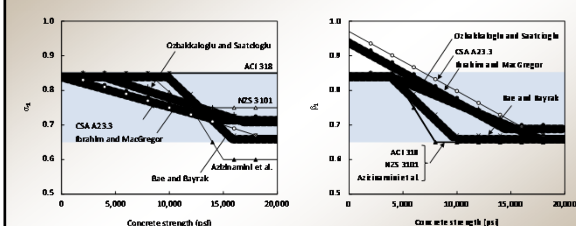
(f_c' in psi)

Concrete Stress Blocks: Proposals

Ibrahim and MacGregor (1997)	$\alpha_1 = 0.85 - 0.0086/1{,}000\times f_c'$ $\alpha_1 \ge 0.725$ $\beta_1 = 0.95 - 0.0172/1{,}000\times f_c'$ $\beta_1 \ge 0.70$
Bae and Bayrak (2003)	$\alpha_1 = 0.85 - 0.028/1{,}000\times(f_c' - 10{,}000)$ $0.85 \ge \alpha_1 \ge 0.67$ $\beta_1 = 0.85 - 0.028/1{,}000\times(f_c' - 4{,}000)$ $0.85 \ge \beta_1 \ge 0.67$
Ozbakkaloglu and Saatcioglu (2004)	$\alpha_1 = 0.85 - 0.01/1{,}000\times(f_c' - 4{,}000)$ $0.85 \ge \alpha_1 \ge 0.72$ $\beta_1 = 0.85 - 0.013/1{,}000\times(f_c' - 4{,}000)$ $0.85 \ge \beta_1 \ge 0.67$
Azizinamini et al. (1994)	$\alpha_1 = 0.85 - 0.05/1{,}000\times(f_c' - 10{,}000)$ $0.85 \ge \alpha_1 \ge 0.60$ $\beta_1 = 0.85 - 0.05/1{,}000\times(f_c' - 4{,}000)$ $0.85 \ge \beta_1 \ge 0.65$

(f_c' in psi)

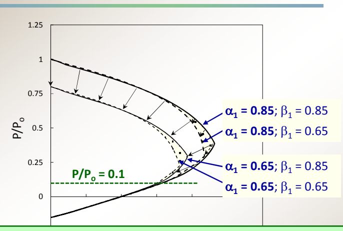
Comparison of Concrete Stress Blocks



(a) α_1 parameter

(b) β_1 parameter

Influence of α_1 and β_1 parameters on P-M interaction curve



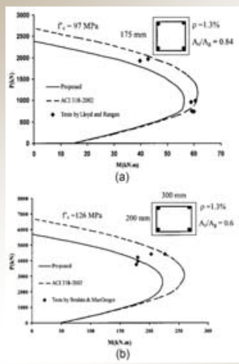
- The change of β_1 parameter has small influence on interaction curves compared to α_1 parameter.
- Interaction curves are less sensitive to the difference of stress block expressions when the axial load level is small ($P/P_o \le 0.1$). As such, flexural strengths of high-strength concrete beams can be calculated using the ACI 318 stress block.

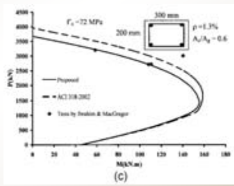
Evaluation of Stress Block Expressions for Chapter 10 of ACI 318-11

- FLEXURE AND AXIAL LOADS -

- 224 tested column database are used.
  - Rectangular concrete columns
  - Compressive strengths of concrete: 1.5 ksi to 18.8 ksi.
  - Yield strengths of rebars: 44 ksi to 82 ksi.
  - Applied axial load: $0.08P_o$ to $0.89P_o$

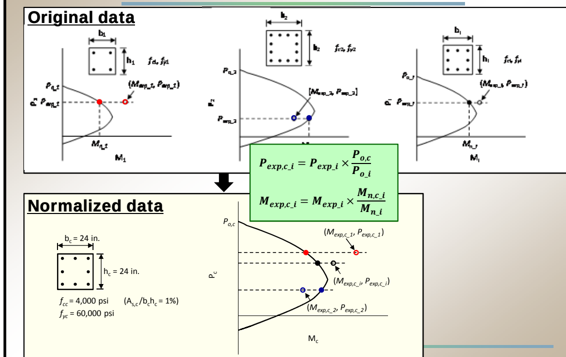
Typical Comparison of Interaction Curves vs. Test Results



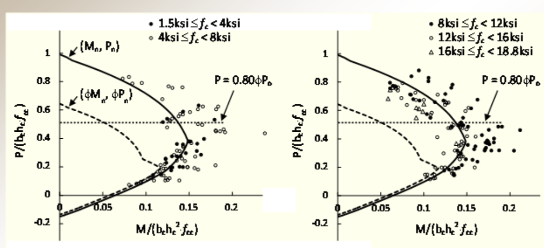


Excerpt from Ozbakkaloglu and Saatcioglu (2004)

Development of Normalized Interaction Curves and Test Results



ACI 318 (2011)

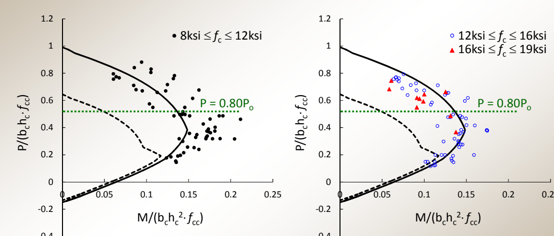


(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

$$P_{n,max} = 0.80\phi[0.85f_c'(A_g - A_{st}) + f_y A_{st}]$$
$$= 0.80\phi P_o = 0.80 \times 0.65 P_o = 0.52 P_o$$

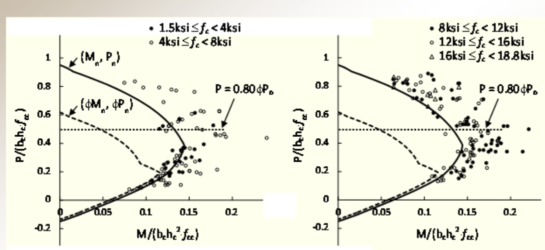
ACI 318 (2011)



(a) Columns with 8ksi ≤ f_c ≤ 12ksi

(b) Columns with f_c > 12ksi

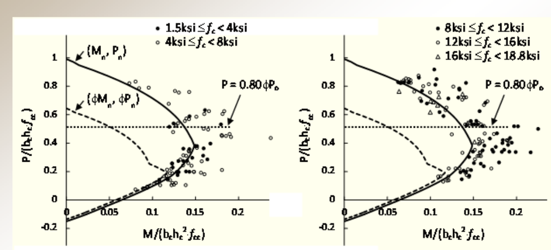
CSA A23.3 (2004)



(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

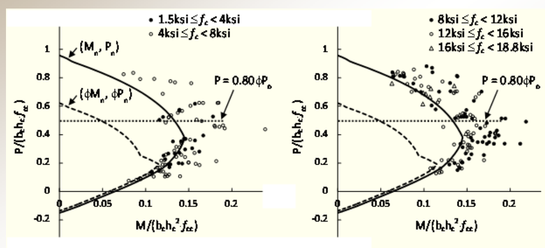
NZS 3101 (2006)



(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

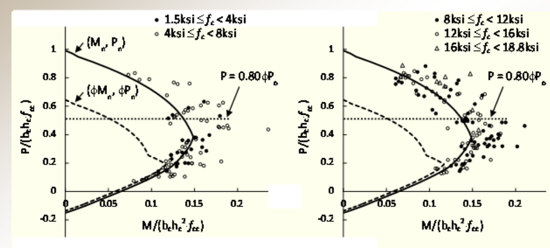
Ibrahim and MacGregor (1997)



(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

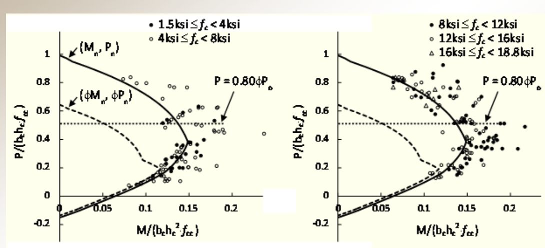
Bae and Bayrak (2003)



(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

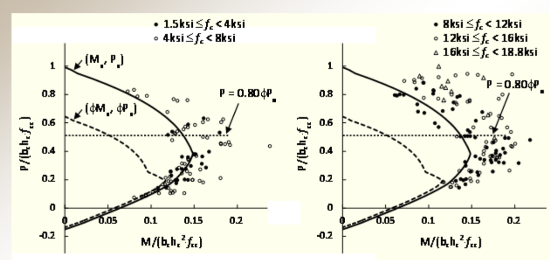
Ozbakkaloglu and Saatcioglu (2004)



(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

Azizinamini et al. (1994)



(a) Columns with f_c < 8,000 psi

(b) Columns with $f_c \geq$ 8,000 psi and f_c < 20,000 psi

Observations

- The ACI 318 stress block gives unconservative prediction of axial and flexural strengths of columns as concrete strength becomes higher.
- The ACI 318 stress block overpredicts column strengths when the concrete strength is greater than 8,000 psi and the level of axial load is high.
- However, the ACI 318 stress block can be used for column design up to the concrete strength of 12,000 psi for practical column design.

Observations

- Regardless of the difference in stress block expressions, those of NSZ 3101, Ibrahim and MacGregor (1997), Bae and Bayrak (2003) and Ozbakkaloglu and Saatcioglu (2004) provide improved predictions of axial and flexural strengths of concrete columns.
- The expressions of CSA A23.3 tends to be conservative.
- The expressions proposed by Azizinamini et al. (1994) produce excessively conservative predictions.

Evaluation of Stress Block Expressions for Chapter 18 of ACI 318-11

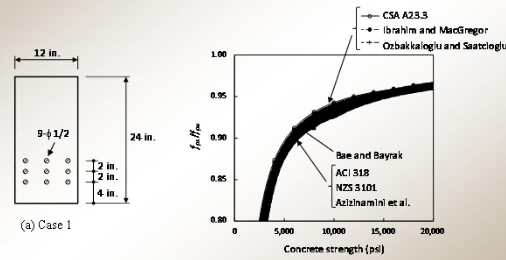
- PRESTRESSED CONCRETE -

- Bonded tendon stress at flexural nominal strength

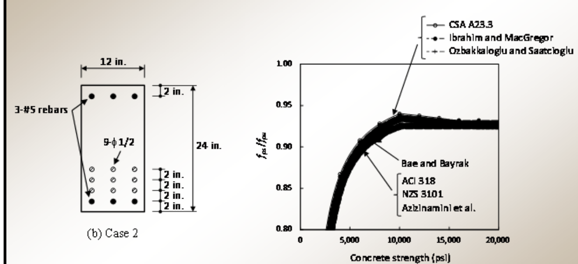
$$f_{ps} = f_{pu}\left\{1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f'_c} + \frac{d}{d_p}(\omega - \omega')\right]\right\}$$

Eq. (18-1) in ACI 318-11

Predicted Bonded Tendon Stress



Predicted Bonded Tendon Stress



Evaluation of Stress Block Expressions for Appendix A of ACI 318-11

- STRUT & TIE MODELS -

- Effective compressive strength of the concrete in a strut

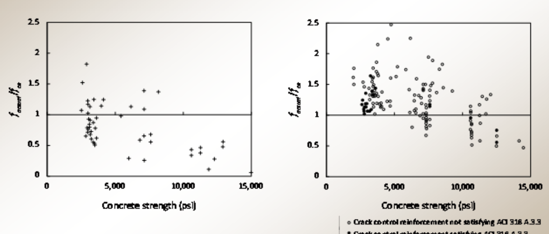
$$f_{ce} = 0.85\beta_s f'_c$$

- Effective compressive stress on a face of a nodal zone

$$f_{ce} = 0.85\beta_n f'_c$$

Comparison of Predicted Concrete Strut Stress and Tested Results

Bahen and Sanders (2009)



Observations

- The use of different expressions of β_1 parameter has negligible impact on the calculated tendon stresses at nominal moment.
- The examination of the predicted compressive strengths of bottle-shaped struts indicated that the necessity to change α_1 parameter of 0.85 in ACI 318 for concrete strength greater than 6,000 psi.
- More research is required to come up with stress block expressions which can provide consistent predictions of beam and column strengths as well as the compressive strengths of struts and nodal zones.

Conclusions

- Flexural strengths of high-strength concrete beams can be calculated using the ACI 318 stress block.
- The ACI 318 stress block gives unconservative prediction of axial and flexural strengths of columns as concrete strength becomes higher.
- The ACI 318 stress block can be used for column design up to the concrete strength of 12,000 psi for practical column design.

Conclusions

- The use of different expressions of β_1 parameter has negligible impact on the calculated tendon stresses at nominal moment.
- The examination of the predicted compressive strengths of bottle-shaped struts indicated that the necessity to change α_1 parameter of 0.85 in ACI 318 for concrete strength greater than 6,000 psi.