CALIBRATION OF RESISTANCE FACTORS FOR THE DESIGN OF CONCRETE STRUCTURES

Andrzej S. Nowak, PhD, Dept. of Civil and Env. Engineering, University of Michigan, Ann Arbor, MI
Maria M. Szerszen, PhD, Dept. of Civil and Env. Engineering, University of Michigan, Ann Arbor, MI

ABSTRACT

The objective of the present study is to determine the resistance factors applicable to ACI 318 Code that are consistent with load combination factors specified by the ASCE 7-98 Standard. The major steps in the code calibration procedure include the development of load and resistance models. The statistical parameters for load components are based on the available literature. The statistical parameters of material properties are based on database provided by industry. The main focus of this study is the verification of resistance models. This paper provides an overview of the code calibration. The reliability analysis is applied in the calibration procedure. The reliability indices are calculated for the variety of structural types and limit states. The final selection of resistance factors is based on the results of the reliability analysis, closeness to the target reliability index, comparison with previous practice, and simplicity of the code.

Keywords: Reliability analysis, Concrete beams, Slab, Columns, Resistance factors, Code calibration.

INTRODUCTION

In the new generation of design codes the acceptability criterion for load and resistance factors is closeness to the target reliability level. The code calibration requires statistical data on load and resistance parameters. Load models are taken from the available literature. The basic combination considered in this study includes dead load and live load. The major effort in the presented study is focused on the development of resistance model.

Material properties are based on recent tests and component behavior is modeled by simulations, as presented in reference[1, 2]. The developed models were used in the calibration of the ACI 318 Code[3]. The obtained resistance parameters can be also applied to revise the AASHTO LRFD Code[4]. The considered structural types include beams, slabs and columns; reinforced concrete and prestressed concrete; cast-in-place and precast. Three categories of concrete are considered: ordinary concrete, high strength concrete and light weight concrete. The statistical parameters are developed for various sizes of reinforcing steel bars and prestressing steel strands. The load carrying capacity of structural components is a function of random variables representing the uncertainties in material properties, dimensions-geometry, and analytical model. The statistical parameters of resistance were obtained by Monte Carlo simulations, using the available behavioral models.

Reliability indices are calculated using the load and resistance models. The target reliability indices are selected based on the current design code. The resistance factors are then determined accordingly.

STRUCTURAL TYPES AND MATERIALS

The considered structural types include:

- flexural members (beams and slabs),
- compression members (axially and eccentrically loaded columns)

The considered limit states include bending moment capacity (for beams and slabs), shear capacity (for beams), and compression capacity (for columns).

Materials considered in the calibration include:

- Ordinary concrete (with $f'_c < 6{,}500$ psi or 45 MPa)
- Light-weight concrete (unit weight ≤ 120 pcf or 1,840 kN/m^3)
- High-strength concrete (with $f'_c \geq 6{,}500$ psi or 45 MPa)
- Reinforcing steel bars
- Prestressing steel strands

The analysis was performed for reinforced concrete and prestressed concrete structural elements in flexure, compression, tension and shear. Plain concrete elements were also considered in flexure, compression, shear and bearing. With regard to fabrication, two categories of concrete materials were included: plant-cast (precast) and cast-in-place (ready mixed concrete, constructed on a site). The database includes the results of standard cylinder tests mostly as 28 day compressive strength. However, for high-strength concrete, also 56 day strength tests were available. Statistical parameters for the considered materials (concrete and steel) were established based on the lower tail of the cumulative distribution curves by fitting curves that best represent the data points.

It is accepted that there can be considerable differences in the quality of concrete, workmanship, curing procedures, and tolerances in dimensions. It is assumed that quality of materials and workmanship is at the average level.

LOAD MODEL

Load components are treated as random variables. Their statistical parameters include bias factor, i.e. the ratio of mean to nominal value, and coefficient of variation, i.e. ratio of the standard deviation and the mean.

Dead load is the weight of structural and non-structural elements permanently connected to the structure. The bias factor value of dead load is, $\lambda = 1.05$, and coefficient of variation, $V = 0.10$ for cast-in-place concrete, and $\lambda = 1.03$, and coefficient of variation, $V = 0.08$ for precast concrete[5]. Since dead load is assumed to be time-invariant, only one set of parameters is needed.

Live load is the weight of people, furniture, partitions, and other items. For the maximum 50-year live load, the bias factor is $\lambda = 1.0$, and the coefficient of variation, V, varies depending on the influence area. V decreases with increasing influence area. The calculations were performed for several influence areas, but the results are presented for 400 ft^2 (about 40 m^2) and $V = 0.18$. For average live load, $\lambda = 0.24$, and $V = 0.65$.

RESISTANCE MODEL

The structural capacity (resistance), R, can be considered as a product of three factors: M, F and P, as follows

$$R = R_n\, M\, F\, P \qquad (1)$$

where R_n is nominal resistance, M is material properties parameter (reflecting variation in material properties like strength of material, modulus of elasticity), F is fabrication factor (representing variation in dimensions, area, moment of inertia), P is professional factor (analysis factor, i.e. the ratio of actual behavior to predicted by analysis).

For each random variable considered in this study, two statistical parameters are determined: bias factor (ratio of the mean to nominal value), and coefficient of variation (ratio of the standard deviation and the mean). The mean value of resistance, m_R, can be taken as a product of nominal resistance and the means of M, F and P,

$$m_R = R_n \times m_M \times m_F \times m_P \tag{2}$$

The bias factor of resistance, λ_R, and the coefficient of variation of R, V_R, are given by:

$$\lambda_R = \lambda_M \times \lambda_F \times \lambda_P \tag{3}$$

$$V_R = \left(V_M^2 + V_F^2 + V_P^2\right)^{1/2} \tag{4}$$

where λ_M is bias factor of M, λ_F is bias of F, λ_P is bias factor of P, V_M is coefficient of variation of M, V_F is coefficient of variation of F, and V_P is coefficient of variation of P.

To determine the statistical parameters of R, bias factor, λ_R, and coefficient of variation, V_R, there is a need for λ and V for the variables M, F and P. For M, the parameters are derived from the material test data provided by the industry. For the other two parameters F and P, λ and V are taken from previous studies documented in the available literature[6].

STRENGTH OF CONCRETE

The test data for ordinary, high strength and light weight concretes were obtained from ready mixed companies and precasting plants representing the continental United States. The statistical parameters of concrete strength, f_c', were calculated from the cumulative distribution functions (CDF's). The CDF curves include all the available samples obtained from different sources (concrete industry) and were plotted separately for each file from the data-base. Then, the distributions were plotted for all files representing the same nominal concrete strength.

CDF's were plotted on the normal probability paper[5]. In most cases, the CDF has a smaller slope for the lower values of strength, and a larger slope (higher degree of variation) for the upper values of strength. This is the result of quality control that penalizes the under-strength much more than the over-strength. In the reliability analysis, only the lower tail of the CDF of resistance is considered. Therefore, the mean and coefficient of variation were determined for the lower tail of the CDF.

The test data for ordinary concrete was obtained in two categories: as ready mixed concrete and plant-cast concrete. The statistical parameters (mean values, bias, λ, and coefficients of variation, V) of f_c' were established based on CDF's, and are listed together with nominal strengths in Table 1 for ready mixed concrete, and in Table 2 for plant-cast concrete.

Table 1. Statistical Parameters for Ordinary Ready Mixed Concrete

f_c'	Number of samples	Mean f_c'	λ	V
20,670 kPa (3,000 psi)	88	27,970 kPa (4,050 psi)	1.35	0.102
24,115 kPa (3,500 psi)	25	29,214 kPa (4,240 psi)	1.21	0.079
27,560 kPa (4,000 psi)	116	34,037 kPa (4,940 psi)	1.235	0.145
31,005 kPa (4,500 psi)	28	35,310 kPa (5,120 psi)	1,14	0.042
34,450 kPa (5,000 psi)	30	39,480 kPa (5,730 psi)	1.15	0.058
41,340 kPa (6,000 psi)	30	46,163 kPa (6,700 psi)	1.12	0.042

Table 2. Statistical Parameters for Ordinary Plant-Cast Concrete

f_c'	Number of samples	Mean f_c'	λ	V
34,450 kPa (5,000 psi)	330	47,610 kPa (6,910 psi)	1.38	0.120
37,895 kPa (5,500 psi)	26	45,267 kPa (6,570 psi)	1.19	0.101
41,340 kPa (6,000 psi)	493	47,885 kPa (6,950 psi)	1.16	0.090
44,785 kPa (6,500 psi)	325	51,124 kPa (7,420 psi)	1.14	0.081

The test data for high strength concrete includes compressive strength tested after 28 days and 56 days. The two groups of test data were considered separately. The statistical parameters, nominal values, and number of samples are presented in Table 3.

Table 3. Statistical Parameters for f_c' of High Strength Concrete

f_c'	28 days				56 days			
	Number of samples	Mean f_c' kPa (psi)	λ	V	Number of samples	Mean f_c' kPa (psi)	λ	V
48,230 kPa (7,000 psi)	210	57,476 (8,340)	1.19	0.115	58	71,883 (10,430)	1.49	0.080
55,120 kPa (8,000 psi)	753	60,253 (8,740)	1.09	0.090	428	60,060 (8,710)	1.09	0.095
62,010 kPa (9,000 psi)	73	71,745 (10,410)	1.16	0.100	N/A	N/A	N/A	N/A
68,900 kPa (10,000 psi)	635	77,740 (11,280)	1.13	0.115	238	81,336 (11,800)	1.18	0.105
82,680 kPa (12,000 psi)	381	85,725 (12,440)	1.04	0.105	190	96,515 (14,010)	1.17	0.105

The statistical parameters for light weight concrete are listed in Table 4.

For comparison, the bias factors (mean-to-nominal ratios) obtained from the test data are shown in Fig. 1. Based on the presented findings, it is recommended to use the bias factor for concrete strength, f_c', as shown by the curve in Fig. 1. The equation for bias factor recommended for ready mixed, plant-cast, high strength and light weight concretes can be calculated from the following formula (obtained by fitting the test data shown in Fig. 1),

$$\lambda = -0.0081 \times f_c^{'3} + 0.1509 \times f_c^{'2} - 0.9338 \times f_c^{'} + 3.0649 \tag{5}$$

Table 4 Statistical Parameters for Light Weight Concrete

f_c'	Number of samples	Mean f_c'	λ	V
20,670 kPa (3,000 psi)	219	29,668 kPa	1.44	0.185
24,115 kPa (3,500 psi)	42	37,350 kPa	1.55	0.135
27,560 kPa (4,000 psi)	140	35,766 kPa	1.30	0.170
34,450 kPa (5,000 psi)	368	37,895 kPa	1.10	0.070

The coefficient of variation of f_c', obtained from the test data is rather uniform; the resulting values are shown in Tables 1-4. The average coefficient of variation of f_c' for all analyzed concretes, except of light weight concrete, is V = 0.101. For light weight concrete, it is recommended to use V = 0.175.

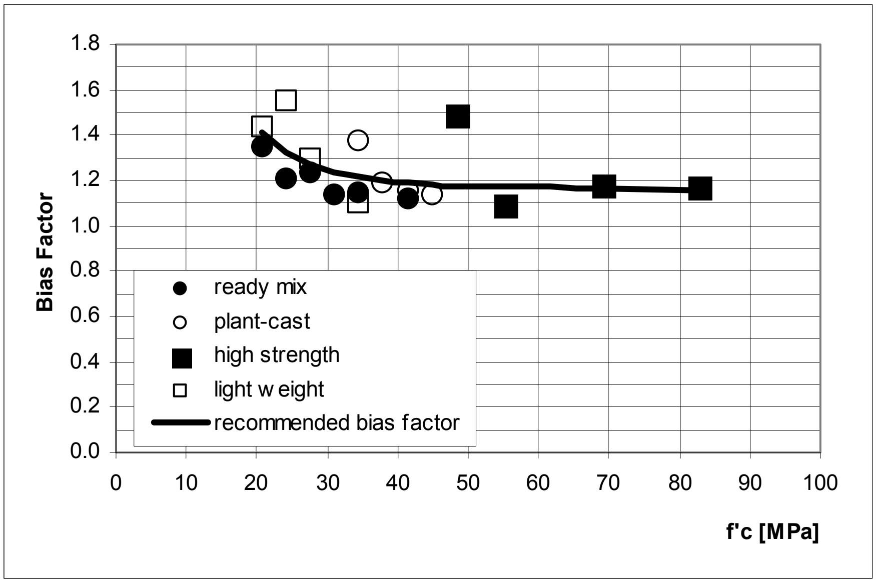

Fig. 1. Recommended bias factor for compressive strength of concrete, f_c'

STRENGTH OF REINFORCING STEEL BARS

Steel reinforcing bars 420 MPa (60 ksi) grade were investigated with bar diameters from 9.5 mm to 34.5 mm (#3 to #11). The statistical parameters of f_y are summarized in Table 5. There was no trend observed in the relationship between the strength and diameter of the rebar. The CDF's for individual data files for all diameters showed the normal distribution pattern.

Table 5. Statistical Parameters for Reinforcing Steel, Grade 420 MPa (60 ksi)

Bar size	Number of samples	Mean yield, f_y MPa (ksi)	λ	V
9.5 mm (#3)	72	496.1 (71)	1.20	0.04
12.5 mm (#4)	79	473.3 (67.5)	1.145	0.065
15.5 mm (#5)	116	465.1 (66.5)	1.125	0.04
19 mm (#6)	38	476.1 (68)	1.15	0.05
22 mm (#7)	29	481.6 (68.5)	1.165	0.05
25 mm (#8)	36	473.7 (67.5)	1.145	0.05
28 mm (#9)	28	475.7 (69)	1.15	0.05
31 mm (#10)	5	470.2 (67)	1.14	0.04
34.5 mm (#11)	13	473.7 (67.5)	1.145	0.035

The bias factors for reinforcing steel bars vary from λ = 1.125 to λ = 1.20, for all sizes. Actually, except of two sizes, the bias factor was within the range of 1.14-1.165. Therefore, the recommended bias factor for f_y is λ = 1.145. The coefficient of variation of f_y varies from V = 0.035 to V = 0.065. The recommended coefficient of variation of f_y is V = 0.05. For comparison, the bias factor for f_y used in previous studies was λ = 1.125, and coefficient of variation, V = 0.10 [6].

STRENGTH OF PRESTRESSING STRANDS

Two grades of prestressing steel strands were investigated: 1,722 MPa (250 ksi) and 1,860 MPa (270 ksi). For grade 1,722 MPa (250 ksi), four strand diameters were considered, from 6.25 mm to 12.5 mm (1/4 in to 1/2 in), and for grade 1860 MPa (270 ksi), three diameters, from 9.5 mm to 12.5 mm (3/8 in to 1/2 in). The statistical parameters of breaking strength for the two considered grades are summarized in Table 6.

The bias factors for prestressing strands vary from λ = 1.04 to λ = 1.14. It is recommended to use λ = 1.045. The coefficient of variation varies from V = 0.007 to V = 0.03. It is recommended to use V = 0.025. For comparison, the statistical parameters used in previous studies for grade 1,860 MPa (270 ksi), were λ = 1.040 and V = 0.025.

Table 6. Statistical Parameters of Breaking Stress for Prestressing Strands

Grade	Size	Number of samples	Mean, f_y [MPa]	λ	V
1722.5 MPa (250 ksi)	6.25 mm (#1/4)	11	1846.5	1.07	0.01
	9.5 mm (#3/8)	83	1908.5	1.11	0.025
	11 mm (#7/16)	114	1853.4	1.08	0.007
	12.5 mm) (#1/2)	115	1963.6	1.14	0.03
1860.3 MPa (270 ksi)	9.5 mm (#3/8)	54	1977.4	1.06	0.03
	11 mm (#7/16)	30	1984.3	1.07	0.01
	12.5 mm (#1/2)	190	1943.0	1.04	0.025

FABRICATION FACTOR

Fabrication factor, F, represents the variation in dimensions and geometry of the considered structural elements. The recommended statistical parameters are based on previous studies by Ellingwood et al. [6]. For the dimensions of concrete components the recommended parameters are listed in Table 7. For steel reinforcing bars and prestressing steel strands, the bias factor of dimensions was selected as λ = 1.0 and coefficient of variation, V = 0.01. The area of reinforcing steel, A_s, was treated as a practically deterministic value, with λ = 1.0 and V = 0.015.

Table 7 Statistical Parameters of Fabrication Factor for Dimensions of Concrete

Item	λ	V
Width of beam, cast-in-place	1.01	0.04
Effective depth of a reinforced concrete beam	0.99	0.04
Effective depth of prestressed concrete beam	1.00	0.025
Effective depth of a slab, cast-in-place	0.92	0.12
Effective depth of a slab, plant-cast	1.00	0.06
Effective depth of a slab, post-tensioned	0.96	0.08
Column width and breadth	1.005	0.04

PROFESSIONAL FACTOR

Professional factor is based on the results of previous studies[6] and engineering judgment. For the investigated structural elements and materials, the bias factors and coefficients of variation are listed in Table 8.

Table 8. Statistical Parameters of Professional Factor

Item	λ	V
Beam, flexure	1.02	0.06
Beam, shear	1.075	0.10
Slab	1.02	0.06
Column, tied	1.00	0.08
Column, spiral	1.05	0.06
Plain concrete	1.02	0.06

STATISTICAL PARAMETERS OF RESISTANCE

The parameters of resistance, R, were calculated by Monte Carlo simulations, using the statistical parameters determined for M, F and P. Deterministic expressions for resistance used in simulations follow the ACI 318-02 code[3]. Material parameters for concrete (ordinary concrete, high strength concrete and light weight concrete) are established based on the cylinder tests data. The relationship between the concrete strength measured on test cylinders and the strength in the working structure is included in the resistance analysis model[7].

The coefficients of variation for both concrete strengths (cylinder tests and actual structure) are assumed to be the same, as far as manufacturing and concrete mix is concerned[8]. For the specified concrete strength, the actual concrete strength in the structure can differ from job to job depending on decisions made by the designer and contractor, but these job-specific differences are taken into account through the use of fabrication and professional factors (λ_F and λ_P).

The data on concrete compressive strength used in this study was obtained from different sources (from different construction sites and/or from different concrete mix plants) so it includes the so-called batch-to-batch variation, which is higher than within-test variation. The investigated data also includes variation caused by different testing methods (data comes from different labs) and even different concrete mix and design ingredients.

A formula for resistance (load carrying capacity) is formulated for each of the considered structural components and materials. The considered parameters include:

- Strength of concrete, f_c', for ordinary concrete, high strength and light weight
- Yield strength of reinforcing steel
- Breaking stress of prestressing steel strands
- Various reinforcement ratio for each case (between minimum and maximum allowed by the ACI 318-02 Code[3]
- Dimensions of the cross section (width, breadth and effective depth)
- Construction type (cast-in-place and plant-cast)

Resistance formulas are presented using the following notation:

A_s = Area of reinforcement, in^2.

A_v = Area of shear reinforcement within a distance s, in^2.

A_g = Gross area of section, in^2.

A_{st} = Area of steel in a column, in^2.

f_y = Specified yield strength of reinforcement, psi.

f'_c = Specified compressive strength of concrete, psi.

a = Depth of equivalent rectangular stress block, in.

b = Width of compression face of member, in.
b_w = Web width, in.
d = Effective depth is the distance from extreme compression fiber to the centroid of tension reinforcement, in.
s = Spacing of shear reinforcement measured along the longitudinal axis of the structural member, in.

Flexure:

$$R = \left(A_s \times f_y\right)\left(d - \frac{a}{2}\right) \tag{6}$$

where: $a = \dfrac{A_{s.} f_y}{0.85 f'_c . b}$

The reinforcement ratios considered in this study were: for beams ρ = 0.6-1.6%, and for slabs ρ = 0.26-0.33%

The statistical parameters of flexural resistance were determined by Monte Carlo simulations, and the following parameters were treated as random variables:

A_s, f'_c, f_y, a, b, d

Shear:

$$V_n = V_c + V_s \tag{7}$$

where:

$V_C = 2\sqrt{f'_c}\, b_w . d$ and $V_s = \dfrac{A_v . f_y . d}{s}$

The spacing of shear rebars considered in this study was 6-12 in.

The statistical parameters of shear resistance were determined by Monte Carlo simulations, and the following parameters were treated as random variables:

A_v, f'_c, f_y, b_w, d, s

Capacity of axially loaded columns:

$$R_n = 0.85 f'_c \left(A_g - A_{st}\right) + f_y A_{st} \tag{8}$$

where:

$$A_g = b \times d$$

The reinforcement ratios for columns considered in this study were ρ = 2.75-4.85%

The statistical parameters of resistance for axially loaded columns were determined by Monte Carlo simulations, and the following parameters were treated as random variables:

$$A_{st},\ f'_c,\ f_y,\ b,\ d$$

The cumulative distribution function (CDF) of resistance is obtained by generating about 400,000 values of R for each considered design case. This served as a basis to calculate the mean of R, m_R, standard deviation, σ_R, and coefficient of variation, V_R. The resistance simulations for all selected design cases were performed for ordinary concrete and various reinforcement ratios for beams, slabs and columns. It was found that the reinforcement ratio has only a small effect on the parameters of resistance.

In addition, simulations of resistance were performed for components with the high strength concrete and light weight concrete, because the bias factors and coefficients of variation for the high strength concrete (for samples tested after 56 days) and light weight concrete significantly differ from those of the ordinary concrete.

The obtained results were reviewed to determine the range of the bias factor, its mean, and coefficient of variation, as listed in Table 9. The simulations were also performed for the statistical parameters of M used in 1970's and early 1980's, and the results are referred to as "Old material data". The results of simulations carried out using the statistical parameters of M developed in this study are denoted as "New material data".

RELIABILITY ANALYSIS

Load and resistance parameters are random variables; therefore, it is convenient to measure the structural performance in terms of the reliability index, β. Various procedures for calculation of β are presented in Nowak and Collins[5]. The reliability index, β, can be considered as a function of the probability of failure, P_F,

$$\beta = -\Phi^{-1}(P_F) \tag{9}$$

where Φ^{-1} = inverse standard normal distribution function.

Table 9. Statistical Parameters of Resistance.

Structural type and limit state	Range of values							
	Old material data		New material data					
			Ordinary concrete		High strength concrete		Light weight concrete	
	λ	V	λ	V	λ	V	λ	V
R/C beam cast-in-place, flexure	1.114	0.119	1.190	0.089	1.160	0.090	1.180	0.090
R/C beam plant cast, flexure	1.128	0.133	1.205	0.081				
R/C beam cast-in-place, shear	1.159	0.120	1.230	0.109	1.190	0.110	1.230	0.110
R/C beam plant cast, shear	1.170	0.116	1.242	0.105				
P/S beam plant cast, flexure	1.034	0.081	1.084	0.073				
P/S beam plant cast, shear	1.130	0.105	1.194	0.103				
R/C slab cast-in-place	1.052	0.169	1.077	0.146	1.070	0.145	1.080	0.150
R/C slab plant cast	1.146	0.116	1.174	0.082				
P/S slab plant cast	1.053	0.070	1.075	0.070				
Post-tensioned slab cast-in-place	0.961	0.146	0.982	0.145	1.030	0.110		
R/C column cast-in-place, tied	1.107	0.136	1.260	0.107	1.200	0.120	1.260	0.130
R/C column plant cast, tied	1.102	0.134	1.252	0.103				
R/C column cast-in-place, spiral	1.163	0.124	1.316	0.097	1.260	0.110	1.330	0.120
R/C column plant cast, spiral	1.156	0.122	1.323	0.091				
P/S column plant cast, tied	1.017	0.094	1.080	0.090				
P/S column plant cast, spiral	1.068	0.076	1.133	0.071				
Plain concrete, flexure, shear	1.004	0.082	1.105	0.082	1.240	0.080	1.400	0.080

The reliability analysis procedure used in this calibration includes the following steps:

(1) Prepare input data:
Structural type and limit state
Nominal values of load components: D (dead load) and L (live load)
Load and resistance factors: γ_D, γ_L, ϕ
The load factors are available, but the ϕ factor is to be determined. However, there is a limited number of possible values for ϕ (they are rounded to the nearest 0.05), therefore, calculations are carried out for several possible values of ϕ.
(2) Calculate load parameters: the mean total load, corresponding coefficient of variation and standard deviation.
(3) Calculate the nominal resistance using the design formula in the code [3]
(4) Determine the statistical parameters of R (Table 9) .
(5) Calculate the reliability index, β,

$$\beta = (m_R - m_Q)/(\sigma_R^2 + \sigma_Q^2)^{0.5} \qquad (10)$$

where m_R is the mean value of resistance, m_Q is the mean value of the total load effect, σ_R is the standard deviation of resistance, and σ_Q is the standard deviation of the total load effect.

The reliability analysis is performed following the procedure described above for the considered structural types and limit states. Reliability Indices are calculated for each type of structural component and material, and for the full range of D/(D+L) ratio, including the case of dead load without any live load (L = 0). The reliability indices are shown for the full range of D/(D+L) ratio and for three different values of ϕ factor: including the recommended value of ϕ, as well as (ϕ - 0.05) and (ϕ + 0.05).

The average reliability indices, determined for ordinary concrete, high strength concrete and light weight concrete are presented in Table 10. These average values are calculated based on the range of reliability indices selected depending on structural component and D/(D+L) ratio. The most probable load ratios are selected as follows: for beams D/(D+L) = from 0.3 to 0.7, for slabs D/(D+L) = from 0.3 to 0.6 and for columns D/(D+L) = from 0.4 to 0.9.

Examples of the reliability indices plotted vs. D/(D+L), for the basic load combination of D+L and for combinations with environmental loads, are shown in Table 10. The resulting β's vary depending on type of component, limit state, and load ratio.

Reliability indices calculated for beams vary depending on the type of beam (reinforced concrete, prestressed concrete, cast-in-place or plant cast) and limit state (flexure or shear). However, most of β's are close to 4 or over. Reliability indices calculated for axially loaded columns are higher then those for beams by about 10–20%.

Table 10. Average Values of the Reliability Indices for Load Combination, D + L.

Structural type and limit state	Old material data 1.4 D+1.7 L	New material data, Proposed design 1.4 D or 1.2 D+1.6 L			
	β	Resistance factor	Ordinary concrete	High strength concrete	Light weight concrete
		ϕ	β	β	β
R/C beam cast-in-place, flexure	3.54	0.95	3.83	3.63	3.75
		0.90	4.19	3.99	4.10
		0.85	4.55	4.36	4.46
R/C beam plant cast, flexure	3.34	0.95	4.31		
		0.90	4.69		
		0.85	5.09		
R/C beam cast-in-place, shear	3.95	0.90	3.78	3.58	3.75
		0.85	4.07	3.87	4.04
		0.80	4.36	4.17	4.33
R/C beam plant cast, shear	4.18	0.90	4.03		
		0.85	4.33		
		0.80	4.63		
P/S beam plant cast, flexure	4.34	0.95	3.75		
		0.90	4.20		
		0.85	4.65		
P/S beam plant cast, shear	4.37	0.90	3.88		
		0.85	4.19		
		0.80	4.51		
R/C slab cast-in-place	2.45	0.95	2.25	2.24	2.21
		0.90	2.48	2.47	2.44
		0.85	2.72	2.71	2.67
R/C slab plant cast	3.84	0.95	4.13		
		0.90	4.51		
		0.85	4.90		
P/S slab plant cast	4.90	0.95	3.82		
		0.90	4.27		
		0.85	4.73		
Post-tensioned slab cast-in-place	2.41	0.95	1.85	2.54	
		0.90	2.09	2.85	
		0.85	2.35	3.17	
R/C column cast-in-place, tied	3.98	0.75	4.68	4.03	3.94
		0.70	4.99	4.32	4.20
		0.65	5.30	4.61	4.45
R/C column plant cast, tied	4.09	0.75	4.93		
		0.70	5.25		
		0.65	5.57		
R/C column cast-in-place, spiral	4.26	0.80	4.97	4.27	4.19
		0.75	5.30	4.57	4.45
		0.70	5.64	4.87	4.71
R/C column plant cast, spiral	4.38	0.80	5.44		
		0.75	5.78		
		0.70	6.13		
P/S column plant cast, tied	5.21	0.75	4.67		
		0.70	5.09		
		0.65	5.51		
P/S column plant cast, spiral	6.05	0.80	5.45		
		0.75	5.96		
		0.70	6.48		
Plain concrete, flexure, shear	5.98	0.70	5.37	6.21	6.93
		0.65	5.84	6.66	7.34
		0.60	6.32	7.11	7.74

It is observed that reliability indices for slabs are lower than for beams, and this applies both to existing design and proposed design code. In slabs, there is a considerable uncertainty about the actual effective depth, and the reliability index is very sensitive to any departure from the specified value of the depth. Effective depth in concrete slabs is usually very small (compared to that of a beam), and even small reduction can drastically reduce reliability index. However, the overall reliability of the slab is considerably higher than the calculated value due to load sharing. The reliability analysis is performed for a 1 ft (or 1 m) wide segment of the slab. The slab as a structural system can be considered as a parallel system of interacting (load sharing) segments. The reliability index of the slab treated as a system is similar, or larger than that of a beam.

The target reliability indices, β_T, are conservatively selected as upper rather than lower limits of the range of β obtained in calculations. The target β is 3.5 for most of the components except of columns, $\beta_T = 4.0$. Special consideration is required for slabs. In cast-in-place slabs, there is a considerable degree of load sharing, and the system reliability is much larger than β for a segment of 1 ft (1 m). This justifies a reduced value of $\beta_T = 2.5$. For precast slab panels, the degree of load sharing can be similar to beams.

Further consideration is required for columns. In this study, only axially loaded columns were included.

LOAD AND RESISTANCE FACTORS

The reliability indices corresponding to various categories of structural types and materials were reviewed and compared to the target values. Based on that analysis, the recommended values of the resistance factor are given in Table 11.

CONCLUSIONS

Resistance parameters are determined on the basis of material tests and other factors (fabrication and professional factors). The data-base was provided by industry representatives covering ordinary ready mixed concrete, plant-cast concrete, high-strength concrete, light-weight concrete, reinforcing steel bars, and prestressing steel strands. The test results were plotted on the normal probability scale for an easier analysis.

The comparison with previous tests (1970's) confirmed that there is an improvement in quality of materials; in particular, it is observed that variation of strength is reduced. The most significant difference between the older data and recent results is in the strength of concrete and yield strength of steel reinforcing bars. It was observed that the safety margin in strength of concrete, in terms of the bias factor (ratio of mean to nominal value), decreases for higher values of strength. The statistical parameters of prestressing strands calculated from the test data confirmed a continued trend of a very low variation. The statistical parameters of resistance are calculated using Monte Carlo simulations.

Table 11. Recommended Resistance Factors.

Structural type and limit state	Resistance factors, φ
R/C Beam cast-in-place, flexure	0.90
R/C beam plant cast, flexure	0.90
R/C Beam cast-in-place, shear	0.85
R/C beam plant cast, shear	0.85
P/S beam plant cast, flexure	0.90
P/C beam plant cast, shear	0.85
R/C slab cast-in-place, flexure	0.90
R/C slab plant cast, flexure	0.90
P/S slab plant cast, flexure	0.90
Post-tensioned slab cast-in-place, flexure	0.90
R/C column cast-in-place, tied	0.75
R/C column plant cast, tied	0.75
R/C column cast-in-place, spiral	0.80
R/C column plant cast, spiral	0.80
P/S column plant cast, tied	0.75
P/S column plant cast, spiral	0.80
Plain concrete, flexure, shear	0.65

CONCLUSIONS

Resistance parameters are determined on the basis of material tests and other factors (fabrication and professional factors). The data-base was provided by industry representatives covering ordinary ready mixed concrete, plant-cast concrete, high-strength concrete, light-weight concrete, reinforcing steel bars, and prestressing steel strands. The test results were plotted on the normal probability scale for an easier analysis.

The comparison with previous tests (1970's) confirmed that there is an improvement in quality of materials; in particular, it is observed that variation of strength is reduced. The most significant difference between the older data and recent results is in the strength of concrete and yield strength of steel reinforcing bars. It was observed that the safety margin in strength of concrete, in terms of the bias factor (ratio of mean to nominal value), decreases for higher values of strength. The statistical parameters of prestressing strands calculated from the test data confirmed a continued trend of a very low variation. The statistical parameters of resistance are calculated using Monte Carlo simulations.

The obtained results provide a basis for the reliability analysis of the reinforced concrete and prestressed concrete components of building structures. The code calibration is presented in Szerszen and Nowak[2].

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REFERENCES

1. Nowak, A.S. and Szerszen, M.M., "Calibration of Design Code for Buildings (ACI 318) Part 1: Statistical Models for Resistance", ACI Structural Journal, Vol. 100, No. 3, 2003, pp. 377-382.
2. Szerszen, M.M. and Nowak, A.S., "Calibration of Design Code for Buildings (ACI 318) Part 2: Reliability Analysis and Resistance Factors", ACI Structural Journal, Vol. 100, No. 3, 2003, pp. 383-391.
3. ACI 318-02, "Building Code Requirements for Structural Concrete", American Concrete Institute, Farmington Hills, Michigan, 2002.
4. AASHTO, "LRFD Bridge Design Specifications", American Association of State Highway and Transportation Officials, Washington, DC., 2nd Edition, 1998.
5. Nowak, A.S. and Collins, K.R., "Reliability of Structures", McGraw-Hill New York, 2000.
6. Ellingwood, B., Galambos, T.V., MacGregor, J.G. and Cornell, C.A., "Development of a Probability Based Load Criterion for American National Standard A58", NBS Special Report 577, U.S. Department of Commerce, National Bureau of Standards, 1980.
7. Bartlett, F.M. and MacGregor, J.G., "Statistical Analysis of the Compressive Strength of Concrete in Structures", ACI Materials Journal, V. 93, No. 2, March –April 1996, pp. 158-168.
8. Bartlett, F.M. and MacGregor, J.G., "Variation of In-Place Concrete Strength in Structures", ACI Materials Journal, V. 96, No. 2, March –April 1999, pp. 261-270.