CHAPTER

4

REINFORCED CONCRETE
A Fundamental Approach - Fifth Edition

REINFORCED CONCRETE

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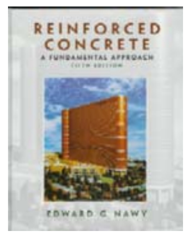

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Introduction

- Concrete is weak in tension but strong in compression.
- Therefore, reinforcement is needed to resist the tensile stresses resulting from the applied loads.
- Additional reinforcement sometimes added to the compression zone to reduce long-term deflection.

Types and Properties of Steel Reinforcement

- Steel reinforcement consists of
  – Bars
  – Wires
  – Welded wire fabric
- The most important properties of steel are:
  – Young's Modulus (Modulus of Elasticity), E
  – Yield Strength, f_y
  – Ultimate Strength, f_u
  – Steel Grade Designation.
  – Size or Diameter of the bar or wire.

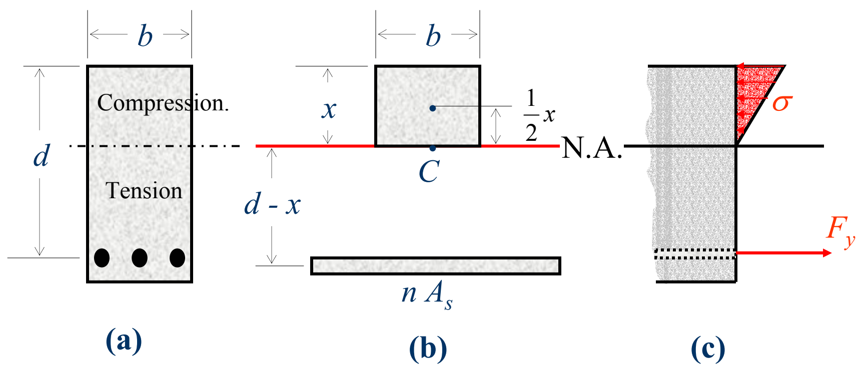
Types and Properties of Steel Reinforcement

- Steel is a high-cost material compared with concrete.
- It follows that the two materials are best used in combination if the concrete is made to resist the compressive stresses and the steel the tensile stresses.
- Concrete cannot withstand very much tensile stress without cracking.

Types and Properties of Steel Reinforcement

- Reinforced Concrete Beam

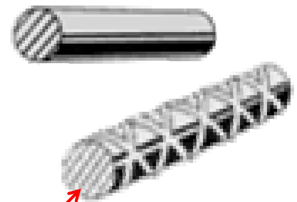
Figure 1



Types and Properties of Steel Reinforcement

- It follows that tensile reinforcement must be embedded in the concrete to overcome the deficiency.
- Forms of Steel Reinforcement
  - Steel Reinforcing Bars
  - Welded wire fabric composed of steel wire.
  - Structural Steel Shapes
  - Steel Pipes.

Types and Properties of Steel Reinforcement



Deformed Bar

Types and Properties of Steel Reinforcement

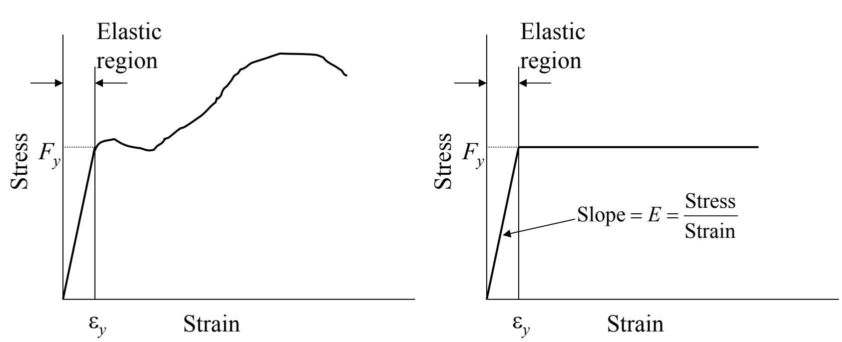
- Bond between Concrete and Steel
  - To increase the bond, projections called *deformations* are rolled on the bar surface as shown in Fig. 1.
- Reinforcing Bars (rebars)
  - The specifications for steel reinforcement published by the **American Society for Testing and Materials** (ASTM) are generally accepted for steel used in reinforced concrete construction in the United States and are identified in the ACI Code.

Types and Properties of Steel Reinforcement

- Yield Stress for Steel
  - Probably the most useful property of reinforced concrete design calculations is the yield stress for steel, f_y.
  - A typical stress-strain diagram for reinforcing steel is shown in Fig. 2a.
  - An idealized stress-strain diagram for reinforcing steel is shown in Fig. 2b.

Types and Properties of Steel Reinforcement

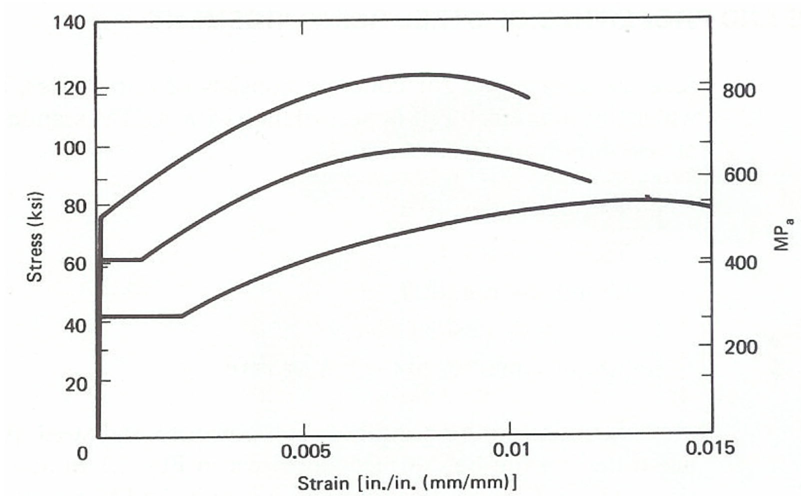
Figure 2. Typical Stress-Strain Curve for Steel



(a) As Determined by Tensile Test **(b) Idealized**

Types and Properties of Steel Reinforcement

Figure 3. Typical Stress-Strain Diagrams for Various Steel



Types and Properties of Steel Reinforcement

- Modulus of Elasticity or Young's Modulus for Steel
  - The modulus of elasticity for reinforcing steel varies over small range, and has been adopted by the ACI Code as

$$E = 29{,}000{,}000 \text{ psi} = 29{,}000 \text{ ksi}$$
$$= 200 \times 10^6 \text{ MPa}$$

Types and Properties of Steel Reinforcement

- Steel Grades and Strengths
  - Table 1 gives reinforcement-grade strengths.
- Geometrical Properties
  - Table 2 provides various sizes of bars in US Customary units, while Table 3 gives the sizes in Metric Units.

Types and Properties of Steel Reinforcement

Table 1. Reinforced Grades and Strengths

1982 Standard Type	Minimum Yield Point or Yield Strength, f_y (psi)	Ultimate Strength, f_u (psi)
Billet steel (A615) Grade 40 Grade 60	40,000 60,000	70,000 90,000
Axial steel (A617) Grade 40 Grade 60	40,000 60,000	70,000 90,000
Low-carbon steel (A706) Grade 60	60,000	80,000
Deformed wire Reinforced Fabric	75,000 70,000	85,000 80,000
Smooth wire Reinforced Fabric	70,000 65,000, 56,000	85,000 75,000, 70,000

Types and Properties of Steel Reinforcement

Table 2. ASTM Standard - English Reinforcing Bars

Bar Designation	Diameter in	Area in^2	Weight lb/ft
#3 [#10]	0.375	0.11	0.376
#4 [#13]	0.500	0.20	0.668
#5 [#16]	0.625	0.31	1.043
#6 [#19]	0.750	0.44	1.502
#7 [#22]	0.875	0.60	2.044
#8 [#25]	1.000	0.79	2.670
#9 [#29]	1.128	1.00	3.400
#10 [#32]	1.270	1.27	4.303
#11 [#36]	1.410	1.56	5.313
#14 [#43]	1.693	2.25	7.650
#18 [#57]	2.257	4.00	13.60

Note: Metric designations are in brackets

Types and Properties of Steel Reinforcement

Table 3. ASTM Standard - Metric Reinforcing Bars

Bar Designation	Diameter mm	Area mm^2	Mass kg/m
#10 [#3]	9.5	71	0.560
#13 [#4]	12.7	129	0.994
#16 [#5]	15.9	199	1.552
#19 [#6]	19.1	284	2.235
#22 [#7]	22.2	387	3.042
#25 [#8]	25.4	510	3.973
#29 [#9]	28.7	645	5.060
#32 [#10]	32.3	819	6.404
#36 [#11]	35.8	1006	7.907
#43 [#14]	43.0	1452	11.38
#57 [#18]	57.3	2581	20.24

Note: Metric designations are in brackets

Types and Properties of Steel Reinforcement

- Reinforcing Bars (rebars)
  - These bars are readily available in straight length of 60 ft.
  - The bars vary in designation from

No. 3 through No. 11

  - With additional bars:

No. 14 and No. 18

Bar Spacing and Concrete Cover for Steel Reinforcement

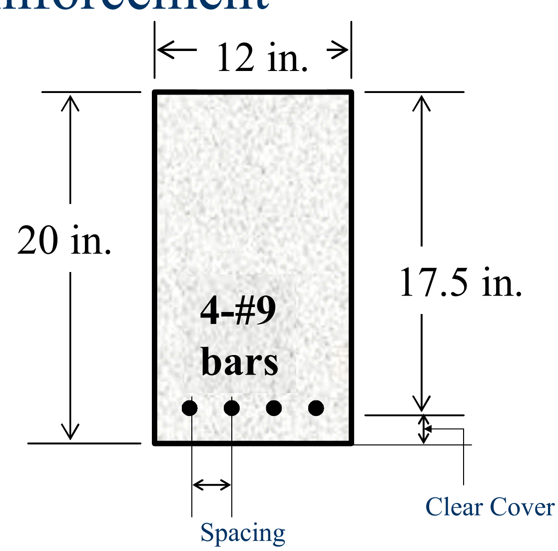
- It is necessary to guard against honeycombing and ensure that the wet concrete mix passes through the reinforcing steel without separation.
- Usually aggregate size in structural concrete contains ¾-in (19 mm) diameter coarse aggregate. Therefore, minimum allowable bar spacing and minimum required cover are needed.

Bar Spacing and Concrete Cover for Steel Reinforcement

- Also, to protect the reinforcement steel from corrosion and loss of strength in cases of fire, the ACI Code 318 required minimum concrete cover:
  - Clear distance between parallel bars in layers must not be less than bar diameter d_b or 1 in. (25.4 mm).
  - Clear distance between longitudinal bars in columns must not be less than $1.5d_b$ or 1.5 in.
  - Minimum clear cover in cast-in-place concrete beams and columns should not be less than 1.5 in (38.1 mm) when there is no exposure to weather or contact with ground.

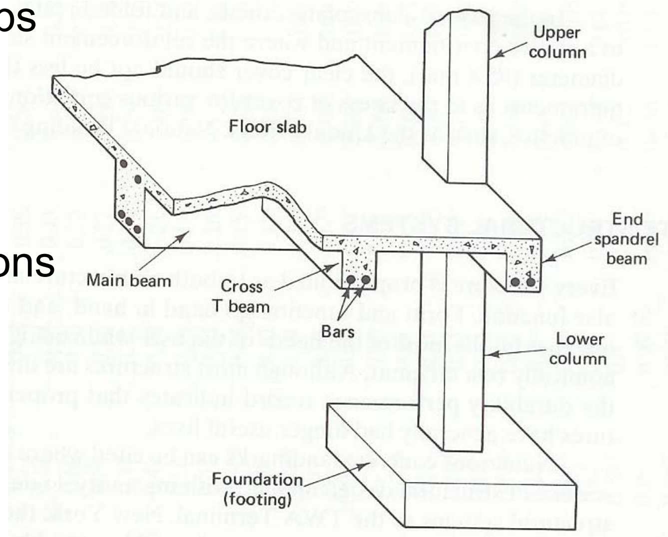
Bar Spacing and Concrete Cover for Steel Reinforcement

- Bar Spacing



Concrete Structural Systems

- Floor Slabs
- Beams
- Columns
- Walls
- Foundations



Reliability and Structural Safety of Concrete Components

- Reliability
  - The reliability of an engineering system can be defined as the system's ability to fulfill its design functions for a specified period of time.
  - In the context of this course, it refers to the estimated percentage of times that the strength of a member will equal or exceed the maximum loading applied to that member during its estimated life (say 25 years).

Reliability and Structural Safety of Concrete Components

- Reliability
  - Motivation
    - Assume that a designer states that his or her designs are 99.6 percent reliable (this is usually the case obtained with most LRFD design).
    - If we consider the designs of 1000 structures, this does not mean that 4 of the 1000 structures will fall flat on the ground, but rather it means that those structures at some time will be loaded into the plastic range and perhaps the strain hardening range. So excessive deformation and slight damage might occur, but not a complete failure.

Reliability and Structural Safety of Concrete Components

- Load and Resistance Factor Design (LRFD) Specifications
  - In the previous example, it would be desirable to have 100% reliability.
  - However, this is an impossible goal statistically. There will always be a chance of failure (unreliability), say 2 or 3 %.
  - The goal of the LRFD Specification was to keep this to very small and consistent percentage.

Reliability and Structural Safety of Concrete Components

- Load and Resistance Factor Design (LRFD) Specifications
  - To do this, the resistance or strength *R* of each member of concrete structure as well as the maximum loading *W*, expected during the life of the structure, are computed.
  - A structure then is s said to be safe if

$$R \geq W \qquad (1)$$

Reliability and Structural Safety of Concrete Components

- LRFD Specifications
  - The basic criterion for strength design may be expressed as

$$\textit{Strength furnished} \geq \textit{Strength required} \qquad (2)$$

  - All members and all sections of members must be proportioned to meet this criterion.
  - Eq. 1 can be thought of as a supply and a demand.

Reliability and Structural Safety of Concrete Components

- LRFD Specifications
  - The supply is considered as the strength furnished, while the demand as the strength required.
  - The required strength may be expressed in the forms of design loads or their related moments, shears, and forces.
  - Design loads may be defined as service loads multiplied by their appropriate factors.

Reliability and Structural Safety of Concrete Components

- LRFD Specifications
  - General Form

$$\phi R_n \geq \sum_{i=1}^{m} \gamma_i W_{ni} \qquad (3)$$

Where

ϕ = strength reduction factor

γ_i = load factor for the i^{th} load component out of n components

R_n = nominal or design strength (stress, moment, force, etc.)

W_{ni} = nominal (or design) value for the i^{th} load component out of m components

Reliability and Structural Safety of Concrete Components

- LRFD Specifications
  – Eq. 3 is the basis for Load and Resistance Factor Design (LRFD) for concrete structural members.
  – This equation uses different partial safety factors for the strength and the load effects.
  – The load factors are usually amplifying factors (>1), while the strength factors are called reduction factors (<1).

Reliability and Structural Safety of Concrete Components

- Probability Based-design Approach Versus Deterministic Approach

$$\frac{R_n}{\text{FS}} \geq \sum_{i=1}^{m} W_{ni}$$

ASD

$$\phi R_n \geq \sum_{i=1}^{m} \gamma_i W_{ni}$$

LRFD

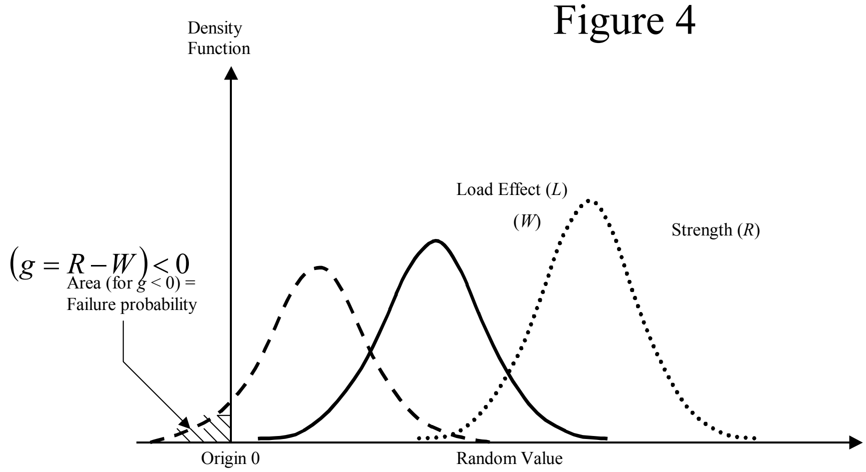
- According to ASD, one factor of safety (FS) is used that accounts for the entire uncertainty in loads and strength.
- According to LRFD (probability-based), different partial safety factors for the different load and strength types are used.

Reliability and Structural Safety of Concrete Components

- LRFD Specifications
  - The actual values of *R* and *W* are random variables and it is therefore impossible to say with 100% certainty that *R* is always equal or greater than *W* for a particular concrete structure.
  - No matter how carefully a structure is designed, there will be always some chance that *W* exceeds *R* as shown in Figure 4.

Reliability and Structural Safety of Concrete Components

Figure 4



Reliability and Structural Safety of Concrete Components

- Reliability (safety) Index β
  - *A measure of reliability can be defined by introducing a parameter β, called the reliability index.*
  - *β can be computed using structural reliability theory and knowledge of the first and second moment statistical characteristics (i.e., mean and COV) for both the strength and load variables.*

Reliability and Structural Safety of Concrete Components

- Reliability (safety) Index β (cont'd)
  - For two variables and linear performance function, the reliability index b can be defined as the shortest distance from the origin to the failure line as shown in Fig. 5. Mathematically, it can be expressed as

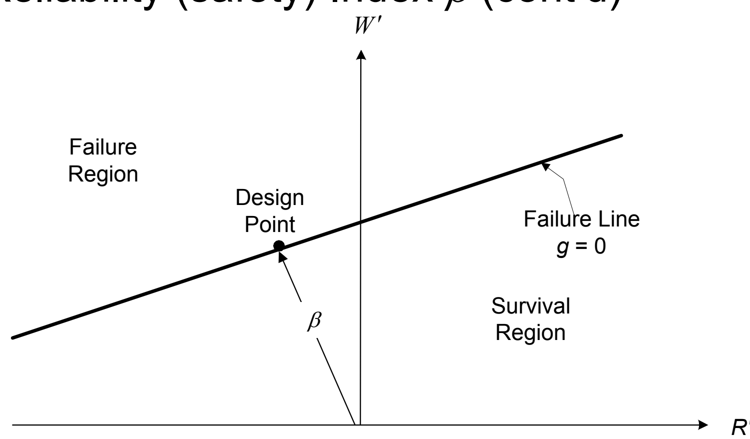
$$\beta = \frac{\mu_R - \mu_W}{\sqrt{\sigma_R^2 - \sigma_W^2}} \qquad (4)$$

μ = mean value of strength or load variable
σ = standard deviation of strength or load variable

Reliability and Structural Safety of Concrete Components

Figure 5

- Reliability (safety) Index β (cont'd)



The reliability index β is the shortest distance from the origin to the failure surface.

Reliability and Structural Safety of Concrete Components

- Reliability (safety) Index β (cont'd)
  - The important relationship between the reliability index β and the probability of failure P_f is given by

$$P_f = 1 - \Phi(\beta) \qquad (5)$$

where $\Phi(.)$ = cumulative probability distribution function of the standard normal distribution

Reliability and Structural Safety of Concrete Components

- LRFD Advantages
  - Provides a more rational approach for new designs and configurations.
  - Provides consistency in reliability.
  - Provides potentially a more economical use of materials.
  - Allows for future changes as a result of gained information in prediction models, and material and load characterization.
  - Easier and consistent for code calibration.

ACI Load Factors and Safety Margins

- General Principles
  - The γ load factors and the ϕ strength reduction factors give an overall safety factor based on load types such as

$$\mathrm{SF} = \frac{\gamma_1 D + \gamma_2 L}{D + L} \times \frac{1}{\phi} \qquad (6)$$

where ϕ is the strength reduction factor and γ_1 and γ_2 are the respective load factors for the dead load D and the live load L.

ACI Load Factors and Safety Margins

- ACI Load Factors *U*
  - The ACI design loads *U* (factored loads) have to be at least equal to the value as obtained by the following equation

$$U = \phi R_n = \text{Maximum of Load Combinations} = \sum_{i=1}^{m} \gamma_i W_{ni} \quad (7)$$

  - The load combinations are specified by ACI and given in the next slide (ACI Eqs. 9-1 to 7).

ACI Load Factors and Safety Margins

- ACI Load Combinations

$$U = 1.4(D + F)) \quad (8a)$$

$$U = 1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R) \quad (8b)$$

$$U = 1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (1.0L \text{ or } 0.8W) \quad (8c)$$

$$U = 1.2D + 1.6W + 0.5L + 1.0(L_r \text{ or } S \text{ or } R) \quad (8d)$$

$$U = 1.2D + 1.0E + 1.0L + 0.2S \quad (8e)$$

$$U = 0.9D + 1.6W + 1.6H \quad (8f)$$

$$U = 0.9D + 1.0E + 1.6H \quad (6g)$$

where

D = dead load; E = earthquake load; F = lateral fluid pressure load;
H = load due to the weight and lateral pressure of soil and water in soil;
L = live load; L_r = roof load; R = rain load; S = snow load;
T = self-straining force such as creep, shrinkage, and temperature effects;
W = wind load.

ACI Load Factors and Safety Margins

- The load factors γ's attempt to assess the possibility that prescribed service loads may be exceeded. Obviously, a live load is more apt to be exceeded than a dead load, which is largely fixed by the weight.

Design Strength Versus Nominal Strength

- The strength of a particular structural unit calculated using the current established procedures is termed *nominal strength*.
- For example, in the case of a beam, the resisting moment capacity of the section calculated using the equations of equilibrium and the properties of concrete and steel is called *nominal resisting moment capacity* M_n of the section.

Design Strength Versus Nominal Strength

- This nominal strength is reduced using a strength factor ϕ to account for inaccuracies in construction, such as in the dimensions or position of reinforcement or variation in properties.
- The reduced strength of the member is defined as the ***design strength*** of the member.

Design Strength Versus Nominal Strength

- Strength Reduction Factor
  - The strength reduction factor ϕ provide for the possibility that small adverse variation in material strength, workmanship, and dimensions may combine to result in undercapacity.

Design Strength Versus Nominal Strength

- ACI Code Provisions
  - In assigning strength reduction factors, the degree of ductility and the importance of the member as well as the degree of accuracy with which the strength of the member can be established are considered.
  - The ACI Code provides for these variables by using the following ϕ factors as provided in Table 4.

Design Strength Versus Nominal Strength

Table 4. Resistance or Strength Reduction Factors

Structural Element	Factor ϕ
Beam or slab; bending or flexure	0.90
Columns with ties	0.65
Columns with spirals	0.75
Columns carrying very small axial load (refer to Chapter 9 for more details)	0.65 – 0.9 or 0.70 – 0.9
Beam: shear and torsion	0.75

Design Strength Versus Nominal Strength

- ACI Code Provisions
  - When the word *design* is used throughout the ACI Code, it indicates that the load factors are included.
  - The subscript *u* is used to indicate design loads, moments, shears, and forces.
  - For example, the design load $w_u = 1.2w_{DL} + 1.6w_{LL}$
  - and the required or design moment strength for dead and live loads is

$$M_u = 1.2M_{DL} + 1.6M_{LL}$$

  - where 1.2 and 1.6 are the load factors.

Design Strength Versus Nominal Strength

- ACI Requirements for Dead and Live Loads
  - For dead and live loads, the ACI Code specifies design loads, design shears, and design moments be obtained from service loads by the using the relation

$$U = 1.2D + 1.6L \qquad (9)$$

Design Strength Versus Nominal Strength

- ACI Requirements for Strength
  - The ACI Code stipulates that the strength (moment, shear, force) furnished shall meet the following requirements

$$\phi R_n \geq 1.2D + 1.6L \qquad (10)$$

where

ϕ = strength reduction factor as provided in Table 4

R_n = nominal strength (stress, moment, force, etc.)

ϕR_n = design strength