1. Introduction

Loads

Loads that act on structures can be divided into three broad categories:
Dead loads are those that are constant in magnitude and fixed in location throughout the lifetime of the structure.
Usually the major part of the dead load is the weight of the structure itself. For buildings, floor fill, floor finish, and plaster ceilings are included as dead loads. For bridges, wearing surfaces, sidewalks, and curbs are included as dead loads.
Dead loads can be calculated with good accuracy from the configuration, dimensions of the structure, and density of the material.
Live loads consist chiefly of occupancy loads in buildings and traffic loads in bridges. They may be fully or partially in place or not present at all, and may also change in location. Their magnitude and distribution at any given time are uncertain.
The minimum live loads for the floors and roof of a building are usually specified in the building code. Table 1.1 (Nilson) presents *Minimum Design Loads for Buildings and Other Structures.*

TABLE 1.1
Minimum uniformly distributed live loads

Occupancy or Use	Live Load, psf
Apartments (see residential)	
Access floor systems	
Office use	50
Computer use	100
Armories and drill rooms	150
Assembly areas and theaters	
Fixed seats (fastened to floor)	60
Lobbies	100
Movable seats	100
Platforms (assembly)	100
Stage floors	150
Balconies (exterior)	100
On one and two-family residences only, and not exceeding 100 ft^2	60
Bowling alleys, poolrooms, and similar recreational areas	75
Catwalks for maintenance access	40
Corridors	
First floor	100
Other floors, same as occupancy served except as indicated	
Dance halls and ballrooms	100
Decks (patio and roof)	
Same as area served, or for the type of occupancy accommodated	
Dining rooms and restaurants	100
Dwellings (see residential)	
Fire escapes	100
On single-family dwellings only	40
Garages (passenger cars only)	40
Trucks and buses[b]	
Grandstands (see stadium and arena bleachers)	
Gymnasiums, main floors, and balconies[c]	100
Hospitals	
Operating rooms, laboratories	60
Private rooms	40
Wards	40
Corridors above first floor	80
Hotels (see residential)	
Libraries	
Reading rooms	60
Stack rooms[d]	150
Corridors above first floor	80
Manufacturing	
Light	125
Heavy	250

(*continued*)

TABLE 1.1
(Continued)

Occupancy or Use	Live Load, psf
Marquees and Canopies	75
Office Buildings	
File and computer rooms shall be designed for heavier loads based on anticipated occupancy	
Lobbies and first-floor corridors	100
Offices	50
Corridors above first floor	80
Penal institutions	
Cell blocks	40
Corridors	100
Residential	
Dwellings (one and two-family)	
Uninhabitable attics without storage	10
Uninhabitable attics with storage	20
Habitable attics and sleeping areas	30
All other areas except stairs and balconies	40
Hotels and multifamily houses	
Private rooms and corridors serving them	40
Public rooms and corridors serving them	100
Reviewing stands, grandstands, and bleachers[c]	100
Schools	
Classrooms	40
Corridors above first floor	80
First-floor corridors	100
Sidewalks, vehicular driveways, and yards, subject to trucking[e]	250
Stadiums and arenas	
Bleachers[c]	100
Fixed seats (fastened to floor)[c]	60
Stairs and exitways	100
One and two-family residences only	40
Storage areas above ceilings	20
Storage warehouses (shall be designed for heavier loads if required for anticipated storage)	
Light	125
Heavy	250
Stores	
Retail	
First floor	100
Upper floors	73
Wholesale, all floors	125
Walkways and elevated platforms (other than exitways)	60
Yards and terraces, pedestrians	100

[a] Pounds per square foot.
[b] Garages accommodating trucks and buses shall be designed in accordance with an approved method that contains provisions for truck and bus loadings.
[c] In addition to the vertical live loads, the design shall include horizontal swaying forces applied to each row of seats as follows: 24 lb per linear ft of seat applied in the direction parallel to each row of seats and 10 lb per linear ft of seat applied in the direction perpendicular to each row of seats. The parallel and perpendicular horizontal swaying forces need not be applied simultaneously.
[d] The loading applies to stack room floors that support nonmobile, double-faced library bookstacks subject to the following limitations: (1) the nominal bookstack unit height shall not exceed 90 in.; (2) the nominal shelf depth shall not exceed 12 in. for each face; and (3) parallel rows of double-faced bookstacks shall be separated by aisles not less than 36 in. wide.
[e] Other uniform loads in accordance with an approved method that contains provisions for truck loadings shall also be considered where appropriate.
Source: From Ref. 1.1. Used by permission of the American Society of Civil Engineers.

(100 psf = 4.8 kN/m^2)

Environmental loads consist mainly of wind pressure and suction, earthquake loads, soil pressures, snow loads, and forces caused by temperature differentials.
Environmental loads at any given time are uncertain both in magnitude and distribution.

Serviceability and Safety of Structures

A structure must be ***safe*** against collapse and ***serviceable*** in use.
Serviceability requires that *deflections* be adequately small; that *cracks* be kept to tolerable limits; that *vibrations* be minimized; etc.
Safety requires that the *strength* of the structure be adequate for all loads that may act on it.
There are number of sources of uncertainty in the analysis, design, and construction of reinforced concrete (RC) structures which requires a definite margin of safety. These sources are:

1. Actual loads may differ from those assumed.
2. Actual loads may distribute in manner different from that assumed.
3. Assumptions and simplifications may result in calculated shears, moments, etc different from those that, in fact, act in the structure.
4. Actual structural behavior may differ from that assumed, owing to imperfect knowledge.
5. Actual member dimensions may differ from those specified.
6. Actual material strength may differ from that specified.
7. Reinforcement may not be in its proper position.

Design Basis:

The ***strength design*** concept is to proportion members, i.e., to select dimensions and reinforcement, so that member strengths are adequate to resist forces resulting from certain hypothetical overload stages, significantly above loads actually to occur in service.
Serviceability limit conditions are an important part of the total design. For example, beam deflections must be limited to acceptable values, and the number and width of flexural cracks at service loads must be controlled.

Design codes and specifications

The American Concrete Institute (ACI) has published the ***Building Code Requirements for Structural Concrete***, ***ACI 318-14*** which serves as a guide in the design and construction of RC structures.

Safety Provisions of the ACI Code

The design strength φS_n of a structure or member must be at least equal to the required strength U calculated from factored loads, i.e.,

Design strength ≥ required strength Or $\varphi S_n \geq U$

In which φ is a strength reduction factor applied to nominal strength S_n.
The required strength U is calculated by applying appropriate load factors to the respective service load: dead load D, live load L, wind load W, earthquake load E, earth pressure H, fluid pressure F, snow load S, rain load R, and environmental effects T.

For a member subjected to moment, shear, and axial load

$$\varphi M_n \geq M_u$$
$$\varphi V_n \geq V_u$$
$$\varphi P_n \geq P_u$$

where subscripts n denote the nominal strengths in flexure, shear, and axial load respectively, and u denote the factored load moment, shear and axial load.
The load factors specified in the ACI Code are summarized in Table 1.2 (Nilson)

TABLE 1.2
Factored load combinations for determining required strength in the ACI Code

Condition	Factored Load or Load Effect
Basic[b]	$U = 1.2D + 1.6L$
Dead plus Fluid[b]	$U = 1.4(D + F)$
Snow, Rain, Temperature, and Wind	$U = 1.2(D + F + T) + 1.6(L + H)$ 1 $0.5(L_r$ or S or $R)$
	$U = 1.2D + 1.6(L_r$ or S or $R) + (1.0L$ or $0.8W)$
	$U = 1.2D + 1.6W + 1.0L + 0.5 \cdot L_r$ or S or $R \cdot$
	$U = 0.9D + 1.6W + 1.6H$
Earthquake	$U = 1.2D + 1.0E + 1.0L + 0.2S$
	$U = 0.9D + 1.0E + 1.6H$

[a] Where the following represent the loads or related internal moments or forces resulting from the listed factors: D = dead load; E = earthquake; F = fluids; H = weight or pressure from soil; L = live load; L_r = roof live load; R = rain; S = snow; T = cumulative effects of temperature, creep, shrinkage, and differential settlement; W = wind.
[b] The ACI Code includes F or H loads in the load combinations. The "Basic" load condition of $1.2D + 1.6L$ reflects the fact that most buildings have neither F nor H loads present and that $1.4D$ rarely governs design.

The strength reduction factors φ in the ACI Code are given in Table 21.2.1:

Table 21.2.1—Strength reduction factors ϕ

Action or structural element		ϕ	Exceptions
(a)	Moment, axial force, or combined moment and axial force	0.65 to 0.90 in accordance with 21.2.2	Near ends of pretensioned members where strands are not fully developed, ϕ shall be in accordance with 21.2.3.
(b)	Shear	0.75	Additional requirements are given in 21.2.4 for structures designed to resist earthquake effects.
(c)	Torsion	0.75	—
(d)	Bearing	0.65	—
(e)	Post-tensioned anchorage zones	0.85	—
(f)	Brackets and corbels	0.75	—
(g)	Struts, ties, nodal zones, and bearing areas designed in accordance with strut-and-tie method in Chapter 23	0.75	—
(h)	Components of connections of precast members controlled by yielding of steel elements in tension	0.90	—
(i)	Plain concrete elements	0.60	—
(j)	Anchors in concrete elements	0.45 to 0.75 in accordance with Chapter 17	—

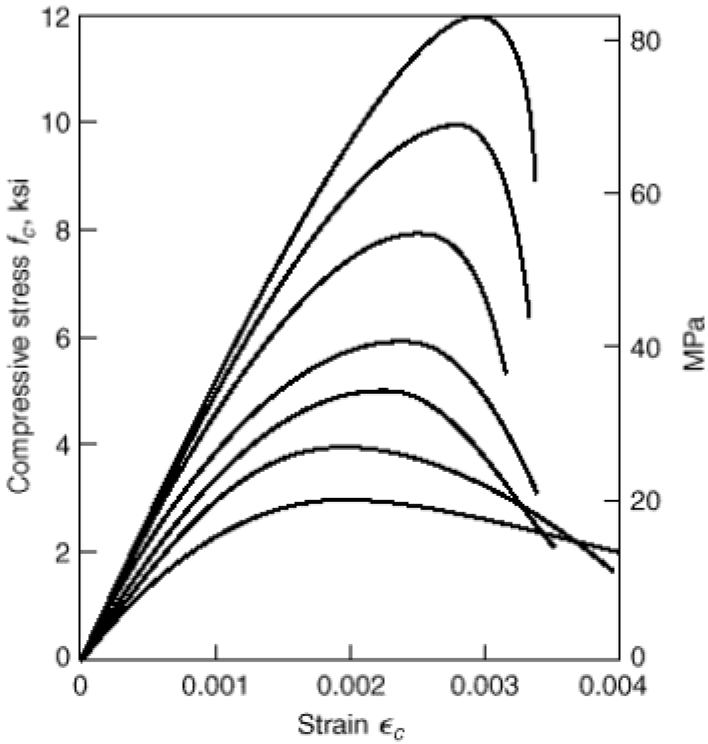
Fundamental Assumptions for RC Behavior

1. The internal forces (moments, shears, and normal and shear stresses) at any section are in equilibrium with the effects of the external loads at that section.
2. The strain in an embedded reinforcing bar is the same as that of the surrounding concrete. It means that perfect bonding exists between concrete and steel at the interface, so that no slip can occur between the two materials.
3. Cross sections that were plane prior to loading continue to be plane in the member under load.
4. Concrete is not capable of resisting any tension stress whatever.
5. The theory is based on the actual stress-strain relationships and strength properties of the two constituent materials.

Properties of Concrete in Compression

Stress-strain Relationship

Since concrete is used mostly in compression, its compressive stress-strain curve is of primary interest. Such curve is obtained by strain measurements in cylindrical tests. Figure below (Nilson) shows a typical set of such curves for 28-day old normal-density concrete (≈ 2300 kg/m^3).



The max compressive strength is reached at a strain that ranges from about 0.002 to 0.003.
In present practice, the specified compressive strength f'_c is commonly in the range from 21 to 35 MPa for normal-density sitecast concrete.
The high-strength concretes, with f'_c to 100 MPa and more are used particularly for heavily-loaded columns in high-rise concrete buildings.

The Modulus of Elasticity E_c (in MPa), i.e., the slope of the initial straight portion of the stress-strain curve, can be computed from the empirical ACI Code equation:

$$E_c = 0.043\, w_c^{1.5} \sqrt{f'_c}$$

Where w_c is the unit weight of concrete (kg/m^3) and f'_c is the strength (MPa)
E_c may be taken as: $E_c = 4700 \sqrt{f'_c}$

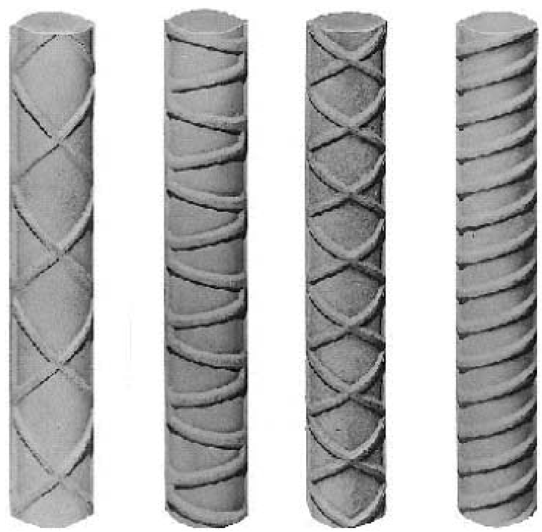
Properties of Concrete in Tension

It is important to predict the tensile strength of concrete. Cracks formation and propagation on the tension side of RC members depend strongly on the tensile strength of concrete.
It is difficult to determine the true tensile strength of concrete. There are three methods as listed below:

Direct tensile strength f'_t ($\approx$ ***0.25 to 0.58***$\sqrt{f'_c}$)
Split-cylinder strength f'_{ct} ($\approx$ ***0.50 to 0.66***$\sqrt{f'_c}$)
Modulus of rupture f'_r ($\approx$ ***0.66 to 1.00***$\sqrt{f'_c}$); ACI Code $f'_r = \mathbf{0.62}\sqrt{f'_c}$

Reinforcing Steels for Concrete

The reinforcing steel and concrete are best used in combination: the concrete is made to resist the compressive stresses and the steel the tensile stresses. Reinforcement is also used for resisting compressive forces in compression members and beams of reduced cross-sectional dimensions.
For effective reinforcing action, it is essential that concrete and steel deform together, i.e., that there be a strong ***bond*** between them. This bond is provided by *chemical adhesion* at the steel-concrete interface, by the *roughness* of the bars and by the rib-shaped *surface deformations* furnished to provide interlocking of the two materials (Fig. below).



Steel Bars for Concrete Reinforcement

Steel reinforcing bars ('rebar') for concrete construction are hot-rolled in much the same way as structural shapes. They are round in cross section and *deformed* with surface ribs for better bonding to concrete. At the end of the rolling line in the mill, the bars are cut to a standard length (commonly 6, 9 or 12 m and in the United States 60 feet, or 18.3 m).
Reinforcing bars are rolled in a limited number of standard diameters.
In the USA, bars are specified by a simple numbering system in which the number corresponds to the number of eighths of an inch of bar diameter (see Table). For example, a number 6 reinforcing bar is 6/8 or 3/4 inch (19 mm)

in diameter, and a number 8 is 8/8 or 1 inch (25.4 mm) in diameter.

ASTM Standard Reinforcing Bars

Bar Size		Nominal Dimensions					
		Diameter		Cross-Sectional Area		Weight	
American	Metric	in.	mm	in.^{2}	mm^2	lb/ft	kg/m
#3	#10	0.375	9.5	0.11	71	0.376	0.560
#4	#13	0.500	12.7	0.20	129	0.668	0.944
#5	#16	0.625	15.9	0.31	199	1.043	1.552
#6	#19	0.750	19.1	0.44	284	1.502	2.235
#7	#22	0.875	22.2	0.60	387	2.044	3.042
#8	#25	1.000	25.4	0.79	510	2.670	3.973
#9	#29	1.128	28.7	1.00	645	3.400	5.060
#10	#32	1.270	32.3	1.27	819	4.303	6.404
#11	#36	1.410	35.8	1.56	1006	5.313	7.907
#14	#43	1.693	43.0	2.25	1452	7.65	11.38
#18	#57	2.257	57.3	4.00	2581	13.6	20.24

Grades and Strengths

Summary of minimum ASTM strength requirements

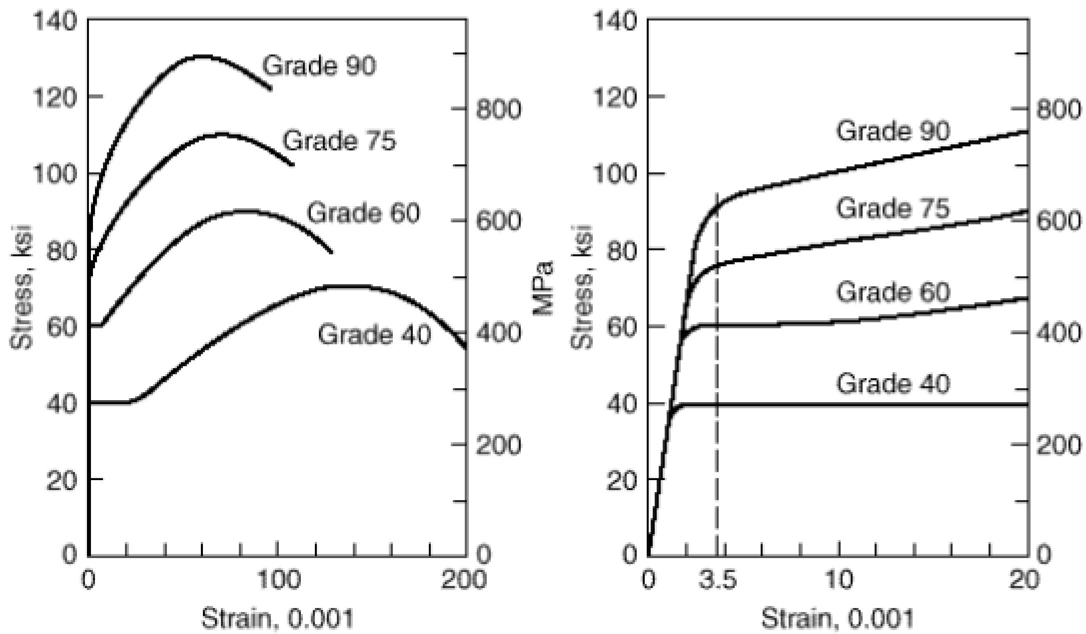
Product	ASTM Specification	Designation	Minimum Yield Strength, psi (MPa)	Minimum Tensile Strength, psi (MPa)
Reinforcing bars	A 615	Grade 40 Grade 60 Grade 75	40,000 (280) 60,000 (420) 75,000 (520)	60,000 (420) 90,000 (620) 100,000 (690)
	A 706	Grade 60	60,000 (420) [78,000 (540) maximum]	80,000 (550)[a]
	A 996	Grade 40 Grade 50 Grade 60	40,000 (280) 50,000 (350) 60,000 (420)	60,000 (420) 80,000 (550) 90,000 (620)
Deformed bar mats	A 184	Same as reinforcing bars		
Zinc-coated bars	A 767	Same as reinforcing bars		
Epoxy-coated bars	A 775, A 934	Same as reinforcing bars		
Stainless-steel bars[b]	A 955	Same as reinforcing bars		
Wire Plain	A 82		70,000 (480)	80,000 (550)
Deformed	A 496		75,000 (515)	85,000 (585)
Welded wire reinforcement Plain W1.2 and larger Smaller than W1.2	A 185		65,000 (450) 56,000 (385)	75,000 (515) 70,000 (485)
Deformed	A 497		70,000 (480)	80,000 (550)

Steel Stress-Strain Curves

The two chief characteristics of bar reinforcement are its *yield point* and its *modulus of elasticity* E_s.

E_s **= 200,000 MPa (200 GPa)** (the same for all reinforcing steel bars).

Typical stress-strain curves of reinforcing steel are shown below:



For low-carbon steels (Grade 40 (280 MPa)), the curve shows an elastic portion followed by a *yield plateau*, i.e., a horizontal portion where strain continues to increase at constant stress. With further strains, the stress begins to increase again (*strain hardening*). The curve then flattens out when the *tensile strength* is reached; it then turns down until fracture occurs.

For high-carbon steels (Grade 60 (420 MPa)) or higher, the curve shows a much shorter (or no) *yield plateau.*
The ACI Code specifies that the yield stress f_y be the stress corresponding to a strain of 0.0035, as shown in figure.