Practical Reinforced Concrete Design

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CHAPTER 1

INTRODUCTION

1.1 Concrete

Concrete is a mixture of gravel, cement, sand, and water. Plain concrete is strong in compression but weak in tension and its properties are reliable in compression but not so in tension. Reinforced concrete is a combination of concrete and steel reinforcement that provides concrete resistance to tension. Reinforced concrete may be the most important material available for construction. It is used in constructing buildings, bridges, dams, retaining walls, tunnels, and many more structures. Too many merits make this structural material the most common construction material all over the world, Table 1-1.

Table 1-1: Concrete strong and weak characteristics

Items	Strong	Weak
Compression	√	-----------
Tension	-----------	√
Resistance to fire and water	√	-----------
Rigid Structure	√	-----------
Low-maintenance material	√	-----------
long service life	√	-----------
Economical Structure	√	-----------
Structural Members Shape Control	√	-----------
Universally Available	√	-----------
Bond With Steel	√	-----------
Ductility and Failure Warning	√	-----------
Aesthetics	√	-----------
A lower grade of skilled labor	√	-----------
Formwork	-----------	√
Large Dead weight	-----------	√
Variations in its Proportioning and Mixing	-----------	√
Shrinkage and Creep	-----------	√
Cracking	-----------	√
Relatively Unpredict Behavior	-----------	√
Inelastic Behavior	-----------	√

1.2 Design Codes

Each design code is a set of simple, concise, illustrated design requirements that provide principles and guidelines for the design of structural members, Table 1-2.

Table 1-2: Codes of design

Design Code	Institute	Country
ACI	American Concrete	USA
ASCE	American Society of Civil Engineers	USA
BS 8110	Board for Building and Civil Engineering,	UK
IS 456	Bureau of Indian Standards	INDIA

1.3 Loads

Loads are due to gravity, earthquake, wind, temperature change, water pressure, blast impact, vibration, gas pressure, shrinkage, friction, creep, and support moment. Loads are subdivided into two groups: dead loads and live loads. Dead loads are assumed to remain constant over the life span of the structure. The structure weight and any permanent loads fixed on the structure are examples of dead loads. Live loads can be removed or replaced on a structure. Occupancy loads, snow loads, wind loads, earthquake loads, vehicle moment, and blast loads are all examples of live loads, Appendix-A.

1.4 Design Methods

1- The working stress method (WSM): This method is based on the principle that both concrete and steel exhibit linear-elastic behavior, with stress and strain maintaining a direct proportionality.

2- The ultimate load method (ULM): In this method ultimate load is used as the design load and the collapse criteria used for the design. Ultimate load is defined as a working load multiplied by a load factor. This gives a better concept of load. carrying capacity of the structure.

$$\text{External Forces} \times \text{Factor of Safety} \leq \text{Internal Resistance of the structure}$$

$$External\ Moment\ M_E \times FOS = Ultimate\ Moment\ M_U \leq Resistant\ Moment\ M_C$$

$$Mu \leq \phi_b Mn = M_C \quad and \quad Vu \leq \phi_S Vn = V_C$$

where;

Mu, *Vu* = external factored moment and shear forces, respectively

Mn, *Vn* = nominal flexural strength and shear strength of member

M_C, V_C = resistant flexural strength and shear strength of member

ϕ_b , ϕ_S = Reduction factors for flexural and shear

Note: Analysis and design of structural members in this book will be based on ULM.

3- The limit state method (LSM): In the limit state method, the structure shall be designed to withstand safely all loads liable to act on it throughout its life, it shall also satisfy the strength and serviceability requirements.

4- Plastic Method: This method is based on the yield line theory. It is a method of calculating the ultimate load-carrying capacity of a structure by considering its nonlinear behavior beyond the elastic limit. In other words, the plastic method is a method of designing a structure based on its plastic moment capacity rather than its elastic moment capacity.

1.5 Load Factors and Load Combinations

Load factors are numbers greater than 1 by which service loads are multiplied to provide sufficient safety in structural design and their magnitude differs from code to code. A load combination results when more than one load type acts on the structure. Building codes usually specify a variety of load combinations together with load factors for each load type in order to ensure the safety of the structure under different maximum expected loading scenarios.

Table 1-3: Selected load factors and load combinations

Design Code	Dead Load Factor (DLF)	Live Load Factor (LLF)	Load Combination
ACI- USA	1.2	1.6	$W_u = 1.2\,DL + 1.6\,LL$
BS 8110- UK	1.4	1.6	$W_u = 1.4\,DL + 1.6\,LL$
IS - INDIA	1.5	1.5	$W_u = 1.5\,DL + 1.5\,LL$

W_u = the design or ultimate load the structure needs to be able to resist
DL = dead load
LL = live load

1.6 Structural Design Procedure

The steps of structural design procedure are:

1- Architect Plans and drawings.
2- Selection of the most adequate, safe, and economical structural system.
3- Performing the structural analysis using computer and manual calculations to determine the maximum moments, shear, torsional forces, axial loads, and other forces.
4- Design the structure members size and reinforcement.
5- Producing structural drawings with specifications and details to be submitted to the contractor.

1.7 Compressive Strength

Compressive strength $\acute{f}c$ can be defined as the capacity of concrete to withstand loads before failure. Of the many tests applied to the concrete, the compressive strength test is the most important, as it gives an idea about the characteristics of the concrete, Table 1-4.

Table 1-4: Concrete cube tests of compressive strength (MPa)

Grade fc'	7-Days MPa	14-Days MPa	28-days MPa
M20	13	18	20
M30	19.25	27	30
M40	26	36	40
M50	32.5	45	50

1.8 Shrinkage of Concrete

Concrete shrinkage is the decrease in length or volume of a concrete caused by changes in moisture content or chemical reactions. All concrete undergoes shrinkage, and there are four categories of shrinkage seen in concrete:

1- Drying shrinkage occurs when water starts evaporating from the exposed surface and the moisture differential along the depth of the slab causes strain which induces tensile stresses. Due to this drying shrinkage, cracks are noticed on the surface of concrete.

2- Chemical shrinkage is the reduction of internal volume of concrete mixtures due to cement hydration reaction.

3- Plastic shrinkage occurs in a freshly mixed concrete, with loss of water by evaporation from its surface, after placing and before hardening of the concrete.

4- Autogenous shrinkage is the uniform reduction of internal moisture due to cement hydration.

1.9 Creep of Concrete

Creep is the deformation induced in the structural member; hence it can be calculated by the creep formula. Creep strain can be related to the modulus of elasticity of concrete at the age of the concrete. Several other items affecting the amount of creep are:

1- The longer the concrete cures before loads are applied, the smaller will be the creep.

2- Creep increases with higher temperatures.

3- The paste of water and cement not the aggregate does the creeping.

4- Reinforcement will greatly reduce creep because steel exhibits very little creep at ordinary stresses.

5- Large concrete members will creep less than smaller thin members.

6- Creep increases with an increase in stress.

7- Creep increases with duration of Loading.

8- Creep is reduced with an increase in the humidity.

9- Well-graded aggregate will produce reduction in creep.

1.10 Unit Weight of Concrete

The unit weight of concrete is the mass or weight of the concrete that is required to fill a container of a specified unit volume. The following values of concrete unit weight γ_c of normal concrete used in structures are:

1- Unit weight of plain concrete using maximum aggregate size of 20 mm varies between 23 $\frac{\text{kN}}{\text{m}^3}$ to 24 $\frac{\text{kN}}{\text{m}^3}$.
2- Unit weight of plain concrete of maximum aggregate size of 100 to 150 mm varies between 24 $\frac{\text{kN}}{\text{m}^3}$ to 25 $\frac{\text{kN}}{\text{m}^3}$.
3- Unit weight of reinforced concrete is about 25 $\frac{\text{kN}}{\text{m}^3}$.

1.11 Stress–Strain Curves

The stress–strain curve for concrete gives the relationship between stress σ and strainƐ. Strain is how much a material stretches or compresses per unit length when stress is applied. We usually assume that concrete will fail at a strain of 0.003 meters per meter. The modulus of elasticity E is the slope of the stress–strain curve in the elastic range $E = \frac{Stress}{Strain} = \frac{\sigma}{\varepsilon}$, $E_c = 4700\sqrt{f`_c}$ for normal weight concrete. Compressive stress $f`_c$ is responsible for the deformation of the material such that the volume of the material reduces $f`_c = \sigma = \frac{Force}{Area}$. The stress-strain curve provides design engineers with a long list of important parameters needed for design application. A stress-strain graph gives us many mechanical properties such as strength, toughness, elasticity, yield point, strain energy, resilience, and elongation during load.

1.12 Reinforcement

Reinforcement for concrete is provided by embedding deformed steel bars or welded wire fabric within freshly made concrete at the time of casting. The purpose of reinforcement is to provide additional strength for concrete where it is needed. The reinforcing used for concrete structures may be in the form of bars or welded wire fabric. Reinforcing bars are referred to as plain or deformed. The deformed bars, which have ribbed projections rolled onto their surfaces to provide better bonding between the concrete and the steel, Figure 1-1.

Figure 1-1: Deformed Bars – Qatar Steel

Reinforcing bars typically come in a few grades 420 MPa, 520 MPa, and 550 MPa. In building construction, Y20 or (Ø20) and Y18 or (Ø18) refer to the bar sizes used for reinforcing concrete structures. Ø20 corresponds to a 20mm diameter bar, while Ø18 corresponds to a 18mm diameter bar.

1.13 Fatigue Strength

Fatigue strength is the highest stress that a material can withstand for a given number of cycles without breaking. Engineering design requires stress limits to ensure fatigue failure does not happen before the lifespan of the materials being used has been reached.

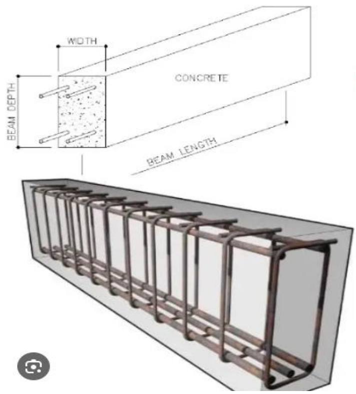
1.14 High Rise Building

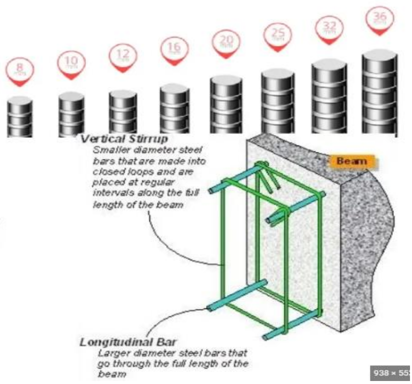
Most building engineers, inspectors, architects and similar professionals define a high-rise as a building that is at least 25 meters tall. High-rise buildings play a crucial role in shaping the urban development of cities around the world. Their importance lies in their ability to accommodate numerous people and activities within limited space, thus maximizing land utilization and contributing to sustainable development, Figure 1-2.

Figure 1-2: High Rise Buildings in Doha - Qatar

CHAPTER 2

ONE -WAY SLAB AND BEAMS





2.1 One Way Slabs

A one-way slab is supported by two parallel walls or beams with a length-to-breadth ratio of two or greater bends only in one direction (the short direction) as it transfers loads to the two parallel walls or beams supporting each other. It spans and bends only in one direction. Simple one-way slab and continuous one-way slab yield strength of non-prestressed reinforcing *fy* and compression strength of concrete *f`c*. The design moment strength Mc results from internal compressive force ***C*** and an internal force ***T*** separated by a lever arm, Figure 2-1.

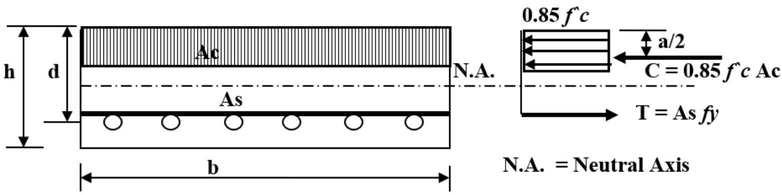


Figure 2-1: Rectangular slab cross section with reinforcement

$$T = As\,fy \qquad \text{Eq. 2-1}$$
$$C = 0.85 f`c\ Ac \qquad \text{Eq. 2-2}$$
$$Ac = b \times a \qquad \text{Eq. 2-3}$$

Having T = C from equilibrium, the compression area

$$Ac = \frac{As * fy}{0.85 * f`c} \qquad \text{Eq. 2-4}$$

And the depth of the compression block

$$a = \frac{fy * As}{0.85 * f`c * b} \qquad \text{Eq. 2-5}$$

Thus, the design moment strength

$$Mc = \varphi_b\ As\ fy\ \left(d - \frac{a}{2}\right) \qquad \text{Eq. 2-6}$$

From flexural point of view a simple one-way slab has a single positive moment, the continuous one-way slab has two moments positive and negative, Figures 2-2 and 2-3.

Where;

φ_b= Bending reduction factor
$fy =$ Specified yield strength of non-prestressed reinforcing
$f`c =$ Specified compression strength of concrete
$As =$ Area of tension steel
$Ac =$ Compression area
$d =$ Effective depth
$a =$ Depth of the compression block
$b =$ Width of the slab cross section
$h =$ Total depth of the slab cross section
Ag = Gross cross-sectional area of a concrete member

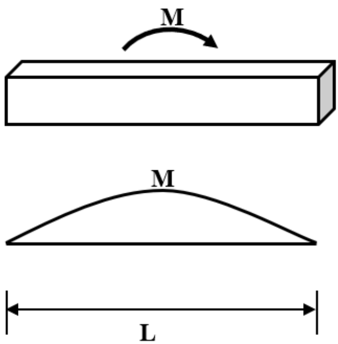


Figure 2-2: Simple one-way slab moment per running meter

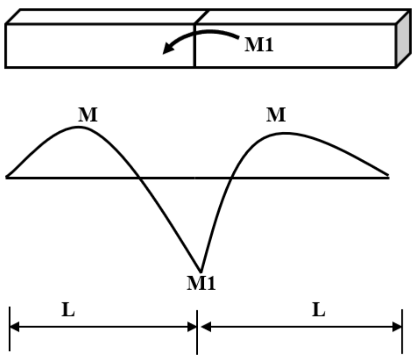


Figure 2-3: Continuous one-way slab moments per running meter

One way slab example:

Design the slabs (S_1) and (S_2), Figure 2-4

I- Design the slab (S_1)

II- Design the slab (S_2)

D.L. =5 kN/m^2, L.L. = 10 kN/m^2, fy = 400 MPa, $f_c' = 30\ MPa,$ $\gamma_{conc} = 25kN/m^3$

d` = 30mm, DLF = 1.4 , LLF = 1.7

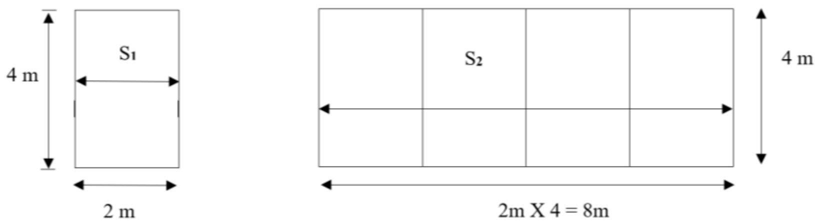


Figure 2-4 simple and continuous one-way slab

Solution:

1- Check slab type (S_1):

$$\frac{Long\ side\ length}{Short\ side\ length} = \frac{L_L}{L_S} \geq 2 \Longrightarrow One\ way\ slab$$

$$\frac{L_L}{L_S} < 2 \Longrightarrow Two\ way\ slab$$

$$\frac{4}{2} = 2 \therefore\ S1\ is\ one\ way\ slab.$$

2- Slab thickness, h, from $\frac{Table\ 9.5a}{ACI\ Code-11} \Longrightarrow h = \frac{l}{20} = \frac{2\times1000}{20} = 100\ mm$

Note: if $f_y \neq 400, \Longrightarrow values\ from\ the\ table \times \left(0.4 + \frac{f_y}{700}\right)$

3- $DL_{slab} = \frac{h}{1000} \times \gamma_c \Longrightarrow \frac{100}{1000} \times 25 = 2.5\ kN/m^2$

$$w_u = 1.4(D.L) + 1.7(L.L) \Longrightarrow 1.4(2.5 + 5) + 1.7(10)$$

$$w_u = 27.5\ kN/m$$

Figure 2-5: Slab load

4- Structural Analysis : $M_u = \frac{w_u(l)^2}{8} = \frac{27.5(2)^2}{8} = 13.75\ kN.m$

5- Check slab thickness:

$$\rho = \frac{1}{2}\rho b = 0.0162 \Longrightarrow M_u = \emptyset \rho f_y b d^2\left(1 - 0.59\rho\frac{f_y}{f_c'}\right)$$

Note: one way slab is one-meter-width ∴ b = 1 m = 1000 mm

$$M_u = 13.75 \times 10^6 = (0.9)(0.0162)(1000)d^2\left(1 - 0.59(0.0162)\frac{f_y}{f_c'}\right)$$

$$d^2 = 2383.4 \Longrightarrow d = 48mm \Longrightarrow h = 48 + 30 = 78 < 100 \quad OK$$

Try
$\rho = 0.35\rho b = 0.0114 \Longrightarrow d = 58mm \Longrightarrow h = 58 + 30 = 88$
$88\ mm < 100mm \quad OK$

Use h=100 mm, d=70mm

6- Reinforcement Steel ***As***

$$\boldsymbol{A_s} = \rho bd = 0.0114 \times 1000 \times 70 = \frac{798mm^2}{m}$$

Bar selection

Bar diameter 14mm ➔ $A_b = 154mm^2$

$$N_b = \frac{A_s}{A_b} \cong 6, Spacing = S = \frac{1000}{6-1} = 200\ mm$$
$$A_s = 923.67mm^2 > 798\ mm^2 OK$$

Use Φ14 @ 200 < $S_{max} = 300mm \begin{pmatrix} 3 \times (h = 100) = 300mm \\ < 450mm \\ \text{ACI code} \end{pmatrix}$

OR, bar diameter 12 mm ➔ $A_b = 113mm^2$
$N_b = \frac{A_s}{A_b} \Longrightarrow Use\ \Phi 12\ @150 \Longrightarrow A_s = 866.3mm^2 > 798mm^2\ OK$
Use Φ12 @150 mm as main reinforcement steel because it is more economical.

Temperature and shrinkage steel

$$A_{st} = 0.002bh \Longrightarrow 0.002(1000)(100) = \frac{200mm^2}{m}$$

$$\emptyset 10mm \Longrightarrow S = 500mm > 300$$

$$\therefore Use\ \Phi 10\ @\ 300mm \begin{pmatrix} 3 \times (h = 100) = 300mm \\ < 450mm \\ \text{ACI code} \end{pmatrix}$$

7- Detailing:

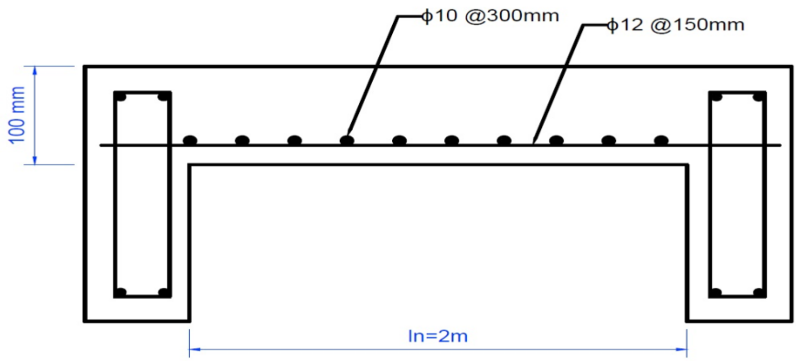


Figure 2-6: Simple one way slab detailing

Solution (*Slab S₂*):

1- Check slab type:

$$\frac{Long\ side\ length}{Short\ side\ length} = \frac{L_L}{L_S} \geq 2 \Rightarrow One\ way\ slab\ ,$$

$$\frac{L_L}{L_S} < 2 \Rightarrow Two\ way\ slab$$

$$\frac{4}{2} = 2\ \therefore\ S2\ is\ contious\ one\ way\ slab.$$

2- Slab thickness h from $\Rightarrow h = \frac{l}{20} = \frac{2\times1000}{20} = 100\ mm$

Note: if $f_y \neq 400, \Rightarrow values\ from\ the\ table \times \left(0.4 + \frac{f_y}{700}\right)$

3- $DL_{slab} = \frac{h}{1000} \times \gamma_c \Rightarrow \frac{100}{1000} \times 25 = 2.5\,\frac{kN}{m^2}$

$w_u = 1.4(D.L) + 1.7(L.L) \Rightarrow 1.4(2.5 + 5) + 1.7(10) = 27.5\ kN/m$

4- Structural analysis to determine the design moments:

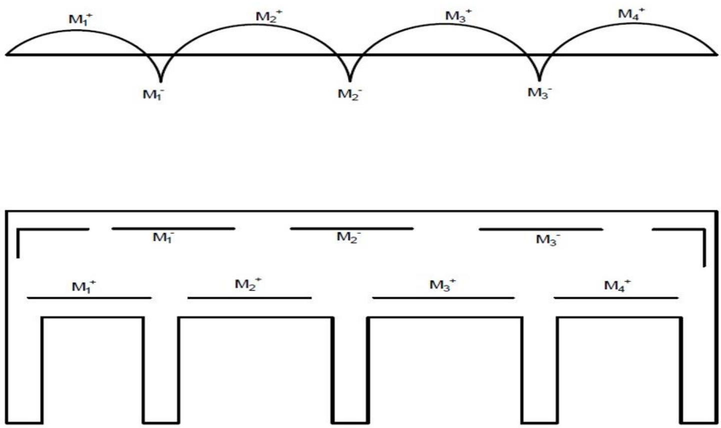


Figure 2-7: Design moments and steel distribution

The moments could be determined using the ACI code method as an approximation method if the conditions are satisfied:

ACI conditions ?

$\frac{S_{LL}}{S_{DL}} = \frac{7.5}{10} = 0.75 < 3$ ➔ Ratio of Service live load to service dead load

$\frac{L_{SPAN}}{S_{SPAN}} = \frac{4}{4} = 1 < 1.2$ ➔ Ratio of Service live load to service dead load

<u>Ok use ACI Approximations</u>

If the conditions are not satisfied, then use more exact methods such as matrix analysis method, moment distribution method or finite element method.

Since the conditions are satisfied then the four span moments are:

$M_1^- = M_2^- = M_3^- = \frac{w_u l^2}{10} = 11 kN.m$ where L is the short length, 2m

$M_1^+ = M_2^+ = M_3^+ = M_4^+ = \frac{w_u l^2}{14} = 7.9 kN.m$ where L is the short length, 2m.

Note that these moments are per meter width of the slab.

5- Check slab thickness:

$$\rho = \frac{1}{2}\rho b = 0.0162 \Longrightarrow M_u = \emptyset \rho f_y b d^2 \left(1 - 0.59\rho \frac{f_y}{f_c'}\right)$$

Note: one way slab is one-meter-wide piece ∴ b = 1 m = 1000 mm

$$M_{1,2,3}^- = 11 \times 10^6 = (0.9)(0.0162)(1000)d^2 \left(1 - 0.59(0.0162)\frac{f_y}{f_c'}\right)$$

$d < 100 \quad OK$

Try

$\rho = 0.35\rho b = 0.0114 \Longrightarrow d < 100 \quad OK$

Use **h=100 mm, d=70mm**

6- Reinforcement Steel ***As***

$\boldsymbol{A_s} = \rho b d = 0.0114 \times 1000 \times 70 = 798 mm^2/m$

Bar selection:

Bar diameter 14mm ➔ $A_b = 154 mm^2$

$$N_b = \frac{A_s}{A_b} \cong 6, Spacing = S = \frac{1000}{6-1} = 200\ mm$$

$A_s = 923.67mm^2 > 798\ mm^2 OK$

Use Φ14 @ 200 < $S_{max} = 300mm \begin{pmatrix} 3 \times (h = 100) = 300mm \\ < 450mm \\ \text{ACI code} \end{pmatrix}$

OR bar diameter 12 mm➔$A_b = 113mm^2$

$N_b = \frac{A_s}{A_b} \Rightarrow Use\ \Phi 12\ @150 \Rightarrow A_s = 866.3mm^2 > 798mm^2\ OK$

Use Φ12 @150 for reinforcement steel because it is more economical.

Temperature and shrinkage steel:

$A_{st} = 0.002bh \Rightarrow 0.002(1000)(100) = 200mm^2/m$

$\emptyset 10mm \Rightarrow S = 500mm > 300$

$\therefore Use\ \Phi 10\ @\ 300mm \begin{pmatrix} 3 \times (h = 100) = 300mm \\ < 450mm \\ \text{ACI code} \end{pmatrix}$

7- Detailing:

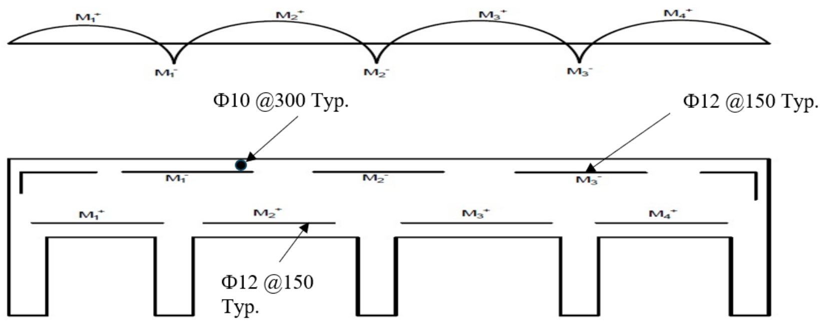


Figure 2-8: Slab Reinforcement

Note: For practical reasons use the same top steel at the ends of the end spans.

Alternative Solution using moment coefficients Method - Table A-10-Appendix A:

The moment coefficients method is used for two-way slab, but it could be used for one-way slab, even though it is conservative for one way slab. Each panel is treated separately based on its boundary conditions, that is either continuous or discontinuous edge. For S_1 all edges are discontinuous, but in S_2 the continuous slab both conditions exist, Figure 2-9.

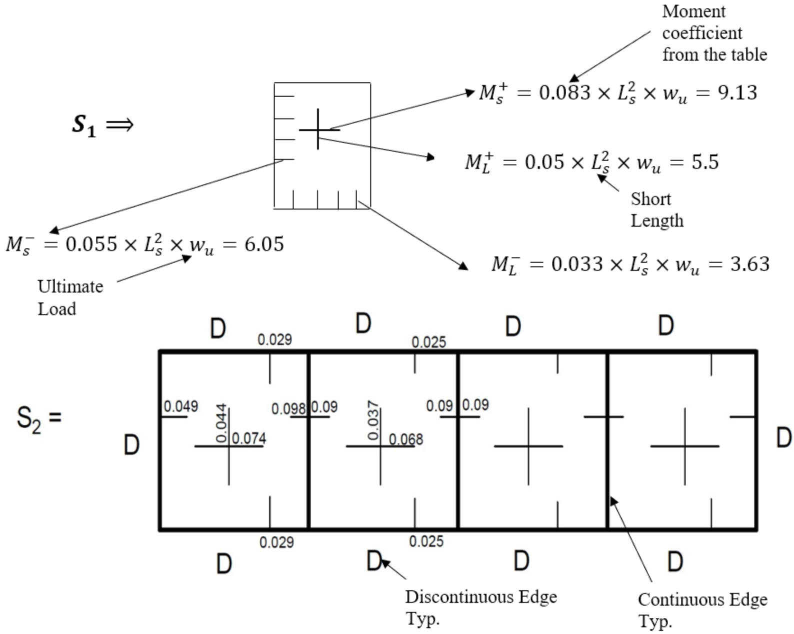


Figure 2-9: Slab Moment Coefficient

Use the coefficients to determine the moments ($\frac{kN \cdot m}{m}$), then follow the same procedure: (steps 4-6) in the previous example solution.

<u>Sample calculation for S_1:</u>

Positive moment in the short direction M_s^+

$$M_s^+ = 0.083 \times L_s^2 \times w_u = 0.083 \times 2^2 \times 27.5 = 9.13 \ kN.m/m$$

2.2 Regular Beams Introduction

Beams are very important structure members and the most common shape of reinforced concrete beams is rectangular cross section. Concrete beams are reinforced with steel rods (reinforcing bars) to resist internal tension forces within the cross section. Safety and reliability are used in the flexural design of reinforced concrete beams using ultimate strength design method USD under the provisions of ACI building code of design, Figure 2-10.

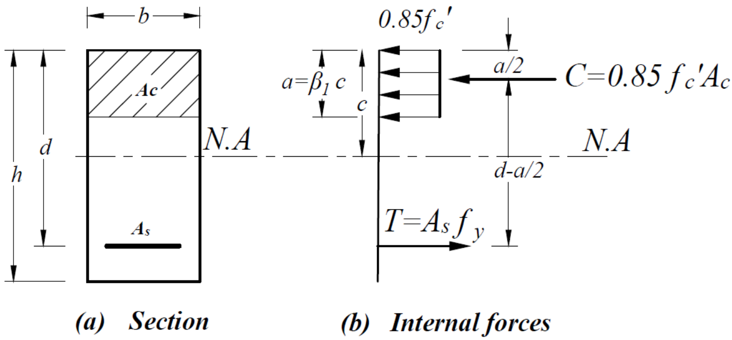


Figure 2-10: Rectangular cross section with single reinforcement [6]

Simple Beam Example:

A simply supported beam has a span length of 4.0 meter as shown in Fig. 2-11.

1. Design the beam for flexural and shear using *ACI code* .
2. Analyze the section for flexural using *BS8110 and EC2*.

Beam width (b) = 250 mm, concrete density = 25 kN/m^3, F_y (steel reinforcement yield strength) = 400 MPa, and f_c' (compressive strength of concrete) = 30MPa

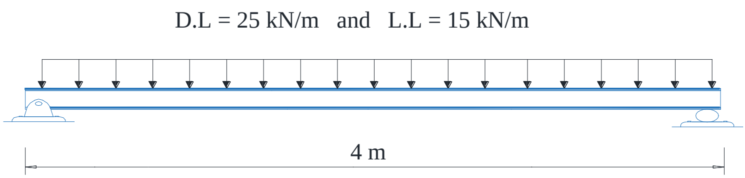


Fig: 2-11

SOLUTION

1- The structural element is modeled as shown in Fig. 2-11a.

2- Compute the factored loads on the beam

$\mathbf{W_u} = 1.4DL + 1.7LL$

$\mathbf{W_u} = 1.4(25) + 1.7(15) = 60.5$ kN/m

3- Perform the structural analysis and draw the shear and moment diagrams as shown in Figs. 2-11b, 2-11c,2-11d, 2-11f, 2-11g and 2-11h.

4-

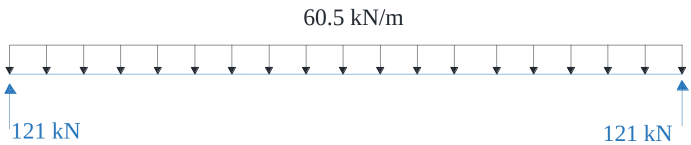


Fig. 2-11a: Applied Loads and Reactions

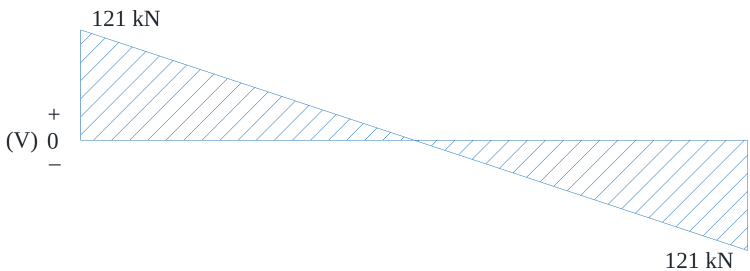


Fig. 2-11b: Shear Diagram *(kN)*

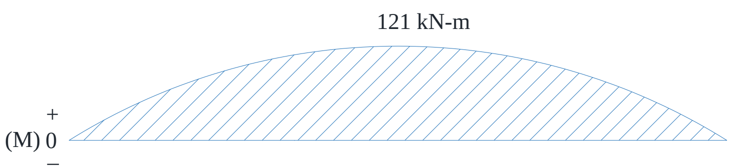


Fig. 2-11c: Moment Diagram *(kN-m)*

5- The beam size and reinforcement are determined using the following ACI-code equation:

$$M_u = \varphi \rho F_y b d^2 \left(1 - 0.59\rho \frac{f_y}{f'_c}\right) \qquad \text{Eq. 2-7}$$

Where $\boldsymbol{M_u}$ = External ultimate moment (*design moment*), ∅ = bending strength reduction factor ($\varphi = 0.9$), ρ = Ratio of the tensile steel area *(A_s)* to the effective concrete area ($\rho = \frac{A_s}{bd}$). The ratio $\boldsymbol{\rho}$ must satisfy the following equation:

$$\left(\rho_{min} = \frac{1.4}{fy} \leq \rho \leq \rho_{max} = 0.75\ \rho_b\right) \qquad \text{Eq. 2-8}$$

Where the balanced reinforcement ratio $\boldsymbol{\rho_b}$ is given by the following equation:

$$\rho_b = \left(\frac{0.85\beta f_c'}{F_y}\right)\left(\frac{600}{600 + F_y}\right) \qquad \text{Eq. 2-9}$$

The parameter $\boldsymbol{\beta}$ is given by the following equation:

$$\beta = 0.85 - \left(\frac{f^{/}c - 30}{7}\right)(0.05) \geq 0.65 \qquad \text{Eq. 2-10}$$

It is a common practice to assume a value of ρ equal to (1/2 ρ_b). Applying Eq. 2-7 and making use of Table A-6:

M_u = 121 kN.m b = 250 mm

$\rho = \frac{1}{2}\rho_b = 0.0162$ (F_y = 400 MPa and f_c' = 30 MPa)

$$121 \times 10^6 = 0.9(0.0162)(400)bd^2\left(1 - 0.59\rho\frac{400}{30}\right)$$

$bd^2 = 23777848.5\ mm^3$ => $\left[\overset{b}{250} \times \overset{d}{308}\right]$

Use b = 250 mm, d = 330 mm,

d` (distance from the external tension fiber to the centroid of the tensile steel) ≈ 70 mm

Thus, $h = d$ + d` = 400 mm