Lecture 10

Serviceability Criteria for Deflection and Crack Control in RC Members

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Learning Outcomes

- **At the end of this lecture, students will be able to;**

  ➢ *Define* short-term and long-term deflection

  ➢ *Explain* crack formation

  ➢ *Identify* relevant ACI codes to control deflection and crack width

Part – I

# Deflections in RC Beams and One-way Slabs

Introduction

- **Background**

  - In previous lectures, we have dealt primarily with the strength design of reinforced concrete beams.

  - Methods have been developed to ensure that beams will have a proper safety margin against failure in flexure or shear, or due to inadequate bond and anchorage of the reinforcement.

  - However, in addition to safety, serviceability requirements must also be ensured so that the structure performs well under service load conditions.

  - Deflection control is an important serviceability consideration in the structural design of concrete buildings.

Introduction

- **Definition**

  - Deflection as defined by ACI concrete Terminology is the movement of a point on a structure or structural element, usually measured as a linear displacement or as succession displacements transverse to a reference line or axis.
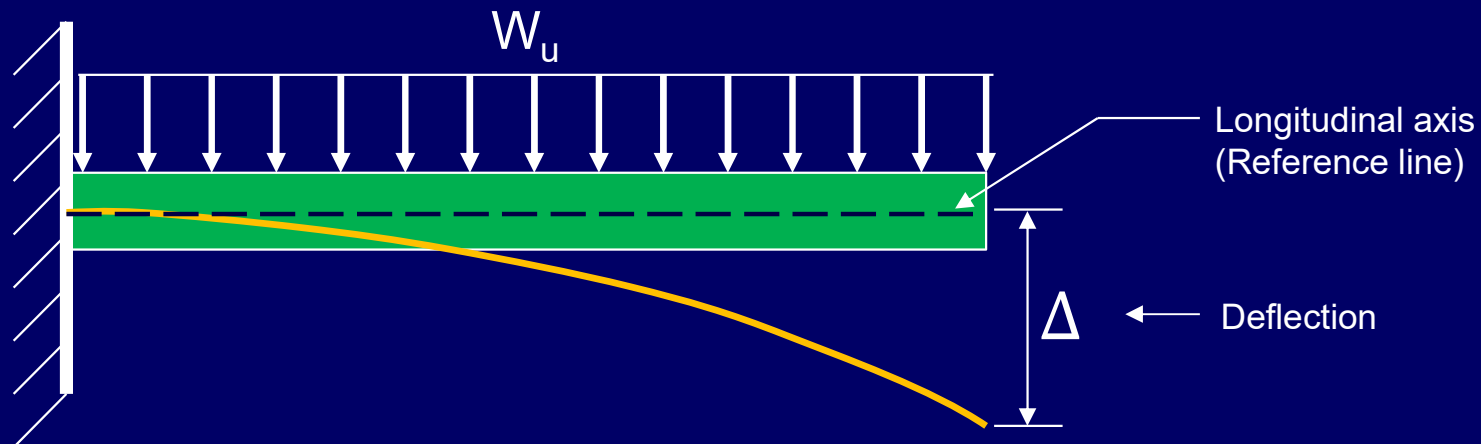
Introduction

- **Deflection Effects**

  - It is important to maintain control of deflections so that members designed mainly for strength at prescribed overloads will also perform well in normal service.

  - Excessive deflections can lead to cracking of supported walls and partitions, ill-fitting doors and windows, poor roof drainage, misalignment of sensitive machinery and equipment, and visually offensive sag etc.

Introduction

- **Types of Deflections**

  1. **Short-term deflections**

     - The immediate deflection after casting and application of partial or full service loads.

  2. **Long-term deflections**

     - Deflection that occurs over time as a result of shrinkage and creep of concrete.

  Both types are discussed in the subsequent slides.

Types of Deflections

- **Immediate (short-term) Deflections**

  - Immediate deflection at a given load in a structure is calculated using equations of elastic deflection.

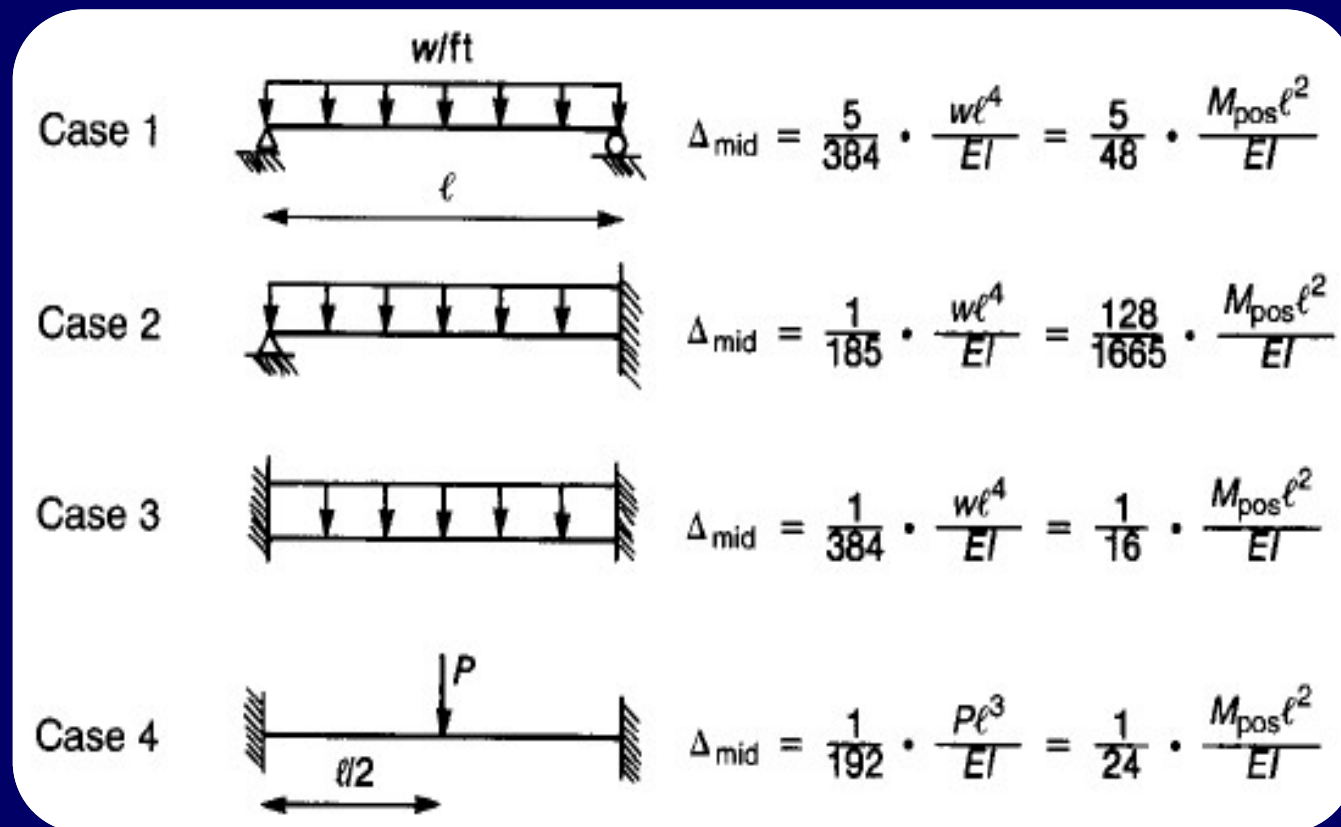 $$\Delta = \frac{f(loads, spans, supports)}{EI}$$

  Where;

  - $f(loads, spans, supports)$ is a function of load, span and support arrangement and

  - EI is the flexural rigidity.

Types of Deflections

- **Immediate (short-term) Deflections**

  - Deflections can be directly computed for different conditions of loading and end conditions as below:

  Case 1
  $$\Delta_{mid} = \frac{5}{384} \cdot \frac{w\ell^4}{EI} = \frac{5}{48} \cdot \frac{M_{pos}\ell^2}{EI}$$

  Case 2
  $$\Delta_{mid} = \frac{1}{185} \cdot \frac{w\ell^4}{EI} = \frac{128}{1665} \cdot \frac{M_{pos}\ell^2}{EI}$$

  Case 3
  $$\Delta_{mid} = \frac{1}{384} \cdot \frac{w\ell^4}{EI} = \frac{1}{16} \cdot \frac{M_{pos}\ell^2}{EI}$$

  Case 4
  $$\Delta_{mid} = \frac{1}{192} \cdot \frac{P\ell^3}{EI} = \frac{1}{24} \cdot \frac{M_{pos}\ell^2}{EI}$$

Types of Deflections

- **Immediate (short-term) Deflections**

  - Determination of modulus of elasticity of concrete

    - As per ACI 318-19, Section 19.2.2.1, Modulus of elasticity E_c for concrete shall be accordance with (a) or (b):

      - For values of w_c between 90 and 160 lb/ft^3

      $$E_c = w_c^{1.5} 33\sqrt{f_c'} \quad (psi) \qquad\qquad (19.2.2.1.a)$$

      - For Normalweight concrete

      $$E_c = 57000\sqrt{f_c'} \quad (psi) \qquad\qquad (19.2.2.1.b)$$

    - w_c in equation (a) is the equilibrium density of concrete mixture.

Types of Deflections

- **Immediate (short-term) Deflections**

  - Determination of effective moment of Inertia (I_e)

    - In elastic deflection equation, the effective moment of inertia I_e is calculated in accordance with ACI 318-19, Section 24.2.3.9a

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g - \left[\left(1 - \frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \le I_g$$

Where;

M_a = Maximum service load moment for which deflections are being considered.

M_{cr} = Cracking Moment = $f_r I_g / y_t$

I_g = Gross moment of inertia

I_{cr} = Moment of inertia of cracked section

Types of Deflections

- **Long-term Deflections**

    - Shrinkage and creep due to sustained loads cause additional long-term deflections over and above those which occur when loads are first placed on the structure.

    - Such deflections are influenced by:

        - Temperature,

        - Humidity,

        - Curing conditions,

        - Age at the time of loading,

        - Quantity of compression reinforcement, and

        - Magnitude of the sustained load.

Types of Deflections

- **Long-term Deflections**

  - Additional long-term deflection resulting from the combined effect of creep and shrinkage is determined by multiplying the immediate deflection caused by the sustained load with the factor ID as given in ACI table 24.2.4.1.3.

  - $\Delta_{(cp+sh)} = \lambda_\Delta (\Delta_i)_{sus}$

    $$\lambda_\Delta = \frac{\xi}{1 + 50\rho'}$$

    $\rho' = A_s'/bd$

Table 24.2.4.1.3	
Sustained load duration $(\Delta_i)_{sus}$, (months)	Time dependent factor, ξ
3	1.0
6	1.2
12	1.4
60 or more	2.0

Types of Deflections

- **Long-term Deflections**

  - It is important to note here that long term deflections are function of immediate deflections due to sustained load only i.e.

    $$\Delta_{(cp + sh)} = \lambda_\Delta (\Delta_i)_{sus}$$

  - Sustained loads are loads that are permanently applied on the structure e.g., dead loads, superimposed dead loads and live loads kept on the structure for long period.

ACI Code Provisions for Deflection Control

1.   Direct Approach

- In direct approach, the deflections are controlled by restricting their magnitude to the permitted limits recommended by ACI 318 Code.

- Deflections are said to be within limits if the combined effect of immediate and long-term deflections does not exceed the limits specified in ACI table 24.2.2 (shown on next slide).

ACI Code Provisions for Deflection Control

1.   Direct Approach

Maximum permissible calculated deflections (ACI Table 24.2.2)			
Member	Condition		Deflection to be considered	Deflection limitation
Flat roofs	Not supporting or attached to nonstructural elements likely to be damaged by large deflections Immediate deflection due to L		Immediate deflection due to maximum of Lr, S, and R	$l/180$
Floors			$l/360$	
Roofs or floors	Supporting or attached to non-structural elements	Likely to be damaged by large deflections	That part of the total deflection occurring after attachment of nonstructural elements, which is the sum of the time-dependent deflection due to all sustained loads and the immediate deflection due to any additional live load	$l/480$
		Not likely to be damaged by large deflections		$l/240$

ACI Code Provisions for Deflection Control

2. **Direct Approach**

- Deflections can also be controlled indirectly by limiting the thickness (depth) of structural members.

- Deflections are said to be within limits if the thickness of beams and one-way slabs are greater than the minimum requirements given in ACI table 7.3.1.1 and 9.3.1.1 (as shown on next slide).

- However, this method is applicable only to the cases of loadings and spans commonly experienced in buildings and cannot be used for unusually large values of loading and span.

ACI Code Provisions for Deflection Control

2.   Direct Approach

Minimum thickness of solid one-way slabs (ACI Table 7.3.1)	
Support condition	**Minimum h**
Simply supported	$l/20$
One end continuous	$l/24$
Both ends continuous	$l/28$
Cantilever	$l/10$

Minimum depth of beam (ACI Table 9.3.1.1)	
Support condition	**Minimum h**
Simply supported	$l/16$
One end continuous	$l/18.5$
Both ends continuous	$l/21$
Cantilever	$l/8$

- l = center-to-center length(already defined)
- for f_y other than 60,000 psi, the expressions in Table 7.3.1.1 and 9.3.1.1 shall be multiplied by (0.4 + f_y /100,000)

Part – II

Cracking in RC Frames

Introduction

- **Crack Formation**

  - All RC beams crack, generally starting at loads well below service level, and possibly even prior to loading due to restrained shrinkage.

  - In a well-designed beam, flexural cracks are fine, so-called hairline cracks, almost invisible to a casual observer, and they permit little if any corrosion to the reinforcement.

Introduction

- **Crack Formation (ACI 24.3.2.1)**

  - As loads are gradually increased above the cracking load, both the number and width of cracks increase.

  - If loads are further increased, crack widths increase further, although the number of cracks do not increase substantially.

  - The limiting value of crack width both for interior and exterior exposures is taken as 0.016 inch (0.4mm).

ACI Code Provisions for Crack Control

- **Approaches**

  - There are two approaches of controlling crack in reinforced concrete members.

  1. **Direct Approach**

     - Expected crack width is calculated and is compared with the maximum permissible limit provided by the code.

  2. **Indirect Approach**

     - Cracking in RC member can be controlled by imposing limit on the maximum bar spacing.

  - Here the indirect approach will be discussed.

ACI Code Provisions for Crack Control

- **Indirect Approach**

  - The maximum center-to-center spacing between the adjacent bars shall not exceed the limits in Table 24.3.2.

  - For deformed bars or wires, maximum spacing s_{max} is given by;

$$s_{max} = Least\ of\ \ 15\left(\frac{40{,}000}{f_s}\right) - 2.5C_c \ \ \ and \ \ 12\left(\frac{40{,}000}{f_s}\right)$$

  Where;

  f_s = the bar stress in ksi under service condition.

  C_c = the clear cover in inches from the nearest surface in tension to the surface of the flexural tension reinforcement.

ACI Code Provisions for Crack Control

- **Indirect Approach**

  - As per ACI 318-19, Section 24.3.2.1, stress f_s in deformed reinforcement closest to the tension face at service loads shall be calculated based on the unfactored moment, or it shall be permitted to take f_s as $(2/3)f_y$.

  - Hence by putting the value of f_s in previous equations, we get

  $$s_{max} = Least\ of\ \ \frac{900}{f_y} - 2.5C_c\ \ and\ \ \frac{720}{f_y}\ \ \ \ (where\ f_y\ is\ in\ ksi\ )$$
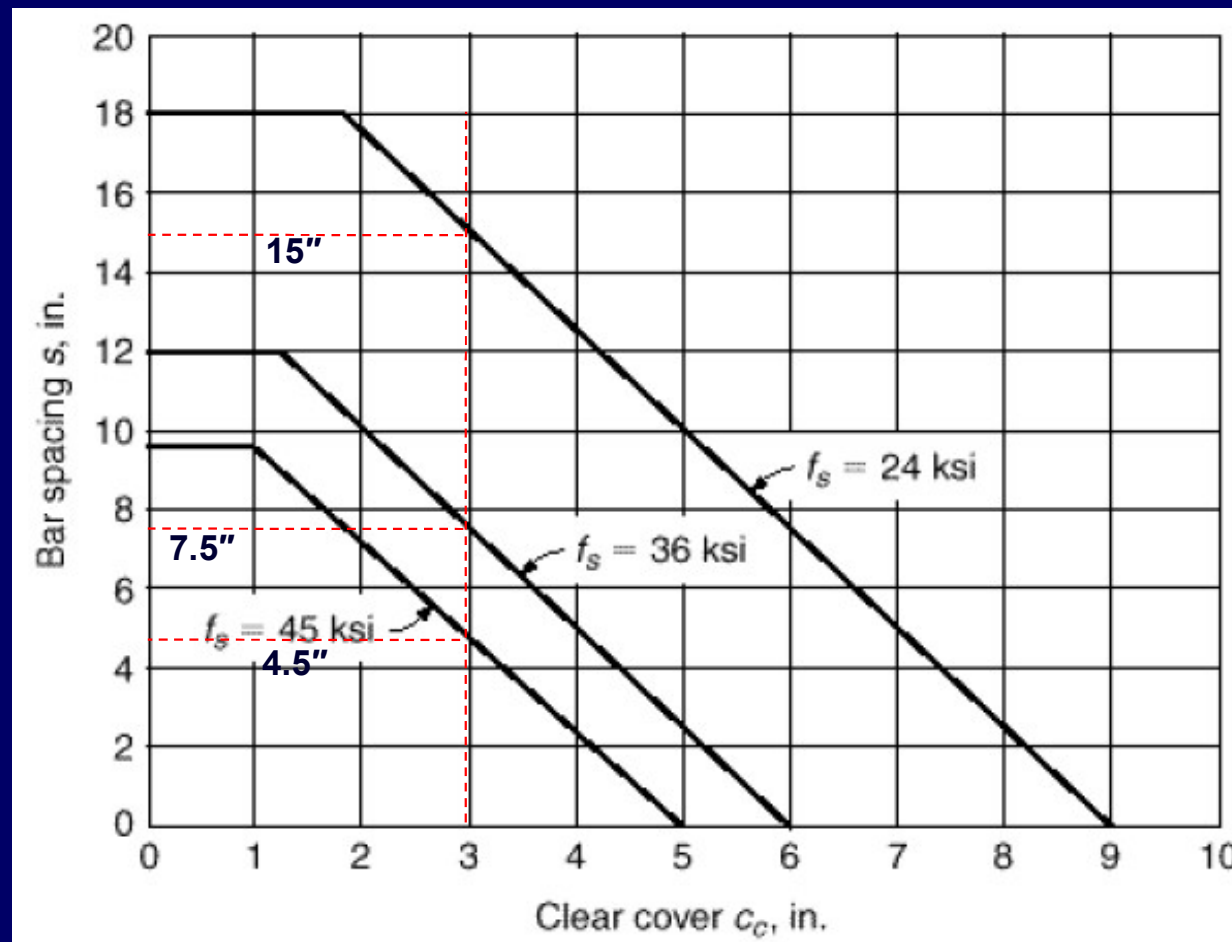
  - Note that the condition $f_s = (2/3)f_y$ is for full service-load condition. For loading less than that, f_s shall be calculated.

ACI Code Provisions for Crack Control

- **Indirect Approach**

  - A useful plot of bar spacing vs concrete cover is provided below.

References

- Design of Concrete Structures 14th / 15th edition by Nilson, Darwin and Dolan.

- Building Code Requirements for Structural Concrete (ACI 318-19)