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Bridge Design - Concrete Design Theory

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Module 1: Concrete Design Theory

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the fundamental limit states and structural material requirements for concrete bridge design according to AASHTO LRFD and California Amendments.
- **Calculate** the factored flexural and shear resistance of reinforced and prestressed concrete components using unified design provisions.
- **Evaluate** reinforcement limits for flexural, shear, and compression members to ensure adequate ductility and strength.

Executive Summary: Modern California bridge design relies on a unified Load and Resistance Factor Design (LRFD) approach for both reinforced and prestressed concrete, accounting for approximately 90% of the state's highway structures. This methodology prioritizes limit state design—specifically Service, Strength, Extreme Event, and Fatigue—incorporating rational models such as Modified Compression Field Theory for shear and strain-compatibility for flexure to ensure structural integrity and durability.

Introduction

Concrete's dominance in California highway structures is due to its versatility in shape, cost-effectiveness, durability, and fire resistance. Design standards have transitioned from Allowable Stress Design (ASD) to the current **AASHTO LRFD Bridge Design Specifications**.

Key advancements in current practice include:

- **Unified design provisions** for both reinforced and prestressed concrete.
- **Modified Compression Field Theory (MCFT)** for shear and torsion analysis.
- **Strut and Tie modeling** for disturbed regions and deep beams.
- **Revised techniques** for estimating prestress losses and end zone analysis.

Structural Materials

Concrete Fundamentals

Compressive strength f'_c is the primary design property.

- **Conventionally Reinforced:** Typically uses $f'_c = 3.6$ ksi.
- **Prestressed Concrete:** Requires a minimum $f'_c = 4.0$ ksi per AASHTO, with California specifying a minimum of 3.6 ksi.

Reinforcing Steel

Main reinforcing bars in California must be **deformed**.

- **Standard:** ASTM A 706/A 706M low-alloy steel (Grade 60).
- **Minor Structures:** ASTM A 615/A 615M (Grade 40 or 60) may be used where specified.
- **Plain Bars:** Reserved for spirals or hoops.

Prestressing Steel

Caltrans designs utilize high-tensile strength steel, specifically **low-relaxation strands** (0.5 in. or 0.6 in. diameter) conforming to ASTM A 416 Grade 270. High-strength bars (ASTM A 722 Type II) are also utilized.

Design Limit States

Components must satisfy four primary limit state groups:

Limit State	Focus Areas	Specific Load Combinations
Service	Stresses, deformations, cracking, and deflection.	Service I, III, and IV.
Strength	Axial, flexural, shear strength, and stability.	Strength I (HL-93) through Strength V.
Extreme Event	Earthquake and collision forces.	Loads are not considered simultaneously.
Fatigue	Reinforcement stress ranges.	Not required for fully prestressed members or deck slabs on multi-girder bridges.

Flexure Design

Strength Limit States: Design Requirement

Equation 1.4-1:

$$M_u \leq \phi M_n = M_r$$

Where:

- **M_u** = Factored moment at the section (kip-in.)
- **M_n** = Nominal flexural resistance (kip-in.)
- **ϕ** = Resistance reduction factor
- **M_r** = Factored flexural resistance (kip-in.)

Section Behavior Categories

LRFD distinguishes sections based on the **Net Tensile Strain (NTS)** in the extreme tension steel:

- **Compression-Controlled:** $NTS \leq 0.002$. These sections behave like columns and require ties/spirals. $\phi = 0.75$.
- **Tension-Controlled:** $NTS \geq 0.005$. ϕ is 1.0 (precast prestressed), 0.95 (CIP prestressed), or 0.90 (non-prestressed).
- **Transition Region:** $0.002 < NTS < 0.005$. ϕ is determined via linear interpolation.

⚠ **Safety Constraint:** Caltrans Amendments require that reinforced concrete sections in flexure be designed for $NTS \geq 0.004$ to ensure the section does not fail in a brittle compression-controlled mode.

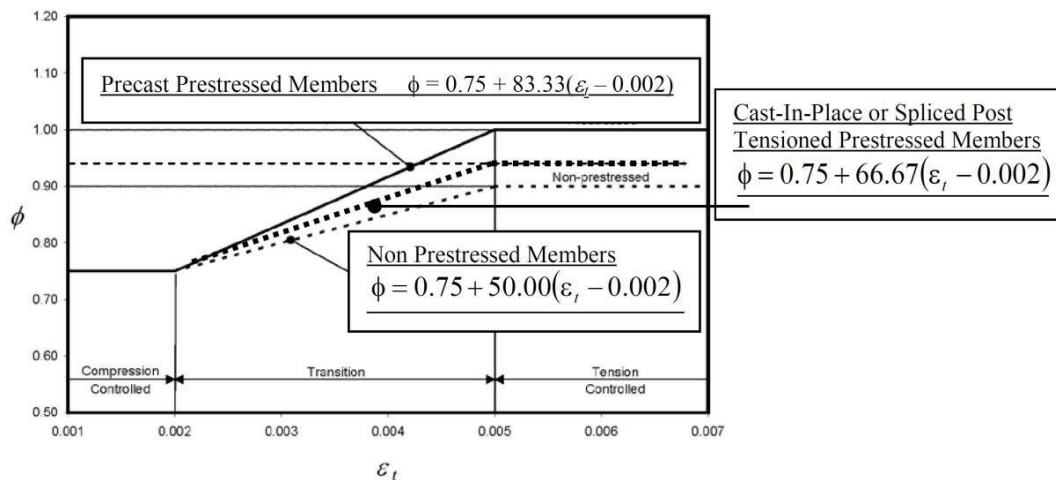


Figure 1.4-1: Resistance Factor Variation for Grade 60 Reinforcement and Prestressing Steel

Nominal Flexural Resistance

Standard assumptions include plane sections remaining plane, concrete tensile strength being neglected, and a maximum usable strain of **0.003** for unconfined concrete.

Equivalent Stress Block: An equivalent rectangular stress block of $0.85 \times f'_c$ is used.

- $a = \beta_1 c$
- $0.65 \leq \beta_1 = 1.05 - 0.05f'_c \leq 0.85$

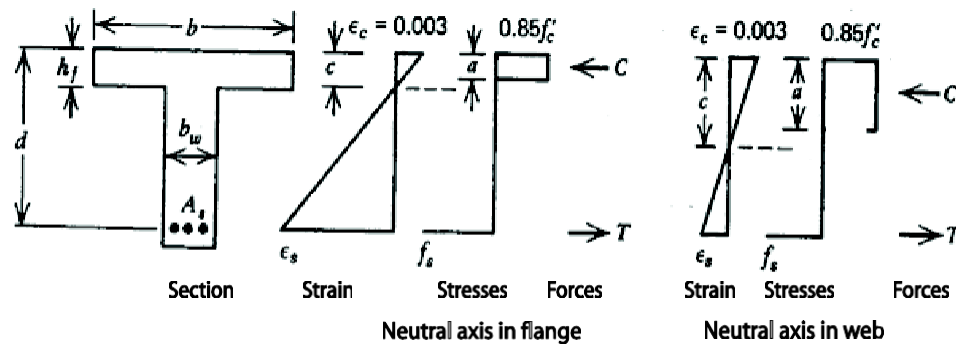


Figure 1.4-2: Stress and Strain Distribution of T-Beam Section in Flexure (shown with mild reinforcement only)

Equation 1.4-2 (Nominal Resistance for Flanged Sections):

$$M_n = A_{ps}f_{ps} \left(d_p - \frac{a}{2} \right) + A_s f_s \left(d_s - \frac{a}{2} \right) - A'_s f'_s \left(d'_s - \frac{a}{2} \right) + 0.85 f'_c (b - b_w) h_f \left(\frac{a}{2} - \frac{h_f}{2} \right)$$

Where:

- **A_{ps}, A_s, A'_s** = Areas of prestressing, tensile mild, and compressive mild steel (in.²)
- **f_{ps}, f_s, f'_s** = Stress in prestressing, tensile mild, and compressive mild steel (ksi)
- **d_p, d_s, d'_s** = Distance from compression face to centroid of respective steel (in.)
- **b, b_w** = Compression face width and web width (in.)
- **h_f** = Flange thickness (in.)

Service Limit States: Stress and Cracking

Elastic behavior is assumed for stress and deflection checks. For normal weight concrete ($w_c = 0.145$ kcf):

Equation 1.4-3 (Modulus of Elasticity):

$$E_c = 1,820 \cdot (f'_c)^{0.5}$$

Where:

- **E_c** = Modulus of elasticity (ksi)
- **f'_c** = Specified compressive strength (ksi)

Table 1.4-1 Stress Limits for Concrete

Condition	Stress	Location	Allowable Stress
Temporary Stress before loss	Tensile	In area other than Precompressed Tensile Zone and without bonded tendons or reinforcement In area with bonded tendons or reinforcement sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5f_y$, not to exceed 30 ksi	$0.0948 \sqrt{f'_{ci}} \leq 0.2$ (ksi) $0.24 \sqrt{f'_{ci}}$ (ksi)
	Compression	All locations	$0.6 f'_c$
Final Stress after loss at service load	Tensile	In the Precompressed Tensile Zone, assuming uncracked section: <ul style="list-style-type: none"> • Components with bonded tendons or reinforcement, and/or are located in Caltrans' Environment Areas I and II • Components with bonded tendons or reinforcement, and/or are located in Caltrans' Environment Area III • Components with unbonded tendons 	$0.19 \sqrt{f'_c}$ (ksi) $0.0948 \sqrt{f'_c}$ (ksi) 0
	Compression	All locations due to: <ul style="list-style-type: none"> • Permanent loads and effective prestress loads • All load combinations 	$0.45 f'_c$ $0.6 f'_c$
Permanent loads only	Tensile	Precompressed Tensile Zone with bonded prestressing tendons or reinforcement	0

Shear Design

Sectional Method vs. Strut and Tie

- **Sectional Method:** Based on MCFT; applicable to undisturbed regions where plane sections remain plane.
- **Strut and Tie Method:** Required for "disturbed regions" (e.g., bent caps with span/depth < 4, pile caps, anchorage zones).



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