ANALYSIS AND DESIGN OF REINFORCED AND PRESTRESSED-CONCRETE GUIDEWAY STRUCTURES

Reported by ACI Committee 358

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These recommendations, prepared by Committee 358, present a procedure for the design and analysis of reinforced and prestressed-concrete guideway structures for public transit. The document is specifically prepared to provide design guidance for elevated transit guideways. For items not covered in this document the engineer is referred to the appropriate highway and railway bridge design codes.

Limit states philosophy has been applied to develop the design criteria. A reliability approach was used in deriving load and resistance factors and in defining load combinations. A target reliability index of 4.0 and a service life of 75 years were taken as the basis for safety analysis. The reliability index is higher than the value generally used for highway bridges, in order to provide a lower probability of failure due to the higher consequences of failure of a guideway structure in a public tramit system The 75 year service life is comparable with that adopted by AASHTO for their updated highway bridge design specifications.

KEYWORDS: Box beams; concrete construction; cracking (fracturing); deformation; fatigue (materials); guideways; loads (forces); monorail systems: partial prestressing; precast concrete; prestressed concrete: prestress loss; rapid transit systems; reinforced concrete; serviceablity; shear properties: structural analysis; structural design: T-beams; torsion; vibration.

CONTENTS

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CHAPTER 1 - SCOPE, DEFINITIONS AND NOTATIONS

1.1- Scope

These recommendations are intended to provide public agencies, consultants, and other interested personnel with comprehensive criteria for the design and analysis of concrete guideways for public transit systems. They differ from those given for bridge design in ACI 343R, AASHTO bridge specifications, and the AREA manual of standard practice.

The design criteria specifically recognize the unique features of concrete transit guideways, namely, guideway/vehicle interaction, rail/structure interaction, special fatigue requirements, and esthetic requirements in urban areas. The criteria are based on current state-of-the-art practice for moderate-speed [up to 100 mph (160 km/h)] vehicles. The application of these criteria for advanced technologies other than those discussed in this report, require an independent assessment.

ACI 343R is referenced for specific items not covered in these recommendations. These references include materials, construction considerations, and segmental construction.

1.2-Definitions

The following terms are defined for general use in this document. For a comprehensive list of terms generally used in the design and analysis of concrete structures, the reader is referred to Chapter 2 of ACI 318 and to ACI 116R. The terminology used in this document conforms with these references.

Broken rail - The fracture of a continuously welded rail.

Concrete, specified compressive strength of f'_c — Compressive strength of concrete used in design and evaluated in accordance with Chapter 5 of ACI 318 is expressed in pounds per square inch (psi) [Megapascals (MPa)]; wherever this quantity is under a radical sign, the square root of the numerical value only is intended and the resultant is in pounds per squa

Concrete-A mixture of portland cement or any other hydraulic cement, fine aggregate, coarse aggregate, and water, with or without admixtures.

Continuously welded rail - Running rails that act as a continuous structural element as a result of full penetration welding of individual lengths of rail; continuously welded rails may be directly fastened to the guideway, in which case their combined load effects must be included in the design.

Dead load -The dead weight supported by a member, as defined in Chapter 3, without load factors.

Design load-All applicable loads and forces and their load effects such as, moments and shears used to proportion members; for design according to Chapter 5, design load refers to load without load factors; for design according to Chapter 6, design load refers to loads multiplied by appropriate load factors, as given in Chapter 4.

Flexural natural frequency- The first vertical frequency of vibration of an unloaded guideway, based on the flexural stiffness and mass distribution of the superstructure.

Live load-The specified live load, without load factors.

Load factor-A factor by which the service load is multiplied to obtain the design load.

Service load-The specified live and dead loads, without load factors.

Standard vehicle-The maximum weight of the vehicle used for design; the standard vehicle weight should allow for the maximum number of seated and standing passengers and should allow for any projected vehicle weight increases if larger vehicles or trains are contemplated for future use.

1.3 - Notation

a = center-to-center distance of shorter dimension of closed rectangular stirrups, in. (mm). Section 5.5.3

a_1 = side dimension of a square post-tensioning anchor, or lesser dimension of a rectangular post-tensioning anchor, or side dimension of a square equivalent in area to a circular post-tensioning anchor, in. (mm). Section 5.8.2.1

e center-lines

of anchors, or twice the distance from the centerline of the anchor to the nearest edge of concrete, whichever is less, in. (mm). Section 5.8.2.1

A = effective tension area of concrete surrounding the main tension reinforcing bars and having the same centroid as that reinforcement, divided by the number of bars, in.^{2} (mm^2); when the main reinforcement consists of several bar sizes, the number of bars should be computed as the total steel area divided by the area of the largest bar used. Section 5.8.1

A = exposed area of a pier perpendicular to the direction of stream flow, ft^2 (m^2). Section 3.3.4

A_{bs} = area of nonprestressed reinforcement located perpendicular to a potential bursting crack, in.^{2} (mm^2). Section 5.8.2.1

A_{oh} = Area enclosed by the centerline of closed transverse torsion reinforcement, in.^{2} (mm^2). Section 5.5.3

A_r = Cross-sectional area of a rail, in.^{2} (mm^2).

A_s' = Area of compression reinforcement, in.^{2} (mm^2).

A_t = Area of one leg of a closed stirrup resisting torsion within a distance, in.^{2} (mm^2).

A_v = Area of shear reinforcement within a distance, or area of shear reinforcement perpendicular to main reinforcement within a distance for deep beams, in.^{2} (mm^2).

b = Width of compressive face of member, in. (mm).

= Center-to-center distance of longer dimension of closed rectangular stirrup, in. (mm). Section 5.5.3

b_b = Width of concrete in the plane of a potential bursting crack, in. (mm). Section 5.8.2

BR = Broken rail forces.

C_d = Horizontal wind drag coefficient.

C_D = Flowing water drag coefficient.

C_e = Wind exposure coefficient.

C_g = Wind gust effect coefficient.

CF = Centrifugal force, kip (kN).

CL = Collision load, kip (kN).

CR = Forces due to creep in concrete, kip (kN).

d = Distance from extreme compressive fiber to centroid of tension reinforcement, in. (mm).

d_c = Thickness of concrete cover measured from the extreme tensile fiber to the center of the bar located closest thereto, in. (mm).

D = Dead load.

DR = Transit vehicle mishap load, due to vehicle derailment, kip (kN).

e = Base of Napierian logarithms.

E_c = Modulus of elasticity of concrete, psi (Pa). Section 5.6.3

E_{ci} = Modulus of elasticity of concrete at transfer of stress, psi (MPa).

E_s = Modulus of elasticity of reinforcement, psi (MPa)

EI = Flexural stiffness of compression members, k-in^2 (kN-mm^2).

EQ = Earthquake force.

E_r = Modulus of elasticity of rail, psi (MPa).

f_{bs} = Bursting stress behind a post-tensioning anchor, ksi (MPa).

f_c = Extreme fiber compressive stress in concrete at service loads, psi (MPa).

f_c' = Specified compressive strength of concrete at 28 days, psi (MPa).

f_{ci}' = Compressive strength of concrete at time of initial prestress, psi (MPa).

f_{cr} = Cracking stress of concrete, psi (MPa).

f_{cri} = Cracking stress of concrete at the time of initial prestress, psi (MPa).

$\sqrt{f_c'}$ = Square root of specified compressive strength of concrete, psi (MPa).

f_{fr} = Stress range in straight flexural reinforcing steel, ksi (MPa).

f_m = Algebraic minimum stress level, tension positive, compression negative, ksi (MPa).

f_{pu} = Ultimate strength of prestressing steel, psi (MPa).

f_{py} = Specified yield strength of prestressing tendons, psi (MPa).

f_r = Axial stress in the continuously welded rail, ksi (MPa). Section 3.4.3

f_s = Tensile stress in reinforcement at service loads, psi (MPa).

f_{sr} = Stress range in shear reinforcement or in welded reinforcing bars, ksi (MPa).

f_{st} = Change in stress in torsion reinforcing due to fatigue loadings, ksi (MPa).

f_{sv} = Change in stress in shear reinforcing due to fatigue loadings, ksi (MPa).

f_y = Specified yield stress, or design yield stress of non-prestressed reinforcement, psi (MPa).

f_1 = Flexural (natural) frequency, Hz.

F_{bs} = Total bursting force behind a post-tensioning anchor, kip (kN).

F_h = Horizontal design pressure due to wind, psi (Pa).

F_r = Axial force in the continuously welded rail, kip (kN).

F_{sj} = Jacking force in a post-tensioning tendon, kip (kN).

F_v = Vertical design pressure due to wind, psi (Pa).

F_R = Radial force per unit length due to curvature of continuously welded rail, k/in (Pa/mm).

g = Acceleration due to gravity = 32.2 ft/sec^2 (9.807 m/sec^2).
h = Overall thickness of member, in. (mm).
h_f = Compression flange thickness of I-and T-sections, in. (mm).
H = Ambient relative humidity. Section 3.4.4
H = Height from ground level to the top of the superstructure. Section 3.3.2
HF = Hunting force.
I = Impact factor.
ICE = Ice pressure.
I_{cr} = Moment of inertia of cracked section transformed to concrete, in.^{4} (m^4).
I_e = Effective moment of inertia for computation of deflections, neglecting the reinforcement, in.^{4} (m^4). Chapter 5
I_g = Moment of inertia of the gross concrete section about its centroidal axis neglecting reinforcement, in.^{4} (m^4).
jd = Distance between tensile and compression forces at a section based on an elastic analysis, in. (mm).
k_r = Average creep ratio.
k_t = $k_,$, as a function of time t.
k_v = A function of r_v for creep and shrinkage strains.
ℓ = Span length, ft (m).
L = Live load.
LF = Longitudinal force.
LF_e = Emergency longitudinal braking force.
LF_n = Normal longitudinal braking force.
M = Mass per unit length, lb/in.-se&in. (kg/m).
M_a = Maximum moment in member at stage for which deflection is being computed, lb-in. (N-mm).
M_{cr} = Cracking moment, lb-m (N-mm).
PS = Forces and effects due to prestressing.
q = Dynamic wind pressure, psf (MPa). Chapter 3.
r_v = Volume-to-surface-area ratio, (volume per unit length of a concrete section divided by the area in contact with freely moving air), in. (mm).
r/h = Ratio of base radius to height of transverse deformations of reinforcing bars; when actual value is not known, use 0.3.
R = Radius of curvature, ft (m). Chapter 3
s = Shear or torsion reinforcement spacing in a direction parallel to the longitudinal reinforcement, in. (mm).
s = Spacing of reinforcement, in. (mm), Section 5.8.2
S = Service load combinations. Chapters 4 and 5.
SF = Stream flow load, lb (N). Chapter 3.
SH = Forces due to shrinkage in concrete.
t = Time, days.
T = Loads due to temperature or thermal gradient in the structure exclusive of rail forces. Chapter 4.
T = Time-dependent factor for sustained load. Section 5.7.2
ΔT = Change in torsion at section due to fatigue loadings. Section 5.5.3
T_0 = Stress-free temperature of rail.
T_1 = Final temperature in the continuously welded rail.
U = Ultimate load combinations.
ΔV = Change in shear at section due to fatigue loadings, kip (kN). Section 5.5.3.
V = Velocity of water, wind, or vehicle, ft/sec (m/sec). Chapter 3.
VCF = Vehicle crossing frequency, Hz. Section 3.3.1.
w_c = Unit weight of concrete, lb/ft^3 (kg/m^3).
W = Wind load. Chapter 3.
WL = Wind load on live load. Chapters 3 and 4.
WS = Wind load on structure. Chapters 3 and 4.
x_m = Location of maximum bursting stress, measured from the loaded face of the end block, in. (mm).
y_t = Distance from the centroidal axis of cross section, neglecting the reinforcement, to the extreme fiber in tension, in. (mm).
z = A quantity limiting distribution of flexural reinforcement.
α = Coefficient of thermal expansion. Chapter 3.
γ = Mass density of water, lb/ft^3 (kg/m^3).
ϵ_i = Initial elastic strain.
ϵ_{cr} = Concrete creep strain at time t.
ϵ_{sh} = Concrete shrinkage strain at time t.
ϵ_{shu} = Concrete shrinkage strain at $t = \infty$.
θ = Angle in degrees between the wind force and a line normal to the guideway centerline.
λ = Multiplier for additional long-time deflection as defined in Section 5.7.2.
ρ = Density of air in Section 3.3.2
ρ_{bs} = Ratio of nonprestressed reinforcement located perpendicular to a potential bursting crack in Section 5.8.2.
ρ' = Compression reinforcement ratio = A_s'/bd.
ϕ = Strength reduction factor.
ψ = A parameter used to evaluate end block stresses. Section 5.8.2.1.

1.4- SI Equivalents

The equations contained in the following chapters are all written in the U.S. inch-pound system of measurements. In most cases, the equivalent SI (metric) equation is also given; however, some equations do not have definitive SI