Tentative Recommendations for Prestressed Concrete*

Reported by ACI-ASCE Joint Committee 323

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This report was submitted to letter ballot of the committee which consists of 33 members; 32 members returned their ballots, of whom 32 have voted affirmatively.

†These members constitute executive group of committee.

‡Deceased: served as committee chairman from 1949 until 1955.

SYNOPSIS

A guide to design and construction of safe, serviceable, linear structural members prestressed with high strength steel. Emphasis is on flexural members —beams, girders, and slabs. Most of the recommendations are applicable to both buildings and bridges. Design chapter treats: loading; allowable stress; prestress loss; flexure and shear; bond and anchorage; composite construction; continuity; end blocks; fire resistance; and cover and spacing of prestressing steel. Concrete, grout, prestressing steel, anchorages, and splices are covered in the section on materials. Construction section includes: transportation, placing, and curing of concrete; forms, shoring, and falsework; placement of prestressing steel and application of the prestressing force; grouting; and handling and erection.

CONTENTS

CHAPTER 1—INTRODUCTION

101—OBJECTIVE

The objective of this report is to recommend those practices in design and construction which will result in prestressed concrete structures that are comparable both in safety and in serviceability to constructions in other materials now commonly used.

This report constitutes a recommended practice, not a building code or specification. Since it was not written as a code, its use or interpretation as one will not serve the best interests of either the public or the engineering profession. Recommendations contained in the report are presented solely for the guidance and information of professional engineers. Safety and economy of structures in prestressed concrete will depend as much on the intelligence and integrity of engineers preparing the design and supervising or carrying out the construction as on the degree to which these recommendations are followed.

102—SCOPE

102.1—Linear prestressing

This report is confined in scope to linear structural members involving prestressing with high strength steel; circularly prestressed members such as tanks or pipes are not covered. These types of construction have been excluded for two reasons. They have been designed and constructed in this country for a great number of years and procedures have been developed on the basis of research and experience which have proved successful in practice. Design and construction of tanks and pipes in prestressed concrete are confined to a relatively small group of specialists and are not likely to be attempted by persons outside that group. For these reasons there seems to be no immediate need for recommendations regarding circularly prestressed structures.

102.2—Flexural members

For the most part, recommendations in this report relate to flexural members—beams, girders, and slabs. Other structural forms, such as columns, ties, arches, shells, trusses, pavements, etc., are treated only briefly or not at all. In some of these cases, such as columns or ties, the principles involved in design are essentially simple and no need was felt to include them in this report. In other cases, insufficient information was available either from research or experience to permit recommendations to be made at this time. This lack of information is due in some instances to the complexity of the type of structure involved and in others to the infrequency of its use in this country.

102.3—Buildings and bridges

These recommendations are intended to apply to both buildings and bridges. The form and nature of this report are such that almost all recommendations made apply without differentiation to both types of structures. Where this is not the case, separate recommendations are made for buildings and bridges.

103—ACCEPTANCE TESTS

It is recognized by the committee that unusual types of construction, design, or materials may be used in such a manner that these recommendations are not applicable or may not have been complied with. Such structures may be adequate for the purpose intended. In these cases it is recommended that tests be made to verify design.

104—NOTATION

104.1—General

Symbols are assembled into sections pertaining to groups of associated terms. The list comprises only the symbols in this report. No attempt is made to present a complete notation for design of prestressed concrete.

104.2—Dimensions and cross-sectional constants

A_b = bearing area of anchor plate of post-tensioning steel

A_c = maximum area of the portion of the anchorage surface that is geometrically similar to and concentric with the area of the bearing plate of post-tensioning steel

A_s = area of main prestressing tensile steel

A_s' = area of conventional tensile steel

A_{sf} = steel area required to develop the ultimate compressive strength of the overhanging portions of the flange

A_{sr} = steel area required to develop the ultimate compressive strength of the web of a flanged section

A_v = area of web reinforcement placed perpendicular to the axis of the member

b = width of flange of a flanged member or width of a rectangular member

b' = width of web of a flanged member

d = distance from extreme compressive fiber to centroid of the prestressing force

I = moment of inertia about the centroid of the cross section

j = ratio of distance between centroid of compression and centroid of tension to the depth d

p = A_s/bd; ratio of prestressing steel

p' = ratio of conventional reinforcement

pf_s'/f_c' = percentage index

s = longitudinal spacing of web reinforcement

t = average thickness of the flange of a flanged member

Q = statical moment of cross section area, above or below the level being investigated for shear, about the centroid

104.3—Loads

D = effect of dead load

L = effect of design live load including impact, where applicable

W = effect of wind load, or earthquake load, or traction forces

V_c = shear carried by concrete

104.4—Stresses and strains

E_c = flexural modulus of elasticity of concrete

E_s = modulus of elasticity of prestressing steel

f_c' = compressive strength of concrete at 28 days

f'_{ci} = compressive strength of concrete at time of initial prestress

f_{cp} = permissible compressive concrete stress on bearing area under anchor plate of post-tensioning steel

f_s' = ultimate strength of prestressing steel

f_{se} = effective steel prestress after losses

f_{si} = initial stress in prestressing steel after seating of the anchorage

f_{su} = stress in prestressing steel at ultimate load

f_{sy} = nominal yield point stress of prestressing steel

f_t' = flexural tensile strength of concrete; modulus of rupture

f_y' = yield point stress of conventional reinforcing steel

k_2 = ratio of distance between extreme compressive fiber and center of compression to depth to neutral axis

k_1k_3 = ratio of average compressive concrete stress to cylinder strength, f_c'

n = ratio of E_s/E_c

u_d = strain in concrete due to creep

u_e = strain in concrete due to elastic shortening

u_s = strain in concrete due to shrinkage

v = shearing stress

δ_1 = ratio of loss in steel stress due to relaxation of prestressing steel

δ_2 = ratio of loss in steel stress due to friction during prestressing

104.5—Friction during prestressing

e = base of Naperian logarithms
K = friction wobble coefficient per ft of prestressing steel
T_o = steel stress at jacking end
T_x = steel stress at any point x
μ = friction curvature coefficient
α = total angular change of prestressing steel profile in radians from jacking end to point x
L = length of prestressing steel element from jacking end to point x

CHAPTER 2—DESIGN

201—GENERAL CONSIDERATIONS

201.1—Purpose

The purpose of design is to define a structure that can be constructed economically, that will perform satisfactorily under service conditions, and will have an adequate ultimate load capacity.

201.2—Mode of failure

Ultimate strength should be governed preferably by elongation of the prestressing steel rather than by shear, bond, or concrete compression.

201.3—Design theory

The elastic theory should be used at design loads with internal stresses limited to recommended values. The ultimate strength theory also should be applied to insure that ultimate capacity provides the recommended load factors.

202—SPECIAL CONSIDERATIONS

202.1—Loading conditions

Consideration should be given to all critical loading conditions in design including those that occur during fabrication, handling, transportation, erection, and construction.

202.2—Deflections

Camber and deflection may be design limitations and should be investigated for both short and long time effects.

202.3—Length changes

Length changes of concrete due to prestress and other causes should be investigated for both short and long time effects.

202.4—Reversal of loading effects

Where reversal of moment or shear may occur it should be considered in the design.

202.5—Buckling

General buckling due to prestressing can occur only over the length between points of contact of the prestressing steel with the concrete.

General buckling of an entire member or local buckling of thin webs and flanges under external loads may occur in prestressed concrete as in members made of other materials and should be provided for in design.

203—ASSUMPTIONS

203.1—Basic assumptions

The following assumptions may be made for design purposes:

a. Strains vary linearly over the depth of the member throughout the entire load range.
b. Before cracking, stress is linearly proportional to strain.
c. After cracking, tension in the concrete is neglected.

203.2—Modulus of elasticity

When accurate values for modulus of elasticity are not available, the following values may be used as a guide:

a. Flexural modulus of elasticity of concrete E_c, in psi, may be assumed to be 1,800,000 plus 500 times the cylinder strength at the age considered. Actual values may vary as much as 25 percent from those given by the foregoing expression. This expression is not applicable to lightweight concrete, for which E_c should be determined by test.

b. Modulus of elasticity of steel, in psi, may be assumed to be 29,000,000 for cold drawn wire, 27,000,000 for 7-wire strand, 25,000,000 for strand with more than 7 wires, and 27,000,000 for alloy steel bars.

203.3—Deflections

Deflection or camber under short time loading may be computed using values of E_c obtained as described in Section 203.2.a.

Deflection associated with dead load, prestress, and live loads sustained for a long time may be computed on the assumption that the corresponding concrete strains are increased as a result of creep. The increase in strain may vary from 100 percent of the elastic strain in very humid atmosphere to 300 percent of the elastic strain in very dry atmosphere. These values may not pertain to concrete made with lightweight aggregates.

204—LOADING STAGES

204.1—Loading

Loading stages listed in the following sections should be investigated. No attempt is made to list all significant loading stages that may occur. Stages listed are those that normally affect the design.

204.2—Initial prestress

Prestressing forces are applied in prearranged sequence and sometimes in stages. If prestressing forces are not counteracted by the effect of the dead load of the member, or if the stressing operation is accompanied by temporary eccentricities, concrete stresses should be investigated.

204.3—Initial prestress plus dead load of member

For determination of concrete stresses at this stage, losses in prestress are those which occur during and immediately after transfer of prestress.

204.4—Transportation and erection

Support conditions for precast members during transportation and erection may differ from those during service loads. Handling stresses should be included together with prestress and dead load. Losses in initial prestress up to time of handling should be considered.

204.5—Design load

This stage includes stress due to effective prestress after losses, dead loads, and maximum specified live load.

204.6—Cracking load

Complete freedom from cracking may or may not be necessary at any particular loading stage. Type and function of the structure and type, frequency, and magnitude of live loads should be considered.

204.7—Temporary overload

This stage refers to any large live load in excess of design load, which is of short-time duration and expected to occur infrequently during life of structure. For such a load, stresses may exceed those recommended for design load but elastic recovery must be assured.

204.8—Ultimate load

Ultimate load is that load which applied statically in a single application causes failure. Such a large load would never intentionally be placed on the structure, but it is used as a measure of safety. In statically determinate structures, failure will occur at a single cross section. In statically indeterminate structures, the load which causes moment in one section to reach its ultimate value may not be sufficient to cause failure of the structure because of moment redistribution. Since it is not always possible to predict that full redistribution will take place in accordance with limit design, it is suggested for the time being that moments be determined by elastic analysis.

205—LOAD FACTORS

205.1—General

A load factor is a multiple of the design loads used to insure safety of the structure.

205.2—Cracking load factors

If cracking of concrete is undesirable, load factors for cracking load should be chosen to reflect the greatest load that can be expected during life of structure.

Formation of a crack under temporary overload may not be objectionable. If reopening such a crack under subsequent design load is objectionable it may be avoided by proper choice of concrete stress permitted for cracking load.

205.3—Ultimate load factors

The ultimate load capacity should be computed since stresses are not linearly proportional to external forces and moments throughout the entire load range. For the present, it is recommended that moments, shears, and thrusts produced by external loads and prestressing forces be investigated by elastic analysis.

The load factors recommended are believed to be consistent with current viewpoints. It may be desirable to modify or expand the load factor formulas to fit special conditions that may occur in unusual structures, extremely long spans, or for unique loadings. Deviations from the recommended values should be substantiated by suitable investigations.

205.3.1—*Buildings*

For the present, to correlate prestressed concrete with reinforced concrete practice in current use, the committee recommends that ultimate load capacity be investigated to insure meeting the following requirements:

$$
\begin{array}{ll}
 & 1.2\,D + 2.4\,L \\
\text{or} & 1.8\,(D + L) \\
\text{or} & 1.2\,D + 2.4\,L + 0.6\,W \\
\text{or} & 1.2\,D + 0.6\,L + 2.4\,W \\
\text{or} & 1.8\,(D + L + \tfrac{1}{2}\,W) \\
\text{or} & 1.8\,(D + \tfrac{1}{2}\,L + W)
\end{array}
$$

whichever is greater.

205.3.2—*Highway bridges*

The following load factors for highway bridges are recommended by a subgroup appointed by American Association of State Highway Officials, Committee on Bridges and Structures.*

$$1.5\,D + 2.5\,L$$

The committee is not prepared at this time to make recommendations for load factors involving the effect of lateral loads on bridges.

205.3.3—*Railway bridges*

Ultimate load factors for railway bridges are currently being studied by the American Railway Engineering Association. The committee is not prepared to recommend such factors at this time.

206—REPETITIVE LOADS

206.1—General

Ultimate strength of concrete or steel subjected to repetitive loading may be less than static strength because of the phenomenon of fatigue. Full importance of fatigue in prestressed concrete members has not yet been determined. Fatigue failure may occur in concrete, steel, anchorages, splices, or bond.

*These load factors are considered adequate for spans of moderate length, simply supported. For exceptionally long spans and for continuous members, special investigation to consider a possible increase in load factors is recommended.

206.2—Concrete

Fatigue strength of concrete in both tension and compression depends on magnitude of stress, range of stress variation, and number of loading cycles. Since high stresses and stress ranges are common, fatigue should be considered when repetition of loading cycles may occur.

Fatigue failure is unlikely if the allowable stresses of Section 207.3.2 are not exceeded and there is no reversal of stress. If a large number of overloads are anticipated a reduction in the safety factor may occur.

206.3—Prestressing steel

Fatigue strength of prestressing steel depends on magnitude and range of stress, and number of cycles of loading. Minimum stress is the effective prestress. Maximum stress and range of stress depend on magnitude of live loads or overloads that may be repeated. Range of stress under service loads will usually be small unless concrete is cracked. Cracking may occur if tension is permitted in concrete. Fatigue failure of steel should be considered in such cases, especially when a high percentage of ultimate strength is used for prestress.

Devices for splicing steel may contain strain concentrations that lower fatigue strength. Consideration should be given to fatigue whenever splices are used.

206.4—Anchorages

If steel is fully bonded, no difficulty should be expected in the anchorage or end bearing as the result of repetitive loads. With unbonded steel, fluctuations in stress due to repeated service loads or overloads are transmitted directly to anchorages and fatigue strength of the anchorage will require special consideration.

206.5—Bond

Failure of bond under repetitive loading is unlikely unless the member is cracked under design loads or a significant number of repetitions of overload. High bond stresses adjacent to cracks may be a source of progressive failure under repeated loads.

206.6—Shear and diagonal tension

Since inclined cracks may form under repetitive loading at appreciably smaller stresses than under static loading, web reinforcement should always be provided in members subjected to repetitive loading.

206.7—Design recommendations

Fatigue should not result in a reduction of strength if the following recommendations are observed. When the recommendations cannot be followed, fatigue strength of all elements comprising the prestressed member should be considered.

a. Flexural compressive concrete stress should not exceed $0.4f_c'$ under either design load or an overload that may be repeated many times.

b. Tension should not be permitted in concrete at the critical cross section under either design load or overloads that may be repeated a large number of times.

c. Reversal of stress should not occur under repeated loads.

d. Prestressing steel should be bonded.

e. Web reinforcement should be provided.

207—ALLOWABLE STEEL AND CONCRETE STRESSES

207.1—Prestressing steel

207.1.1—*Temporary stresses*

Under normal design loads stress in prestressing steel will almost always be less than stress at initial prestress. Stress at the anchorage immediately after seating has been effected should not exceed $0.70f_s'$ for material having stress-strain properties defined in Chapter 3. Overstressing for a short period of time to $0.80f_s'$ may be permitted provided the stress, after seating of anchorage occurs, does not exceed $0.70f_s'$.

207.1.2—*Stress at design loads*

Effective steel stress after losses described in Section 208 should not exceed:

$$0.60f_s' \text{ or } 0.80f_{sy}$$

whichever is smaller.

207.2—Non-prestressed reinforcement

Non-prestressed reinforcement provided to resist tension in conformance with requirements of Section 207.3.1.b.2 may be assumed stressed to 20,000 psi.

207.3—Concrete

207.3.1—*Temporary stresses*

Concrete stress in psi before losses due to creep and shrinkage should not exceed the following:

a. Compression
  For pretensioned members.................................. $0.60f'_{ci}$
  For post-tensioned members.................................. $0.55f'_{ci}$

b. Tension
  1. For members without non-prestressed reinforcement:
    Single element.................................. $3\sqrt{f'_{ci}}$
    Segmental element.................................. zero
  2. For members with non-prestressed reinforcement provided to resist the tensile force in the concrete, computed on the basis of an uncracked section:
    Single element.................................. $6\sqrt{f'_{ci}}$
    Segmental element.................................. $3\sqrt{f'_{ci}}$

207.3.2—*Stresses at design loads*

After full prestress losses, stresses in psi should not exceed the following:

a. Compression
   1. Single element
      a. Bridge members .... $0.40f_c'$
      b. Building members .... $0.45f_c'$
   2. Segmental elements
      a. Bridge members .... $0.40f_c'$
      b. Building members .... $0.45f_c'$

b. Flexural tension in the precompressed tensile zone
   1. Single element
      a. Bridge members .... zero
      b. Pretensioned building elements not exposed to weather or corrosive atmosphere .... $6\sqrt{f_c'}$
      c. Post-tensioned bonded elements not exposed to weather or corrosive atmosphere .... $3\sqrt{f_c'}$
   2. Segmental elements
      a. Bridge members .... zero
      b. Building members .... zero

Allowable flexural tension of $6\sqrt{f_c'}$ in Section 207.3.2.b.1.b may be exceeded provided it is shown by tests that the structure will behave properly under service conditions and meet any necessary requirement for cracking load or temporary overload.

207.3.3—*Stress at cracking load*

Flexural tensile strength (modulus of rupture) should preferably be determined by test. When test data are not available the ultimate flexural tensile stress in psi may be assumed as:

$$f_t' = 7.5\sqrt{f_c'}$$

For lightweight concrete, f_t' should be determined by tests.

207.3.4—*Anchorage bearing stresses*

The maximum allowable stress at post-tensioning anchorage in end blocks adequately reinforced in conformance with Section 214.4 may be assumed as:

$$f_{cp} = 0.6\,f'_{ci}\,\sqrt[3]{A_c/A_b}$$

where A_b = bearing area of the anchor plate.
A_c = maximum area of portion of the member that is geometrically similar to and concentric with the area of bearing plate.

The allowable value of f_{cp} should not exceed f'_{ci}.

208—LOSS OF PRESTRESS

208.1—Introduction

Initial prestress is that stress in steel which exists immediately after seating of anchorage. Stress diminishes with time and finally reaches a stable condition of effective prestress assumed to be permanent.

208.2—Sources of prestress loss

208.2.1—*Friction loss in post-tensioned steel*

If post-tensioned steel is draped, or irregularities exist in alignment of ducts, steel stress will be less within the member than at the jack because of friction between prestressing steel and duct. Magnitude of this friction should be estimated for design and verified during stressing operation.

Friction loss may be estimated from an analysis of forces exerted by prestressing steel on duct. One method for determination of friction loss at any point is given below.

$$T_o = T_x \, e^{(KL + \mu\alpha)}$$

where T_o = steel stress at jacking end

T_x = steel stress at point x

e = base of Naperian logarithms

K = friction wobble coefficient per ft of prestressing steel

L = length of prestressing steel element from jacking end to point x in ft

μ = friction curvature coefficient

α = total angular change of prestressing steel element in radians from jack to point x

For small values of KL and $\mu\alpha$ the following formula may be used:

$$T_o = T_x (1 + KL + \mu \, \alpha)$$

The following values of K and μ are typical and may be used as a guide. They may vary appreciably with duct material and method of construction. Values of K and μ used in design should be indicated on the plans for guidance in selection of materials and methods that will produce results approaching the assumed values.

Type of steel	Type of duct or sheath	Usual range of observed values		Suggested design values	
		K	μ	K	μ
Wire cables	Bright metal sheathing	0.0005-0.0030	0.15-0.35	0.0020	0.30
	Galvanized metal sheathing			0.0015	0.25
	Greased or asphalt-coated and wrapped	0.0030	0.25-0.35	0.0020	0.30
High strength bars	Bright metal sheathing	0.0001-0.0005	0.08-0.30	0.0003	0.20
	Galvanized metal sheathing			0.0002	0.15
Galvanized strand	Bright metal sheathing	0.0005-0.0020	0.15-0.30	0.0015	0.25
	Galvanized metal sheathing			0.0010	0.20

Workmanship in placing, supporting, tying, and fabricating prestressing elements and ducts influences the magnitude of wobble factor, K. The larger the sheath or duct in relation to the size of prestressing steel element, the smaller K will be. With normal placing tolerances wobble effect may be neglected if sheath is 1 in. greater in diameter than prestressing steel element.

Effect of overestimating friction loss should be considered since excessive prestress may cause undesirable permanent stress conditions. Underestimating friction loss may result in an error in computing cracking load and deflection.

208.2.2—*Elastic shortening of concrete*

Loss of prestress caused by elastic shortening of the concrete occurs in prestressed concrete members. This loss equals $n\,(\Delta f_c)$. For pretensioned concrete, Δf_c is the concrete stress at the center of gravity of the prestressing steel for which the losses are being computed. For post-tensioned concrete where the steel elements may not be tensioned simultaneously, Δf_c is the average concrete stress along one prestressing element from end to end of the beam caused by subsequent post-tensioning of adjacent elements.

208.2.3—*Shrinkage of concrete*

Shrinkage depends on many variables. Unit shrinkage strain may vary from near 0 to 0.0005. A value between 0.0002 and 0.0003 is commonly used for calculation of prestress loss. Shrinkage loss may be greater in pretensioned members where the prestress is transferred to the concrete at an earlier age than is usual for post-tensioned members. Shrinkage of lightweight concrete may be greater than the values obtained with the above factors.

208.2.4—*Creep of concrete*

Creep is the time-dependent strain of concrete caused by stress. For pretensioned and post-tensioned bonded members, concrete stress is taken at center of gravity of prestressing steel under effect of prestress and permanent loads (normal conditions of unloaded structure).

In post-tensioned unbonded members, stress is the average concrete stress along the profile of center of gravity of prestressing steel under the effect of prestress and permanent loads. Additional strain due to creep may be assumed to vary from 100 percent of elastic strain for concrete in very humid atmosphere to 300 percent of elastic strain in very dry atmosphere.

Creep of some lightweight concretes may be greater than indicated above.

208.2.5—*Relaxation of steel stress*

Loss of stress due to relaxation of prestressing steel should be provided for in design in accordance with test data furnished by the steel manufacturer. Loss due to relaxation depends primarily on properties of the steel and initial prestress. This loss is generally assumed in the range of 2 to 8 percent of initial steel stress.

208.3—Alternate procedures for estimating prestress losses

Two methods are suggested for estimating prestress losses. Method 1 should be used when individual losses may be predicted with reasonable accuracy. Method 2 applies when specific loss data are lacking.

The ultimate strength is not significantly affected by the magnitude of steel stress loss. An error in choosing the loss is reflected in the cracking load and amount of camber.

208.3.1—*Method 1*

The total stress loss in prestressing steel:

$$\Delta f_s = (u_s + u_e + u_d)\, E_s + \delta_1 f_{si} + \delta_2 f_{si}$$

208.3.2—*Method 2*

Loss in steel stress not including friction loss may be assumed as follows:

Pretensioning	35,000 psi
Post-tensioning	25,000 psi

For camber calculations these values may be excessive.

208.4—Lightweight concrete

Losses due to concrete shrinkage, elastic shortening, and creep should be based on results of tests made with the lightweight aggregate to be used.

209—FLEXURE

209.1—Stresses due to dead, live, and impact loads

Prestressed concrete members may be assumed to function as uncracked members subjected to combined axial and bending forces provided stresses do not exceed those given in Section 207.

In calculations of section properties prior to grouting, areas of the open ducts should be deducted unless relatively small. The transformed area of bonded reinforcement may be included in pretensioned members and post-tensioned members after grouting.

For calculation of stress due to prestress in T-beams no definite recommendations are made at this time, but attention should be given to the possibility that the entire available flange width may be included in calculation of section properties.

209.2—Ultimate flexural strength

209.2.1—*General method*

(a) *Rectangular sections*—For rectangular sections or flanged sections in which the neutral axis lies within the flange, ultimate flexural strength may be expressed as:

$$M_u = A_s f_{su}\, d \left(1 - \frac{k_2}{k_1 k_3} \frac{p f_{su}}{f_c'}\right) \qquad \text{(a)}$$

where f_{su} = average stress in prestressing reinforcement at ultimate load
d = depth to centroid of force
k_2 = ratio of distance between extreme compressive fiber and center of compression to the depth to neutral axis
k_1k_3 = ratio of average compressive concrete stress to the cylinder strength, f_c'

The results of numerous tests have shown that the factor k_2/k_1k_3 may be taken equal to 0.6 for members and materials considered in this report. Determination of the value of f_{su} requires knowledge of the stress-strain characteristics of the prestressing steel, effective prestress and crushing strain of the concrete. Assumptions must be made regarding the relation between steel and concrete strains. These assumptions will be different for bonded and unbonded construction.

The ultimate moment may be computed from Eq. (a) whenever sufficient information is available for the determination of f_{su}. The approximate method of Section 209.2.2 may be used if the required conditions are satisfied.

(b) *Flanged sections*—If a flange thickness is less than $1.4dpf_{su}/f_c'$, the neutral axis will usually fall outside the flange and the following approximate expression for ultimate moment should be used:

$$M_u = A_{sr}f_{su}\, d\left(1 - 0.6\frac{A_{sr}f_{su}}{b'df_c'}\right) + 0.85\, f_c'\, (b - b')t\, (d - 0.5t) \quad \text{(b)}$$

where $A_{sr} = A_s - A_{sf}$ = the steel area required to develop the ultimate compressive strength of the web of a flanged section

$A_{sf} = 0.85f_c'\,(b - b')t/f_{su}$ = steel area required to develop the ultimate compressive strength of the overhanging portions of the flange.

t = average thickness of flange

The expressions for f_{su} given in Section 209.2.2 may be used if the required conditions are satisfied.

209.2.2—*Approximate method*

The following approximate expressions for f_{su} may be used in Eq. (a) and (b) of Section 209.2.1 provided the following conditions are satisfied:

1. The stress-strain properties of the prestressing steel are reasonably similar to those described in Section 304.
2. The effective prestress after losses is not less than $0.5f_s'$.

(a) *Bonded members*

$$f_{su} = f_s'\left(1 - 0.5\frac{pf_s'}{f_c'}\right)$$

(b) *Unbonded members*—Ultimate flexural strength in unbonded members generally occurs at lower values of steel stress than in bonded members. Wide variations between stress levels reported by different investigators reflect the fact that several factors influence the stress developed by unbonded steel at ultimate moment. These factors include: magnitude of effective prestress, profile of the prestressing steel, shape of the bending moment diagram, length/depth ratio of the member, magnitude of the friction coefficient between the prestressing steel and duct, and amount of bonded non-prestressed supplementary steel.

Unless the proper value of f_{su} is known from tests of members closely approximating proposed construction with respect to the several factors listed in the preceding paragraph, it is recommended that:

$$f_{su} = f_{se} + 15{,}000$$

209.2.3—*Maximum steel percentage*

To avoid approaching the condition of over-reinforced beams for which the ultimate flexural strength becomes dependent on the concrete strength, the ratio of prestressing steel preferably should be such that pf_{su}/f_c' for rectangular sections, and $A_{sr}f_{su}/b'df_c'$ for flanged sections are not more than 0.30.

If a steel ratio in excess of this amount is used, the ultimate flexural moment shall be taken as not greater than the following values when either the general or approximate method of calculation is used.

(a) *Rectangular sections*

$$M_u = 0.25\, f_c'bd^2$$

(b) *Flanged sections*—If the flange thickness is less than 1.4 dpf_{su}/f_c' the neutral axis will usually fall outside the flange and the following formula is recommended.

$$M_u = 0.25bd^2f_c' + 0.85f_c'\,(b - b')t(d - 0.5t)$$

209.2.4—*Non-prestressed reinforcement in conjunction with prestressing steel*

209.2.4.1—*Conventional reinforcement*—Non-prestressed conventional reinforcement may be considered to contribute to the tensile force in the beam at ultimate moment an amount equal to its area times its yield point provided that

$$\frac{pf_{su}}{f_c'} + \frac{p'f_y'}{f_c'} \text{ does not exceed 0.3}$$

where f_y' = yield point of conventional reinforcement
p' = ratio of conventional reinforcement

209.2.4.2—*High tensile strength reinforcement*—If untensioned prestressing steel or other high tensile strength reinforcement is used in conjunction with prestressed reinforcement, the ultimate moment should be calculated by means of the general method of Section 209.2.1.

210—SHEAR

210.1—General

210.1.1—*Ultimate strength*

It is essential that shear failure should not occur before ultimate flexural strength required in Section 209.2 is developed. If this condition is satisfied, it is unnecessary to investigate shear or principal tensile stresses at design loads.

210.1.2—*Inclined cracking*

Formation of inclined cracks precedes failure in shear. They are caused by inclined principal tensile stresses that are the resultant of shearing stresses and normal bending stresses. Compressive prestress reduces the principal tensile stress thereby increasing the load necessary to cause inclined cracks. The use of thin webs will increase inclined stresses.

210.1.3—*Conditions for shear failure*

The resistance to formation of inclined cracks is greater with larger prestress and increasing web thickness. The significance of inclined cracks is less with low ultimate flexural strength caused by low ratio of reinforcement. Their significance is also less with low shear/moment ratios. If inclined cracks occur in an unreinforced web, sudden failure by shear is almost certain. If the web is adequately reinforced, ultimate flexural strength can be developed.

210.2—Web reinforcement

210.2.1—*Critical percentage of tensile steel*

Experimental data, although limited, indicate that inclined tension cracks will not form and web reinforcement will not be required if the following condition is satisfied:

$$\frac{pf_s'}{f_c'} \lesseqgtr 0.3\frac{f_{se}}{f_s'}\frac{b'}{b}$$

where b' = thickness of web; b = width of flange corresponding to that used in computing p

This expression may be conservative for members having span/depth ratios greater than about 15 or for uniformly loaded members. In such cases, web reinforcement may not be required even though the percentage index, pf_s'/f_c', exceeds that given in the above expression. The omission of web reinforcement in such members may be allowed when justified by tests.

210.2.2—*Design of web reinforcement*

The amount of web reinforcement necessary to develop required ultimate flexural capacity is a function of the difference between inclined cracking load and ultimate load in flexure. This difference varies rather widely as a function of prestress force, web thickness, amount of tensile reinforcement, and shear/moment ratio but is usually smaller for prestressed concrete than for conventional reinforced concrete. Current design procedures for web reinforcement in reinforced concrete are conservative for prestressed concrete.

Available test data indicate that the following expression for area of web reinforcement, with its factor of ½, will give reasonably conservative results for prestressed members of usual dimensions and properties. Since the formula does not involve the prestress force it may not be conservative for very low prestress or where only a portion of the reinforcement is stressed. For such cases it may be necessary to increase the factor of ½ as the member approaches the condition of conventionally reinforced concrete.

$$A_v = \frac{1}{2}\frac{(V_u - V_c)s}{f_y'jd}$$

where A_v = area of web reinforcement at spacing s, placed perpendicular to the axis of the member
V_u = shear due to specified ultimate load and effect of prestressing
V_c = $0.06f_c'\ b'\ jd$ but not more than $180\ b'\ jd$
s = longitudinal spacing of web reinforcement
f_y' = yield strength of web reinforcement

210.2.3—*Minimum quantity of web reinforcement*

Because of the nature and limited knowledge of shear failures, it is suggested that some web reinforcement be provided even though the criterion of Section 210.2.1 is satisfied.

Where the web reinforcement is designed by Section 210.2.2, the minimum amount of web reinforcement should be $A_v = 0.0025b's$. This requirement may be excessive for members with unusually thick webs and the amount of web reinforcement may be reduced if tests demonstrate that the member can develop its required flexural capacity.

Heavily loaded members with thin webs and relatively small span/depth ratios, such as highway bridge girders and crane girders should have web reinforcement (see Section 206.6).

210.2.4—*Spacing of web reinforcement*

The spacing of web reinforcement should not exceed three-quarters the depth of the member. In members with relatively thin webs, spacing should preferably not exceed the clear height of the web.

210.2.5—*Critical sections for shear*

Because formation of inclined cracks reduces flexural capacity the critical sections for shear will usually not be near the ends of the span where the shear is a maximum but at some point away from the ends in a region of high moment.

For the design of web reinforcement in simply supported members carrying moving loads, it is recommended that shear be investigated only within the middle half of the span length. The web reinforcement required at the quarter-points should then be used throughout the outer quarters of the span.

For simply supported members carrying only uniformly distributed load, the maximum web reinforcement may be taken as that required at a distance from the support equal to the depth of member. This amount of web reinforcement should be provided from this point to the end of member. In the middle third of the span length, the amount of web reinforcement provided should not be less than that required at third-points of the span.

211—BOND AND ANCHORAGE

211.1—Pretensioning

211.1.1—*Prestress transfer bond*

Bond between the pretensioned steel and concrete is necessary to establish a prestress in the concrete. The transfer of force from the steel to the concrete takes place in a finite length in the end region of a member and the function of the resulting bond, termed "prestress transfer bond," is anchorage of prestressing steel. Prestressing force varies from near zero at the end to a maximum value some distance from the end.

Transfer length will generally be of minor significance in long members, but it should be considered for short members or those in which the loading conditions may cause cracking in or near the region of prestress transfer.

211.1.2—*Flexural bond*

Flexural bond is the bond stress developed as a consequence of flexure. Bond stress at design loads in uncracked members is usually not critical since the increase in steel stress resulting from flexure is usually not significant. If cracking is anticipated under design loads, bond stress should be given special consideration.

211.1.3—*Significance of bond stress at ultimate load*

Bond failure should not occur prior to the development of the required ultimate flexural capacity.

For span lengths usually associated with prestressed concrete, bond failure is not a significant design factor. Bond adequacy in extremely short members should be investigated by test.

The factors affecting bond are concrete strength, perimeter shape, area and surface condition of prestressing steel, stress in the steel at ultimate strength, length of transfer zone, and superimposed load pattern.

212—COMPOSITE CONSTRUCTION

212.1—Introduction

Prestressed concrete structures of composite construction are comprised of prestressed concrete elements and plain or conventionally reinforced concrete elements interconnected in such a manner that the two components function as an integral unit. The prestressed elements may be pretensioned or post-tensioned and may be precast or cast in place. The plain or reinforced concrete elements are usually cast in place.

212.2—Interaction

212.2.1—*Shear connection*

To insure integral action of a composite structure at all loads, a connection should be provided between the component elements of the structure capable of performing two functions:

(1) To transfer shear without slip along the contact surfaces, and
(2) To prevent separation of the elements in a direction perpendicular to the contact surfaces.

212.2.2—*Transfer of shear*

Slip may be prevented and shear transferred along the contact surfaces either by bond or by shear keys. It should be assumed that the entire shear is transferred either by bond or by shear keys.

212.2.3—*Anchorage against separation*

Mechanical anchorage in the form of vertical ties should be provided to prevent separation of the component elements in the direction perpendicular to the contact surfaces. Web reinforcement or steel dowels adequately embedded on each side of the contact surface will provide satisfactory mechanical anchorage.

212.3—Design of shear connection

212.3.1—*Loading stage*

The shear connection should be designed for ultimate load.

212.3.2—*Magnitude and transfer of ultimate shear*

The shear at any point along the contact surface may be computed by the usual method as $v = (V_u Q)/I$. If the bond capacity is less than the computed shear, full width shear keys should be provided throughout the length of the member. Keys should be proportioned according to concrete strength of each component of the composite member.*

212.3.3—*Capacity of bond*

The following values are suggested for ultimate bond resistance of the contact surfaces.

When minimum steel tie requirements of Section 212.3.4 are followed . . . . 75 psi

When minimum steel tie requirements of Section 212.3.4 are followed and the contact surface on the precast element is artificially roughened . . . . 150 psi

When additional steel ties in excess of the requirements of Section 212.3.4 are used and the contact surface of the precast element is artificially roughened . . . . 225 psi

212.3.4—*Vertical ties*

In the absence of experimental information on the capacity of vertical ties it is recommended that all web reinforcement be extended into the cast-in-place concrete.

Spacing of vertical ties should not exceed four times the minimum thickness of the composite elements, or 24 in. whichever is less. The total area of vertical ties should not be less than that provided by two #3 bars spaced at 12 in.

*Lack of experimental data makes the committee hesitate to recommend a shear stress at the root of a key. Indications are that for keys on bridge girders in current use shear stress at the root of a key as high as $0.3f_c'$ would sometimes be required to transmit ultimate shear force.

For light pretensioned members such as those used for building floors not subjected to repetitive loads the above minimum requirements may be too severe. The committee is not prepared to recommend an amount or spacing of steel for this type member.

212.4—Design of composite structures

212.4.1—*Design of composite section.*

Physical properties of the composite section should be computed on the assumption of complete interaction between component elements. For structures composed of concretes of different qualities, the area of one of the component elements should be transformed in accordance with the ratio of the two moduli of elasticity.

212.4.2—*Beam and slab construction*

If the structure is composed of beams with a cast-in-place slab placed on top of the beams, effective slab width should be computed in the same manner as for integral T-beams.

212.4.3—*Allowable stress with different concrete strengths*

In structures composed of elements with different concrete strengths, the allowable stresses should be governed by strength of the portion under consideration.

212.4.4—*Superposition of stress*

Stresses may be superposed in design calculations that involve elastic stresses. Superposition of stresses should not be used in computing ultimate strength since inelastic action of the material is involved.

212.4.5—*Stress after structure becomes integral*

The properties of the composite cross section should be used in computing stresses due to loads applied after the structure becomes integral.

212.4.6—*Shrinkage stresses*

In structures with a cast-in-place slab supported by precast beams, the differential shrinkage tends to cause tensile stresses in the slab and in the bottom of precast beams. Stresses due to differential shrinkage are important only insofar as they affect cracking load. When cracking load is significant, such stresses should be added to the effects of loads.

212.4.7—*Ultimate strength*

Ultimate strength of a composite section should be computed in the same manner as ultimate strength of an integral member of the same shape.

213—CONTINUITY

213.1—Determination of moments, shears, and thrusts

Moments, shears, and thrusts produced by external loads and prestressing force should be determined by elastic analysis. Effects of axial deformation should be considered. Determination of effects produced by the prestressing forces should take into account the restraint of attached structural elements and supports.

213.2—Stresses

Allowable stresses are those recommended in Section 207.

213.2.1—*Prestress*

When prestressing is to be applied in more than one stage, the internal stresses should be investigated at each stage.

213.3—Frictional losses

Frictional losses in continuous post-tensioned steel may be more significant than in simply supported members.

213.4—Ultimate strength

The ultimate strength of a continuous member should be evaluated not only at points of maximum moment, but also at intermediate points. In applying ultimate load factors where dead load causes effects opposite to those of live load, consideration should be given to load factor combinations in which dead load factor may equal one. It is recommended that moment redistribution not be considered in design at the present time.

214—END BLOCKS

214.1—Purpose

An enlarged end section, called an end block, may be required to transmit concentrated prestressing forces in a shaped member from the anchorage area to the basic cross section.

End blocks may be required to provide sufficient area for bearing of anchorages in post-tensioned design. They may be needed to transmit vertical and lateral forces to supports and to facilitate end detailing.

214.2—Requirements

In pretensioned members with large concentrated eccentric prestressing elements, end blocks should be used. For lightly pretensioned members, or members of approximately rectangular shape, end blocks may be omitted. However, reinforcement should always be provided in the anchorage zone.

In post-tensioned, shaped members, end blocks should be provided.

214.3—Proportioning

End blocks are usually proportioned by experience. Depending on the degree of concentration and eccentricity of the prestressing force at the end surface, the length of the end block should be from one-half the depth of the member to the full depth. In general, shallow members should have an end block length equal to the depth, and deep beams should have an end block length equal to three-quarters of the depth. Length of an end block can be considered as the distance from beginning of anchorage area to the point where the end block intersects the narrowest width of member.

214.4—Reinforcement

Reinforcing is necessary to resist tensile bursting and spalling forces induced by the concentrated loads of the prestressing steel. A reinforcing grid with both vertical and horizontal steel in the plane of the cross section should be provided directly beneath anchorages to resist spalling forces. Closely spaced reinforcement should be placed both vertically and horizontally throughout the length of the end block to resist tensile forces.

215—FIRE RESISTANCE

215.1—General

The fire resistance of both prestressed concrete and reinforced concrete is subject to the same general limitations. One is the rate of heat transmission through the concrete from the surface exposed to fire to the unexposed surface. The other is the reduction of steel strength at the temperatures induced in the steel during the test. Either limitation may govern.

215.2—Heat transmission

Since the rate of heat transmission through prestressed concrete is similar to that of reinforced concrete of the same composition, the critical dimensions to control temperature rise at the unexposed surface will be the same in prestressed or reinforced concrete members.

215.3—Load-carrying capacity

The ability of the structure to carry required loads during fire test depends largely on thickness of cover over prestressing steel. The following minimum thicknesses of concrete cover on prestressing steel and end anchorages are recommended for various fire ratings:

Hour rating	1 hr	2 hr	3 hr	4 hr
Minimum concrete cover	1½ in.	2½ in.	3 in.	4 in.

Data now available are insufficient to make recommendations for such factors as shape of cross section, type and arrangement of prestressing steel. The cover thicknesses recommended are believed to be conservative.

216—COVER AND SPACING OF PRESTRESSING STEEL

216.1—Cover

The following minimum clear concrete covers are recommended for prestressing steel, ducts, and non-prestressed steel.

	Minimum concrete cover
Concrete surfaces exposed to weather	1½ in.
Concrete surfaces in contact with ground	2 in.
Beams and girders not exposed to weather	
Prestressing steel, and main reinforcing steel	1½ in.
Stirrups and ties	1 in.
Slabs and joists not exposed to weather	¾ in.

216.2—Spacing at ends

216.2.1—*Spacing of pretensioning steel*

Minimum horizontal or vertical clear spacing between pretensioning steel elements at ends of members should be three times the diameter of the steel or 1⅓ times the maximum size of coarse aggregate, whichever is greater.

216.2.2—*Spacing of post-tensioning ducts*

The clear space between conduits at the ends should be a minimum of 1½ in. or 1½ times the maximum size of coarse aggregate, whichever is greater.

216.2.3—*Dimensions of post-tensioning ducts*

When steel is placed inside conduits which are to be filled with cement grout, such conduits should have a minimum inside diameter ¼ in. larger than the diameter of the prestressing steel.

216.3—Draped prestressing steel

When prestressing steel is placed in a curved or deflected position, steel or conduits may be bundled together in the middle third of the span length provided the minimum spacing recommended in Section 216.2.1 and 216.2.2 is maintained for a minimum distance of 3 ft at each end of member. The committee is not prepared to suggest limits for the number of conduits or prestressing steel elements that may be bundled horizontally and vertically. Excessive bundling may lead to insufficient bond capacity in pretensioned members, resulting in bond slip.

CHAPTER 3—MATERIALS

301—INTRODUCTION

The nature and economics of prestressed concrete construction require the use of high strength materials. Ability to sustain high stresses with a minimum of time-dependent change in stress or strain is essential.

These requirements are more severe than those for conventionally reinforced concrete. Highest standards of manufacture and construction should be observed. Prior to adoption of new materials, sufficient test data should be obtained to verify properties assumed in design.

302—CONCRETE

302.1—Scope

Particular attention should be given to properties of individual materials used in prestressed concrete and their effect on compressive strength, modulus of elasticity, drying shrinkage, creep, bond strength, and uniformity of concrete in place.

When new materials and methods are employed, trial mix investigations should include tests for drying shrinkage, creep, and modulus of elasticity.

302.2—Materials

302.2.1—*Portland cement*

Portland cement should conform to one of the following:

Specifications for Portland Cement (ASTM C 150)
Specifications for Air-Entraining Portland Cement (ASTM C 175)
Specifications for Portland Blast Furnace Slag Cement (ASTM C 205)
Specifications for Portland-Pozzolan Cement (ASTM C 340)

302.2.2—*Concrete aggregates*

Concrete aggregates should conform to one of the following:

Specifications for Concrete Aggregates (ASTM C 33)
Specifications for Lightweight Aggregates for Structural Concrete (ASTM C 330)

Mineral composition and soundness of aggregates may have a marked influence on compressive strength, modulus of elasticity, drying shrinkage, and creep.

Concretes made with some lightweight aggregates may exhibit a lower modulus of elasticity, greater creep and drying shrinkage than do concretes of the same strength made with aggregates of normal weight.

The range of properties possible in the same concrete mix with different lightweight aggregates may be large. Therefore, it is recommended that test data should be obtained for compressive strength, modulus of elasticity, drying shrinkage, creep, modulus of rupture, and bond.

302.2.3—*Water*

Water for mixing concrete should be clean and free of injurious quantities of substances harmful to concrete or to prestressing steel. Sea water should not be used for making prestressed concrete.

302.2.4—*Admixtures*

Certain admixtures may be beneficial to fresh or hardened concrete. However, admixtures should not be used until shown by test to have no harmful effect on the steel or concrete.

The use of calcium chloride or an admixture containing calcium chloride is not recommended where it may come in contact with prestressing steel.

302.3—Proportioning, batching and mixing

The proportioning of materials, batching, and mixing of concrete for prestressing should be done in accordance with the *ACI Manual of Concrete Inspection*, the U. S. Bureau of Reclamation *Concrete Manual*, or other comparable regulations including ACI Standards "Recommended Practice for Winter Concreting (ACI 604-56)," "Recommended Practice for Selecting Proportions for Concrete (ACI 613-54)," "Recommended Practice for Measuring, Mixing, and Placing Concrete (ACI 614-42);" and "Standard Specifications for Ready-Mix Concrete" (ASTM C 94).

Available materials should be proportioned to produce concrete meeting specification requirements with a minimum water content. Slump of fresh concrete should be as low as feasible. Cement, sand, and narrow-size ranges of coarse aggregate should be separately batched by weight. Water and some liquid admixtures may be batched by volume with accurate measuring equipment. Close control of all materials and operations is essential.

302.4—Strength

The strength required at given ages should be specified by the designer. Controlled concrete should be used and tested in accordance with Section 304 as modified by Section A602(f) of "Building Code Requirements for Reinforced Concrete (ACI 318-56)."

303—GROUT

303.1—General

When required by job specifications, post-tensioned steel should be grouted to completely fill the void surrounding the prestressing steel with a portland cement grout to insure high flexural bond strength and provide permanent protection for the steel.

303.2—Materials

Grout should be made of either (a) cement and water or (b) cement, fine sand, and water. Mix (a) should be used where the cavity is very small. Either Mix (a) or Mix (b) may be used where the cavity is relatively large. Admixtures should conform to recommendations of Section 303.2.4.

303.2.1—*Portland cement*

Same as Section 302.2.1.

303.2.2—*Sand*

Sand should preferably be a natural quartz sand meeting "Tentative Specification for Aggregate for Masonry Mortar (ASTM C 144)," except for gradation requirements. The sand should pass a No. 30 sieve, about 50 percent should pass a No. 50 sieve, and about 20 percent should pass a No. 100 sieve.

303.2.3—*Water*

Same as Section 302.2.3.

303.2.4—*Admixtures*

Certain admixtures may be beneficial to fresh or hardened grout. However, no admixture should be used until shown by test to have no harmful effect on the steel or grout.

Calcium chloride or an admixture containing calcium chloride is not recommended for use in grouting post-tensioned members.

303.3—Proportioning

Proportions of grouting materials should be based on results of tests made on fresh and hardened grout prior to beginning work. Grout should have the consistency of thick cream or heavy paint. When permitted to stand until setting takes place, grout should neither bleed nor segregate.

304—PRESTRESSING STEEL

304.1—*General*

High tensile strength steel is required in prestressed concrete to provide necessary internal concrete stresses after losses have occurred. The following four types are in common use:

(a) High tensile strength single wire, applied in the form of assemblies made up of two or more substantially parallel wires. They may be used for either pretensioning or post-tensioning purposes.

(b) Small diameter, high strength strand, shop fabricated, is usually made up of six wires spiraled around a center wire. Small diameter strand is normally, though not exclusively, used for pretensioning purposes.

(c) Large diameter high strength strand is usually shop fabricated with factory attached end fittings for post-tensioned construction. It has 7, 19, 37, or more individual wires.

(d) High strength alloy steel bars are produced by a cold stretching or drawing process. They are currently available in diameters ranging from ½ to 1⅛ in. Alloy steel bars are used principally for post-tensioned construction.

Each type of prestressing steel should be made to distinctly separate specifications, of which the following sections give a general description.*

304.2—High tensile strength single wire

High tensile strength single wire is generally made from high carbon steel hot rolled into rods. It is then heat treated by a process termed "patenting" and cold drawn to produce the required final tensile strength. In its most commonly used form the wire is then stress relieved by a controlled time-temperature treatment that improves elastic properties within the tensile range usually employed in prestressing concrete. It also produces a straighter, more easily handled wire.

High tensile strength wire produced by the oil tempering process is not recommended for use in prestressed concrete.

304.2.1—*Ultimate tensile strength*

High tensile strength wire for prestressed concrete is made to minimum tensile strengths as high as 250,000 psi for a diameter of 0.196 in. Higher tensile strengths are available at smaller diameters and lower tensile strengths at larger diameters.

304.2.2—*Shape of stress-strain curve*

Stress relieved wire for prestressing should display a high yield strength and a reasonable elongation before rupture. Minimum yield strength at 1 percent elongation under test load should be equal to 85 percent of specified ultimate tensile strength. Minimum elongation after rupture should be 4 percent in 10 in. Elongation tests should conform to "Specification for Mechanical Testing of Steel Products" (ASTM A 370-54T).

*The American Society for Testing Materials is currently formulating specifications for prestressing steels.

304.2.3—*Ductility*

Wire for prestressing should be capable of a reasonable amount of cold deformation without failure. It should have a minimum reduction in cross-sectional area of 30 percent at rupture.

304.2.4—*Creep and relaxation*

Data concerning typical creep and stress relaxation properties of the material should be obtained from the manufacturer. Special acceptance tests for individual lots are usually expensive and unnecessary.

Creep tests and short-term relaxation tests do not necessarily represent long-time stress relaxation characteristics.

304.3—Small diameter high strength wire strand

Small diameter high strength strand is normally made of seven wires. A straight center wire is enclosed tightly by six spirally wound outer wires. Because of its small diameter, strand can be given a final stress-relieving treatment similar to that for single wires. This treatment improves elasticity and handling characteristics. Acceptance tests, when required, should be made on the strand rather than single wires.

Physical properties should be based on the total metallic area of all the individual wires. Ultimate tensile strength, shape of stress-strain curve, ductility, creep and relaxation should be the same as described in Section 304.2 (high tensile strength single wire) except as follows:

(a) Minimum elongation at rupture, 3.5 percent in 24 in.

(b) Minimum yield strength at 1 percent elongation under test load equal to 85 percent of specified ultimate tensile strength.

304.4—Large diameter high strength wire strand

Large strand may be made of 7, 19, 37, or more galvanized or uncoated hard-drawn wires, spirally wound. Galvanized strand is most commonly used.

Because large diameter strand cannot be given a final stress-relieving treatment, some of its physical properties differ from those of wire or small strand. Acceptance tests, when required, should be based on properties of the strand rather than individual wires.

304.5—Cold stretched high strength alloy steel bars

These bars are usually made from alloy steel designated AISI 5160 or AISI 9260. After hot rolling, the bars are either heat treated or cold worked. Each bar is then cold stretched to a minimum of 90 percent of the specified ultimate strength.

304.5.1—*Ultimate tensile strength*

High strength alloy steel bars are produced with a minimum tensile strength of 145,000 psi for all diameters.

304.5.2—*Shape of stress-strain curve*

High strength bars for prestressing should have a minimum yield strength at 0.2 percent permanent strain equal to 90 percent of the specified ultimate tensile strength. Minimum elongation after rupture should be 4 percent in a length of 20 diameters.

304.5.3—*Ductility*

Bars for prestressing should be capable of a reasonable amount of cold deformation without failure. The bar should have a reduction of area of not less than 15 percent at rupture.

304.5.4—*Creep and relaxation*

Data concerning typical creep and stress relaxation properties of the material should be obtained from the manufacturer. Special acceptance tests for individual lots are usually expensive and unnecessary.

Creep tests and short-term relaxation tests do not necessarily represent long-time stress relaxation characteristics.

304.6—Corrosion

Since prestressing steels are susceptible to corrosion, they should be protected during storage, transit, and construction.

The term stress corrosion is applied to the embrittlement of steel that occurs under the combined effects of high stress and some corrosive environments. It may take place without apparent surface impairment.

Normally, steel cast in concrete or properly grouted will not be subject to such corrosion. When post-tensioned steel is not grouted, special precautions should be taken to protect the steel (see Section 404.3.2).

305—ANCHORAGES AND SPLICES

305.1—General

Anchorages for post-tensioning elements now in general use consist of:

Threaded ends and wedge anchors for bars; factory attached end fittings for large diameter strand; button-head, sandwich plate, and conical wedges for parallel lay wire systems; and conical wedges for small diameter strand.

Splices are used primarily for bars and consist of threaded couplings.

305.2—Ultimate strength

Anchorages and splices should be capable of developing the ultimate strength of attached steel elements without excessive deformation.

305.3—Anchorage set

Movement of prestressing steel in anchorage during seating should be stated by the manufacturer and substantiated by test data.

CHAPTER 4—CONSTRUCTION

401—INTRODUCTION

This chapter outlines construction procedures that should result in sound and durable structures.

Prestressed concrete members are composed of high strength concrete and steel. Design stresses are closely controlled, but behavior in service depends upon the specified concrete being properly placed in forms of the correct dimensions around accurately positioned prestressing steel or ductwork for steel. Construction requires accuracy and care. Deviation from careful workmanship may result in an unsafe structure and should not be condoned.

402—TRANSPORTING, PLACING, AND CURING OF CONCRETE

402.1—General

Quality of the finished concrete members depends on care used in transporting, placing, and curing. Recommended practice is outlined in "Building Code Requirements for Reinforced Concrete (ACI 318-56)," Sections 403-406, and "Recommended Practice for Measuring, Mixing, and Placing Concrete (ACI 614-42)."

402.2—Placing

Low slump, high cement content mixes should be placed in the shortest possible time after mixing is completed to prevent loss of workability.

Concrete should be deposited close to its final position. The method of placement should be such that segregation will not occur.

402.3—Vibration

Internal or external vibration or both are usually necessary to produce dense, well-compacted concrete.

Vibrators should not be used to move concrete horizontally in the form. Overvibration should also be avoided.

When internal vibration is used, vibrator heads should be smaller than the minimum distance between ducts or prestressing steel. Care must be exercised to avoid damage to or misalignment of ducts for post-tensioning steel.

Vibration is not a substitute for workability. Judgment should be used in specifying slump, and approved methods of vibration used to achieve maximum compaction.

402.4—Construction joints

In long cast-in-place members the use of construction joints is recommended (1) to reduce cracking near columns caused by settlement or movement of shoring and falsework, and (2) to allow for shrinkage. In general, joints should be placed near falsework supports.

Construction joints preferably should be perpendicular to prestressing steel. Joints should not be made parallel to prestressing steel unless the provisions of Section 212 (composite construction) are followed.

402.5—Curing

Curing should start soon after finishing. If high temperature curing is used, an initial setting time prior to application of heat should be required. Curing should continue until the required strength for application of the prestress force is reached. Fresh concrete should be protected from rain or the rapid loss of moisture prior to the curing period. Rapid drying should be prevented until the final design strength is obtained.

When high temperature curing is used, the rate of heating and cooling should be controlled to reduce thermal shock to the concrete.

Where identical precast members are required, curing conditions should be uniform to maintain proper quality control.

402.6—Protection from freezing

During periods of freezing temperatures, ungrouted ducts should be blown clear of water or protected against freezing.

403—FORMS, SHORING, AND FALSEWORK

403.1—General

Quality of concrete members depends on the care used in constructing forms and falsework. Correct practices outlined in "Building Code Requirements for Reinforced Concrete (ACI 318-56)" Sections 501 and 502 are recommended.

403.2—Special requirements

Forms for pretensioned members should be constructed to permit movement of the member without damage during release of the prestressing force.

Forms for post-tensioned members should be constructed to minimize restraint to elastic shortening during prestressing and shrinkage. Deflection of members due to the prestressing force and deformation of falsework should be considered in design. Form supports may be removed when sufficient prestressing has been applied to carry dead load, formwork carried by the member, and anticipated construction loads.

404—PLACEMENT OF PRESTRESSING STEEL AND APPLICATION OF PRESTRESSING FORCE

404.1—General

The location of the center of gravity of the prestressing steel, initial and final prestressing force, and the assumed losses due to creep, shrinkage, elastic shortening, and friction shown on the plans are based on the use of specified materials. Other materials not specified but capable of producing the same results may be used with approval of the engineer.

Unless tolerances for location of the prestressing steel are shown, a variation of $\pm$ 1/8 in. to $\pm$ 1/4 in. depending on size of the member, is suggested as maximum permissible.

404.2—Pretensioning steel

404.2.1—*General*

Steel should be kept clean and dry. Foreign matter, grease, oil, paint, and loose rust should be removed prior to casting concrete. A light coat of rust is permissible and sometimes preferable provided loose rust has been removed and the surface of the steel is not pitted.

404.2.2—*Measurement of prestressing force*

Pretensioning force should be determined by measuring elongation and checking jack pressure on a calibrated gage. Measurement of elongation will usually give more consistent results. When there is a difference of over 5 percent between the steel stress determined from elongation and from the gage reading, the cause of the discrepancy should be ascertained and corrected.

If several wires or strands are stretched simultaneously, provision must be made to induce the same initial stress in each.

404.2.3—*Transfer of prestressing force*

The force in the prestressing steel should be transferred to the concrete smoothly and gradually. If the force in the wires or strands is transferred individually, a sequence of release should be established by the engineer to avoid subjecting the member to unanticipated stresses. Any variation in this sequence should be submitted to the engineer for approval.

404.2.4—*Protection*

Ends of pretensioning steel exposed to weather or corrosive atmosphere should be protected by a coating of asphaltic material. They should preferably be recessed in the member, coated with asphaltic material and covered with mortar.

404.3—Post-tensioning steel

404.3.1—*General*

The steel should be kept clean and dry. For bonded construction, foreign matter, grease, oil, paint, and loose rust should be removed prior to placing steel in ducts. A light coat of rust is permissible provided loose rust has been removed and the surface of the steel is not pitted.

404.3.2—*Protection*

For general use in unbonded construction, galvanizing may be considered to protect the steel from corrosion when coated with grease or asphalt-impregnated material and enclosed in a sheath. Uncoated galvanized steel may be used when it is accessible for inspection and points of bearing are equipped with special shoes to prevent damage to the galvanizing.

If wrappings and coatings are used on nongalvanized steel, the coating should protect the steel from corrosion during shipment, storage, construction, and after the steel is in place. It should permit movement of steel during stressing with minimum friction. The method of protection should be specified or approved by the engineer.

Anchorage and end fittings should be given protective treatment consistent with that given the prestressing steel. They should preferably be recessed in the member and covered with mortar.

404.3.3—*Placement of steel and enclosures*

Ducts or enclosures for prestressing steel are formed in the concrete using tubing, metallic casings, or other materials. They should be positioned and secured to maintain the prestressing steel within the allowable placement tolerances.

For bonded construction, ducts or duct-forming devices should be free from grease, paint, or other foreign matter. Ducts should be protected against entrance of foreign matter prior to grouting.

Anchorage hardware to be cast in the member should be firmly fastened to forms in the proper location.

404.3.4—*Measurement of the prestressing force*

Values of total elongation, corrected for assumed friction loss and anchorage set, and corresponding jack pressures at various increments of prestress should be supplied by the engineer. When a difference of over 5 percent exists between steel stress determined from the corrected elongation and from corresponding gage reading, stressing operation should cease. If the cause of the discrepancy is neither faulty measurement nor equipment, the engineer should be consulted.

404.3.4.1—*Factors influencing friction*—As prestressing force is applied, friction between prestressing steel and curved enclosure reduces steel stress at points away from the jack. The amount of friction loss is a function of degree of curvature, type and length of prestressing steel, duct material, presence of friction reducing agents, accuracy of placing the duct, and degree of disturbance during concrete placement.

It is the responsibility of the contractor to be aware of these factors. He should use materials specified and insure that the quality of workmanship results in accurate duct positioning with minimum displacement during construction.

404.3.5—*Prestressing in stages*

When the prestressing force is to be applied in more than one stage, excessive concrete stresses should be avoided during intermediate stages. The engineer will designate location and magnitude of the forces to be used for each stage and allowable external loads that may be placed on the member. The contractor should be aware of the significance of overloading the member.

404.3.6—*Anchorage set*

For friction type anchorages the manufacturer or supplier should state the amount of slip normally expected in seating the anchorage device.

404.3.7—*Effect of temperature*

Changes in temperature should have little effect on prestressing reinforcement unless there is a significant temperature differential between concrete and steel.

405—GROUTING

405.1—General

When grouting is specified for post-tensioned members it should completely fill all enclosure voids.

405.2—Mixing

Grout should be mixed in a mechanical mixer. Immediately after mixing, it should be passed through a strainer into pumping equipment which provides for recirculation. Grout should be pumped into the duct as soon as possible after mixing but may be pumped as long as it retains the proper consistency.

405.3—Arrangement of grout pipes

Ducts must be provided with entrance and discharge ports, each of which can be closed. Extension pipes may be used when necessary.

For long members, grout may be introduced at one end until it discharges from an intermediate point. The point of application may then be moved successively forward. Grout may be introduced at an intermediate point if discharge ports are provided at duct ends. The sequence of grouting should be planned to insure complete filling. Devices for bleeding air may be required at high points of the duct profile.

405.4—Test for passage of grout

Free passage of grout from entrance to discharge port must be assured. Tests may be made by pumping water, air, or other fluids through the duct.

405.5—Application of grout

Grout should be applied continuously until it flows steadily from the discharge port indicating removal of trapped air and water. The discharge port should then be closed and grouting pressure maintained for the length of time necessary to insure complete filling of the void. The entrance should then be closed and the pumping nozzle removed.

405.6—Protection against freezing

Adequate precautions must be taken to prevent freezing fresh grout.

406—HANDLING AND ERECTION

Where precast members are specified, methods of handling and/or the sequence of erection should be indicated. When these are not indicated on the plans, the contractor should submit for approval the location of pick-up points, minimum concrete strength when handled, method of transporting, and sequence of erection.

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