ASCE STANDARD

ASCE/SEI
19–10

Structural Applications of Steel Cables for Buildings

This document uses both the
International System of Units (SI)
and customary units

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ASCE STANDARD ASCE/SEI 19-10

American Society of Civil Engineers

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ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

SEI ASCE STRUCTURAL ENGINEERING INSTITUTE

Library of Congress Cataloging-in-Publication Data

Structural applications of steel cables for buildings / American Society of Civil Engineers.
p. cm. — (ASCE Standard ASCE/SEI ; 19-10)
"This document uses both the International System of Units (SI) and customary units."
Includes bibliographical references and index.
ISBN 978-0-7844-1124-7
1. Cable structures–Standards–United States. 2. Cables–Standards–United States.
I. American Society of Civil Engineers.
TA660.C3S77 2010
624.1′774–dc22
2010038365

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia 20191
www.pubs.asce.org

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ISBN 978-0-7844-1124-7
Manufactured in the United States of America.

18 17 16 15 14 13 12 11 10 1 2 3 4 5

STANDARDS

In 2003, the Board of Direction approved the revision to the ASCE Rules for Standards Committees to govern the writing and maintenance of standards developed by the Society. All such standards are developed by a consensus standards process managed by the Society's Codes and Standards Committee (CSC). The consensus process includes balloting by a balanced standards committee made up of Society members and nonmembers, balloting by the membership of the Society as a whole, and balloting by the public. All standards are updated or reaffirmed by the same process at intervals not exceeding five years.

The following standards have been issued:

ANSI/ASCE 1-82 N-725 Guideline for Design and Analysis of Nuclear Safety Related Earth Structures
ASCE/EWRI 2-06 Measurement of Oxygen Transfer in Clean Water
ANSI/ASCE 3-91 Standard for the Structural Design of Composite Slabs and ANSI/ASCE 9-91 Standard Practice for the Construction and Inspection of Composite Slabs
ASCE 4-98 Seismic Analysis of Safety-Related Nuclear Structures
Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02) and Specifications for Masonry Structures (ACI 530.1-02/ASCE 6-02/TMS 602-02)
ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures
SEI/ASCE 8-02 Standard Specification for the Design of Cold-Formed Stainless Steel Structural Members
ANSI/ASCE 9-91 listed with ASCE 3-91
ASCE 10-97 Design of Latticed Steel Transmission Structures
SEI/ASCE 11-99 Guideline for Structural Condition Assessment of Existing Buildings
ASCE/EWRI 12-05 Guideline for the Design of Urban Subsurface Drainage
ASCE/EWRI 13-05 Standard Guidelines for Installation of Urban Subsurface Drainage
ASCE/EWRI 14-05 Standard Guidelines for Operation and Maintenance of Urban Subsurface Drainage
ASCE 15-98 Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD)
ASCE 16-95 Standard for Load Resistance Factor Design (LRFD) of Engineered Wood Construction
ASCE 17-96 Air-Supported Structures
ASCE 18-96 Standard Guidelines for In-Process Oxygen Transfer Testing
ASCE/SEI 19-10 Structural Applications of Steel Cables for Buildings
ASCE 20-96 Standard Guidelines for the Design and Installation of Pile Foundations
ANSI/ASCE/T&DI 21-05 Automated People Mover Standards—Part 1
ANSI/ASCE/T&DI 21.2-08 Automated People Mover Standards—Part 2
ANSI/ASCE/T&DI 21.3-08 Automated People Mover Standards—Part 3
ANSI/ASCE/T&DI 21.4-08 Automated People Mover Standards—Part 4
SEI/ASCE 23-97 Specification for Structural Steel Beams with Web Openings
ASCE/SEI 24-05 Flood Resistant Design and Construction
ASCE/SEI 25-06 Earthquake-Actuated Automatic Gas Shutoff Devices
ASCE 26-97 Standard Practice for Design of Buried Precast Concrete Box Sections
ASCE 27-00 Standard Practice for Direct Design of Precast Concrete Pipe for Jacking in Trenchless Construction
ASCE 28-00 Standard Practice for Direct Design of Precast Concrete Box Sections for Jacking in Trenchless Construction
ASCE/SEI/SFPE 29-05 Standard Calculation Methods for Structural Fire Protection
SEI/ASCE 30-00 Guideline for Condition Assessment of the Building Envelope
SEI/ASCE 31-03 Seismic Evaluation of Existing Buildings
SEI/ASCE 32-01 Design and Construction of Frost-Protected Shallow Foundations
EWRI/ASCE 33-01 Comprehensive Transboundary International Water Quality Management Agreement
EWRI/ASCE 34-01 Standard Guidelines for Artificial Recharge of Ground Water
EWRI/ASCE 35-01 Guidelines for Quality Assurance of Installed Fine-Pore Aeration Equipment
CI/ASCE 36-01 Standard Construction Guidelines for Microtunneling
SEI/ASCE 37-02 Design Loads on Structures during Construction
CI/ASCE 38-02 Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data

EWRI/ASCE 39-03 Standard Practice for the Design and Operation of Hail Suppression Projects
ASCE/EWRI 40-03 Regulated Riparian Model Water Code
ASCE/SEI 41-06 Seismic Rehabilitation of Existing Buildings
ASCE/EWRI 42-04 Standard Practice for the Design and Operation of Precipitation Enhancement Projects
ASCE/SEI 43-05 Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities
ASCE/EWRI 44-05 Standard Practice for the Design and Operation of Supercooled Fog Dispersal Projects
ASCE/EWRI 45-05 Standard Guidelines for the Design of Urban Stormwater Systems
ASCE/EWRI 46-05 Standard Guidelines for the Installation of Urban Stormwater Systems
ASCE/EWRI 47-05 Standard Guidelines for the Operation and Maintenance of Urban Stormwater Systems
ASCE/SEI 48-05 Design of Steel Transmission Pole Structures
ASCE/EWRI 50-08 Standard Guideline for Fitting Saturated Hydraulic Conductivity Using Probability Density Functions
ASCE/EWRI 51-08 Standard Guideline for Calculating the Effective Saturated Hydraulic Conductivity
ASCE/SEI 52-10 Design of Fiberglass-Reinforced Plastic (FRP) Stacks
ASCE/G-I 53-10 Compaction Grouting Consensus Guide
ASCE/EWRI 54-10 Standard Guideline for the Geostatistical Estimation and Block-Averaging of Homogeneous and Isotropic Saturated Hydraulic Conductivity
ASCE/SEI 55-10 Tensile Membrane Structures
ASCE/T&DI/ICPI 58-10 Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways

FOREWORD

This Standard is an updated and expanded version of ASCE Standard 19-96, which it replaces. It has been prepared in accordance with recognized engineering principles. This Standard should not be used without first securing competent advice with respect to its suitability for a given application. The publication of the material contained herein is not intended as a representation or warranty on the part of the American Society of Civil Engineers, or of any other person named herein, that this information is suitable for a general or particular use, nor does it promise freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability for its use.

As background, development of this Standard can be traced to the *Tentative Criteria for Structural Applications of Steel Cables for Buildings* published by the American Iron and Steel Institute (AISI) in 1966. Later influential publications were *Design Fundamentals of Cable Roof Structures* published by AISI in 1969; the paper titled "Cable-Suspended Roof Construction State-of-the-Art" in the *Journal of the Structural Division*, ASCE, 1971; the *Manual for Structural Applications of Steel Cables for Buildings*, AISI, 1973; and the prior edition of this Standard, ASCE 19-96. References used to develop particular provisions of this Standard are included in the Selected Bibliography to be found in the Commentary.

ACKNOWLEDGMENTS

The American Society of Civil Engineers (ASCE) acknowledges the devoted efforts of the Structural Applications of Steel Cables for Buildings Standards Committee (the Committee) of the Codes and Standards Activities Committee. This group consists of individuals from many backgrounds, including consulting engineering, research, manufacturing, fabrication, education, and government.

This is the second edition of ASCE Standard 19 and supersedes ASCE Standard 19-96. It was prepared through the standards process by balloting in compliance with procedures of ASCE's Codes and Standards Committee. The membership of the Structural Applications of Steel Cables for Buildings Committee changed during the decade in which it developed this second edition of the Standard. There was also valuable input from industry outside the Committee. The Committee members who actively attended meetings and/or contributed significant material through correspondence are:

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CONTENTS

ASCE STANDARD 19-10

STRUCTURAL APPLICATIONS OF STEEL CABLES FOR BUILDINGS

1.0 GENERAL

1.1 SCOPE

This Standard provides requirements for the structural design, contract documents, shop drawings, fabrication, and installation of cables for use as static structural elements for the support and bracing of buildings and other cable-supported structures not subjected to vehicle loads. Parts of buildings to which this Standard is applicable include roofs, floors, curtain walls, masts, and nets. Guyed utility towers and vehicular bridges are not covered by this Standard. This Standard applies to carbon steel and stainless steel cables.

1.2 GLOSSARY

Anchorage: the structural connection at which the cable is terminated.

Cable: a flexible tension member, strand, or rope.

Clamp: a cable fitting that transfers force by friction.

Damper: an active or passive device attached to the cable structure that modifies the structural response to dynamic loads.

Deflector: a grooved cable support used to create an angle change in the cable. Also known as a saddle.

Fitting: any accessory used as an attachment to, or support for, the cable or its components.

Grade: classification of cable by nominal cable strength and/or metallic composition of wire.

Modulus of Elasticity: the slope of the secant to the stress–strain curve between the stress at 10% of the nominal cable strength and 90% of the prestretching force.

Nominal Cable Strength: strength of a cable in units of force, as given in ASTM or other applicable standards.

Prestressing: tensioning a cable at installation.

Prestretching: tensioning a helically twisted cable according to a predetermined program in order to minimize constructional stretch.

Prestretching Force: tensile force applied to a cable one or more times and held for a specified duration during prestretching.

Rope: a plurality of strands twisted about an axis, or about a core which may be a strand or another wire rope.

Strand: a plurality of wires helically twisted about an axis.

Termination: a device, also known as an end fitting, attached to a cable to transfer the tension in the cable to its supporting anchorage.

Wire: a single continuous length of steel with a circular or noncircular cross section. Wires of

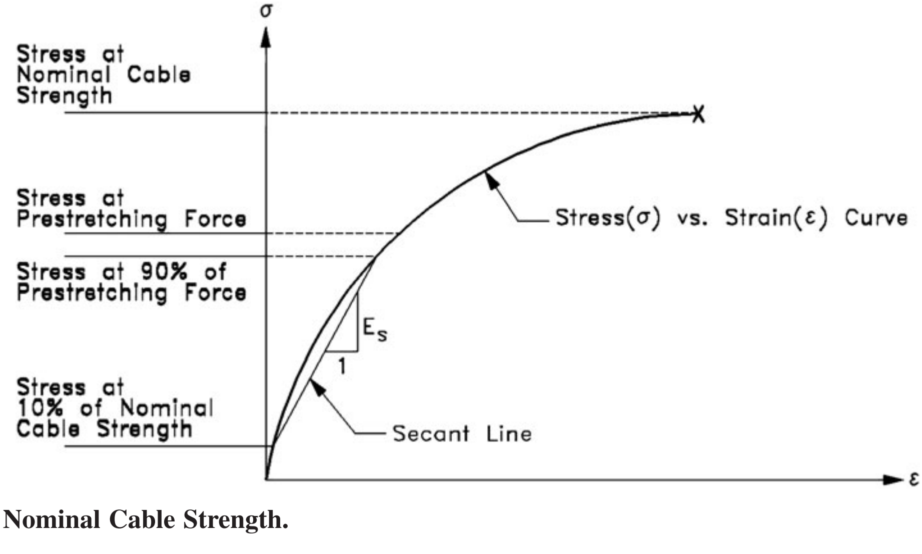


FIGURE 1-1. Nominal Cable Strength.

circular cross section are cold-drawn from rod. Wires of noncircular cross section are either cold-drawn or cold-rolled from rod.

1.3 SYMBOLS AND NOTATION

C = erection or temporary load during construction
D = dead load due to weight of the structure and the permanent features on the structure
D_i = weight of ice
E = earthquake load
E_S = modulus of elasticity (secant)
L = live load due to occupancy and movable equipment
L_r = roof live load
P = prestress force
R = rain load
S = snow load
S_d = design strength of the cable, computed using S_n and reduction factors
S_n = nominal cable strength
T = cable tension
W = wind load
W_i = wind load on cable coated with ice
N_d = deflector reduction factor
N_f = fitting reduction factor
Δ_t = temperature change

1.4 REFERENCE STANDARDS

For design loadings, see Section 3.2.1.
For cable materials, see Section 4.1.
For nondestructive examination of cables and fittings, see Sections 5.2 and 9.0.
For corrosion and fire-protective coatings, see Section 6.0.

2.0 CONTRACT DOCUMENTS AND SHOP DRAWINGS

2.1 CONTRACT DOCUMENTS

2.1.1 Contract Drawings

The Contract Drawings shall indicate the horizontal and vertical location of the cables and their connections for a specified load and temperature, typically the final dead load condition at the ambient temperature. Dimensions and loading data shall be shown to enable the computation of cable lengths under the specified condition. Required prestressing at erection shall be shown.

Terminations, fittings, anchorages, and other support details shall be fully detailed or sufficient data shall be provided to enable their selection and procurement. The required camber of supporting structural members and the required initial out-of-plumb of columns shall be shown on the drawings. The erection procedure modeled in the structural analysis and design shall be outlined in the contract documents with a statement indicating whether it is a suggested procedure or is mandatory because of controlling loadings or displacements of the cables or supporting structure.

2.1.2 Contract Specifications

For each type of cable in the proposed cable structure, the Contract Specifications shall indicate the diameter (size), the type of cable, the wire coating, the grade of cable, prestretching requirements, and the applicable material or testing specification. If there are additional design requirements for cables, they shall be included in the Contract Specifications. The required tension in the cables when length and diameter measurements are made shall be indicated. Cable and fitting manufacturing tolerances required for design or erection conditions shall also be given. The Contract Documents shall also state the erection tolerances, both for the final geometry of the system and the prestressing forces. The Contract Specifications shall identify all other required submittals, including shop drawings and test reports.

2.2 SHOP DRAWINGS

Drawings for the fabrication of cables and fittings shall reflect the requirements indicated in the Contract Documents. Exact locations, material, sizes, and lengths of all cables and fittings shall be shown, as well as fabricating and preparation procedures for cables and fittings. Where approved substitutions or changes from the Contract Documents are made, an alternate member or fitting shall be detailed that will satisfy the loading and configurations indicated in the Contract Documents.

As part of the Shop Drawings, separate erection drawings shall be prepared to show the critical sequence, procedures, and methods of erection. The Erection Drawings shall be accompanied by an erection analysis; see Section 3.4.5.

Shop Drawings and test reports shall be submitted to the Engineer for review.

3.0 DESIGN CONSIDERATIONS

3.1 DESIGN BASIS

The cable system, including its masts and struts, shall be designed to safely support the design loading specified herein without exceeding the allowable force in any member. It shall also be designed to have adequate rigidity in order to limit displacements to values that would not adversely affect the serviceability of the structure.

3.1.1 Structural Integrity

The complete structural system of the building, including the cable system with its masts and struts, shall be configured with regard to maximizing structural redundancy and robustness. Failure or malfunction of any one local component should not create a dangerous condition or collapse of a larger part of the structure.

3.1.2 Replacement of Members

Cables and struts shall be designed to be replaceable.

3.2 DESIGN LOADINGS

3.2.1 Loads

In the absence of an applicable local building code, the design loads shall be those given in ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*. Additional load provisions shall be based on the following considerations: aerodynamic effects on individual cables and complete cable structures, either by means of numerical dynamic analysis or through wind tunnel tests; wind-induced structural vibration and fatigue effects; and the effects of creep.

3.2.2 Load Combinations

Cable tension, T_n, which is the effect of load, shall be calculated for the following load combinations:

T_1 = cable tension due to $D + P$
T_2 = cable tension due to $D + P + L$
T_3 = cable tension due to $D + P + (L_r$ or S or $R)$
T_4 = cable tension due to $D + P + 0.75\ L + 0.75\ (L_r$ or S or $R)$
T_5 = cable tension due to $D + P + (0.6\ W$ or $0.7\ E)$
T_{6a} = cable tension due to $D + P + 0.75\ L + 0.75\ (0.6\ W) + 0.75\ (L_r$ or S or $R)$
T_{6b} = cable tension due to $D + P + 0.75\ L + 0.75\ (0.7\ E) + 0.75\ S$
T_7 = cable tension due to $0.6\ D + P + 0.6\ W$
T_8 = cable tension due to $0.6\ D + P + 0.7\ E$
T_9 = cable tension due to C + the erection components of D, L, P, and W.

The tension T_2 and T_4 shall be computed for the full range of temperature to which the structure is assumed to be subjected.

3.2.3 Load Combinations Including Atmospheric Ice Loads

When the structure is subjected to atmospheric ice and wind-on-ice loads, cable tensions due to the following load combinations shall be considered:

1. $0.7\ D_i$ shall be added to the equation for T_2.
2. (L_r or S or R) in the equation for T_3 shall be replaced by $0.7\ D_i + 0.7\ W_i + S$.
3. W in the equation for T_7 shall be replaced by $0.7\ D_i + 0.7\ W_i$.

3.3 CABLE STRENGTH

3.3.1 Design Strength

The design strength, S_d, of each cable shall be equal to or greater than $2.2\ T_n$, where the load combination number $n = 1$ to 9.

The design strength, S_d, of the cable shall normally be taken as the smaller of:

$$S_d = S_n \times N_f \text{ or } S_d = S_n \times N_d$$

in which

S_n = nominal cable strength.
N_f = fitting reduction factor, and
N_d = deflector reduction factor ($N_d = 1$ for the case of no deflector).

3.3.1.1 Fitting Reduction Factor

To account for the reduction in available strength caused by the action of the end fitting in transferring tension from the cable to the fitting, the factor given in Table 3-1 shall be applied.

3.3.1.2 Deflection Reduction Factor

To account for the reduction in available strength due to curvature of the cable over a saddle, the factors given in Table 3-2 shall be applied.

Table 3-2 applies to saddles for which the live load changes the deflection angle of the cable less than 2 degrees for strand and 4 degrees for rope, per saddle end. For anticipated larger deflection angle changes, the deflection reduction factor shall be

Table 3-1 Fitting Reduction Factors

Type of Termination	Fitting Reduction Factor N_f	
	Rope	Strand
Poured socket (zinc, zinc-aluminum-mischmetal alloy, or resin)	1.00	1.00
Swaged socket	1.00[a]	0.90[b]

[a] Regular lay ropes only. Verify with manufacturer for sizes over 2 in. (51 mm).

[b] Confirm with manufacturer.

Table 3-2 Deflector Reduction Factors

Ratio: Saddle Radius to Rope Diameter	Ratio: Saddle Radius to Strand Diameter	Deflector Reduction Factor N_d
15 and over	20 and over	1.0
14	19	0.95
13	18	0.90
12	17	0.85
11	16	0.80
10 minimum	15 minimum	0.75

determined by an approved method. Table 3-2 is limited to curvature induced by saddles.

3.3.1.3 Elevated Temperature Effect

The possibility of elevated temperature above 200 °F (93 °C) and its effect on the mechanical and physical properties of cables and end fittings shall be considered during the design. For temperatures above 200 °F (93 °C), the nominal cable strength, S_n, and the cable's modulus of elasticity, E_s, shall be appropriately reduced in calculations.

3.3.1.4 Fatigue Strength

The possible reduction in cable strength due to fatigue shall be evaluated when the cable will undergo repetitive fluctuating loads, vibration due to wind or rain, or other dynamic effects. Fluctuating tension-tension or bending and tension shall be considered.

Factors that decrease a cable's fatigue strength are provided in the Commentary, Section C3.3.1.4.

3.3.1.5 Creep Effect

Creep, or long-term elongation of a prestretched cable, shall be evaluated. Factors influencing creep are provided in the Commentary, Section C3.3.1.5.

3.3.2 End Fittings

Fittings shall develop an ultimate strength greater than the specified nominal cable strength. Moreover, fittings shall be designed such that the computed average stresses across the fitting body are less than the yield stress of the fitting material under a static tension force. The static tension force shall be equal to the specified nominal strength of the rope or strand for which the fitting is designed. Localized yielding at stress concentrations, such as at the line contact of pins and the roots of screw threads, is permitted at the cable working tension. Under special circumstances, overdesigned cables may terminate with conventionally sized fittings, or conventionally designed cables may terminate with oversize fittings. Such designs shall be based on data supplied by an assembler or a fitting manufacturer regarding fit of the cable in the fitting and the stresses in the fitting.

3.4 STRUCTURAL ANALYSIS

3.4.1 General Considerations

Cable systems inherently exhibit nonlinear behavior. Therefore, the design basis for cable systems shall include nonlinear considerations and analyses. Commentary Section C3.4.1 provides a brief discussion of the nonlinear behavior of cable systems. The structural analysis shall be based on the following considerations in addition to those mentioned elsewhere in this Standard:

- Elastic stretch of the cables and deformation of the supporting structure shall be taken into account in the design.
- Nonlinear analyses shall be performed if it is determined that the magnitudes of the cable displacements are such that the equilibrium equations should be based on the geometry of the displaced structure.

3.4.2 Serviceability

At an early stage of the structural design, the Owner, Architect, and Engineer shall establish the serviceability requirements for the cable system, including requirements for cable repair and replacement. Local building ordinances shall be taken into account. Numerical analyses shall be performed to demonstrate that the serviceability requirements for deflection and vibration will be met.

3.4.3 Vibrations

The effect of dynamic loading on cable stresses, fatigue, and deflections of the individual cable and the entire structure shall be considered in the design.

3.4.4 Deflections

Cables shall be so proportioned that the maximum deflections under the combined action of applied loads, temperate change, and cable stretch will satisfy the serviceability requirements.

3.4.5 Erection Analysis

A structural analysis shall be performed for the suggested or mandatory erection procedure considering the effects listed in Section 3.4.1. Should deviations be made in the suggested erection procedure, the erector shall have an independent professional engineer experienced in cable-system erection perform an erection analysis to match the revised methods, equipment, and sequence.

4.0 CABLE MATERIALS

4.1 CABLE SPECIFICATIONS

This Standard applies to cables conforming to the following standard specifications:

ASTM A368-95a(2009). *Standard Specification for Stainless Steel Wire Strand*
ASTM A474-03(2008). *Standard Specification for Aluminum-Coated Steel Wire Strand*
ASTM A475-03(2009)e1. *Standard Specification for Zinc-Coated Steel Wire Strand*
ASTM A492-95(2009). *Standard Specification for Stainless Steel Rope Wire*
ASTM A586-04a(2009)e1. *Standard Specification for Zinc-Coated Parallel and Helical Steel Wire Structural Strand*
ASTM A603-98(2009)e1. *Standard Specification for Zinc-Coated Steel Structural Wire Rope*
ASTM A855/A855M-03(2009). *Standard Specification for Zinc-5% Aluminum-Mischmetal Alloy-Coated Steel Wire Strand*
ASTM A1023/A1023M-09 (2009). *Standard Specification for Carbon Steel Wire Ropes for General Purposes*, *Table 9* (for specific application, see Commentary Section C4.0)
UNE-EN 12385-10:2004 + A1:2008 (2008). *Steel Wire Ropes – Safety – Part 10: Spiral Ropes for General Structural Applications*

Some of the above cable specifications apply to cables of a specific construction. This Standard does not exclude cables of other construction provided that the chemical and mechanical properties of the wires constituting the cables conform to the requirements of one of the above specifications, *and provided that the cables do not have nonmetallic (fiber) cores.* Stainless steel cable construction similar to the above specifications is acceptable provided that the stainless steel wire conforms to ASTM A492.

4.2 PRESTRETCHING

For each type and construction of cable specified in the Contract Documents, the prestretching requirements shall be explicitly stated. For prestretched cables, the minimum value of the modulus of elasticity, E_s, of the cable after prestretching shall be specified. Prestretching force shall not exceed 55% of the minimum breaking force. For cables more than 2.5 in. (63 mm) in diameter, consultation with cable manufacturers during structural design is recommended.

5.0 FITTINGS

5.1 MATERIALS

When selecting fitting materials, the compatibility of the cable and fitting materials shall be considered. Compatibility includes thermal expansion and corrodibility.

5.2 INSPECTION

Stock or standard sockets shall be subjected to the manufacturer's quality control testing. For special sockets, additional inspection and/or proof loading of the fittings shall be specified. Approved ASTM nondestructive testing procedures are: magnetic particle, dye penetrant, ultrasonics, and radiography. No cracks or other injurious defects shall be present in the fittings. The design documents shall specify the type of nondestructive tests, the frequency of testing, and acceptance criteria.

The following standards for nondestructive testing of *fittings* may be used:

ASTM E94-04 (2004). *Standard Guide for Radiographic Examination*
ASTM E125-63(2008). *Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings*
ASTM E165-09 (2009). *Standard Practice for Liquid Penetrant Examination for General Industry*
ASTM E709-08 (2008). *Standard Guide for Magnetic Particle Testing*
ASTM E1030-05 (2005). *Standard Test Method for Radiographic Examination of Metallic Castings*

ASTM E1417-05e1 (2005). *Standard Practice for Liquid Penetrant Testing*
ASTM E1444-05 (2005). *Standard Practice for Magnetic Particle Testing*
ASTM E1742-08a (2008). *Standard Practice for Radiographic Examination*

5.3 END FITTINGS

End fittings preferably shall be accessible and positioned so as not to create a collection basin for dirt or moisture. Additional corrosion protection for cables entering a fitting where dirt and moisture may accumulate shall be provided. Examples of representative end fittings are contained in the Commentary Appendices A.2 and A.3.

5.3.1 Zinc-Poured and Mischmetal-Poured Fittings

Zinc for zinc-poured fittings shall conform to prime western, high-grade, or higher-purity zinc as defined in ASTM B6-09 (2009). The service temperature for zinc-poured fittings shall not exceed 250 °F (120 °C). The use of mischmetal-poured fittings may be approved when based on data supplied by the cable manufacturer.

5.3.2 Resin-Poured Fittings

The resin used in thermoset resin sockets shall have suitable characteristics and properties for both uncured and cured conditions. Approval of resin properties (including shelf life) and any precautions for its use (including service temperature range) shall be based on data supplied by the resin manufacturer. Sockets shall have been specifically designed for resin socketing.

5.3.3 Swaged Fittings

Swaged fittings may be utilized provided they meet the strength requirement of Section 3.3.2 and Table 3-1.

5.4 SADDLES AND CLAMPS

Factors that shall be considered in the design of saddles and clamps include: bearing pressures, cable compaction, deflection angles, friction, and groove contour as prescribed by cable manufacturers. All surfaces of the saddles and clamps in contact with the cable shall be free of projections, sharp corners, and edges. Curved contact surfaces of saddles shall extend a distance sufficient to ensure that the cable will not contact the end of the saddle groove for any condition of cable deflection.

6.0 PROTECTIVE COATINGS

Cables exposed to atmospheric conditions shall have corrosion protection at least equivalent to Class A zinc coating on all wires as defined in ASTM A586 and A603, except those composed of stainless steel wires. Heavier Class B or Class C zinc coatings, or other approved equivalent coatings, shall be considered for severe environmental exposure. Fire-protective coatings shall not be considered as corrosion protection.

In addition to previously cited specifications, the following specifications apply to corrosion and fire protective coatings and shall be referenced:

ASTM B6-09 (2009). *Standard Specification for Zinc*
ASTM A780/A780M-09 (2009). *Standard Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings*
ASTM E119-10a (2010). *Standard Test Methods for Fire Tests of Building Construction and Materials*
ASCE/SEI/SFPE 29-05 (2007). *Standard Calculation Methods for Structural Fire Protection*

6.1 CORROSION PROTECTION

Basic corrosion protection shall be provided for all cable systems. As a minimum, each individual carbon steel cable wire, exclusive of stainless steel wires, shall be galvanized with zinc or a zinc-aluminum-mischmetal alloy. The in-service exposure of the cable shall be considered when specifying the required galvanizing thickness.

When it is deemed necessary to use a second corrosion protection system such as an interior cable filling or an exterior cable coating/covering, the two systems shall be checked for possible incompatibilities.

Cable terminations and cable grooves in clamps and saddles shall be galvanized or zinc-metalized, and be stainless steel for stainless steel cables.

6.2 FIRE PROTECTION

Cable assemblies shall be protected to be fire-resistant to the extent required by codes and standards of the Authority Having Jurisdiction.

6.2.1 Fire-Resistance Ratings and Fire Tests

The fire-resistance rating of cable assemblies shall be determined in accordance with the test procedures set forth in ASTM E119 or the alternative method described in Section 6.2.2. Where cable assemblies that have not been tested as part of a fire-resistance-rated assembly are incorporated into such assembly, sufficient data shall be prepared to show that the fire-resistance rating of the assembly is not reduced.

6.2.2 Alternative Methods for Determining Fire Resistance

The application of any of the alternative methods described herein shall be based on the fire exposure and acceptance criteria specified in ASTM E119. The required fire resistance of cable shall be permitted to be established by any of the following methods or procedures:

- Fire-resistant designs documented in sources approved by the Responsible Design Professional and the Authority Having Jurisdiction.
- Prescriptive designs of fire-resistance-rated building elements contained in the codes and standards of the Authority Having Jurisdiction.
- Calculated fire resistance in accordance with the provisions of Chapter 5 of ASCE/SEI/SFPE 29-05.
- Engineering analysis based on a comparison of building element designs having fire-resistance rating as determined by test procedures set forth in ASTM E119.
- Alternative protection methods approved by the Responsible Design Professional and the Authority Having Jurisdiction as equal to or better than the level of fire safety provided by cable assemblies, that are fire-resistance rated in accordance with the test procedures set forth in ASTM E119.

7.0 FABRICATION, SHIPPING, AND RECEIVING

7.1 SOCKETING

Sockets shall be attached by an approved method. For resin socketing, the resin manufacturer's recommendations regarding the ambient temperature and the temperature of the cable and fitting shall be strictly observed.

7.2 PROOF LOADING OF ASSEMBLIES

When required in the contract documents, assemblies with attached sockets shall be proof loaded to the tension force specified in order to verify the integrity of socketing. With prior approval by the Engineer, the fabricator may proof load both ends of each assembly independently by utilizing approved cable grips, instead of loading the entire assembly at once.

7.3 PRESTRETCHING

Cables shall be prestretched to achieve the minimum values of the modulus of elasticity specified in the ASTM specification covering the product, unless other modulus values are called for in the Contract Documents.

7.4 CABLE LENGTH MEASUREMENTS

Length measurements of the cable shall be made after prestretching under the cable tensions specified in the Contract Documents.

7.5 STRIPING

When specified by the Contract Documents, a longitudinal paint stripe shall be applied to the cable while it is subjected to the tension specified for length measurements.

7.6 SHIPPING

Cable assemblies shall be shipped on reels or in coils. Rope shall not be wound onto a reel or into a coil that has a diameter less than 25 times the rope diameter.

Both wire diameter and cable prestretch influence cable flexibility. Smaller reel or coil diameters shall be approved only after consultation with cable manufacturers and acceptance of their shipping practices. Utmost care shall be exercised during shipment and handling to avoid damage to the cables and their coatings.

7.7 RECEIVING

Material receipt certifications shall be used to document all structural materials delivered to the site, and to document all nonconformances of the delivered materials. The erector shall notify the manufacturer and the Engineer of any nonconformances.

8.0 ERECTION

8.1 ERECTION PROCEDURE

The construction Contract Documents shall show a recommended erection procedure for the proposed structure. That procedure shall reflect all assumptions regarding the erection sequence made during the structural design. Unless otherwise stated in the Contract Documents, the contractor shall follow the recommended erection procedure or follow an approved alternate erection procedure. The erector shall submit an execution plan for the specific erection procedure and equipment, with a timeline for installation and for duration of work activities, and with a risk management plan.

8.2 CABLE INSTALLATION

Care shall be exercised during erection to avoid damaging the cables and their coatings. The cables shall not be dragged over or around any objects that will scrape, abrade, or distort the wires, thereby causing damage to the markings, protective coating, or cable assemblies. Cables shall not be bent sharper than as specified in Section 7.6. Striped cables shall be erected such that the paint stripe applied during measuring is straight after erection.

8.3 INTERMEDIATE FITTINGS

Intermediate saddles and clamps shall be attached in a manner that will not damage the cables. Such fittings shall be positioned so as not to induce twist in the cable, and shall be designed to transmit the forces introduced by the attached structural members.

9.0 POST-CONSTRUCTION CONSIDERATIONS AND INSPECTION

Structural cable elements and their associated components shall be inspected and maintained during the working life of the structure. Inspection procedures shall be developed by the Engineer and be included in a structure maintenance manual held by the Owner. A Professional Engineer shall direct the inspection.

In addition to previously cited specifications for nondestructive inspection of cable elements and components, the following specification should be referenced: ASTM E1571-06, *Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope.*

9.1 MAINTENANCE CONSIDERATIONS

Maintenance shall be performed to keep cables and their components functioning as intended. Maintenance shall be ongoing and also shall follow all routine, in-depth, and emergency inspections as required on the basis of the inspections.

9.2 ROUTINE INSPECTIONS

All cables and their associated elements shall receive a routine inspection on a 2-year cycle to determine their physical and functional condition, and to identify any changes that deviate from the original approved installation. These routine inspections may be primarily visual inspections performed from ground level or other accessible walkways or platforms. Every cable element shall be inspected, and binoculars shall be used to inspect inaccessible components. Special cable guides, boots, anchorage covers, etc. that would hide the cable from view need not be removed.

The level of effort for a routine inspection shall be sufficient to detect major damage or conditions that deviate from the original approved installation or prior inspection. These conditions would include, but are not limited to, cable corrosion and/or major failures of the cable’s coating system, and any major damage due to unusual wind-induced vibrations.

9.3 IN-DEPTH INSPECTIONS

All cables and their associated elements shall receive an in-depth inspection on a 6-year cycle. It is the intent of the in-depth inspection to identify deficiencies not readily detectable during the routine inspection.

In-depth inspections are to be performed at arm’s length, and will normally require equipment such as lifts, cranes, bucket trucks, ropes, or aerial work platforms for access. Existing protective coverings, cable guides, boots, cuffs, or jackets shall be removed on a representative sample of the cables as part of this inspection. Special attention shall be paid to areas near anchorages where moisture may tend to accumulate and where cable wires may tend to bend at the fitting.

Routine inspections are not required to be performed in the same year as an in-depth inspection.

However, an unscheduled in-depth inspection may be warranted due to findings of a routine inspection.

The level of effort for an in-depth inspection shall be sufficient to identify corrosion, cable wire cracks or breaks, cable slippage or loosening at the end fittings, cracks in the end fitting castings, and wire section loss due to either corrosion or abrasion. Breaks in individual wires, often near end fittings, may be caused by fatigue. An acceptable limit on the number of observable wire breaks shall be established, along with a recommended cable replacement procedure if the limit is attained.

At the discretion of the Engineer, nondestructive inspection techniques shall be required as part of an in-depth inspection. The Engineer is cautioned that while many of these techniques may detect broken wires within clear runs of cable length between end fittings, they are often ineffective in detecting flaws in the most susceptible areas, namely, at the end fittings.

9.4 EMERGENCY INSPECTIONS

An emergency inspection is an unscheduled inspection to assess structural damage resulting from unusual environmental events, storms, human actions, or fire exposure.

In the interest of public safety, the level of effort for an emergency inspection shall be sufficient to determine whether there is a need to either establish load restrictions or to temporarily close part or all of the structure. At the discretion of the Engineer, nondestructive inspection or cable removal with laboratory testing shall be required. A follow-up in-depth inspection may be required to more fully document the extent of damage and confirm the urgency for repair work.

9.5 SPECIAL INSPECTION AND TESTING

Depending upon previous inspection results, degree of deterioration, environmental conditions, and the length of time the cable has been in service, consideration shall be given to removing, testing, or replacing one or more cables. Cables selected for removal will normally be those experiencing the greatest degree of deterioration or those located in the most vulnerable areas of the structure.

The type of test(s) performed on the removed cable shall be at the discretion of the Engineer.

9.6 INSPECTION RESULTS

Results of all inspections and recommended follow-up actions shall be written and filed with the structure maintenance manual.

COMMENTARY TO ASCE STANDARD 19-10 STRUCTURAL APPLICATIONS OF STEEL CABLES FOR BUILDINGS

This Commentary is not part of the American Society of Civil Engineers Standard *Structural Applications of Steel Cables for Buildings*. It is included for informational purposes.

C1.0 GENERAL

C1.1 SCOPE

Although permanent steel suspended roofs (in the general sense) were built in the United States at least as far back as 1931, no standard for the design of cable building structures was available in the United States before ASCE 19-96. In 1966, the *Tentative Criteria for Structural Applications of Steel Cables for Buildings* was published by the American Iron and Steel Institute (AISI). Shortly thereafter, *Design Fundamentals* was published by U.S. Steel (Scalzi et al. 1969). The AISI *Criteria* was later revised to form the *Manual for Structural Application of Steel Cables for Buildings* published in 1973 by AISI. Both documents addressed the use of zinc-coated steel structural strand (ASTM A586), historically known as “bridge strand,” and zinc-coated steel structural wire rope (ASTM A603), which is commonly termed “bridge rope.”

In 1996 ASCE issued Standard 19-96 entitled *Structural Applications of Steel Cables for Buildings*. The Standard treated a wider range of metal wire strand and rope products than the *Manual*. Furthermore, in contrast to the *Criteria* and the *Manual*, the Standard was written in mandatory language.

Structural rope and structural strand are both used in static applications to transmit force. Structural strand has a higher modulus of elasticity and a greater minimum breaking force for a given size, and is usually the choice in applications where the structural assembly is straight. However, if the structural assembly makes a significant bend over an object, structural rope is used. Structural rope adjusts to bend better than structural strand. Both products are flexible, but to different degrees. See Table 3-2 for deflection reduction factors.

Since ASCE 19-96 was published, there have been changes in the reference specifications as well as globalization of construction. The time has arrived for updating the Standard to include new ASTM specifications, international cable products, and cable construction practices. In the present documents, some products used as cables in ASCE 19-96 have been removed from the text body or are restricted for use as cables. These products include parallel wire strand (unique handling requirements and limited use in recent years), seven-wire prestressing strand (manufactured specifically for concrete products and requires different fitting factors), and steel rod (other design codes apply and its makeup does not fit the definition of strand or rope).

The scope of the updated Standard is broadened to include cable-supported walkways. For cable-supported highway bridges, the reader is referred to the Post-Tensioning Institute *Recommendations for Stay Cable Design, Testing and Installation* (PTI 2001) and specialty books such as Gimsing (1997) and Walther (1999), and the *ICE Manual of Bridge Engineering* (2008). For guy-supported communication and utility towers, the reader is referred to ASCE 10-97, *Design of Latticed Steel Transmission Structures* (ASCE 2000), and ASCE Manual 91, *Design of Guyed Electrical Transmission Structures* (ASCE 1997).

The sections of this Commentary have titles and are numbered to correspond to the sections of the Standard to which they refer. Because it is not necessary to have supplementary materials for every section in the Standard, there are gaps in the Commentary numbering.

C1.2 GLOSSARY

Some manufacturers and some ASTM specifications refer to nominal cable strength as “minimum breaking strength” or “minimum breaking force.”

Prestressing and prestretching are not synonymous. Prestressing is conducted where and when a cable is installed; prestretching is generally a shop operation performed before a cable is shipped. Prestretching is sometimes conducted without first having fittings installed.

Rope and strand are defined without a restriction on the cross-sectional shape of the wires of which the rope or strand is constructed. “Locked-coil strands” is U.S. terminology; in Europe they are referred to as “locked-coil ropes.”

C2.0 CONTRACT DOCUMENTS AND SHOP DRAWINGS

C2.1 CONTRACT DRAWINGS

C2.1.1 Contract Drawings

In addition to the usual engineering data necessary for fabrication and erection, additional information is required for cable structures peculiar to their behavior. Sufficient detail of loading versus configuration of the cables should be provided to account for their load-adaptive behavior. The centerline length, accounting for the sag and creep of each cable segment between attachments under the corresponding tension at a specific temperature, should be shown on the contract drawings. Likewise, erection sequence or procedure, or both, may produce a configuration, loading, or reaction not obvious from the configurations shown on the drawings. These configurations may not be readily determinable by the erector and therefore need to be described by the Engineer. The behavior of cable structures may require that the Designer pay considerably more attention to erection procedures than is normally given to rigid structures.

C2.1.2 Contract Specifications

Compared to conventional building construction, the Contract Specifications should reflect the unusual requirements necessary for cable structures. Additional coverage and detail are likely to be required in specifying material, loading criteria, fabrication, and erection.

Relative to material, when strand or wire rope is specified by reference to an ASTM standard specification, the Contract Specifications for test reports could include a requirement for both mill test reports for the wire and product test reports for the strand or rope. For example, for zinc-coated strand specified by reference to ASTM A586, the mill test reports for the wire could include the heat number(s) for the base metal carbon steel, the zinc-coated wire diameter, the 0.7% elongation under load (EUL) yield stress, the tensile strength, the total elongation before fracture measured over a 10-in. gage length, and the wire wrapping ductility test result. Also, for this example, the product test reports for the strand should include the number of layers of wire and the number and size of wires in each layer.

Because the ASTM specifications for zinc-coated strand and wire rope do not require that a test sample for minimum breaking strength and modulus of elasticity be taken from each manufactured length of cable (run of cable, not fabricated length), the Contract Specifications should identify whether such test samples should be taken. Data should be reported on the cable breaking strength and the modulus of elasticity.

In the case of stainless steel wire strands, the mill test reports could identify the grade of stainless steel used for the wire and the chemical composition of the wire.

In addition to the information required by ASTM A586 and A603, other design requirements may need to be specified. These include striping, end termination type/orientation/size, and length tolerance. Manufacturers should be contacted for the specific requirements.

The Contract Specification should provide the following guidelines for acceptable tolerances of the cable length beyond which additional analysis may be required:

- For a cable length of 120 ft (36.59 m) or less, the cut length of cable shall be determined so that the length of cable shall be within ± 0.03% of the theoretical length after prestretching, except that lengths less than 28 ft (8.54 m) shall have a tolerance of ± 0.1 in. (2.54 mm).
- For a cable length longer than 120 ft (36.59 m), the cut length of cable shall be determined so that the cable length shall be within $\left[\pm\left(0.0217\times\sqrt{\text{cable length in feet}}\pm 0.197\right.\right]$ in., or $\left[\pm\sqrt{\text{cable length in m}}\pm 5\right]$ mm of the theoretical length after prestretching.

The Contract Specification should state that the contractor should consider cable creep, socket seating, and elongation of cables due to clamping action. The contractor should submit erection sequencing drawings and calculations.

C2.2 SHOP DRAWINGS

Besides reflecting the contract documents in the usual manner, Shop Drawings for cable structures require more detail in order to adequately indicate cable preparation and treatment. Critical or unusual fabrication; prestretching, marking, and striping; as well as the fittings themselves are matters that need to be addressed on shop drawings for cable structures. Assembly length should account for socket seating.

The requirement for erection drawings introduces the potential in cable applications for a design where erection may produce the worst or critical loading state for cables, fittings, or anchorages. Where erection affects design, involvement of the engineer in all phases of the erection process of the project is required.

C3.0 DESIGN CONSIDERATIONS

C3.1 DESIGN BASIS

The cable system, including masts and struts, must have adequate strength to support the design loads safely. The components shall be designed to resist design member forces: axial force, bending, and buckling (or a combination of these internal forces) at unit stresses (forces) less than the allowable stresses (allowable forces) for the material and cross section of the component. The cable system shall be designed using working stress design (WSD) or allowable stress design (ASD). The remainder of the building structural system may be designed using ASD or strength design (ultimate strength design; USD, or load and resistance factor design; LRFD).

Serviceability shall be ensured by configuring and sizing the cable structure so that displacements due to the maximum service actions will not cause excessive damage to finishes, etc. When computing these displacements, the deformations of the remainder of the building's structural system may have to be considered.

C3.1.1 Structural Integrity

The collapses at the Ronan Point apartment house in London, the Alfred P. Murrah Federal Building in Oklahoma City, and the World Trade Center towers in New York illustrate the consequences of local collapses that progressed to a disproportionate part of the whole building. ASCE/SEI 7-10 requires that buildings be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage. Similar provisions are included in Eurocode, which has specific provisions regarding the components that shall be permitted to fail without excessive risk of overall collapse. The Commentary in ASCE/SEI 7-10 suggests precautions that may be taken to improve robustness. Although they do not specifically address cable structures, the suggested approaches are valid for all buildings. For example, the building should not collapse if any column is removed by explosion; the collapse of one floor should not cause lower floors to collapse, etc. Analogously, a cable structure should not collapse if one local element of the cable system is damaged, regardless of the cause.

C3.2 DESIGN LOADINGS

C3.2.1 Loads

Because cable force is affected by change in length and geometry, creep will influence cable force.

C3.2.2 Load Combinations

The load combinations adopted for this Standard are similar to the basic combinations for allowable stress design (ASD) in Section 2.4.1 of ASCE/SEI 7-10.

C3.3 CABLE STRENGTH

C3.3.1 Design Strength

The amplification factor of 2.2 is intended to safeguard against accidental overloads, deviation in material properties, and fabrication tolerances that may adversely affect the structural behavior of the cable assembly and thus the cable structure as a whole.

C3.3.1.3 Elevated Temperature Effect

Physical properties of cable materials are affected by elevated temperature, such as heat of a fire. Three variables affect these properties: temperature of the cable, the cable's exposure time to the elevated temperature, and the unit stress in the cable during the time it is exposed to elevated temperature.

Three factors should be considered. The first is the change in the length of the wires during the temperature rise. The second is the possible permanent change in the metallurgy of the wires as a result of high temperature. Wire used for structural cables is cold drawn; it has a high tensile strength due to that cold work. Heat from fire causes the material to return toward its annealed condition, thereby reducing its strength. The third factor, elevated temperature, also affects the capacity of socketing materials.

C3.3.1.4 Fatigue Strength

The structural application of steel cables for buildings does not generally involve large, fluctuating tension-to-tension load ranges in the cables. Thus, cable fatigue due to fluctuating tension-to-tension loads is not usually a limiting initial design consideration in building applications. On this point, the application of steel cables in buildings is unlike the use of steel cables in vehicular bridge construction.

However, building components displace under the actions of dynamic and environmental effects. Wind- and rain-induced vibrations can lead to fluctuating bending, torsion, and tension loads in cables. A need for fatigue evaluation can develop, particularly near areas of rotational rigidity such as at end fittings and around sheaves and saddles. Moreover, vibrational movement in cables can lead to fretting, in which there is rubbing of one wire against another due to motion of cable.

The effect of fatigue in steel cables is progressive fracture of individual wires. As individual wires break, the breaking strength of the cable is reduced. If a large number of wire breaks occur, the breaking strength of the cable can be diminished to the extent that it underachieves, possibly significantly, the nominal breaking strength. This is why the Standard specifies placing a limit on the number of observable wire breaks (observed during inspections) and specifying a cable replacement procedure.

Cable fatigue has been studied both experimentally and analytically since the late 1950s. The studies have indicated that the following factors can influence (generally decreasing) a cable's fatigue strength:

- An increasing fluctuating load range relative to the nominal breaking strength
- A decrease in the number of wires in a strand, for the same net area
- A decrease in the ratio of deflector or sheave radius-to-cable diameter
- With dynamic effects, a decrease in cable diameter
- The type of end fitting

While cable fatigue tests and studies have addressed numerous cable parameters—type of end fitting, manufacturing process, cable construction (rope, strand, lay, number of wires), presence of deflector or sheaves—no inclusive criterion for fatigue life has yet been established. Still, guidelines and rules have been promulgated for some applications; see Appendix D.

C3.3.1.5 Creep Effect

Because creep causes changes in cable length and/or geometry, creep will influence the force in the cable. Creep is the long-term cable elongation after prestretching. Though prestretching initially seats the cable wires into a more compact cross section to obtain homogenous elastic cable elongations, creep will still occur on all cables under service loads.

Creep has been found to occur within 200 h under static load testing, and also in completed structures after the application of several load effects. The amount of creep depends on the cable construction, the diameter and number of wires, load level, load duration, and temperature.

Generally, lower stress levels will result in a slower creep rate. The magnitude of total accumulated creep will normally vary from 0.01% to 0.06% of the original cable length.

C3.4 STRUCTURAL ANALYSIS

C3.4.1 General Considerations

The forces within the cables and the supporting structure should be determined by accepted procedures of structural analysis. Physical model testing may be useful for preliminary shape-finding and obtaining force estimates. Elastic stretch of the cables should be accounted for in the structural analysis. Moreover, because cable assemblies are usually quite long, the effect of ambient temperature changes on the cable geometry and changes in axial forces should be evaluated.

Cable elements are primarily loaded in tension and have little or no bending or shear stiffness. Therefore, they rely on their shape and internal prestress to achieve stability and to carry loads. Consequently, pretensioned cable elements tend to exhibit geometric nonlinear behavior. A doubling (or a halving) of the cable load does not double (or halve) the load effect (tension or displacement) in the cable. Nonlinear material properties are typically not an issue for cable elements under service loads.

Nonlinear analyses of cable-supported structures are typically necessary to account for the following:

- The effect of joint displacements on equilibrium
- Nonlinear terms in the equations for change of length
- Nonlinear constitutive equations

Of these, the influence of joint displacements is the most important. If dead load effects and prestress are large compared to live load effects, nonlinear analyses may not be required.

C3.4.3 Vibrations

Dynamic analyses may be performed using any recognized procedure. Because vibration studies are made on the configuration of the completed structure (total dead load plus prestress state), a linear analysis is often satisfactory. Dampers may be installed in order to modify dynamic response.

C3.4.4 Deflections

The usual engineering considerations for deflections also apply to cable structures. Careful consideration should be given to deflection due to creep and shrinkage of supporting members. The total (long-term) deflection of structural members should be determined and the movement of cable supports considered.

C3.4.5 Erection Analyses

The ratio of the applied load to the previously imposed load may be high during erection. Therefore, joint displacements can be expected to be an important factor in the description of structural behavior at this design stage. Nonlinear analysis is often required for erection calculations even though it may not be required for the design of the completed structure. A special case of erection analysis is required when one or more cables is (are) being replaced due to damage. As part of the replacement process, analyses should be made accounting for the loading on other cables as one cable is being replaced.

C4.0 CABLE MATERIALS

Cable materials should be selected on the basis of their suitability for the intended structural application. Historically, cables used to structurally support and/or brace buildings and structures have strand conforming to ASTM A586 [minimum diameter of ½ in. (12.7 mm)] or wire rope conforming to ASTM 603 [minimum diameter of ⅜ in. (9.5 mm)]. Cables ⅜ in. (9.5 mm) or greater in diameter conforming to the other listed specifications are also acceptable, excluding cables with fiber cores (natural or synthetic) because such cores (1) can retain fluid, which may promote internal corrosion in moist atmospheres, and (2) are subject to heat-induced softening and charring that impairs support function.

Table 9 of ASTM A1023/A1023M-09 *Standard Specification for Stranded Carbon Steel Wire Ropes for General Purposes* is listed in order to allow the use of small diameter (galvanized) specialty cord for the purpose of providing earthquake-load-resistant sway bracing of nonstructural architectural, electrical, and mechanical components.

The Standard allows the use of strands made with wires of noncircular construction. For example, locked-coil strands have one or more outer layers of wires that have a Z-shaped cross section. Because of the interlocking action of those wires when the strand is under tension, the strand is almost sealed against the entrance of moisture and loss of inner filling. Because no U.S. specification exists, refer to UNE-EN 12385-10:2004+A1:2008 *Steel Wire Ropes – Safety – Spiral Ropes for General Applications*.

Some common cable constructions are illustrated in Appendix A.1.

C5.0 FITTINGS

It is recommended that fittings be of proven designs. When the application requires special fittings, manufacturers of cables and manufacturers of fittings should be consulted for guidance. Zinc-poured sockets, resin-poured sockets, and swaged fittings are common in the United States; and zinc-aluminum-mischmetal alloy-poured sockets are used by European cable manufacturers. When resin-poured sockets are used, the designer should contact the code Authority Having Jurisdiction to confirm that the resin meets the applicable requirements of the code with regard to structural supports that are required to be noncombustible structural materials.

Engineering considerations should include, but not be limited to: wedging action of poured zinc sockets, fatigue strength, swageability of swaged fittings, friction losses, inspection, and fatigue strength of threaded sections, nuts, pins, and pin plates. Appendices A.2 and A.3 illustrate some representative end fittings.

Appendix B offers guidelines for the design of saddles. When using galvanized cables, the saddle groove surface in contact with the strand may be coated with zinc deposited by metalizing. A 1/32-in. (1-mm) thickness is sometimes used, but the designer should recognize that the coefficient of friction between the cable and saddle surface is a function of the zinc deposit thickness. Guidelines for the design of clamps are presented in Appendix C.

C6.0 PROTECTIVE COATINGS

It is well known that corrosion protection is needed to minimize loss of wire cross section. Less well known are the stress corrosion problems encountered in some highly stressed cable systems. Protective coatings other than zinc may be used, provided they are shown by test or experience to offer adequate corrosion protection. Consideration of supplemental protection methods shall especially include effects on cable installation, dripping or staining, odors, and other possibly detrimental effects. Additional protection may be provided by combining two or more compatible protective systems.

As indicated in the Standard, ferrous cables are usually zinc-coated. Class A coating is quite adequate for indoor use and most outdoor exposures under normal or ordinary conditions. Class B and C zinc coatings and zinc-aluminum-mischmetal alloy coatings are available for use where more severe exposures are anticipated. The designer should consult the cable manufacturer regarding the availability of Class B and C zinc coatings and zinc-aluminum-mischmetal alloy coatings for the wire sizes that may be necessary to make a particular cable.

For exposures involving condensation, salt, or chemicals, additional protection may be required. Among the possible protective methods are coating, use of rust-preventive compounds, blocking compounds, and metallic coatings other than pure zinc, such as zinc-aluminum-mischmetal alloy. Only protective coatings satisfying all applicable environmental codes and regulations should be used. Additionally, only protective coatings with historical proven success in shop or field testing should be used.

Zinc, metallic, or other wire coatings provided as the primary corrosion protection shall be shop-applied to ensure bonding to the individual wires. Blocking compounds must be shop-applied to ensure complete blocking. Cable coatings are field-applied. Rust-preventive compounds may be shop- or field-applied, depending on the specific compound's characteristics. Due to the variety of protection systems available, it is suggested that the cable manufacturer be consulted**.**

Repair of damaged galvanized coatings is described in ASTM A780/A780M-09, *Standard Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings*. Zinc-rich paints may be used for field or shop repair. Zinc-based solders should normally be used for shop repairs only, as temperature control is required to avoid heat damage to adjacent wires and coatings. Sprayed zinc is not appropriate for finished cable repair.

C6.1 CORROSION PROTECTION

Zinc-aluminum-mischmetal alloy coatings have been used successfully on many international cable projects utilizing ferrous wire cables. Performance of these systems suggests superior corrosion protection versus conventional heavy galvanizing with the same coating thickness.

Filling the cable interior during cable stranding operations restricts the ingress of moisture. Cable interior voids can be filled with an active or passive material. An example of an active material may be a suspension of zinc in polyurethane oil. An example of a passive material may be a permanent elastic-plastic wax or aluminum flake in hydrocarbon resin. Cable coating systems may consist of paint, hydrocarbon resin, cable wrap/jacket, or other proprietary product. When used in conjunction with inner filling materials, these coatings shall be checked for possible incompatibilities. It should be noted that cable wraps or jackets will make direct visual inspection of the cable impossible.

C6.2 FIRE PROTECTION

The responsible design professional or codes and standards of the Authority Having Jurisdiction may require that cable assemblies be fire-resistant. Codes and standards generally require that building elements be fire-resistance-rated based on the size and use of buildings. Most single-story buildings are not required by codes to have fire-resistance-rated building elements. Buildings more than three stories in height are often required to have fire-resistance-rated building elements, and high-rise buildings are nearly always required to have fire-resistance-rated building elements. In general, the code required amount of fire resistance (fire-resistance rating), varies from 1 to 3 h depending on the size and use of buildings. Some building codes have exception provisions that allow an automatic fire sprinkler system to be substituted for 1-h fire resistance of building elements.

C6.2.1 Fire Resistance Ratings and Fire Tests

The fire test standard for the fire-resistance rating of building elements that is specified in virtually all codes of the United States is the ASTM E119 Standard. Testing laboratories, such as Underwriters Laboratories, publish listings of fire-resistance-rated materials which may directly or indirectly address the required fire resistance of cable assemblies. Such tests may also be utilized as the basis of alternative methods, as further addressed in Section 6.2.2.

Cables and their assemblies can be fire-protected by intumescent paints, spray-on fireproofing with cementitious mixture or with sprayed fiber, and thermo pipe insulation directly applied to cables and their assemblies.

A Fritz Engineering Laboratory Report (Slutter 1969) gives results of fire tests performed on structural strands and fittings coated with the fireproofing materials listed above.

C6.2.2 Alternative Methods for Determining Fire Resistance

The provisions for alternative methods for determining fire resistance are based on Chapter 7 of the *2006 International Building Code* (IBC) (ICC 2006). These provisions are performance-based alternatives to specific testing under ASTM E119. Chapter 7 of the IBC also has generic descriptions of various fire-resistance-rated steel building elements, which could be utilized as the basis of determining an acceptable fire-resistance rating for cable assemblies.

C7.0 FABRICATION, SHIPPING, AND RECEIVING

The term "fabrication" as used in the Standard signifies manufacturing operations such as prestretching, measuring, cutting, socketing, proof-testing end fittings, and reeling or coiling wire strands or ropes.

Proper attachment of the sockets is crucial to the performance of a cable. It is recommended that zinc-poured sockets and resin-poured sockets be attached as described in the *Wire Rope Sling Users Manual* (WRTB 2007), or by an accepted industry equivalent.

Elongation of a twisted wire cable subjected to tension results from a combination of elastic or recoverable stretch of the wire material, and inelastic or constructional stretch. The latter results from the equipment utilized in manufacturing the cable, the arrangement of the wires within the cable, and the length of lay (helical pitch) of the cable components. To minimize the effect of constructional stretch, the cable is prestretched by applying a predetermined tension, usually not exceeding 55% of the nominal strength of the cable. After prestretching, the cable has better-defined and more-uniform elastic properties. For large-diameter cables, the capacity of the manufacturer's equipment may not be adequate to tension the ropes to 55% of the nominal strength. Therefore, it is desirable to consult a cable manufacturer prior to finalizing the specification for prestretching.

After the uniform elastic properties of the cable have been established, overall lengths and fitting positions can be measured within close tolerances for tensions less than about 90% of the prestretching tension. The elastic response of the prestretched cable within the completed structure can be confidently predicted.

All fittings and clamps should be carefully attached to cables in order to develop the efficiency shown in Table 3-1. It is advisable to specify standard clamps and fittings from fitting or cable manufacturers. If other fittings or clamps are required, their design should be discussed with a cable fabricator or fitting manufacturer.

Individual cable manufacturers use different ratios of coil diameter (or reel diameter) to cable diameter when shipping cables. Generally, larger-diameter cables require a larger coiling or reeling diameter than do smaller-diameter cables, particularly for strands. However, cables with some combinations of strand-wire diameter and cable prestretching require larger coiling/reeling diameters. Coil diameters will also vary with type of cable construction. For example, Z-Lock cables require a larger coil diameter than cables conforming to ASTM A475-03(2009)e1, *Standard Specification for Zinc-Coated Steel Wire Strand*, having the same cable diameter.

C8.0 ERECTION

C8.1 ERECTION PROCEDURE

As stated in the Standard, the erection procedure includes the erection sequence for the cable installation, and monitoring of corresponding forces and geometry for each erection stage. This monitoring requires a means of verifying the actual forces and geometry at each erection stage compared to the values obtained by analysis. Monitoring at an earlier stage is important because correction of cable forces and/or geometry at a later construction stage is often difficult. Because of the cable interaction in a structure, only the tension in preselected cables needs to be checked as verification for the overall cable structure. The engineer's suggested outlined erection procedure, or the procedure proposed by the contractor and approved by the engineer, should identify these cables and their forces at each erection stage.

A moderate tensioning rate of all cables is recommended (cables should not be pretensioned through shock-applied loads). During critical stages under high forces, small, synchronized cable tensioning steps should be applied in sequence to avoid unexpected force increases in individual members.

Tensioning forces should be monitored and recorded to avoid unforeseen overloading of individual cables.

The geometry of individual tension members should be monitored carefully during all lifting and tensioning operations. After tensioning, the engineer should review the measured cable forces and final geometry. The ambient temperature during tensioning operations should be recorded.

C9.0 POST-CONSTRUCTION CONSIDERATIONS AND INSPECTION

Cables and their associated elements need to be maintained and inspected during the working life of the structure. As compared to structural steel sections, cables have a greater surface perimeter for a given area of steel. Because of this, cables are subject to a greater rate of corrosion and tensile capacity loss than other steel member types. It is the owner's responsibility to regularly inspect and maintain the structure. The inspection schedule outlined in the Standard follows closely federally mandated inspection requirements for publicly owned bridges.

Cable inspection procedures are based upon Chapter 21 of the U.S. Federal Highway Administration's *Bridge Inspector's Training Manual/90* (FHA 1991).

C9.1 MAINTENANCE CONSIDERATIONS

Maintenance can normally be performed by the owner's building maintenance staff for such items as painting rusting components or cleaning off debris and bird droppings that could trap moisture and promote corrosion. More critical maintenance may require greater maintenance expertise.

C9.2 ROUTINE INSPECTIONS

Routine inspections are performed without the aid of special equipment. They are generally visual inspections, though components located near the ground or easily accessible will normally be inspected close-up. As-built plans, shop drawings, repair plans, and previous inspection reports will greatly assist the inspector.

It is expected that moderate to major areas of coating failure, corrosion, and their extents can be observed during a routine inspection. Broken surface wires that have unraveled or broomed out should also be detected. Major damage, deterioration, apparent loss of tension, and deviations from the original geometry found during a routine inspection should be immediately reported to the owner, and follow-up actions discussed.

C9.3 IN-DEPTH INSPECTIONS

In-depth inspections are intended to find deficiencies not readily detectable during a routine inspection. These items include severe corrosion or pack rust between individual cable wires or the end fittings; individual cracked or broken wires (especially near end fittings and clamps where localized bending may occur); cracks in the fitting castings; fretting rust caused by wires, pins, or plates rubbing against one another; wire section loss; and slippage/loosening at the end fittings. On some structures, it may be required to investigate areas not readily accessible for visual examination, such as cables covered with cable protection not easily removed without damage. A plan for replacing damaged covers, wraps, etc. should be established prior to the actual work.

Nondestructive testing procedures, including electromagnetic, radiographic, magnetic flux, acoustic, and high-energy x-ray procedures, are available to detect broken wires and deterioration, when performed and interpreted by experienced technicians. The methods are most reliable away from end fittings.

C9.4 EMERGENCY INSPECTIONS

Emergency inspections are performed after the cable system experiences sudden damage due to either environmental factors (such as snow or wind overloads), human interactions (such as accidents or intentional acts), or fire exposure. Another condition that may warrant an emergency inspection is unusual or excessive cable vibration due to wind.

Generally, the owner or a law enforcement officer will notify the appropriate individuals to request such an inspection. The inspector should determine the need for restricting live loads, if such loads can be regulated. Structure evacuation/closure should also be considered as an immediate recommendation until temporary shoring is in place. Due consideration for the inspector's own safety needs to be considered before entering the site. If excessive cable vibration due to wind is the reason for the inspection, the cable amplitude and the wind speed and direction should be noted. A record shall be kept of other factors which may be relevant, such as the presence of ice or water on the cables, or the extent of any damage has been established.

Though the outer wires of an overloaded or damaged cable may not have broken after an extreme event, nondestructive testing may be required to investigate the condition of the internal wires. Any cable protection should be removed in suspect areas to properly evaluate the cable's condition.

C9.5 SPECIAL INSPECTION AND TESTING

For many applications, cables may support static loads in an interior or protected environment. At the engineer's judgment, such conditions may not warrant removing/testing/replacement of a cable during the structure's life. When such ideal conditions do not exist, special inspection and testing may be required.

If corrosion inside the cable is accompanied by progressive loss of metallic cross section, the corrosion product buildup will cause the cable to bulge, making the problem detectable by external inspection. However, dissimilar metals, water, contaminants, and anaerobic conditions may be present at some cable installations. These situations, occurring with work-hardened steel wires operating at high stress levels and with relative movements between neighboring wires, make it feasible that individual wire failures could occur by mechanisms such as stress corrosion cracking, hydrogen embrittlement, fretting corrosion, or microbial corrosion action. Such failures may generate little corrosion product and could easily go unnoticed during external cable inspections. It is for all of these situations that special inspection and testing should be considered.

Destructive testing is one method of evaluating the internal wire condition. If it is determined that destructive testing is warranted, a representative cable sample(s) should be chosen for removal and testing. The sample(s) should include those with details that are experiencing, or are susceptible to, the worst deterioration (such as at the low points of a cable where moisture would tend to accumulate). Evaluation may include cable tensile breaking test at the socketed ends, a count of the broken wires, and wire tests for tensile strength (ASTM A586 and A603), ductility, and galvanized coating (ASTM A90/A90M-09, *Standard Test Method for Weight [Mass] of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings*, and A239-95(2009)e1, *Standard Practice for Locating the Thinnest Spot in a Zinc (Galvanized) Coating on Iron or Steel Articles*). Results can be compared to the originally specified material after fabrication. It should be noted that with respect to the tensile strength results, ASTM A586 and A603 dictate that the wire conforms to the required mechanical properties prior to cable fabrication. Other ASTM specifications, such as ASTM A474 and A475, may have different criteria. Tests conducted on wire extracted from cables may not present the same properties as the originally drawn and galvanized wire.

SELECTED BIBLIOGRAPHY

American Institute of Steel Construction (AISC). (2005). *Specification for structural steel buildings*, AISC, Chicago, Ill.

American Iron and Steel Institute (AISI) Committee on Building Research and Technology. (1966). *Tentative criteria for structural applications of steel cables for buildings*, AISI, Washington, D.C.

American Petroleum Institute (API). (1993). "Recommended practice for design, analysis, and maintenance of moorings for floating production systems." *API recommended practice 2FP1*, 1st ed., Order No. 811-00525, API, Washington, D.C.

American Society of Civil Engineers (ASCE). (2007). ASCE/SEI/SFPE 29-05. *Standard calculation methods for structural fire protection*, ASCE Press, Reston, Va.

ASCE. (2010). ASCE/SEI 7-10. *Minimum design loads for buildings and other structures*, ASCE Press, Reston, Va.

ASCE. (2000). ASCE 10-97. *Design of latticed steel transmission structures*, ASCE, Reston, Va.

ASCE. (1997). *Design of guyed electrical transmission structures: ASCE manuals and reports on engineering practice No. 91*, ASCE, Reston, Va.

ASCE, Committee on Cable-Stayed Bridges. (1992). *Guidelines for the design of cable-stayed bridges*, ASCE, Reston, Va.

ASCE. (1981). "Long span roof structures." *Symp. Proc., Ann. Convention and Exhibit*, St. Louis, Mo., October 26–30, ASCE Press, Reston, Va.

ASCE, Structural Division, Subcommittee on Cable-Suspended Structures of the Committee on Metals. (1971). "Cable-suspended roof construction state-of-the-art." *ASCE J. Struct. Div.*, 97, ST6, 1715–1761.

ASTM International (ASTM). (2009). ASTM E119-08a: *Standard test methods for fire tests of building construction and materials*, ASTM International, West Conshohocken, Pa.

Bridon International, Ltd. (2007). *Structural systems*, 3rd ed., Bridon International, Ltd., Doncaster, UK.

Brockenbrough, R. L., and Johnston, B. G. (1981). *Steel design manual*, U.S. Steel Corp., Pittsburgh, Pa.

Buchhold, H. A. (1985). *An introduction to cable roof structures*, Cambridge University Press, Cambridge, UK.

Colorado Fuel and Iron Corp. (1966). *Roebling wire rope handbook*, Colorado Fuel and Iron Corp., Trenton, N.J.

Costello, G. A. (1997). "A theory of fatigue." *Theory of wire rope*, 2nd ed. Springer-Verlag, New York, Chapter 10.

Federal Highway Administration (FHA). (1991). *Bridge inspector's training manual/90*: *Turner-Fairbank Highway Research Center Report No. FHWA-PD-91-015*, Federal Highway Administration, Washington, D.C.

Feyrer, K. (2003). "Endurance of wire ropes under fluctuating tension." *OIPEEC Bulletin 85*, <http://www.oipeec.org/pages/publications.htm> (May 10, 2010).

Feyrer, K. (1995). "Endurance formula for wire ropes under fluctuating tension." *OIPEEC Bulletin 70*, <http://www.oipeec.org/pages/publications.htm> (May 10, 2010).

Fisher, J. W., and Viest, I. M. (1961). "Fatigue tests of bridge materials of the AASTHO road test." *Highway Research Board Special Report No. 66*, Highway Research Board, National Research Council, Washington D.C.

Fleming, J. F. (1974). "Fatigue of cables." *University of Pittsburgh Research Report No. SETEC CE 74*-079, American Iron and Steel Institute (AISI) Project No. 1201-311, AISI, Washington, D.C.

Gimsing, N. J. (1997). *Cable supported bridges*, 2nd ed., John Wiley & Sons, Inc., New York.

ICE Manual of Bridge Engineering. (2008). 2nd ed., G. Parke and N. Hewson, eds., Thomas Telford, London.

International Code Council (ICC). (2006). *International building code*, ICC, Washington, D.C.

Irvine, H. M. (1992). *Cable structures*, Dover Publications, Mineola, N.Y.

Krishna, P. (1978). *Cable-suspended roofs*, McGraw-Hill, New York.

Laura, P. A .A. (1993). "Nondestructive testing and structural condition monitoring of mechanical cables." *Applied Mechanics Rev.*, 46(4), 133–138.

Otto, F., ed. (1969). *Tensile structures*, Vol. 2, The M.I.T. Press, Cambridge, Mass.

Paton, A. G., Casey, N. F., Fairbairn, J., and Banks, W. M. (2001). "Advances in the fatigue assessment of wire ropes." *Ocean Engineering 28*, Elsevier Science, Ltd., Oxford, UK, pp. 491–518.

Podolny, W., Jr., and Scalzi, J. B. (1986) *Construction and design of cable-stayed bridges*, 2nd ed., John Wiley & Sons, Inc., New York.

Post-Tensioning Institute (PTI). (2001). "Recommendations for stay cable design, testing and installation." *PTI guide specification*, 4th Edition, PTI, Phoenix, Ariz.

PTI. (1987). *Post-tensioning manual*, 4th ed., PTI, Phoenix, Ariz.

Raoof, M. (1996) "Axial fatigue life prediction of bridge cables." J. E. Harding, G. A. R. Parke, and M. J. Ryall, eds., *Bridge management 3*, E & FN Spon, London.

Reemsnyder, H. S. (1972). *The mechanical behavior and fatigue resistance of steel wire, strand and rope.* Ad Hoc Committee on Mechanical Rope and Cable, National Materials Advisory Board, National Research Council, Washington D.C.

Ridge, I. M. L., Chaplin, C. R., and Zheng, J. (2001). "Effect of degradation and impaired quality on wire rope bending over sheave fatigue endurance." *Engineering Failure Analysis 8*, Elsevier Science, Ltd., Oxford, UK, pp. 173–187.

Scalzi, J. B., Podolny, W. Jr., and Teng, W. C. (1969). *Design fundamentals of cable roof structures*, U.S. Steel Corp., Pittsburgh, Pa.

Simiu, E., and Scanlon, R. H. (1996). *Wind effects on structures*, 3rd ed., John Wiley & Sons, Inc., New York.

Slutter, R. G. (1969). "Fire tests of structural strand and fittings." *Fritz Engineering Laboratory Report No. 200.69.476.2*, Lehigh University, Bethlehem, Pa.

Stahl, F. L. and Gagnon, C. P. (1996). *Cable corrosion in bridges and other structures*, ASCE Press, Reston, Va.

Walther, R., Houriet, B., Isler, W., Moia, P., and Klein, J.-F. (1999). *Cable stayed bridges*, 2nd ed., Thomas Telford, London.

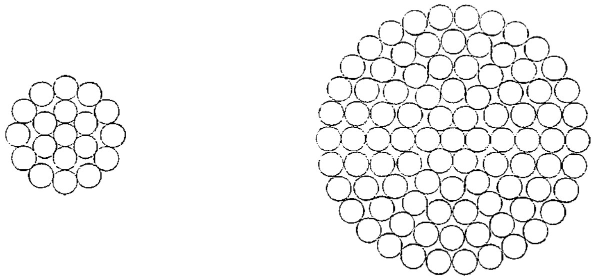
Wire Rope Technical Board (WRTB). (2007). *Wire rope sling users manual*, 3rd ed., WRTB, Alexandria, Va.

WRTB. (1993). *Wire rope users manual*, 4th ed., WRTB, Alexandria, Va.

Zhang, Z., and Costello, G. A. (1996). "Fatigue design of wire rope." *Wire Journal Int.*, 29, 2, 106–115.

APPENDIX A: CABLES AND FITTINGS

A.1 CABLE CROSS SECTIONS



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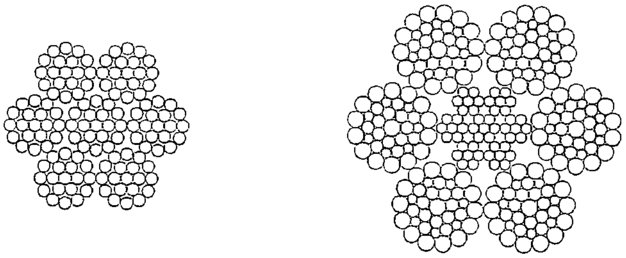
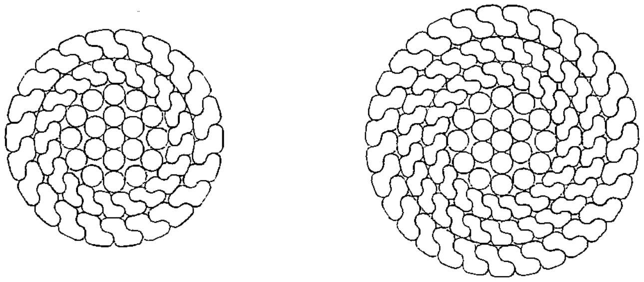
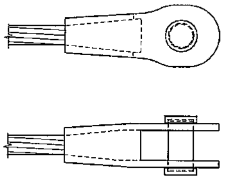


b.) WIRE ROPE



c.) LOCKED COIL STRAND

A.2 SOCKET FITTINGS



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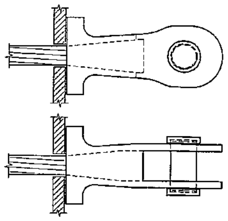

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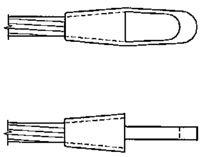

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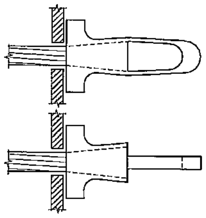

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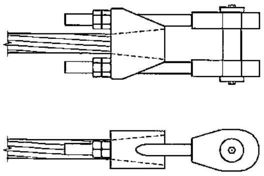

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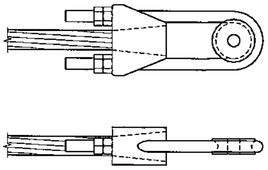

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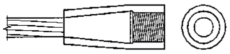

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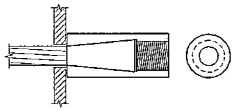
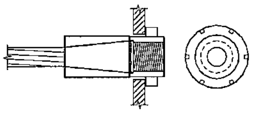
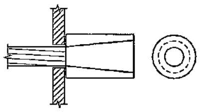


h.) INTERNALLY THREADED (CYLINDRICAL) SOCKET WITH BEARING

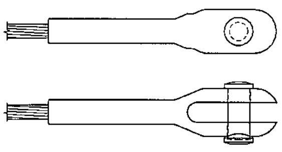


i.) TENSILE STRAND (THREADED CYLINDRICAL) SOCKET WITH BEARING NUT



j.) ANCHOR (PLAIN CYLINDRICAL) SOCKET WITH BEARING

A.3 SWAGED FITTINGS



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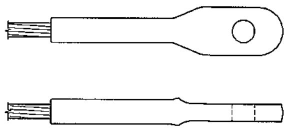
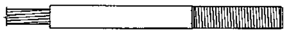


b.) CLOSED SWAGED SOCKET



c.) THREADED SWAGED SOCKET

APPENDIX B: SADDLES

The following criteria apply only to saddles where the live load changes the cable deflection angle less than 2 degrees for strand and 4 degrees for wire rope per saddle end. If the criteria do not apply, a wire rope and strand specialist should be consulted. If it is desired to support a cable consisting of a bundle of strands or ropes in a saddle, a wire rope and strand specialist should be consulted.

Saddle groove diameters recommended for individual wire ropes and strands should be the nominal diameter of the cable plus positive tolerances. Table B-1 provides recommended tolerances in fractional dimensions. These are generally in the range of +3% minimum to +11% maximum, compared to the cable diameter.

The maximum design coefficient of friction recommended to prevent sliding in a saddle should be 7%. This provides a factor of safety with respect to the actual coefficient. It must be recognized that the actual coefficient is a variable and can be much higher than 7%, perhaps as high as 12% to 15%.

The recommended maximum allowable projected bearing pressure exerted on the strand or rope by the saddle should be 4,000 psi (27.6 MPa) for 3-in. (76-mm)-diameter cables and larger, increasing linearly to 6,000 psi (41.4 MPa) for 1-in. (25-mm)-diameter cables and smaller.

Cast saddle grooves should have a smooth surface. All rough and high spots should be removed.

Table B-1 Saddle Groove Diameter Tolerances

Wire Ropes			Strands		
	Tolerance (in.)			Tolerance (in.)	
Wire Rope Diameter (in.)	Min.	Max.	Strand Diameter (in.)	Min.	Max.
3/8 to 1-1/8	+1/32	+3/32	1/2 to 1-1/2	+1/32	+3/32
1-3/16 to 1-1/2	+1/16	+1/8	1-9/16 to 2-1/2	+1/16	+1/8
1-9/16 to 3	+1/8	+3/16	Over 2-1/2	+1/8	+3/16
Over 3	+3/16	+5/16			

Note: 1 in. = 25.4 mm.

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APPENDIX C: CLAMPS

The recommended groove diameter of clamps shall be the nominal diameter of the cable plus positive tolerances. Table C-1 provides recommended tolerances in fractional dimensions. These are generally in the range of +3% minimum to +11% maximum compared to the cable diameter.

The depth of the groove in the clamps shall be such that when the clamps are fully tightened their faces will not be in contact with each other.

The maximum design coefficient of friction recommended to prevent slipping of the clamps on the strand or rope shall be 7%.

The recommended maximum allowable projected bearing pressure exerted on the strand or rope by the clamp should be 4,000 psi (27.6 MPa) for 3-in. (76-mm) size and larger, increasing linearly to 6,000 psi (41.4 MPa) for 1-in. (25-mm) size.

Cast clamps shall have a smooth surface in the grooves. All rough and high spots shall be removed.

All edges that contact the strand or wire rope shall be sufficiently rounded to suit all conditions of design and erection.

The nuts on the bolts of the clamps shall be alternately and gradually tightened to avoid any excessive unequal stressing of the clamp components or the cable to which the clamp is being attached.

The recommended angular change in direction of the cable at a clamp of the type shown in Figure C-1 shall not exceed 1.5 degrees for strand or 3 degrees for wire rope.

Table C-1 Clamp Groove Diameter Tolerances

Wire Ropes			Strands		
	Tolerance (in.)			Tolerance (in.)	
Wire Rope Diameter (in.)	Min.	Max.	Strand Diameter (in.)	Min.	Max.
3/8 to 1-1/8	+1/32	+3/32	1/2 to 1-1/2	+1/32	+3/32
1-3/16 to 1-1/2	+1/16	+1/8	1-9/16 to 2-1/2	+1/16	+1/8
1-9/16 to 2-1/8	+3/32	+5/32	Over 2-1/2	+1/8	+3/16
2-3/16 to 3	+1/8	+3/16			
Over 3	+5/32	+1/4			

Note: 1 in. = 25.4 mm.

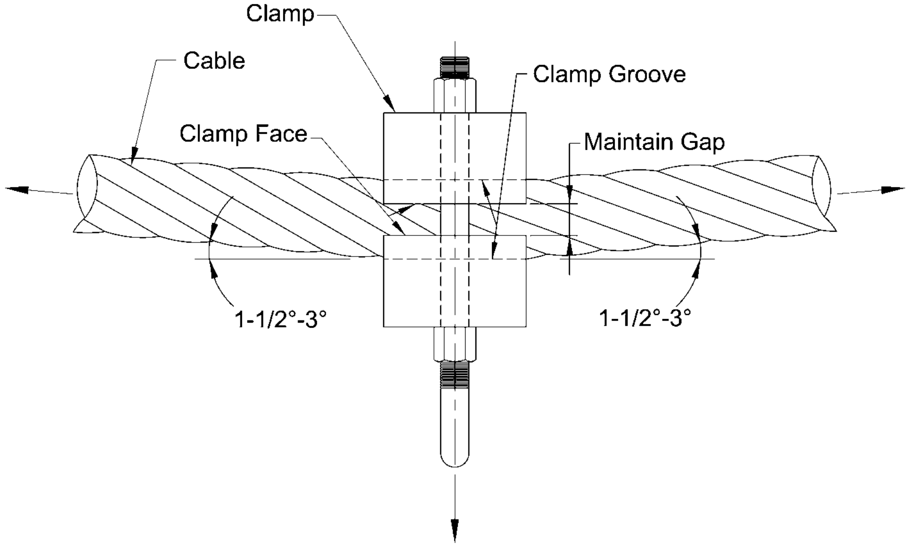

FIGURE C-1. Cable Clamp Fitting.

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APPENDIX D: FATIGUE

Empirical equations that predict cable fatigue life have been developed that are simple to use, but are rope- or strand-specific. For six-strand wire rope, Paton et al. (2001) proposed the equation:

$$N = [479.4/R]^{3.74}$$

in which N = fatigue life in cycles and R = the fluctuating axial load range expressed as a percentage of nominal breaking strength. Also, the American Petroleum Institute, in *API Recommended Practice 2FP1* (API 1993), for cable systems for wire rope moorings provides the equation:

$$N = 731/[P^{4.09}]$$

in which P = the ratio (not percentage) of load range-to-nominal breaking strength. API recommends dividing the calculated fatigue life N by 3.0 to arrive at a design service life.

As further sources, the Post-Tensioning Institute (PTI 2001; 1987) and the British Standards Institution, in BS-EN 1993-1-11:2006 *Eurocode 3: Design of Steel Structures: Design of Structures with Tension Components*, treat cable fatigue.

INDEX