PTI DC45.1-12

Recommendations for Stay Cable Design, Testing, and Installation

POST-TENSIONING INSTITUTE ®

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RECOMMENDATIONS

1.0 — SCOPE

These Recommendations pertain to the design, testing and installation of stay cables for cable-stayed bridges using prestressing wires, strand or bar as the main tension element. Recommendations are presented only for stay cables used in redundant cable-stayed bridges. These Recommendations are intended to be used in conjunction with the appropriate provisions of the "LRFD Bridge Design Specifications," from the American Association of State Highway and Transportation Officials (AASHTO LRFD).[1*]

This edition supersedes all previous editions. Standards and specifications shall refer to the latest edition unless a specific date is given.

1.1 — Referenced standards and specifications

1.1.1 — American Association of State Highway and Transportation Officials (AASHTO)

AASHTO "LRFD Bridge Design Specifications SI Units"

1.1.2 — American Welding Society (AWS)

D10.9, Standard for Qualification of Welding Procedures and Welders for Piping and Tubing

D10.11, Recommended Practices for Root Pass Welding of Pipe Without Backing

*Number refers to references listed in Section 8.0.

COMMENTARY

C1.0 — SCOPE

These Recommendations do not deal with the design of cable-stayed bridges in general, but are limited to considerations of design, inspection, testing and installation of stay cables. Stay cables utilizing helical or locked-coil strands, or wire ropes are not covered by these Recommendations.

Redundant cable-stayed bridges are bridges that are designed so that loss of an individual stay cable would not result in significant structural damage or failure of the bridge.

These Recommendations have been drafted on the basis of a typical U.S. construction contract in the public sector where there are three distinct and separate parties, namely:

- The Owner (i.e. Government or Public Agency)
- The Designer (i.e. the Engineer)
- The Contractor (i.e. the Bridge Builder)

The procedures herein reflect this organizational and contractual hierarchy. Elsewhere, contractual arrangements may differ. Likewise on Design-Build projects, the contractual arrangements are different.

Design procedures not covered by this document should be carried out by a Professional Engineer qualified in cable-stayed bridge design. Alternative methods should provide a level of safety and performance equivalent to a design conforming to these Recommendations.

C1.1 — Referenced standards and specifications

See Section 8.0 for more information about the sources of these documents.

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1.1.3 — ASTM International

A36/A36M, Standard Specification for Carbon Structural Steel

A53, Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless

A82, Standard Specification for Steel Wire, Plain, for Concrete Reinforcement

A123/A123M, Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products

A416/A416M , "Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete"

A421/A421M, Standard Specification for Uncoated Stress-Relieved Steel Wire for Prestressed Concrete

A673/A673M, Standard Specification for Sampling Procedure for Impact Testing of Structural Steel

A700, Standard Practices for Packaging, Marking and Loading Methods for Steel Products for Domestic Shipment

A722/A722M, Standard Specification for Uncoated High-Strength Steel Bar for Prestressing Concrete

A775/A775M, Standard Specification for Epoxy-Coated Reinforcing Steel Bars

A882/A882M, Standard Specification for Epoxy-Coated Seven Wire Prestressing Steel Strand

B117, Standard Practice for Operating Salt Spray (Fog) Apparatus

C150, Standard Specification for Portland Cement

C939, Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)

C940, Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory

C942, Standard Test Method for Compressive Strength of Grouts for Preplaced- Aggregate Concrete in the Laboratory

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C1202, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

D638, Standard Test Method for Tensile Properties of Plastics

D746, Standard Test Method for Brittleness Temperature of Plastics and Elastomers by Impact

D790, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

D968, Standard Test Methods for Abrasion Resistance of Organic Coatings by Falling Abrasive

D1000, Standard Test Method for Pressure- Sensitive Adhesive-Coated Tapes Used for Electrical and Electronic Applications

D1004, Standard Test Method for Initial Tear Resistance of Plastic Film and Sheeting

D1238, Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer

D1505, Standard Test Method for Density of Plastics by the Density-Gradient Technique

D1693, Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics

D2240, Standard Test Method for Rubber Property Durometer Hardness

D2657, Standard Practice for Heat Fusion Joining of Polyolefin Pipe and Fittings

D2837, Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials

D3035, Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter

D3350, Standard Specification for Polyethylene Plastics Pipe and Fittings Materials

D3359, Standard Test Methods for Measuring Adhesion by Tape Test

D4101, Standard Specification for Propylene Plastic Injection and Extrusion Materials

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D4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

D4976, Standard Specification for Polyethylene Plastics Molding and Extrusion Materials

E119, Standard Test Methods for Fire Tests of Building Construction and Materials

F714, Standard Specification for Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Outside Diameter

F1055, Standard Specification for Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing

G5, Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements

G14, Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)

G20, Standard Test Method for Chemical Resistance of Pipeline Coatings

G155, Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials

SI10-10 IEEE/ASTM SI 10, American National Standard for Metric Practice

1.1.4 — British Standards Institute

BS 5896, Specification for High Tensile Steel Wire and Strand for the Prestressing of Concrete

1.1.5 — California Department of Transportation (CALTRANS)

Standard Specification, July 1995

1.1.6 — European Committee for Standardization

EN 10138, Prestressing Steel

1.1.7 — Federal Highway Administration (FHWA)

FHWA-RD-74-018, Non Metallic Coatings for Reinforcing Bars

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1.1.8 — French Association for Standardization

NF A 35-035, Hot-Dip Zinc or Zinc Aluminum Coated Prestressing Smooth Wires and Seven-Wire Strands

1.1.9 — German Institute for Standardization

DIN 1072, Road and Foot Bridges; Design Loads

1.1.10 — International Federation for Structural Concrete (*fib*)

fib Bulletin 30, Acceptance of Stay Cable Systems Using Prestressing Steels

1.1.11 — Post-Tensioning Institute (PTI)

Acceptance Standard for Post-Tensioning Systems

Specification for Grouting of Post-Tensioned Structures

Specification for Unbonded Single Strand Tendons

1.1.12 — SSPC: Society for Protective Coatings

SP10/NACE No 2, Near White Blast Cleaning

PA2, Measurement of Dry Coating Thickness with Magnetic Gauges

1.1.13 — Swiss Society of Engineers and Architects

SIA 160, Actions on Structures

2.0 — NOTATION, DEFINITIONS, AND ABBREVIATIONS

2.1 — Notation

Notation is in accordance with the AASHTO "LRFD Bridge Design Specifications"[1] with additional terminology as listed below.

A = constant (Eq. 5-5)

A_s = nominal area of steel (Eq. 5-6)

ADTT = average daily truck traffic (Section 5.1.3)

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C2.1 — Notation

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C_D = drag coefficient (Section 5.1.5)

D = cable diameter (Eq. C5.1.5-1a, C5.2.3-1, C5.2.3-2)

E = elastic modulus (Eq. 5-2)

E_{eff} = effective modulus of elasticity (Eq. 5-6)

f = bending stress in the cable (Eq. 5-2)

f_s' = minimum ultimate tensile stress (Section 3.2.1.1)

f_{sa}' = actual ultimate tensile stress of prestressing steel (wire, strand or bar) in the MTE of a stay cable (Sections 3.2.2.1, 4.2, Appendix A)

f_y' = minimum yield stress (Section 2.3.1.1)

F = mean cable force under fatigue conditions (Eq. C5.7.2-1)

g_B = turbulence gust factor (Eq. C5.1.5-1b, C5.1.5-2)

g_R = dynamic response gust factor (Eq. C5.1.5-1b, C5.1.5-2)

m = cable mass per unit length (Eq. C5.1.5-3)

n = number of strands in a bundle (Eq. C5.7.2-1)

N = 365 days x N_y x 1 cycle x ADTT (Eq. 5-5)

N_y = design life of the cable in years (Section 5.3.5)

p_D = dynamic wind load in any direction for the single cable (Eq. C5.1.5-2, C5.1.5-3)

p_L = total peak wind load in lateral direction acting simultaneously on all cables (Eq. C5.1.5-1b)

p_S = mean wind load in lateral direction acting simultaneously on all cables (Eq. C.1.5-1a, C5.1.5-1b, C5.1.5-2)

q_{Design} = mean design wind pressure at middle cable elevation (Eq. C5.1.5-1a)

Qi = force effect (Eq. 5-1)

r = radius of the cross section of either wire, strand or bundle (Eq. 5-2)

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All stress is based on "nominal" area as defined in the appropriate ASTM Standard.

The actual ultimate tensile strength of prestressing steel usually exceeds the minimum specified ultimate tensile strength established in the applicable ASTM specifications (see Section 3.0) by 1% to 5% as a manufacturing tolerance.

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R = the radius of the saddle bend (Eq. C5.7.2-1)

R_n = nominal resistance: nominal breaking strength for strength limit states, and nominal yield strength for service limit states (Eq. 5-1)

R_r = factored resistance (Eq. 5-1)

S = longitudinal effective cable stiffness (Eq. 5-6)

S_C = mass-damping parameter (Scruton number) (Eq. C5.2.3-1)

γ_i = load factor: a statistically based multiplier applied to force effects (Eq. 5-1)

ΔF = stress range due to the passage of the fatigue load multiplied by 1.4 (Eq. 5-3)

$(\Delta F)_n$ = nominal fatigue resistance (Eq. 5-3)

$(\Delta F)_{TH}$ = constant amplitude fatigue threshold (Eq. 5-4)

η = a factor relating to ductility, redundancy and operational importance (Eq. 5-1)

ξ = ratio of structural damping-to critical damping (Eq. C5.2.3-1)

ρ = air density (Eq. C5.2.3-1)

φ = fundamental frequency of cable assuming a single sine wave mode shape (Eq. C.5.1.5-3)

ϕ = resistance factor: a statistically based multiplier applied to nominal resistance (Eq. 5-1)

χ = local radius of curvature in the cable (Eq. 5-2)

2.2 — Definitions

Anchorage (socket) – device comprising all components and materials required to retain the force in a stressed cable-stay and to transmit this force to the bridge superstructure or tower. A distinction is made between active (stressing) anchorages and fixed end (non-stressing) anchorages.

Anchorage length – the length of cable within the hardware that serves to anchor the cable tension elements, including that length of cable where the tensile elements are directed into the anchor hardware.

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C2.2 — Definitions

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Barrier – a covering over the MTE that protects the MTE from corrosion. A barrier may provide protection by physical or electro-chemical means, or through a combination of the two.

Blocking agent – a filler or coating that serves to prevent the passage of water to or around the MTE.

Centralizer – a non-load bearing device between the MTE bundle and the inside of the external stay pipe used to fix the position of the MTE bundle transversely within the stay pipe.

Deviator – the component which serves to deviate the path of the MTE at the end(s) of the transition length.

External barrier – a barrier that is exposed to the outside environment in the design condition for the barrier.

Free length – the length of cable beyond the cable anchorage and transition assembly that affects the MTE, such as trumpets, tension rings or other strand guides.

Grout – a mixture of portland cement, water and approved admixtures. (See PTI Guide Specification for Grouting Post-Tensioned Structures, Third Edition, 2012)

Guide pipe – the structural assembly that aligns the cable at either the deck or the tower, and against which the cable damper or alignment device acts to resist lateral motion of the cable.

Internal barrier – a barrier immediately adjacent to the MTE that protects the MTE from corrosion.

Lollipop – a length of single strand, bar or wire encapsulated with a single barrier material or compound over its length (See Section 4.1.4.1.)

Main tension element (MTE) – the load resisting prestressing material (strand, wire or bar) that is designed to carry the tensile load in the cable.

Manufactured length of strand – one continuous length of strand produced from a stress-relieving or low relaxation treatment line.

Nested barrier – a barrier in series with another barrier.

Polyvinyl flouride tape (PVF) – tape with backing made from a glossy PVF film or equal (See Appendix C).

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These devices have traditionally been helical wire or plastic spacer devices, used to provide clearance between stay pipe and MTE bundle for grouting or vibration control.

It is normal practice to coil this length into separate reels or reeless packs for shipment.

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Prestressing steel – prestressing wire, strand or bar as specified in Section 3.0 used as the MTE of the stay cable.

Saddle – a structural device that allows both deviation of the MTE and transfer of stay force into the bridge structure without breaking the continuity of the MTE. (These provisions do not cover frictionless saddles. See Section 5.7)

Sheathed strand – prestressing steel strand coated with a corrosion inhibiting coating and covered by an extruded polyethylene or polypropylene material.

Stay cable – the complete cable system including anchorages, main tension elements, sheathing and all corrosion protection materials and devices.

Stay pipe – the external covering of the assembled cable, comprised of either high density polyethylene (HDPE) pipe or metal pipe, or other materials and shapes to provide part of the corrosion protective system, and/or to control temperature variation and/or rain-wind induced vibrations.

Transition length – the length of cable where the MTE is deviated from its neutral grouping of individual prestressing materials within the stay pipe to the grouping of the individual prestressing materials at the anchorage.

COMMENTARY

These Recommendations address the use of pipe material as an external covering of the stay cable. Other technologies that are available for covering stay assemblies are not specifically addressed in these Recommendations.

2.3 — Abbreviations

AUTS = actual ultimate tensile strength

HDPE = high density polyethylene

HDPP = high density polypropylene

Mg = megagram (= metric "ton" or "tonne")

MTE = main tension element

MUTS = minimum ultimate tensile strength

PVF = polyvinyl fluoride

C2.3 — Abbreviations

The SI unit of mass is the kilogram (kg). The name ton has been given to several large mass units that are widely used in commerce and technology. The long ton of 2,240 lb, the short ton of 2,000 lb, and the metric ton (tonne) of 1,000 kg, which is almost 2,205 lb are not SI terms. (See SI10-10 IEEE/ASTM SI 10)

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SDR = Standard Dimension Ratio (ratio of outside pipe diameter to minimum wall thickness)

3.0 — MATERIALS

3.1 — General

These Recommendations cover materials for stay cable systems utilizing prestressing steel.

3.2 — Main tension elements

The main tension elements (MTE) for stay cables covered by these Recommendations shall conform to the following specifications.

3.2.1 — Wire

Wire used in stay cables shall conform to ASTM A421/A421M, "Standard Specification for Uncoated Stress Relieved Steel Wire for Prestressed Concrete," Type BA.

3.2.1.1 — Quality Control

Unless otherwise stated herein one test for every 2.5 Mg or portion thereof shall be made for the following:

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C3.2 — Main tension elements

For bridges built outside the U.S., comparable national specifications should be used if available. Specific standards may have different minimum requirements than those of the referenced ASTMs. In the event those standards are applied for design by the Engineer, the minimum standards in these Recommendations should be substituted for as appropriate.

C3.2.1 — Wire

Either stress-relieved (normal-relaxation) or low-relaxation wire for prestressed concrete may be used for stay cable application since the creep (or relaxation) is negligible under normal working stress.

Outside the U.S. hot dip galvanized wire has been used for a number of cable stayed bridges without low-relaxation treatment. At the present time, there is no ASTM specification for hot dip galvanized wire that is suitable for stay cable application. Among the requirements for this type of wire are tensile strength, load at 1% extension, elongation, coating weight, straightness (cast) and fatigue resistance.

The French Standard NF A 35-035 is often used as an international reference for stay cable grade galvanized strand or wire. An unofficial English translation of selected sections in the February 2001 version of this standard is included in Appendix B for reference.

This reference is for galvanization only; all other material properties and testing are as specified in Sections 3 and 4 of the Recommendations.

C3.2.1.1 — Quality control

Minimum Ultimate Tensile Strength (MUTS) is equal to $f_s' \times$ "nominal area" of steel.

RECOMMENDATIONS

A. Minimum specified ultimate tensile stress:
$f_s' = 1655$ MPa

B. Minimum yield stress:
$f_y' = 0.90\ f_s'$ for low relaxation wire
$f_y' = 0.85\ f_s'$ for stress relieved wire

C. Elastic modulus:
$E = 200{,}000$ MPa ± 5%

D. Ductility:
(i) Reduction of area due to necking at rupture:
At least 30%

(ii) After three "to and fro" bends through ± 90°F around a mandrel with a diameter of 5 wire diameters:
No failure

E. Fatigue and static strength:
One 5 m long wire sample shall be taken from every 20 Mg or portion thereof produced from each heat of steel. All prestressing wires and derived test samples shall be marked in such a manner as to ensure traceability during production, transit, storage and testing. The test specimens shall be a minimum length of 300 mm. They shall be anchored in such a way as to avoid failures in the anchorage zone. Should any specimen fail within the anchorage zone, the test shall be discarded and another specimen used from the same sample.

The wire specimens shall be tested at an upper stress of $0.45f_s'$ or $0.55f_s'$. At least 30% of the samples shall be tested at $0.55f_s'$. The stress range shall be according to Table 3-1 for the selected number of cycles. At least 5% of the wire tests shall be to 2 million cycles. A static test to failure shall be conducted after each wire fatigue test. Wire specimens shall provide not less than 0.95 MUTS in the static test. Wire tested without failure for the selected number of cycles and the related stress range, as specified above, shall be considered acceptable. In case the first valid test specimen from each sample fails the fatigue or static test, two additional tests shall be made on test specimens from the same sample. If further failures occur, the wire quantity represented by the sample shall be rejected.

F. Corrosion:
Prior to shipment from the manufacturer, all wires shall be free from visible corrosion. One 5 m long wire sample shall be taken from every 10 Mg or portion

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These ductility requirements are in addition to the ASTM A421/A421M requirement for total elongation under load of not less than 4% when measured in a gauge length of 250 mm.

When choosing the fatigue stress range for the quality control tests, the values from Table 3-1 may be plotted on a log-log plot and straight line interpolation between points on such a plot may be used to select stress range values and the corresponding required number of load cycles for accelerated testing. (See Fig. C3.1)

Table 3-1—Summary of stress ranges for fatigue tests

Type of stay	No. of cycles	Stay test fatigue stress range*, MPa	Component fatigue test stress range†, MPa**
Strand‡ or uncoupled bars§	2×10^6+	159	213
	2×10^6		228
	5×10^5		302
	1×10^5		443
Wire‖	2×10^6+	194	282
	2×10^6		297
	5×10^5		370
	1×10^5		512
Bars§ with (epoxy-filled) couplers	2×10^6+	105	99
	2×10^6		122
	5×10^5		164
	1×10^5		244

*To ensure fatigue quality of stays, it is recommended that stay specimens be tested at 2×10^6 cycles.
†Individual strand, bar, wire, or glued, coupled bar, respectively.
‡See Section 3.2.2 and 3.2.3.
§See Section 3.2.4.
‖See Section 3.2.1.
**Upper-bound stress level shall be $0.45f_s'$.

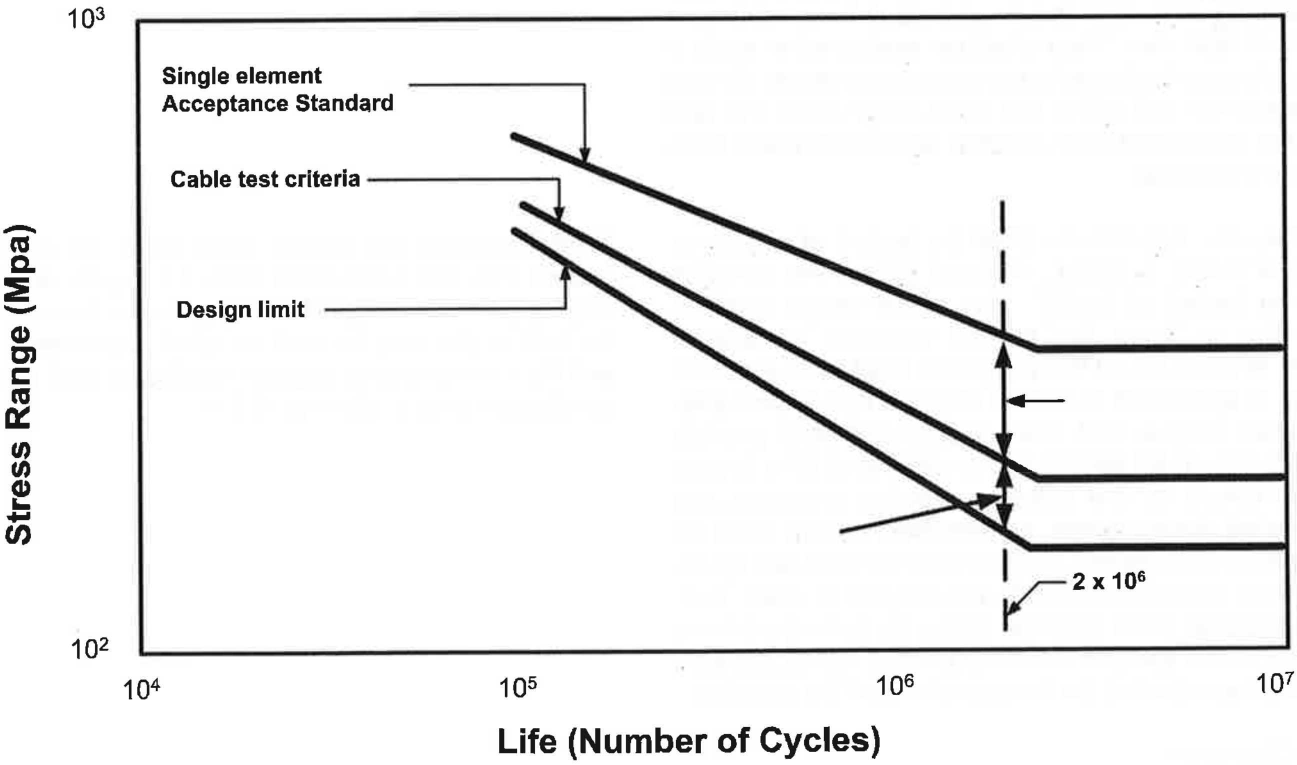

Fig. C3.1—Fatigue safety philosophy. (Note: Δ_1 is quality assurance [17 MPa coupled bar, 69 MPa strand and uncoupled bar, 103 MPa wire] and Δ_2 is length effect, anchorage riser, safety [35 MPa].)

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thereof produced from each heat of steel. The sample wires steel surfaces shall be thoroughly exposed (when coated) and inspected for evidence of corrosion. If visible corrosion is found, the wire quantity represented by that sample shall be rejected.

3.2.2 — Strand

Strand used in stay cables shall conform to ASTM A416/A416M "Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete," and shall be weldless, low-relaxation grade.

3.2.2.1 — Quality control

Unless otherwise stated herein, one test for each manufactured length or 20 Mg, whichever is less or portion thereof shall be made for the following:

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C3.2.2 — Strand

The frequency of occurrence of welds in wire rod should be limited to one weld per each 500 kg of rod.

Low-relaxation grade is recommended because the low-relaxation strand: (1) has proven to have a sound tensile strength throughout the entire length as it has been subjected to a near breaking load in the low-relaxation treatment; (2) has better straightness (cast) for easy cable fabrication.

Hot dip galvanized strand has been used on several major cable-stayed bridges outside the U.S. Galvanized strand is made from either as-galvanized wires (in Japan) or drawn-galvanized wires (in Europe). The advantage of as-galvanized wire is heavier coating weight (300 g/m^2 or more) for better corrosion protection. The advantage of drawn-galvanized wire, on the other hand, is improved fatigue performance and tighter control on tolerance.

Low-relaxation grade is often times recommended for galvanized strand as well because of the above mentioned reasons.

Galvanized strand should meet or exceed the requirements of ASTM A416 as well as the requirements of Section 3.2.2.1. Galvanized prestressing strand may be used in contact with cement grout provided the steel has been manufactured in accordance with the latest ASTM A416, BS 5896 or EN 10138 standard. Experience has shown that strand manufactured to these standards is not susceptible to hydrogen embrittlement.

The French Standard NF A 35-035 is often used as an international reference for stay cable grade galvanized strand or wire. An unofficial English translation of selected sections in the February 2001 version of this standard is included in Appendix B for reference.

This reference is for galvanization only; all other material properties and testing are as specified in Sections 3 and 4 of the Recommendations.

C3.2.2.1 — Quality control

The provisions of this section apply to all strands including uncoated, galvanized, epoxy-coated, and sheathed strands.

RECOMMENDATIONS

A. Minimum ultimate tensile stress:
$f_s' = 1860$ MPa

B. Minimum yield stress:
$f_y' = 0.90\ f_s'$

C. Elastic modulus:
$E = 197{,}000$ MPa ± 5%

D. Ductility:

A "One Pin Test" as outlined in Appendix A shall be conducted on a sample taken from each manufactured length or 20 Mg (whichever is less) or portion thereof. For acceptance, the tensile force in the sample during the One Pin Test shall equal at least 0.8 f_{sa}'. The sample taken for the One Pin Test shall be long enough for two ultimate strength tests and three one pin tests. If the first specimen fails the One Pin Test, two additional samples shall be tested. If both samples pass, the material is acceptable. If either sample fails, the manufactured length represented by that sample shall be rejected.

E. Fatigue and static strength:

One 5 m long strand sample shall be taken from each manufactured length or each 20 Mg, whichever is less. All prestressing strands and derived test samples shall be marked in such a manner as to ensure traceability during production, transit, storage and testing. The test specimens shall be a minimum length of 1 m.

They shall be anchored in such a way as to avoid failures in the anchorage zone. Should any specimen fail within the anchorage zone, the test shall be discarded and another specimen used from the same sample.

The strand specimens shall be tested at an upper stress of $0.45f_s'$ or $0.55f_s'$. At least 30% of the samples shall be tested at $0.55f_s'$. The stress range shall be according to Table 3-1 for the selected number of cycles. At least 5% of the strand tests shall be to 2 million cycles. A static test to failure shall be conducted after completion of each strand fatigue test. Specimens shall provide not less than 0.95 MUTS in the static test. Strand tested without failure for the selected number of cycles and the related stress range, as specified above, shall be considered acceptable. In case the first valid test specimen from each sample fails the fatigue or static test, two additional tests shall

COMMENTARY

The One-Pin Test for ductility is in addition to the requirement of ASTM A416/A416M that the total elongation, under load, shall not be less than 3.5% measured in a gauge length of not less than 610 mm.

When choosing the fatigue stress range for the quality control tests, the values from Table 3-1 may be plotted on a log-log plot and straight line interpolation between points on such a plot may be used to select stress range values and the corresponding required number of load cycles for accelerated testing. (See Fig. C3.1)

The variable phi factor provisions for low fatigue demand applications may allow up to a $0.6f_s'$ upper stress range in service. For strand meeting the material performance requirements of this section, the variation in fatigue strength represented by the normal Wohler curve also addresses the material requirements for the low fatigue range case. As a result, additional testing is not required for the low fatigue demand case.

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be made on test specimens from the same sample. If further failures occur, the manufactured length represented by that sample shall be rejected. If both tests pass, the strand shall be considered acceptable.

F. Corrosion:

Prior to shipment from the manufacturer, all strands shall be free from visible corrosion. One 5 m strand sample shall be taken at random from each manufactured length or 10 Mg (whichever is less) or portion thereof. The sample strand steel surfaces shall be thoroughly exposed including the center wire and inspected for evidence of corrosion. If any visible corrosion is found, the manufactured length represented by that sample shall be rejected.

3.2.3 — Epoxy-coated strand

Epoxy-coated strand shall conform to ASTM A882M/A882M, "Standard Specification for Epoxy Coated Seven-Wire Prestressing Steel Strand." It shall be of the type in which the interstices of the strand are filled with epoxy, and the strand shall be weldless, low-relaxation grade.

The Special Provisions for the project should require creep tests from the producer to verify design assumptions.

3.2.3.1 — Quality control

The manufacturer shall furnish, at the time of shipment, written certification that the epoxy-coated strands meet the requirements of these Recommendations (Section 3.2.2.1) and ASTM A882/A882M.

COMMENTARY

C3.2.3 — Epoxy-coated strand

Epoxy-coated and filled strand which conforms to Supplement I of ASTM A882/A882M is produced such that the void spaces are filled with epoxy to prevent migration of corrosive media, either by capillary action or other hydrostatic forces. Accordingly, this is the preferred epoxy-coated strand for use in stay cables. The designer should be aware that pure relaxation values (as used in prestressed concrete applications) for epoxy-coated strand (at a stress level of 0.7 MUTS) are increased by a factor of 2.5 for 15 mm diameter strand. In the application for cable-stays, the phenomenon is not relaxation but creep of the coating (at the dead load stress level). Initially, the load is carried by the coating but subsequently is transferred to the strand. For design purposes, creep (elongation) in the strand may be assumed at 0.025% for the life of the structure based on the dead load stress level. Creep tests should require a determination of creep values at one hour intervals for the first six hours and then daily during the first 100 hours (1,000-hour test period). This is approximately the period of the inclined portion of the creep curve before the curve levels off. It is also during this time period that a variation in creep is observed between epoxy-filled strand and uncoated strand. This data can then be used by the Engineer to adjust the design if necessary.

RECOMMENDATIONS

3.2.3.2 — Surface preparation

When more than a 7-day period is anticipated between completion of the strand manufacturing process and application of the epoxy coating, the strand shall be protected against corrosion in accordance with the requirements of the California Department of Transportation.

The surface of the strand to be epoxy-coated shall be clean and without any visible corrosion products at the time of coating.

3.2.3.3 — Application of epoxy coating

The thickness of epoxy coating on all strand supplied on an order shall be within plus or minus 65 micro-m of the nominal thickness, or otherwise as required for the wedge design by the cable supplier. The cable supplier shall test 3 samples each of the maximum and minimum coating thickness with the wedge system being supplied for a given project. Each sample shall consist of one strand with two wedges, and shall be tested in accordance with component criteria in Table 3-1. All six tests shall pass without failure.

3.2.3.4 — Inspection of materials

The inspector representing the Owner shall have unrestricted access to all manufacturing fabrication and testing performed at the manufacturer's facilities, independent laboratory or shipping and storage facilities. The manufacturer shall afford the inspector the necessary facilities to confirm that the material is being furnished in accordance with these Recommendations. All tests and inspections shall be made prior to shipment, unless otherwise specified.

3.2.3.5 — Replacement of rejected epoxy strand

Epoxy-coated strand represented by test samples that do not meet the requirements of these Recommendations shall be rejected. Any damaged epoxy coating or underlying corrosion on the strand shall be cause for rejection of the strand.

3.2.4 — Bar

Bars used in stay cables shall conform to ASTM A722/A722M, "Standard Specification for Uncoated High Strength Steel Bar for Prestressing Concrete."

COMMENTARY

C3.2.3.2 — Surface preparation

Section 50-1.05 of the State of California Department of Transportation "Standard Specification"[2] for prestressing concrete includes a requirement for packaging of prestressing steel. Packaging which conforms to this requirement has come to be known as "Calwrap."

C3.2.3.3 — Application of epoxy coating

Where wedges bite through epoxy coating, control of the thickness of the epoxy coating is necessary to ensure that the teeth of the wedges penetrate through the epoxy into the strand. Wedge compatibility with epoxy-coated strand and epoxy thickness is critical to performance.

C3.2.4 — Bar

Bar coating such as hot dipped galvanizing per ASTM A123/A123M "Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products" or epoxy

RECOMMENDATIONS

COMMENTARY

coating per ASTM A775/A775M "Standard Specification for Epoxy-Coated Reinforcing Steel Bars" may be used. The methods used to clean bars before coating should preclude hydrogen embrittlement. The coating should not be removed to install the anchorage. Bars should be galvanized or coated prior to being subjected to the material test requirements found elsewhere in these Recommendations.

3.2.4.1 — Quality control

Bars shall be in accordance with ASTM A722/A722M, Type 1 or Type 2, including the supplementary requirements of S1, S2, S3 and S4.

Unless otherwise stated herein, one test for every 20 Mg or portion thereof produced from each heat of steel shall be made for the following:

A. Minimum ultimate tensile stress:
$f_s' = 1035$ MPa

B. Minimum yield stress :
$f_y' = 0.85\ f_s'$ Type 1
$f_y' = 0.80\ f_s'$ Type 2

C. Elastic modulus:
$E = 200{,}000$ MPa ± 5%

D. Ductility
Test per ASTM A722/A722M, S1.

E. Fatigue and static strength:
One 5 m long bar sample shall be taken from every 20 Mg or portion thereof produced from each heat of steel. All prestressing bars and derived test samples shall be marked in such a manner as to ensure traceability during production, transit, storage and testing. The test specimens shall be a minimum length of 20 diameters, but not less than 610 mm. They shall be anchored in such a way as to avoid failures in the anchorage zone. Should any specimen fail within the anchorage zone, the test shall be discarded and another specimen used from the same sample.

The bar specimens shall be tested at an upper stress of $0.45f_s'$ or $0.55f_s'$. At least 30% of the samples shall be tested at $0.55f_s'$. The stress range shall be according to Table 3-1 for the selected number of cycles. At least 5% of the bar tests shall be to 2 million cycles. A static test to failure shall be conducted after each bar fatigue test. Specimen shall provide not less than 0.95 MUTS in the static test. Bar specimens

RECOMMENDATIONS

tested without failure for the selected number of cycles and the related stress range, as specified above, shall be considered acceptable. In case the first valid test specimen from each sample fails the fatigue or static test, two additional tests shall be made on test specimens from the same sample. If further failures occur, the bar quantity represented by that sample shall be rejected.

F. Corrosion:

Prior to shipping all bars shall be free from visible corrosion. One 5 m bar sample shall be taken at random from every 20 Mg or portion thereof produced from each heat of steel. The sample bar steel surface shall be thoroughly exposed (when coated) and inspected for evidence of corrosion. If any visible corrosion is found, the bar quantity represented by that sample shall be rejected.

3.2.5 — Wire or strand not specifically itemized in ASTM A421/A421M or A416/A416M

Wire or strand not specifically itemized in ASTM A421/A421M or A416/A416M may be used provided it conforms to the minimum requirements of these specifications and has no properties which are less satisfactory than those listed in ASTM A421/A421M or A416/A416M.

3.2.6 — Bars not specifically itemized in ASTM A722/A722M

Bars not specifically itemized in ASTM A722/A722M, including bars with a minimum ultimate tensile strength greater than 1035 MPa, may be used provided the bars conform to all other requirements of ASTM A722/A722M (including, in particular, those of Section 3, 4, and 5 therein) and have no properties which make them less satisfactory than those listed in ASTM A722/A722M.

COMMENTARY

C3.2.5 — Wire or strand not specifically itemized in ASTM A421/A421M or A416/A416M

Provisions should be made for new steels which would include new sizes, or improved characteristics of relaxation, bond, or mechanical properties. However, use of wire, or strand not covered by ASTM Specifications should be permitted only when the supplier provides conclusive test data substantiating that all characteristics of the material are comparable to the properties of steels conforming to the applicable ASTM Specification. In particular, the stress corrosion characteristics of steels produced by quench and temper heat treatment should be carefully evaluated.

Creep properties of new steel should be determined by adequate testing (minimum 1,000 hours). Creep tests for stay cable material should be conducted at a stress level comparable to stresses produced by sustained loads in a cable-stayed bridge (about $0.40f_s'$).

C3.2.6 — Bars not specifically itemized in ASTM A722/A722M

ASTM A722/A722M covers bars with minimum ultimate tensile strength of 1035 MPa. Bars with 1105 MPa ultimate tensile strength meeting all the requirements of ASTM A722/A722M have been used in the United States.

The stress corrosion characteristics of steels produced by quench and temper heat treatment and steels produced by methods other than ASTM A722/A722M should be carefully evaluated.

RECOMMENDATIONS

3.3 — Individually sheathed strands with corrosion inhibiting coating

The manufacturer shall furnish, at the time of shipment, written certification that the sheathed strands meet the requirements of these Recommendations.

3.3.1 — Surface preparation

When more than a 7-day period is anticipated between completion of the strand manufacturing process and application of the corrosion inhibiting coatings, the strand shall be protected against corrosion in accordance with the requirements of the California Department of Transportation.

The surface of the steel strand to be coated with the corrosion inhibiting coating shall be clean and without any visible corrosion at the time of coating.

3.3.2 — Application of corrosion inhibiting coating

The amount of corrosion inhibiting coating used shall be sufficient to ensure essentially complete filling of the annular space between the strand and the sheathing and between the wires. The coating shall extend over the entire strand length.

The performance specification for the corrosion inhibiting coating shall comply with the requirement of Table 1 from the PTI "Specification for Unbonded Single Strand Tendons."[3]

3.3.3 — Application of sheathing

The HDPE or HDPP sheathing shall be produced by an extrusion process. The minimum thickness of the sheathing shall be 1.25 mm.

3.3.4 — Inspection

The inspector representing the Owner shall have unrestricted access to all manufacturing, fabrication, and testing performed at the manufacturer's facili-

COMMENTARY

C3.3 — Individually sheathed strands with corrosion inhibiting coating

This process is similar to but not the same as the fabrication of unbonded monostrand tendons. The two major differences are:

1. The wires are unstranded, coated and then restranded.

2. No minimum amount of corrosion inhibiting coating is specified except sufficient to coat the wires.

C3.3.1 — Surface preparation

See Commentary Section C3.2.3.2.

Strand that has shown signs of visible surface corrosion that can be cleaned with a soft untreated cloth may be cleaned by the supplier prior to coating, subject to the approval of the Engineer. Procedures should assure that corrosion is not present between the king wire and outer wires.

C3.3.3 — Application of sheathing

See Section 3.3.9 for performance tests, including water tightness.

RECOMMENDATIONS

Table 3-2—Acceptable properties of polyethylene and polypropylene material

Property	ASTM test method	Value
Density, g/cm^3	D1505	0.941 to 0.965
Melt index, g/10 minutes	D1238	0.2 to 1.0
Flexural modulus, MPa	D790	550 to 1100
Tensile strength at yield, MPa	D638	21 to 28
Elongation at rupture	D638	500 to 700%
Hardness	D2240	64 to 65
Low temperature brittleness	D746	–40°C at 50% flexibility, minutes

ties, independent laboratory or shipping and storage facilities. The manufacturer shall afford the inspector the necessary facilities to confirm that the material is being furnished in accordance with this specification. All tests and inspections shall be made prior to shipment, unless otherwise specified.

3.3.5 — Replacement of rejected sheathed strand

HDPE or HDPP sheathed strand represented by test samples that do not meet the requirements of these Recommendations shall be rejected. Any damaged HDPE or HDPP sheath or underlying corrosion on the strand shall be rejected. At the manufacturer's option, such strand shall be replaced or, alternatively, may be stripped of sheathing, recleaned, recoated, resheathed and resubmitted for acceptance testing in accordance with the requirements of these Recommendations.

3.3.6 — High density polyethylene material for sheathed strand

The Contractor shall furnish to the Engineer a certified test report prepared by an independent laboratory documenting compliance of the HDPE material with items A through D below.

A. HDPE material shall meet the specific requirements of ASTM D4976 "Standard Specification for Polyethylene Plastics Molding and Extrusion Materials." The resultant acceptable values of the primary properties for this HDPE material are shown in Table 3-2.

COMMENTARY

C3.3.5 — Replacement of rejected sheathed strand

Minor scuffs or surface abrasions are not considered rejectable damage.

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B. The material shall be UV stabilized and suffer no property degradation for a minimum of 6 months. In applications where the HDPE sheathed strand may be exposed to UV radiation for periods in excess of 6 months, the requirements of Section 3.5.3.2C shall apply.

C. HDPE material shall not react with cementitious grout, the prestressing steel corrosion inhibiting coating material or any other material it is permitted to come in contact with as part of the stay cable steel and shall be free of water soluble chloride.

D. HDPE material shall be chemically stable without embrittlement or softening over the anticipated exposure temperature and the service life of the structure.

3.3.7 — Polypropylene material for sheathed strand

The Contractor shall furnish to the Engineer a certified test report prepared by an independent laboratory documenting compliance of the HDPP material with items A through D below.

A. HDPP material shall meet the requirements of ASTM D4101 "Standard Specification for Propylene Plastic Injection and Extrusion Materials." The resultant acceptable values of the primary properties for the HDPP material are shown in Table 3-2.

B. The HDPP material shall be UV stabilized and suffer no property degradation for a minimum of 6 months. In applications where the HDPP sheathed strand may be exposed to UV radiation for periods in excess of 6 months, the performance requirements of Section 3.5.3.2C shall apply.

C. HDPP material shall not react with cementitious grout and steel and shall be free of water soluble chloride.

D. HDPP material shall be chemically stable without embrittlement or softening over the anticipated exposure temperature and the design service life of the structure.

3.3.8 — Corrosion inhibiting coating material

The corrosion inhibiting coating material shall have the following properties:

- Provide corrosion protection to the prestressing steel.
- Resist flow from the sheathing within the anticipated temperature range of exposure

COMMENTARY

C3.3.8 — Corrosion inhibiting coating material

This section is based on the PTI "Specification for Unbonded Single Strand Tendons."[3]

RECOMMENDATIONS

including the temperature of the manufacturing process of the sheathed strand.

- Provide a continuous non brittle film at the lowest anticipated temperature of exposure.
- Be chemically stable and non reactive with the prestressing steel and the sheathing material or any other material it is permitted to come in contact with as part of the stay.

Tests for the corrosion inhibiting coating shall meet the requirements of Table 1 of the PTI "Specification for Unbonded Single Strand Tendons"[3] or the provisions of *fib* Bulletin 30 Section 5.6[4] and be conducted by an approved testing laboratory. All test data shall be furnished to the Engineer prior to shipment of the strand.

3.3.9 — Performance tests for individually sheathed polyethylene or polypropylene strand

The Contractor shall furnish to the Engineer, a test report prepared by an independent laboratory documenting compliance with items A through E below. HDPE or HDPP sheathed strand shall meet the following requirements:

A. Chemical resistance test – The chemical resistance of the sheathing shall be evaluated in accordance with ASTM G20 "Standard Test Method for Chemical Resistance of Pipeline Coatings", by immersing coated strands in each of the following: a 3M (Molar) aqueous solution of $CaCl_2$, a 3M (Molar) aqueous solution of NaOH, and a solution saturated with $Ca(OH)_2$. In addition, to simulate cementitious grout, an aqueous solution of potassium hydroxide and an aqueous solution of sodium hydroxide shall be utilized for this test. Tests with specimens without damage to the sheathing and specimens with intentional 6 mm diameter holes drilled through the sheathing shall be performed at 24 ± 2° C. Minimum test time shall be 45 days. The polyethylene must not soften, crack, or be visually deteriorated.

B. Chloride permeability test – The chloride permeability characteristics of the films of cured coating having the minimum thickness as proposed for use shall be measured by the methods outlined in FHWA-RD-74-018, "Non-metallic coatings for Reinforcing Bars." The test shall be performed at 24 ± 2° C for 45 days. The accumulative concentration of chloride ion permeating through the film shall be less than 1×10^{-4} M.

COMMENTARY

The tests for corrosion inhibiting material are considered to be base line tests to ensure that minimum corrosion protection properties of active blocking agents are provided. New developments of materials may not meet some of these test requirements, and in such case other and more comprehensive tests or review of the acceptance criteria may be necessary to ascertain their adequacy.

C3.3.9 — Performance tests for individually sheathed polyethylene or polypropylene strand

These requirements are adapted from ASTM A882/A882M.

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C. Impact test – The resistance of a strand sheathing to mechanical damage shall be determined by the falling weight test. A test apparatus similar to that described in ASTM G14 "Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)" shall be used along with a 1.8 kg tup. Impact shall occur on the crown areas on the sheathed strand. The test shall be performed at room temperature. With an impact of 9 N-m, no shattering, cracking, of the sheathing shall occur except at the impact area, that is, the area permanently deformed by the tup.

D. Abrasion resistance test – The resistance of the strand sheathing to abrasion shall be determined by the falling sand method of ASTM D968 "Standard Test Method for Abrasion Resistance of Organic Coatings by Falling Abrasive" adopted for testing sheathed strand. The net loss of sheathing shall not exceed 0.25 mm per 1,000 L of abrasive.

E. Salt spray (fog) test – Sheathed strand specimens shall be tensioned to 70 percent of the minimum ultimate tensile strength and exposed to salt fog for 3,000 hours in accordance with ASTM B117. Care shall be taken to protect the end anchorage used from salt fog or corrosion so as not to influence the test results. Observations for signs of corrosion shall be made and recorded every 250 hours. After 3,000 hours of exposure, no evidence of corrosion shall be present, and the specimen shall be holiday free. After the salt spray (fog) test is completed, the specimen shall undergo a tensile test, in conformance with ASTM A416/A416M. No cracks visible to the unaided eye shall occur in the HDPE or HDPP up to an elongation of 1 percent (yield point).

F. Watertightness Test – The stay cable supplier shall propose a watertightness test to the approval of the Engineer. One test of the void filling manufacturing process of the sheathed strand as per the approved test procedure shall be carried out per production run or portion thereof.

COMMENTARY

Results from previous tests may be accepted for a current project in view of the length of time needed to complete these tasks. See Section 4.1.4.1.

One such test is the Static Watertightness Test set forth in the French Standard XP A35-037-2[5] and described below: The test consists of an imposed head of water on the ends of a test piece of the as-delivered product, (see Fig. C3.2) and to measure the mass change of the test piece after a given time and the product quantity obtained at the other end.

The length of the test piece is equal to 1 m. It is weighed before the test. The balance used for weighing shall be accurate at least within ± 0.1 g.

The water pressure to be applied shall correspond to the pressure due to a vertical column of water of 1 m height. The test piece is placed horizontally.

After testing, the mass variation of the test piece and the quantity of product obtained at the beaker[6] shall be equal to zero.

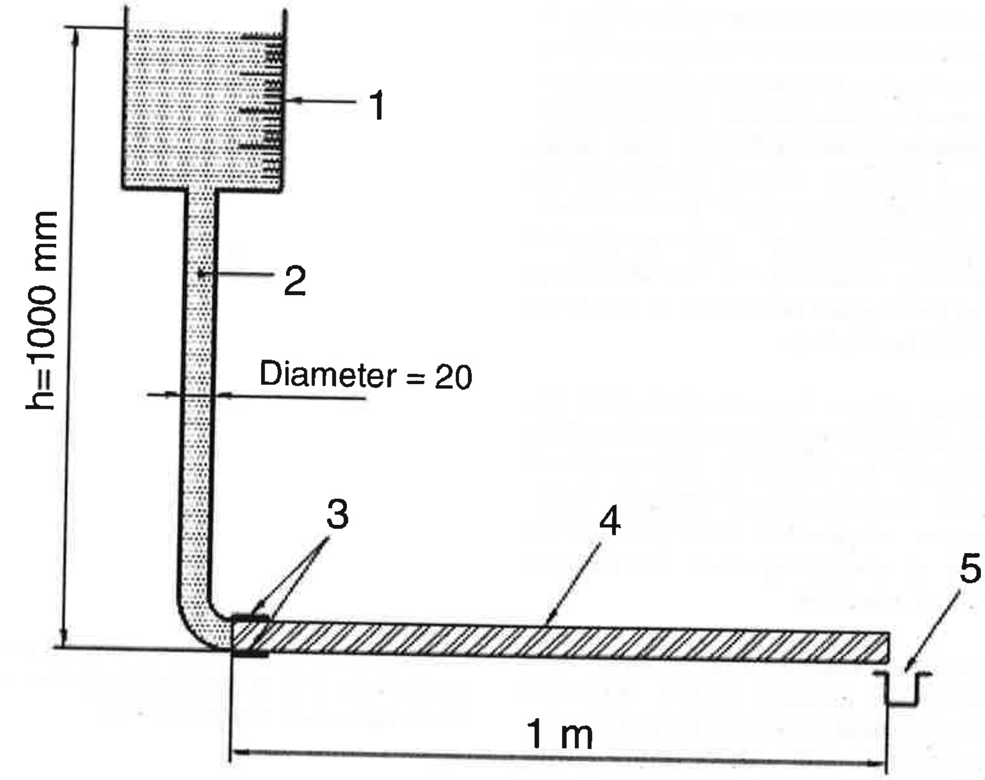

Fig. C3.2—Static watertightness test. (Note: 1 is divisions; 2 is water; 3 is seal; 4 is HDPE or HDPP sheath; and 5 is beaker.)

3.4 — Anchorage components

Materials used in anchorages or sockets shall be as specified by the contract special provisions and/or by the specialist contractor at the time of acceptance testing of the stay cable.

3.5 — Stay pipe

3.5.1 — Cross sectional area

For in-situ fabricated stay cables, the ratio of the inside diameter cross sectional area of the pipe to the tensile element area as defined by the circumscribed circle, shall be as required for the cable supplier's installation system. The tensile element area shall include the cross sectional area of coatings used for corrosion protection. This requirement need not apply when a sheath is installed over the tensile elements after assembly, or for prefabricated stay cables.

COMMENTARY

C3.4 — Anchorage components

The purpose of this provision is to insure that the anchorage components incorporated into the structure are the same as those used in the systems qualification test program (Chapter 4).

C3.5 — Stay pipe

C3.5.1 — Cross sectional area

A minimum ratio of 2.0 is recommended to facilitate installation of tensile elements in stay cables fabricated in-situ. This is a net area, after consideration of any centralizers or other internal elements. The supplier should demonstrate the feasibility of installation if a ratio less than 2.0 is proposed.

RECOMMENDATIONS

3.5.2 — Steel pipe

Steel pipe shall be a black steel pipe conforming to the requirements of ASTM A53, "Standard Specification for Pipe, Steel, Black and Hot-Dipped Zinc-Coated, Welded and Seamless" Type E, Grade B. Sampling and testing procedures shall be in accordance with ASTM A673/A673M "Standard Specification for Sampling Procedure for Impact Testing of Structural Steel". The (H) frequency of heat testing shall be used. Wall thickness shall be sufficient to withstand handling, erection, and service stresses in addition to grouting pressures and shall be a minimum of 10 mm. The material supplied shall meet a longitudinal Charpy V notch test of not less than 20 N-m at 21° C unless specified otherwise by the contract special provisions. A certificate of analysis shall be furnished for each shipment of pipe stating that the material supplied meets this specification and showing results of tests. All pipe ends shall be fully welded as required in Section 6.8.2.1. Welding shall not be performed with cable stay material inside the pipe. The Contractor shall submit the welding details and procedures to achieve the weld to the Engineer for approval. 100% of all field welds shall be tested by ultrasonic methods and/or radiographic (non-destructive) testing as specified by the contract special provisions.

Tests to verify the mechanical properties of the pipe may be performed by the Engineer on each size of pipe used. Samples for verification testing shall consist of one 1.8 m length of pipe per size and thickness.

COMMENTARY

C3.5.2 — Steel pipe

The details of the connection between the steel pipe and the anchorage for certain proprietary systems may not require welding. System supplier shall demonstrate the adequacy of any connection to the satisfaction of the Engineer.

3.5.2.1 — Coating

Coating for the outside steel pipe shall consist of a three-coat system as listed below or, alternatively, a system as approved by the Owner may be used.

A: A shop-applied prime coat of self curing inorganic zinc coating.

B: A field-applied epoxy intermediate coat.

C: A field-applied polyurethane finish coat.

Recommendation of detailed coating procedures are described in Appendix.C.3.

C3.5.2.1 — Coating

If environmental restraints prohibit the use of conventional paint systems, wrapping of the steel pipe with PVF tape may be considered as an architectural alternative.

Tape wrapping is not considered to be the equivalent of a three-coat paint system or other approved paint system from a corrosion protection standpoint.

RECOMMENDATIONS

3.5.3 — High density polyethylene pipe

Stay pipe shall be black or coextruded with fully bonded black core and colored exterior HDPE plastic pipe conforming to the requirements of the following sections. Subject to the approval of the Engineer, the Contractor shall be permitted to propose a full thickness color HDPE pipe, provided that these requirements are met:

The exposed surfaces of all pipes shall be of material that has demonstrated an Ultraviolet (UV) resistance (UV + visible) in a climate equivalent to a UV intensity of 21×10^7 J/m^2 per year with an average temperature of 22° C. Oxidation visible under a microscope with 100 magnification shall not occur before 15 years. Demonstration shall be based on a scientific method approved by the Engineer.

3.5.3.1 — Pipe specifications

A. HDPE pipe in nominal diameters from 12.5 mm to 75 mm shall meet the requirements of ASTM D3035 "Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameters".

B. HDPE pipe in nominal diameters from 75 mm to 150 mm shall meet the requirements of ASTM D3035 or ASTM F714 "Standard Specification for Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Outside Diameter".

C. HDPE pipe sheathing in nominal diameters greater than 150 mm shall meet the requirements of ASTM F714.

3.5.3.2 — Material specifications

A. HDPE pipe material shall meet the specific cell category requirements for class PE 325443 and class PE 345444 materials as defined by Table 1 of ASTM D3350. The resultant acceptable range of primary properties for these HDPE materials is as shown in Table 3-3.

B. Material properties shall be certified by the resin manufacturer.

C. Only 100% virgin materials shall be used. The use of regrind is not permitted.

COMMENTARY

C3.5.3 — High density polyethylene pipe

These Recommendations refer to discrete lengths of pipe and are not meant to apply to the continuous extrusions over wire or strand.

The intensity noted is consistent with temperate climates typical of the northern US. These intensity levels may not be appropriate for more tropical climates or those in the arid west. If higher intensities are required as a design basis, they should be shown on the plans or called for in the project specifications.

Acceptable scientific methods for the demonstration of UV resistance include the occurrence of visible signs of oxidation or change of colometric value ΔE and change of mechanical characteristics as specified in the project specification or as acceptable to the Engineer.

C3.5.3.2 — Material specifications

See Commentary Section C3.5.3.

RECOMMENDATIONS

D. Colored raw material shall be stabilized for UV resistance, heat resistance, and micro crack resistance.

E. HDPE material shall not react with any filler, prestressing steel, corrosion inhibiting coating or any other material it is permitted to come in contact with, as part of the stay cable and shall be free of water soluble chloride. The Contractor shall furnish to the Engineer a certified test report covering the quality of the HDPE material performed by an approved independent laboratory.

3.5.3.3 — Wall thickness

The maximum Standard Dimension Ratio (SDR) shall be 18 (SDR = ratio of outside diameter to minimum wall thickness) for grouted systems, and 32 for ungrouted systems. The minimum thickness shall be 6 mm.

Wall thickness shall be sufficient to withstand handling and construction loadings as well as 125% of maximum filling pressure for grouted or injected stay pipes.

Table 3-3—Acceptable properties of high-density polyethylene pipe material

Property	ASTM test method	Value
Density, g/cm^3	D1505	>0.940
Melt index, g/10 minutes	D1238	0.35 to 1.4
Flexural modulus, MPa	D790	>750
Elongation at break test (at 23°C, test speed 50 mm/minute) Testing shall be performed once for each pipe dimension per lot.	D638	350%
Tensile strength at yield, MPa	D638	>21
Environmental stress crack resistance (F20, hours)	D1693 (Cond C)	600
Min hydrostatic design basis as applied to filled pipes only, MPa	D2837	8.6 to 11.03

COMMENTARY

C3.5.3.3 — Wall thickness

For grouted systems, the SDR requirement for the HDPE pipe is based on the radial pressure due to grouting or filling and the anticipated temperature variation during the service life of the structure. The SDR value of 18 assumes the grout controls are applied and the minimum service temperature is –30° C. If conditions vary significantly, a re-evaluation of the SDR may be appropriate.

For ungrouted systems, the SDR requirement should be considered an absolute maximum to be verified for each situation by reviewing factors such as:

A. Clamping conditions of any vibration suppression devices.

B. Rattling of cables

C. Handling

D. Local flexure of pipe at the clamps and at terminators and attachments to transition pipes etc.

E. Compression or tension forces in the pipe.

RECOMMENDATIONS

4.0 — SYSTEMS QUALIFICATION & TESTING

4.1 — Corrosion protection

4.1.1 — General

This specification covers only stay cable systems that use prestressing wire, strand or bar for the main tension elements. As a result, the corrosion protection systems are limited to those that are most appropriate for the protection of these elements.

Stay cables shall be provided with a corrosion protection system capable of protecting the MTE from corrosion for the design life of the cables. A minimum of two nested qualified barriers shall be provided for MTE corrosion protection. Requirements for the corrosion protection system are divided into the free length and the anchorage length.

In addition, temporary corrosion protection shall be provided if the permanent corrosion protection system is not installed at the time of stay cable fabrication.

COMMENTARY

C4.1.1 — General

There are a number of corrosion protection systems available for use in stay cables. In general, a typical stay cable system has an external pipe surrounding the tension elements. The pipe may have a blocking agent injected. In addition, the tension elements can have individual barriers to provide additional levels of protection as needed. Thus, the corrosion protection system is composed of nested barriers which provide redundancy of corrosion protection. Increasing the number of effective barriers increases the redundancy and thus improves the reliability of the corrosion protection system.

There are a variety of systems that have traditionally been used for corrosion protection, including HDPE pipe, grout, epoxy-coated strand, and sheathed strand. The Engineer should not presume that all of these traditional systems will necessarily pass the barrier definition and qualification testing of Section 4.1.4.1.

The following provisions define a two-stage process for qualification of corrosion protection systems. The first process (Section 4.1.4) is used to establish the effectiveness of proposed barriers to corrosion, and is intended to qualify each proposed barrier for use in the overall system.

The second process (Section 4.1.6) is used to test the corrosion protection system for the assembled cable, and represents the acceptance standard for the cable system being supplied.

The performance standard in Section 4.1.4 is intended to apply to the design of the system, and any changes to the system design. Therefore, the testing in Section 4.1.4 is intended as a pre-qualification test, and is not to be applied on the project specific basis. The test in Section 4.1.6 is to be applied with fatigue test specimens on either a prototype or project specific basis, as is the case for the fatigue acceptance tests.

Further background information on corrosion protection can be found in Reference 5.

RECOMMENDATIONS

Unless noted otherwise, all barrier qualification and temporary corrosion tests shall consist of three independent specimens, each 2 m long. In order to satisfy these Recommendations, all specimens shall satisfy the acceptance criteria as noted in this Section.

The Supplier's quality control program shall include provisions to assure that the materials used in each cable installation are of the same specification and quality as those used for the qualification testing required under this Section.

4.1.2 — Barriers

Corrosion protection shall be provided for the MTE using at least two complete nested barriers. Internal barriers shall completely encase the MTE for the full free length and the anchorage length. The external barrier shall completely encase the inner barrier for the full free length. The barriers shall be arranged such that if corrosive elements breach the external barrier, the interior barrier will protect the main tension element.

When a physical barrier is to be used as the internal barrier on each prestressing strand, the barrier shall completely cover the exterior of the strand as well as completely fill the interstitial spaces between the wires with inert material. The internal barrier shall not permit free water to enter the interstitial space.

4.1.2.1 — Anchorage/free length interface

If the barrier systems are not continuous across the interface between the anchorage and free length then additional protection shall be provided to protect the MTE.

4.1.3 — Materials

Materials used in the corrosion protection system shall meet the requirements given in Section 3.0. Materials not specified in these Recommendations shall be subjected to quality control tests verifying performance equal to the requirements of Section 3.0 before consideration for use in the corrosion protection system.

COMMENTARY

C4.1.2 — Barriers

The Committee has agreed that a redundant corrosion protection system should be specified. To this end, it is necessary to define separate barriers. Redundancy is satisfied by requiring at least two nested qualified barriers in any corrosion protection system. If the external barrier is somehow breached then the secondary barrier provides a backup corrosion protection system. If, in the future, new material becomes available and is demonstrated sufficient for use as a solitary barrier in the corrosion protection system, then exceptions can be made for this material.

C4.1.2.1 — Anchorage/free length interface

Not all corrosion protection systems are necessarily continuous throughout the free length and anchorage length. One example is greased and sheathed strand. The sheathing must be discontinued at the anchorage to allow for connection. These provisions allow a transition of protection systems as the MTE enters the anchorage region. In this case, the barrier qualification applies to the free length of cable.

RECOMMENDATIONS

Materials and design details for the prototype tests shall be the same quality and shall meet all of the same certifications as those used for the actual structure. Changes to basic materials or design shall be cause for re-qualification in accordance with these Recommendations. Use of alternative materials shall be subject to the approval of the Engineer.

4.1.4 — Qualification of barriers

4.1.4.1 — Internal barriers

Internal barriers shall be subjected to a salt fog test. The specimen shall be prepared using samples of the MTE wire, strand, or bar. If the barrier is to be applied to the MTE sample during the manufacturing process then the test shall be conducted with the MTE stressed to 50% of MUTS. If the barrier is applied after the MTE is assembled, then the MTE shall be stressed to 30% MUTS prior to application of the barrier. After the barrier has been applied and cured, the specimen shall be stressed to 50% MUTS for the salt fog test. The prepared salt fog test specimens shall be exposed to salt for 3,000 hours in accordance with ASTM B117. Care should be taken to protect or seal the end anchorage from salt fog or corrosion so as not to unduly influence the test results. After 3,000 hours of exposure, the specimen shall be detensioned and removed from the test apparatus. Seven-wire strand shall be destranded and fully inspected on all surfaces. Acceptance criteria shall be in accordance with Section 4.1.7.

4.1.4.2 — External barriers

External barriers shall meet the requirements of Section 4.1.4.1. The external barrier test shall demonstrate that the external barrier alone can protect the MTE as indicated in Section 4.1.4.1 above. If the external barrier will be strained by virtue of compatibility with the MTE in the actual cable installation, then the external barrier shall be similarly strained for the tests required under this Section. The circumference and thickness of external barriers shall be consistent with those used for the range of cable sizes in the Supplier's inventory.

Inspection of any metallic barrier material after testing shall reveal no evidence of rust.

COMMENTARY

C4.1.4.1 — Internal barriers

The intent is that the salt fog test would be performed on all of the materials that would be considered "barriers," and passage would serve as the definition for a single barrier. Tests in the fog cabinet could be conducted for specimens that are individually protected (such as greased and sheathed, epoxy-coated, galvanized) on each barrier element at a time (e.g. grease alone, sheathing alone, etc - if greased and sheathed is to be used as only one barrier, then both would be on the strand as tested). In addition, blocking materials such as epoxy, polymer modified grout, polyurethane, etc. could be tested by constructing strand, bar or wire "lollipops" with the proposed materials. The thickness of cover for blocking materials should be equal to the thickness of cover between the external sheathing and the MTE bundle.

In order to qualify as a barrier, each separate barrier must protect the MTE without assistance from other barriers. Therefore, each barrier is tested independently.

This barrier test may be combined with the material tests required under Section 3.3.9.

C4.1.4.2 — External barriers

If the external barrier is made compatible with the MTE by virtue of the bonding filler, then the external barrier will develop tension strains as the cable is loaded. This strain may affect the performance of the barrier, and should be modeled in these tests.

See C4.1.1 for further information.

RECOMMENDATIONS

Any external barrier that is susceptible to degradation from exposure to ultraviolet light and/or moisture shall be subjected to testing in a weatherometer in accordance with ASTM G155. The length of test specimen shall be compatible with size limitations of the weatherometer.

4.1.5 — Qualification of temporary corrosion protection system

A sample consisting of not less than 3 strands, 15 wires, or 2 bars shall be placed in a prototype of the temporary corrosion protection system. This prototype shall include all elements of the temporary system for the free length of cable, including inhibitors, sheathing, coatings, or other external elements of the system as it will be installed in the field. Sample ends shall be sealed. The prototype shall be exposed in a weatherometer to thermal and wetting cycles of a number equivalent to 125% of the number of days for which the system will be qualified. Temperature cycles shall range from not less than 5° C to not more than 38° C. Wetting in each cycle shall consist of water spray applied at 5° C as necessary to completely wet the specimen. Acceptance shall be in accordance with Section 4.1.7.

Where permanent corrosion protection is not in place during construction, temporary corrosion protection shall encompass the entire length of MTE prior to cable assembly and installation.

4.1.6 — Qualification of anchorage assembly

Corrosion protection systems at the anchorage shall be tested as complete assemblies using cable components that have been qualified in accordance with Section 4.1.4. The provisions of *fib* Bulletin 30, Section 6.2.3 may be substituted for the provisions in Sections 4.1.6.1 through 4.1.6.3. If the *fib* procedure is used, the optional cap test shown in Fig 6.3 of Bulletin 30[4] shall be included and immersed into the dyed solution as part of the *fib* test.

4.1.6.1 — Leak test

One fully assembled stay cable anchorage, complete with transition zone, a minimum of one meter of free length, and all caps and seals, coatings and coverings that will be installed in the actual application shall be subjected to a leak test as defined in this Section.

COMMENTARY

More research is needed here to determine how long and what type of exposure will be required to simulate exposure to UV for the life of the structure. This provision is intended to cover nonmetallic sheathing (HDPE or HDPP) that could be susceptible to UV degradation. It is not intended to be used on steel or other metallic pipe.

C4.1.5 — Qualification of temporary corrosion protection system

This temporary corrosion protection test is for the free length of cable only. Additional measures may be necessary if strand tails are subjected to the atmosphere during cable installation. In addition, details should be provided to the Engineer for review that show the manner by which the anchorage region will be protected from the intrusion of water during cable installation.

C4.1.6 — Qualification of anchorage assembly

The corrosion protection provided in the free length is adequately covered by the material and performance specifications to be qualified as a barrier. However, there is a need to test the system as a part of the pre-qualification procedure to ensure that transitions in barrier systems and other assembled components work together as anticipated in the field environment.

C4.1.6.1 — Leak test

The intent of this provision is to take one of the test specimens from the fatigue test and subject it to a leak test after completion of the fatigue acceptance test.

The specimen used for this corrosion test need only be subject to the fatigue stress range of the Recommendations.

RECOMMENDATIONS

The specimen shall be the smallest stay cable anchorage assembly tested under the provisions of Section 4.2, but shall not be subjected to the ultimate tensile test after the fatigue test. All connections, clamps, caps, seals, adhesives, coatings or other corrosion protection details that will be subjected to stress in the loaded cable shall be installed on the specimen before it is subjected to the fatigue test under Section 4.2. Grease caps, strand caps, or other seals at the rear of the anchorage that are not subject to live load stress or strain may be omitted from the fatigue test and added to the cable for the corrosion test, provided that they will be added to the installed cable after stressing in the field. Special sealers, tapes, clamps or other devices that will not be part of the installed cable may not be used for the leak test.

4.1.6.2 — Preparation

The specimen shall be placed in a chamber so that the anchorage assembly, transition zone, and all connections between the transition zone and free length of cable are subjected to not less than a 3 m head of water and dye solution. The solution shall contain 3% by volume of red dye #2. Head may be applied by static measure or pumping.

If the fatigue assemblies are cut in the free length to produce the specimen for this leak test, the free end of the specimen shall be sealed against leakage. This free end need not be subjected to the leak test, provided the required head can be established at the level of the transition connection as noted above.

4.1.6.3 — Testing

The test specimen shall be subject to the required head of red dye solution for a continuous period of 96 hours. At the end of this period, the specimen shall be removed from the test solution and immediately subject to destructive examination in accordance with Section 4.1.7.

COMMENTARY

C4.1.6.2 — Preparation

The PTI "Manual for Certification of Plants Producing Unbonded Single Strand Tendons"[7] includes an acceptable test device for testing leak tightness, provided that the standpipe is modified for the 3 m head as required in these Recommendations.

Red dye #2 is a natural plant extract from the species of amaranth plants. Its purpose in this test is simply to act as a clear indicator of water migration. Alternative dyes or indicators are allowed if they meet this goal.

Where grouted cables are tested, a reaction frame will be needed for both the fatigue and corrosion tests to prevent unloading of the grouted specimen, and associated damage to the cable. This reaction frame shall not limit the required head of solution on the cable.

C4.1.6.3 — Testing

The specimen may be wiped dry on the exterior to facilitate handling as it is removed from the red dye solution. However, solution may not be removed from the interior of the specimen as it is dissected. The dissection process should be videotaped to document any incidence of dye reaching the MTE as a result of the dissection process (which shall not be cause for rejection of the specimen).

RECOMMENDATIONS

4.1.7 — Acceptance criteria

4.1.7.1 — Barriers

Each tested barrier sample shall be destructively examined and recorded by color photographs. The dissected samples shall be destranded (in the case of strand) and compared with the reference standards for surface corrosion. In order to be acceptable, the tested sample shall not show signs of tensile element corrosion that cannot be fully removed by wiping with a soft untreated cotton cloth. Photograph 2 of the PCI reference shall apply (Fig. 4.1). Any pitting shall be cause for rejection.

4.1.7.2 — Anchorage assembly

The tested anchorage assembly shall be dissected to inspect the MTE for signs of dye. Specimens will be acceptable if visual inspection shows that dye has not reached the MTE.

The above testing procedures notwithstanding, all elements of the specified corrosion protection system shall be inspected during and at the end of bridge construction, and shall be totally intact as the bridge construction phase is completed. Nothing in this testing program should be construed as permitting partial damage to the corrosion protection system as the bridge is placed into service.

4.1.8 — Documentation

Each test produced under these Recommendations shall be documented by a written report. The report shall include, but not be limited to the following information:

- Complete description of the test set-up, design details of all cable components and test procedures
- Complete description of the chamber and methods used for the salt fog testing
- Complete description of all materials used for all components of the tests, including material sources and certifications
- Complete documentation of the results from testing, including color photographs or color copies of photographs that document the condition of all MTE and metallic elements of the prototype specimens tests from companion wires, strands or bars.

COMMENTARY

C4.1.7 — Acceptance criteria

C4.1.7.1 — Barriers

For reference to corrosion standards for strand, see article in the *PCI Journal* May-June 1992,[8] Galvanized strands may show signs of zinc oxidation as the result of an active corrosion cell. This is not cause for rejection of the sample. However, any underlying corrosion of the tensile element in the case of galvanized wire shall be cause for rejection.

C4.1.7.2 — Anchorage assembly

This section of the Recommendations is not intended to cover project specific quality control and inspection programs that are necessary to assure proper assembly and installation of the systems qualified under these Recommendations.

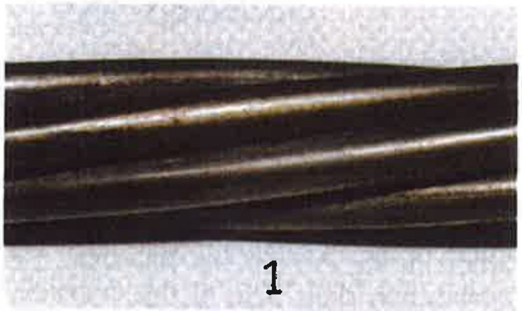

Photo 1. Strand surface before cleaning

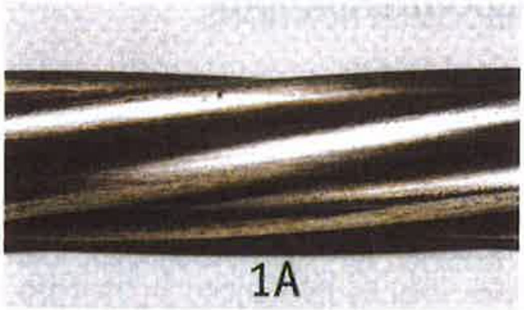

Photo 1A. Strand surface after cleaning

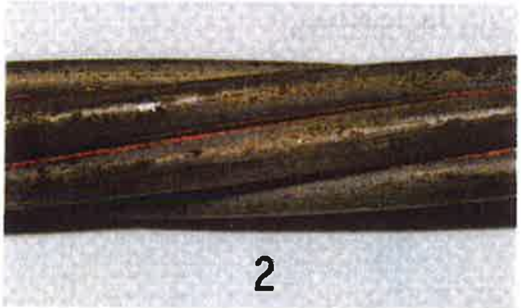

Photo 2. Strand surface before cleaning

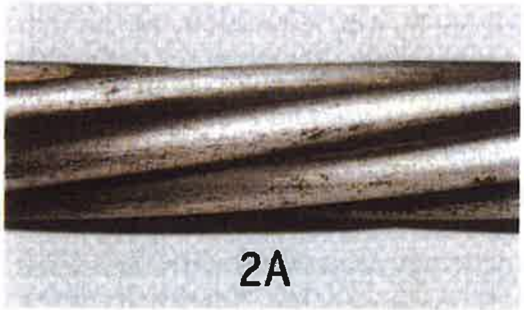

Photo 2A. Strand surface after cleaning

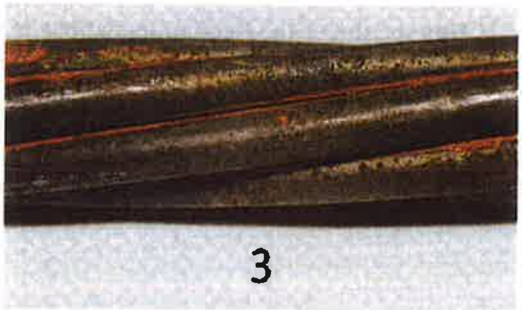

Photo 3. Strand surface before cleaning

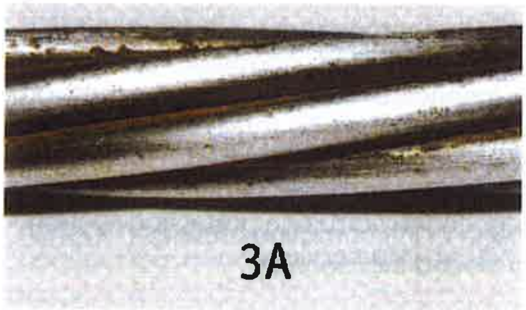

Photo 3A. Strand surface after cleaning

Photo 4. Strand surface before cleaning

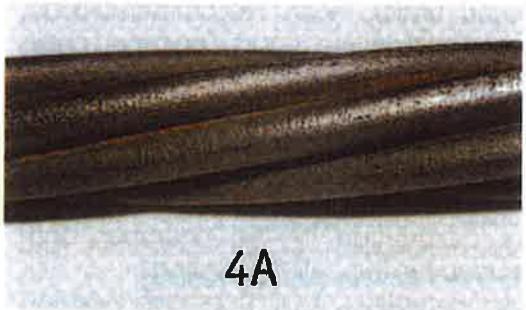

Photo 4A. Strand surface after cleaning

Fig. 4.1—Guide for evaluating degree of rusting on prestressed concrete strand.[8] (Printed with permission from PCI.)

Photo 5. Strand surface before cleaning

Photo 5A. Strand surface after cleaning

Photo 6. Strand surface before cleaning

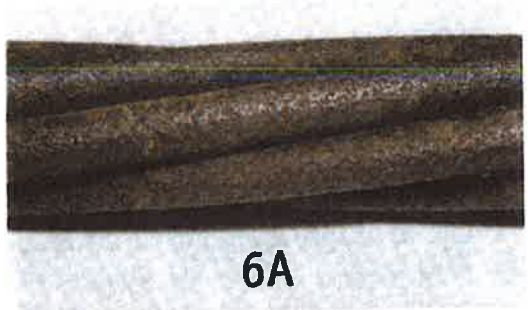

Photo 6A. Strand surface after cleaning

Photo 7. Strand surface before cleaning

Photo 7A. Strand surface after cleaning

Photo 8. Strand surface before cleaning

Photo 8A. Strand surface after cleaning

Fig. 4.1 (cont.)—Guide for evaluating degree of rusting on prestressed concrete strand.[8] *(Printed with permission from PCI.)*

RECOMMENDATIONS

4.2 — Acceptance testing of stay cables

The fatigue and static strength of the proposed stay cable system shall be demonstrated for each project either by project specific testing or by acceptance of prior tests as provided by Section 4.3.

Tests of at least 3 representative stay cable specimens shall be carried out. Stay cables are to be tested with all load bearing appurtenances.

When grout is utilized in the bridge cable stay (see Appendix C), an unstressed mock-up with a minimum length of 3 m shall be designed and constructed to simulate field conditions including any potential migration of bleed water to uncoated areas of the strand and anchorage material. The mock-up should be autopsied after 7 to 14 days to assure there are no adverse corrosive effects. This testing should be completed prior to fatigue acceptance testing. All materials to be used in the mock-up test (water, cement, admixtures, etc.) and grouting procedures shall be the same as that to be used for the prototype cable-stay.

Stay cable specimens shall be grouted when grout is utilized in the bridge cable stays. The grouting shall take place while the test cable is subjected to a stress of 75% of the fatigue range below the upper test stress of 0.45 f_s'.

Stay cable specimens shall have a minimum length of 3.5 m. The anchorages of the stay cable specimens shall be supported on wedge-shaped shim plates, creating angular deviations of 0.01 radians, and oriented such as to create an S-shaped cable profile. (Fig. 4.2) The 2 of the 3 stay cable specimens shall be tested for 2 million cycles for an upper stress of 0.45f_s' and a stress range as shown in Table 3-1. The third cable specimen shall be tested for 2 million cycles at an upper stress of 0.55f_s' and a stress range of 6.5% f_s' for strand or bars, 7.5%f_s' for wire. During fatigue testing, not more than 2% of the number of individual wires (rounded to the nearest whole number) may fail. Any failure of bars shall result in rejection of the stay cable system. No failure shall occur in the anchorage material, or in any component of the anchorage during the fatigue tests. Any failure of anchorage components or anchorage material during the fatigue test shall be cause for rejection of the test.

The cracking of welds or bolts at connections between various segments of the pipe (steel or HDPE) and between the sheathing and the anchorage shall not

COMMENTARY

C4.2 — Acceptance testing of stay cables

The fatigue strength of test cables depends, to certain degree, on their length. Most previous tests have been made with specimens about 5.5 m long.

The 3 stay cable test specimens should represent the largest, the smallest, and the average sizes (areas of MTE) of all bridge cables. If bar stays will utilize couplers, they should be included in the tests.

The grout test is to check for corrosive or undesirable bleed characteristics of grout in a grouted, bare MTE system, or wherever grout comes in contact with MTE or structural steel components. This test is separate from the corrosion performance tests of Section 4.1, and is to be conducted on a project specific basis.

In grouted cables with steel pipe, unintended bond between grout and pipe could introduce fatigue damage to the sheathing and its connections. Therefore, testing of cables with HDPE or steel pipe should be performed with grout when grout is used in the bridge stay cables, to evaluate potential negative impact on the integrity of the sheathing. It is recommended that stay cable specimens be tested at the stress ranges specified in this section even when the stress range values in the cable stays due to truck loading are lower. This is to ensure that all cable systems have uniform and high levels of quality and reliability. Fatigue stresses calculated by designers may not include all the actions and conditions present in the real structure. This may result in higher fatigue stress ranges and/or number of cycles than calculated. Also, the lengths of test cables are far shorter than the bridge cables. Short-length cables will have a smaller probability of fatigue failure than long cables.[9] The duration of testing is also very short compared to the design life of the cable-stayed bridge. Therefore, the effects of time and service environment (such as corrosion) on fatigue are not considered. Finally, the quality of workmanship and materials during installation of test cables in the laboratory is likely better than that achieved in the field. Therefore, the fatigue testing requirements serve as both a quality control and performance standard for the proprietary anchorage design offered by the supplier.

The acceptance testing of stay cables includes bending effects to simulate the consequences of installation tolerances of anchorages and of other sources of bending. The magnitude of the angular deviation causing bending has been chosen such as to be fatigue-relevant. Larger angular deviations can apply for which the static strength of the anchorages should be designed in accordance with Section 5.3.4.1. However, these larger angular deviations are

RECOMMENDATIONS | **COMMENTARY**

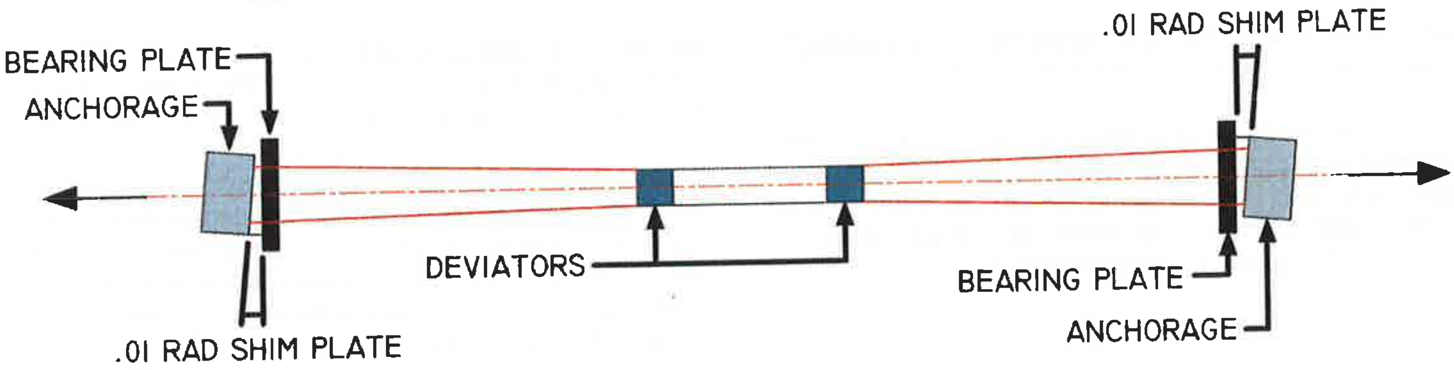

Fig. 4.2—Fatigue test setup.

be allowed during fatigue loading. Evidence of partial or full fracture due to fatigue in the connection welds and/or bolts shall be cause for the failure of the test.

After fatigue loading, the test specimen (except the specimen used for corrosion testing) shall be reloaded, with the wedge-shaped shim plates remaining in place, and shall develop a minimum tensile force equal to 92% of the actual ultimate tensile strength of the cable or 95% of the minimum ultimate tensile strength of the cable, whichever is greater. The actual ultimate tensile strength of the test cable shall be determined from the results of tensile tests on the individual wires, strands, or bars. Any failure of anchorage components during the static test shall be cause for rejection of the test.

After conclusion of fatigue and static tests, all test cables shall be dissected and their contents carefully examined. All wire or bar failures and their locations shall be identified.

Presence of corrosion or moisture inside cables shall be documented during the dissection of cables. All strands, wires, or bars shall be free of visible corrosion after the conclusion of load tests. The acceptance criteria for corrosion shall be based on the provisions of Section 4.1.7. Each selected strand, wire or bar shall be completely exposed (including center wire in the case of strands) to permit close inspection of the steel surface. Presence of moisture in contact with MTE or the anchorage shall be evaluated by the Engineer for acceptance or rejection.

The actual fatigue strength of the stay cable test material shall be determined from the results of fatigue tests from companion wires, strands or bars. Test procedures for the individual companion specimen

considered to occur with a relatively low number of cycles and therefore, are not considered fatigue relevant.

The 2% wire breakage limit is intended to be based on wire breaks detected by instrumentation of the test set up for fatigue testing. Redundant devices shall be used to verify an indication of wire breaks. Wire condition is to be confirmed during the autopsy of the specimen following the static test. For application to small stays having less than 125 wires, the 2% criteria is very restrictive and may be interpreted as not more than 3 wires.

Previous tests of grouted cables utilizing steel pipe sheathing revealed fatigue damage to welded or bolted connections between various pipe segments and between the pipe and cable anchorage.[10] This was a direct result of the unintended development of sufficient bond between steel pipe and grout to transfer cable forces to the steel pipe. Similar attention should be paid to bolted or welded HDPE connections, as damage to these connections have also been observed in some tests.

The actual ultimate tensile strength of prestressing steel usually exceeds the minimum specified ultimate tensile strength established in the applicable ASTM specifications (see Section 3.0) by 1 to 5 % as a manufacturing tolerance.

In some tests cracking of strand wedges may be observed in the static strength test. Cracking may also occur in the filler material inside the anchorage sockets of some cable systems. These types of cracking in the strength test are normal for these anchorage components, and should not be considered as cause for rejection of the full-scale cable ultimate strength tests.

Actual cable strength is to be based on testing of the lot of MTE used for each respective test. This strength is therefore based on actual material strength and actual area of

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fatigue tests shall be as outlined for fatigue strength tests in Sections 3.2.1.1, 3.2.2.1, or 3.2.4.1.

The "One-Pin Test" as outlined in Section 3.2.2.1 and Appendix A shall be conducted on a sample from each manufactured length of strand used in the stay cable specimen. If the specimen fails at less than 0.8 f_{sa}', then the strand lot shall be rejected.

4.2.1 — Limitations of full scale acceptance testing of stay cables—seismic loading

When seismic time-history analysis predicts net cable tension loads less than 10% of MUTS, cables and their anchorages shall be designed to assure adequate seismic performance. Full scale verification testing of cable and anchorage systems designed to prevent seismic liftoff should be evaluated on a project-by-project basis.

4.3 — Acceptance of prior tests of stay cables

When the stay cable tests have been conducted for previous projects on specimens similar in design and details to those proposed for a new project, the previous tests may, at the Engineer's discretion, be used as the basis for stay cable approval on the new project. However, the quality control tests outlined in Section 3.2 shall establish that the prestressing steel supplied for the new project has fatigue characteristics comparable to the prestressing steel used in the acceptance tests of the stay cable specimens in the previous project. Further, the stay anchorage hardware shall be the same as in the previous tests.

4.4 — Quality control of other stay cable components

Appropriate quality control tests shall be conducted in accordance with accepted standards for all materials incorporated in the cable stay, and for all procedures involved in the fabrication of cable stays.

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the MTE. The minimum cable strength is based on ASTM minimum specified criteria for the MTE material, and is based on nominal dimensions.

In some stay cable acceptance tests, extensive corrosion and/or free grout water were observed during dissection.[10] Considering that the observed corrosion appeared in a short time frame of a few weeks (testing duration) and long-term fatigue performance is highly influenced by corrosion, it is essential that such observations be reviewed.

C4.2.1 — Limitations of full scale acceptance testing of stay cables—seismic loading

Stay Cable acceptance testing provisions of these Recommendations are not intended to verify stay cable and stay cable anchorage performance under cable unloading and reloading associated with response of the superstructure to seismic ground motion. Anchorages, shim plates, locking rings or wedges may be susceptible to dislodging and damage under seismic loading, and associated dynamic effects on anchor pipes or damping devices may increase demands on these components.

C4.3 — Acceptance of prior tests of stay cables

The PTI "Guide Specification - Acceptance Standard for Post-Tensioning Systems"[11] could serve as a more official basis for acceptance of prior tests.

Use of acceptance tests of stay cable specimens from previous projects eliminates the significant expense and time devoted to new acceptance tests for each project. For smaller stay cable bridges, the test program costs may be a significant percentage of the project budget.

C4.4 — Quality control of other stay cable components

The variety of materials and procedures that may be involved in the various cable stay systems precludes a detailed listing in these Recommendations.

RECOMMENDATIONS | COMMENTARY

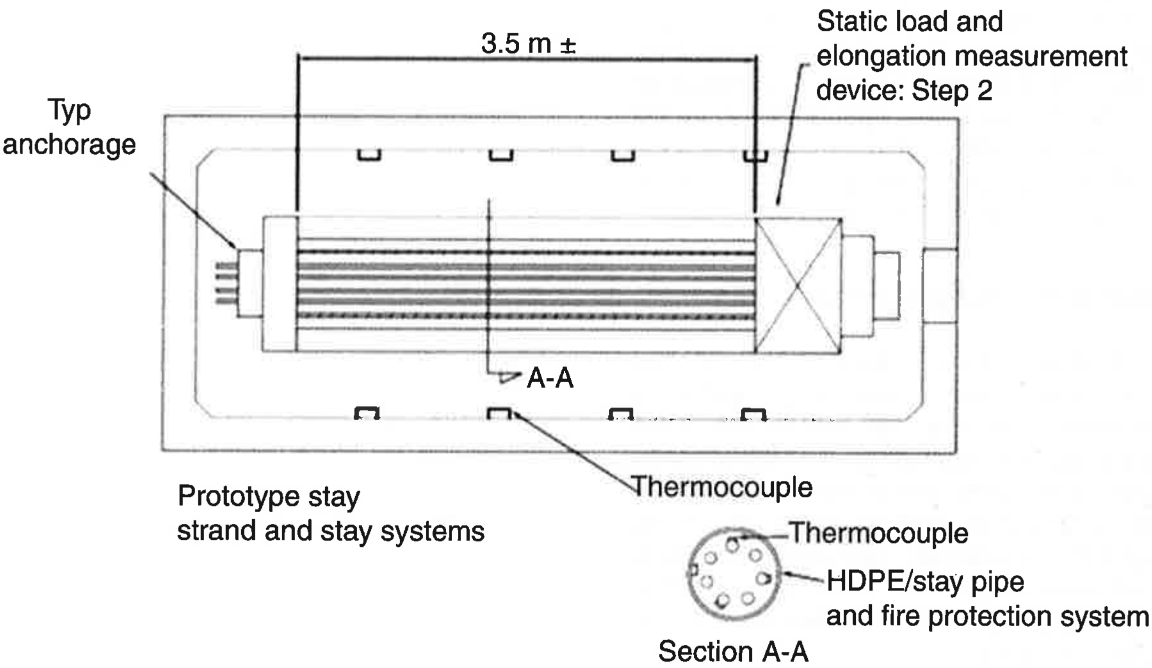

Fig. 4.3—Stay-cable specimen for fire-resistance testing.

4.5 — Fire resistance qualification testing

Stay systems rated with fire resistance characteristics shall be qualified by physical testing in a qualified independent testing laboratory to establish a fire rating.

The rating shall be stated as a time of protection of the stay cable specimen from an external source of 1100 degrees C. The certification shall consist of two phases – a test of insulating fire protection materials followed by a load test of high-temperature strength.

The stay cable specimen shall consist of a size with breaking strength of 1600 KN or greater, the prototype MTE and corrosion protection elements, prototype HDPE or other stay pipe material and configuration, and a full anchorage element. (See Fig 4.3). The proposed fire resistant stay cable specimen must demonstrate fire endurance of 30 minutes or greater, as determined by the time required to reach a temperature of 300 degrees C measured on the outer layer of the MTE.

Following demonstration of fire endurance, a tensile test stay cable specimen of the same materials and

C4.5 — Fire resistance qualification testing

Fire rating requirements will be established by the Owner if these are to be a project criterion.

The cable fire rating is a measure of fire resistance for a structural element ability to maintain its fire resistant properties. As applied to cable stayed bridge construction, fire resistance is based on protection of the MTE to a level that will retain the MTE's ability to carry applied design load. Note that following the fire event the entire cable system, including the MTE, may need to be replaced.

The 30-minute fire rating for fire-resistant stay cables is a minimum standard for fire resistance that may be used in lieu of or in conjunction with cable loss requirements in these Recommendations where Owner's criteria includes fire hazard mitigation requirements.

Test method information cited in Section 4.5 is based on ASTM E119-08a, "Standard Test Methods for Fire Tests of Building Construction and Materials."

RECOMMENDATIONS

fabrication details shall be placed in a tension frame, and uniformly heated to a minimum of 300 degrees C. The cable shall be tensioned to 0.45 MUTS at a temperature of 300 degrees C and held for no less than 30 minutes. The load test phase is acceptable if the cable is able to resist the applied load for 30 minutes without slip or failure of anchorage components. The load test phase must be acceptable in order to achieve a fire rating under these provisions.

4.5.1 — Furnace & test temperatures

The insulation test shall be conducted in a furnace capable of generating and sustaining, within 5 minutes of the start of the fire test and for the duration of the test period, a temperature of 1100 degrees Celsius, by igniting gas jets and/or hydrocarbon fuel jets. The target temperature shall be measured by no fewer than eight thermocouples distributed to show the temperature near all parts of the specimen. The temperatures shall be read and recorded at intervals not exceeding two minutes.

4.5.2 — Test specimen & monitoring temperature of MTE

The test specimens shall be representative of the cable construction that the test is intended to assess, as to materials, workmanship, and details such as dimensions of parts, and shall be built under conditions representative of those applied in construction and operation, including fire protection and corrosion protection systems. The physical properties of the materials shall be recorded. The size and dimensions of the test specimen shall apply for rating cables of dimensions within the range of stay sizes offered for qualification. Temperatures of the specimen shall be measured directly atop the outer layer of the MTE and beneath the fire and corrosion protection systems at no fewer than eight locations. During the fire, MTE temperatures shall be read and recorded at intervals not exceeding two minutes.

4.6 — Summary of testing requirements

A summary of qualification and acceptance testing for stay cables is shown in Table 4-1.

COMMENTARY

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Table 4-1—Summary of testing requirements

Testing	Section
General testing of materials	4.1.3
Salt fog test for internal barriers	4.1.4.1
Salt fog test for external barriers	4.1.4.2
Weatherometer for temporary corrosion protection	4.1.5
Leak test	4.1.6.1
Anchorage fatigue test	4.2
Fire-resistance qualification testing	4.5

5.0 — LRFD DESIGN

5.1 — Loads

The loads (including those loads applied during construction) assumed for design purposes shall be noted on the plans.

5.1.1 — Dead loads

Dead loads shall be in compliance with the AASHTO LRFD Bridge Design Specifications which will be referred to as AASHTO LRFD. For stay forces, the weight of the main tension element, and any additions to the stay, such as sheaths, cement grout, etc., shall be included as dead load in the stay.

5.1.2 — Live loads

The stays shall be designed for the appropriate number of traffic lanes as specified in the AASHTO LRFD Specs. The design load is designated as a HL-93 loading which consists of a design truck or design tandem, in combination with a design lane load.

Except as modified by Article 3.6.3.1 of the AASHTO LRFD, each traffic lane under consideration shall be occupied by either the design truck or design tandem, in addition to the design lane load. The design lane load occupies 3 m transversely within the design lane.

COMMENTARY

C5.0 — LRFD DESIGN

Some earlier editions of these Recommendations referred to much of the design criteria contained in the AASHTO Standard Specifications for Highway Bridges which supported allowable stress design concepts. This edition of the Recommendations follows the concepts of Load and Resistance Factor Design (LRFD) and should be used in conjunction with the AASHTO LRFD Bridge Design Specifications.[1]

C5.1.1 — Dead loads

The unit weight (mass) of common construction materials is contained in Table 3.5.1-1 of the AASHTO LRFD Bridge Design Specifications.

C5.1.2 — Live loads

The loading and spacing of the axles of the design truck is as shown in Fig. 3.6.1.2.2-1 of AASHTO LRFD. The design truck is equivalent to the AASHTO HS20 truck.

The design lane load consists of 9.3 kN/m uniformly distributed longitudinal load which may be continuous or discontinuous as necessary to produce the maximum force effect.

The design tandem consists of two 110 kN axles spaced 1.2 m apart with an 1.8 m transverse spacing of wheels.

Other live loads, such as rail transit loads, pedestrian loads, etc. need also to be considered where appropriate.

RECOMMENDATIONS

5.1.3 — Fatigue load

The fatigue load shall be a single design truck occupying a single lane in each traffic direction. The single lane shall be that which results in the maximum effect on the stay cable(s) being designed. The fatigue design truck shall have a constant spacing of 9 m between the two rear axles. The fatigue design truck calculated design value shall be multiplied by the factor 1.4.

The frequency of the fatigue load shall be taken as the average daily truck traffic in a single lane $(ADTT)_{SL}$ in each direction. See Article 3.6.1.4 of the AASHTO LRFD.

5.1.4 — Dynamic load allowance

The static effects of the design truck or design tandem other than centrifugal and braking forces, shall be increased by the percentage specified in AASHTO LRFD Table 3.6.2.1-1. The dynamic load allowance shall be applied to the calculation of fatigue effects but shall not be applied to the design lane effects or pedestrian loads.

COMMENTARY

C5.1.3 — Fatigue load

The ASCE report "Recommended Design Loads on Bridges"[12] shows that there is a significant margin of safety in the load definition for fatigue. In reports[13,14] on load measurements on a cable-stayed highway bridge over a three-month period, the maximum values of the axial cable stresses recorded under flowing traffic were only 13 percent of the design cable stresses from the specified traffic loading according to DIN 1072. Under an artificially produced, extremely unfavorable traffic jam, 37 percent of the design stresses from traffic loading were reached. The Swiss Standard SIA 160 provides for the use of reduced live load for fatigue design to reflect the results of their findings and other studies.

In consideration of the above, the use of loaded multiple lanes for fatigue design has been replaced in these Recommendations by a single lane loaded in each traffic direction. In addition the design tandem loading need not be considered for fatigue design.[15]

The fatigue provisions of AASHTO LRFD were developed for short spans. To account for the longer spans of cable-stayed bridges the factor in Section 5.1.3 was developed. This resulted in an increase in AASHTO LRFD effective design value to approximately that which would be obtained by loading adjacent lanes as specified in the third edition of the Recommendations. The Engineer has the design option of performing a more rigorous analysis in lieu of using the 1.4 factor.

AASHTO fatigue demand and live load criteria are based on typical *ADTT*. Two-dimensional frame analyses of traffic loads may be conservative for backstays, and 3D space frame analyses may result in a more accurate distribution of stay forces near supports. Exceptional truck traffic volumes and unusual bridge layouts may warrant special study.

RECOMMENDATIONS

5.1.5 — Wind loads on stay cables

Attention shall be given to the effects of both static and dynamic wind loads on stay cables. Design recommendations regarding cable vibrations due to dynamic wind loads are given in Section 5.2.

COMMENTARY

C5.1.5 — Wind loads on stay cables

For the determination of the static aerodynamic loads on circular cables, a classical drag coefficient C_D = 1.2 can be used for most purposes. Values in the range of 0.6 to 0.8 have been determined from project-specific testing. A project-specific analysis should consider influences such as Reynolds number, surface roughness and wind turbulence.[16] Allowance should be made for changing surface conditions over the life of the bridge. A lower bound of 0.7 is suggested.

The following recommendations are appropriate for preliminary design or design of smaller bridges. Project-specific studies are recommended for the detailed design of long-span bridges.

Wind load on stay cables may be determined by the following formulae in lieu of project specific values.

$$p_S = q_{Design} C_D D; \quad \text{mean in lateral direction} \qquad \text{(C5.1.5-1a)}$$

$$p_L = p_S g_B g_R; \quad \text{peak total in lateral direction} \qquad \text{(C5.1.5-1b)}$$

The above equations are for the simultaneous loading on all cables; where q_{Design} is the design wind pressure (mean) at middle cable elevation, and g_B = 1.5 ~ 2.0 is a turbulence gust factor which varies depending on bridge span and local turbulence conditions. The dynamic response gust factor g_R = 1.1 is recommended when considering simultaneous loading on all stays.

Eq. (C5.1.5-1a) and (C5.1.5-1b) result in static equivalent wind loads on cables, assuming that even if vibrations are present, they are likely uncorrelated over the length of the bridge. These loads are to be applied laterally in combination with other design loads including buffeting loads on the deck and towers.

A second case is recommended to assess individually each single cable, with g_R = 1.5 accounting for residual instabilities on an individual cable.

The dynamic loads in any direction for the single cable can be estimate as

$$p_D = p_S (g_B - 1) g_R \qquad \text{(C5.1.5-2)}$$

RECOMMENDATIONS

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Conservatively these are to be applied in any plane passing along the cable axis. The associated deflections may be used as a guideline to evaluate wind driven cable movements. These can be estimated based on the simplified formula

$$\delta = \frac{p_D}{(2\pi\varphi)^2 m} \qquad \text{(C5.1.5-3)}$$

where φ is the cable fundamental frequency assuming a single sine wave mode shape. Eqs. (C5.1.5-1) through (C5.1.5-3) are proposed for preliminary design considerations.

5.1.6 — Thermal loads

All steel and concrete structures shall be designed for AASHTO LRFD requirements for uniform temperature ranges and thermal effects. In addition, non-uniform temperature variations shall be considered. Consideration shall be given to wrapping the high density HDPE pipe with white tape, using a light colored HDPE pipe or painting the steel pipe with a light color to minimize thermal effects.

C5.1.6 — Thermal loads

A temperature difference between the HDPE or other sheathing and the MTE may affect the design of any expansion joint details for the PE pipe.

Non uniform temperature variations also affect the design or assembly of the girder.[17] These effects may include the following:

a) Temperature differential between stay cables and deck or between stay cables and pylon. Site specific numbers should be developed for temperature differentials. Values of 8° C and 22° C have been used for white-taped or brightly colored stays, and black stays, respectively.

b) Temperature differential between stays left and right of pylons (as seen in longitudinal elevation).

c) Thermal gradient through the deck, as specified in the AASHTO LRFD.

5.2 — Wind-induced vibrations

Consideration shall be given to the potential for wind-induced stay-cable vibrations during erection and in service. The Engineer shall evaluate the significance of these vibrations on stay cable and bridge performance, and shall define design or supply requirements for special damping devices, stabilizing cables, or special surface treatments used to minimize cable vibrations.

C5.2 — Wind-induced vibrations

Stay cables are prone to vibrations due to dynamic wind loads. Large-amplitude cable vibrations have occurred in several major cable-stayed bridges. Vibrations often take place during construction before mechanical damping devices are installed or if grouted, before grouting of the cables. Modest vibrations at this time can generally be tolerated.

Wind vibrations may produce a low amplitude, high cycle fatigue condition on the MTE or ancillary devices associated with the stay system or connections with the bridge. Performance requirements vary with each bridge,

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and should be considered by the designer. Generally, an aesthetic criterion for service level vibrations less than 1 cable diameter will not result in excessive demands on the cable system for modern anchorage and damping systems.

5.2.1 — Mechanisms of dynamic excitation

Cable vibrations can be excited by dynamic wind forces acting on the cable. Such forces are caused by turbulence in the on-coming air flow (buffeting), vortex shedding in the wake behind the cable, self-induction (galloping), fluid-elastic interaction between neighboring cables (wake galloping), or by interaction between rain, wind and cable. The designer shall give consideration to the particular significance of self-excited vibrations (rain-wind and galloping interaction) as outlined in Sections 5.2.3.2 and 5.2.3.3.

Consideration shall also be given to the possibility of cable vibrations and forced vibrations that are caused by dynamic forces acting on other parts of the structure (e.g., girder or pylon).

The effect of local terrain features on wind-induced vibrations shall be taken into consideration.

C5.2.1 — Mechanisms of dynamic excitation

Forces due to buffeting or vortex shedding do not originate from the cable motion, and therefore will not lead to aeroelastic instability but only to vibrations of limited amplitude. These vibrations can occur in all wind speed ranges. On the other hand, the flow forces acting during self-excited vibrations are a function of the motion of the cable itself (feedback). The ensuing aeroelastic instability leads to vibrations of large amplitude. These vibrations start in a sudden fashion when the wind speed exceeds a certain critical value (critical wind speed).[18-20]

Forces acting on deck or pylon, e.g., due to vortex shedding, buffeting or traffic loads, may excite overall bridge modes that involve only small deck motions but substantial cable motions.[18,19,21,22]

Large-amplitude cable vibrations in moderate wind in only one span of a symmetrical two-span cable-stayed bridge have been observed. The bridge crosses a curved gorge and the terrain is strongly non-symmetrical.

5.2.2 — Monitoring of cable vibrations

Monitoring of cable vibrations shall be performed as specified in Sections 6.9.2 and 7.6.

5.2.3 — Design provisions

5.2.3.1 — Contingency measures

Provisions shall be made in the design of the bridge to enable implementation of vibration-suppressing measures during or after erection if unforeseen vibrations occur. Examples of vibration-suppressing measures are outlined in Sections 5.2.3.5 through 5.2.3.7.

C5.2.3.1 — Contingency measures

The mechanisms of dynamic excitation are not fully understood. Also, in the case of cable vibrations induced by forces acting on deck or pylon, it is difficult to model the structure with an accuracy sufficient to make reliable predictions.

Implementation of additional measures in the case of unforeseen vibrations should therefore be possible.

5.2.3.2 — Rain-wind induced vibrations

Consideration shall be given to the possibility of rain-wind induced vibrations.[20] If studies show such vibrations can be expected, mitigating measures as outlined in Sections 5.2.3.4 through 5.2.3.7 are required.

C5.2.3.2 — Rain-wind induced vibrations

The following tentative stability criterion for rain-wind induced vibrations of smooth circular cables has been proposed[18]:

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$$Sc = \frac{m\xi}{\rho D^2} \geq 10$$

(C5.2.3-1)

where
m is the cable mass per unit length
ξ is the ratio of structural damping to critical damping
ρ is the air density
D is the cable diameter

The expression ($m\xi/\rho D^2$) is called the mass-damping parameter or Scruton number Sc. Note that modification to cable shape may allow this criterion to be relaxed if proven by wind tunnel tests. A value of 5 has been proposed in lieu of the lower limit of 10 in Equation (C5.2.3-1) for special helix or dimpled stay pipes with special testing to verify this value. Equation (C5.2.3-1) implies that for typical cable mass densities and diameters, a damping ratio of ξ equal to 0.5% to 1.0 % (depending on the actual values of m and D) would be sufficient to suppress rain-wind induced vibrations.

5.2.3.3 — Cable galloping

Attention shall be given to the possibility of galloping excitations.

C5.2.3.3 — Cable galloping

Accumulation of snow or ice on cables may result in galloping excitations according to the Den Hartog criterion. Significant increase in damping may be required to limit displacements from this source. Requirements will vary based on the wind regime. A minimum structural damping for the icing condition may be established based on the following classical equation.

$$V_{onset} = U_R fD,\ U_R = \frac{8\pi S_c}{-\left(\frac{dC_L}{d\alpha} + C_D\right)} \qquad \text{(C5.2.3-2)}$$

Using typical parameters:

$C_D \approx 1.0$
$dC_L/d\alpha \approx -2.0$ and
Sc defined as per Section 5.2.3.2

V_{onset} may be established for an infrequent occurrence based on the local climatology. A return period of 20 years is recommended where these conditions are expected.

Research and testing have shown that inclined galloping of dry cables is a potential instability condition that should be considered.[23-25] Significant vibrations in dry condi-

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tions were observed[26,27] that could not be explained either as vortex shedding nor as direct buffeting or structurally induced vibrations. The most recent research[23-25] attempts to predict the onset of instability speeds and as well the required minimum damping for suppressing galloping.

Based on the existing research data,[23,24] the minimum damping required to suppress galloping both for in-plane and out-of-plane cable vibrations is dependent upon cable frequency and the degree of turbulence, with greater turbulence lowering the damping requirement.

Inclined cable galloping is not a common phenomenon in completed bridges during service, and research is ongoing into the isolated cases that have occurred. The phenomenon has been reproduced in the wind tunnel only for short sections of smooth cable and for a narrow band of Reynolds numbers. Factors such as surface condition, variations in velocity along the cable, and degree of turbulence are believed to affect the potential for this phenomenon to occur in the field. While the current theoretical formulations based on cable frequency imply a more critical condition for longer cables, the likely incoherence of wind conditions along these cables may explain the lack of this phenomenon in practice. At the time of this writing, conservative recommendations may be found in references cited above. Designers should refer to the latest experimental findings for guidance.

5.2.3.4 — Aerodynamic contour of cable

The contour of the cable cross-section should be circular. If a non-circular shape is to be used, or if such a shape might develop due to icing, the effect on self-excited vibrations (galloping) shall be considered.

The cable surface can be modified in order to improve its dynamic behavior under the action of wind, or under the combined action of wind and rain. The effect of such modifications on all possible kinds of dynamic excitation, as well as on the static drag coefficient, shall be considered.

C5.2.3.4 — Aerodynamic contour of cable

Vertical circular cables cannot gallop because of cross-sectional symmetry. Small deviations from a perfectly circular shape may imply galloping instability. The corresponding critical wind speed is usually determined by using a combination of wind-tunnel measurements and analytical methods.[28] Inclined circular cables can gallop as they present an apparent elliptical cross-section to horizontal wind[18]; this case is covered by the commentary to Section 5.2.3.3.

According to wind-tunnel studies,[29-34] certain modifications of the cable surface, e.g. addition of well defined protrusions or dimples seem effective in suppressing rain-wind induced vibrations by influencing the behavior of the water rivulets. Increasing the general surface roughness may have some benefit as well, although it has not been systematically researched to date.

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5.2.3.5 — Damping

The structural damping of the cable shall be sufficient to limit amplitudes of vibrations and to prevent aeroelastic instability. The placement of damping material in the ring space between cable and steel exit pipes of pylon and deck anchorages is recommended. Additional damping, if necessary, can be provided by mechanical damping devices attached to the deck.

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C5.2.3.5 — Damping

The amount of structural damping influences both the amplitude of vibrations due to buffeting or vortex shedding and the critical wind speed for the onset of aeroelastic galloping and rain-wind induced vibrations.

Published analysis methods for predicting the intrinsic structural damping ratio ξ inherent in bridge cables are currently not well developed. A wide range of values for intrinsic structural damping has been measured on stay cables ranging from $\xi \cong 0.05\%$ to $\xi \cong 0.3\%$. Methods of predicting the amount of damping achieved by some special devices such as hydraulic dampers are well developed and are published in references.[35-39]

Since the effectiveness of damping devices depends upon the support and details of damper installation, the effective structural damping of stay cables should be verified by testing after installation.

5.2.3.6 — Stabilizing cables

The natural frequencies of each main cable, and thus, its resistance against dynamic excitation can be raised by connecting the main cables with transverse elements such as stabilizing cables which may terminate at a main cable or at the deck (tie-down cables).

Use of flexible cables (structural rope) are recommended rather than prestressing strands or other stiff elements. Design of stabilizing cables shall include consideration of fatigue in the stabilizing cable section and connections, and the effects of stabilizing cable forces on stay pipes, stay cable geometry, and minimum anchor pipe forces and fatigue stresses in Section 5.9.

When transverse elements are used, their effect on sag and inclination of the connected main cables, and the necessity to consider this effect in the analysis of the bridge system and in the detailing of the main cable anchorages shall be evaluated by the Engineer.

When such elements are permanent parts of the structure (or are in place over an extended period of time) attention shall be given to Section 5.2.3.7.

C5.2.3.6 — Stabilizing cables

The critical wind speed for the onset of aeroelastic instability is increased by raising the natural frequencies of the main cables.[18,21] This can be accomplished by shortening the effective free length of the main cables by means of transverse connections. Such elements are also sources of additional damping.

The stabilizing cables can be detensioned by dynamic wind loads acting on the connected main cables. Complete detensioning would result in shock upon reloading and must be avoided by sufficiently pretensioning the stabilizing cables.[34] The pretensioning force in each segment of stabilizing cable between attachment points is suggested to be at least twice the force in the same segment resulting from dynamic wind loads on the main connected cables. An estimate of the dynamic wind loads on the main cables is obtained by multiplying the static drag force normal to, and in the plane of, the main cables by a gust factor of 2.

The main cable sag is sensitive to transverse forces introduced by stabilizing cables. Such forces can change the main cable inclination at the anchorages and reduce the main cables efficiency to carry vertical deck loads.[34]

For short periods of time during construction, main cable vibrations can often be controlled by means of simple hemp ropes tensioned by hand and attached to the deck.

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5.2.3.7 — Connections

The detailing of connections between main cables and stabilizing cables shall be appropriate to avoid negative effects on the main cables such as fatigue and fretting corrosion of cable strands or wires, or damage of the cable pipe through excessive transverse clamping pressure. Sharp corners where the cables enter the connection shall be avoided.

When a stabilizing cable is connected to an ungrouted main cable, excessive stresses on the main cable pipe shall be avoided.

5.2.3.8 — Rattling

Individually protected strands shall be permitted to be encased in an outer pipe without void filler. If this system is used, attention shall be given to the possibility of vibration of the pipe against the tension elements producing a rattling noise. Any measures necessary to correct this condition are the responsibility of the cable system supplier, and shall be specified and installed to the satisfaction of the Engineer.

5.3 — Design

5.3.1 — Design limit states

Design of the main tensile element (MTE) for stay cables shall satisfy Equation 5-1 for each of the strength, service, extreme event and fatigue limit states.

$$\eta \Sigma \gamma_\iota Q_i \leq \phi R_n = R_r \qquad (5\text{-}1)$$

where:

γ_ι = load factor

ϕ = resistance factor

Q_i = force effect, axial load or axial plus bending, as applicable

R_n = nominal resistance

R_r = factored resistance

COMMENTARY

C5.2.3.7 — Connections

Oscillations caused by wake galloping have caused fatigue failure of the outer strands of bridge hangers at end clamps. Vibrations of main cables may cause fatigue failure of the connection between the stabilizing cables and the main cables. Viscoelastic bushings can reduce fatigue and be a source of additional damping.

Excessive stresses on the main cable pipe can be avoided by centralizers or other devices at the attachment points.

C5.2.3.8 — Rattling

Rattling can be prevented by the installation of centralizers or other devices at an appropriate spacing.

Additional information and data on bridge and cable vibrations can be obtained from references.[40-44]

C5.3.1 — Design limit states

Equation 5-1 need not apply to the design of the anchorages of the cables. The anchorage is a proprietary item qualified under Section 4.2. Additional design requirements for non-fatigue relevant lateral loads applied to stay cable anchorages are specified in Section 5.3.4.1, and those applied to stay cable deck pipes are specified in Section 5.9.

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η > 0.95; a factor relating to ductility, redundancy and operational importance. (See Sections 1.3.3, 1.3.4 and 1.3.5 of AASHTO LRFD.). The factor η = 1 for these Recommendations.

5.3.2 — Load factors and combinations

The load factors and combinations for the limit states contained in Tables 3.4.1-1 and 3.4.1-2 of the AASHTO LRFD and as supplemented by these Recommendations shall be used where appropriate.

5.3.2.1 — Construction limit state

The following limit states shall be applied to the construction load condition for stay design:

Strength limit state:
1.2 (*DC* + *DW* + *CE* + *CLE*) + 1.2 (*WS* + *WE* + *WUP*) + 1.4 *CLL*

Extreme limit state:
1.1 (*DC* + *DW* + *CE* + *CLE*) + 1.0 *AI*

Erection, material and equipment loads that are controlled or weighed for construction shall be considered as dead load (*DC*) for this limit state.

5.3.3 — Resistance factors

For the limit states referred to in Table 3.4.1-1 of AASHTO LRFD, the following resistance factors shall apply:

Strength A - Axial Only ϕ = 0.65 to 0.75 per diagram Fig. 5.1

Strength B - Axial and Bending combined ϕ = 0.78

Extreme Event ϕ = 0.95

Fatigue ϕ =1.0

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These Recommendations cover redundant design of bridges based on the loss of one cable. A factor η of 1.0 for this case results in a design safety index consistent with designs based on the 3rd edition of these Recommendations.

C5.3.2.1 — Construction limit state

This construction limit state corresponds to the construction stress allowable state in prior editions. The Strength IV case in AASHTO LRFD need not be applied to the construction condition.

See AASHTO LRFD 5.14.2.3.2 for definitions of loadings. Loadings *U* (segment unbalance) and *A* (segment weight) are included in the stage-by-stage assignment of *DC*. Segment lifting load A should include an appropriate impact factor for lifting, typically 1.1.

C5.3.3 — Resistance factors

The axial only resistance factor is based on the level of maximum unfactored stay demand from *LL* plus wind. The axial only phi factor is 0.75 for *LL*+*W* demand less than 2.5% of MUTS, and 0.65 for *LL*+*W* demand greater than 7.5% of MUTS, with a linear variation in between these two values. Unfactored *LL*+*W* stress is taken from AASHTO Service I, or otherwise as defined in project specifications by the Owner.

Both a pure axial and a combined axial plus bending condition are to be checked and the phi factors set for each stay once for the entire project; phi factors do not vary by load case. The bending case shall be checked for all angular deviations of the stay element as a unit, including construction tolerances for stay assembly. Angular deviations of strands

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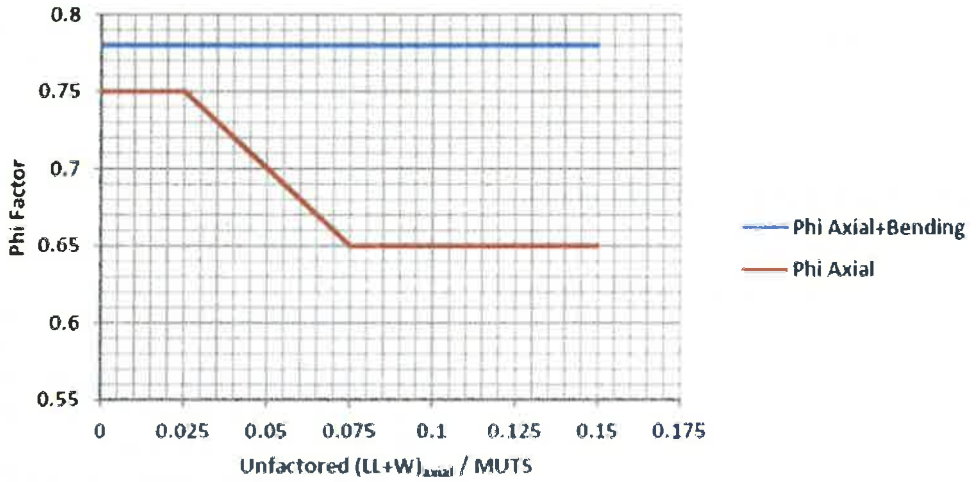

Fig. 5.1—Strength resistance factors ϕ.

within stay anchorage assemblies are addressed through the stay anchorage fatigue performance testing, and are not added to the deflections of the general stay element.

Maximum resistance factor for extreme limit state is 0.95 to reflect minimum strength requirements for qualification of anchorage design in Chapter 4. At the strength limit state only, the combination of axial plus bending effects may be based on an interaction diagram for the MTE that considers strain compatibility for net curvature strains on the element. At the fatigue limit state, elastic bending and axial stresses should be added directly.

5.3.3.1 — Special seismic resistance factors

Where net cable tensions derived by dynamic analysis for the Extreme limit states fall below 10% of MUTS, special consideration shall be given to modified resistance factors for anchorage systems, subject to the provisions of Section 4.2.1.

C5.3.3.1 — Special seismic resistance factors

This provision is to address anchorage strength for an unloading or dynamic compression condition. The range of possible response is quite variable, and an assessment of strength conditions should be conducted on a case by case basis.

5.3.4 — Bending effects—free length

Bending stresses in stay cables shall be avoided or reduced by suitable detailing and/or use of specific devices.

Bending stresses in stay cables shall be calculated and combined with the axial stresses for the verification of the design limit states, Eq. (5-2).

Bending stresses shall be calculated from the stay cable curvature ($1/\chi$) determined for a cable under the design axial force and with flexural stiffness as follows:

C5.3.4 — Bending effects—free length

The intention of this provision is to include local bending stresses in the axial limit state, rather than to establish limit states for axial-flexure interaction.

Bending stresses typically occur near anchorages, saddles, and attachments to the stay cables which impose some lateral displacement. Bending effects in anchorages are considered by testing and anchorage design by the stay system supplier in Sections 4.2 and 5.3.4.1, respectively.

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$$f = (1/\chi)Er \qquad (5\text{-}2)$$

Where

r is the relevant distance of the strand extreme fiber to the neutral axis for bending and

χ is the local radius of curvature in the cable at the local detail being examined.

5.3.4.1 — Strength of stay cable anchorages for lateral loads

Stay cable anchorage assemblies and all their components shall be designed for a minimum lateral load of 2.5% of the maximum static cable force at either construction or service conditions. The lateral load shall be applied at the cable entry into the anchorage or at the relevant location where the cable will be deviated.

5.3.5 — Fatigue limit state

η and φ = 1.0 in the strength limit state equation gives the fatigue limit state equation as follows:

$$\gamma(\Delta F) \leq (\Delta F)_{\eta} \qquad (5\text{-}3)$$

γ = 0.75 = Load factor

(ΔF) = stress range due to the passage of the fatigue load multiplied by the factor 1.4, see Section 5.1.3.

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Bending effects in the stay cable free length at dampers and stabilizing stay connections are considered in this Section. Bending in saddles is considered in Section 5.7.2.3.

The flexural stiffness of the stay cable and the relevant distance of the extreme fiber to the neutral axis for bending depend on the actual type of stay cable utilized. For stay cables with bare MTE and fully grouted the stiffness may be calculated for the composite steel-grout section with the nominal cable diameter, and r may be assumed as 50% of the nominal cable diameter. For individually protected MTE without grouting of the stay cable the stiffness may be assumed as the sum of the stiffness of each individual MTE. If the MTE is a wire or bar, r may be assumed as 50% of the nominal diameter of the MTE. If the MTE is a strand, r may be assumed to be the center to center distance between the king wire and an exterior wire.

C5.3.4.1 — Strength of stay cable anchorages for lateral loads

This lateral load is assumed to be caused by an angular deviation of the stay cable of 2.5×10^{-2} radians occurring at the entrance of the stay cable into the anchorage or at any other location in the anchorage where the stay cable may be assumed to be deviated. Such angular deviations may occur during construction before the guide deviators are installed or during service conditions if the guide deviators are removed or replaced with special damping devices to control cable vibrations. Guide deviators need to be designed for the same lateral load.

Stay cable anchorages are not tested for the maximum probable bending effects, see Section 4.2. Therefore, they are required to be designed for the maximum effects of stay cable angular deviations during construction and service life.

C.5.3.5 — Fatigue limit state

See Commentary to Section 5.1.3.

Fatigue strength values for strand stay cables are based on considerations of a summary of individual strand tests[45] and test results on assembled strand stay cable specimens. Indications are that the difference in fatigue strength between individual strands and assembled stay cables are less than for wire stay-cables.

The results of many fatigue tests on individual wires and parallel wire stay cables have been summarized in a paper

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$(\Delta F)_\eta$ = nominal fatigue resistance

In order to determine $(\Delta F)_\eta$, let

$$G = \frac{1}{2}(\Delta F)_{TH} \tag{5-4}$$

$(\Delta F)_{TH}$ = Constant amplitude fatigue threshold (see Table 5-1)

If $\gamma(\Delta F) \le G$ then $(\Delta F)_\eta = G$

Else if $\gamma(\Delta F) \le B$ then $(\Delta F)_\eta = B$

If $(\Delta F)_\eta$ does not equal G or B then $\gamma(\Delta F)$ is too high and measures must be taken to reduce it.

$$B = \left(\frac{A}{N}\right)^{\frac{1}{3}} \tag{5-5}$$

A = constant (see Table 5-1)

N = 365 days x Ny x 1 cycle x $(ADTT)_{SL}$

$(ADTT)_{SL}$ = Average daily truck traffic in one direction and in one lane

Ny = Design life of cables in years

N = Number of cycles due to passage of fatigue design truck during design life of cables.

Table 5-1—Fatigue constants

Type of stay	A x 10^{11} MPa^3	$(\Delta F)_{TH}$ threshold, MPa
Parallel strands	39.3	110
Parallel wires	74.3	145
Uncoupled bars	39.3	110
Epoxy-coated bars	7.2	48

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presented at the IABSE 1982 Colloquium.[46] In order to arrive at lower bound design values, based on contemporary U.S. materials, the fatigue ranges for stay cables from the above noted paper have been somewhat reduced for the fatigue design criteria in this Section. A graphic presentation of the fatigue safety philosophy is provided in Fig. 3.1.

The requirement on heavy traffic volume bridges that the maximum stress range experienced by a detail be less than the constant amplitude fatigue threshold stress provides for a theoretically infinite fatigue life. The 1/2 in Eq. (5-4) is to account for the maximum stress range being twice that of $\gamma(\Delta F)$.

See Section 3.6.1.4.2 of AASHTO LRFD for calculation of $(ADTT)_{SL}$.

The design life of the cables need not be the same as the design life of the bridge which could be in the range of 100 to 200 years. It is suggested that 75 years would be appropriate for cables.

The fatigue range for individual wires, strands and bars, depends on their quality and may vary considerably. For assembled stay cables, an additional variation is introduced by the type of the anchorage which may or may not decrease the fatigue strength of the stay cables in their free lengths.

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5.4 — Cable replacement

The design of cable-stayed structures shall provide for the replacement of any individual cable with a reduction of the live load in the area of the cable under exchange.

5.5 — Loss of cable

All cable-stayed bridges shall be capable of withstanding the loss of any one cable without the occurrence of structural instability.

The impact dynamic force resulting from the sudden rupture of a cable shall be 2.0 times the static force in the cable, or the force as determined by non-linear dynamic analysis of a sudden cable rupture, but in no case less than 1.5 times the static force in the cable. This force shall be applied at both the top and bottom anchorage locations.

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C5.4 — Cable replacement

The designer should consider the implications of cable exchange and provide general recommendations on the plans for any precautions or changes in traffic flow required by the exchange.

The suggested load factors and combinations for this condition are as follows:

Cable Exchange:
1.2 *DC* + 1.4 *DW*+1.5 (*LL**+ *IM*) + Cable Exchange Forces

*At least one lane of live load shifted away from the cable under exchange.

The definitions of the symbols are given in Section 3.3.2 of AASHTO LRFD. A resistance factor is suggested for this strength limit state event for axial plus bending.

C5.5 — Loss of cable

For the extreme event of loss of one cable, the following load factors and combination are suggested for the remaining structure:

Loss of One Cable: 1.1 *DC* + 1.35 *DW* + 0.75(*LL***+*IM*) + 1.1 *CLDF CLDF* = Cable Loss Dynamic Forces

**Full live load placed in actual striped lanes

The load factor of 1.1 on the Cable Loss Dynamic Force is to account for a variation of final cable force in construction relative to the force level assumed in design.

For analysis using elastic superposition and the static equivalent 2.0 factor, the initial statical system prior to cable rupture should be used to compute the effects of all permanent and live loads. A second statical system without the ruptured cable should be used to compute the effects of the dynamic force to be superimposed on the initial system. If a non-linear dynamic analysis is used, the dynamic model should be initialized with the full permanent load and live load condition for the bridge.

The resistance factor $\phi = 0.95$ is suggested for this extreme limit state event.

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5.5.1 — Cable loss due to fire

Design criteria shall be established for the extreme event of a fire on the superstructure of the bridge. Criteria shall be established based on whether fire suppression, assumed cable loss, fire protection, or a combination thereof, is to be employed as a design strategy for fire resistance.

Design for fire protection shall be based on qualification testing of fire resistant stay cable systems which protect cable MTE from reaching a temperature greater than 300 degrees C for a period of not less than 30 minutes in accordance with Section 4.5.

COMMENTARY

C5.5.1 — Cable loss due to fire

Cable loss from fire is a subset of cable loss provisions in 5.5. Cable loss from fire need not be combined with the cable loss from other events.

Cable temperature and associated heat loading on stay cables depends upon the power of the fire, the distance of the fire from the cable element, and the duration of the fire event.

For a nominal working stress of less than 0.45 F_{pu}, typical MTE material can sustain a temperature of not more than 400 degrees C without entering the plasticity domain. The flash point of HDPE is 330 degrees C. 300 degrees C provides a safety margin regarding these two figures. However, MTE that has reached this material temperature will need to be replaced after the fire event.

The extreme event load and resistance factors are recommended for the fire condition with *CLDF* = 0.0 (cable loss from fire is assumed to be gradual).

5.6 — Construction

The construction loads assumed for design purposes shall be shown on the plans.

The effect of permanent superimposed erection loads on the stresses and deformations shall be added to the LRFD combinations referred to in Section 5.3.2 as permanent dead load.

The combinations must satisfy the equations shown in Section 5.3.2.1 at the time of completion of the structure as well as for any future superimposed dead load and effects of creep and shrinkage.

Checks shall be made to evaluate the effects of creep of the superstructure concrete on change of force in the stay cables and related changes in stresses in the superstructure.

C5.6 — Construction

Wind loads for cantilever construction of cable-stayed bridges should be determined by special studies. Reference should be made to previous experience or wind tunnel tests.

5.7 — Design of cable saddles

5.7.1 — General

Cable saddle design shall be the responsibility of the bridge designer. The bridge designer shall detail cable saddles, transition details, and cable finishes at the

C5.7.1 — General

Unlike cable anchorage design, the design of saddles is an integral element of pylon conceptual design and the geometric layout of the towerhead. In general, a supplier

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cable saddle so as to provide a complete design on the Plans. Cable saddles shall be designed to resist both primary and secondary forces that effect the cable element, cable pipe, pylon and appurtenances in the saddle region. Saddle details shall provide for replacement in accordance with Section 5.4 without the need to remove more than one cable at a time, and shall provide for cable loss in accordance with Section 5.5.

Saddles shall be subjected to tests in advance of construction by the designer in accordance with Section 5.7.4 of these Recommendations.

5.7.2 — Design criteria

5.7.2.1 — Cable radius

Cable bend radii shall be no less than 3 m if supported as a single strand, and no less than 4 m if bundled as a multi-strand stay, unless fatigue testing of saddle design is conducted to demonstrate that the required fatigue strength can be achieved in the presence of normal compressive stress. If cushioning material such as epoxy or HDPE monostrand sheathing is used to reduce inter-strand fretting, the material dimensions and specifications shall be the same in the prototype as in the final installation.

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cannot alter the critical geometric features of a saddle design without re-designing the entire towerhead. Therefore, the bridge designer must establish functional saddle design details as part of the contract plans.

The designer may allow alternative saddle details by specifying all design criteria, including but not limited to geometry, static and dynamic loads, fatigue design basis, slip and fretting design basis, and maximum normal pressures.

C5.7.2.1 — Cable radius

These radii are based on examples of existing bridges using saddle details with similar radii. However, it is well known that fatigue strength is reduced in the presence of significant lateral (normal) stress, and there are examples of notching and fretting caused by differential strains in strand bundles. These factors should be taken into account as saddle geometry is established by the designer. Tests on bare post-tensioning strands in curved ducts performed at the University of Texas[47] revealed the following threshold for the onset of fretting fatigue:

$$R > F * n - 0.4 / 90.0 \qquad \text{(C5.7.2-1)}$$

for minimum radius of bare strands subject to a mean stress of 650 MPa and a stress range of 200 MPa.

where
R = bend radius (meters)
n = number of strands in a bundle
F = mean cable force under fatigue conditions (kN)

These results applied to a duct area diameter approximately 2.75 times the tendon area. Use of larger ducts with fewer strands tends to improve performance. Also, strand for these tests was general commercial grade, and not pre-selected based on the material requirements of these Recommendations.

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5.7.2.2 — Slip and force transfer

Cable saddles and transition details shall be designed to preclude slip and fretting of the cable for all strength limit states. A resistance factor of 0.65 shall be used against the friction coefficient in the strength limit state. Saddle details shall be designed to prevent deterioration of force transfer due to fatigue stresses on the MTE and saddle. Saddles also need to be checked for slip at the ultimate limit states.

5.7.2.3 — Cable bending stresses

Cables shall be sized such that the bending stress, when added to the other service stresses acting along the saddle do not exceed the limits given in Section 5.3.

5.7.2.4 — Component design specification

Structural design of saddle components shall conform to the applicable sections of AASHTO LRFD.

Referring to Section 5.5; where cable saddles are used in design, sudden cable loss shall be computed for each side of the stay in turn, with the loss of both fore and back stay portions of the cable assumed to be lost due to cable rupture.

5.7.3 — Detailing

5.7.3.1 — Corrosion protection system

Saddles shall be detailed to allow corrosion protection systems to be effective all the way through the saddle.

5.7.3.2 — Qualification of saddle corrosion protection system details

Corrosion protection systems for saddles shall be qualified in accordance with Section 4.1. Corrosion protection system qualification shall be conducted for all saddle details, beginning with the transition or coupling to the saddle, and continuing through the saddle.

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C5.7.2.2 — Slip and force transfer

Refer to Section 5.7.4.3 for determination of friction coefficient.

C5.7.2.3 — Cable bending stresses

Bending stress from curvature may be determined by the expression in Eq. 5-2, where χ is the radius of the saddle bend.

A bundle is considered bent as a unit only in the case where sections remain plane during bending. This is generally not the case with saddle cables, since most cable assembly is performed strand by strand.

C5.7.3.1 — Corrosion protection system

The requirements for nested barriers in Section 4.1.2 need to be provided completely through the saddle.

C5.7.3.2 — Qualification of saddle corrosion protection system details

These tests shall be conducted as part of the saddle design, and may, of necessity, be project specific tests.

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5.7.4 — Testing

5.7.4.1 — Saddle design testing

Cable saddle design methods and assumptions shall be verified by testing or by reference to previous records of successful testing in accordance with Section 4.3. All structural details of design shall be identical to the previous testing in order to qualify for reference.

5.7.4.2 — Fatigue testing

The stay cable specimen with saddle shall be installed initially to the intended geometry (free length tangent to the saddle ends). The saddle shall then be lifted such as to generate an angular rotation of 10^{-2} radians of the free length in the plane of the specimen and be tensioned to an axial stress of $0.45f_s'$ minus 50% of the stress range required in Section 5.3.5. The stay cable specimen shall be tested for 2 million cycles for an upper stress of $0.45f_s'$ and the stress range required in Section 5.3.5 plus 35 MPa through vertical movement of the saddle.

Acceptance criteria for testing shall be in accordance with Section 4.2.

5.7.4.3 — Friction testing

Friction testing shall be conducted to verify slip coefficients for design. If clamping devices are used to design against slip, these details shall be tested, and shall be included with the testing conducted under Section 5.7.4.2.

5.8 — Alternative stay cable systems

If allowed in the special provisions, the Contractor may propose an alternate stay cable system other than that assumed for the design. All options and/or variations indicated in this section are subject to approval by the Engineer.

Sizing of stay cables for static loads shown on the plans shall be based on the provisions of Section 5.3. The sizing for fatigue shall be done for fatigue cable forces shown on the plans using design fatigue strength values based on test data acceptable to the Engineer, and maintaining the testing standards in Section 4.2.

COMMENTARY

C5.7.4.2 — Fatigue testing

Saddle testing is to be conducted to computed fatigue design levels, since saddle design criteria is now provided in these Recommendations. Saddles are not considered anchorages under Section 4.2 of these Recommendations. Bending effects caused by installation tolerances at saddles are considered similarly to anchorages. These fatigue levels are not the same as the testing levels of Table 3-1.

Failure of either nested barrier of the corrosion protection system within or leading to the saddle represents a failure of the fatigue test.

C5.8 — Alternative stay cable systems

As outlined above, the actual fatigue strength of the individual tension members and the assembled stay cables may vary considerably depending on materials and structural details. The fatigue requirements for the stay cables also vary depending on the type, location and intended use of the bridge under consideration. Contractors should, therefore, be permitted to submit for approval that type of stay cable, which in their opinion, is best suited for the job independent of the type of stay cable assumed in the design. The quality control requirements for such alternate cables should be the same as for those assumed in the design. The Contractor may use additional materials in selected stay cables if considered necessary to meet loading and fatigue requirements.

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If the stay cable end anchor heads proposed by the Contractor have different dimensions and/or support details than those shown on the plans, the Contractor shall be responsible for the redesign of the stay cable anchorage areas, including details at the towers and the girder, and shall ensure their compatibility with the structure.

If the longitudinal effective cable stiffness

$$S = A_s \times E_{eff} \quad (5\text{-}6)$$

where:

A_s = Area of steel

E_{eff} = Effective modulus of elasticity

is less than 95% or more than 105% of the effective longitudinal stiffness assumed in the design for stay cables, a re-analysis of the cable stayed bridge structure shall be performed.

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The forces in the structural members of the bridge depend on the cable stiffness. The consequences of considerable deviation from the stiffness originally assumed in the design have to be accounted for. To facilitate calculations, it is recommended that design values of the longitudinal effective cable stiffness be stated on the plans.

5.9 — Guide pipe minimum design forces

Cable guide pipe assemblies and all their components shall be designed for the following minimum lateral loads applied at the centerline of cable support at the exit point of the guide pipe:

i) Strength Limit States = 2.5% of the maximum static cable force

ii) Fatigue Limit State = 4% of the cable fatigue load or 1.5% of the maximum *LL* cable force, whichever is greater.

The wall thickness of the guide pipe shall not be less than 9 mm. The guide pipe shall be fabricated perpendicular to the face of the bearing surface of the cable anchorage within 0.15 degree tolerance. The guide pipe assembly shall be installed within 0.3 degrees (+/-) of the planned pipe alignment. Materials and fabrication requirements shall be consistent with strength and fatigue demand requirements.

C5.9 — Guide pipe minimum design forces

Where the Guide Pipe is integral with the stay anchorage without direct support to the structure, Section 5.3.4.1 will apply to the anchorage design.

Additional corrosion protection measures are recommended for the guide pipe above and below the embedment point into a concrete bridge deck.

Additional requirements on guide pipe tolerance may be requested by the Engineer after considering the combined effect of tolerances and deflections. Guide pipe stiffness may be an integral component of certain cable damping systems, in which case pipe stiffness should be factored into the evaluation of damper design.

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5.10 — Extrados/low fatigue stay systems

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Section deleted in this edition. See Section 5.3.3.

Section 5.3.3 addresses requirements for low fatigue stay systems.

6.0 — INSTALLATION OF STAY CABLES

6.1 — Quality control program

The Contractor is responsible for installing stay cable material that conforms to these Recommendations in an undamaged condition. In order to assure that only conforming material is introduced into the work, the Contractor shall develop a comprehensive Quality Control Program (QCP) that covers the procurement, packaging, transport and delivery of all stay cable materials and components of the stay cables. This program shall include, but not be limited to, all procedures and practices necessary for the final installation of stay cables that meet the requirements of these Recommendations without residual damage to any component of the stay cable system.

As a minimum, the Quality Control Program shall include the following items:

- Packaging and shipping for MTE and all protective materials.
- Records for traceability and shelf life of all materials.
- Inspection of materials to assure conformance with the Recommendations, and to assure that materials are undamaged as they are installed in the bridge.
- Limitations on storage and handling, including time periods for storing materials, temperature and humidity limitations for materials, temporary corrosion protection, and any limitations on temporary storage or protection that shall be permitted to affect performance of the completed stay design.
- Coiling limitations for materials subject to set or plastic deformations, including prefabricated cables, HDPE pipe, PE and PP sheathed strand or epoxy-coated strands.
- Limitations on coatings, repair of coating damage, and supplemental protection for coated materials.

C6.1 — Quality control program

As the procurement and installation of the cable stays is the responsibility of the prime construction Contractor, it is recommended that the process be placed under a Quality Control Program that is acceptable to the Owner and approved by the Owner and the Engineer. The procedures and resources needed for monitoring the QC program are the responsibility of the Owner and the Engineer.

A program of inspection, monitoring and review of material supply and storage should cover all phases of material handling so as to assure compliance with this section. The precise guidelines to be followed will vary with the variety of products being supplied.

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The Quality Control Program shall be submitted to the Engineer for approval prior to supplying any stay cable materials. Permanent records shall be established and maintained by the Contractor for all procurement, inspection, sampling, testing and installation in accordance with the requirements of these Recommendations. Copies of the records shall be distributed in accordance with the project requirements.

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The following sections address the recommended minimum standards for acceptance of stay cable materials and components to be incorporated in the project. This should be used as a guide to develop the QC program.

6.2 — Fabrication

6.2.1 — General

Stay cable shall be fabricated in a manner consistent with the design and testing requirements for the stay cable system cited in these Recommendations.

6.2.2 — Pre-fabrication

Strand and bar cables shall be permitted to be prefabricated into fixed length cables or fabricated in situ. Wire cables shall be prefabricated into fixed length cables prior to installation.

6.2.3 — Site fabrication

For site fabrication, appropriate measures shall be taken to ensure that all stay cable elements are installed parallel to one another.

6.3 — Handling of stay cable components

6.3.1 — Procedures

Procedures shall be developed to assure that stay cable components will not be damaged during handling. HDPE pipe shall be supported to prevent buckling.

C6.3.1 — Procedures

Cuts, scrapes or gouges in the HDPE pipe may result in cracks or splits due to vibrations and/or weathering. Grouting pressure is known to cause splitting of HDPE pipe with relatively minor initial damage; see Appendix C.4.

6.3.2 — Cable protection and coiling

Stay cables shall be protected from corrosives, heat, abrasion and other harmful effects throughout fabrication and installation. Where HDPE pipe is used for corrosion protection and is preassembled with MTE, the HDPE pipe shall be warmed and maintained to a minimum of 24° C and maximum of 50° C prior to coiling or uncoiling pipe material. The reel diameter shall be at least 17 times the outside diameter of the

C6.3.2 — Cable protection and coiling

The protection of HDPE pipe is related to both temperature and physical handling, which are controlled by the supplier and erector. If the erector can demonstrate that through the use of special techniques, he can handle HDPE pipe without damage, other minimum temperatures may be considered.

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HDPE pipe. The HDPE pipe shall be slowly coiled or uncoiled so as not to damage the pipe. HDPE shall not be stored at a temperature greater than 50° C.

6.3.3 — Equipment and lifting devices

Spreader bars and slings or other appropriate devices shall be used to handle all prefabricated cables. The minimum bending diameter for all such cables during handling shall be 25 times the diameter of the cable pipe. Slings or similar devices shall be positioned to carry both the anchor and adjacent cable in a tangent position, preventing bending of the cable at the anchor. All equipment for handling the stay cable components shall have padded contact areas. All bundling bands shall be padded and protection provided to prevent damage to any component. All components of cables shall be lifted with a strong back, spreader strand, multiple supports, or a platform bridge to prevent abrasion. The components shall not be dropped or dragged.

6.3.4 — Damage and repair

All damage to stay cables or components thereof shall be evaluated and remedied prior to installation of the cable. Damaged strand, bar, or wire shall be replaced. Damage to non load carrying components and corrosion protection systems shall be repaired to meet all performance standards of these Recommendations prior to installing stay cables.

6.4 — Packing and shipping

6.4.1 — Stay cable metallic components

The manufacturers of stay cable strands, wires or bars, stay anchorages, and socket assemblies shall assign an individual number to each lot of wire, strand, bar, anchorages, and socket assemblies at the time of manufacturing. Assignment of lots for strands, wires or bars shall conform to the quality control sampling frequency. All of these materials shall be identified in such a manner as to ensure positive traceability during production, transit, storage, installation and testing. Materials which cannot be positively identified as to lot number shall not be incorporated into the work.

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C6.3.4 — Damage and repair

Repair procedures of damaged non load carrying components and corrosion protection systems should be prequalified.

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6.4.2 — Strands, wires, and bars

Strands, wires, or bars shall be packaged and shipped in accordance with the applicable requirements of ASTM A700, "Standard Practices for Packaging, Marking, and Loading Methods for Steel Products for Domestic Shipment," for the protection of the steel against physical damage and corrosion. To prevent the disturbance of any protective packaging during sample testing, the supplier shall provide repair methods and quality test procedures. The number and the size of the samples shall be determined by the Engineer.

All coils of wires or strands or package of bars shall be transported by closed bed trucks or containers to avoid exposing packaging to weather.

The shipping package of the strands, wires, or bars shall be marked with the manufacturer's name, order number, package number, heat number, length of the strands, wires or bars, weight of the package, and customer's name. In addition, the shipping package shall be clearly marked "high strength prestressing steel strands, wires or bars." All tags shall be securely affixed to the package container to prevent loss in transit.

6.4.2.1 — Bare strands and wires

The strands or wires shall be wound or spooled on reels for shipment and handling at the job site. Prior to being wound, an approved corrosion inhibitor, which prevents corrosion or other results of corrosion, shall be applied directly to the steel. Each coil shall be triple wrapped with approved waterproof paper or plastic, or approved methods, to prevent corrosion.

The corrosion inhibitor shall have no deleterious effect on any of the stay cable materials or bond strength of the strands or wires where bond strength is an element of the MTE or the stay or stay anchor design.

6.4.2.2 — Bare bars

All steel bars shall be sealed for the protection of the steel against physical damage and corrosion. Prior to being packaged, an approved corrosion inhibitor, which prevents corrosion or other results of corrosion, shall be applied directly to the steel. Each container or case shall be lined with approved waterproof paper or plastic and shall be reinforced with bands or wire at the ends and at intermediate points, as required.

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The corrosion inhibitor shall have no deleterious effect on any of stay cable materials or bond strength of the bars where bond strength is an element of the MTE or the stay or stay anchor design.

6.4.2.3 — Epoxy-coated, galvanized or sheathed strand

Galvanized strands shall be packaged and handled to prevent damage to the galvanized coating.

Epoxy coated or sheathed strands shall be spooled on reels for ease in shipment and handling at the job site.

Each spool of epoxy-coated or sheathed strand shall be wrapped with approved material or protected by other approved methods. It shall ensure protection of coated or sheathed strand and have no adhering foreign matter or damage to the epoxy coating or the sheath material.

To prevent deterioration of the epoxy coating or sheathing caused by ultra violet rays, the reels shall be covered with an ultra violet resistant cover as a protection from the direct radiation of the sun.

6.4.3 — Anchor and socket assemblies

All anchors and socket assemblies shall be packaged in containers or shipping forms for the protection of all assemblies against physical damage and corrosion. Prior to being packaged, the outer steel surface of the anchorage shall be coated with self curing inorganic zinc prime coat or other approved coating. The socket assemblies where applicable, shall also be coated with the self curing inorganic zinc primer. The bare steel where coating is not applicable shall be protected from corrosion using the approved corrosion inhibitor in the packing forms or container.

6.4.4 — Pipe

A certificate of analysis shall be furnished for each shipment of pipe stating the material supplied meets these Recommendations. Results of testing performed shall be included.

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6.4.4.1 — High density polyethylene pipe without tension element

High Density Polyethylene (HDPE) pipe without the MTE installed shall not be spooled on reels for shipment or handling at the job site.

6.4.4.2 — Steel pipe

All steel pipe shall be packaged in containers or shipping forms for the protection of the steel against physical damage and corrosion. Prior to being packaged, the outer steel surface shall be coated with a self curing inorganic zinc prime coat.

All packages shall be marked with the manufacturer's name, order number, package number, heat number, length of the pipe, weight of the package, and customer's name. In addition, the package shall be clearly marked "Stay Cable Steel Pipe." All tags shall be securely affixed to the package to prevent loss in transit.

6.4.5 — Pre-assembled cables with HDPE pipe

Completed cables shall be wound or spooled on reels for shipment and handling at the job site. The reels shall be of a sufficient diameter (at least 17 times the outside diameter of the HDPE pipe) to prevent damage to the cable pipe.

6.5 — Material site inspection

Materials or components that have suffered damage, such that they no longer comply with these Recommendations, shall not be incorporated into the project. Materials for which the shelf life has expired shall not be used.

Materials or components in damaged wrapping, forms or packages shall be subjected to the inspections and acceptance criteria set forth in Section 6.7 - Pre-installation Inspection.

6.6 — Storage

6.6.1 — Requirements and limitations

Prior to installation, storage of materials and components at the project site shall be in accordance with the approved QC program.

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6.6.2 — Facility

All coiled strands or wires, packaged bars, pipe, anchors and socket assemblies, and pre-assembled cables shall be stored in a weatherproof enclosure at or near the job site in order to prevent corrosion prior to installation.

All coiled strands or wires, packaged bars, pipe, anchors and socket assemblies, and pre-assembled cables shall not be stored in direct contact with the ground.

6.6.3 — Environmental control

An air conditioning and dehumidifying system shall be used to control humidity in the enclosure for storage of all bare MTE materials. The humidity control system shall maintain relative humidity lower than 60 percent. Strand that is fully assembled with at least one qualified barrier system throughout the length of strand shall be protected from moisture and any other contamination that would compromise the performance of the MTE.

Coiled prefabricated cables shall be coiled, stored and uncoiled at temperatures and in such a manner that preclude permanent deformation or cracking of the HDPE pipe.

6.7 — Pre-installation inspection

6.7.1 — Bare, epoxy-coated, galvanized or sheathed strands and wire

When uncoiled, the strand or wire shall lay straight within a specified offset from a theoretical centerline in any 1.8 m of length. Sharp kinks or short radius bends (less than the reel radius) shall be cause for rejection.

6.7.2 — Bare strands and wires

When uncoiled, wire or strand shall be inspected for physical damage or corrosion. Any wires or strand showing physical damage shall be replaced.

Wires or strands with visible corrosion shall be evaluated for acceptance in accordance with Section 4.1.7.1.

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C6.6.3 — Environmental control

Atmospheric corrosion commences at 60 percent relative humidity, which applies to any storage conditions for bare strand. Bare strand materials should be stored to prevent any corrosion prior to application of corrosion protection barriers and final assembly of the stay. Inspection of strand samples after storage should not evidence any deterioration of strand or protective coatings.

See Section 6.3.2 for recommended handling of HDPE pipe.

C6.7.1 — Bare, epoxy-coated, galvanized or sheathed strands and wire

Sharp kinks or short radius bends produce shear stresses at these areas and result in reducing the service life of strands or wires. Experience indicates that the offset of epoxy-coated strand can be in excess of 102 mm in 1.8 m. This is due to a set in the epoxy and does not affect the properties of the strand. If a lesser offset is required, the Contractor should discuss special reel/pack dimensions and other alternatives with the strand supplier.

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6.7.3 — Epoxy-coated or sheathed strands

When uncoiled, the condition of the coating or sheathing on the strands shall be inspected and tested for any damage. Damage shall be repaired in a satisfactory manner proposed by the cable supplier and approved by the Engineer, otherwise the material or component shall be replaced. Epoxy-coated or sheathed strands shall be completely free of damage to the coating or sheathing before erection.

6.7.4 — Bar

Steel bars that have physical damage shall be replaced. Bars with visible corrosion shall be evaluated for acceptance.

6.7.5 — High density polyethylene pipe

The HDPE pipe shall be inspected for any physical damage such as cuts or abrasions. If more than 5% of the HDPE pipe thickness is lost by abrasion or if any visual cut is observed, the HDPE pipe shall be repaired in a manner proposed by the cable supplier and subject to the approval of the Engineer - otherwise the pipe shall be replaced.

6.7.6 — Steel pipe

If any physical damage is observed, the pipe shall be repaired, if possible, or rejected. Primer coating condition shall also be inspected for any defects and damage. If any coating defects or corrosion damage is detected, it shall be repaired in a manner proposed by the Contractor and subject to the approval of the Engineer. Pipe that cannot be repaired shall be replaced.

6.7.7 — Pre-assembled cable

When uncoiled, the pipe shall be inspected for any permanent deformations and damage. Any pipe damaged or deformed, inconsistent with its function, shall be repaired in a manner proposed by the Contractor and subject to the approval of the Engineer. Pre-assembled cable that cannot be repaired shall be replaced.

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C6.7.4 — Bar

Local corrosion of bars produces stress concentration and results in a reduction in service life. Corrosion may be cause for rejection.

C6.7.5 — High density polyethylene pipe

It is advised that severely damaged HDPE pipe be replaced not repaired.

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6.7.8 — Anchors and socket assemblies

All steel surfaces shall be inspected for any physical damage or corrosion. If any physical damage is observed on the anchors or socket assemblies, they shall be repaired, if possible, or be replaced, subject to the approval of the Engineer. If there are any coating defects or corrosion on the steel, it shall be repaired in a manner proposed by the Contractor and subject to the approval of the Engineer. The anchors or socket assemblies that cannot be repaired shall be replaced. All anchorage hardware shall be cleaned and coated at the end of construction in accordance with the project specifications.

6.8 — Stay pipe assembly preparation

6.8.1 — High density polyethylene pipe

Welding for HDPE pipe shall conform to ASTM D2657 "Standard Practice for Heat Fusion Joining of Polyolefin Pipe and Fittings".

6.8.1.1 — Pipe length

The required pipe length for each cable shall be obtained by continuous extrusion or by fusion welding of standard length sections of pipe.

6.8.1.2 — Fusion welds

All fusion welds, both butt and socket type, shall be capable of developing the full yield strength of the pipe cross section.

In addition, the fabricator shall submit three samples to qualify the fusion procedure, both butt and lap joints, to develop the full yield strength of the pipe cross section. Each sample shall consist of a 1.8 m length of pipe per size per thickness.

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C6.8.1.2 — Fusion welds

General techniques of fusion joining can be found in ASTM D2657 "Standard Practice for Heat Fusion Joining of Polyolefin Pipe and Fittings". The electro-fusion welding process is covered by ASTM F1055 "Standard Specification for Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing". Full yield strength welds are recommended to assure that the corrosion protection afforded by the HDPE pipe is not compromised by a local pipe failure. If design details are devised where the vapor barrier of the HDPE pipe can be assured without full strength welds, these details may be considered.

Electro-fusion welding of HDPE pipes may be appropriate for locations where telescoping HDPE pipes are required. Fusion welding of HDPE pipe is extensively used in the natural gas industry. The fusion weld is made by turning the mating surfaces of the coupler and pipe into a molten material by heating wires embedded in the coupler. The temperature and pressure of the molten material, which

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are important elements of the process, depend only on the geometry of the fittings and the electrical parameters of the welding operation. The electrical parameters are machine controlled. Experience has shown that except under ideal conditions, hand welding does not develop the full yield strength of HDPE pipes.

6.8.2 — Steel pipe

6.8.2.1 — Welding requirements

Welding of steel pipe, trumpets and couplers shall conform to the following requirements:

A. Welding procedures and welding qualification shall be level AR 1 in conformance to the requirements of AWS D10.9, "Standard for Qualification of Welding Procedures and Welders for Piping and Tubing" or NASI/AWS D10.11, "Recommended Practices for Root Pass Welding of Pipe Without Backing."

B. Minimum preheat and interpass temperature for material thickness 13 mm up to and including 25 mm when welding with other than low hydrogen electrodes shall be 37.8° C.

C. When welding with low hydrogen electrodes, the minimum preheat and interpass temperatures specified for ASTM A36/A36M steel shall apply.

D. Electroslag and electrogas welding processes shall not be used.

Welding shall be performed using approved procedures, techniques, and equipment to prevent any backup plates, weld reinforcements or deposits on the inside surface of the pipes beyond the permitted tolerance. Any weld deposits or backup strips that exceed the specified tolerance shall be corrected, using approved methods and equipment, without damaging the pipe or if it cannot be properly corrected, the pipe shall be rejected and replaced by the Contractor.

Effort shall be made to make as few field welds as possible. Welding of trumpets to pipe anchorages, welding of pipe anchorage to pipe casings, and welding of pipe casings to pipe couplers shall be full penetration groove butt welds and shall be done in the shop. Pipe casings shall be splice welded in the longest possible section taking into consideration the maximum allowed or practical length in shipping, handling, and lifting to the bridge deck. All shop and

C6.8.2.1 — Welding requirements

Tolerances for weld deposits or back up should be specified in order to prevent their interference with the pulling or pushing of the MTE or grouting operations.

RECOMMENDATIONS

field splice welding of the pipe casing shall be full penetration groove butt weld.

6.8.2.2 — Inspection for steel pipe welding

Welding methods and procedures including any preheating requirements, types of electrodes, type of manual and automatic welding, proposed modification to pipe ends to permit welding with or without a backup strip, and other information pertinent to welding the various components of the stay cables shall be furnished to the Engineer for approval prior to proceeding with any weld.

The inside diameter of the pipe, especially at the welded joint, shall not be less than the theoretical inside diameter of the pipe (as determined in ASTM A53) minus 3 mm. The inside of the pipes shall be inspected using TV surveillance system, furnished and operated by the Contractor, and monitored by the Engineer to check the inside surface condition of the pipes.

See Section 3.5.2 for additional requirements.

6.9 — Installation

6.9.1 — Installation program

Cables shall be installed and/or adjusted in accordance with an engineered cable installation program that prescribes cable force and elongation for each stay cable. This program shall stipulate the permissible variance for force and elongation for each cable to be installed or adjusted.

The engineered program shall include consideration of actual construction loads and statical conditions at the time of cable installation. Changes to construction procedures from those assumed in the development of the cable program shall be incorporated in revisions to the cable installation program.

Cable assembly shall be in accordance with the methods statement provided by the cable supplier.

COMMENTARY

C.6.8.2.2 — Inspection for steel pipe welding

It is recommended that welds be 100% nondestructively tested using penetrating dyes, x-ray or ultrasonic methods.

C6.9.1 — Installation program

Due to the potentially large effect on cable forces associated with changes in deck weight and excessive tolerance in jack calibration for initial cable installation operations, some geometric control is necessary for all cable installation operations. Where cables are prefabricated, the most reliable control is on the cable length. Where cables are assembled in-situ, the surveyed positions of the deck and tower must be used to establish this control. Where the structural geometry is used for this purpose, the position of construction loads is of primary importance. Deck conditions must match the theoretical conditions assumed for camber in this case.

RECOMMENDATIONS

Where cables are fabricated in-situ, superstructure geometry shall be used in lieu of initial cable elongation.

6.9.1.1 — Cable alignment and centering devices

Install guide pipe to the tolerance specified in Section 5.9.

6.9.1.2 — Minimum cable forces

Where wedge anchored strands are used as the MTE, minimum wedge seating forces such as power seating or other suitable means specified by the cable supplier shall be applied at installation to prevent slipping at the anchorage.

6.9.2 — Vibration control

Contractor shall make provisions to facilitate rapid introduction of temporary vibration suppression measures for cables deemed susceptible to vibration during construction. Refer also to Section 5.2.

The cables shall be monitored for vibrations throughout erection until the permanent installation of cables and all appurtenances is completed.

6.9.3 — Jacks and gauges

Jacks and gauges for cable installation shall be calibrated using a load cell or calibrated static load machine within 1 month prior to the beginning of cable installation, and every 6 months thereafter, for the duration of cable installation. The 6-month recalibration may be performed using a master gauge, provided that the master gauge is calibrated with the field gauges at the time of initial jack calibration.

COMMENTARY

C6.9.1.1 — Cable alignment and centering devices

Construction tolerance for setting the guide pipes is often consumed by local variance during setting of the anchorages as well as the global variance of the coordinates of the cable anchorages.

Therefore, in addition to setting realistic tolerances, considerations should be given to developing details for mounting guide pipes and centering devices that could be realigned to suit the final achieved alignment of the stay cable.

C6.9.2 — Vibration control

The effect of wind on non-completed stays may create significant vibrations. If not controlled, these vibrations may induce unanticipated fatigue stresses at the anchorage.

Monitoring of cable vibrations should be done at least by visual inspection. Preferable are methods that allow a more accurate determination of the involved amplitudes, modes and frequencies, and the concomitant wind and rain characteristics.

C6.9.3 — Jacks and gauges

The intent is that jacks and gauges be calibrated specifically for the project before use. In the interim, after calibration but before use, they should not be used for other purposes or in a manner that would affect calibration. Responsibility for control of master gauges and the execution and witnessing of recalibration is a matter of contract administration not specifically addressed herein.

RECOMMENDATIONS

6.9.4 — Stressing

Cables consisting of bars or strand individually anchored shall be permitted to be tensioned one by one provided that it can be demonstrated in advance, to the satisfaction of the Engineer, that the final tension and elongation of each tensile element will be equalized within a range of +/- 2.5% MUTS for the tension element.

6.9.5 — Detensioning

Stay cables shall be designed and installed with sufficient shims or other devices to facilitate cable replacement and cable adjustments. The capability for replacement and adjustments shall sufficiently reduce the force in the stay without releasing stay anchorage component devices. For the purpose of cable replacement, the reference target for detensioning capability shall be the as-engineered state at the end of construction.

COMMENTARY

C6.9.4 — Stressing

This provision is to clarify the application for strands with low stress, where stressing is below the tolerance threshold for jacking equipment and variance is relatively greater due to strand modulus. Additional considerations may be necessary for very short cables, where tolerances on installation methods are amplified by the short gauge length of the cable.

The installation of strands by tensioning one by one (sometimes called monostrand stressing) may experience mechanical interlocking between strands during stressing. Selection of material and installation procedures should be made to avoid such interlocking.

Variance of final forces amongst individually installed strands has been successfully minimized by the length method, the force method, or a combination of the two. The length method involves having each strand in the bundle measured and marked with the theoretical length; each strand would be stressed and anchored according to the theoretical length provided good correlation is found with the expected stressing forces. The force method involves the installation of a load cell in a reference strand; after stressing the reference strand to the predetermined force, each successive installation would end with the new strand anchored at a load which matches the force in the reference strand. A combination of the force and length methods follows a concept that is similar to checking elongation in a post-tensioning tendon, except the displacements at the anchor points have to be taken into account; at least one strand in the bundle should be marked with a theoretical length reference. Some aspects of these applications may be patented.

C6.9.5 — Detensioning

It is particularly important for strand cables to have sufficient shims or other adjustment capabilities for force reduction. This is because reseating of wedges for force reduction would leave wedge marks along the free length of the strands, which is generally considered unacceptable. Past recommendations have recommended a minimum detensioning capability on the order of 75 mm. Larger or smaller values may be appropriate, depending upon the type of bridge and other details of the cable system.

RECOMMENDATIONS

6.9.6 — Installation records

6.9.6.1 — Monitoring

The cable installation program shall include provisions for monitoring the installation of each cable. Stay cable installation procedures shall be certified by the system supplier. Installation should be accomplished by one of the two following recommended methods:

1. The installation of the stay cable is performed by the stay cable supplier.

2. The installation of the stay cable is performed by the Contractor and monitored by the cable supplier.

6.9.6.2 — Permanent records

Records shall include survey records; date, time, ambient temperatures and weather conditions; cable forces; cable elongation measurements; shim pack or lock nut setting; deck loading conditions, and all other special notations necessary and sufficient to establish the conditions under which the cable was installed.

Permanent records shall include the as-built profile grade of the deck along the gutter line and adjacent to each cable stay, as well as the final cable load in each cable. This set of records shall constitute the Base Line survey of the structure.

7.0 — STAY CABLE INSPECTION AND MONITORING

U.S. cable stayed bridges are comparatively new, yet comprise a wide range of designs for anchorage and corrosion protection. Effective, preventative inspection and maintenance requires awareness of bridge specific system details and adaptation of suitable inspection tools and criteria.

COMMENTARY

C6.9.6.1 — Monitoring

The supplier of the stay cable system should preferably be responsible for installation. As a minimum requirement, the recommendations for monitoring and certification of the installation should be provided by the system supplier.

C6.9.6.2 — Permanent records

It is recommended that survey be conducted of the bridge deck and tower prior to and following each cable installation. Due consideration should be given to the effects of temperature on stay cable installation. Surveys are generally performed in the pre-dawn hours to minimize the influence of temperature.

C7.0 — STAY CABLE INSPECTION AND MONITORING

Recommendations in this Section are relevant to the needs of both newer and older stay cable systems. U.S. stay cables incorporate bar, parallel wire and parallel strand MTEs. Anchorages and corrosion protection systems of stay cables vary widely. Anchorages encompass point anchorages (wedge, buttonhead and swaged), bond sockets, and threaded systems. Corrosion protection measures including cementitious grout, epoxy, wax, grease, HDPE sheathing and pipe, steel pipe, and other systems have been used. All these variables, and the anticipated future advances in stay cable technology, affect selection of stay cable inspection and monitoring procedures. Awareness of cable as-built characteristics and inspection and maintenance history is critical to inspection and monitoring.

RECOMMENDATIONS

7.1 — General

7.1.1 — Design considerations

Consideration shall be given during the design stage to permit adequate inspection of stay cable components for possible corrosion, and other damage and aging which occurs during the life of the structure.

7.1.2 — Inspection and maintenance

An inspection and maintenance program that specifies the methods and frequencies of inspections shall be prepared with appropriate input from the cable supplier, the designer, and the bridge owner's maintenance forces.

7.1.3 — Inspections

In the United States, it is recommended that stay cables be inspected periodically as part of the bridge inspection program required by federal regulations. Generally, guidelines for inspection and maintenance of the stay cable system installed shall be documented to address the following:

A. Checklist for routine inspection

B. Checklist for in-depth inspection

C. Frequency of each level of inspection

D. Basis for evaluation of physical findings

E. Checklist for routine maintenance

COMMENTARY

C7.1.1 — Design considerations

Commonly reported impediments to proper inspection and maintenance issues for earlier stay cable designs include:

- Inability to inspect the elements inside the cable and the anchorage areas.
- Lack of information on the system of cable stays
- General lack of effective and practical non-destructive technique to determine the health of the stays.

The list of issues above is by no means exhaustive. NCHRP Synthesis 353,[48] published in 2006, provides background information as well as guidance for inspection and maintenance procedures, which can be used by designers to enhance implementation of future inspections of stay cables.

C7.1.2 — Inspection and maintenance

It is not likely that a single inspection method would provide answers for all questions regarding the condition of stay cables. In most cases, a combination of visual and nondestructive testing techniques may be needed to confirm the overall condition of stays. It is, therefore, necessary for the Owner's stay cable inspection specialists to specify the types of inspection that will be utilized. This section indicates possible methods that may be utilized.

C7.1.3 — Inspections

Permanent records of as-built profile and cable force have been established under Section 6.9.6.2.

The level and frequency of inspections is bridge specific and dependent on the history and current performance of the stays. In the extreme case, the effectiveness of the inspections and the ability to locate distress and corrosion may be evaluated by removing cable sheathing in isolated areas, or by removing and replacing a cable. With certain newer, ungrouted stay cable systems individual tension elements can be removed for detailed inspection.

RECOMMENDATIONS

It is recommended that the inspection program shall include the following:

A. A survey of the profile that may indicate unintended change in cable forces

B. Verification of cable forces by a method consistent with the cable system supplied

7.2 — Visual inspection of stays

Close-up visual inspection shall be conducted to detect and/or examine irregularities. Where evidence of deterioration is visible on the surface, further investigation shall be made to determine the extent of the deterioration.

The following features and inspection tasks should be considered:

- Corrosion staining at anchorages
- Stay pipe surface uniformity and soundness
- Stay pipe splitting or corrosion staining
- Protective tape tears
- Weld soundness in stay pipes
- Soundness of previous repairs
- Integrity of neoprene sleeves and boots
- Fit and integrity of accessories - dampers, clamps, ties, etc.
- Conditions at superstructure drains near anchorages
- Uniformity of cable sag
- Cable concentricity within guide pipes
- Conditions within anchorage caps
- Any leakages of hydraulic fluids or silicone from dampers

For grouted stay cables, inspection requires attention to unique features of these cables. Soundness of grout should be evaluated. The inspector needs to note that deposition of minerals leached out of the grout may be indicative of passage of moisture and deterioration.

Where a closer visual inspection of grouted stays is required at suspect locations, "windows" or "portholes"

COMMENTARY

C7.2 — Visual inspection of stays

Detailed inspections require measuring tools and access trolley vehicles. Fig. C7.1 shows such a vehicle owned by Louisiana DOTD, in use on the Hale Boggs Bridge. A summary of hands-on stay cable visual inspection techniques and findings from several bridges was compiled by Mehrabi.[49]

The stay anchorage(s) are usually covered with a cap or cover to protect the ends of the wires or strands that protrude beyond the anchor body This cap should be removed during scheduled visual inspection, and observations made as to any accumulation of water, dampness, visible corrosion of the ends of the MTE, wedges, button heads, or any signs of corrosion at the interfaces of any shim plates or interface of the anchor and bearing plate or any other hardware that may be present.

The removal of anchorage caps is not a routine inspection activity. Wax and grease, if packed in the anchorage for corrosion protection, should only be removed and replaced by a specialist company.

For grouted stays, visual inspection will only indicate potential deterioration if deterioration is visible on the surface. Even though there is no evidence of deterioration on the surface, it is possible that hidden corrosion may be taking place.

The "windows" or "portholes" used for the inspection of the Pasco-Kennewick Bridge were rectangular in shape,

RECOMMENDATIONS

can be cut into the exterior cable-stay pipe and the grout removed to obtain access to the MTE. Procedures shall be developed and effective corrosion protection shall be provided to preserve the condition of the as-constructed stay after repair.

COMMENTARY

measuring approximately 150 by 300 mm, Fig. C7.2. The grout cover should be carefully chipped out so as not to nick or damage the MTE. Upon completion of the visual inspection, the windows must be repaired. The following is a suggested repair technique: The void produced by the removal of the grout and the thickness of the cable-stay pipe cover is overfilled by a stiff epoxy to approximately 20 mm above the profile of the exterior pipe covering. A replacement cover, cut to fill the opening of the window, is then pressed into the stiff epoxy causing the epoxy to squeeze out on all sides of the patch. Trim and clean the epoxy joints to provide a smooth surface with a profile matching the original exterior pipe covering. Verify sealing of the patch.

Fig. C7.1—Inspection trolley in use on the Hale Boggs Bridge near New Orleans, LA.

Fig. C7.2—Cable-stay window for Paco-Kennewick Bridge.

RECOMMENDATIONS

7.3 — Condition evaluation

The first standard survey shall be conducted to coincide with the first biannual inspection after the opening of the bridge. The survey shall comprise a survey of the profile grade of the deck and/or a verification of cable stay loads. The results of this survey and subsequent surveys shall be compared to the Base Line survery described under Section 6.9.6.2.

The second and subsequent surveys shall be repeated at every other biannual inspection unless the performance and condition of the structure and the stays require more frequent surveys or justifies reduced frequencies.

The survey of the profile grade of the deck shall be taken along the gutter lines and adjacent to each cable stay. Verification of cable stay loads is for comparison to as-built records.

7.4 — Non-destructive evaluation and monitoring

At prescribed intervals as determined by the Owner, or as warranted by the condition evaluation, the cable stays shall be inspected or monitored by an appropriate combination of non-destructive inspection and/or monitoring methods. Available methods for stay cables that may be considered include the following: Inspection Methods and Diagnostic Tools:

COMMENTARY

C7.3 — Condition evaluation

Cable forces may be checked using the vibration method. A research project sponsored by the Federal Highway Administration provides detailed experimental and analytical procedures for stay cable force measurement.[50] Accelerometers or non-contact laser vibrometers can be used to measure vibrations. To improve accuracy, it is necessary to include cable bending stiffness, sag-extensibility, and dampers into the analytical relationships.[49]

Active corrosion of the cable stays will eventually manifest itself by a loss of section of the MTE and broken elements, i.e., wire, strand or bars, possibly in conjunction with fatigue. In the case of ungrouted stay cables, broken tension elements and significant loss of MTE section will likely result in a near-immediate loss of cable-stay load and changes in deck geometry. This is not necessarily true for grouted stays because an isolated broken wire or strand in a grouted stay can redevelop its load within a short distance through the grout. Caution should therefore be applied when reviewing grouted stay cable forces which do not change over time, since it cannot be assumed that there is no section loss of MTE.

In general, the integrity of cable stays should be correlated with other findings during inspection instead of relying solely on stay forces and deck geometry.

The Owner should consider what measures, if any, should be required during construction to establish a base line condition evaluation.

C7.4 — Non-destructive evaluation and monitoring

A comprehensive overview of nondestructive test methods, including promising future NDT developments is described in NCHRP Synthesis 353.[48]

RECOMMENDATIONS

- Vibration Method
- Probe/Scope
- Ultrasonic Testing

COMMENTARY

The vibration method[50] is accomplished using a contacting (e.g. accelerometer) or non-contacting (e.g. laser vibrometer) sensor. Either sensor is capable of accurately measuring vibrations of the cable. Where a laser vibrometer is used, no special attachments need to be placed on the cable, eliminating need for access equipment. Collected data are used to determine the frequencies of vibration. The measured frequencies are then used to calculate forces. The effects of bending stiffness of the cable, neoprene rings, cable sag, and change in stiffness at the cable sockets are considered for higher degree of accuracy.

Probe/Scope: Borescopes or videoscopes have been used to check the external condition of the cable and presence of moisture and sign of deterioration inside guide pipes and anchorage chambers.

Ultrasonic Testing: Ultrasonic testing has applicability for detection of wire and strand conditions within certain stay cable anchorages. An ultrasonic transducer is coupled to the end of each wire and a high-frequency stress wave is sent into the wire. The reflections are monitored by the same sensor and displayed. A trained technician can view the record and decide if a wire break has occurred. Although this method has been used on a limited number of bridges in the U.S. and elsewhere, there has not been a systematic research effort aimed at determining its overall reliability and effectiveness.

This method has been used for parallel wire cables and cables comprised of 7-wire strand. A mock-up of the anchorage in question is needed, upon which calibration can be made of known defects and their locations.

Due to the limited length over which the ultrasonic pulses can travel due to signal loss with distance, this method is applicable to evaluation of MTE in the vicinity (1 to 3 meters) of ends of cable anchorages. The quality of this method is highly dependent on prior testing and calibration on a mock-up specimen, and the experience of the operating technician.

Considerable expertise and experience is required in order to interpret these test results.

Case Studies and References - Suzuki et al. (1988)[51]; Prato et al. (1997)[52]; Tabatabai et al. (1998)[53]; Ciolko and Yen (1999).[54] Additional information can also be found in Reference 55.

RECOMMENDATIONS

- Radiographic Inspections

- Magnetic Perturbation

Long Term Monitoring:

- Acoustic Monitoring

COMMENTARY

Radiographic Inspections: These methods have the potential for successfully assessing conditions of cable anchorages and stay cable free length where the perimeter of the anchorages can be accessed. This method has been used on the anchorages of the Meridian Bridge in California, and feasibility/calibration trials were also conducted in preparation for the stay cable inspection program for the Hale Boggs Mississippi Bridge in Louisiana.[49] However, safety issues, cost, and logistics of working with larger and heavier equipment make adaptation of the technique prohibitive, except for unusually complex or emergency situations.

Magnetic Method: A prototype Magnetic Perturbation NDE Cable System was developed by a FHWA initiated research contract with Texas Research Institute Austin, Inc.[55,56] It has been used in experimental trials on two cable stayed bridges and on one stay cable laboratory test specimen. A commercial, self propelled system capable of evaluating stay cables has been developed in Switzerland.[57]

Data acquisition is accomplished by scanning along a cable using a powerful electromagnet with attached sensors to detect magnetic anomalies produced by corrosion pits, fatigue cracks, and fractures in the wire. Provided a sufficiently powerful electro-magnet is employed, the direct current magnetic field can penetrate the wrapping, HDPE pipe, cement grout and penetrate deep into large diameter cables. The utilization of steel pipe sheathing seriously inhibits the capability of this equipment.

Field demonstrations of a grouted parallel wire system encased in HDPE were conducted on the Luling[58] and Pasco-Kennewick[59] cable-stayed bridges; no damage was found.

An evaluation of a failed fatigue acceptance cable stay specimen proved that the system was quite capable of detecting fatigue fractures in the grouted seven-wire strands encased in HDPE pipe of the damaged cable stay.[56] However, the available magnetic perturbation technology is only used in accessible areas of the stay cables.

Acoustic Monitoring: As wire breaks, a stress wave propagates along the length of the cable in both directions. Acoustic monitoring of stay cables involves attaching accelerometers at both ends of the stay cable to detect this stress wave. The recorded response or "signature" can be analyzed to determine if the event is in fact a wire break and not some other form of ambient noise. By analyzing the arrival times at multiple sensors the location of the wire

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COMMENTARY

break can be calculated. Acoustic monitoring is applied to a structure in a long term fashion to detect wire breaks as they occur and can detect if there are active areas of breaking wires from corrosion or fatigue damage. However, since it is a passive system it cannot be used to estimate how many existing broken wires are in the cable.

This technology first used by stay cable testing labs in Europe, was adopted for use at a stay cable testing laboratory to monitor occurrence of wire breaks in cable fatigue specimens.[60]

A commercial system is currently available and has been installed on 24 bridges worldwide to detect breaking steel wires, including 6 cable-stayed bridges. The detection system relies on proprietary software to identify wire breaks. In grouted cables, the attenuation of the wave is significantly higher than in the ungrouted cables. This technology is adaptable to continual development of stay systems in that system specific "signatures" can be established through recognition of induced wire breaks in system prototypes; thus, acoustic monitoring has the potential of detecting wire breaks in the free length and the cable anchorages.

7.5 — Frequency of inspection

The National Bridge Inspection Standards (NBIS) require inspection of bridges every two years.

Frequency and level of inspections shall be conducted according to the specific features and needs of a structure.

C7.5 — Frequency of inspection

It is important to periodically assess in detail the condition of the stay cables so the condition of the important structural elements is known. Generally, inspections and surveys that reveal no signs of deterioration or change in profile and cable forces would justify less frequent and reduced level of inspections.

A possible frequency of inspection for grouted stays that show indications of deterioration may be as follows: a visual inspection every two years, a more detailed inspection (using non-destructive methods) of the MTE in the anchorage zone every four years, a condition evaluation (see Section 7.3) every six years or when circumstances dictate, and an inspection along the free length of the cable (using magnetic perturbation, or appropriate substitute) every ten years or when circumstances dictate.

Acoustic monitoring can be considered where cable stays show signs of deterioration. The extent of monitoring and its integration into the inspection program will vary according to the conditions and specifics of the stay system.

RECOMMENDATIONS

7.6 — Monitoring of cable vibrations

It is recommended that cables be monitored regularly for excessive wind induced vibration.

COMMENTARY

C7.6 — Monitoring of cable vibrations

Monitoring of cable vibrations should be done at least by visual inspection. Preferable are methods that allow a more accurate determination of the involved amplitudes, modes and frequencies, and the concomitant wind and rain characteristics.

RECOMMENDATIONS

7.7 — Cable inspection & maintenance manual

7.7.1 — Items for inspection & maintenance manual

The following shall be considered as essential items for a maintenance manual to cover stay systems:

- Bridge description
- Design Considerations
- Loads
- Stay cable details
- Stay cable as-built drawings covering anchorage design, material used, repairs done during construction, history of problems during construction
- Inspection and maintenance frequencies, qualifications of inspection teams
- Information on access: platforms, ladder and snooper trucks as might be applicable
- Cable re-tensioning procedures where applicable
- Cable replacement procedures including traffic patterns and specific replacement procedures
- Inspection procedures for anchorages, guide pipes, neoprene boots, neoprene washers, sheathing, cross cables, dampers, etc. including identification of critical areas and how / where to look for moisture and corrosion
- List of designers, contractors, and suppliers of stay cables and components.
- Summary of qualification test results for MTE
- Summary of qualification test results for the entire stay cable system
- Deck elevation surveys
- Repair procedures including sheathing repair, PVF tape repair, repair of damage to guide pipes and welded connections
- Description of methods for measuring cable forces

COMMENTARY

C7.7.1 — Items for inspection & maintenance manual

Excerpt from Report - NCHRP Synthesis 353.[48]

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APPENDIX A—DETAILS OF "ONE PIN TEST"

This test provides a measure of the ductility of 12.7 mm and 15 mm diameter 7-wire strands.

Section 4.2 of the Recommendations requires that the fatigue strength of the stay cable system be demonstrated by tests of at least three stay cable specimens. Passage of these tests does not insure similar properties for all of the strand produced for the project.

Application of the "One-Pin Test" to each manufactured length of strand gives much better assurance as the ductility of that length of strand. In this instance, the term ductile strand means a strand with minimum notch sensitivity. Low notch sensitivity is essential for strands or wires held in wedge type grips and subjected to repeated loads.

Section 3.2.2.1 requires tests on "each manufactured length, or every 10 Mg (whichever is less)." Two apparently identical wires from the same heat of steel can have very different properties in their final condition. If, for instance, one or more of the cooling blocks in the wire drawing machine gets too hot, the resulting wire will have very poor ductility, but this will not be visible to the eye. Strand with wire of this type would fail the "One-Pin Test".

Several procedures for checking notch sensitivity were investigated during preparation of the 1986 Edition of these Recommendations. It was concluded that the "One-Pin Test" is the only one that adequately measures notch sensitivity.

Test procedure

- Cut a strand sample long enough for two ultimate strength tests and three pin tests.
- Load one piece to failure and record actual ultimate strength = f'sa.
- If first test fails at the grip, load a second sample to failure.
- Use the highest value as f'sa. This value is not acceptable if the elongation in 610 mm does not exceed 3.5%.
- Load a sample to failure in the pin test device and record the load at failure as FR. Loading speed shall be uniform and not greater than 30 MPa per second.

$$\text{Pin Test Efficiency } (PTE) = \frac{F_R}{f_{sa}'}$$

The PTE for strand used in stay cables shall not be less than 0.80 (See Section 3.2.2.1).

Details of the one-pin device are shown in Figs. A.1 and A.2

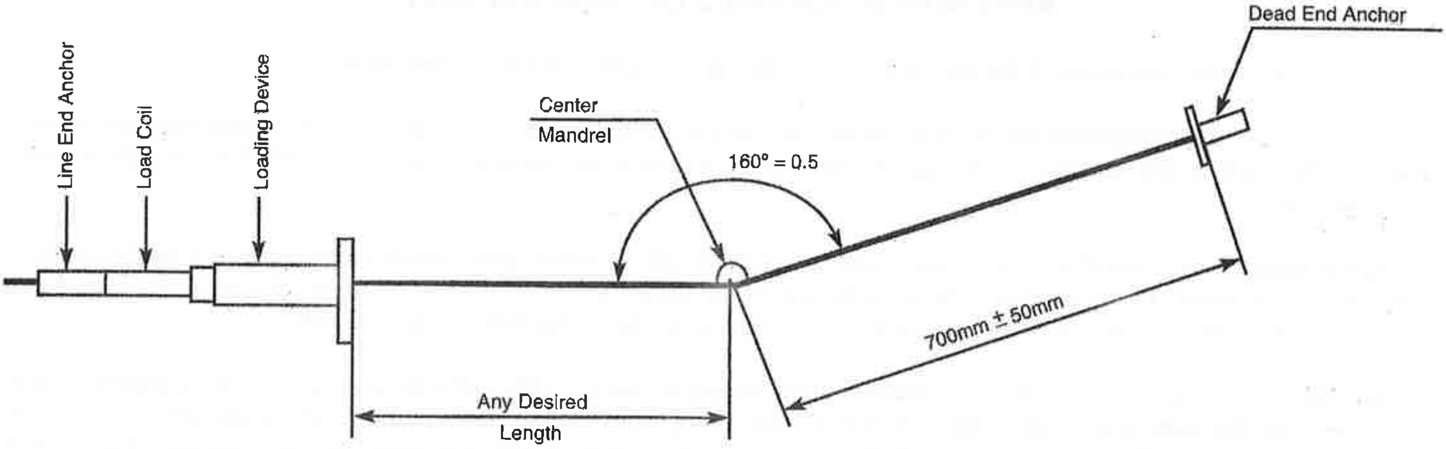

Fig. A.1—Basic details of one pin test device.

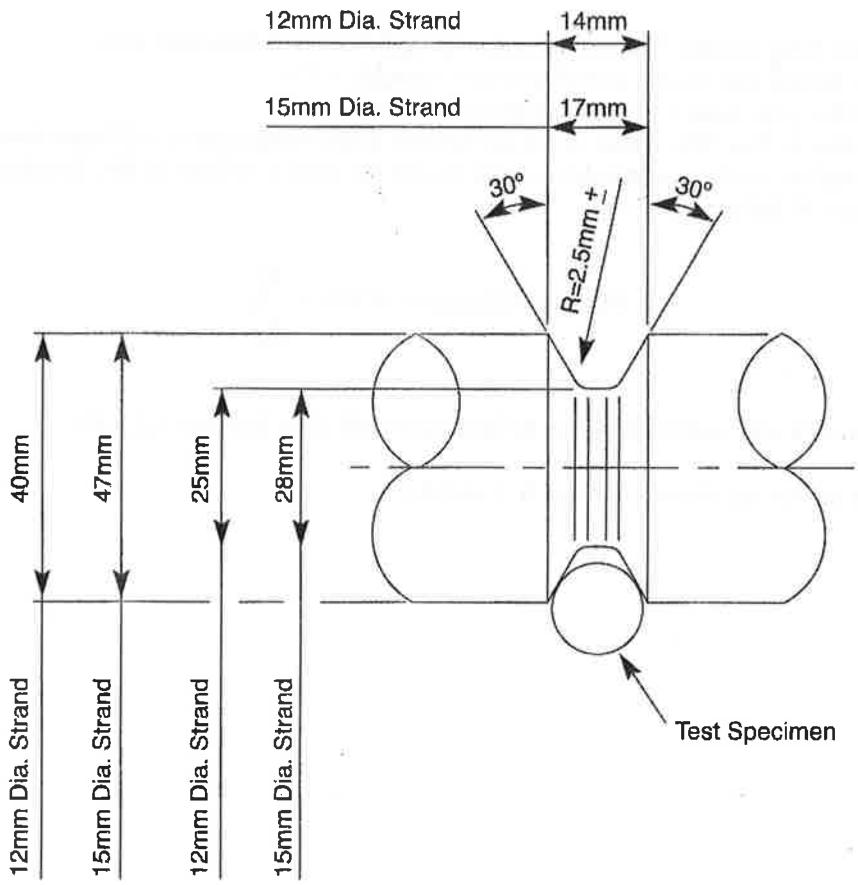

Fig. A.2—Detail of center mandrel.

APPENDIX B—SAMPLE OF GALVANIZED STRAND SPECIFICATIONS

EXCERPTS FROM ENGLISH TRANSLATION OF THE FRENCH STANDARD
NF A 35-035 VERSION PUBLISHED IN JANUARY 2001

"HOT-DIP ZINC OR ZINC-ALUMINIUM COATED PRESTRESSING
SMOOTH WIRES AND 7-WIRE STRANDS"

Translation prepared by the Steel Industry Standardization Office
(Standardization Office collaborating with AFNOR for the steel products,
Approved by ministerial decision dated 24 September 1984)

Table of Contents

1.0 — SCOPE

This Standard specifies:

- The geometrical, mechanical and technological properties and the characteristics of the metallic coating for hot-dip Zinc or Zinc-aluminum coated smooth wires and 7-wire strands used for prestressing; and
- The conditions of inspection for all these properties and characteristics.

It concerns:

- The hot-dip Zinc or Zinc-aluminum coated smooth prestressing wires of 5 mm to 7 mm in nominal diameter, nominal tensile strength of 1670 MPa, 1770 MPa, 1860 MPa (see Table 3) and categories A and B, and
- The hot-dip Zinc or Zinc aluminum 7-coated wire prestressing strands with a nominal diameter between 12,5 mm and 12,7 mm and nominal tensile strength 1770 MPa or 1860 MPa and categories A and B,

used in reinforced and prestressed concrete structures.

This standard does not apply to hot-dip metal coated reinforcing steels (see A 35-025).

2.0 — NORMATIVE REFERENCES

This standard incorporates by dated or undated references provisions from other publications. These normative references are cited at the appropriate place in the text and the publications are listed as follows. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

NF A 03-010	Metallic materials – Wire – Reverse bend test
NF A 03-715	Isothermal relaxation test of strands and twisted cables used as reinforcement in prestressed constructions
NF A 03-716	Isothermal relaxation test of wires and bars used as reinforcement in prestressed constructions
NF EN 10002-1	Metallic materials – Tensile testing – Part 1: Method of test (as ambient temperature)
NF EN 10020	Definition and classification of grades of steel
NF EN 10027-1	Designation systems for steels – Part 1: Steel names, principal symbols
NF EN 10079	Definition of steel products
NF EN 10204	Metallic products – Types of inspection documents
NF EN ISO 1460	Metallic coatings – Hot-dip galvanized coatings on ferrous materials – Gravimetric determination of the mass per unit area
NF EN ISO 1461	Hot-dip galvanized coatings on fabricated iron and steel articles - Specification

3.0 — DEFINITIONS

For the purpose of this standard, hot-dip coating is any operation during which the element to be coated (smooth wire or constituent wire of a strand) is coated with Zinc or Zinc-aluminum by passing into a bath of molten Zinc and/or a bath of molten Zinc-aluminum.

Note 1: In the rest of the text of this standard, the expression "hot-dip" is implied before the words coating, coated or to coat.

Note 2: In the text, the words galvanization, galvanized or galvanize are also used for Zinc coating.

4.0 — CLASSIFICATION AND DESIGNATION

4.1 — Classification

The steel covered by this standard are classified as non-alloy special steels according to NR EN 10020.

4.2—Designation

The steel names given in Table 1 are allocated for the concerned grades according to NF EN 10027-1.

Table 1—Steel names of grades of coated prestressing steels

Prestressing steel category	Designation*
Coated wire	Y1670C + *Z* or *ZA* Y1770C + *Z* or *ZA* Y1860C + *Z* or *ZA*
Seven-coated wire strand	Y1860S7 + *Z* or *ZA* Y1770S7 + *Z* or *ZA*

*Y means "prestressing steel"; C means "cold drawn wire"; S7 means "7-wire strand"; *Z* means "Zinc coated (galvanized) product"; *ZA* means "product coated with Zinc-aluminum."

The full designation of the steels covered by this standard includes in the order:

- The steel name of the grade of the coated prestressing steel (see Table 1)
- The diameter of the steel, in millimeters, and its category.

EXAMPLE

Y1860S7+ *Z* -15,2-A

Designates a prestressing strand with seven galvanized wire of nominal tensile strength 1860 MPa, 15,2 mm in diameter and category A.

Note: When agreed between the parties and alternately to the above mentioned requirements, the designation of the steels covered by this standard can be composed of the following information separated by a dash:

- S7 (only in the case of 7-wire strands);
- Nominal diameter in millimeters;
- Nominal tensile strength in MPa;
- Type of coating (*Z* or *ZA*).

5.0—MANUFACTURE

The coating method of the coated smooth prestressing wires or the constituent wires of the coated prestressing strand is at the discretion of the manufacturer.

In the case of strands, the coating of the constituent wires of the strand shall be done before standing.

6.0—REQUIREMENTS

6.1—Geometrical properties

The geometrical properties are the nominal diameter and the nominal cross-sectional area, which includes the steel and the metallic coating.

Table 2 gives these values for the coated prestressing steels referred to by this standard and the tolerances on the nominal cross-sectional area.

Table 2 also gives the nominal values for the mass per meter and the relevant tolerances. For the calculation of the mass per meter, the density of prestressing steels in taken equal to 7 810 kg/m³.

Table 2—Nominal diameters, nominal cross-sectional areas, and tolerances

Prestressing steel category	Nominal diameter, mm	Nominal cross-sectional area A_n, mm^2	Tolerance on cross-sectional area*, %	Nominal mass per meter*, g/m	Tolerance on the mass per meter*, g/m
Coated smooth wire	5	19.6	±2	153	±3
	6	28.3	±2	221	±4
	7	38.5	±2	301	±6
Coated seven-wire strand	12.5	93	±2	726	±15
	12.9	100	±2	781	±16
	15.2	140	±2	1093	±22
	15.7	150	±2	1172	±24

*The nominal values and the tolerances apply to coated products and therefore are to be understood including the coating.

Table 3—Specified values for mechanical properties

Prestressing steel category	Nominal diameter, mm	Nominal tensile strength*	F_m, kN	$Fp_{0.1}$, kN	A_{gt}, %	Z†	$\rho_{1000/0.7}$, %
Coated smooth wire	5	1770	34.7	31.0	3.5	Ductile break visible to the naked eye	2.5
		1860	36.5	32.5			
	6	1670	47.3	42.0			
		1770	50.1	44.6			
	7	1670	64.3	57			
		1770	68.1	60.6			
Coated seven-wire strand	12.5	1770	164	146	3.5	Ductile break visible to the naked eye	2.5
		1860	173	154			
	12.9	1770	177	158			
		1860	186	166			
	15.2	1770	248	220			
		1860	260	230			
	157	1770	265	236			
		1860	279	248			

*The notion of nominal tensile strength is only used for designation purposes; the value corresponds to the rounded value of the tensile strength of the prestressing steel in MPa.
†In case of dispute, the constriction coefficient shall be measured and be equal to or greater than 25%.
‡By agreement between the purchaser and the manufacturer, a specified value of 4.5% may be fixed for $\rho_{1000/0.8}$.

6.2—Mechanical properties

The mechanical properties are:

- The maximal load (F_m)
- The 0,1 % proof load ($F_{p0.1}$);
- The total percentage elongation at maximum load (A_{gt});
- The constriction coefficient (Z);
- The isothermal relaxation after 1 000 h from an initial load of $0.7F_{me(\rho1000/0.7)}$, being the actual maximum load determined by two tensile test on test pieces adjacent to the one submitted to relaxation test.

Table 3 gives the specified values of the mechanical properties for the coated prestressing steels defined by this standard.

The isothermal relaxation at $0{,}8F_{me(\rho1000/0.8)}$ may be an optional requirement by agreement between the purchaser and the manufacturer (see Table 3).

For F_m and $F_{p0.1}$, the specified values are 5% fractiles to which are associated minimal values respectively equal to 98% and 95% of the specified value of the relevant fractile for F_m and $F_{p0.1}$.

For A_{gt} and Z, the specified values are minimal values. For $_{(\rho 1000/0.7)}$ and $_{(\rho 1000/0.8)}$, the specified value is a minimal value.

6.3 — Technological properties

6.3.1 — Coated smooth wires

6.3.1.1 — General

The Technological properties of the coated smooth wires are:

- The resistance to reverse bending
- The fatigue resistance.

6.3.1.2 — General

The coated smooth wires of categories A and B shall withstand without failure 5 reverse bends according to 9.2.

6.3.1.3 — Fatigue resistance

6.3.1.3.1 — Coated smooth wires of category A

The coated smooth wires of category A shall withstand without failure 2 millions cycles of stress fluctuating down from 0,7 to 0,7 with

$$\frac{2\Delta F_a}{A_n} = 200 \text{ MPa}$$

6.3.1.3.2 — Coated smooth wires of category B

The coated smooth wires of category B shall withstand without failure 2 million cycles of stress fluctuating down from 0,45 to 0,45 with

$$\frac{2\Delta F_a}{A_n} = 300 \text{ MPa}$$

6.3.2 — Coated seven wire strand

6.3.2.1 — General

The technological properties are:

- The ability to resist to multiaxial stresses (deflected tension)
- The fatigue resistance.

6.3.2.2 — Ability to resist to multiaxial stresses (deflected tension)

6.3.2.2.1 — Coated seven wire strand of category A

The coated seven wire strands of category A shall have a deflected tensile coefficient lower than or equal to 28%.

6.3.2.2.2 — Coated seven wire strand of category B

The coated seven wire strand of category B shall have a deflected tensile coefficient lower than or equal to 20%.

6.3.2.3 — Fatigue resistance

6.3.2.3.1 — Coated seven wire strand of category A

The coated seven wire strands of category A shall withstand without failure 2 million cycles of stress fluctuating down $0{,}7F_{me}$ to $0{,}7F_{me} - 2\Delta F_{a1}$ with

$$\frac{2\Delta F_a}{A_n} = 190 \text{ MPa}$$

6.3.2.3.1 — Coated seven wire strand of category B

The coated seven wire strands of category B shall withstand without failure 2 million cycles of stress fluctuating $0{,}45F_{me}$ to $0{,}45F_{me} - 2\Delta F_{a1}$ with

$$\frac{2\Delta F_a}{A_n} = 300 \text{ MPa}$$

6.4 — Properties of the metallic coating

6.4.1 — General

The properties which characterize the metallic coating are:

- The mass of coating per area unit;
- The adhesive strength;
- The continuity;
- The aspect.

6.4.2 — Mass of coating per area unit

The mass is measured according to the provision given in 9.6.

6.4.3 — Adhesive strength

After the winding test described in 9.7, the coating layer of the whorls shall not present exfoliations or cracks. Neverthe-less the test is deemed to be satisfactory when small flaws possibly detected by a visual examination without assistance do not allow to loose the coating when rubbing with the finger without using a nail.

6.4.4 — Continuity

The continuity of the coating shall be such that after the test described in 9.8, the test piece shall not exhibit bright and adhesive layer of salmon-colored cooper which indicates bare steel at this place, at any point located at more than 25 mm of the immersed end.

7.0 — CONFORMITY WITH THE STANDARD – INSPECTION DOCUMENTS

A batch is deemed to conform to the standard:

- Either when it comes from a producer who gets the certification* of these steels; in this case, the products are inspected by the producer under the conditions defined by the certification. They are only the subject of a verification of the identification and aspect by the user;
- Or it is submitted to acceptable testing generally carried out at the factory before delivery according† to the rules defined in clause 8.

The type of inspection document shall be indicated at the time of ordering; the different types of inspection documents are defined in NF EN 10204.

* At this time, it is the homologation granted by International Prestressing Committee (Secretariat : Laboratorie des Ponts et Chaussées, 58 bd Lefébvre – 75732 PARIS CEDEX 15),

† When the acceptance testing of the products cannot be carried out before delivery, an inspection according to the provisions defined in this standard shall be carried out by an approved body, before use.

8.0 — SAMPLING AND ACCEPTANCE TESTING

Otherwise agreed, the following rules are applied;

8.1 — Sampling

The inspection may be done either by cast or by batch.
The way of sampling is to be foreseen at the time of ordering.

8.2 — Inspection unit

The inspection unit is composed of coated products coming from the same factory and of the same grade and nominal diameter manufactured according to the same process; the mass of each inspection unit being:

- For the inspection per cast; not more than 40 t or part thereof,
- For the inspection per batch, not more than 20 t or part thereof.

When the number of coils is lower than 3, the number taken samples is equal to 3. When the number of coils is greater than or equal to 3, one sample is taken per coil and the maximum number of samples is limited to 12. On each sample, one series of tests is carried out as follows:

- One tensile test (with measurement of $F_{p0.1}$, F_m, A_{gt}, Z),
- One determination of the mass per meter,
- One reverse bend test (for coated wires),
- One control of the metallic coating (mass of coating per area unit, adhesive strength and continuity)

Per inspection unit of coated strands, one deflected tensile test is carried out.

Data concerning relaxation and fatigue behavior may be taken by agreement between the purchaser and the producer from reports of tests made by the producer on identical products of recent manufacture (less than two years).

8.3 — Interpretation of the results

The minimum and/or maximum specified values shall be fulfilled for all controlled properties.
For F_m and $F_{p0.1}$, the following criteria shall be fulfilled:

$$m - k(n) \times s \geq V_s$$

where m is the average of the n obtained results (n between 3 and 12);

$$m = \frac{1}{n}\sum_{i=l}^{n} x_i$$

in which x_i represents the observed individual values;
$k(n)$ is the coefficient given in Table 4

Table 4—Values of $k(n)$

n	$k(n)$	n	$k(n)$
3	7.66	8	3.19
4	5.14	9	3.03
5	4.20	10	2.91
6	3.71	11	2.82
7	3.40	12	2.74

s is the estimated standard deviation

$$s = \sqrt{\frac{\sum_{i-l}^{n}(x_i - m)^2}{n-1}}$$

V_s is the specified value for F_m or $F_{p0.1}$ (5 % fractile).
When these conditions are not met, the batch id considered as non-conforming.

9.0 — TEST METHODS

The test methods described in 9.1 to 9.8 are carried out on non-machined pieces of coated wires or seven coated wire strands.

9.1 — Tensile test

9.1.1 The tensile test is carried out on the product as delivered according to NF EN 10002-1.

9.1.2 The total percentage elongation at maximal load (A_{gt}) is the increase of the gauge length of the test piece under maximal load and is expressed as a percentage of the initial gauge length.

This gauge length is at least 100 mm for the wires and at least 500 mm for the strands.

The elongation is measured with an extensometer allowing measurements with an accuracy better than 0,1 % of its gauge length. In the case of wires, it is allowed to determine by a manual method by drawing gauge marks (see NF EN 10002-1).

9.2 — Reverse bend test

The reverse bend test is carried out according to NF A 03-010.

9.3 — Deflected tensile test

The deflected tensile test is carried out on 7-coated wire strands according to annex A of this standard.

9.4 — Relaxation test

The fatigue test is carried out according to annex B of this standard.

9.5 — Fatigue test

The fatigue test is carried out according to annex B of this standard.

9.6 — Determination of the mass of metallic coating per surface unit

The determination of the mass of zinc per surface unit is carried out according to NF EN ISO 1460.

A sample with a length not less than 150 mm should be used.

In the case of strands, the mass of the coating per surface unit should be determined on at lease two constituent wires; the value to be compared to the requirements given in 6.4.2 is the average value of the masses per surface unit of each wire.

9.7 — Verification of the adhesive strength of the metallic coating

The adhesive strength of the metallic coating is verified by winding at least 6 turns of the coated wire or one of the constituent wires of the coated strand on a cylindric mandrel the diameter of which is given in Table 5.

Table 5—Diameter of the mandrel for the winding test

Prestressing steel category	Nominal diameter, mm	Diameter of the mandrel, mm
Coated smooth wire	5	25
	6	30
	7	35
Seven coated wire strand	12.5	20
	12.9	20
	15.2	25
	15.7	25

The test piece is composed of a piece of wire of sufficient length to correctly carry out the test.

The winding shall be done at a speed as uniform as possible, not more than 15 tr/min and in any case sufficiently reduced in order not to provoke any significant heating of the coating.

For the coated seven wire strands, the test is carried out at least on two constituent wires.

9.8 — Verification of the continuity of the metallic coating

The continuity of the metallic coating is controlled according to annex C of this standard.

9.9 — Cancellation of a test

When a test does not give the specified results because of a fault of execution, the test is cancelled. By fault of execution, it is understood any defective preparation, inaccurate fitting on the test machine, a dysfunctionning of this one or any other analogous anomaly.

10.0 — INFORMATION TO BE SUPPLIED BY THE PURCHASER

The following information shall be supplied by the purchaser at the time of consultation and ordering"

(a) designation of the product,
(b) ordered quantity
(c) requirements concerning packaging and protection.

11.0 — DELIVERY CONDITIONS

11.1 — Packaging, handling, storage, transport

The products are delivered in coils with an appropriate packaging in order not to alter the metallic coating during handling, storage or transport.

11.2 — Labeling

Labeling is such that it allows to ensure traceability of the product. A label shall be steadily fixed on each coil and include at least the following information:

- Factory of production;
- Designation of the product according to 4.2;
- Number of batch or equivalent indications which allow to report to inspection documents;
- Mass of coil.

11.3 — Delivery documents

Any delivery shall be accompanied with a delivery certificate including all the necessary information to identify the delivery and a load-elongation diagram which characterizes the delivery.

ANNEX A (NORMATIVE)—DEFLECTED TENSILE TEST METHOD (REFER TO ONE PIN TEST IN PTI RECOMMENDATIONS, APPENDIX A)

A.1 — Principle of the test

The test consists to submit each test piece of prestressing strand deflected on a mandrel to a tensile load till failure of at least one constituent wire of the strand.

A.2 — Symbols

L = Total length between the anchorages of the test pieces, in millimeters.

F_{me} = Maximum load, in newtons, determined by at least two tensile tests on test pieces coming from the sampling submitted to deflected tensile testing.

$F_{m,d}$ = Maximal load, in newtons, reached at the "active" side during the deflected tensile test on a test piece.

D_i = Deflected tensile coefficient of one test piece obtained at the active side, in %:

$$D_i = \left(1 - \frac{F_{m,d}}{F_{me}}\right) \times 100$$

D = Deflected tensile coefficient of the sampled obtained at the active side, in %:

$$D = \frac{\sum_{i=1}^{n} D_i}{n}$$

n is equal to or greater than 5.

a = Deviation angle (see Figure A.1).

A.3 — Test pieces

The test is carried out on a minimum of 5 test pieces per sample.

The test pieces are taken in the product as used between two test pieces for tensile tests which allow to determine F_{me}.

The length of the test piece shall be sufficient to allow to grip it in the testing device.

A.4 — Testing device

The testing device shall be built in order to be stiff. The test piece is gripped in the testing device by means of two anchorages; the anchorage located on the same side than the tensioning device is called "active"; the anchorage at the opposite side is called "passive". Refer to PTI Recommendations, Appendix A

ANNEX B (NORMATIVE)—FATIGUE TEST (SEE PTI RECOMMENDATIONS, CHAPTER 3)

ANNEX C (NORMATIVE)—METHOD OF VERIFICATION OF THE CONTINUITY OF THE METALLIC COATING

C.1 — Principle

The test consists to submit a test piece of coated smooth wire or constituent wire of coated strand to two 60 s immersion in a solution of copper sulphate which progressively dissolves the metallic coating and then reveals possible defects in the continuity of the coating.

Note: The above mentioned value of 60 s applies to zinc coatings. In the case of zinc- aluminum coatings, the kinetics of the reaction with the copper sulphate is faster; shorter immersion times should be applied; unless condition determined by prior testing are defined, two immersions of 45 s should be applied.

C.2 — Test piece

The test piece is composed by a piece of wire of about 250 mm long. This test piece is completely degreased with an appropriate solvent. Then it is rinsed out with distilled water and wiped with clean cotton wool. Then is shall only be handled in the part which is not aimed at being immersed.

C.3 — Reactive

The used of reactive is a fresh solution of copper sulphate, prepared from crystallized pure copper sulphate ($SO_4Cu,5H_2O$) at the rate of 314 g of salt added into 100 ml of distilled water which corresponds to a proportion of 275 g of salt per liter of solution. The density of this solution shall be 1,17 ± 0,002 at 20°C ± 2 °C.

The preparation of the solution shall be completely done without heating. The liquor shall never be heated even for finishing off the solution. To avoid the operation takes too long time, it can be preceded as follows: the salt to be dissolved is ground then consumed by successive parts of the water to be used. After total dissolution, the different partial solutions are mixed by shaking.

When crystallized purified powder copper sulphate of commercial quality is not used, it is necessary to neutralize the solution by chemically pure copper oxide in excess and to pour off before use (order of magnitude 1g to 2 g of pulverized copper oxide or copper carbonate per liter of solution).

C.4 — Procedure

The here above specified reactive is take in a glass vessel of at least 8 cm in inner diameter in order to fill it on a height of at least 10 cm. The wire test piece is submitted to successive immersions in the reactive which shall be maintained at 20 °C ± 2 °C during the test duration.

The test piece is maintained in a vertical position and shall neither be in contact with the walls of the vessel nor be shaken during the immersion period.

Just after each immersion, the test piece is wiped and washed with running water and the copper which is laid down and is not adhesive, is slightly wiped away with absorbent cotton-wool.

The used solution is renewed every time the realized test series has lead to a maximal dissolution of 5 g of zinc or zinc-aluminum per liter of reactive.

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APPENDIX C — CORROSION PROTECTION SYSTEM DETAIL

App.C.1 — Temporary corrosion protection

Temporary corrosion protection of the bare steel tension elements shall be provided as required by stay cable details, the period of time between installation of the stay cable and grouting, and the exposure conditions.

Individual bare wires, strands or bars shall be coated with an approved water soluble corrosion inhibitor prior to their insertion into the pipe. Appropriate polarization and exposure testing shall be conducted by the approved testing laboratory to determine the effectiveness of the corrosion inhibitor to provide corrosion protection. The polarization tests shall conform to ASTM G5, "Standard Reference Test Methods for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements." Bond testing shall be performed to prove that the proposed corrosion inhibitor does not impair the bond strength between the cementitious grout and steel tension elements. During and after cable threading operation, water, rain or snow shall not be introduced into the pipe. Within every 3 months following threading installation and prior to grouting operation if used, the corrosion inhibitor shall be reapplied by re-application from the top of the pipe.

App.C.2 — Wrapping with PVF tape

PVF tape normally has a 115 micro-m minimum total thickness, however a 125 micro-m thickness is recommended.

The PVF tape shall have a uniform synthetic pressure sensitive adhesive applied to its underside and be laminated to a release liner carrier which shall separate smoothly from the tape and adhesive without damage to the tape and adhesive. The tape shall be self extinguishing after exposure to flame, and meet the following test requirements:

A. Physical properties in accordance with ASTM D1000 "Standard Test Method for Pressure-Sensitive Adhesive - Coated Tapes Used for Electrical and Electronic Applications."

(i) Tensile Strength (4.7 ± 0.36 kN/m-width)
(ii) Elongation (90% minimum - 130% maximum)
(iii) Stiffness 55 ± 10 mg/25 mm x 25 mm (Tappi T543 test method)

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C.App.C.2 — Wrapping with PVF tape

This tape is used over the black HDPE stay pipe to control temperature variation of the cable stay. Glossy tape is necessary for good heat reflection from the stay pipe surface. The PVF tape once used as the primary means to protect the sheathing from ultraviolet rays has gradually been replaced by the use of co-extruded color PE pipes for new construction.

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(iv) Tear 18 N ASTM D 1004 test method)

B. Adhesion properties in accordance with ASTM D1000

(i) Adhesion to PE pipe
328 ± 22 N/m – width
(ii) Adhesion to steel pipe
As specified by the tape manufacturer and approved by the Engineer
(iii) Adhesion to PVF backing.
660 ± 110 N/m – width

The tape shall retain its properties after prolonged exposure to atmospheric conditions ranging from -1° C to 55° C and strong sunlight. It shall have the capability of withstanding water immersion without disintegration or loss of bond.

Prior to wrapping, PVF tape shall be stored in a suitable place with cool and dry conditions at 24° C ± 3° C at 50% ± 5% relative humidity.

A single wrap of tape with 115 micro-m minimum thickness (total thickness including backing) is mandatory to provide sufficient stiffness for proper wrapping without wrinkles, bubbles or other defects, and to ensure total adhesion to the HDPE surfaces for long-time performance.

Before installation of the tape, the Engineer shall require a demonstration of the tape wrapping operation on a pipe section about 6 m long.

When HDPE pipe is used, wrapping of the stay cable with PVF tape is generally recommended as an additional corrosion preventive measure, and as a means of reducing temperature variations in stay cables unless co-extruded HDPE is used. Stay cables using steel pipe shall be painted to prevent corrosion and to reduce temperature variations. As an alternative to painting, steel pipe may be taped as desired by the Owner where environmental constraints exist.

The Contractor shall demonstrate the cable wrapping process on a 6 m section of pipe before wrapping commences.

Wrapping shall be done in relatively cool, dry ambient conditions to ensure smooth application. To prevent heated pipe from softening the tape as it is wrapped,

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ASTM D 1004 "Standard Test Method for Initial Tear Resistant of Plastic Film and Sheeting"

This high adhesion is necessary to eliminate the need for steel bands at tape splices and to ensure a tight seal against moisture.

PVF tape should not be relied upon to seal splits or cracks in HDPE pipe sheathing. Such areas should not be covered with tape before repairing the damaged sheathing.

The surface preparation of HDPE pipe requires deburring, patching, smoothing and cleaning. Remove grease and dirt from the surface using a cloth soaked in a suitable safe cleaning solvent such as VM & P Naptha and isopropyl alcohol–but use no oily or soapy solution that leaves a film behind.

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the preferred ambient conditions are between 21° C and 27° C–up to a maximum of 29° C, or down to a minimum of 2° C.

Wrapping shall be done in a helical manner from bottom of stay to top, using manual or semiautomatic machinery under moderate tension with a 50 + 10% overlap so as to result in a smooth, wrinkle-free sealed surface. Exposed corners or damaged areas shall be manually overwrapped at "0" pitch.

Splicing rolls of tape together shall be permitted to be done simply by careful overlapping the trailing end of one roll by 51 mm minimum onto the leading end of new roll and continuing the wrapping process. Each splice shall be manually overwrapped at "0" pitch, or shall be permitted to be secured with any other method approved by the Engineer.

Steel bands shall be provided at ends of the stay pipe to ensure a permanent seal overlapping holds down splices adequately, against moisture. Steel bands are not required at interior tape splices.

App.C.3 — Coating for steel pipe

App.C.3.1 — Shop applied prime coat

Surface preparation and the application of the inorganic zinc prime coat shall be made for cable and anchor sockets, bearing plates, all steel pipe, split washers, and shim. Intermediate and finish coats shall be field applied after erection and stressing of the stay cables is complete.

App.C.3.1.1 — Surface preparation

Clean all existing bare steel surface to require complete coating in accordance with SSPC: Society for Protective Coatings as follows:

A. Sandblast steel surface in accordance with SSPC-SP10/NACE No. 2 "Near White Blast Cleaning."

B. Blasted surface shall provide 25 to 50 micro m profile.

Do not prepare more surfaces than can be painted within one 8-hour workday. Surfaces prepared in excess of that which cannot be primed within 8 hours shall be recleaned.

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App.C.3.1.2 — Prime coat preparation

A. Maintain containers used in mixing and application of paint in a clean condition, free of foreign material and residue

B. Stir material before application to produce a mixture of uniform density. Stir as required during application. Do not stir surface film into material. Remove film and if necessary strain material before using.

C. Use only thinner approved by the paint manufacturer and only within recommended limits.

App.C.3.1.3 — Prime coat application

A. Immediately after surface preparation and before surface rust appears, apply one coat of specific prime coat in accordance with manufacturer's instructions and at a rate to provide a uniform dry film thickness specified. The prime coat dry film thickness shall be minimum 75 micro-m but no more than 125 micro-m. Coat with the primer until all surface is fully covered.

B. The primer shall be applied when the surface temperature of the steel is at minimum 10° C and maximum 57° C. The primer shall also be applied when relative humidity is less than 85% and surface temperature is at least 3° C above the dew point. The application shall also be made when ambient temperature is between 10° C and 49° C.

App.C.3.1.4 — Quality inspection for prime coat

The painting inspector shall perform these tests during surface preparation and coating application to ensure compliance with these Recommendations and the coating manufacturer's specifications. These tests will include, but not be limited to:

A. Adhesion will be evaluated with either a tape adhesion test, ASTM D 3359 "Standard Test Methods for Measuring Adhesion by Tape Test"; or pull-off test, ASTM D 4541 "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers." At least three patches per continuous sheathing shall be tested between the primer and substrate. Failure of two of the three patches shall be cause for rejection of the prime coating.

B. Temperature of the environment and structure temperature shall be measured using appropriate thermometers

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C. Relative humidity shall be measured using a sling psychrometer

D. Surface cleanliness standard panels shall be supplied from the National Association of Corrosion Engineers (NACE).

E. Surface profile shall be measured with either a dial gage or surface replication tape.

F. Cleanliness of the blast air by blowing the air into a clean white cloth or blotter for a few minutes and examining the cloth for oil or water.

G. Wet film thickness using a contact gage and dry film thickness using a magnetic dry film thickness. Tests shall be conducted in accordance with SSPC-PA 2, "Measurement of Dry Coating Thickness with Magnetic Gages."

App.C.3.2 — Field applied intermediate and finish coats

Surface of steel pipe shall be painted with epoxy intermediate coat and polyurethane finish coat on the shop applied inorganic zinc rich primer.

All field weld areas and coated surface damaged during handling, erection and construction operations shall be blast cleaned, prepared and field coated with the inorganic zinc primer. No application of intermediate or finish coat shall be made until the qualified corrosion engineer's inspection and acceptance of the prime coat.

A. Surface preparation-Painted surface shall be prepared for the intermediate and finish coats as follows:

Wash intact coated surface with a tri-sodium phosphate and water solution and stiff bristle brushes. Rinse with clean potable water and allow to dry prior to coating application. Do not prepare more surface than can be coated within one 8 hour workday. Surface prepared in excess of that which cannot be coated within one 8-hour period shall be recleaned.

B. Paint mixing-Carefully mix, if necessary, and prepare paint materials in accordance with manufacturer's directions. Stir material before application to produce a mixture of uniform density; stir as required during application. Do not stir surface film into material. Remove film and if necessary, strain material before using. Use only thickness approved by the paint manufacturer and only within recommended limits. Tint each

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undercoat a lighter shade to facilitate identification of each coat where multiple coats of the same material are applied. Tint undercoats to match the color of the finish coat, but provide sufficient differences in shade of undercoats to distinguish each separate coat.

C. Elapsed time between coats-Allow sufficient time between successive coats to permit proper drying. Do not recoat until paint has dried to where it feels filmy, and does not deform or feel sticky under moderate thumb pressure and where application of another coat of paint does not cause lifting or loss of adhesion of the undercoat.

D. Application-The epoxy intermediate coat shall be applied to the zinc primer coat as recommended by the manufacturer in a single application employing multiple spray passes to achieve a dry film thickness of 100-150 micro-m.

The polyurethane finish coat shall be then applied to all of the epoxy intermediate coat applications in a time period ranging from 2 days to 30 days from the time the intermediate coat was applied. The finish coat application time period may be changed at the direction of the corrosion engineer when inclement weather conditions prevail. The finish coat shall be applied as recommended by the manufacturer in a single application employing a multiple spray "pass" to achieve a dry film thickness of 50-75 micro-m.

E. Shelf life and pot life for paints-Materials not in use shall be stored in tightly covered containers in a well ventilated area at a minimum ambient temperature of 7° C. Maintain containers used for storage of paints in a clean condition, free of foreign materials and residue. Paints for which the manufacturer's recommended shelf life has expired shall be discarded. Mixed paint which the paint manufacturer's recommended pot life has expired shall also be discarded.

F. Inspection for coating application-Until the corrosion engineer's inspection and acceptance of the prime or intermediate coat no application of intermediate or finish coat shall be made.

App.C.4 — Portland cement grout

App.C.4.1 — General

Grouting materials and procedures shall be in accordance with PTI M55.1-12, "Specification for Grouting of Post-Tensioned Structures."

APPENDIX D — CONVERSION FACTORS SI TO US UNITS

Basic units		
Quantity	**Unit**	**Symbol**
length	meter	m
mass	kilogram	kg
time	second	s
temperature	Celsius	C
SI prefixes		
Prefix	**Symbol**	**Factor**
mega	M	10^6
kilo	k	10^3
milli	m	10^{-3}
micro	µ	10^{-6}

Conversion factors – SI units to English units			
Quantity	**Multiply**	**By**	**to Obtain**
force	newton (N)	0.2248	lb
mass	kg	0.06848	slug (lb·sec^2/ft)
length	m	3.281	ft
	mm	0.3937	in.
area	mm^2	0.001550	in.^{2}
mass density	kg/m^3	0.001940	slug/ft^3
moment	N·M	0.7376	lb·ft
stress	Pascal (Pa)	0.0001450	lb/in.^{2}
	MPa = N/mm^2	0.1450	kip/in.^{2}
damping	N·s/m	0.005711	lb·sec/in.
velocity	m/s	3.281	ft/sec
	km/hour	0.6215	mile/hour
acceleration	m/sec^2	3.281	ft/sec^2

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The Post-Tensioning Institute

Established in 1976, the Post-Tensioning Institute is recognized as the worldwide authority on post-tensioning. PTI is dedicated to expanding post-tensioning applications through marketing, education, research, teamwork, and code development while advancing the quality, safety, efficiency, profitability, and use of post-tensioning systems.

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