2016 PTI Convention
Long Beach, California

Technical Session 2

Bridge Design and Construction

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32 Years of PTI's Development of Recommendations for Cable Stayed Bridges

by David Goodyear

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Presentation Goals:

- Review progression of Recommendations
- Review basis for some of the origin of provisions
- Recognize the contributions of PTI

"The disadvantage of men not knowing the past is that they do not know the present." (G. K. Chesterton, 1933)

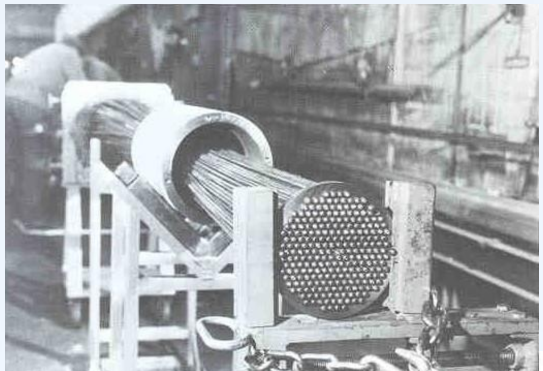
Stay Cable Technology

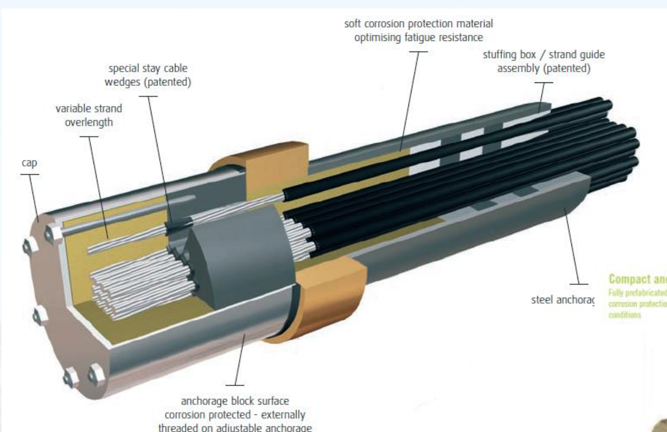
The Unique Aesthetic and Structural Feature…and Economical Feature of our Cable-Stayed Bridges

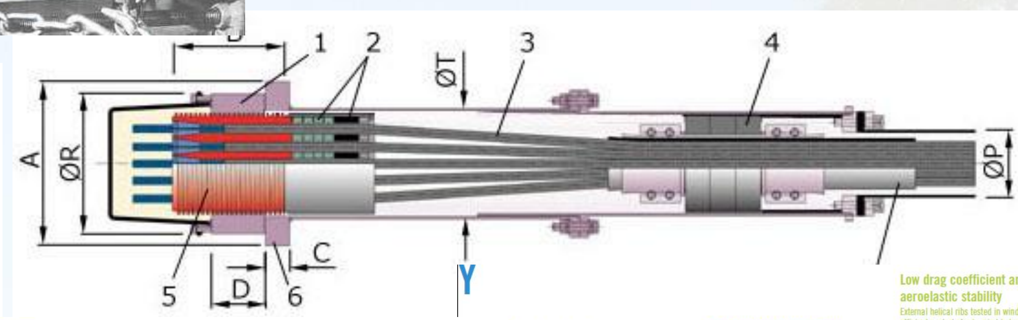
- PTI was the first national/international stay cable standard
- Based on ‘Buy America’ at a time of transition for wire manufacture
- Later fib standard built on PTI with modifications for European practice

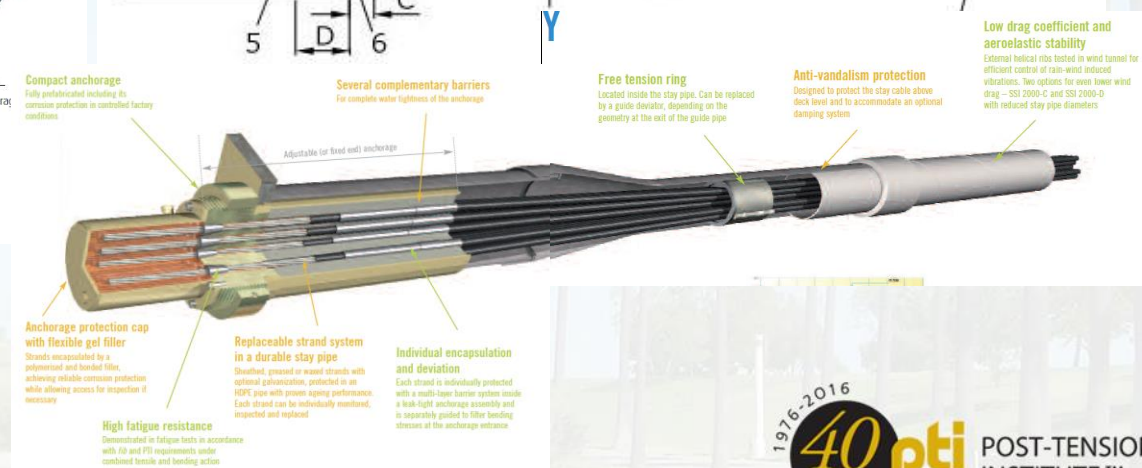
Modern Stay Cable Anchorages

Hi-Am Anchor









Strand Anchors

Stay Cable Spec – Path of Progress

- Pre-1983 Specifications all custom (and different)
- After East Huntington bid (1980), PTI organized a standing committee for stay cables
- Fatigue approach from spec to spec ad-hoc
- Main motivation was the fatigue and residual strength requirement in EH Special Provision – opined to be too restrictive and non-competitive for strand systems

Original Committee

1. **Cliff Freyermuth, PTI - Chair**
2. Professor John Breen, UT at Austin
3. Gerard Fox, HNTB
4. Fred Blanchard, Sverdrup
5. Louis Garrido, LA DOTD
6. John Kulicki, Modjeski and Masters
7. Joeseph LoBuono, LBA
8. Peter Matt, VSL
9. Jean Muller, F+M
10. Jack Oiknine, Prescon
11. Walter Podolny, FHWA
12. Kent Preston, Florida Wire and Cable
13. Wayne Hennenberger, TXDOT
14. David Goodyear for Arvid Grant, AGA
15. Don Schultz, CTL
16. Charles Redfield, TYLI
17. Morris Schupack, Schupack Suarez
18. Khaled Shawwaf, DSI
19. Holger Svensson, LAP
20. David Swanson, VSL
21. Yoshito Tanaka, Shinko Wire
22. Man Chung Tang, DRC
23. Gerd Thielen, Dyckerhoff and Widmann

Professor Breen – Chair of the Fatigue Subcommittee

Suppliers DSI, Prescon, VSL and Freyssinet all engaged

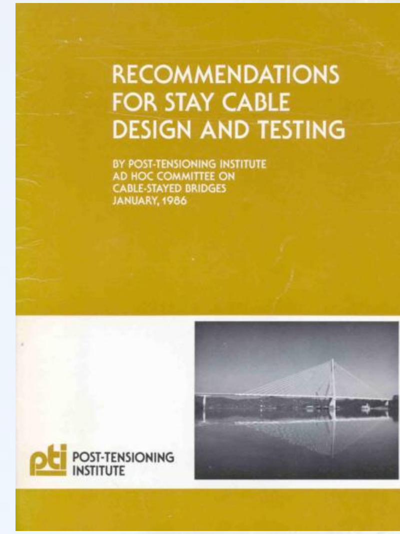
Designers Sverdrup, HNTB, TYLI, M+M, LAP, DRC, AGA, F+M represented designers active in the US

Walter – FHWA – one man, 24 votes

Kent Preston – link to Roebling wire history

MANY COMPETITORS PUT IN THE SAME ROOM WITH A COMMON GOAL – GET CONSENSUS ON A STANDARD SPEC

PTI – 1st Edition '84-'86



- Primary focus on fatigue
- Recommendations in context of AASHTO
- Recognition of stay anchorage as proprietary supplier item
- Established fatigue and strength criteria for anchorage
- Adopted methods specifications for more conventional aspects of supply

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Key Provisions

5.0 DESIGN CRITERIA

5.1 Static loads

For all stay cables the allowable tensile stress shall be:

a) 0.45 f'_s for AASHTO Group I loading.

b) 0.50 f'_s for all other AASHTO Group loadings. (To be used in lieu of AASHTO allowable overstress factors.)

c) 0.56 f'_s during construction or stay cable replacement. (NOTE: f'_s = design value of guaranteed ultimate tensile strength - GUTS.)

- Key Resolutions
  - .45 ult for working stress (Muller dissent)
  - No FOS on fatigue – same reliability approach as AASHTO
  - Wire AASHTO Cat B, glued bars AASHTO Cat D (wire same as EH)
  - 3 fatigue tests for prequalification
  - One pin test (Preston)
  - 95% residual strength (actual)
  - Design for single cable loss

TABLE 10.3.1A — ALLOWABLE FATIGUE STRESS RANGE

Redundant Load Path Structures*				
Allowable Range of Stress, F_{sr} (ksi)[a]				
Category	For 100,000 Cycles	For 500,000 Cycles	For 2,000,000 Cycles	For Over 2,000,000 Cycles
B	45	27.5	18	16
D	27	16	10	7
Nonredundant Load Path Structures				
Allowable Range of Stress, F_{sr} (ksi)[a]				
Category	For 100,000 Cycles	For 500,000 Cycles	For 2,000,000 Cycles	For Over 2,000,000 Cycles
B	27.5	18	16	16
D	16	10	7	5

TABLE 1. SUMMARY OF FATIGUE STRESS RANGE VALUES, F_{sr} (ksi)[a]

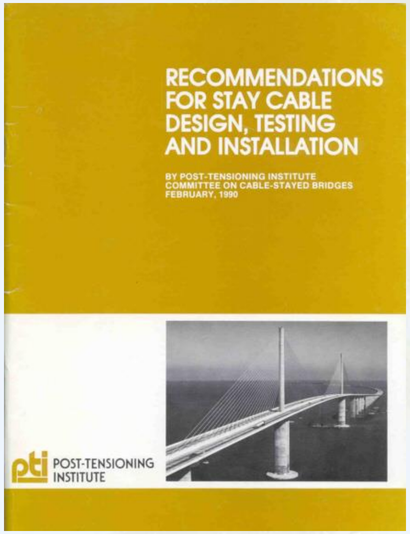
Type of Stay	No. of Cycles (b)	Allowable Design Fatigue Stress Range		Stay Test Fatigue Stress Range (c)*	Component Fatigue Test Stress Range (d)*
		Redundant Load Path	Nonredundant Load Path		
Strand (e) or uncoupled	$2x10^6$ +	16	16		26
bars (f)	$2x10^6$	18	16	23	28
AASHTO	$5x10^5$	27.5	18		37.5
Category B	$1x10^5$	45	27.5		55
Wire (g)	$2x10^6$ +	21	21		41
AASHTO	$2x10^6$	23	21	28	43
Category B	$5x10^5$	32.5	23		52.5
plus 5 ksi	$1x10^5$	50	32.5		70
Bars (f) with (epoxy	$2x10^6$ +	7	5		17
filled)	$2x10^6$	10	7	15	17.5
couplers AASHTO Category D	$5x10^5$	16	10		23.5

(a) Any flexural stress range in excess of 3 ksi shall be added to the axial fatigue stress range due to live load plus impact.

(b) See Table 10.3.2A

(c) To ensure fatigue quality of stays, it is recommended that the stay specimens be tested at $2x10^6$ cycles.

PTI – Second Edition ‘87-’90



- Reacted to challenges of implementation
  - Details of fatigue testing
  - Recognized fatigue testing as a measure of design quality control
  - PVF tape specs+HDPE details
- Increased focus on corrosion
  - Added methods specs for materials and grouting
- Added provisions for Installation and Erection

Key Provisions

3.4.3 PVF tape

The 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 without tearing. The tape shall be self-extinguishing after exposure to flame, and meet the following test requirements:

A. Physical properties in accordance with ASTM D1000.

Tensile Strength 27± 2 lbs/inch-width (.48 kg/mm ± .036)

Elongation 90% minimum

*Stiffness 55 ± 10

*Tear as specified

B. Adhesion properties in accordance with ASTM D1000.

8.2 Handling

8.2.1 Procedures shall be developed to assure that stay cable components will not be damaged during handling. PE pipe sheathing shall be supported (maintained in tension) from the pylon prior to grouting to prevent buckling.

8.2.2 Stay cables shall be protected from corrosives, heat, abrasion and other harmful effects throughout fabrication and installation. Where PE pipe is used for corrosion protection, the PE pipe shall be warmed to a minimum of 70 degrees F prior to coiling or uncoiling pipe material. The reel diameter shall be at least 18 times the outside diameter of the PE pipe.

8.3 Installation

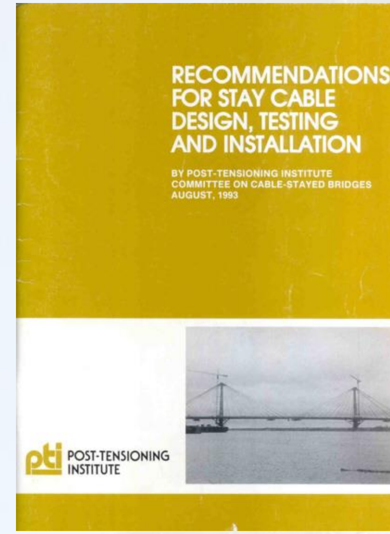
8.3.1 Cables shall be installed in accordance with an engineered cable installation program that prescribes cable force and elongation for the installation of each stay cable. The engineered program shall include consideration of actual construction loads and statical conditions at the time of cable 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.

- Added PVF tape spec
- Added pre-testing condition for stress condition with grout and steel pipe for test (test range on strand)
- Added installation protocols
  - Full unit jacking required-Weirton
- Added QC protocols

PTI – Third Edition ‘90-’93

- Major expansion in coverage of ancillary items
- More focus on corrosion, but retained reference to PT methods
- Introduction of erection to grade (vs. cable force or length)
- Fatigue acceptance lowered from 95% AUTS to 95% of GUTS (Burlington or Quincy?)



Key Provisions

In addition, appropriate polarization testing shall be conducted by an independent corrosion laboratory to determine that the steel strand, wire or bar is not subject to corrosion by the proposed cementitious grout for the service life of the designed cable stay. The tests shall conform to ASTM G5, "Standard Reference Test Methods for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements" or accelerated corrosion test method as developed in the FHWA Research Project, "Grouting Technology for Bonded Tendons in Post-Tensioned Bridge Structures" (FHWA Publication No.FHWA-RD-90-102). The electrochemical corrosion test instrument shall be capable to compensate IR drop for the potential readings and have a high input impedance on the order of 10^{11} to 10^{14} ohm to minimize error during measurements.

Stay cables which fail to meet the 95 percent GUTS criteria in the static test, but provide strength of 90 to 94.99 percent of GUTS in the static test may be accepted at the discretion of the Engineer, provided that the cross sectional area of the stay cable material (wire, strand, or bar) is increased by the ratio:

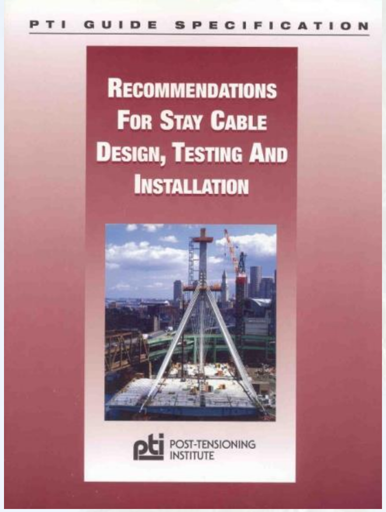
$$\frac{95}{\text{result of static test (\%)}}$$

Corrosion protection of stay cable materials to date has mostly been achieved by grouting the stay cable material inside a steel or polyethylene pipe, with or without additional tape wrapping. Corrosion protection may also be obtained by use of fillers such as grease, wax, tar epoxy, polymer concrete, and polybutadiene polyurethane. Additional corrosion protection may be obtained by use of greased and plastic sheathed tendons[4], epoxy coated strand, or galvanized strand. Galvanized strand shall not be used in direct contact with cement grout.

- Added detail for HDPE pressures, cracking , welding and alternative wraps (Watson alarm)
- Added epoxy strand (filled) with bite-through wedges; first notes on greased and sheathed
- Added corrosion quals for grout
- Added (short-term) bailout for failed fatigue tests
- Prohibited galv strand in contact with grout (short term provision - KapShuiMun)
- Still full jacking, but beginning of Jean-Philippe quest for isotens'g

PTI – Fourth Edition ‘93-2000

- <u>Major revision</u> in format and form – LRFD/Metric, and content
- Added performance criteria for corrosion protection
- Added design provisions for saddle design
- Added cable vibration/wind provisions (Burlington, Baytown, etc)
- Refined 95% fatigue acceptance criteria to > 92% AUTS, 95% GUTS



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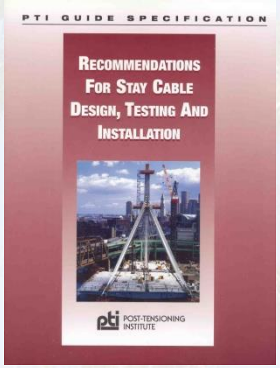
Corrosion Protection – Key to Maintenance



- Abandoned the methods specs, and developed a new performance spec
- Variety of approaches to spec testing criteria explored
- Adopted two stage barrier, with each held to performance standard
- Large-scale leak test of fatigue specimen

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Corrosion Performance Criteria

- 4.1.7 Acceptance Criteria
- 4.1.7.1 Barriers:
- 4.1.7.2 Anchorage Assembly:

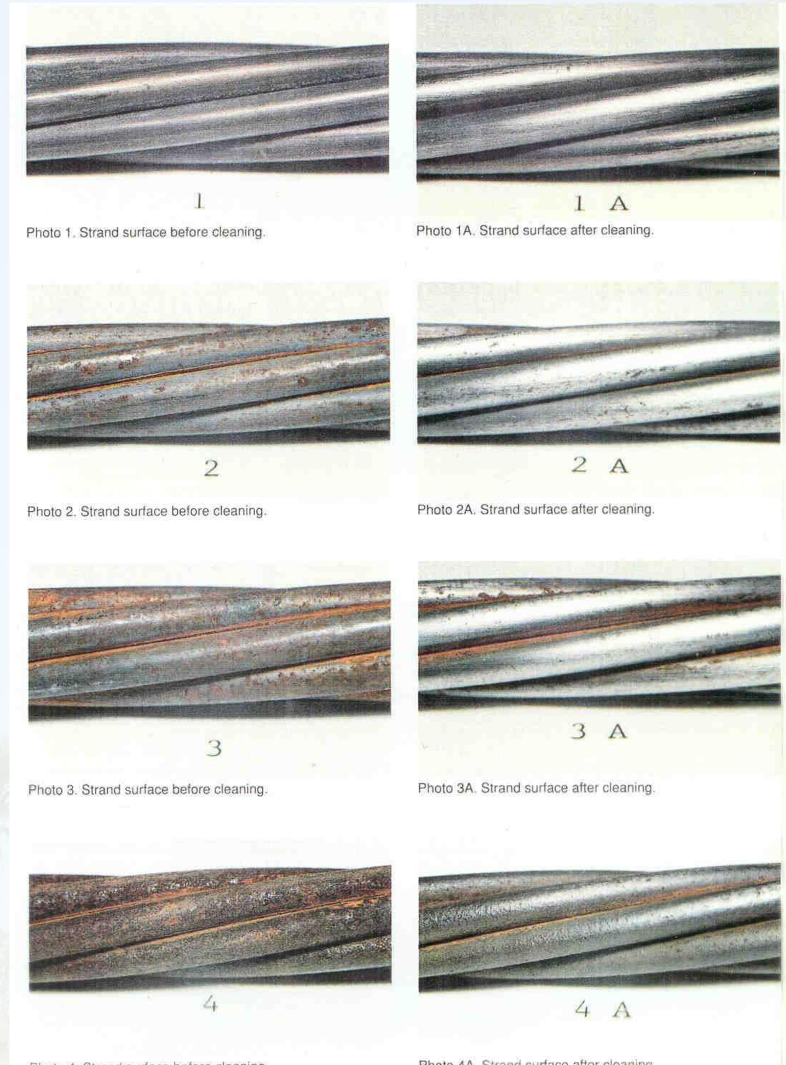
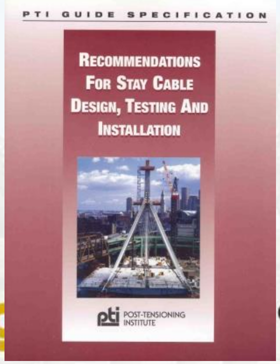


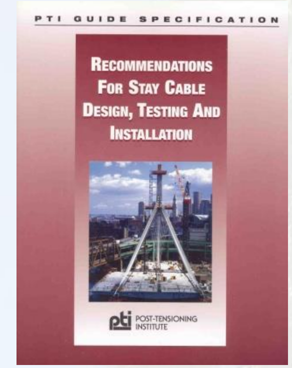
Photo 1. Strand surface before cleaning.
Photo 1A. Strand surface after cleaning.
Photo 2. Strand surface before cleaning.
Photo 2A. Strand surface after cleaning.
Photo 3. Strand surface before cleaning.
Photo 3A. Strand surface after cleaning.
Photo 4. Strand surface before cleaning.
Photo 4A. Strand surface after cleaning.

Saddle Design

- Recognized that saddles are a designer item (C+D testing)
- Established design rules to remove from realm of vendor qualification testing
- Design rules address effect of lateral pressure on fatigue strength
  - Added bending to stress allowable
  - Added criteria for mono-tube or sheath cushioning for lateral pressure
  - LRFD design for components



Cable Vibration Provisions



- Primary focus on rain-wind stability criteria
- Galloping (inclined cables) criteria
- Provisions for stabilizing cables
- Wind studies and monitoring

The following tentative stability criterion for rain-wind induced vibrations of smooth circular cables has been proposed: (16)

$$\frac{m\xi}{\rho D^2} \geq 10 \qquad (5\text{-}1)$$

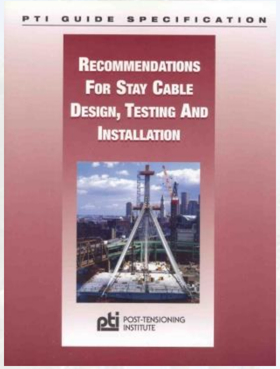
where m is the cable mass per unit length, ξ is the damping ratio-to-critical, ρ is the air density, and D is the cable diameter. The expression $\left(m\xi / \rho D^2\right)$ is

$$U_{crit} = cND\sqrt{\frac{m\xi}{\rho D^2}} \qquad (5\text{-}2)$$

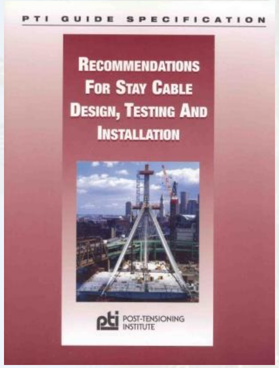
where c is a constant, N is the fundamental natural frequency of the cable, D is the cable diameter, and $\left(m\xi / \rho D^2\right)$ is the mass-damping parameter defined

4th Edition Addenda

- Cable galloping commentary addressed current research
- Clarified cable loss design criteria
- Deleted service limit state
- Stay guide pipe connection design (Baytown)
- Modified inter-stay MTE variation (short cables)



Cable Loss Criteria



- Confusion regarding statical system for analysis
- Address the ‘analysis factor’ – the potential for analysis methods to alter safety index (similar concept to IBC seismic)

5.5 Loss of Cable

Modify the second paragraph as follows “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.”

C.5.5 Loss of Cable

Modify the loss of cable Extreme Load case as follows:

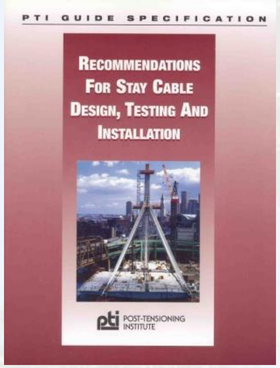
1.1 DC + 1.35 DW + 0.75(LL**+IM) + 1.1 Cable Loss Dynamic Forces

Add the following to the commentary:
“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.

Guide Pipe Connection Design

- Limited examples of pipe failure
- Assembly tolerance on a few projects raised concern over force demand and durability
- Not addressed in parent LRFD criteria – stay cable specific



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% 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 "Guide Pipe" is defined as 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.

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 0.4 degrees of the planned pipe alignment.

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

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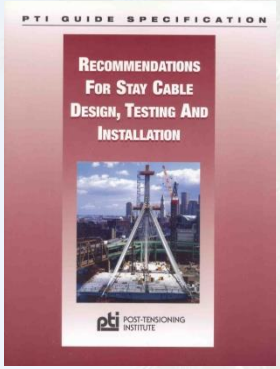
MTE Variation



- Origins of old criteria in monostrand stressing without computation or control (Jean-Phillip prevailed)
- Modern systems warranted new criteria
- Tolerance of measurement on the order of old criteria – effect varies with length
- Practical considerations – variation itself not significant

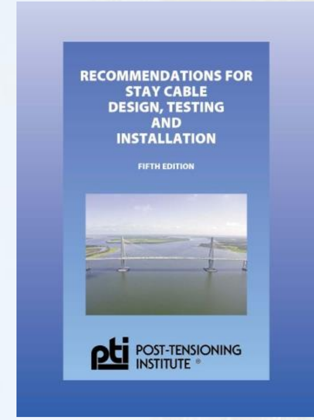
6.9.4 Stressing

Modify the provision as follows:

"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."

Modification of 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 gage length of the cable.

PTI – 5th Edition



New Topics and Criteria

- Bending fatigue
- Updated Materials
- Extrados Criteria
- High seismic testing
- Updated Wind Criteria

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PTI 5th Edition – Bending Fatigue

Tolerance on fabrication and erection can effect service condition of stay. Parametric vibrations, live load movement and wind vibrations of stay all have a bending component.

<u>Revisions</u>:

1. Add imposed anchorage angle for fatigue test
2. Add lateral force design requirements at dampers

5th Edition – Extrados Design Criteria

Extrados bridges appear as a subset of cable-stayed bridges, using much of the same hardware and technology. Yet, depending upon the design parameters, stay demands can differ.

Revisions:

1. Define threshold(s) of behavior to distinguish a full cable-stayed bridge from an extrados bridge.
2. Define exemptions to or modification of stay criteria for extrados category.

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5th Edition – High Seismic Criteria

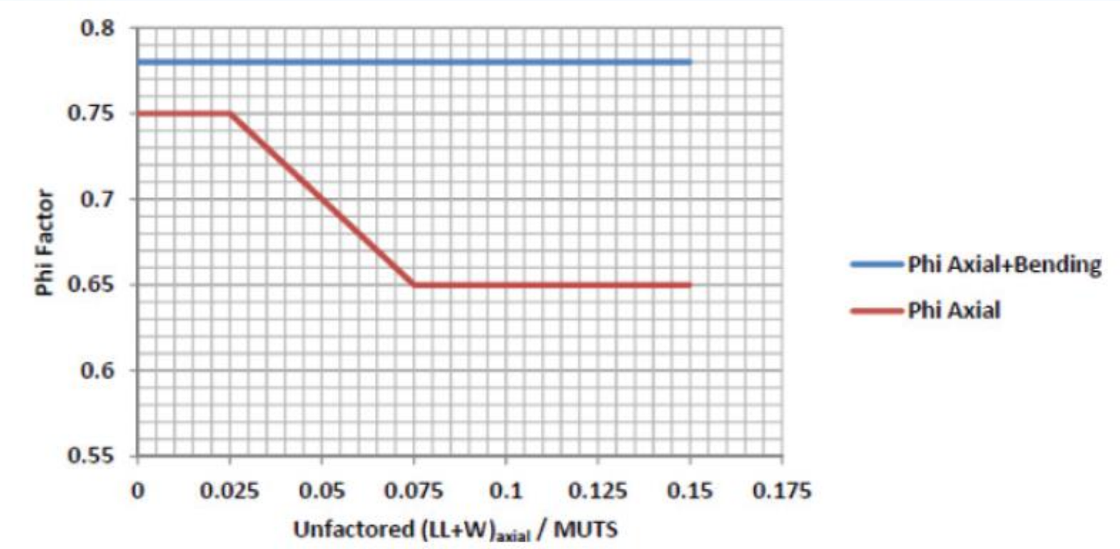
Stay anchorage design is based on performance testing. The current testing range is based on a minimum tensile load on the anchorage (nominal dead load).

Revisions:

1. Identify force threshold where standard testing conditions do not apply.
2. Identify basis for supplemental testing requirements when minimum anchor tension is not met.

6^{th} Edition

- New provisions for fire rating (WIP)
- Update of material provisions/fib coordination
- New provisions for phi-factor / extradosed bridge design rules (Jean Muller was right)



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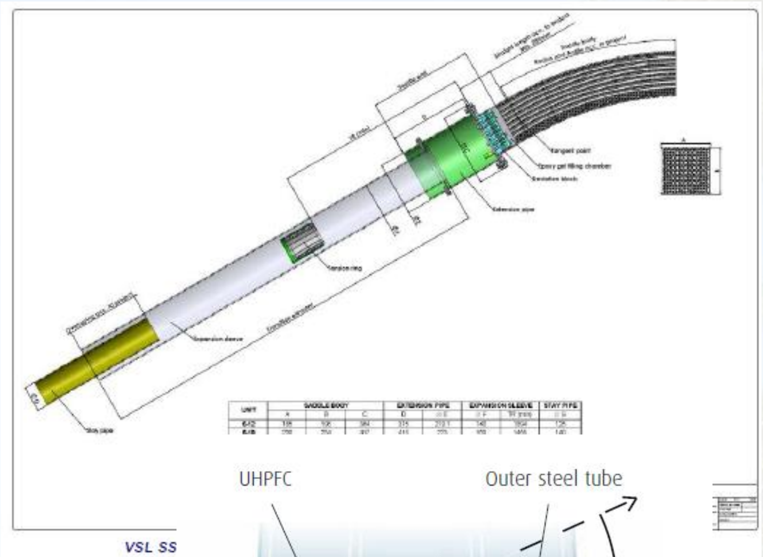
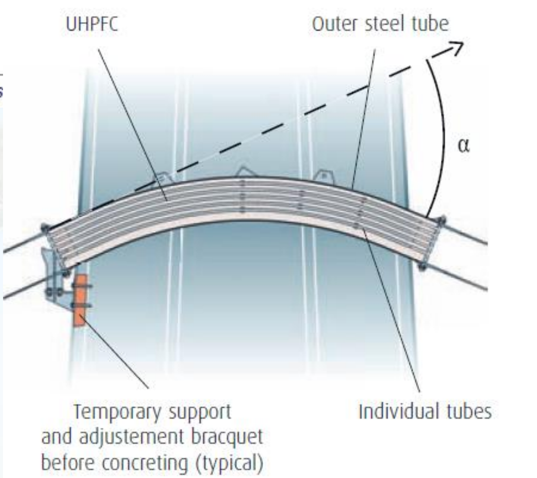
New Vendor Saddles

- 6th ed retains designer responsibility for saddles
- Vendors now offer solutions, but use of solutions still constrains tower design and geometrics
- 7th ed will see return to performance testing for saddles by vendor; newer fire provisions, new load factors for post-construction check on cables





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State of the Art




- As with most ‘specifications’, PTI development has been event driven
- The founding engineering principles have generally remained in tact
- The commercial inputs have wavered
- The state of the art owes much to the investment and developments of competing suppliers
- With exception of the buy America, the commercial offerings today are quite mature and reliable, thanks in part to the initiative of PTI to set the first standards for the design and construction industry.




Thank You!

Questions ?

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