Experience, Developments and Trends for Improved Durability of Stay Cables

Expériences, développements et tendances pour améliorer la durabilité des haubans

Schrägseilkabel: Praxis, Entwicklungen und Trends für verbesserte Dauerhaftigkeit

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SUMMARY

While fatigue performance is a primary consideration, corrosion protection of a stay cable is also of fundamental importance in assessing the long term performance. This paper reviews the past performance, new developments and trends for various types of stay cables and their constituent components. This paper also introduces a new type of stay cable in which a complete high quality protection system is provided through well developed details.

RÉSUMÉ

Bien que la résistance à la fatigue est une première considération, la protection contre la corrosion d'un hauban a aussi une importance fondamentale pour l'évaluation de la performance à long terme. Cet article met en évidence les performances antérieures, les nouveaux développements et tendances de plusieurs types de haubans et de leurs composants. Il présente aussi un nouveau type de hauban pour lequel un nouveau système de protection de haute qualité est analysé au travers de ses détails.

ZUSAMMENFASSUNG

Ermüdungsfestigkeit ist die Hauptanforderung für Schrägseile. Aber auch der Korrosionsschutz ist von fundamentaler Wichtigkeit, besonders für die Abschätzung des Langzeitverhaltens. Der Aufsatz beschreibt bisherige Erfahrungen, neue Entwicklungen und Trends für verschiedene Arten von Schrägkabeln und deren Hauptkomponenten. Es wird aber auch ein neuer Schrägseiltyp vorgestellt, welcher sich durch ein hochwertiges Schutzsystem und durch gut durchdachte Detaillösungen auszeichnet.

1. INTRODUCTION

For reasons of economy and aesthetic appeal, Cable Stayed Bridges continue to constitute a successful and important form of structure. The primary structural element, the stay cable, in its current state is a result of continual development, not in part due to the desire to improve overall corrosion protection and durability. In the first section of the paper below, major stay cable types are analyzed from a corrosion protection viewpoint. Failures and successes are presented. In the latter part of this paper, the trends in corrosion protection development, the "Multiple-Barrier" and the "Inspectability Approach" are discussed. Finally, a new stay cable type, the SSI Monostrand, is presented.

2. REVIEW OF CURRENT STAY CABLE TYPES

The various types of stay cables available fall into three main categories: locked coil, parallel wire and parallel strand. All employ high tensile steel as the essential load carrying member. These systems differentiate themselves in the manner of anchorage, free length arrangement and approach to corrosion protection. These details are largely interrelated, and to some extent determine the way in which the cables must or can be fabricated and installed on site. In the section below these cable types are reviewed for general performance, particularly with an emphasis on the durability that the particular system offers.

2.1 Helical and Locked Coil Cables:

These are built-up from round, trapezoidal and Z-shaped cold drawn high strength wires (f_{ptk}= 1470 Mpa, E_S = 170.0 GPa). The arrangement of varying shapes of wire result in very compact cables, this has some advantages, but also results in a stiff cable which approaches the behavior of a solid section from a flexural view point. The anchorage of a locked coil cable is normally a socket formed from a molten metal into which the cable is cast, adjustability being provided with ring nuts, etc. If cable vibrations and displacement are not isolated from the anchorage by dampers, high bending stresses are present with associated fatigue.

Corrosion protection of locked coil cables originally consisted of the bare wires packed with red lead during fabrication, with surface coatings of red lead and a finishing coat. With this treatment there were notable corrosion failures (wire fractures). Lack of access for surface inspectability and maintenance, poor or missing moisture seals at the anchorages and scorching of the internal cable corrosion protection adjacent to the anchorage (during casting of the socket) contributed. In a number of cases, corrosion was exacerbated by fatigue (stress corrosion), particularly adjacent to the anchorage [2,3].

Recent improvements in locked coil corrosion protection and detailing include using hot dip galvanized wires, replacing environmentally unacceptable red lead, with zinc dust-rich polyurethane, or aluminum-rich phenolformaldehyde resin, and using zinc chromates and iron-rich polyurethane outer coatings. The sensitive socket zone detailing is now given total isolation from moisture and contamination, and the socket heat scorched zone is typically injected with corrosion inhibiting compounds. Other future improvements may include different metallic coatings and fillers, wider use of Polyethylene (PE) pipe and stainless steel casings. This corrosion protection approach, along with the physical composition of these cables, makes visual inspection of the whole cable impossible. Although non-destructive scanning can be used on the cable proper, this proves difficult in the most sensitive zone around the anchorage.

2.2 Parallel Wire Cables

These compact bundles of parallel 7 mm prestressing wires (f_{ptk}= 1670 MPa, E= 205.0 GPa), are normally anchored using a combination of bearing plate and a socket filled with cold-cast materials such as a zinc enriched resin with steel ball bearings. Corrosion protection generally consists of bare or galvanized wires within a PE pipe or extruded PE sheath with a cementitious grout (not combined with galvanized wire), polymer grout or wax/grease type compounds. No major corrosion problems have been reported with these cable types; problems being limited to protective sheaths. Fatigue strength for small cables is excellent, however, for larger size parallel wire cables, there is a poorer fatigue performance particularly in the zone directly adjacent to the socket [6]. Due to the anchorage type, these stay cables require expensive prefabrication onto reels for transportation, and heavier more sophisticated installation equipment. Their composition does not permit direct visual inspection.

2.3 Parallel Strand Cables

These bundles of 15 mm strand, (f_{ptk} = 1770-1860 MPa, E_s= 195.0 GPa) are normally anchored using wedges, with one proprietary system relying on a bonded socket. Corrosion protection varies widely from bare strands and cement grout within a PE or steel sheath, to more sophisticated robust multiple-barrier systems. No major remedial work has been necessitated by corrosion of the steel on these cable types also, damage being limited to protective sheaths. Fatigue for large tendons is normally good with a similar performance level to large parallel wire systems ($\Delta\sigma$= 200 MPa, 2.0 x 10^6 cycles, upper stress = 0.45 f_{pkt}). Parallel strand systems permit greater flexibility in fabrication and installation, from total prefabrication to strand-by-strand installation, with or without a stay sheath and grout. Depending on the cable configuration, various levels of direct visual inspection are possible.

2.4 Cable Sheaths

These can serve a dual purpose, first as the outermost corrosion protection barrier, and second as a tube form for grouting where grout is used.

- Polyethylene Stay Pipes: Dosed with 2% carbon-black have an excellent resistance to UV radiation. Tests on samples taken from existing bridges as well as other weather resistance tests indicate that PE pipes do not deteriorate under exposure [2]. Some problems have been recorded during grouting of PE stay cables (longitudinal cracks). This can be controlled by limiting the PE pipe strain during grouting (up to 2%) and minimizing PE sheath temperatures [1,4]. PE pipe butt weld failures have also taught us to require full strength butt welds and to minimize stay pipe restraints during coiling. Based on past performances, PE pipes will continue to provide an efficient outer corrosion barrier. It is likely that colored PE pipes will become more widely used, however, current reluctance by manufacturers to guarantee the life of this product delays acceptance. Until that time, to improve aesthetics as well as reduce stay cable temperatures, adhesive Tedlar tape, strengthened with glass-reinforced polyester fiber will continue to be used to wrap the PE pipe. This has a life expectancy of 25 years or more [2].
- Steel Stay Pipes: Their use is not as common as PE and potentially more problematic. Black steel stay pipes require fully tested, butt welded connections and suitable corrosion protection for the exposed surface to minimize corrosion and fatigue failures at the pipe connection welds. If welds crack, they are impossible to re-weld due to the proximity to the strands within the pipe [1,4].

2.5 Cement and Polymer Grouts, Greases and Wax Fillers

- Cement Grouts: These have been widely used to date. Stay cable grout must contain no harmful chemicals, have good fluidity ensuring thorough penetration, and minimum shrinkage and bleeding. Admixtures are essential to improve grout properties. It is generally accepted and confirmed by examination of existing bridge stays that total encapsulation in an alkaline grout environment effectively passivates bare strand [2], however, the reliability of a particular grout mix for corrosion protection should be confirmed in a suitability/compatibility test before approval for use. It is also known that grout cracks under dynamic loading, leaving pathways for aggressive chemicals should penetration of the stay pipe occur. Fretting corrosion of the strand is also a possibility adjacent to the crack. Recent test results have confirmed this problem for bare and epoxy coated strand [7,8]. In view of these concerns and observations, the use of grout has been questioned for reliability as a corrosion inhibiting layer in a stay cable.
- Polymer Grout: Flexible, crack-free polymer cement grouts are extremely effective and do not shrink or bleed. They have had limited use in Europe and Japan; high cost preventing wide spread use. A crack-free polybutadine polyurethane "grout" has been successfully used in Japan. It is a highly flexible, low-weight, two-part polymer with low viscosity allowing excellent penetration [6]. However, this "grout" is also very costly and overly sensitive to work procedures [1].
- Petroleum waxes and greases: Used on certain parallel wire and strand cables. These compounds are injected in a liquid state (85° - 105°C) and at ambient temperatures they solidify with a micro-crystalline

structure. They are hydrophobic and exhibit high adhesive properties making them effective moisture barriers although not truly corrosion inhibiting. Tests carried out on various greases and waxes suggest, however, that wax type compounds can crack on cooling below their solidification point due to differential internal stresses [5]. These cracks do not close upon return to ambient temperatures. Specially formalized softer thixotropic grease type compounds with constant viscosity over a large range of temperatures are preferable, however, expansion under elevated temperatures must be checked to avoid overstressing of the sheathing.

2.6 Coated Strands

Temporary corrosion protection for bare strand before the grouting of stay cables is frequently a vapor-phase inhibitor (VPI). A disadvantage of this approach is the possibility of strand corrosion damage prior to and after strand installation due to loss of VPI coating. Because of this, and the general trend to multiple barrier systems, a number of coated strand types are now commonly used.

- Monostrands: A PE sheath (minimum of 1.0 mm) with grease filling all strand interstices provides a robust two-layer system for temporary and final permanent corrosion protection.
- Galvanized Strand: High quality fatigue rated galvanized strand is available in Europe and Japan. All individual wires are hot dip zinc coated and redrawn prior to stranding. The tensile strength (f_{ptk}) is higher than bare strand to compensate for loss of steel tensile area caused by the zinc thickness. Galvanized strand provides a robust mechanical and cathodic protection to the steel (temporary, sacrificial protection). They should not, however, be used with cement grout due to potential hydrogen enbrittlement problems.
- Epoxy Coated: As with the monostrand, this product is intended to provide both temporary and permanent corrosion protection. Although it is reported to be suitable for applications in which fatigue resistance is important [9], recent axial fatigue test results on full size stay specimens using non-intersticially epoxy coated strand, showed a number of disturbing observations, including significant interstitial strand corrosion and the possible non-ductile failure mode of several strands (all wires failing at a single location) [8].

3. TRENDS IN STAY CABLES CORROSION PROTECTION

The above review of stay cables defined what has been successful. Combining these winning components into a successful corrosion protection system requires careful detailing. The cement grouted bare strand and external pipe stay cable is a fairly basic solution. Essentially, it offers no more than one guaranteed corrosion barrier (grout may be unreliable once the sheath is compromised) and is very difficult to inspect non-destructively. From this perspective, the current trends in stay cable development can be described as:

- "The Multiple Barrier System": Here more than one robust material barrier forms a multi-layered defense system against corrosive attack. With this approach, reliability and therefore life expectancy, is increased with each effective barrier. Part of the Multiple-barrier System is normally a temporary corrosion protection barrier. In combination with the outer stay pipe, and grout if employed, robust and reliable, three, four and even five barrier systems are possible. Disadvantages of this approach are: a) each barrier makes direct inspection of the stay cable more difficult, and b) full or partial prefabrication is necessary, requiring expensive transportation and sophisticated heavy installation equipment.
- "The Inspectability Approach": Provides easier access for visual inspection of the cables. These cables are often a bundle of strands without an external stay pipe or grouting. The strands may be galvanized and coated with a layer of epoxy tar and plastic sheathing. Where defects are observed, the defective strands may be replaced. This approach lends itself to light erection methods. Disadvantages of the Inspectable Approach include: a) mechanical protection, fire resistance and durability are reduced, b) visual inspection of any but the outermost strands is difficult, and c) inspection of the anchorage zones is difficult.

Both approaches have advantages and disadvantages, however, due to their mutually exclusive nature. Current development of stay cable protection systems tends to choose one method or the other.

4. AN INSPECTABLE MULTIPLE-BARRIER STAY CABLE

4.1 The SSI-Monostrand Stay Cable System

Despite the conclusions on the direction of stay cable development stated above, VSL has recently developed the SSI-Monostrand Stay Cable System, which actually combines the features of both the Multiple Barrier System and the Inspectability Approach without any of the major disadvantages of each method independently. The main features of this stay cable are as follows:

- A Multiple-barrier system with excellent temporary protection and a minimum of three effective corrosion protection layers;
- Stay cables for which site installation is simple;
- A stay cable in which individual strands may easily be visually inspected, adjusted, and replaced at any time.

With this system using independent monstrands, flexural stresses due to cable vibrations and applied displacements are at least one order of magnitude smaller-at the anchorages-than those for locked coil and bonded strand cables. This is a consequence of a combination of the individual strands, not the composite stay diameter, contributing to the overall stay cable stiffness.

In the development of this system using monostrands, numerous tests have been performed including corrosion protection materials, tests on cable anchorages and strand removability tests. Full-scale fatigue testing on entire cable specimens have also been carried out for cable sizes of 32, 55, and 61 No. 15.7 mm strands. These have demonstrated excellent fatigue characteristics of the system.

A monostrand system has been employed on both the Kemijoki River Bridge, Finland and the Polcevera Bridge, Italy, and is currently planned for incorporation as the SSI Monostrand System in three new projects: the Safti Bridge, Singapore, the River Leven Bridge, Scotland, and the Batam Tonton Bridge, Indonesia.

4.2 Multiple Barrier System

The multiple barriers of the SSI Monostrand System comprise the following:

- Outer PE Stay Pipe — Corrosion Barrier 1
- Monostrand PE sheath — Corrosion Barrier 2
- Grease coat to strand — Corrosion Barrier 3
- Optional galvanizing — Corrosion Barrier 4

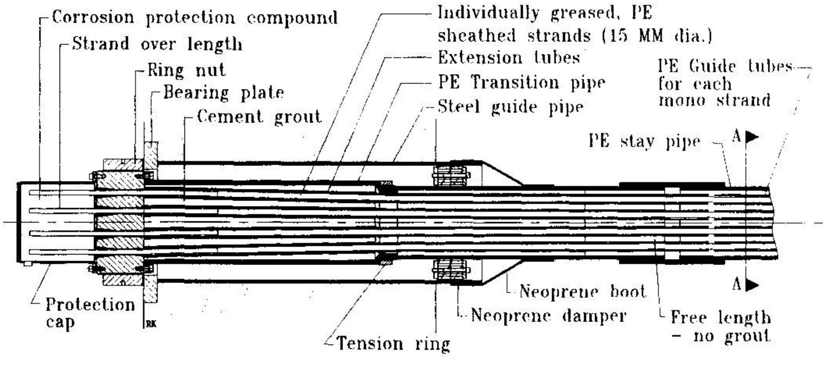

Figure 1: SSI Monostrand Anchorage

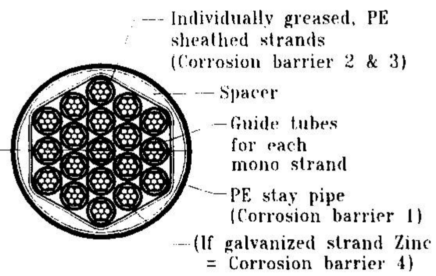

Figure 2: Section - SSI Stay Cable

4.3 Stay Cable Installation

The stay cables are erected in the following manner:

- The anchorages and transition pipes are prefabricated as is the PE stay pipe, including the parallel PE guide tube bundle within.

- This partially assembled, but lightweight, stay cable shell is hoisted and secured in position.
- Strands are installed one by one, up or down the dedicated PE guide tubes within the stay pipe.
- The stay cable is stressed, using a monostrand and/or a multistrand jack; then, the anchorages are sealed.

This installation method does not require heavy hoisting equipment and there is no grouting of the stay free length, a major benefit to the overall bridge programme.

4.4 Stay Cable Surveillance and Replacement

This stay cable, using independent non-grouted monostrands, would form part of a regular surveillance and maintenance program for a bridge structure.

- Individual strands can be retracted, inspected, and tested when required. This allows direct confirmation of the well-being of the tensile element, and will identify and locate problems for attention, if necessary.
- Any monostrand, or the entire cable unit, can be monitored for load, and adjusted at any stage in the life of the structure.
- The removal of any monostrand is possible for direct visual examination or replacement. This is achieved by releasing the monostrand load and simply pulling the strand out. During this process, a replacement strand can be pulled in at the same time.

5. CONCLUSION

In their present form, stay cables have reached a high level of development. Although there is an ambiguity between reliability of protection and inspectability of stay cables, the adoption of new systems will provide a reliable temporary corrosion protection during construction, better overall resistance against corrosion and potentially easier surveillance. It is quite apparent that there is a lack of available project information on what level of corrosion protection is required to ensure sufficient durability. It would be in the interest of all parties involved in cable stayed bridge construction to collect more data on the performance of stay cables in existing structures. This will allow the drafting of proper and effective performance specifications for use in future projects.

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