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Current Corrosion Protection Methods for Cable Stays

Méthodes actuelles de protection contre la corrosion des câbles

Aktuelle Korrosionsschutzmethoden für Schrägseile

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SUMMARY

In the last decade there has been increasing concern as to the vulnerability of cable stays to corrosion damage, especially in harsh environments. As is evidenced in this paper, corrosion protection systems have been evolving and will continue to do so. Research and ingenuity have produced increasingly more efficient corrosion protection systems. This paper attempts to present and document in an orderly fashion the developments that have occurred and are occurring and to project, to a limited degree, possible future developments.

RÉSUMÉ

Au cours des dix dernières années, la tendance à la corrosion des câbles de ponts suspendus et à haubans, en particulier dans les climats rudes, est devenue très inquiétante. Comme le montre ce rapport, les moyens de protection contre la corrosion évoluent sans cesse. Ce rapport présente et documente méthodiquement les améliorations déjà mises en oeuvre, et celles en cours de développement; il indique aussi certaines des futures améliorations possibles.

ZUSAMMENFASSUNG

Im Verlauf der letzten zehn Jahre hat man sich über die Anfälligkeit von Schrägseilen gegen Korrosionsschäden, besonders bei rauhen Umweltverhältnissen, zunehmend Gedanken gemacht. Wie aus dieser Abhandlung hervorgeht, haben sich Korrosionsschutzsysteme einer Entwicklung unterzogen und werden sich auch künftig weiterentwickeln. Forschungsarbeit und Erfindungsgabe haben dazu beigetragen, dass Korrosionsschutzsysteme in zunehmendem Masse effizienter werden. Ziel dieser Abhandlung ist die Darstellung und der ordnungsgemässe dokumentarische Nachweis der bisherigen und gegenwärtigen Entwicklung sowie der Vorausblick auf mögliche künftige Entwicklungen.

1. INTRODUCTION

One of the biggest potential problems for cable stayed bridges is that of possible corrosion of the stay cable. A widely published report [1] concerning extensive corrosion of cable stays created considerable consternation among the bridge design community. Although this report was hotly and emotionally debated, perhaps its overriding and redeeming attribute is that it brought into the forefront the problem of corrosion protection of cable stays and may have provided the impetus for subsequent developments. This is not to say that the problem was not known or of concern to those engaged in the design of cable-stayed bridges.

2. REQUIREMENTS OF A CORROSION PROTECTION SYSTEM

General requirements for a protective system are as follows:

- no adverse effect on the strength and/or ductility of the steel cable.
- compatible with regard to physical and chemical characteristics, especially for multiple barrier systems.
- resistant to those influences that might be present during shipping, installation and service. These influences may be of different character, e.g., mechanical (impact, abrasion); thermal (solar energy, fire, freezing); ultra violet radiation; vandalism.
- durable for the expected service life or replaceable without jeopardizing the stability and durability of the stay and/or structure.
- no adverse effect on the environment.
- practical and easy to install.
- economical to construct and maintain.

Corrosion protection systems may be either two-phase or single-phase. In the two-phase method the permanent corrosion protection is applied as the last operation of construction of the structure. This means that a temporary corrosion protection is required during a construction period that may be two to four years or longer in duration. The effectiveness of most temporary corrosion protection methods is short lived. If replenishment is overlooked or not accomplished, for whatever reason, there is a distinct risk of corrosion occurring before the permanent corrosion protection can be applied and the risk of having to replace the cable. There is currently a trend to a single-phase corrosion protection system that provides both the temporary and permanent system simultaneously, i.e., a system that provides protection from manufacture of the cable throughout its service life.

3. ZINC COATED SYSTEM

Cable stays of most early cable-stayed bridges consisted of zinc coated or galvanized locked-coil strand, e.g., the Lake Maracaibo Bridge in Venezuela (constructed in 1962). In many cases, these strands also had a paint coating. Zinc is a sacrificial coating, i.e., it is consumable with time in an aggressive environment. In the harsh environment of Lake Maracaibo the galvanized locked-coil strands had to be replaced in 1980 after 18 years of service and currently, the replacement strands are being threatened once again by corrosion [2].

In the case of galvanized wire or strand encapsulated in grout the zinc coating may react with some cements releasing hydrogen gas. This reaction is apparently dependent upon the cement alkalies, type of steel and the composition of the zinc coating. When galvanized strand is embedded in cementitious grout, the corrosion rate of zinc itself is accelerated [3]. As a result, zinc as an anode or sacrificial metal coating is not the same as in atmospheric conditions.

4. SHEATHED AND INJECTED STAY SYSTEMS

4.1 Cable Stay Sheathing

The purpose of the stay sheathing is twofold: to provide a form for the injected cement grout and as an anti-corrosion barrier for the stay cables. Two types of sheathing have been used: a high-density polyethylene (HDPE) and steel pipe.

During the period from 1961 to 1988, 53 cable-stayed bridges were constructed with HDPE stay sheathing. Of these, only two developed longitudinal cracking in the HDPE pipe, which was attributed to overstressing during grouting operations [4]. The cause of this distress is known and accounted for in current criteria [5]. In both cases the damaged HDPE pipes were successfully repaired.

Typically, lengths of steel pipe sheathing are butt welded together on the project site. Of six bridges with steel pipe sheathing, known to the author, one developed corrosion at the butt welded joints. If stress corrosion cracking were to occur and propagate, there is no known practical retrofit procedure short of dismantling and replacing the stay(s). Because of the close proximity of the strands, attempting to weld the cracks would risk adversely affecting the metallurgy of the wires.

4.2 Cementitious Grout

Cementitious grout with its alkaline properties provides an active corrosion protection to the prestressing steel. However, recent autopsies of grouted cable stay fatigue test specimens confirm that under cyclic loading the grout cracks. The cracks occur in the grout every 25 to 50 mm. The significance of this is that should the sheathing be compromised by a propagating crack emanating from a defective butt-weld in a steel sheathing or a crack resulting from circumferential overstrain in a HDPE sheathing, a direct path is available for aggressive corrosive agents to the prestressing steel. Further, there is the potential for fretting corrosion to occur because of the presence of a crack in the grout.

4.3 Alternatives to Cementitious Grout for Cable Stays

Alternatives to cementitious grout have been sought, considered and used for cable stays to overcome the above faults of a sheathed and injected stay system.

A polymer cement grout has been used in Japan to achieve a crack resistant grout under design load for cable stays. The injection method is the same as that used for normal cement grout. Advantages of this material are that it is 20 times more ductile in elongation than normal portland cement grout, does not shrink, does not bleed during curing, offers high resistance to cracking under dynamic loading, no special techniques or equipment are required for grouting, and it can be used in combination with galvanized wire without a concern for chemical reaction between the zinc and cement. Disadvantages are that the material cost is relatively expensive, and the viscosity and hardening are temperature dependent.

A polybutadiene polyurethane has also been used in Japan to produce a crack free grout. It is a two component material with proportions of liquid A to liquid B of 2.5 to 1.0, where liquid A is a polybutadiene polyurethane polyol resin and liquid B is a isocyanate hardener. This material has a very low viscosity and easily penetrates the interstices of the strand. When hardened, it is very flexible and has a very high ultimate elongation of 280%. Specific gravity is one-half that of cement grout. Disadvantages are that it is relatively expensive in material and execution costs, delicate to handle, highly temperature dependent, and flammable.

Another alternative to cement grout is petroleum wax enriched with corrosion inhibiting additives. However, research conducted for the Kemijoki River Bridge at the arctic circle in Rovaniemi, Finland, indicated a general unsuitability of "wax-like" injected materials [6]. The term "wax-like" refers to materials that must be heated and melted for injection and which solidify upon cooling. As a general rule, these materials have a melting and solidification temperature of approximately 60 to 85°C. During the cooling process the material shrinks and upon reaching the solidification point, and lower temperatures, the shrinkage is restrained. Internal stresses, bond stresses with respect to the strand and other components and possible cavities can occur. A further complication is that solidification is not uniform through the thickness, the surfaces tend to solidify first with respect to the interior. At or near the solidification point the material can accept these stresses, at a further lowering of the temperature the stresses developed cannot be accommodated and cracks develop at the surfaces to be protected. Once cracks and cavities develop, the stresses are relieved, and the process is not reversible and the corrosion protection is lost. A cold injected soft material has been developed which also shrinks, but is capable of remaining adhering to the surrounding surfaces with cavities occurring in the interior of the material which are self-healing upon returning to a normal ambient temperature. The substance is reported [6] to be thixotropic, have an approximate constant viscosity over a wide temperature range and remain pumpable down to a temperature of -18°C.

5. MULTIPLE BARRIER CABLE STAYS

The use of alternative materials for cementitious grout attempts to overcome the problem of grout cracking and thus obviate the potential of a direct path for the corrosive agents to the steel in the event the outside sheathing is compromised. However, the use of alternative materials for cementitious grout does not overcome the problem related to temporary corrosion protection of the steel strands.

To overcome the potential problems of a sheathed and grouted system, multiple barrier systems have been developed. The concept simply provides multiple corrosion barriers such that one or more materials take over the protective function for a material that has failed, or stated another way, provides increased redundancy in the corrosion protection system.

Generally, these additional barriers are provided by one of the following two methods:

- Individual greased and sheathed strands (the so-called monostrand method). It should be noted that the word grease as used in this context is generic, the material may be grease, wax, epoxy-tar or some other appropriate material.
- A coating applied directly to the strand such as galvanizing, epoxy, or a ceramic material (as used in the automotive industry for brake cables).

Both of the above systems are installed or applied prior to shipment, thus, they are not only incorporated into the final total corrosion protection system, but also provide the temporary corrosion protection during shipping, storage, after installation until the final grouting operation, and during service life.

5.1 Monostrand Systems

The so-called monostrand system as used for cable stays is a adaptation or transfer of technology of the monostrands that are used for parking garage or flat slab construction. The stay consists of a parallel bundle of 15 mm diameter unbonded prestressing strands that are individually greased and sheathed, enclosed in a HDPE pipe and grouted. The corrosion protection of unbonded prestressing strand relies to a large extent on the prevention of moisture and corrosive materials from reaching the steel. Therefore, the sheathing on the individual strands must be completely watertight throughout its length, up to and including the anchorages.

A recent innovation from conventionally sheathed strands is the application of a corrosion inhibiting material directly to each of the seven individual wires of each strand and extruding a HDPE jacket over each strand. During the application of the corrosion inhibiting material the seven-wire strand is put through a destranding operation (in a finite length), a coating operation which covers the entire surface of each wire and restranding to the original configuration. The corrosion inhibiting material is a soft petroleum base wax that can be applied at ambient temperature, displaces any moisture on the surface of the steel, has a melting point over 260°C, and offers superior corrosion protection.

5.2 Coatings

In the search for corrosion protection methods and materials consideration has been given to coatings applied directly to the prestressing steel. Galvanized prestressing wire has been used in some multibarrier systems. As previously discussed, galvanized prestressing steel should never be used where it is in direct contact with cementitious grout and the designer must be cognizant of the effects of galvanizing on the material properties of the steel.

In recent years, research has focused on the use of epoxies to coat prestressing steel. A recent development is an epoxy filled strand whereby the interstices between the wires are filled with epoxy. This eliminates the concern for corrosive agents gaining access to the interior of the strand. Epoxy coating of the individual strands provides both temporary and permanent corrosion protection to the strand and eliminates the concern for aggressive corrosion agents reaching the prestressing steel as a result of cracked cement grout and potential cracks in the outside sheathing. So as not to compromise the effectiveness of the system, attention must be paid to the anchorage details. Special wedges are required that bite through the epoxy thickness and grip the prestressing strand. The epoxy should not be stripped from the strand.

Recent technology in the automotive industry for parking brake cable shows promise for a technology transfer to prestressing strand [7]. The adaptation of ceramic coatings from the automotive industry to cable-stay bridge stays should be investigated. The current production proven designs validated by years of service and millions of meters of production appear to be readily adaptable to the bridge stay environment.

6. CABLE STAY INSPECTION

The U.S. Federal Highway Administration (FHWA) National Bridge Inspection Standards (NBIS) require inspection of bridges every two years. Current stay construction/fabrication is such that inspection of a stay cable, requiring access to the steel wire or strand, would require a partial destruction of the stay. A FHWA research program has successfully developed a method of non-destructive investigation of stay cables by the magnetic field perturbation method (MPC). The method has been successfully used to inspect the stays of several cable-stay bridges.

The self-propelled inspection module can be positioned on the stay at the deck level and acquire data the entire length of the stay. Thus, the need for scaffolding and large cranes with their associated hazards and costs is negated. Also, personnel hazards and traffic congestion is minimized. The direct current magnetic field can penetrate the wrapping, HDPE sheathing, cement grout and penetrate deep into large diameter cables. The utilization of steel pipe cable stay sheathing seriously inhibits the capability of this equipment [8].

7. ECONOMIC EVALUATION

Because cable stays, including corrosion protection systems, are normally bid as a lump sum item, it is difficult to obtain economic evaluations of the cost of corrosion protection systems. However, for a cable-stay bridge recently completed, utilizing epoxy coated 15 mm diameter strand for the cable stays, the following data was obtained:

- Structure bid cost:

Substructure	$ 6,579,000
Superstructure	22,143,000
Total bid cost	28,722,000

- Stay bid cost 5,314,000
- Cost of epoxy coating 349,470

Epoxy Coating Cost as Related to Structure bid Cost:
- 6.58% of cable stay system
- 1.58% of superstructure cost
- 1.22% of total project cost

The cost of replacing one stay has been estimated at approximately $300,000 which is almost equal to the cost of providing the additional corrosion barrier, represented by the epoxy coating, for all the stays in the bridge. Aside from the tangible cost of stay replacement there are intangible costs which must be considered such as traffic congestion, person hours lost while sitting in a traffic jam, fuel consumption and the inconvenience to the traveling public.

8. CONCLUSION

In the last decade there has become an increasing concern as to the vulnerability of the stays to corrosion damage, especially in harsh environments. As is evidenced in this paper, corrosion protection systems have been evolving and will continue to do so. Research and ingenuity have responded to the problem with increasingly more efficient corrosion protection systems. Several methodologies are being considered or used to provide a more effective and direct corrosion protection to the prestressing steel elements of the cable stays. Only time will determine which systems will withstand the comparative tests of effectiveness, implementability and economics. The cost of providing an additional corrosion protection barrier beyond that provided by the external sheathing and cementitious grout has been shown to be approximately 1 to 1.5% of total structure cost. Given the potential of increased service life and the costly ramifications of not providing an adequate corrosion protection, the owner must consider whether he can afford not to be without the increased corrosion protection that can be provided by current protection systems.

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