Session D2

Design and Construction Issues for Stay Cables
Aspects importants dans la conception et la mise en place de haubans
Wichtige Aspekte in Projektierung und Erstellung von Schrägseilen

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International Survey of Current Opinion on Bridge Stay Cable Systems

Sondage international sur les systèmes de ponts à haubans

Internationale Meinungsumfrage über Brückenschrägkabel-Systeme

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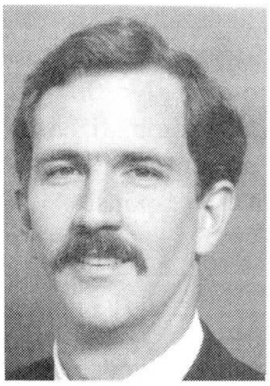

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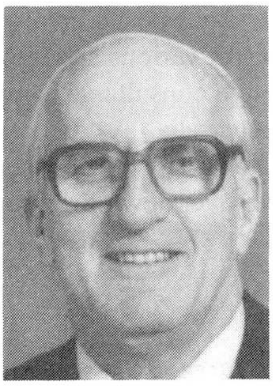

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SUMMARY

In a broad international survey, a total of 190 owners, contractors, design consultants, suppliers, and research institutes were queried to determine current thinking in the area of bridge stay cable design and construction. The questionnaire addressed only the stay cable and did not cover any other aspects of a cable-stayed bridge. From a design perspective, the traditional system using parallel strand or wire with a "Hi-Am" type socket was very highly rated among the 62 respondents. However, from a durability perspective much concern was shown regarding traditional cement grout stay cable protection systems. The survey also indicted increasing interest in other recently introduced stay cable corrosion protection systems.

RÉSUMÉ

Dans le cadre d'un sondage international, un questionnaire fut envoyé à 190 propriétaires, entrepreneurs, ingénieurs, fournisseurs, et instituts de recherches, pour connaître l'opinion actuelle pour le calcul et la construction des ponts à haubans. Le questionnaire se limita aux câbles de haubans et ne couvrit aucun autre aspect des ponts à haubans. Du point de vue calcul et conception, les 62 répondants donnèrent une note élevée au système traditionnel utilisant un toron parallèle avec un manchon du genre "Hi-Am". Toutefois, du point de vue durabilité, les répondants exprimèrent des doutes sur le système de protection traditionnel utilisant des coulis de ciment. Le sondage indiqua aussi un intérêt accru pour les systèmes de protection récemment introduits.

ZUSAMMENFASSUNG

In einer weitreichenden, internationalen Umfrage wurden 190 Bauherren, Baufirmen, Ingenieurbüros, Spannsystem-Hersteller und Forschungsinstitute über ihre Ansichten hinsichtlich Schrägkabelentwurf und -konstruktion befragt. Die Umfrage beschränkte sich auf das Schrägkabel selbst und schloss andere Aspekte von Schrägkabelbrücken aus. Hinsichtlich des Entwurfes wurde das traditionelle System mit parallelen Drähten oder Litzen mit einer "Hi-Am"-artigen Verankerung in den 62 Umfrageergebnissen sehr hoch eingestuft. Hinsichtlich Dauerhaftigkeit zeigten sich jedoch vielfach Bedenken gegenüber traditionellen Zementmörtel-Schrägkabel-Schutzsystemen. Die Umfrage deutete auch auf zunehmendes Interesse an anderen neuen Schrägkabel-Korrosions-schutzsystemen hin.

1. Introduction

The cable-stayed bridge industry is at a critical stage. A number of problems and questions have risen concerning traditional methods of corrosion protection for the stays. A number of new protective systems have been proposed. Discussions within technical committees involved in cable stay design and construction indicated a need for a compilation of the knowledge and expectations of those involved in the design, assembly, erection and maintenance of stay cables. In May 1993, an international survey was undertaken to sample the opinions of the industry on the design, fabrication, installation, and long term durability of stay cables and to determine current trends.

The scope of the survey encompassed only the stay cable and did not address any other aspect of the cable-stayed bridge. The questions posed involved strength, fatigue resistance, durability, cost, constructability and aesthetics of various stay cable components and systems. Surveys were sent to 190 owners, contractors, design consultants, suppliers, and research institutes covering North America, Europe, Asia and Australia. A comprehensive report was prepared which summarized in detail the large amount of data received.[1] However, this data is too copious to present herein. Therefore, this paper gives an overview of the survey and the trends observed in the responses.

2. Description of Survey

The survey was composed of three parts: cover letter, stay cable terminology for the survey, and stay cable questionnaire. The cover letter introduced the survey, and described why the survey was being conducted, and how the information to be gathered would be used. The stay cable terminology was a glossary of terms used in the survey so that all responses would have the same basis. The questionnaire was divided into eight sections as shown in Figure 2.1.

0. Addresee Information.
1. Design.
2. Corrosion Protection.
3. Inspectability/Durability.
4. Installation.
5. Aesthetics.
6. Marketing.
7. Past Experience.

Figure 2.1 - Sections of Questionnaire.

10............meaning excellent or clear first choice
8.......................meaning very good or desirable
6............................meaning good or acceptable
4.................. meaning marginal or questionable
2........................ meaning poor or objectionable
0.........meaning very bad or totally objectionable

Figure 2.2 - Rating System for Answering Questions.

Each section contained several questions related to the section topic. There were a total of 29 questions. Eighteen questions were in a format which provided several alternatives that were to be numerically rated using the scale presented in Figure 2.2. In addition, 7 yes/no questions were asked as well as 4 essay questions.

3. Survey Distribution

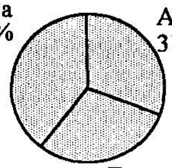
The first mailing of surveys was made in February 1993 in which approximately 190 surveys were distributed. Follow up letters were sent. The survey closed in November 1993. A total of 83 replies had been received. Of these, 62 completed the survey (respondents) while the remaining replies declined to participate due to lack of experience or knowledge.

4. Analysis of Survey

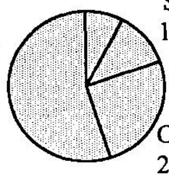
In order to make interpretation and comparison of data as convenient as possible, the results were assembled into a graphical format. Initially all responses were plotted to give trends of the group as a whole ("All" category). However, it is of interest to examine possible variations in responses relative to location or industry sector of the respondent. The three geographical categories selected were North America, Europe and Asia/Australia. The four industry sector categories selected were Supplier, Owner/Authority (Owner), Design Consultant/Research and Development (Designer), and Contractor.

4.1 Distribution of Respondents

A database was formed using the results of the numerically rated questions and yes/no questions. The distribution of the respondents according to geography and industry sector is shown in Figure 4.1. The geographical distribution of responses is reasonably balanced with North America having the highest percentage. However, the distribution of industry sector is weighted heavily toward the Designer category at 55% with Owner category having 25% of the responses. This was roughly the distribution of the industry categories in the mailing list.



(a) Distribution of Responses by Geographical Category



(b) Distribution of Responses by Industry Category

Figure 4.1 - Distribution of Responses

4.2 Graphical Presentation of Survey Data

In order to obtain meaningful data from this survey, it was necessary to develop means of presenting data which would allow quick detection of trends. In order to make this possible, the results of the survey were assembled into bar charts. A group of eight bar charts were prepared for each question in the survey. The first chart summarized the response of all respondents (All) and also included other relevant comments made by the respondents. The next three bar charts were summarized by geographical categories and the final four charts were summarized by industry categories. The bar charts were assembled for the questions requiring the use of the numerical rating and also yes/no questions. This was accomplished by extracting the numerical responses from the database for the particular category of geography or industry sector. The extracted numerical responses were then summed and divided by the total number of responses multiplied by 10. This gave the percentage of the maximum possible approval rating (which is 100%) for each given selection in the question. For example, if the particular selection was given a 100% approval rating, this would mean that all respondents had given that selection a rating of ten. The bar charts were then compiled comparing the approval rating for each of the possible selections for a given question with the maximum possible approval rating always being 100 percent. The Yes/No questions were compiled into bar charts which gave the percentage of yes and no answers out of the total number of responses. An example of the bar charts which were generated is presented in Figure 4.2.

Question 1.3 asked for the three most important performance aspects/ requirements for a stay cable. The response styles and lengths for this question were quite varied. During the initial review of the answers to this question, keywords were selected which matched or described the responses given.

Many of these keywords were appropriate for more than one response. In this manner ten keywords were developed which were used to characterize an important aspect/requirement for a stay cable. The keywords and their general definition are included in Figure 4.3 along with the results for this question. Any other responses were given "other" as a keyword. Three of the keywords which closely matched the response given in each question were then entered into the database. The database was then searched for the number of times the keyword was used for each category. These results were then placed in a bar chart for each category. The bar chart lists the keywords and shows the number of times that keyword is used as a percentage of the total number of questions for that particular category. Note that while there is a total possible percentage of 300% (if the percentage for all keywords is summed) since there are three keywords for each question, if each respondent expressed a major concern for one aspect (say durability), that would be entered as one keyword and the maximum percentage would be 100 percent. All graphs are included in Reference 1 which can be obtained on request to the authors (FSEL, Bldg. 177, 10100 Burnet Road, Austin, TX, 78758, USA)

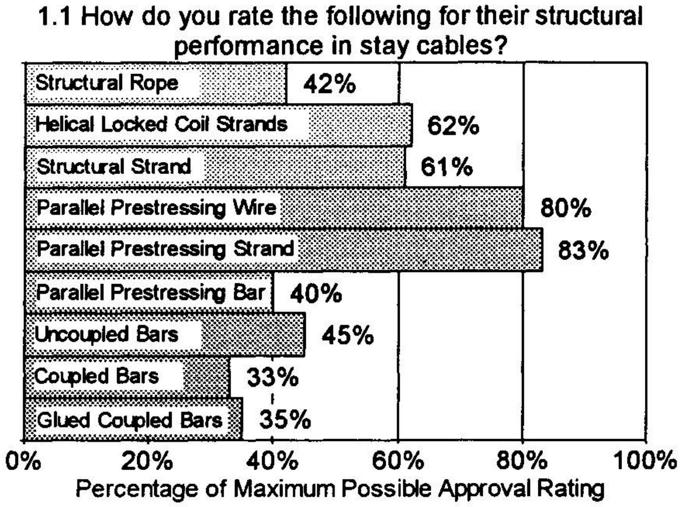


Figure 4.2 - Example of Graphical Presentation of Responses.

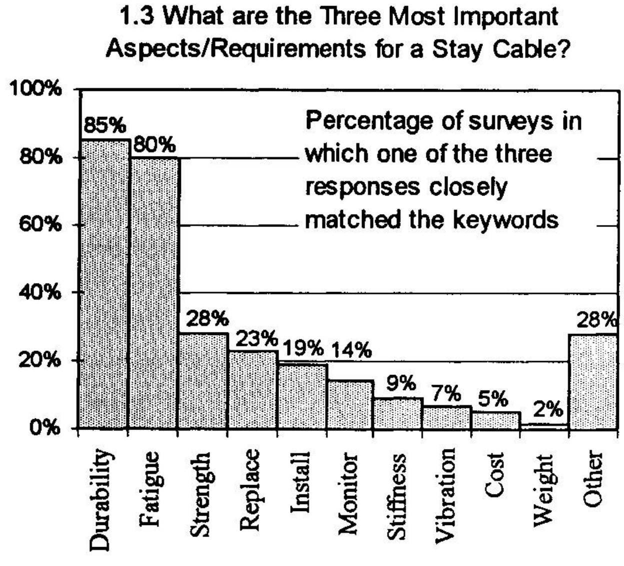


Figure 4.3 - All Respondents Response To Question Concerning Important Aspects Of Stay Cable.

<u>Durability</u> - Ability of stay cable to successfully resist corrosive elements.
<u>Fatigue</u> - Ability of stay cable to successfully resist cyclic loading.
<u>Strength</u> - Ability of stay cable to successfully resist static loading.
<u>Replace</u> - Stay cable can be easily replaced.
<u>Install</u> - Stay cable can be easily installed.
<u>Monitor</u> - Stay cable can be easily monitored.
<u>Stiffness</u> - High axial stiffness of stay cable.
<u>Vibration</u> - Reduced problems with vibration.
<u>Cost</u> - Low cost.
<u>Weight</u> - Low weight.

5. Discussion of Results

This section provides an overview of the results as well as a discussion of the significance. There were approximately 160 bar charts created using the data from the questionnaires. This prohibits even a partial presentation of the results in this paper due to the volume. Consequently, this section discusses the results (as interpreted from the bar charts) briefly for each question. Trends which were deemed significant are also noted. In interpreting the results it is important to recognize that no costs or relative costs between various alternatives were given to the respondents in the survey documents.

5.1 Design

Structural Performance - Parallel strand was given the highest rating in the All category at 83% while parallel wire was rated second highest at a somewhat surprising 80 percent. It was surprising because most bridges now being built seem to use parallel strand. Helical locked coil strand received a relatively high rating (greater than 60%) while prestressing bars had a very low rating (less than 40%) in the All category. Ratings for strand and for wire were close for Europe and Asia/Australia but wire lags behind strand in N. America (76% to 85% respectively). Helical locked coil strand was rated higher in Europe (75%) than in N. America and Asia/Australia (50% and 63% respectively). It is interesting to note that the Owner category gave wire a slightly higher rating than strand while all other industry categories rated strand slightly higher.

Anchorage Systems - Hi-Am type sockets were most preferred (86%) and wedges alone were least preferred (63%) for the All category. In addition, wedge type anchorage with bonding of the tension elements in a socket received a rating of 75 percent. This trend was typical for all other categories.

Important Aspects/Requirements for Stay Cable - In nearly all categories the Durability and Fatigue keywords were rated very high as compared to all other keywords. The only dissension was the Contractor category which rated Install and Fatigue as the two highest rated keywords. The ratings of the remaining keywords were not consistent among the various categories. Strength was rated third for the All category and for N. America and Asia/Australia, while Replace and Monitor were rated at third for Europe. Strength and Replace were both rated third by the Owner category while all other industry categories rated Strength third.

While all categories agreed that durability and fatigue strength were two of the most important aspects of a stay cable there was some disagreement about the third aspect. For the Owner category, Replace was given the same rating as Strength while the Europe category gave equal importance to Replace and Monitor in their third choice.

Fatigue Stress Range - This question gave five stress ranges (50, 100, 150, 200, and 250 MPa) and asked the respondent to indicate the minimum or desirable stress range using the rating system. Each category gave their highest rating to the stress range of 200 MPa. One respondent indicated that the answer would depend on the percentage of the live load for the individual project while another indicated that it would depend on the type of bridge, traffic loading and stay material.

In addition to the standard format, the responses were also examined by calculating the percentage of the total number of respondents which gave a particular stress range their top rating. In the All respondent category 47% gave 200 MPa their highest rating. Both N. America and Europe followed this trend with 46% and 64% for 200 MPa respectively. However, Asia/Australia were evenly divided between 150 MPa and 200 MPa at 33% each. It is interesting to note that the Designer category was less conservative with 250 MPa receiving the highest percentage of top ratings while all other industry categories gave 200 MPa the highest percentage of top ratings.

Saddles - In all categories the majority of the respondents did not favor the use of saddles. It is interesting to note that Asia/Australia had the least objection to saddles (53% no), Europe had the most objection (76% no) while N. America is between the two with 58% no. It is also interesting to note that the Designer category had the least objection to saddles while all other industry categories had much stronger objections.

Analysis for Bending Stresses - Under lateral loads and wind or traffic vibration stay cables can develop bending stresses which may be significant. Forty-one percent of the respondents did not perform a specific analysis for these bending stresses while 35% ran some type of analysis to determine stresses. There was no clear agreement on the methods which should be used to perform these analyses. Some discussed beam/column theory while others mentioned using non-linear computer programs to analyze the stays. Twenty-four percent did not feel they had the experience to answer the question.

5.2 Corrosion Protection

Material Configuration - The All category rated parallel wire as the highest for ease and reliability of corrosion protection with a 79% rating while parallel strand was close behind with 77 percent. The ratings for strand and wire were slightly higher in structural performance (83% and 80%) than in this question (77% and 79%). Prestressing bar was treated more favorably for corrosion protection with a rating of 70% as compared to a rating of 40% for structural performance. As with structural performance, Europe (72%) rated helical locked coil strand higher than N. America (55%) or Asia/Australia (66%). Strand was rated slightly higher than wire in N. America while both Europe and Asia/Australia rated wire slightly higher than strand. Suppliers rated strand higher than wire (93% to 83%). However, all other industry categories ranked wire higher than strand.

Protection Systems - Monostrand with galvanized tension elements had the highest rating in the All category with 84% while epoxy-coated and filled elements were slightly lower with 76 percent. It is interesting to note that in the All category epoxy-coating and cement grout had nearly the same rating (58% and 56% respectively). It is also interesting to note that N. America rated the epoxy-coated and filled element the highest (82%) while both Europe and Asia/Australia rated the galvanized monostrand the highest (85% and 88% respectively). The N. America category rated the galvanized monostrand very close to the top with 81 percent. In all categories there was a significant difference between the galvanized and the considerably lower ungalvanized monostrand. The results are particularly surprising since most bridges completed to date have used cement grouted bare tension elements which finished fairly low in the survey. This system seemed popular mostly with the supplier category.

Blocking Compound - Blocking compound was defined in the survey questionnaire as "The material used to fill the void between the tension elements and the outer sheathing. It may be an integral part of the corrosion protection system. Examples are cement or epoxy grouts, greases and waxes." All selections except for "no blocking compound" were rated very close within a range of 59% to 66% by the All category. This could mean that no significant differences were seen between the possible choices. The N. America category rated cement grout the highest (68%) and Asia/Australia rated it close to the top (67%) while Europe rated it relatively low (48%). Europe preferred the two-part epoxy system while Asia/Australia preferred polyurethane. In the industry categories it is interesting to note that the Owner category preferred cement grout while the Designer category preferred the two-part epoxy system.

Sheathing System - High Density Polyethylene (HDPE) sheathing was preferred among all categories. Other sheathing systems such as steel, copper or stainless steel had strong support. "No sheathing" was given as a choice but most respondents felt some type of sheathing should be provided.

Corrosion Protection Systems - The most highly rated choice in the All category was the monostrand with galvanized tension elements and external sheath at 74 percent. Close behind were monostrand with bare elements, cement grout and external HDPE (70%) and galvanized tension elements with wax and external HDPE sheath (73%). The distribution of ratings both according to geography and industry were similar to the All category. N. America and Asia/Australia (73% and 74% respectively) rated the epoxy-coated system more favorably than Europe (56%). The All category rated the traditional "suspension bridge" type corrosion protection of exposed galvanized elements at 38 percent. This low value was typical for the other categories as well. It is interesting to note that the bare tension element with cement grout and HDPE sheath was 59% for the All category.

Although this question offered nine stay cable systems which were to be rated by the respondent for corrosion protection, there were many combinations of stay cable systems. The selections given were intended to represent a good cross-section of the available systems and components. However, several suggestions for alternative systems were made by respondents not satisfied with the selections given. One suggestion was galvanized strand, individually sheathed with external HDPE sheath extruded or fitted tightly on bundle. Another option suggested was galvanized wire tension element with an external HDPE sheath extruded over the bundle.

Portland Cement Grout Blocking Compound - In all categories except Europe the majority of the respondents believed that a portland cement grout blocking compound was an adequate corrosion protection system. Several respondents qualified their response by saying that the grout should be used in a HDPE sheath, while one said that the HDPE sheathing was considered to be the main corrosion protection. The reasons given in support of the cement grout blocking system were that it provides an alkaline environment around the steel, experience has shown it works, and some answered yes even though they were not completely convinced. Some reasons given for answering no to this question were that cracks from vibration and live load stresses were unavoidable.

Grout Encasement - All categories had a majority answer yes when asked if they believe that the tensile elements are completely encased in grout. Reasons given for answering yes were that experience to date has been good or that they were not really convinced but answered yes anyway. Reasons given for answering no were that ideal grouting conditions are not possible and there are going to be voids from bleeding. Designers were least convinced with 56% responding yes while the Owner category had the most positive responses at 87 percent.

Temporary Protection Systems - The All category rated galvanizing, epoxy coating and filling, and greased and sheathed monostrand as the top choices (77%, 76%, and 72% respectively). The top rated choices varied geographically. N. America rated epoxy-coated and filled as the top choice at 80% while Europe and Asia/Australia rated galvanizing as the top choice at 84% and 74% respectively. Top choices also varied according to industry category. The Supplier category rated epoxy-coating and filling top at 83% while all other categories rated galvanizing as the top choice. Water soluble oils and desiccants were rated substantially lower.

5.3 Inspectability/Durability

Inspectability versus Protection - In general, all categories were willing to settle for limited visual inspectability if multiple protection was provided.

Replacement of Stay Cables - All categories overwhelmingly rated replacement of the entire stay as desirable over replacement of individual strand or wire.

Design Life - The results of this question were somewhat confusing. The question asked what design life was expected from: (a) a stay without an expected replacement and (b) if one replacement is expected during the life of the bridge. From a purely logical point of view the design life given for the stay which is to be replaced should be lower than that of the stay which is to be replaced once for a given life of a bridge. The results did not reflect this trend, which indicates that the respondents may have misunderstood the question. Nevertheless, the results from the question were useful in determining the life respondents expect from a stay cable. The All category expected a life of 60 years from a stay that is not intended to be replaced. The Owner category expected the longest life (76 years) while the Contractor category expected the shortest life (33 years). N. America and Asia/Australia were close in their expectations (67 and 65 years respectively) while Europe expected a much lower life at 45 years.

Need for Replacement - In all categories except Supplier, a majority of the respondents agreed that there would need to be a replacement of a stay cable or component during the life of the structure. Some reasons given for the positive response were: only for accidental events, include the cost of replacement in maintenance. Those that disagreed indicated either that no structure should be designed with the aim of replacing it or that it should only be for accidental events.

5.4 Installation

Installation of Stay Cable - All categories except for the Contractor preferred a fully shop prefabricated stay cable as compared to a stay assembled in place or assembled at the site. The Contractor category preferred a stay assembled in place.

Stressing Procedure - This question asked if the respondent preferred to stress the tension elements individually using a method to ensure that each tension element has the same stress or to stress the stay as a unit. All categories except Contractor rated stressing of the stay as a unit as the best method for stressing. The Contractor category rated both options equally. Another option given by a respondent was to stress the individual strands initially to a low level and then stress the stay to the final level as a unit.

Installation of Blocking Compound - Injection or grouting after stay cable installation is the method most highly rated by the All category (72%). Injection of grouting before installation using a flexible blocking compound was close behind (70%). Both N. America and Asia/Australia rated the in place installation highest while Europe rated preinjection with a flexible blocking compound higher.

Installer - Results tended to differ for the question of who should install the stay cable. In the All category an 81% rating was given to the main contractor installation with supervision of the supplier. For the geographical categories N. America and Asia/Australia gave the highest rating to the same choice. However, Europe rated installation by the stay supplier highest (77%). In the industry categories the Contractor and Supplier gave their highest rating to installation by stay cable supplier. Owner and Designer rated installation by the main contractor with supervision by the stay supplier the highest.

Grout Admixtures - A number of admixtures were mentioned in this question. The main concern seemed to be to provide a grout which has nonshrink, low bleed, and pumpable properties. Also mentioned were prohibiting admixture use or prohibiting use of a portland cement grout at all.

5.5 Aesthetics

Color Selection - For all categories it was important to the majority of the respondents to be able to select the color of the stay cable.

Stay Diameter - For All, N. America, Asia/Australia, Owner, Designer, and Contractor categories the majority of the respondents felt it was not important to have the smallest diameter stay cable diameter. However, the majority of the Europe and Supplier category felt it was important to minimize the stay diameter. The reasons given for having the smallest diameter (yes) were better response to wind forces or easier to handle, while some reasons for not having the smallest diameter (no) were that other factors were more important or that it is only important for longer spans where wind response may be a problem. It is interesting to note that a large majority (74%) of the N. America category responses were no while 75% of the Europe category were yes. A similar trend was noted between the Supplier (57% yes) and Owner (67% no) categories.

5.6 Marketing

Documentation - The All category rated the need for "technical documentation on system and design/installation documentation and design/installation support" very close (80% and 79%) while "stay cable system documentation only" is rated at 62 percent. This trend held for all categories except Europe which rated "technical documentation on system and design/installation" at 81% while the other two choices are less than 74 percent.

Meetings Concerning Stay Cables - A large majority of the respondents in all categories expressed an interest in regular contacts/meetings between authorities, designers, contractors, and stay cable suppliers.

Suppliers and System Familiarity - The question asked what stay cable suppliers and systems do you recognize or have you used. A total of 23 stay cable suppliers were listed with VSL, BBR, DSI, and Freyssinet taking the top four positions when considering the number of times they were mentioned. It should be noted that a higher ranking does not necessarily indicate that the products of the companies are preferred but rather that they are recognized. In the second part of the question, many different stay cable systems were listed. To simplify the tabulation of systems, the list was broken into various groups based on the description of the tension element. The systems most often mentioned were parallel strand at 44, while parallel wire was mentioned 16 times and parallel bar was mentioned 9 times. Also mentioned were epoxy-coated strand, greased and sheathed strand, galvanized wire, long lay wire, locked coil and structural strand.

5.7 Past Experience

This question requested that the respondent list past/recent experience positive or negative with stay cable projects. Comments made in this section were extensive and covered many different aspects of stay systems. The comments did not generally follow a particular theme or idea. Rather, they were a collection of the respondents' good and bad experiences with stay cable systems. Several comments were even directly contradictory such as in the use of epoxy coating. One respondent suggested that epoxy coating does not work as a barrier while another suggested that it increases the level of protection.

6. Trends

It is unwise to make recommendations or draw conclusions concerning the use of stay cables based solely on a mail survey of this nature. However, many respondents went to a great deal of effort to express their opinions and experiences. The compilation of this information can certainly indicate trends. In view of the scattered information in this area, such trends can be highly useful to the stay cable community.

6.1 Design

From a structural performance aspect the following items were very highly rated in the All category of respondents:

- Parallel strand or parallel prestressing wire.
- Hi-Am type anchorage.
- Place anchorages at towers (no saddles).
- Use fatigue stress range: 200 MPa.
- Three most important aspects of stay: durability, fatigue resistance, strength.

6.2 Corrosion Protection

For corrosion protection the following items were very highly rated in the All category of respondents:

- Parallel wire or parallel strand.
- Greased and plastic sheathed galvanized tension element.
- Epoxy coated and filled tension element.
- Some type of blocking system (numerous with about the same rating).
- HDPE external sheath.
- System: greased and individually sheathed galvanized tension element, with wax or cement grout and external HDPE.
- Portland cement grout is felt to be an adequate corrosion protective system and the grout is believed to completely encase the tension elements, although European respondents doubt the adequacy of the grout.
- Galvanizing, epoxy coating or greased and sheathed monostrand are preferred.

6.3 Inspectability/Durability

For inspection and durability the following items were very highly rated in the All category of respondents:

- Multiple protection and limited visual inspection but other monitoring options (electrical/magnetic).
- The entire stay should be replaceable as opposed to individual elements of the stay.
- Stay life expectancy is bimodal with a large group favoring 26-50 years and another favoring 76-100 years. Average stay life expectancy is 60 years.

6.4 Installation

For installation of the stay, the following items were very highly rated in the All category of respondents:

- Fully shop fabricated stay including blocking compound.

– Stress entire stay as a unit as opposed to stressing individual elements.
– Blocking compound should be installed after stay has been erected is slightly preferred over blocking installation before stay installation.
– Main contractor should install stay cables with supervision of stay supplier or the stay supplier should install the cables.

6.5 Aesthetics

For aesthetics, the following items were rated very highly in the All category of respondents:

– It is important to be able to chose the color of the stay.
– There is much varying opinion on whether it is important to have the smallest possible stay diameter.

6.6 Marketing

For marketing, the following items were very highly rated in the All category of respondents:

– Require technical documentation on system and design installation and provide design/installation support.
– There is a very strong interest in regular meetings concerning stay cables.

References

1. HAMILTON III, H. R. and BREEN, J. E., Stay Cable Survey, Phil M. Ferguson Structural Engineering Laboratory, The University of Texas at Austin, February, 1995.

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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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Walter Podolny has been with the Federal Highway Administration for the past 23 years. In 1992 he served as chairman of an international review panel convened by the Asian Development Bank for the 602 m span cable-stayed Yangpu Bridge in Shanghai, China.

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.

<u>5.1 Monostrand Systems</u>

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.

REFERENCES

1. WATSON, S. C. and STAFFORD, D., Cables in Trouble. Civil Engineering, ASCE, Vol. 58, No. 4, April 1988, pp. 38-41.

2. MANZANAREZ, R., SEIM, C. AND SMITH, D., Beyond Engineering: The Politics of Maracaibo. Civil Engineering, ASCE, Vol. 61, No. 3, March 1991, pp.

3. SLUNDER, D. J. and BOYD, W. K., Zinc, Its Corrosion Resistance. 2nd Ed., International Lead Zinc Research Organization, Inc., New York, New York, 1983.

4. Newsletter, Post-Tensioning Institute, Phoenix, Arizona, June 30, 1988.

5. Recommendations for Stay Cable Design, Testing and Installation. Post-Tensioning Institute, Phoenix, Arizona, August 1993.

6. BUERGI, P., Recent Approaches to Corrosion Protection in Stay Cable Design. IABSE Symposium, Leningrad, USSR, September 11-14, 1991.

7. SWAIT, W. J. and FUNAHASHI, M., Corrosion Protection Systems for Bridge Stay Cables and Anchorages. Report No. FHWA-RD-91-050, Federal Highway Administration, Washington, D.C., May 1991.

8. BARTON, J. R., TELLER, C. M. and SUHLER, S. A., Design, Develop and Fabricate a Prototype Nondestructive Inspection and Monitoring System for Structural Cables and Strands of Suspension Bridges. Report No. FHWA-RD-89-158, Final Report, Federal Highway Administration, Washington, D.C., May 1989.

Developments in Non-Destructive Stay Cable Inspection Methods

Développements de méthodes d'inspection non destructives pour les câbles de haubans

Neuere Entwicklungen zerstörungsfreier Prüfverfahren für Schrägkabel

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SUMMARY

While durability and inspectability of the steel tension elements are amongst the primary objectives of good stay cable detailing, these two objectives are contradictory to an extent, because a robust multilayer approach to corrosion protection prevents easy access to the steel tension elements for inspection. The paper describes some non-destructive inspection methods that have been used on stay cables, but also introduces methods used for inspecting prestressing tendons in concrete structures and ground anchors that could be suitable for the surveillance of stay cables.

RÉSUMÉ

La durabilité et la possibilité d'inspecter les éléments sous tension constituent les critères principaux pris en compte dans la conception des détails des haubans. Ces deux objectifs sont en un certain sens contradictoires vu qu'une protection multicouche contre la corrosion rend difficile l'accès aux éléments sous tension. L'article décrit quelques méthodes de contrôle non destructives qui ont été utilisées pour les haubans. Il présente également des méthodes dont l'usage a été limité jusqu'ici à l'inspection des câbles de précontrainte dans les structures en béton et le contrôle des tirants, mais qui pourrait être étendu à la surveillance des haubans.

ZUSAMMENFASSUNG

Dauerhaftigkeit und Ueberwachbarkeit der Stahl-Zugglieder sind die Hauptziele einer durchdachten Detailentwicklung von Schrägkabeln. Dennoch widersprechen sich diese beiden Ziele zu einem gewissen Grad, da ein robuster, mehrlagiger Korrosionsschutz die Zugänglichkeit zu den Stahlzuggliedern zu Inspektionszwecken erschwert. Der Aufsatz beschreibt zerstörungsfreie Prüfmethoden, welche bereits für die Ueberwachung von Schrägkabeln eingesetzt wurden. Es werden aber auch Methoden vorgestellt die bisher zur Ueberwachung von einbetonierten Spannkabeln und Bodenankern eingesetzt wurden, jedoch auf Anwendungen bei Schrägkabeln erweitert werden konnten.

1. INTRODUCTION

The stay cables of cable-stayed bridges are primary structural elements and because there is only a limited degree of redundancy, failure of a stay cable may have serious consequences for the entire structure. On the other hand, the high tensile strength steel used as the load-carrying member in cable stays is relatively sensitive to corrosion. Therefore, durability and inspectability of stay cables are amongst the primary objectives to be achieved by a good design of a cable-stayed bridge.

Visual inspection of the steel tension elements is the most direct way to determine their state since it does not rely on the calibration and interpretation of measuring techniques. However, direct visual inspection of the tension elements is not normally possible without partially injuring the various corrosion protection layers. Even then, for most types of stay cable it is only possible to gain access for visual inspection of the outer surfaces of the outer layer of strands or wires, while the inner ones remain inaccessible. Hence, indirect methods to evaluate the state of the stay cables are often the only available option for bridge owners. In the following a brief description of the various compositions of parallel strand stay cables is given. Then a number of different non-destructive inspection and surveillance methods are briefly described. The merits and limitations of each method are discussed with particular regard to the feasibility to inspect stay cables of different compositions.

2. PARALLEL STRAND STAY CABLE COMPOSITIONS

Fig. 1 shows five different compositions of parallel strand stay cables. The most basic yet widely used type consists of a parallel bundle of bare seven-wire prestressing strands contained in a thick-walled HDPE pipe which is injected with cement grout, Fig. 1a. The cement grout passivates the steel elements and thus is essential for the corrosion protection. The tough outer stay pipe provides the first barrier against both mechanical and corrosive impacts. Less common is the use of a steel pipe instead of the HDPE pipe. Fig. 1b shows another form of parallel strand stay cable. The strands are galvanised and instead of cement grout the HDPE stay pipe is injected with a flexible filler, e.g. petroleum wax.

The stay cable shown in Fig. 1c is composed of a bundle of individually greased and HDPE-sheathed strands ("monostrands") as they are used in unbonded post-tensioned slabs. The bundle is contained in a thickwalled HDPE pipe which is injected with cement grout, similar to the type shown in Fig. 1a. In this composition the cement grout serves primarily as mechanical protection, and to prevent relative lateral movement between the monostrands and the stay pipe. Since the steel strands are not in direct contact with the cement grout, the grout does not act to passivate the steel. The composition shown in Fig. 1d is made up of a bundle of galvanised strands individually covered by a tightly extruded HDPE sheath. A petroleum wax layer between the strand and the HDPE sheath provides a further corrosion protection barrier. In some cases the bundle is not protected by an outer sheath, in others two interlocking HDPE half shells are clamped onto the strand bundle to improve the aerodynamic behaviour of the stay, and to provide some extra mechanical protection.

Finally, the stay cable shown in Fig. 1e is composed of individually greased and HDPE sheathed strands, each one contained in a HDPE tube. The whole arrangement is contained in an outer HDPE pipe. No filler is provided, except for local polyurethane foam injections at approximately 6 to 10 m centres, acting to center the bundle within the stay pipe and to prevent relative lateral movement between the bundle and the stay pipe. The stay cable is installed by pushing single monostrands into the pre-installed stay pipe / guide tube bundle assembly. The individual HDPE- guide tubes are provided to assure a parallel bundle, and to allow the removal and replacement of individual monostrands without de-tensioning of the entire stay cable.

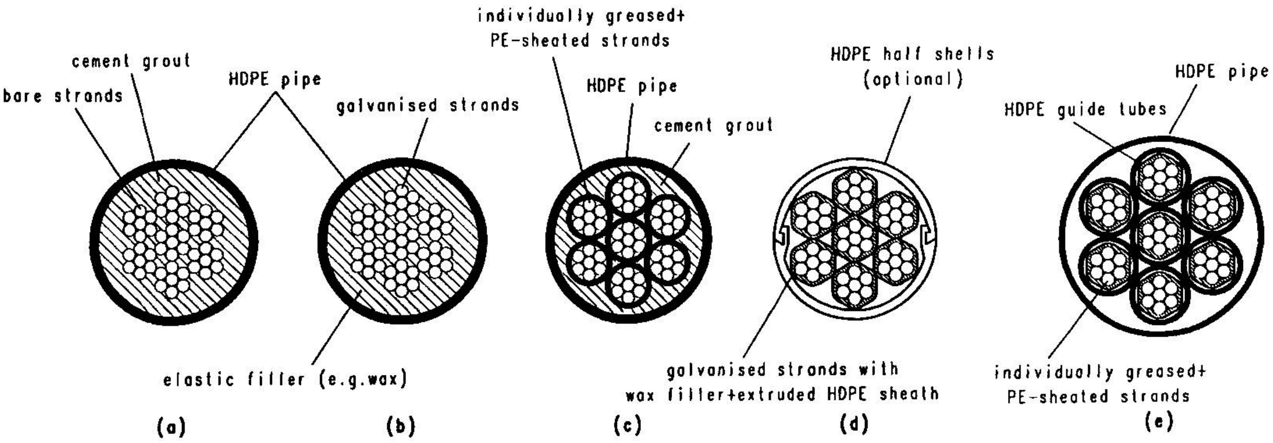

Fig. 1 Different Compositions of Parallel Strand Stay Cables

3. NON-DESTRUCTIVE INSPECTION AND SURVEILLANCE METHODS

The ultimate objective of the inspection or the surveillance of stay cables is to determine whether the main tension elements, i.e. the wires or strands, are still sound, or whether corrosion or wire breakages due to fatigue or fretting have taken place, threatening the safety of the structure. The inspection methods can be categorised in different ways, e.g. into global measuring techniques that can identify the existence of a problem without being able to locate it, and techniques that can pin-point where a wire breakage or a corrosion area exists. Another important criterion for the choice of suitable inspection and surveillance techniques is whether or not they are able to identify problems where they most often occur, namely in the anchorage and transition zones of the stay cables. An inspection that leads to the conclusion that the cable is sound in the free length, but leaves any doubt about the condition of the tension elements inside the anchorages is not sufficient to determine the remaining service life of the cable.

3.1. Direct Force Measurement

The direct measurement of the actual stay cable force is possible by a lift-off test using a calibrated multistrand stressing jack. The force indicated by the pressure gauge when the anchorhead (or ring nut) just starts to lift off the bearing plate is a fairly accurate measure of the cable force, because of the relatively great length of stay cables, and because there are no friction losses as in a post-tensioning cable inside an embedded corrugated duct. Of course it is also possible, yet expensive to install a permanent load cell at the stay cable anchorage, allowing continuous surveillance of the cable force.

This global measurement does not give any clue as to possible local reductions of steel area due to corrosion or fatigue, because even for stay cable compositions without bond between the individual strands the breaking of a few individual wires will not significantly reduce the overall stiffness of the cable.

3.2 Indirect Force Measurement - Dynamic Method

The actual cable force can also be measured indirectly by evaluating the dynamic properties of the cable subjected to free damped vibrations. This method has been used, for example, on the Alamillo Bridge in Spain [1], and on the Polcevera Bridge in Italy [2]. This is also a global measurement and can therefore be used on all types of stay cable.

While the cable mass per unit length is usually accurately known, the vibrating wire method can, at best only provide an approximation of the cable force since the underlying assumptions, zero flexural stiffness and hinged anchorages, no relative displacement of the anchorage points (i.e. infinitely rigid pylon and deck), and inextensibility of the cable only apply approximately to actual stay cables. If accompanied by dynamic analyses using finite element models representative of the actual cable properties and anchorage boundary conditions, the evaluation of the measurements can be more meaningful [2].

3.3 Indirect Force Measurement through Measuring the Cable Length

The cable force can also be determined by measuring the cable length. With known steel cross sectional area and equivalent modulus (based on cable theory) the cable force can be calculated. There are various ways to measure the cable length with sufficient accuracy, the most basic one being the known surveying methods using theodolites and electronic distance measuring instruments. A more sophisticated method is to install optical fibre sensors forming an integral part of the strand bundle. The length is then determined by accurately measuring the travel time of light impulses along the length of the sensor and back, the signal being reflected at a mirror at the far end of the sensor. By integrating semi-permeable reflectors at regular intervals along the sensor, length changes between these reflectors can be measured, thus providing a means to detect strain variations along the stay cable that may arise from local cross section reductions (broken strands or wires). The method has been used for the surveillance of permanent ground and rock anchors [3], [4]. The extension of this method to stay cables is possible, in principle but may need some modifications. The method would be suitable for all parallel strand or parallel wire compositions. An even higher level of sophistication would be to integrate optical fibre sensors into each strand, thus allowing local over-stresses to be determined more readily than by a global measurement of length changes of the complete strand bundle.

3.4 Potential Field Measurement

The detection of active corrosion of the strands or wires taking place somewhere along the length of the stay cable is possible by measuring the electrical potential between a copper wire and the steel. Both the copper wire and the tension elements must be fully embedded in an electrolytic filler, e.g. cement grout (but must not be in metallic contact with each other). The method has been used for the surveillance of permanent, single bar ground / rock anchors up to 26 m length [5]. The extension to stay cables having a composition similar to Fig. 1a or 1c is possible, in principle. The potential field method is a global method, it can only indicate whether corrosion processes are active somewhere along the length of the stay cable, including the anchorage zones. An indication where the corrosion takes place is not possible. It is important to stress that corrosion can only be detected while it is active. Corrosion that has taken place at some time in the past but come to a standstill cannot be detected.

3.5 Reflectometric Impulse Measuring Technique (RIMT)

The reflectometric impulse measuring technique (RIMT) has been used in Europe and Canada to inspect soil / rock anchors and prestressing tendons in concrete structures. The technique is based on very high frequency echo, with the steel tendon under study acting as the conductor and the surrounding concrete or soil as the ground connection. The very short duration electrical pulse signal is fed into the tendon at one end and the reflections from the far end, as well as from any possible defects present along the length of the tendon are recorded at the same end. By examining the time history of the sent and reflected signal it is possible in theory to identify, quantify and locate anomalies such as wire breakages or even corroded areas, and voids in the cement grout. An initial measurement for future reference, i.e. a sort of "foot print" of the sound cable is almost a pre-requisite for a meaningful interpretation of future in-service measurements.

The reliability and the limitations of the method are rated differently by various researchers. While in [6] it is summarised that the method is suitable to measure tendons up to 200 m long, and that corrosion or wire breakages can be detected if the corresponding cross section reduction is at least about 15 %, the findings from [7] are less promising: It was not possible to identify 6 broken wires out of 42. Based on the experience of the measurements in [7] the present technology reaches a limit of reliability for cable lengths of about 50 m. The RIMT method has been used to inspect the prestressed concrete stays of the Polcevera Bridge [2] and reasonable agreement with accompanying (partially destructive) visual inspections is reported. In principle the RIMT method can be used on all types of stay cables, however the main limitation will be the length.

3.6 Electrical Resistance Measurements

The detection of local cross-sectional area reductions due to wire breakages or corrosion is also possible, in theory by measuring the end-to-end ohmic resistance of the strand bundle acting as a conductor. Since the ohmic resistance is very sensitive to temperature influences, however the degree of accuracy obtainable in practice depends largely on how good the temperature compensation is. Also, the accuracy of volt meters available today is a considerable limiting factor. Since all strands or wires are electrically connected at the anchorages the method does not allow the location of a reduction in cross section. In particular, problems within the anchorage cannot be detected. Trial measurements based on this principle were not able to detect a 14 % cross sectional area reduction of a 100 m long grouted post-tensioning cable [7].

3.7 Magnetic-Inductive Scanning

The most reliable indirect method for stay cable inspection is the magnetic-inductive scanning. This method is also widely used for the inspection of suspension cables of cable car systems. The principle of this method is based on the disturbance of the magnetic field of the magnetised steel tension elements at locations with corrison pits and/or wire breakages. Either a permanent magnet, or an electromagnet is moved along the cable while a sufficiently sensitive magnetic sensor integrated into the device measures the strength and polarisation of the resulting magnetic field. Any anomalies, in particular local changes of the polarisation are indicators for metalurgic and/or mechanical defects. Tests at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) have successfully detected a single wire breakage located in the centre of a parallel wire stay cable of 200 mm outside diameter and consisting of 252 7 mm diameter wires [8]. Acc. to [8] not only broken wires but also corroded areas can be detected. Devices using electromagnets weigh 20-65 kg (depending on the maximum cable diameter that can be scanned) while those with a permanent magnet weigh up to 10 times as much. Compared to most others the method is quite economical, allowing 4 to 8 cables to be tested per day. The only disadvantage is that the anchorage zones cannot be scanned since the device is mounted around the cable.

3.8. Ultrasonic Reflex Scanning

The ultrasonic reflex scanning technique could be useful to inspect the steel elements within the anchorage zones of stay cables. This inspection would then be carried out additionally to other test methods, e.g. magnetic scanning, to extend the findings to the otherwise hidden anchorage zones. Tests have been carried out successfully on anchorages of parallel wire stay cables [9].

3.9 Visual Inspection of Individual Strands

A stay cable composition similar to the one shown in Fig. 1e allows the complete removal and replacement of individual strands for visual inspection of the entire length of the strand, including the end parts where it is anchored. This is perhaps the most significant advantage of this inspection method compared to most other methods which do not allow a conclusive evaluation of the state of the steel tension elements within the immediate anchorage regions.

Using a single strand jack with a pressure gauge and a special nose, the actual cable force is measured on at least three different strands by pulling on the protruding end until the wedges are just unseated. The average of the forces thus determined is the force to which the replacement strand is to be stressed, using a single strand jack. Depending on the cable length, the complete de-tensioning of the strand to be removed may require an extension of the protruding strand tail. This is possible by butt-welding. The principle feasibility of a sufficiently strong weld connection has been demonstrated by tests [10].

3.10 Outlook

A significant improvement of the reliability and accuracy of both RIMT and end-to-end electrical resistance measurements can be expected if the individual strands of a stay cable can be electrically insulated from each other not only in the free length of the cable (as in Fig. 1c, 1d, 1e) but also in the anchor head. This would allow individual strands to be measured separately, with only little influence from the other strands. A single broken wire, within one strand corresponds to a 14 % area reduction and should be detectible by a volt meter available today. With the rapid progress in material technology it is expected that suitable yet still economic materials will be available soon to manufacture anchorages that will enable electrical measurements of individual strands.

4. CONCLUSIONS

While a number of non-destructive inspection methods are available that have been used on, or could be extended to stay cables, most of the methods are still not sufficiently reliable, or too expensive. While visual inspection of the steel tension elements is desirable, providing this possibility should in no way compromise the durability provided by robust, multilayer corrosion protection. Visual inspection of strands taken out of a stay cable at random is made possible by appropriate detailing of the stay cable and its anchorages. This possibility should be used more frequently by bridge owners when specifying stay cables for new bridges.

5. REFERENCES

1. J.R. Casas, "A combined Method for Measuring Cable Forces: The Cable-Stayed Alamillo Bridge, Spain", Structural Engineering International 4/94.
2. G. Camomilla, M. Donferri, A. Gennari Santori and L. Materazzi, "Reflectometric and dynamic measurements on the stays of the Polcevera viaduct in Genoa (Italy), Proceedings, 2nd International Conference on Bridge Management, University of Surrey (UK) April 1993
3. I. Feddersen, K. Schütt, "Die Zugversuche und Eignungsprüfungen an den Verpressankern und ihre langfristige Ueberwachung", Beitrag 15, "Edertalsperre 1994", Special Publication published by Wasser- und Schiffahrtsdirektion Mitte, Hannover (Germany), 1994.
4. H.J. Miesseler, R. Lessing, "Projekt Hector Malot, Paris - Bericht über Verformungsmessungen an einem Stahllitzenerdanker mit Lichtwellenleitersensoren", Report by SICOM GmbH, Köln (Germany), January 1993.
5. B. Wietek, "Permanentes Messsystem für Daueranker", Tiefbau, Ingenieurbau, Strassenbau, Heft 10, Oktober 1992.
6. H. Kapp, G. Nava, N. Seifert, "Integritäts- und Korrosionsprüfungen an Vorspannkabeln in Brückenbauwerken. Die reflektometrische Impulsmessung", Forschungsbericht über Forschungsaufträge 83/88 und 81/90 (Bundesamt für Strassenbau), St. Gallen (Schweiz), Dezember 1991.
7. Experience from pilot projects bridges "Burg-Aderahubel", N1, Kt. Freiburg (Switzerland) and "P.S. du Milieu", N1, Kt. Waadt (Switzerland), private communication.
8. Swiss Federal Laboratories for Materials Testing and Research (EMPA), private communication.
9. Becker K., Nöller H.: Zerstörungsfreie Prüfungen an den Endverbindungen von Spiralseilen und Paralleldrahtbündeln mittels Ultraschall, Der Maschinenschaden, 61 (1988), Heft 3, S. 104-106.
10. A. Gnägi, "Litzenaustauschversuch", Test Report 313, VSL International Ltd., Berne (Switzerland), 20. December 1990.

Durability in the Design of American Precast Segmental Cable-Stayed Bridges

Durabilité des ponts haubanés américains construits par encorbellement

Dauerhaftigkeit bei der Segmentbauweise amerikanischer Schrägseilbrücken

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SUMMARY

As the use of cable-stayed bridges in America has continued to increase, ever greater attention has been focused on assuring the durability of these structures. This paper relates experience in the design and construction of precast segmental cable-stayed bridges in America. The summary of this experience is reflected in a design philosophy for durability. This philosophy has four parts: use high quality, long lasting material, work the materials at conservative levels of stress, provide redundant protection systems for stay cables, and develop maintainable, replaceable details.

RÉSUMÉ

L'utilisation de ponts haubanés continuant d'augmenter aux États-Unis, une attention toujours plus grande est portée à la durabilité de ces structures. L'article relate l'expérience américaine dans le dimensionnement et la construction par encorbellement d'éléments préfabriqués de ponts haubanés. Un résumé de cette expérience se retrouve dans la philosophie de durabilité, qui comporte quatre points: utiliser des matériaux de très bonnes qualité et longévité, faire travailler ces matériaux à des niveaux de contraintes modérés, fournir des systèmes de protection redondants pour les haubans, et concevoir des détails dont l'entretien et le remplacement sont aisés.

ZUSAMMENFASSUNG

Angesichts der fortschreitenden Zunahme von Schrägseilbrücken in den USA, richtete sich die Aufmerksamkeit immer schärfer auf die Dauerhaftigkeit dieser Bauwerke. Der Beitrag verbindet Erfahrungen im Entwurf und in der Bauausführung und mündet in einer Entwurfsphilosophie im Hinblick auf Dauerhaftigkeit. Diese Philosophie besteht aus vier Teilen: Verwendung hochgradiger, dauerhafter Materialien, mässige Materialbeanspruchung, redundante Schutzsysteme für die Schrägkabel und Entwicklung haltbarer, wartungsfreundlicher, austauschbarer Konstruktionsdetails.

1. INTRODUCTION

Over the last 15 years, precast segmental concrete cable-stayed construction has effectively built several of America's long span bridges. We have been fortunate to be involved in some phase of 20 of these bridges, completing 9 through final design, 4 projects of which have been constructed. The span lengths of these projects range from 300' to 1700'.

This paper presents a design philosophy, along with example projects where the philosophy has been implemented, that we believe will result in a highly durable precast segmental concrete cable-stayed bridge. The components of this philosophy are: use high quality, long lasting materials, work the materials at conservative stress levels, provide redundant protection systems for stay cables and develop maintainable, replaceable details.

2. HIGH QUALITY, LONG LASTING MATERIALS

A bridge deck constructed with precast concrete offers high quality. The precast concrete segments are produced in a near factory-like setting. This concrete mixes, with strengths between 5,500 psi and 6,500 psi, are rich in cement content and by using pozzolan admixtures, the porosity of the finished product is very low. The procedures for mixing, placing, finishing and curing the precast segments are carefully controlled, assuring high quality.

The Varina-Enon Bridge crossing the James River near Richmond, Virginia is a good example of a bridge which incorporates materials of superior quality. The bridge has a total length of 4,680'. It is constructed using twin parallel box girders of constant depth throughout the entire bridge length, including the 630' cable-stayed main span. The two box girders are connected transversely by precast delta frames, which also provide anchor locations for the central plane of supporting stay cables.

The typical concrete strength used for the segments was 5,500 psi. The strength was increased to 6,000 psi near the pylon to help resist the large compressive stresses resulting from the horizontal stay cable force components. The stay cables were made with as many as 81 - 0.6" diameter 7-wire prestressing strands, grouted inside polyethylene sheathing and wrapped with Tedlar tape.

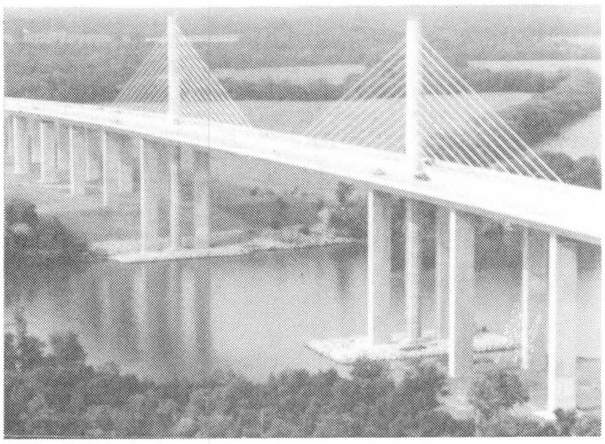


Figure 2.1 - Varina-Enon Bridge, Virginia

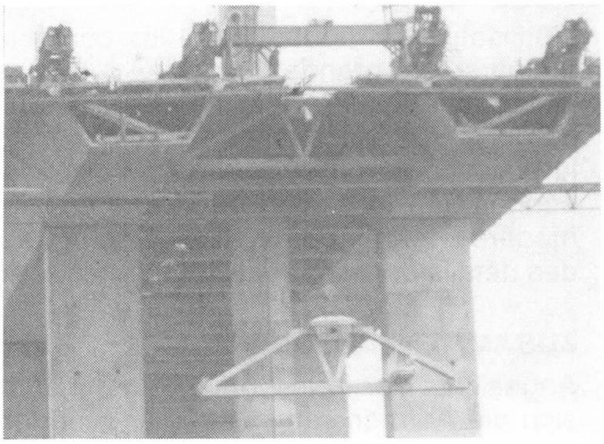


Figure 2.2 - Precast Delta Frames

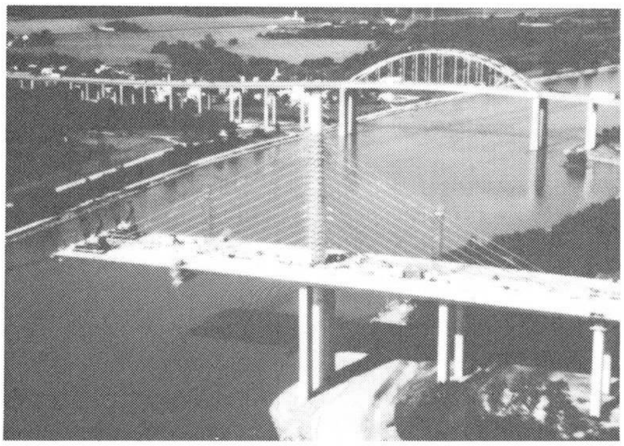
3. CONSERVATIVE STRESS LEVELS

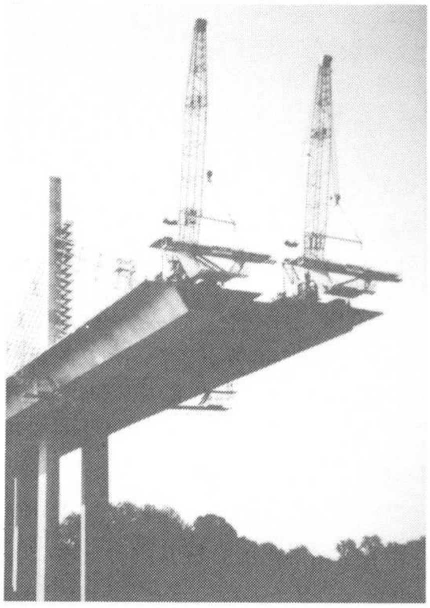
Working together with high quality materials is the fact that precast segmental concrete cable-stayed bridges operate at relatively low stresses. The precast concrete used is limited in compression to 40% its compressive strength under all combinations of loads. Longitudinally, the precast joints are prestressed to provide compression under all loads. Transversely, the top slab of these bridges are post-tensioned, producing a tension free deck design, precompressed in both directions.

The stay cables are also subject to significantly lower stresses, and stress variations, relative to design code limits than most tension elements. The maximum stress in the stay cables is limited to 45% of the guaranteed ultimate tensile strength. The weights of the precast segmental concrete superstructures, coupled with high flexural and torsional rigidities produce low stress variations in the stay cables due to traffic live loading.

The Chesapeake & Delaware (C&D) Canal Bridge is part of Delaware Route 1 crossing the Chesapeake & Delaware Canal just south of Wilmington, Delaware. This bridge, with a total length of 4,650', was built using the same principles as the Varina-Enon Bridge. The twin box girders are joined transversely in the 750' main span by delta-frames and transverse post-tensioning.

The bridge was designed to carry 4 lanes of HS25 loading in each direction. Extensive fatigue testing, as is typical for all cable-stayed bridges in America, was performed for full size stay cable specimen. The cables are made of up to 85 - 0.6", 7-wire prestressing strands grouted inside steel sheathing. The range of stress for the axial fatigue test is 23 ksi for 2 million cycles. The maximum stress variation in a stay cable caused by the design live load with impact is only 3 ksi. This is an extremely conservative design, even when taking into account the differences between the test amplitude and number of cycles versus the actual fatigue characteristics of the projected traffic.





Figures 3.1 and 3.2 - Chesapeake & Delaware Canal Bridge, Delaware. Progressive cantilever construction of the 750' cable-stayed main span.

4. REDUNDANT PROTECTION SYSTEMS FOR STAY CABLES

Two primary systems of corrosion protection have been employed for cable-stayed bridges in America. Both of these systems are based on using 7-wire, 270 ksi prestressing strand for the stay cable. In the first system, the multiple strand stay cable inside of steel pipes. Sections of steel pipe are welded together insitu to form the entire length of sheathing. After the stay cable is stressed, the area between the steel sheathing and stay cable is injected with a cementatious grout. After construction is compete, the stay sheathing receives a 3-part paint system. The second system uses a polyethylene sheathing instead of the steel pipe. The sheathing is grouted as before, and wrapped with a protective tape. Using either of these systems provides a protection system with three levels of redundancy; stay cable strand surrounded by grout, enclosed with sheathing that is protected with an externally applied continuous coating. An additional level of protection is sometimes used to isolate the strands from the surrounding grout. The strands are either epoxy coated or placed in individual plastic sheaths.

The Sunshine Skyway Bridge crosses Tampa Bay, Florida, and connects St. Petersburg with the Sarasota/Bradenton area. The total project length is 21,878′. The main span unit is continuous over its 4,000′ length. The main span length is 1,200′. Construction of the 4,000′ main unit uses 95′-3" wide precast segments erected using the balanced cantilever method. The stay cables for this project are protected by grout, continuous steel sheathing, and a 3-part paint system. The stay cables are continuous through the pylon and are anchored at either end in the bridge deck.

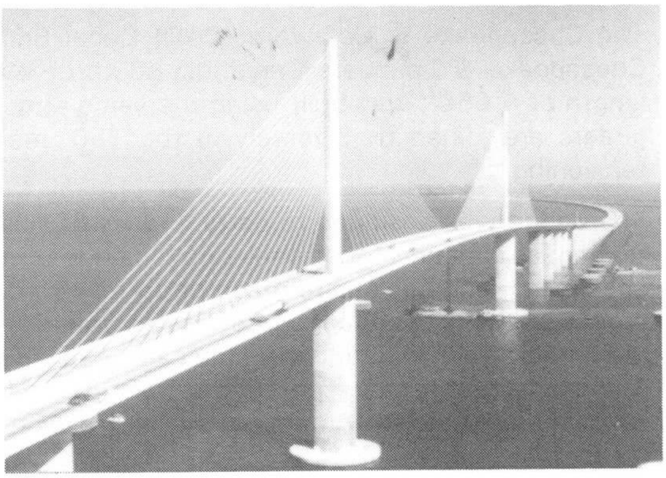
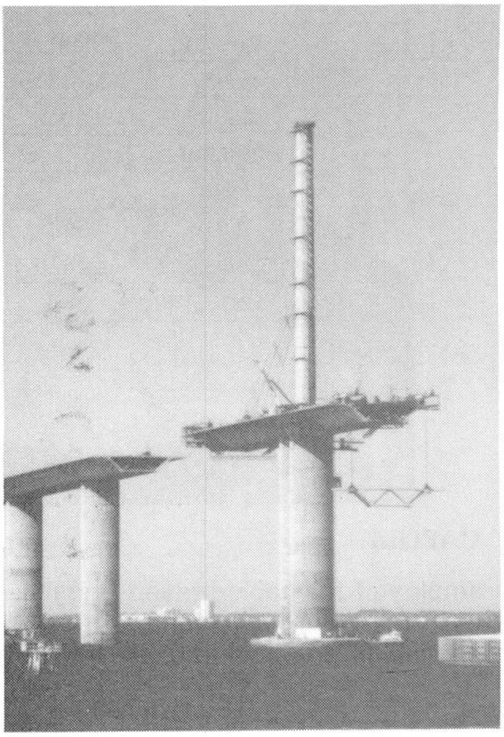
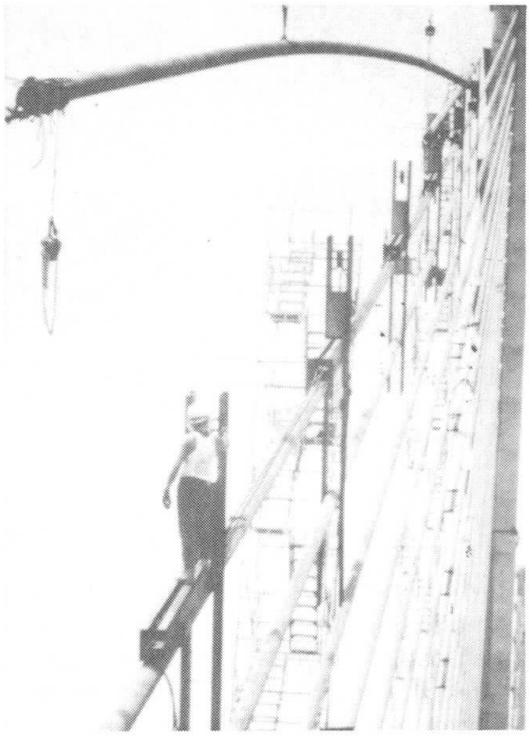


Figure 4.1 - (Right) Sunshine Skyway Bridge, Tampa, Florida.

Figure 4.2 - (Below) Balanced cantilever construction of the 1,200′ cable-stayed main span.

Figure 4.3 - (Below Right) Installation of the steel pipe sheathing for the stay cables.





5. MAINTAINABLE, REPLACEABLE DETAILS

Not withstanding high quality materials, low stress levels, and redundant stay cable protection, maintenance will be required to ensure the ability of these bridges to stand up to the wear and tear of everyday operation. The designs of these bridges must therefore accommodate this anticipated maintenance by developing details that facilitate maintenance and, where necessary, replacement of key components.

The most critical elements that need to be detailed for maintenance and possible replacement are the stay cables. The design criteria for the removal of stay cables for each of the bridges presented in this paper is that any one cable may be replaced under full live loading. To accomplish this, the concrete details should be selected for easy access to the ends of the stays for slackening. The stay cable anchor details should allow for removal of the stay cables through larger diameter guide pipes with relative ease.

The Neches River Bridge in Port Arthur, Texas is a good example of the implementation of these principles. The bridge made of a single trapezoidal box girder with a width of approximately 61 feet. In addition to having a precast segmental superstructure, the pylons and side piers were also built using precast segments. As the bridge is cantilevered in one direction from the pylons, the pylon itself is built vertically in segments. One precast pylon segment is added for each two segments added to the bridge deck. The stay cables were prefabricated to their full length on the completed portion of deck. The stay strands are enclosed in polyethylene sheathing and passes through a prefabricated steel saddle at its midpoint. When needed, the stay is lifted and the steel saddle is placed on bearing seats at the top of the pylon. In addition to simplifying the construction process, the steel saddles are easily accessible and removable.

Figure 5.1 - (Right) Neches River Bridge, Port Arthur, Texas.

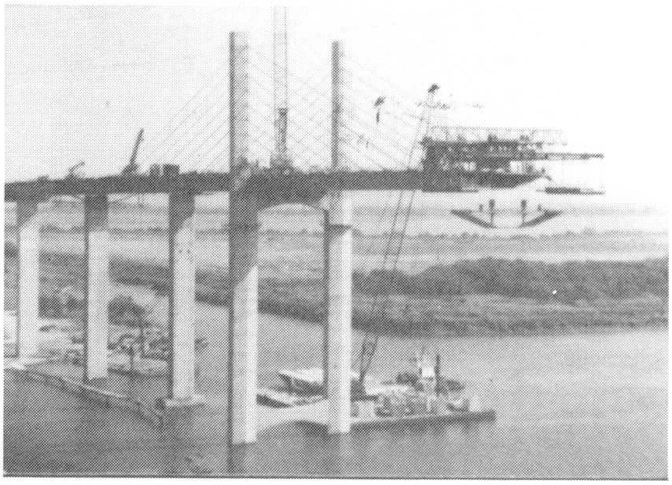


Figure 5.2 - (Below Right) Progressive cantilever construction of the 640' cable-stayed main span.

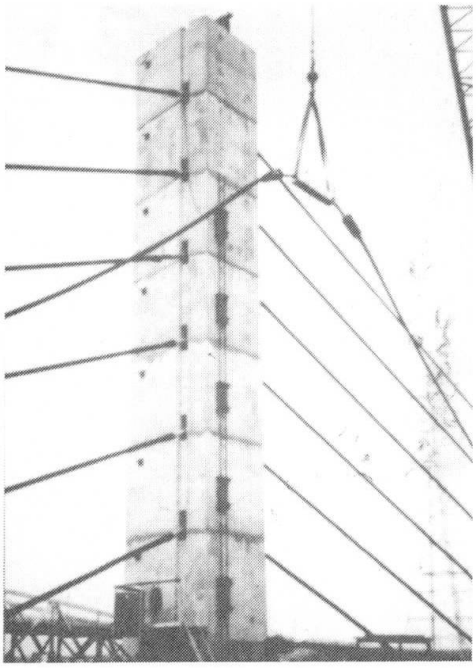


Figure 5.3 - (Below) One of the stay cable assemblies being lifted in place. The stay cables are continuous through the pre-fabricated pylon saddles.

In addition to developing details that facilitate the maintenance of cable-stayed bridges, the designer, with his intimate knowledge of the behavior of the bridge, should develop procedures to assist the owner in his maintenance efforts. This information is often developed in the form of a maintenance manual. These manuals provide the following types of information:

- a brief description of the behavior of the bridge
- definitions of the key elements for maintenance
- recommendations for the frequency and method of inspections
- limiting criteria which would indicate remedial action is required
- descriptions of the approach to remedial actions

6. CONCLUSION

There are few objective guidelines for developing durable bridge designs. In addition, there is only a limited amount of performance history of cable-stayed bridges in America. However, by applying the design philosophy presented above, verified by complete construction and service experiences, durable precast segmental concrete cable-stayed bridges can be obtained.

Cable-Corrosion-Protection Systems for Cable-Supported Bridges in Japan

Protection contre la corrosion des câbles de ponts suspendus et haubanés au Japon

Kabelkorrosionsschutzsysteme für Kabelbrücken in Japan

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SUMMARY

The paper discusses the changes in cable-corrosion-protection systems for Japanese cable-supported bridges. For cable-stayed bridges, non-grout-type cable is becoming the most dominant system due to its good workability on site. For suspension bridges, the wire-wrapping method has been widely used. The validity of this system in Japan is discussed.

RÉSUMÉ

L'article traite de l'évolution du système de protection contre la corrosion des câbles de ponts suspendus et à haubans au Japon. Pour les ponts haubanés, le câble sans injection est devenu le plus courant en raison de sa mise en place facile. Pour les ponts suspendus, la méthode par enroulement a été la plus couramment adoptée. La validité de ce système au Japon fait l'objet d'une discussion.

ZUSAMMENFASSUNG

In der vorliegenden Abhandlung wird die Entwicklung von Kabelkorrosionsschutzsystemen für japanische Kabelbrücken diskutiert. Im Falle von Schrägseilbrücken wird heute wegen der guten Verarbeitbarkeit vor Ort hauptsächlich mit nichtinduzierten Kabeln gearbeitet. Für Hängebrücken findet hauptsächlich das Drahtwicklungsverfahren Anwendung. Die Brauchbarkeit dieses Systems wird in Japan diskutiert.

1 INTRODUCTION

It is said that the first modern cable-stayed bridge in the world was built in Sweden in 1955, the Strömsund Bridge. So, only 40 years has passed since then. In Japan, it was only in 1968, when the Onomichi-Bridge, the first long-span cable-stayed bridge was built. For the cable-corrosion-protection systems of the cable-stayed bridges, several methods have been tried in this short period. But, even at present, we still do not find any final solution. In the former part of the paper, we overview how the cable-corrosion protection systems for the Japanese long-span cable-stayed bridges have changed and discuss merits and problems of each protection system.

On the other hand, the history of modern suspension bridge started in the U.S.A. about a century ago. For the cable-corrosion-protection system, wire-wrapping method has been adopted on many bridges. In the latter part of the paper, we briefly refer to the investigation for the validity of wire-wrapping method in the high-humid atmosphere like Japan, which is now being proceeded by the Honshu- Shikoku Bridges Authority.

2 CABLE-CORROSION-PROTECTION SYSTEMS FOR CABLE-STAYED BRIDGES

Table-1 is the chronological list of Japanese cable-stayed bridges, whose span length is larger than 200m. From this table, we can see how the cable-corrosion-protection systems have changed in Japan. The details will be discussed in the following chapters.

Table-1 Cables for Japanese cable-stayed bridges

	Bridge	Completion	Main Span (m)	Cable							
				Type[1]	Wire[2]	Size(mm)	No. of Planes	Cable Pattern[3]	No. of Cables	Corrosion -Protection[4]	Grout
Steel	Onomichi Br.	1968	215	LCR	galv	Max φ70x4	2	C	2	Paint	Nongrout
	Toyosato Br.	1970	216	PWS	galv	φ5x127, 154	1	F	2	Plastic-Covering(H)	Nongrout
	Suehiro Br.	1975	250	PWS	galv	φ5x(169x7+127x6)	1	F	2	Plastic-Covering(H)	Nongrout
	Kamome Br.	1975	240	PWS	galv	φ5x114, 184, 271	1	F	10	Plastic-Covering(P)	Nongrout
	Rokkou Br.	1976	220	PWS	galv	φ5x217	2	F	5	Plastic-Covering(P)	Nongrout
	Yamatogawa Br.	1982	355	PWS	galv	φ5x217x19	1	H	4	Plastic-Covering(P)	Nongrout
	Meiko Nishi Br.(1st)	1985	405	PWS	galv	φ5x163~379	2	F	12	PE-envelope	Cement, wire coating
	Yasaka Br.	1987	240	PWS	nongalv	φ7x 73~301	2	O	6	PE-envelope	Cement
	Katsushika Harp Br.	1987	200	PWS	nongalv	φ7x121~313	1	F	21	PE-envelope(D)	Cement
	Torikainiwaji Br.	1987	200	PWS	nongalv	φ7x379~421	1	F	8	PE-envelope(D)	Polymer Cement
	Iwagurojima Br.	1988	420	PWS	galv	φ7x139~277	2 × 2	F	11	PE-envelope(D)	Polybutadiene resin
	Hitsuishijima Br.	1988	420	PWS	galv	φ7x139~277	2 × 2	F	11	PE-envelope(D)	Polybutadiene resin
	Tokachi Chuou Br.	1988	250	PWS	nongalv	φ7x 85~301	2	F	7	PE-envelope	Cement
	Yokohama Bay Br.	1989	460	PWS	galv	φ7x199~421	2	F	11	PE-envelope	Nongrout
	Tenpozan Br.	1989	350	PWS	nongalv	φ7x211~349	2	F	9	PE-envelope	Cement, wire coating
	Sugawarashirokita Br.	1989	238	PWS	galv	φ7x 91~163	1	F	11	PE-envelope	Nongrout
	Ikuchi BR.	1991	490	PWS	galv	φ7x151~241	2	F	14	PE-envelope	Nongrout
	Higashi Kobe Br.	1993	485	PWS	galv	φ7x265~367	2	H	12	PE-envelope(D)	Nongrout
	Kemi 1st Br.	1993	238.8	PWS	galv	φ7x151~301	2	F	10	PE-envelope	Nongrout
	Tsurumi Tubasa Br.	1994	510	PWS	galv	φ7x283~499	1	F	17	PE-envelope	Nongrout
	Meiko Higashi Br.	1997(U.C.)	410	PWS	galv	φ7x199~349	2	F	12	PE-envelope	Nongrout
	Meiko Nishi Br.(2nd)	1997(U.C.)	405	PWS	galv	φ7x109~199	2	F	12	PE-envelope	Nongrout
	Meiko Chuou Br.	1997(U.C.)	590	PWS	galv	φ7x199~397	2	F	17	PE-envelope	Nongrout
	Tatara Br.	1999(U.C.)	890	PWS	galv	φ7x163~379	2	F	21	PE-envelope	Nongrout
PC	Yobuko Br.	1990	250	PS	nongalv	φ11.1~φ12.7x19	2	H	17	PE-envelope	Nongrout
	Aomori Br.	1992	240	PS	nongalv	φ15.2x61~73	1	F	10	FRP-envelope	Cement
	Tokachi Br.	1995(U.C.)	251	PS	nongalv	φ15.2x55~61	1	F	16	PE-envelope	Cement
	Ikarajima Br.	1996(U.C.)	260	PS	nongalv	φ11.1~φ15.2x19	2	F	16	PE-envelope	Nongrout
	Notojima Br.	1999(U.C.)	230	PS	nongalv	φ15.2x27~48	2	F	14	PE-envelope	Cement
	Ayunose Br.	1999(U.C.)	200	PS	nongalv	φ15.2x19~27	2	F	12	FRP-envelope	Cement

1)LCR : Locked Coil Rope, PWS : Parallel Wire Strand, PS : Prestressing-wire Strand
2)galv : galvanized wire, nongalv : nongalvanized wire
3)Cable Pattern (F : Fan, H : Harp, C : Convergent, O : Others)
4)Plastic-Covering(H) : hand-lay-up, Plastic-Covering(P) : prefabricated-segment, PE-envelope(D) : Double Envelope

2.1 Corrosion-protection for locked coil ropes (bridges in 1960s)

In most of the cable-stayed bridges in the 1960s, locked-coil-ropes (LCR) have been selected as cable materials, especially in Germany. In the German bridges, in these days, LCR were manufactured of ungalvanized wires in fear of hydrogen brittlement. And the voids were filled with red lead during rope closing. After application of all permanent loads, the surface of the cable was thoroughly cleaned and two basic coats of red lead and two finishing coats like iron glimmer were applied.

In Japan, however, LCR were manufactured using galvanized wires, applying a minimum amount of lubricating oil during closing to avoid any concern about the future stains of the surface. The outer surfaces were usually painted after the dead load has been fully applied. In the Onomichi Bridge, whose cable is LCR, for example, the cable repainting has been done almost every 5 years, and the cables are now judged to be healthy by the observation from the outer surface, after 26 years of bridge life. The recent German corrosion-protection practice for LCR has been modified, taking into account of cable corrosions in some cable-stayed bridges. In the new practice, wires are to be galvanized with a zinc weight of 280g/mm^2. The inner voids are to be filled with polyurethane with zinc dust, or linseed oil with red lead. Outer surface is to be coated with polyurethane.

2.2 Corrosion-protection for PWS-cables (bridges in 1970s)

Entering into the 1970s, LCR was still the most popular cable material for cable-stayed bridges in foreign countries, especially in European countries. In Japan, however, manufacturing technology of the parallel-wire-strand (PWS) had been developed for the suspension bridges of the Honshu-Shikoku Bridge Project. Then, the PWS, comprising of galvanized wire of 5mm in diameter, was introduced into the cables for cable- stayed bridges. A 'PWS' is a bundle of galvanized wires arranged in parallel to construct a hexagonal cross section without any tendency to twist. A large 'PWS' is sometimes used as an individual cable, but in many cases a multiple number of 'PWSs' are bundled into one large cable.

PWS-cables were applied, for example, in Toyosato Bridge, Kamome Bridge, Rokko Bridge, Suehiro Bridge and Yamatogawa Bridge, all of which were built in 1970s. The corrosion-protection for the PWS-cable was usually performed by a plastic-covering. The plastic-covering, in early 1970s, was done by a hand-lay-up method. This is to coat a fiber-reinforced-plastic (FRP) layer, on the cable on site. In the latter 1970s, a prefabricated-segment method was newly developed to improve the workability of a hand-lay-up method. This is to fabricate the FRP segments in the shop, and only to connect them on site to form the covering. But, for these works, an installation of temporary footway along each stay cable, a catwalk, is indispensable. At the same time, some expansion joints have to be installed on the covering with some intervals, because the difference of the expansion-and-contraction between the cable and covering has to be absorbed. In some cable-stayed bridges, lasting about 20 years, some damages are found like small cracks on the covering and some deterioration on expansion joints. Then, some repairing works are required for these plastic-coverings, at present.

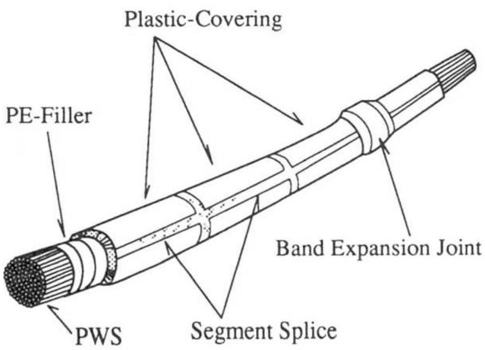

Fig. 1 Plastic coverings on PWS (prefabricated-segment method)

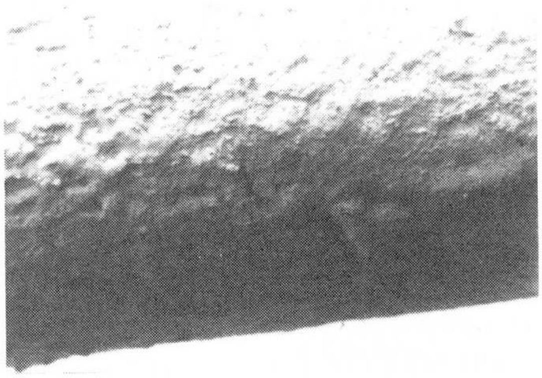

Photo 1 Cracks on plastic-covering (20 years after completion)

2.3 Corrosion-protection for grouted-parallel-wire-cables (bridges in 1980s)

A Parallel-Wire-Cable (PWC) is a parallel wire bundle of prestressing wires (not galvanized), incorporated as a tension member in a polyethylene (PE) tube filled with cement grout for corrosion protection. In the 1980s, PWC became popular in the Japanese cable-stayed bridges, using high-strength wires of 7mm in diameter and fatigue-resistant anchor sockets as the end fittings. In this system, PE is enveloped in the shop, and grout is done on site, and a catwalk installation is not required at the site. For the PE material, high- density PE was selected, to resist weathering, high-pressure, high-heat and external injury. At the same time, 2-3% of carbon is mixed to protect the tube from ultra-violet rays.

When heavier corrosion-protection is required for the important bridge or for the bridge at severe site conditions, additional protection methods have to be applied as follows.

(1) Use of two-layer-PE-tube:
This is to use two layers of PE tubes, so that the cracks on the surface do not reach to the cables. This was applied, for example, to Hitsuishijima Bridge, Iwakurojma Bridge, Katsushika-Harp Bridge and Torikainiwaji Bridge.

(2) Use of galvanized wires:
This is to use galvanized wires instead of nongalvanized prestressing wires. As hydrogen is produced with zinc and cement milk, there is a fear of hydrogen brittlement. Then, for galvanized wires, following countermeasures are required.

1) By coating a polyester coating on galvanized wires, zinc is isolated from cement milk. This was applied in the 1st-Meikounishi Bridge.

2) Instead of cement milk, synthetic resin like poly-butadiene was selected for the grout material. This method is not only good to solve the problem of hydrogen brittlement, but also good to protect the grout material from cracks, caused by the expansion-and-contraction of the cable, which is sometimes seen in the cement grout. But, this method is very expensive because of its large scaffoldings, and it also requires very severe quality-control, which makes the work on site complicated. This was applied to the Hitsuishijima Bridge and Iwakurojima Bridge.

As described above, the problem of a grout-type cable is its troublesome work on site and cable-quality's dependence on site work. In the prestressed concrete bridges, however, prestressing-wire-strands with PE-tube and cement grout are still the dominant cable materials, because their procurement is easy and cost-saving for contractors.

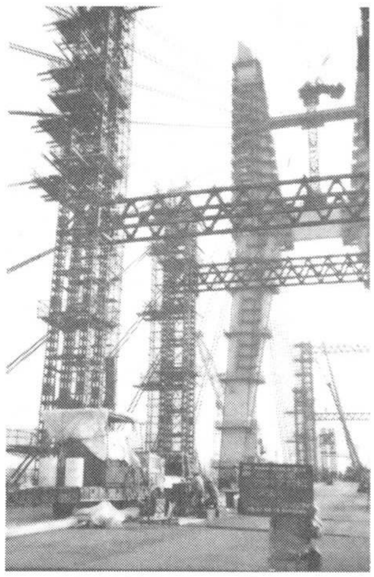

Photo. 2 Grouting of polybutadiene resin (Iwakurojima Bridge)

2.4 Corrosion-protection for nongrout-type cables (bridges in 1990s)

Based on the above background, nongrout-type cables, which does not need complicated grouting, have come into wide use in the Japanese steel cable-stayed bridges from late 1980s. In these cables, parallely-bundled galvanized steel wires are tightly enveloped by PE-covering to isolate the cable from outside, in the completely quality-controlled shop. Both ends of the cable is anchored by fatigue-resistant end- fittings, for which several structures are manufactured by some companies. These cables are featured as follows.

(1) To enable the reeling of the cable, each wire is bundled with a lay-angle of not more than 4 degrees. The experiments show that this lay-angle will not deteriorate cable's properties like the Young's modulus, tensile strength, and fatigue strength, comparing with values of each wire.

(2) PE-envelope is completely shop-fabricated by a directly extruded PE jacket, after wrapping the bundled wires with a corrosion-protection tape or after coating wires with corrosion-protection

compound. This cable-work does not require further works on site, like scaffoldings-installation and groutings, after cables are erected. Due to the good workability of the nongrout-cables, the selection of multi-cable-bridges became easier.

(3) Even when the PE-envelope is injured, the durability of the cable can be kept for some time, as wires are galvanized. Of course, the replacement of injured PE-envelope can be done easily. Then, the inspection of the cable can be done, by tearing off part of the PE-envelope, and by watching the cable from the torn-PE-window.

(4) The color of the PE-covering is black, as carbon is mixed in it. To manufacture colored cables other than black, cable-coloring technologies have been developed. One is to extrude a colored thin fluoro polymer on the black PE layer to change the black cable to colored one. Another is a paint coating system. It consists of an application of a primer, made from adhesive components for PE-envelope and for the finish coat, and a baking of the primer with the far infrared ray. The finish coat is usually done by fluoro-olefin paint. The light color is not only good for the good sceneries but also good for the temperature control of the cables.

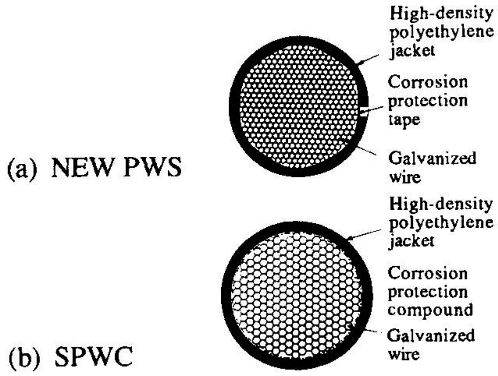

Fig. 2 Nongrout-Type-Cables

3 CABLE-CORROSION-PROTECTION SYSTEMS FOR SUSPENSION BRIDGES

In most of the Japanese suspension bridges, parallelly-bundled galvanized steel wires of 5mm in diameter are used. For the corrosion-protection, its outer surface is usually coated by corrosion-inhibiting paste, on which galvanized steel wires are wrapped tightly circumferentially. This system has been widely used in many bridges. In this system, however, intrusion of rain during the cable-erection cannot be protected. According to the inspection of U.S. suspension bridges, which was executed by watching inside of the cable with the aid of wedges, although some corrosions of galvanized wires were seen in a few layers of outer cables, the inside were judged to be healthy.

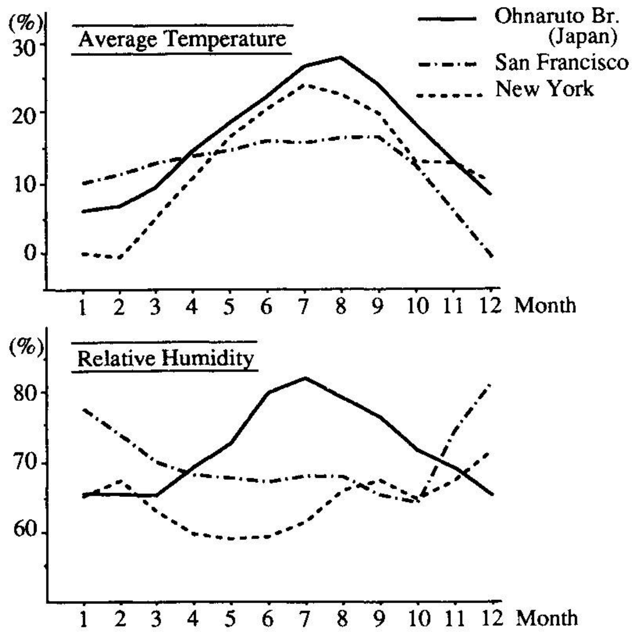

Fig. 3 Comparison of meteorological conditions between Japan and U.S.A.

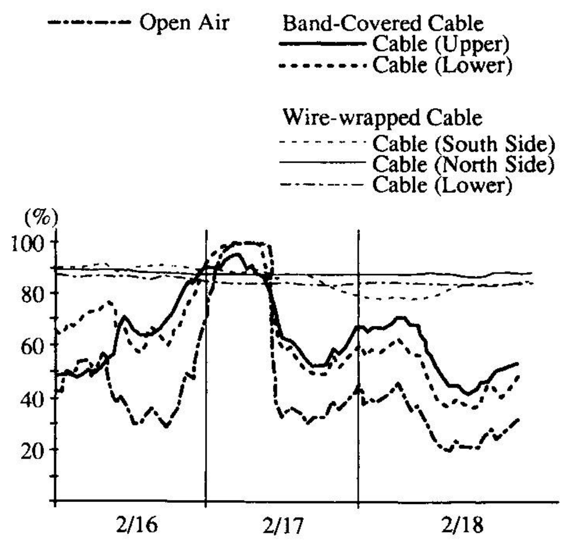

Fig. 4 Measurement of the humidity in the cable

As shown in Fig-3, Japanese meteorological condition is higher in the temperature and the humidity than in the U.S.A. Then, the validity of the wire-wrapping method in this atmosphere should be checked. The inspection of the cable of the Innoshima Bridge, lasting about 10 years, shows that some corrosions were seen in the wires of a few outer layers in the wire-wrapped cable, like American bridges. On the other hand, the band-covered cable, where any paste is not coated, were healthy. The difference of the cable's atmosphere between the wire-wrapped cable and band-covered cable was researched in the Ohnaruto Bridge. As shown in Fig-4, the wire-wrapped cables are always in high-humid environment, regardless of the humidity in the open air. On the other hand, the humidity under the cable-bands varies in accordance with the change of that in the open air. This means that there is a close relationship between cable's corrosion and high-humid environment.

Considering the severe meteorological environment of Japan, we judged that the humid atmosphere, which might cause the cable's corrosion, should be removed. From these standpoints, the Honshu-Shikoku Bridge Authority (HSBA) started the research for the dehumidification system of the cable. At present, air-blowing test by dehumidifier is proceeded at the Honshu-Shikoku Bridges, and came to the stage of almost practical use. We hope that the details will be presented in the near future.

4 CONCLUDING REMARKS

(1) In the Japanese cable-stayed bridges, cable-corrosion-protection systems have changed in the short history. In steel bridges, nongrout-type cables, which consist of parallely-bundled-galvanized-steel-wires and extruded PE-covering without grout, are becoming the most popular cable material. This is, firstly, due to the manufacturing-technology at the quality-controlled shop, and secondly due to the good workability on site.

(2) A research has been conducted for the validity of wire-wrapping method, which is mostly accepted for cable-corrosion-protection system in the Japanese suspension bridges. The research shows that the high-humid atmosphere might cause the corrosion of galvanized wires, and that it might be removed by dehumidification system.

5 REFERENCES

(1) M. Ohashi: "Cables for Cable-Stayed Bridges", Cable-Stayed Bridges: Recent Developments and their Futures, ELSEVIER, December 1991, pp.125-150.

(2) Civil Engineering ASCE,April 1988, pp.38-41, October 1988, pp.46-49

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

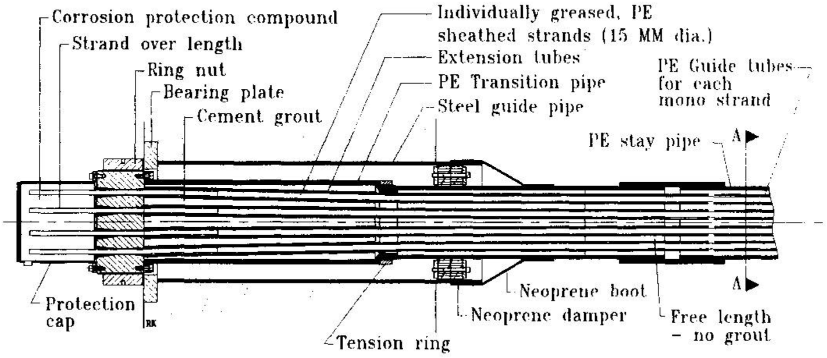

Figure 1: SSI Monostrand Anchorage

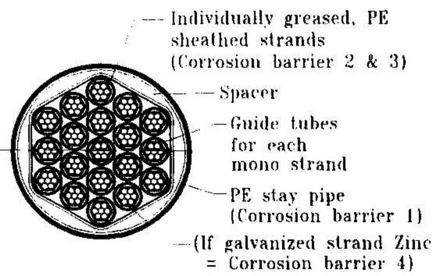

Figure 2: Section - SSI Stay Cable

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.

REFERENCES

1. PODOLNY, W., Current Corrosion Protection Methods for Cable Stays. Third International Concrete Bridge Symposium, ACI 1992 Convention, Washington DC, 1992.
2. SAUL, R. and SVENSSON, H.S., On The Corrosion Protection of Stay Cables, Wilhelm Ernst and Sohn Verlag für Architektur und technische Wissenschaften, Berlin, 1990.
3. WATSON, C.S. and STAFFORD, D., Cables in trouble, Civil Engineering, ASCE, April 1988, pp. 38-41.
4. Recommendations for Stay Cable Design and Testing, PTI Ad Hoc Committee on Cable-Stayed Bridges, USA, March 1993.
5. BUERGI, P., Recent Approaches to Corrosion Protection in Stay Cable Design, IABSE Symposium, Leningrad, 1991.
6. TAKENA, K., MIKI, C., SHIMOKAWA, H. and SAKAMOTO, K., Fatigue Resistance of Large Diameter Cables for Cable Stayed Bridges, Journal of Struct. Eng., Vol. 118, No. 3, 1992.
7. Combined Axial-Flexural Fatigue Test of 82 Strand Stay Cable Specimen, Construction Technology Laboratories, Inc., Illinois, February 1995.
8. Fatigue and Static Tests of 85 Strand Stay Cable Specimen, Construction Technology Laboratories, Inc., Illinois, July 1993.
9. MOORE, M., Use of Epoxy Coated Prestressing Strand in Concrete Bridge Structures, FIP94, XII Congress, Washington DC, May 29- June 2, 1994.

Investigation of Corrosion Protection Systems for Bridge Stay Cables

Systèmes de protection contre la corrosion pour les câbles de ponts à haubans

Untersuchung von Korrosionsschutzsystemen für Brückenschrägkabel

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SUMMARY

Of paramount importance for bridge stay cables is a dependable corrosion protection system. A recent survey indicated a general concern over the ability of the traditional cement grout system to provide dependable corrosion protection. The initial phases of a current experimental program investigated the effectiveness of the cement grout corrosion protection system with and without temporary corrosion protection on the strands. The baseline specimen used bare strand in Portland cement grout with no temporary corrosion protection added. Variables included use of temporary corrosion protection and different axial and transverse loading configurations.

RÉSUMÉ

Des systèmes fiables de protection contre la corrosion pour les câbles de ponts à haubans sont d'une importance extrême. Une étude récente a indiqué que les coulis de ciment traditionnels ne sont pas très fiables dans la protection contre la corrosion. Les phases initiales d'une recherche expérimentale en cours se sont axées sur l'efficacité des coulis d'injection comme système de protection contre la corrosion, avec ou sans protection des torons contre la corrosion. Le spécimen de comparaison comporte un toron dans du ciment portland sans addition de protection temporaire contre la corrosion. Parmi les variables d'études figurent la protection temporaire contre la corrosion et des procédures différentes de chargements transversaux et longitudinaux.

ZUSAMMENFASSUNG

Ein zuverlässiges Korrosionsschutzsystem ist von höchster Bedeutung für Schrägkabel in Brücken. Eine vor Kurzem durchgeführte Umfrage wies darauf hin, dass Bedenken hinsichtlich der Zuverlässigkeit traditioneller Zementmörtel Korrosionsschutzsysteme bestehen. Dieser Aufsatz berichtet von der ersten Phase eines Forschungsprojektes in dem die Wirksamkeit von Zementmörtel Korrosionsschutzsystemen mit und ohne provisorischem Korrosionsschutz für die Litzen untersucht wurde. Im Grundversuch wurden nackte Litzen mit Portland Zementmörtel ohne temporärem Litzen-Korrosionsschutz geprüft. In weiteren Versuchen wurde die Benutzung von temporärem Litzen-Korrosionsschutz und verschiedene axiale und transversale Belastungskombinationen als Variable eingeführt.

1. Introduction

An experimental program is currently underway at the University of Texas at Austin to investigate the effectiveness of corrosion protection systems of several currently used stay cable systems. The major component of the experimental program involves durability testing of eight large-scale stay cable specimens. The results from the tests on the first four specimens, which have been completed, are presented in this paper. The second set of tests, which are currently underway, focus on improved systems of corrosion protection for the individual strand including galvanizing, epoxy coating, and greasing and sheathing. In addition, an improved grout over bare strand will be tested. The specimens are subjected to an artificially severe exposure which is not intended to represent a specific exposure condition but rather a loss of sheathing and exposure to an aqueous salt solution to illustrate the relative effectiveness of the different protective systems.

2. Specimen Design and Construction

2.1 Materials and Configuration

Each specimen was constructed with twelve 12.7 mm dia. seven wire strands (Figure 2.1) with a guaranteed ultimate tensile strength (GUTS) of 1860 MPa. The sheathing along the free length of the specimen was transparent PVC pipe while the transition sheathing was transparent acrylic pipe. This allowed visual observation of the internal stay during tensioning, grouting, loading, and accelerated corrosion tests. The "live end" anchorage was a 254 mm dia. threaded anchorhead with a ring nut to allow adjustment in the tension of the stay. The opposite "dead end" anchorage utilized a 152 mm dia. anchorhead.

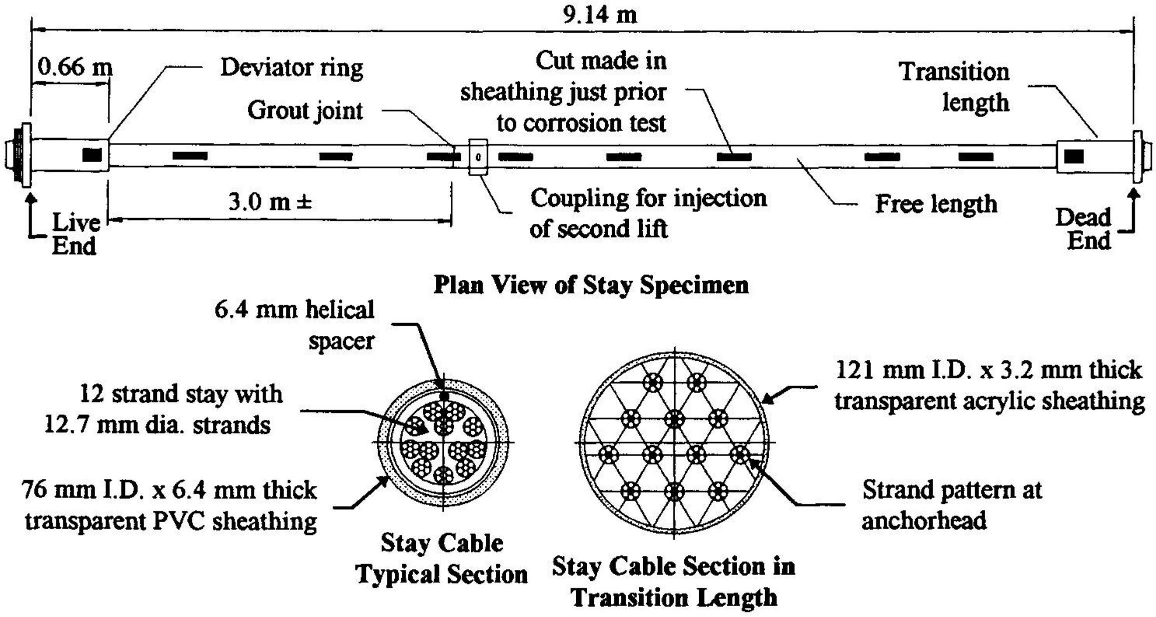

Figure 2.1 - Details of Large Scale Stay Cable Specimens.

The stay specimens in this initial series were:

- **LS1**: Bare strand stressed to axial dead load levels but with no additional axial or transverse load prior to and during corrosion test.
- **LS2**: Bare strand stressed to axial dead load levels and then loaded with additional axial or transverse load prior to and during corrosion test.
- **LS3**: Strand with temporary corrosion protection (TCP) and stressed to axial dead load levels but with no additional axial or transverse load prior to and during corrosion test.
- **LS4**: Strand with TCP and stressed to axial dead load levels and then loaded with additional axial or transverse load prior to and during corrosion test.

PTI *Recommendations for Stay Cable Design, Testing and Installation* (PTI Recommendations) requires the use of temporary corrosion protection on bare tension elements for corrosion protection in the time between erection and injection with grout.[2] An emulsifiable oil (Dromus B manufactured by Shell Oil) was used for the temporary corrosion protection in these tests. The stay was not flushed prior to grouting.

2.2 Assembly

Each stay was assembled, stressed, grouted, and tested in a structural steel reaction frame. The frame reacted the specimen force which allowed the specimens to be moved to different areas in the laboratory for each phase of testing.

Following assembly of the stay each strand was stressed individually from the dead end with a monostrand jack. The strands were retensioned once to reduce the difference in stress between each strand due to elastic shortening of the frame. The basic tension level was 30% GUTS which simulated a typical bridge dead load level. The final adjustment to the tension prior to grouting was made from the live end by adjusting the ring nut.

After stressing, the frame was placed in the grouting position at a 35 deg. angle with the live end at the bottom. This was to simulate a typical stay grouting orientation in the field. The grouting was completed in two lifts. The first lift was injected into the live end grout cap, through the anchorhead, and up the stay approximately half the free length. After the grout had cured for 24 hours the second lift was injected into the stay just above where the first lift ended, was pushed through the remainder of the stay, the dead end anchorhead, and discharged from the dead end grout cap. The grout mix used a 0.4 water/cement ratio (by weight) with the addition of an anti-bleed admixture Sikament 300 SC (as manufactured by Sika Corporation) at the rate of 2.2% cement weight.

2.3 Loading Prior to Corrosion Test

Following the 28-day curing period for the grout, the corrosion tests were started immediately on LS1 and LS3 with the stay stress levels at the dead load level. However, LS2 and LS4 were given temporary additional loads prior to starting the corrosion tests to simulate loading conditions which a stay might experience following grouting. Two temporary additional load configurations were imposed on the specimens.

The first additional load configuration was a single point load perpendicular to the stay axis applied at midspan (Figure 2.2). During the application of this load, supports were installed at the interface between the transition length and the free length. These supports simulated dampers which are typically installed on stays to reduce vibrations. They also alter the pattern of bending stresses in the stay when it is subjected to lateral loads. The intent of applying this lateral load was to simulate the stresses which may occur near the anchorage region caused by wind or light earthquake loads and to determine their effect on the corrosion protection provided by the grout.

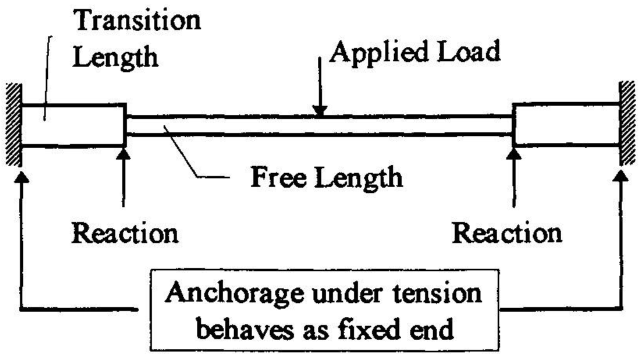

Figure 2.2 - Lateral Loading Conditions for Large Scale Specimens

The second additional load configuration was the application of additional axial load through the live end anchorage to simulate live loads. The stay axial load was increased from 30% GUTS to 45% GUTS, which is the prescribed dead plus live load allowable stress in PTI Recommendations.

The transparent sheathing allowed the specimen to be monitored visually for cracking in the grout during loading. Crack locations were marked on the sheathing for reference during the accelerated corrosion tests. Crack widths were also measured using a portable microscope at regular intervals throughout the loading cycle. Some portions of the specimen such as the anchorage region and load points were hidden from view by the frame or loading devices. This prevented the search for cracks in these areas during the application of additional load. Upon completion of the loading the specimens were subjected to the accelerated corrosion test.

3. Accelerated Corrosion Tests

In a comprehensive international survey, it was found that the average life which the bridge owners surveyed expected from the stay cables on their bridges was in the range of 75 years.[3] This presents a dilemma when designing an experimental program which is intended to test the durability of a bridge stay cable. Static and fatigue loading can be simulated in the laboratory in such a way as to mimic, reasonably well, the critical load effects which the structure might experience in its lifetime. However, durability is very much a time related and site specific characteristic. Ambient temperature, thermal heating, precipitation, humidity and pollutants all combine to "load" the structure in a very complex and little understood manner. To develop a test which directly addresses all of these areas is not economically feasible or considering the extremely long time duration not even technologically desirable.

Accelerated corrosion tests have been developed which can provide a basis with which to select corrosion resistant materials for long term use without having tested them for the expected life of the structure. One example of this is the macrocell test which is designed to represent corrosion of reinforcement in a concrete bridge deck.[4] The macrocell specimen is constructed to represent a small section of bridge deck and is then ponded with salt water in wet/dry cycles to represent the application of deicing salts, but in a much accelerated manner.

The goal in designing the accelerated corrosion test was to identify a realistic but severe corrosion mechanism, somewhat similar to the macrocell test, by which the cable could be tested in a reasonable amount of time. The stay configuration which was tested in this first series has essentially two layers of protection: the PE sheathing and the portland cement grout. PE pipe, when intact, provides an excellent barrier to moisture. However, it has been documented that some bridges in service have developed cracks or breaks in the PE sheathing.[5] Consequently, it was decided that the protection provided by the portland cement grout after a local break in the PE sheath would be the focus of the accelerated corrosion tests. Small local openings were made in the sheathing (to simulate accidental breaks) of each specimen and salt solution was ponded on the exposed grout surface in wet/dry cycles. Application of the salt solution represents an accelerated version of the intrusion of airborne chlorides which would occur on a bridge near the seacoast or in a region where heavy applications of deicing salts are used.

There were 8 locations along the free length of the specimens where a 25 mm by 280 mm section of the sheathing was removed (Figure 2.1). There was also one location on each transition length where a 50 mm by 150 mm section of sheathing was removed. An acrylic dam was attached to each of the openings to allow ponding of a 5% (by weight) salt water solution. Once the sheathing had been removed and the dams were in place the salt water was applied in cycles of two weeks wet and two weeks dry. The accelerated corrosion test lasted for a total of three months which permitted three wet and three dry cycles. Half-cell potentials were taken on the surface of the grout in each of the openings prior to initiating the accelerated corrosion test and at every interval between cycles.

All specimens were at a minimum axial stress level of 30% GUTS during the corrosion tests. In addition, specimens LS2 and LS4 were given additional axial loading during the accelerated corrosion tests. One week into each wet cycle, increased axial load was applied to specimens LS2 and LS4. Each was loaded from 30% to 45% GUTS for ten cycles. The load was held at 30% and 45% GUTS for one minute during each cycle. Following ten load cycles the stress was reduce to 30% GUTS.

After completion of the accelerated corrosion tests, the specimens were detensioned and completely disassembled. Each part of the stay was inspected for corrosion including the strands deviator ring, wedges, anchorage, and end cap.

4. Results and Discussion

Air Pockets in Grout - Figure 4.1 shows the orientation of the specimens when the grout was injected. Although the stays were grouted under ideal laboratory conditions, air pockets formed in the grout in all of the specimens. As Figure 4.1 indicates, some formations were more severe than others with all of the air pockets forming in the top side of the stay. In addition, air pockets formed in the unvented corners of the specimen such as at the top end of the live end transition length and the underside of the dead end anchorhead. Generally, the shape of the air pockets along the free length of the stay could be described as very wide cracks in the grout. They were not actual grout cracks because they formed prior to the grout setting. The anti-bleed admixture thickens the grout as well as retarding the initial set. It is hypothesized that, because of the high viscosity of the grout, air was trapped between the strands during injection. After injection, while the grout was still fresh, the air pockets slowly migrated to thé top side of the stay, leaving the strand unprotected in that area. This is consistent with observations made after the grouting. After completion of the grouting, the air pockets would initially appear at the top side of the stay and migrate slowly towards the top of the grout lift. The air pocket would then stop moving when the grout reached initial set. Injection of the stay at an angle to simulate field conditions rather than vertical, as is generally done in stay acceptance tests, was an important aspect of the stay testing. If the stay specimens had been injected in the prone or vertical position the air pockets may not have formed.

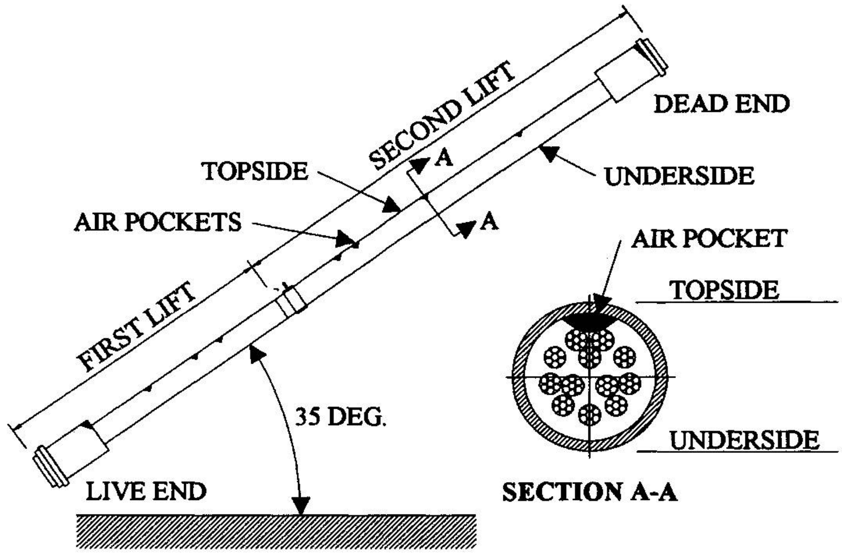

Figure 4.1 - Schematic Elevation of Specimen in Grouting Position

Shrinkage Cracking of Grout - Prior to the application of additional axial load on specimens LS2 and LS4 and prior to cutting openings in the sheathing on all specimens, the grout remained uncracked, as determined by visual observations. Once the sheathing had been opened locally, the exposed area of grout dried and localized shrinkage cracking occurred. The cracks were oriented both perpendicular and parallel to the axis of the stay. Depending on the ambient humidity, the cracking usually occurred within 2 to 3 days after the sheathing had been opened locally and only occurred in and around the opening in the sheathing.

Cracking of the Grout under Load - Specimens LS2 and LS 4 were given additional loads axially and laterally after grouting but prior to initiating the accelerated corrosion tests. During lateral loading a small amount of cracking was audible through the complete loading cycle. However, cracks were not visible at any of the visually accessible locations along the length of the stay. During additional axial loading, cracks were also audible but a much larger number of cracks were heard than in lateral loading. Cracking was heard immediately upon initiation of the increased axial loading at slightly above 30% GUTS and was audible through 34% GUTS. Above 34% there was no audible cracking detected. Cracks were noted at 33% GUTS on LS2 and at 36% GUTS on LS4. However, it is suspected that the cracks on LS4 may have been visible at a lower stress level because, on that specimen, crack inspection did not begin until the load was at 36% GUTS. In summary, the cracking occurred at very low increased stress in the stay relative to the allowable stress range. This indicates that a stay does not have to be heavily loaded in order to cause grout cracking.

Corrosion Occurred Rapidly - Corrosion product had appeared on the surface of the grout in at least one opening in all the specimens by the end of the second wet cycle. Typically, this corrosion was occurring at the intersection between the strands and the grout cracks. This location was determined during demolition of the specimens following completion of the corrosion tests. This behavior indicates that the permeability of the grout is of little significance when the sheathing is broken and the grout cracks.

Location of Corrosion - Although the majority of the corrosion found during the demolition of the specimens was on the strands under openings cut in the sheathing, corrosion was also found in locations away from the openings especially under air pockets in the grout. Corrosion was found in the anchorage region including especially the interface between the wedges and strand. Very heavy damage was found between the inner and outer wires of the top strand in specimen LS2, while there was no damage found on the exterior wires. This indicates wide ranging transport or migration of the salt water along the stay.

No Additional Protection Provided by TCP - There was no discernible improvement in the performance after grouting of the specimens which were coated with TCP during assembly.

5. Conclusions

Four large scale stay cable specimens have been subjected to an artificially severe environment with the purpose of providing a comparison of the relative effectiveness of the currently used corrosion protection systems. Openings were made in the sheathing which represented accidental breaks in an actual stay. The exposed surface of the grout was then ponded with salt water. In addition to providing a basis with which to compare the improved systems, the testing uncovered many interesting behavioral tendencies. The most important of these is that within two to three days of cutting an opening in the sheath the grout in the immediate vicinity of the opening will shrink and crack. This finding essentially voids the concept that a stay system which has bare strand with or without TCP in a PE sheath and is injected with portland cement grout is a "two barrier system." At any location where a break in the sheathing occurs the grout will probably crack, allowing immediate access of air and moisture and also chlorides or pollutants, if present. Effectively, the corrosion protection system of the stay cable is reduced to the PE sheathing. Based on these findings, it is recommended that this method of providing corrosion protection be improved. Additional layers of protection should be used to provide more redundancy in the current corrosion protection systems. Examples of some improvements are epoxy-coating, galvanizing, or greasing and sheathing. It would appear that improvements in the grout which can inhibit or prevent corrosion of the strand might also be compromised by the cracking. The second series of stay specimens in this study will investigate some of these possible improvements.

6. Acknowledgements

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7. References

1. HAMILTON III, H. R. and BREEN, J. E., International Survey of Current Operation on Bridge Stay Cable Systems, IABSE Symposium, San Francisco, August 23-25, 1995.
2. Post-Tensioning Institute Committee for Cable-Stayed Bridges, Recommendations for Stay Cable Design, Testing and Installation, August, 1993.
3. HAMILTON III, H. R. and BREEN, J. E., Stay Cable Survey, Phil M. Ferguson Structural Engineering Laboratory, The University of Texas at Austin, February, 1995.
4. ASTM G109-92, Standard Test Method for Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments.
5. WATSON, S. C. and STAFFORD, D., Cables in Trouble, ASCE Civil Engineering, April, 1988.

Stay Cable Corrosion Protection with Petroleum Wax

Protection des haubans contre la corrosion avec de la cire pétrolière

Korrosionsschutz von Schrägseilen mit Ölwachs

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SUMMARY

Stay cable technology has been extensively developed in recent years. Owners and authorities are considering lifespan of 120 years and even more. Consequently, corrosion protection materials and systems have been developed and tested. Large research programmes have been initiated all over the world. The purpose of this paper is to present the latest developments about petroleum wax used as corrosion protection for stay cables and to consider various aspects such as: fatigue resistance and fretting corrosion, individually protected galvanised and waxed strands, injection operations and connections details.

RÉSUMÉ

La technologie des haubans a fait l'objet d'un large renouvellement durant les dernières années. Les clients envisagent des durées de vie de 120 ans et plus; en conséquence, de nouveaux systèmes et matériaux de protection contre la corrosion ont été développés et testés partout dans le monde. Cet article présente les derniers progrès réalisés avec la cire pétrolière et les résultats positifs obtenus en matière de résistance à la fatigue et de protection contre la corrosion.

ZUSAMMENFASSUNG

Während den letzten Jahren wurde die Schrägseiltechnik erneuert. Die Bauherren beabsichtigten Lebensdauern von 120 Jahren und mehr; infolgedessen wurden neue Schutzvorrichtungen und Werkstoffe gegen die Korrosion weltweit entwickelt und erprobt. Dieser Artikel legt die neuesten Fortschritte über Ölwachs und die positiven Ergebnisse bezüglich der Widerstandsfähigkeit gegen die Ermüdung und den Schutz gegen die Korrosion vor.

1. INTRODUCTION

The stay cable technology has been extensively renovated during the last ten years. This development founds its origin in the owner's requests for having the longest life span as possible (120 years for instance) and in the contractor's demand for simplicity and efficiency, but also in the significant improvements recently made in the materials themselves.

How to increase the life span ? By providing a better quality product from the very beginning of the construction and by developing the surveillance concept since there are no material suppliers able to give today a 120 years guarantee ! Therefore, the service life of a stay cable is largely dependent upon the effectiveness and durability of the corrosion protection.

Cement grout was used in the early days as corrosion protection. This was the direct application of the technique used for post-tensioned cables in bridges. However, this product showed rapidly its limits :

- The cement grout is heavy ; it represents a significant part of the stay weight, which becomes a disadvantage in large bridges.
- The requirements of good quality grouting implied the use of large diameter duct, thus increasing wind effect. Grouting operations are questionable
- The cement grout in the anchorage zone has a negative influence to the fatigue resistance of the stay. It induces fretting corrosion.
- The cement grout creates a group effect which reduces the performance of the stays.

A soft material having excellent corrosion protection characteristics needed to be considered.
Also temporary corrosion protection rapidly appeared to be a necessity in the site conditions :

- harsh environment : humidity, salted atmosphere, temperature variations,
- construction requirements : storage, transport, handling.

Thus individually protected galvanized strands are commonly used today. They consist of hot dip galvanized strands coated with high density polyethylene and provided with a protective filler inside the interstices between the king wire and the outer wires and around the outer wires. This protection filler is also used as the permanent corrosion protection material in the anchorage area. It consists of a petroleum wax (INJECTELF CP or HPF type). This paper presents the latest developments and corrosion protection characteristics of this material.

2. PETROLEUM WAX FOR CORROSION PROTECTION

2.1 Definition

Several petroleum products are proposed and have been used. It is necessary to define each of these products for clarification . :

- Gatch : mix of paraffin and waxes including a high percentage of oil (up to 30 %)
- Crystalline paraffin : this product is obtained by disoiling of the gatch during crystallisation.
- Microcrystalline wax : this product is obtained from heavy components of distillation.
- Petrolatum : a mix of paraffin and oils.
- Vaseline : result of refining and dilution of petrolatum.

2.2 Petroleum wax characteristics

The product described hereafter is a microcrystalline wax INJECTELF CP HPF which has been specially developped by the Laboratoire Central des Ponts et Chaussées at Paris with a french oil company [1].
Waxes are made of saturated hydrocarbures according to formula $C_n H_{2n+2}$ types with a high percentage of ramified chains and a microcrystallisation. This explains its flexibility, and its adesive properties to various supports. Somme specific additives provide excellent behaviour under extreme pressure (fretting corrosion) [2] and[3].

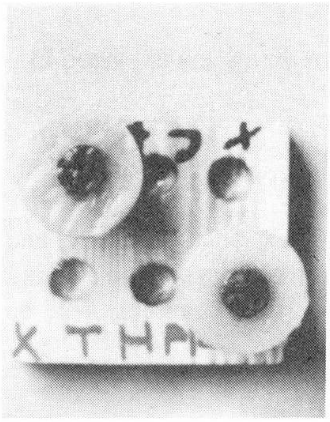
2.3 Corrosion protection properties

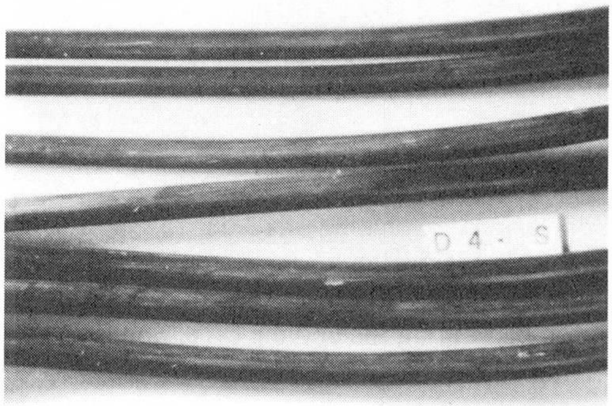
A series of comparative stress corrosion tests have been carried out [4] in distilled water at the LCPC according to the French standard NF A05-302.

The samples for tests were taken in the same coil of a strand T12,4-III-TBR.

The mechanical characteristics of these non-protected prestressing steels were determined by tensile tests before and after the stress corrosion tests and were considered as a basis for comparison. These basis corrosion tests were continued till rupture of a least one of the individual strand wires.

Before applying the protection products, the strands have been examined on a magnetoscopic device neither crack nor micro crack has been observed. Some of the protection products have been spread on the sample surface in two layers : one so called thin layer through which the steel was still visible. A so called thick layer (0.5 to 1 mm) under which the steel disappeared. The protected samples (two samples per tested product) were put in waterproof cells then installed on constant length devices. The loading was made with a jack ; once the load applied, filling the cell with water and circulating it were done as quick as possible.





Taking into account the available test devices, twelve products were being tested by the LCPC at Nantes during 270 days, the left three products by the LCPC at Paris during 6 months for the first series and 31 months for the second test series with and interruption of one month after 22 months.
For all the protection products, we observed that they bring an increase in the life time of the strands in the standardized stress-corrosion testconditions (NF A 05-302).

Results obtained after 31 months on three different samples (Complex aluminium grease,wax,calcium grease) have demonstrated the better behaviour of the petroleum wax.

- 31 months without rupture to be compared with the 4 months life time of the non-protected strands coming from the same coil.
- No pit
- No mechanical characteristic losses
- Rupture in the emerged zone. This proves that the observed dissolution spots in the immerged were zones of little importance and had no detrimental effect.

2.4 Low temperature behaviour of the wax

It has been reported [5] that wax was showing irreversible cracking at -50°C. A series of tests have been carried out at the LCPC at Paris with different waxes : one having a melting point at 70/75°C (type a) and another at 110/115°C (type b). The tests parameters were the injection temperature 95°C, 105°C, 125°C. Then, the test samples were subjected to the following temperature cycles.

Temperature Cycles	**Initial Temperature**		**- 40°C**		**- 50°C**		**Final Temperature**
		TIME	**IN**	**MINUTES**			
1	**24°C**	**32'**	**3'**	**5'**	**3'**	**23'**	**6°C**
2	**20°C**	**17'**	**6'**	**3'**	**-**	**13'**	**6°C**
3	**16°C**	**17'**	**6'**	**3'**	**-**	**18'**	**5°C**

Results :

- Cracking was observed after cooling at ambient temperature while using wax type b in an empty pot while injecting at the highest temperature 125°C..

- No cracking was observed with type b when a steel rod (10 mm diameter) is placed in the centre of the pot and the highest injection temperature.

- No cracking was observed with wax of type a in any condition.

Conclusion : Cracking may be observed at ambient temperature if the wax characteristics and injection specifications have not been properly selected. This cracking will remain during the cooling cycle. However if no cracking is observed at ambient temperature no further cracking will be developed during the cooling cycle down to -50°C.

3. APPLICATIONS

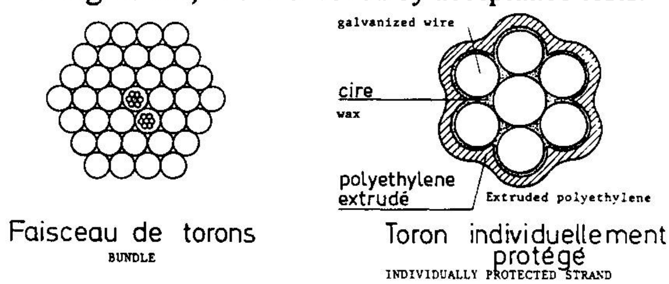
3.1 Stay cables with petroleum wax injected on site .

Tampico bridge (Mexico) built in 1984-1988 was the first cable stayed bridge using this technique. Stays consist of an overall HDPE duct in which galvanized strand are threaded. Wax injection was carried out on the deck then the stay was lifted into place and tensioned. For other bridges, (ELORN) France, the galvanized strands were threaded and tensioned strand by strand , then the wax injection was done after drecking the perfect tightness of the duct.

3.2 Stay cables with individually protected galvanized strands.

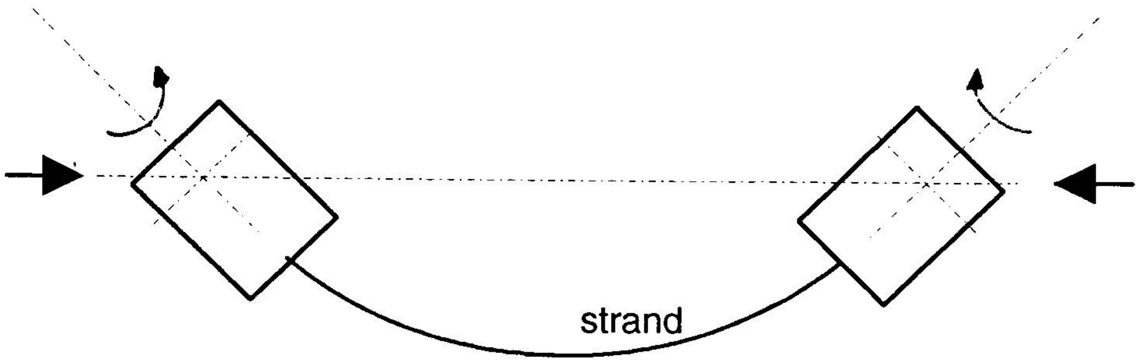
3.2.1 Description

The individually protected strand [6], recommended by Freyssinet is an industrial product entirely protected in factory by several barriers, which, starting from the outer part of the strand, are composed of :
. an extruded plastic layer with a minimum thickness of 1,5 mm (generally HDPE-High Density polyethylene).
. A zinc coating produced by hot dip galvanization, wire-drawn in such a way that the thickness of the finished coating is not less than 25 microns ($180g/m^2$).
. A protective filler made of petroleum wax (Injectelf CP-HPF type). It fills in the inter-wire voids ; water is prevented from running down ; this is checked by acceptance tests.



One may notice that steel protection is achieved quite early in the strand fabrication process, therefore preventing any chance of corrosion between successive operations. As soon as it leaves the factory, the "individually protected strand" product is therefore perfectly waterproof and efficiently protected against environmental attack.

In the anchorage area, the HDPE confinement is stripped out and replaced by a wax protection which completely fills the volume between the anchorage stuffing box and the cover containing the anchorage head : but during construction, a continous corrosion protection is maintained with the galvanization.



Rotative bending test

3.2.2 Rotative bending test

The Laboratoire Central des Ponts et Chaussées (Paris) has carried out a series of tests with various samples showing the beneficial role of the wax intermediate filler.
- Testing arrangement : an axial horizontal force creates the buckling of the sample. Then a rotative movement is applied at both ends. Thus the extreme fibber of a cross section is alternatively in tension and compression.

- Results :
No damage was observed on the HDPE duct for all the three tests.
A similar test carried out on a sample with no wax failed : the duct starts cracking at 300 000 cycles.

3.2.3 Temperature tests
Several non stressed samples with wax filler were subjected to a series of severetemperature cycles. The testing procedure was as follows : 20 cycles from +30°C to -60°C were applied to several samples with different end conditions (HDPE duct either free or fixed to the strand). Then samples were taken to -198°C during 32 minutes.
No damages at all were observed. However, when there is no wax filler, there is a rapid deterioration of the duct.

4 - CONCLUSION

All these numerous and variouus testings have given us a better knowledge of the petroleum wax as a corrosion protection material for stay cable. They have given us also a lot of confidence by the positive achievements which have been obtained. The individually protected galvanized strands thread and stressed strand by strand into an overall HDPE duct is probably one of the best answers to owners requirements for extending the lifespan of cable stayed structures.

References

[1] Utilisation de la cire pétrolière dans le domaine du génie civil. - A. Chabert.
FIP/AFPC - 16/20 février 1986. New Delhi (Inde)

[2] Injection à la cire pétrolière des câbles de précontrainte - Mise en oeuvre en première mondiale au viaduc de la Boivre. - A. Chabert - S. Barbaut - M. Ivanoff - Revue Travaux n° 597-mars 1985.

[3] Injection de conduits de précontrainte à l'avancement à l'aide d'une cire pétrolière.-A. Chabert - R. Fava - R. Bondil - Revue Travaux N° 601 - juillet /août 1985.

[4] Protective Products for Prestressing steels. A. Chabert - B. Creton
Internacional Symposium on innovations in the applications of precasting and prestressing
27/29 November 1990-Singapore.

[5] Recent Approaches to Corrosion Protection in stay cable-design - P. Buergi
IABSE Symposium, Leningrad, USSR, Septembre 11-14, 1991.

[6] Individually protected strands
A. Chabert - P. Jartoux
FIP Symposium Kyoto Oct. 1993.

Robustness of Stranded Cables in Suspended Bridges

Robustesse des câbles à torons dans les ponts suspendus

Die Robustheit von Seilen im Brückenbau

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SUMMARY

Locked coil spiral ropes have proven themselves in bridge construction in Europe. Of course, special attention has to be paid to the characteristics of these tendons in the zones of anchorage, deviation and transversial compression. If the special features described in this paper are adhered to during construction, assembly and later on during maintenance, robustness and a long lifespan can be expected from these elements.

RÉSUMÉ

En Europe, les câbles à torons gainés ont fait leurs preuves dans la construction de ponts. Il faut naturellement porter une attention particulière aux caractéristiques de ces éléments de traction dans les zones d'ancrage, de déviation et de compression transversale. Tenant compte des remarques faites dans cet article sur la construction, l'assemblage et la maintenance ultérieure des torons, on peut s'attendre à une grande robustesse et une durée de vie importante de ces éléments.

ZUSAMMENFASSUNG

In Europa sind sehr gute Erfahrungen mit vollverschlossenen Spiralseilen im Brückenbau gemacht worden. Dabei muss auf die Eigenart dieser Zugelemente im Verankerungs-, Umlenk- und Querpressbereich natürlich besonders eingegangen werden. Werden bei der Konstruktion, der Montage und der späteren Wartung die in diesem Bericht angespro-chenen Besonderheiten der vollverschlossenen Spiralseile beachtet, dann kann von ihnen eine grosse Robustheit und lange Lebensdauer erwartet werden.

Locked coil spiral ropes measuring up to 180 mm in diameter and consisting of high-strength steel wires are complex structural ties, but if used correctly they are very robust and durable and have proven themselves very well in bridge- and building-construction [1], [2].

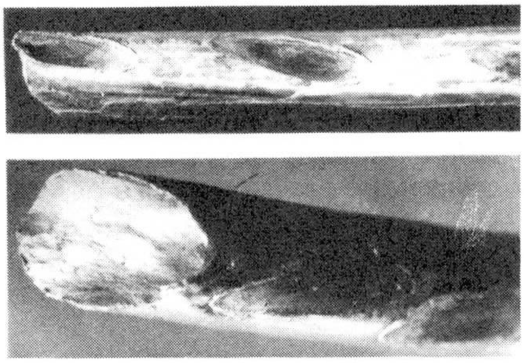
CHARACTERISTICS AND MECHANICAL BEHAVIOUR OF LOCKED COIL SPIRAL ROPES

The individual wires are arranged in helixes with alternating lay direction. This results in low bending- and constraint stress when bending the whole cable (Fig. 2). With increasing cable tension the radial pressure between the wires, resulting from the helix, increases and the relative movements of the wires decrease more and more. Frictional resistances in the cable and local deformation at the crossings of wires of neighboring layers (Fig. 1) result in a non-linear stress-strain relationship of the cables as a whole; this is especially evident during the first loading.

Even if shortly before failure the radial pressure of the wire-helixes compresses the spiral rope radially to such a degree that the entire cable reacts almost like a solid bar, integrating also single prematurely broken wires within less than one lay-length. The ultimate load is approx. 5 % less due to the helical or spiral geometry than the total of all single wires' strenghts and the tension stiffness is about 15 % less than that of an individual wire [3].

The wires are integrated by static friction occurring between neighboring wires. To overcome this, energy dissipates resulting negatively in fretting corrosion and positively in increased damping. The tension stiffness of the cable drops considerably after the wires start moving against each other thus overcoming the static friction [4].

For over 100 years now Z-shaped wires are used for the outer layers of spiral ropes, with their "heads" pressing more and more on the "foot" of the neighboring wire under increasing longitudinal tension thus locking the cable mechanically. Z-wires fill the cable cross-section better than round wires and their "heads" form a smooth cable surface (Fig. 4). A disadvantage of this type of wire with line pressing on the neighboring wires are their intensive friction movements along these lines due to stretching or compressing of the wire spirals. In the case of round wires this contact lines are only accidental. They occur methodically as soon as the gap between the wires closes due to transversal contraction.



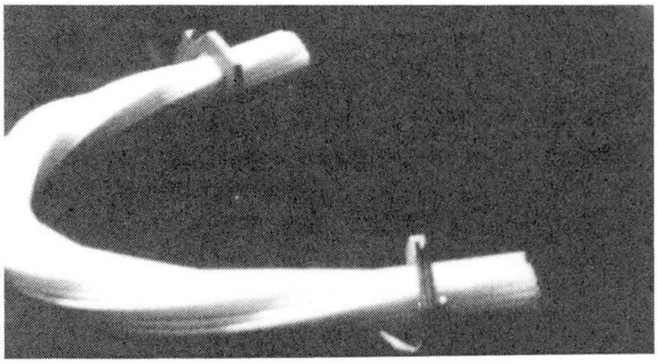


Fig. 1: A deformed round wire taken from a rope's core.

Fig. 2: Arrangement of wires in a curved and twisted hexagonal wire bundle.

In case of a clamp, to suspend a hangar or secondary rope from a main cable or rope, the radial prestressing forces have to be as intensive as possible and the transition zones should not be too long, because with varying cable load they allow for fretting inside the rope and between the cable surface and the clamps. (This is a result of recent research and contradicts the general opinion recommending soft transition zones.) Since the cable under increasing longitudinal load withdraws from transversal compression of the clamp due to its transversal contraction, even high clamp pressures are only effective under dead load and service loads but will not affect the ultimate load [3], [5].

DURABLE PROTECTION OF WIRES AND LOCKED COIL ROPES

Nowadays all wires are hot dip galvanized and emphasis has to be put on the galvanization not becoming too thick because then it cannot be applied evenly especially to Z-wires. The layer of a zinc-iron-alloy should not become so thick that it reacts brittle, showing early cracks or extensive flaking.

Now a metal layer consisting of a zinc-aluminum-alloy can be applied to wires. The zinc-iron-alloy layer is reduced to a minimal thickness compared to the generally used galvanization and the Zn-Al-alloy is 2 to 3 times as hard as pure zinc applied as an outer layer during the hot dip galvanizing process [9].

Even though extensive flaking occurs at a reduced pace compared to high-grade zinc and when using the Zn-Al-alloy only a thin zinc-iron-layer has to be applied, it has to be observed that, when using this type of layering (Galfan), all advantages of the hot dip galvanization are preserved. In Germany such metall layers are tested [10].

Still, red lead based on linseed oil is preferably used to fill the cavities of spiral ropes because for example poly-oil with zinc powder (zinc powder paint), hydrocarbon-synthetic-resin with aluminum particles (metal coat) or poly-waxes (APP or Cordalen) are sophisticated means of protection. A deliberate pigmentation with zinc powder or zinc chromate does not only bring advantages by absorbing moisture. Under certain temperature conditions and with a faulty mixture of a PV-resin used as binder, strong blistering may occur in the presence of residual moisture.

Amount and type of pigmentation decisively determine the friction resistance. Zinc powder increases it, aluminum particles decrease it.

A two-component resin or dehydrogenating oil used as binder is determining the remaining viscosity of the filling during the aging process. On the one side filling material may escape through gaps (bleeding) and harmful substances may enter through cracks. Here red lead, also generally applied between galvanized wires, act most favourably. All other materials have to be tested individually and used according to the respective requirements and only with extreme discretion [11].

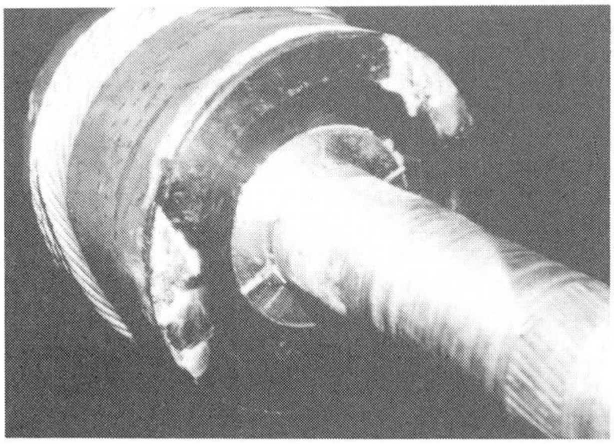
The outer layer of locked coil ropes with its complete, smooth surface is applied with a brush in several layers up to a thickness of 500 µm. In Germany a polyutherane-based resin is used with a coloured finish. Its pigmentation has to guarantee sufficient UV-protection as well as shock-resistance. This layering has proven itself up to now as long as the filling material does not produce any gas. The more gas is produced, the more permeable and thin the layering has to be.

The movements of a spiral rope at the points of transition to anchor sockets or to the clamping resp. deviation zones must be distributed evenly using bond transition lines. The bond joints to be used have to be made of permanently elastic material and be carefully detailled. A bond joint moving distinctively must be equipped with sufficiently adhesive contact areas between the bond and the mobile edges, and be the thinnest at its center. The joint may not withdraw from its flanks and must distribute a relative movement as acceptable elongation along a finite length (Fig. 6).

Protection from vandalism, fire, shock or saline splash should be achieved without mantling the cable any further [13]. At points exposed to unfavourable attacks, the galvanization wore off sometimes within weeks. The fillers and paints applied incorrectly may become brittle when exposed to UV-radiation resp. rust may form after minimal damage (Fig. 6). The damage mechanisms may be disastrous, because if the cable's resistance is reduced only on a short stretch, the entire element becomes useless. By-passing these areas is rarely possible [14].

Therefore it makes sense to emphasize control and maintenance, rather than waiting until repair and renewal (replacement) become necessary. In any case replacement is more expensive and riskier than reasonable maintenance, including the renewal of the corrosion-protection every 10 to 20 years. These are also the periods in which traffic, coating systems and the climatic situation change and therefore longer-term predictions can rarely be ventured.

Locked coil spiral ropes are usually **anchored** in wedge-shaped metal cast steel sockets. Such socketing using hard zinc alloy is to fix the cable preferably at the exit of the socket by means of ahigh radial pressure. Thus a high friction resistance between the cable and its socket transfers the load over a short distance and fretting of the wires is reduced or eliminated. The usual casting length of 5 times the cable diameter is required only to cater for shrinking of the metal grout in the cone. The rear part of the cone containing the rope's broom does not render support under constant load and under service loads. In addition an attempt has to be made to leave the circular slot between the cable and socket as wide as possible to avoid fretting by allowing for an elastic shear deformation of the metal grout (Fig. 3). This prevents fretting corrosion under pulsating cable loads [6], [7].



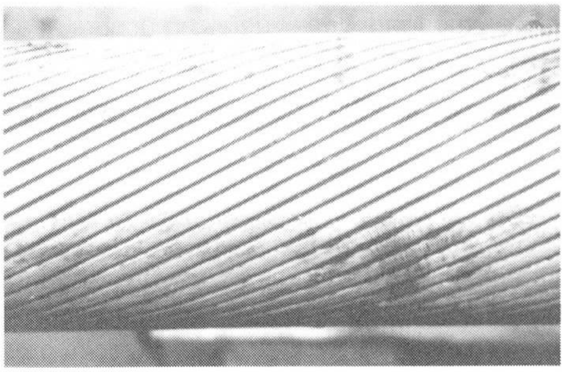


Fig. 3: Spiral rope with a wide circular slot between cable and socket to prevent fretting corrosion.

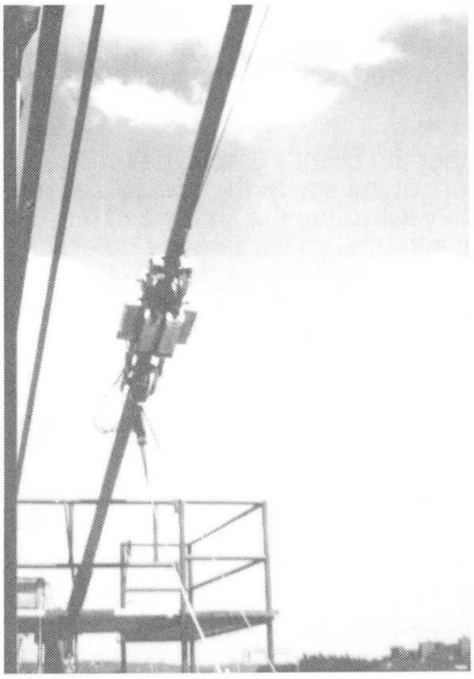
Fig. 4: the smooth surface of the Z-shaped outer layers of a locked coil rope.

In the case of a locked coil spiral rope being **deviated** over a saddle, the radius should not be smaller than 10 times the rope's diameter, because then only the wires in the cable remain consolidated. The deviation length should correspond to an integer multiple of the outer lay-length in order to allow for length adjustment of the individual wires (Fig. 2). If the wires are not too thick and thus their bending stresses remain minor, and if the cable is fixed firmly in a groove, neither a deviation nor a clamp or the anchoring should affect negatively the dynamic strength of a locked coil rope.

ROPES USED AS SUSPENSION CABLES OR STAY CABLES

Ropes are tendons which due to their small ratio of diameter and span assume a shape which is prescribed by the equlibrium between tensile force they transfer and their deadload. Their loadbearing behaviour is governed by their geometrical stiffness. Their joints, i. e. anchorages, clamps or curvatures are disturbance zones. The cable itself has to absorb the angular changes at fixed joints. In this case stranded tendons are considered to be very robust.

Large angular changes usually occur under low tension and with long ropes and may result from vibrations caused by wind and traffic. From the wide spectrum of wind-gusts the ropes filter those a corresponding to their natural frequencies. The initiation caused by turbulences in the laminar wind (Karmann-Effect) is not affected even if the cable vibrations reach higher amplitudes. Accordingly vibrations induced fromn the bridge girder due to vehicles resp. sequences of vehicles may lead to high amplitudes. Except for angular changes at the ends, these vibrations do not result in substandtial stress amplitudes [8]. Ropes are better suited to resist angular changes than bundles. Compared to bundled strands, with strands consisting of 7 wires which are individually protected, but exposing a large surface, locked coil ropes are less sensitive. Ropes may be inspected individually and defects in the surface may be determined and repaired. This is not possible in the case of bundled single strands. Their development resulted in the tendons becoming one-way-products. Replacing ropes or bundles changes the state of stress of a structure calling for additional action.



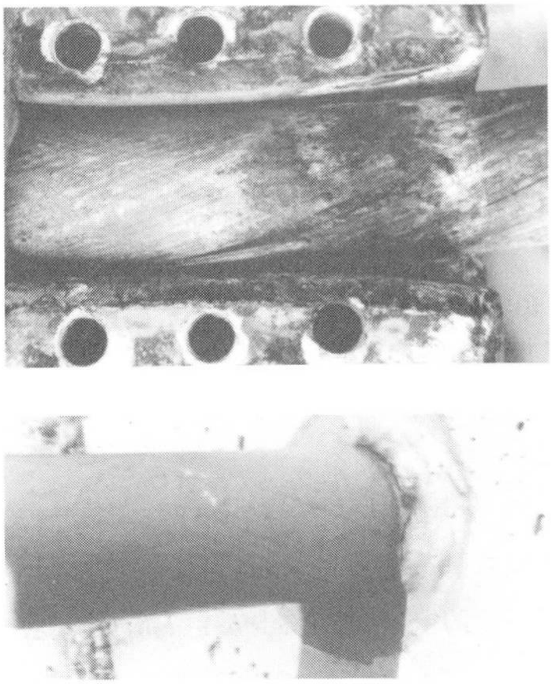


Fig. 5: Inspection of the individual cables by using magnet-inductive procedures. The apparatus moves along the rope and produces a graphical diagnosis.

Fig. 6: Damage to a cable at the entry to a deviation groove due to the use of the wrong sealing, which was also applied incorrectly (above) and cracks in a seal due to UV-radiation and cable movement (below), allowing water to penetrate.

What possibilities are there to maintain the structure? The spacing between the tendons should allow free access for inspection and maintenance. The tendon-units should be, neither too large nor too small to be checked (Fig. 7).

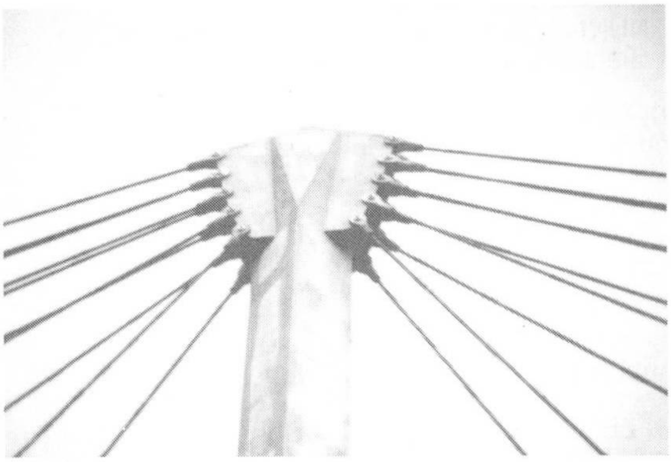


Fig. 7: Open rope bundles for large bridges. Gaps or slots must be avoided. Either care for close contact or provide ventilation and drainage.

Fig. 8: Mast head of a pedestrian bridge with easy access to the cable anchorings for inspection and maintenance.

It is possible to visually inspect the ropes using baskets running on the bridge cable, and to detect wire failures by means of magnet-inductive procedures (Fig. 5). In both cases the rope has to be freely laid up to the entries in the joints or anchorages (Fig. 8). Covered sections of tendons are dangerous [15], [16].

Laymen are unable to evaluate a cable after prolonged use. Either the client's employee (bridge inspector) familiar with the whole structure and constantly present at the site or the specialized rope inspector (expert) are of particular importance here. Together they will serve the safety and durability of a cable structure better than any sophisticated mechanical automatism for damage detection.

REFERENCES

[1] ROBINSON, R.: Brighter Future for Stay Cables, Civil Engineering, October 1998

[2] SCHLAICH, J.; GABRIEL, K; BERGERMANN, R.: On Cable Structures - Research - Design - Construction. The 1985 Int. Eng. Symp. on Struc. Steel, Chicago 1985

[3] GABRIEL, K.: Konstruktion und Bemessung in "Stehende Drahtseile", expert Verlag 1990

[4] RAOOF, M.; HUANG, Y.P.: Freebending characteristic of axially preloaded spiral strands Struct. Buildings 94 (1992) pp. 469-484

[5] ALTMANN, H.: Seilkonstruktionen - Untersuchungen an Klemmen für vollverschlossene SFB 64, Universität Stuttgart 1972

[6] GABRIEL, K.: On the Fatigue Strength of Wires in Spiral Ropes. Jour. of Energy Resources Technology, Vol. 107, March 1985

[7] GABRIEL, K.; HEIMES, F.: The Mechanics of Socketing. The Zinc Alloy Castcone as a Special Compound Structure. Proc. of 1. Int. Offshore and Polar Eng. Converence, Edinjburgh 1991

[8] STAROSSEK, U.: Cable Dynamics - A Review. Struc. Eng. Int., Vol. 4, Aug. 1994

[9] NÜNNINGHOFF, R.; SCZEPINSKY, K.: Galfan - ein neuartiger, verbesserter Korrosionsschutz für Stahldrähte. DRAHT 38 (1984), H. 1 and 2.

[10] BERGERMANN, R.; GÖPPERT, K.: The new Cable-Membrane Structure for the Neckarstadion Roof in Stuttgart. Fourth Int. Conf. on Space Struc., Guildford 1993

[11] SCZYSLO, S.: Brückenseile aus der Sicht der Straßenbauverwaltung. Anforderungen, Erfahrungen, Korrosionsschutz. Bauingenieur d67 (1992), pp. 347-358

[12] SAUL, R.; SVENSSON, H.: On the Corrosion Protection of Stay Cables. Stahlbau (1990), pp. 165-176

[13] POINEAU, D.: Origine des Pathologies, Observations, Diagnostic dans les Ouvrages d'Art. Annales de l'Inst. Technique, No. 523, May 1994

[14] ZELLNER, W.; SAUL, R.: Über Erfahrungen beim Umbau und Sanieren von Brücken. Bautechnik 2 (1985)

[15] HÖHLE, H.-W.; BECKER, K.; FUCHS, D.; NÖLLER, H.: Seile unter Zugbelastung. Materialprüfung 35 (1993), H. 3

[16] HÖHLE, H.-W.: Expert System for integrated Cable Inspection. Wire Rope News & Sling Technology, Oct. 1993