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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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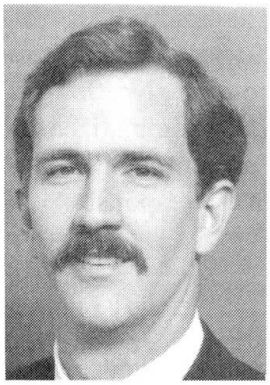

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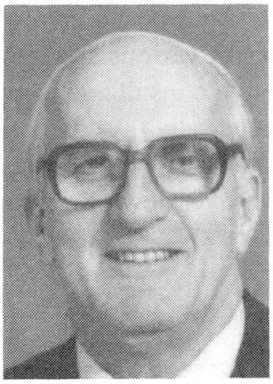

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SUMMARY

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

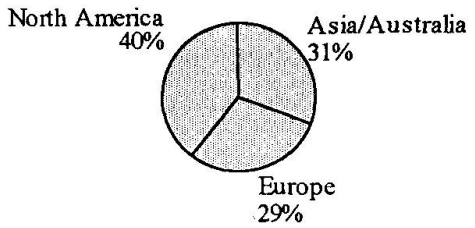
The first mailing of surveys was made in February 1993 in which approximately 190 surveys were distributed. Follow up letters were sent. The survey closed in November 1993. A total of 83 replies had been received. Of these, 62 completed the survey (respondents) while the remaining replies declined to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

4. Analysis of Survey

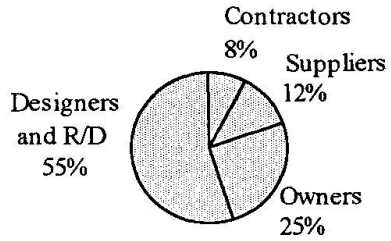
In order to make interpretation and comparison of data as convenient as possible, the results were assembled into a graphical format. Initially all responses were plotted to give trends of the group as a whole ("All" category). However, it is of interest to examine possible variations in responses relative 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)

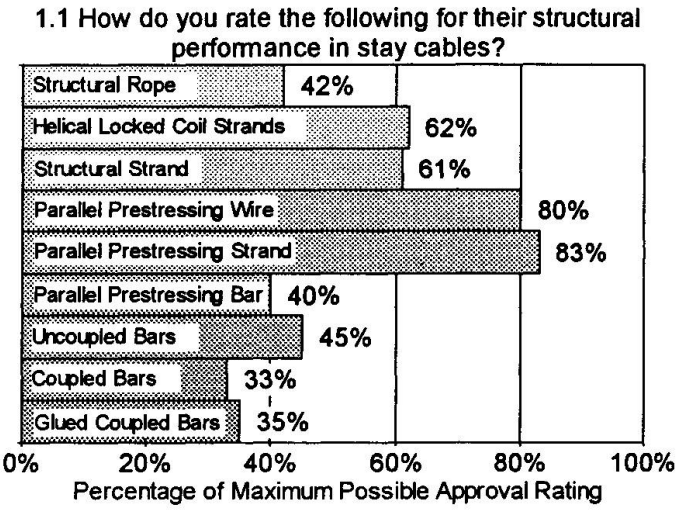


Figure 4.2 - Example of Graphical Presentation of Responses.

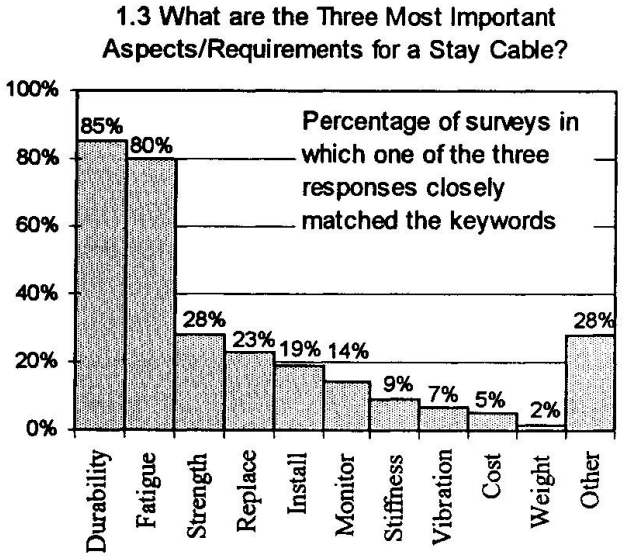


Figure 4.3 - All Respondents Response To Question Concerning Important Aspects Of Stay Cable.

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

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