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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.

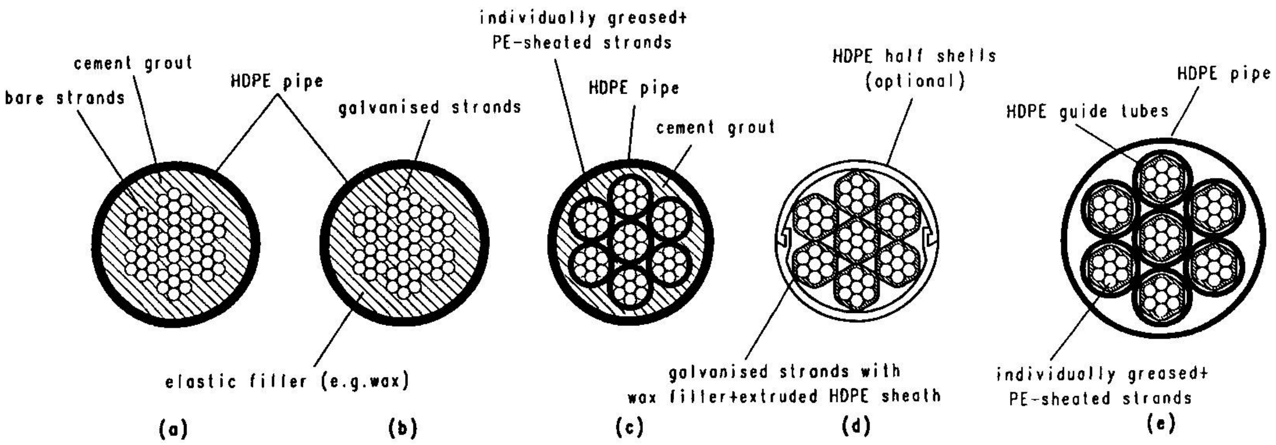

Fig. 1 Different Compositions of Parallel Strand Stay Cables

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.

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