Over the last 25 years, cable-stayed bridges have become increasingly popular for medium- and long-span crossings of waterways. Their popularity stems from advancements in prestressed concrete structure technology and economic advantages over other types of structures. A cable stay system consists of the tension element (stressing steel, cable sheath, and cementitious grout) and anchorages. There are three different arrangements of stay cables (Fig. 1). The fan arrangement distributes the load close to the top of the pylon. The harp arrangement, in which the stay cables are parallel to one another, distributes the load along the pylon. This reduces the buckling effects of the pylon. The mix arrangement, which combines the fan and harp, is derived from the fan concept but spaces the anchorages along the pylon.

The tension elements are designed to carry dead load tensile stresses together with positive and negative stress fluctuations caused by live loads, wind and thermal loads, and local bending. In general, the allowable axial tensile stress under design service loads is limited to approximately 45 percent of the guaranteed ultimate tensile strength of the high strength steel. Since all service loads contribute to the fatigue of the tensioned elements, the residual load capacity of the tension elements under actual service loading with respect to time is important.

Of equal or more importance is the effect of corrosion protection systems of the stay cables and anchorages. Cable-stayed bridges are designed with redundancy in the cable system, and can withstand the sudden loss of a single cable. However, if the failure is caused by corrosion, the remaining cable structural integrity may also be compromised and the additional redistribution of forces from the lost support may cause further cable failure. Under this scenario, progressive structural collapse is possible. Fatigue resistance can be evaluated on the basis of an expected life time approach or by more traditional endurance limit verifications. However, when coupled with corrosion, fatigue failure at a given stress level usually occurs within fewer cycles, and the calculated or tested fatigue endurance limit is no longer valid.

For this reason, high static strength and fatigue resistance of stay cables, along with corrosion protection, have been the largest concern of the design engineer, and the choice of corrosion protection is more critical for stays than for any other bridge component. Previously, corrosion protection systems were based on the experience of the manufacturers and design engineers.

History of cable-stayed bridges

The cable-stayed bridge became popular after the construction of the first one in France during the early 1800s. However, after two catastrophic incidents — the collapse of the Dryburgh-Abbey Bridge in 1818 in Great Britain, and the Saale River Bridge in 1824 in Germany — the French scientist Navier recommended that suspension bridges be built as an alternative to cable-stayed bridges.

After World War II, the need to rebuild the many destroyed bridges arose, and the European community reviewed the development of the cable-stayed bridge. The first modern cable-stayed bridge was the Stromsund Bridge in Sweden, built in 1955. The first three major cable-stayed bridges constructed in the United States were the Pasco-Kennewick Bridge (Fig. 2),...
built between 1975 and 1979 across the Columbia River in Washington; the Luling Bridge, built between 1979 and 1983 across the Mississippi River in Louisiana; and the East Huntington Bridge (Fig. 3), built between 1974 and 1985 across the Ohio River in West Virginia. Presently, approximately 15 major cable-stayed bridges have been constructed in the United States.

**Development of cable components**

**Tension element — high stressing steel**

High strength steel is manufactured by the controlled addition of carbon and magnesium to iron. Residual elements are kept to a minimum, and harmful impurities are virtually eliminated. The first three major cable-stayed bridges in the United States used parallel wires (Fig. 4). The Dame Point Bridge in Florida was first constructed using stay cables of parallel bars (Fig. 5).

Parallel wires are $\frac{1}{8}$ in. (6.4 mm) in diameter, and are cold-drawn, stress-relieved, prestressing steel. The minimum guaranteed ultimate tensile strength is 240 ksi (1655 MPa), and the minimum yield strength is 204 ksi (1407 MPa). Parallel bars are typically $\frac{3}{8}$ to $1\frac{1}{8}$ in. (16 to 35 mm) in diameter, hot rolled, cold stressed, and stress relieved. The minimum guaranteed ultimate tensile strength is 150 ksi (1000 MPa). There are two types of steel for stay cables. The minimum yield strength is 127.5 ksi (879 MPa) for Type I and 120 ksi (830 MPa) for Type II.

Seven-wire strands have become popular for the stays as a result of the lack of commercial availability of $\frac{1}{4}$ in. (6.4 mm) diameter prestressing wire (Fig. 6). Current state-of-the-art parallel strand stays are 0.6 in. (15 mm) diameter, low-relaxation, weldless grade strand. The minimum guaranteed ultimate tensile strength is 270 ksi (1860 MPa), and the minimum yield strength is 243 ksi (1680 MPa). Until today, bare steel has been used in the United States. Zinc coating over the bare steel provides corrosion protection to the steel when exposed to aggressive environments. However, the possibility of hydrogen embrittlement due to the galvanizing process and cathodic reactions has been suspected. Evidence supporting this concern has not been elucidated.

Recently, fusion-bonded, epoxy-coated strand (Fig. 7) has been developed to improve corrosion protection. The first appearance of epoxy-coated strand for a stay cable was in 1986 on the Bayview cable-stayed bridge across the Mississippi River in Illinois. Epoxy coating is applied to a strand by an electrostatic deposition method. Typical thickness of the coating is 30±5 mils (0.76 ± 0.13 mm), which is much thicker than the typical epoxy coating thickness for reinforcing steel (5 to 12 mils (0.1 to 3 mm)).

Steel wire ropes are available for use as stay cables. But, because their stiffness is relatively low, they are not commonly used for cable-stayed bridges.

**Tension element — grout**

In the United States, only Type I or Type II portland cement mortars with admixtures has been used for cable-stayed bridges.
bridges. Cementitious grout is commonly used because of its inherent alkalinity, which produces a passive film on the steel surface. In addition, grouts used for stay cables generally possess good workability. They have few air voids, retain their volume after placement, and have sufficient strength. They also exhibit good fluidity, have minimum bleeding, and bond well.

Water for grout must be free of harmful substances such as nitrates, sulfides, sulfates, and chlorides. Admixtures are generally in liquid or powder form and produce a thixotropic consistency of grout in a short mixture time. Corrosive materials such as chlorides, fluorides, sulfides, nitrates, or aluminum powder are prohibited. Generally, two types of admixtures have been used in the United States. One is an anti-bleeding agent, and the other is a non-shrink admixture.

A cementitious barrier can provide reliable corrosion protection to stay cables. However, this barrier is only effective if the outer cable sheathing is intact. If the sheathing fails to prevent moisture or any corrosive substances into the cementitious barrier, the thin cementitious cover over the prestressing steel offers limited corrosion protection. Furthermore, cementitious mortars are subject to cracking under the dynamic loads expected in the stay cable system.

Several different grout materials have been used in the cable-stayed bridges in foreign countries. A petroleum wax blocking compound has been developed and used in France. The claimed advantages of this compound are crack-free service life under compressive and tensile loads and high ohmic resistance to reduce corrosion current flow. For transport and grouting, the wax compound is heated to a liquid state. When the wax is close to fusion temperatures, 85 to 105 C (185 to 221 F), it has a liquid consistency, and its viscosity is comparable to that of a fine-grade oil. During grouting, any stagnation defect will translate into a leak, which will be very difficult to fix because of the solidification of the wax in the already-grouted part. Therefore, a vacuum test to detect any leak prior to grouting is required.

A polybutadien polyurethane grouting material was used to provide crack-free grout under dynamic loading in Japan. The claimed advantages of this material are low viscosity to allow easy penetration into the tiny interstices of the strand, high flexibility, and dielectric properties to prevent corrosion. The claimed disadvantages are the high material and installation cost, the requirement for delicate handling, and flammability.

Polymer cementitious mortar has also been used in Japan on cable-stayed bridges. The polymer cementitious mortar consists of poly-acrylic ester emulsion, portland cement, and a defoaming agent. The claimed advantages of this material are high crack resistance under dynamic loading, no bleeding during curing, no shrinkage, higher ductility than portland cement grout in elongation, and no special techniques or equipment required for grouting. The claimed disadvantages are higher material cost than portland cement mortar, and temperature-dependent viscosity and hardening.

Tension element — cable sheath

The cable sheath has to fulfill three principal functions: to serve as a corrosion barrier for the stressing steel in the cable; to serve as formwork for injecting grout; and to contribute to the live load bearing of the cable forces through its longitudinal stiffness.

Sheathing material must therefore have the following properties:
- resistance to fatigue from cyclic stresses resulting from expected service life changes;
- resistance to ultraviolet degradation;
- non-reaction with the grout material and steel;
- resistance to damage during shipping, handling, fabricating, installation, and grouting;
- resistance to the intrusion of water, gas, and other corrosive substances;
- low creep characteristics;
- compatibility with the ambient environment.

In general, high-density polyethylene or steel pipe has been used for cable sheath material. The wall thickness must be enough to provide adequate fluid and air tightness while still providing sufficient resistance to the grouting pressures. Carbon black is added to the polyethylene resin to provide resistance to ultraviolet degradation. Fig. 8 shows an example of weather resistance test results for polyethylene pipe with and without carbon black. High density polyethylene
sheathing is an air-tight material. A \( \frac{3}{4} \) in. (6.4 mm) thickness of this material provides the same vapor barrier as a 35 ft (10.7 m) thick concrete wall. Therefore, if the polyethylene sheath is not damaged, it can effectively prevent gas penetration to the cable, which is important when Portland cement mortar is used. The corrosion protection of bare steel in cementitious mortar is provided by a passive film which is formed on the steel surface by the highly alkaline environment produced from cement hydration. However, carbon dioxide from the air reacts with the calcium hydroxide in the cementitious mortar and reduces the pH of the grout. If enough carbon dioxide penetrates the mortar to the steel, it is no longer able to maintain the passive film, and corrosion results.

Black polyethylene pipe has a thermal coefficient of expansion about six times that of cementitious mortar and steel. Therefore, it is not compatible with the cable stay by itself. Polyethylene pipe is wrapped with a lightweight tape to help control temperature variations and reduce the magnitude of the differential stresses that may contribute to the damage to the pipe.

The Dame Point Bridge (Fig. 9) and the Sunshine Skyway Bridge (Fig. 10) both used steel sheathing. Steel sheathing for stay cables is typically black steel pipe. The steel pipes are welded together at the job site. If the load-bearing capacity of the steel sheathing is intentionally taken into account, the limited fatigue resistance of the transverse welds is critical. The advantages of steel sheathing are the increased stiffness to the cable for live load, high water and gas tightness, high wind vibration damping, and the applicability of higher precompression to the cementitious grout. Disadvantages include a higher installation cost, difficulty in detecting damage of the stressing steel inside the sheathing, and the requirement for corrosion protection for the steel sheath.

**Anchorage**

Both the stressing and the dead-end anchorages typically consist of a bearing plate, an anchor tube or socket, wedges, a transition pipe, a tension ring, a connection pipe, and a protection cap with grout and air vents. The typical socket has a conical interior shape with a conical recess. At the large end of the conical recess, there is a shoulder on which rests an anchor plate. A popular socket used for cable-stayed bridges is the Hi-AM anchor, which has a high fatigue resistance. The content of Hi-AM socketing anchorages is different from the conventional zinc-poured sockets for wire ropes and the wedge anchorages for post-tensioning tendons. The space in the Hi-AM socket is filled with 0.05 in. (1.3 mm) steel balls and epoxy resin mixed with zinc powder. The anchorage mechanism of the Hi-AM anchor socket is primarily an arch action of wires and steel balls in the conical space of the socket. The stress applied to the cable does not reach to the anchor plate under normal loading conditions. Zinc powder is added to improve the fluidity and thermal properties of the epoxy resin.

A wide variety of anchorages are continually being designed to provide high performance under static load and fatigue. Due to the development of epoxy-coated strand, the cable sockets were modified for the Bayview Bridge in Quincy, Illinois. New anchors, swedges, were substituted for the wedges that were used with the Hi-AM anchors. A swedge is made of a softer material than the stay. The swedge is forced on the stay and deforms at the anchor plate to act like a button head, thus restricting the stay.

**Temporary control**

Typically, before the wires or strands are pulled through the sheathing, each wire or strand is dipped or sprayed with a water-soluble oil corrosion inhibitor. It takes more than one year to install all the cables in a typical cable-stayed bridge. Therefore, the wires or strands in the first cable sheathing may be kept for one year without further corrosion protection. The wires or strands cannot be inspected prior to grouting to see if any corrosion damage has occurred.

**Concerns on a stay cable system**

Despite all the corrosion prevention methods that are employed, the potential for corrosion-related problems on cable-stayed bridges is a concern. Specific areas of concern relative to corrosion are as follows:

- The stress factors on the corrosion protection system are generally incurred after installation. Stresses to corrosion protection system components during transportation, storage, fabrication, and installation may be serious and must be considered for durable corrosion protection.
- Sheathing is the first protection barrier to the outside environment. Durability of the sheathing is critical during the cable service life. Failure of the sheathing can result in corrosion of the bare steel tension elements embedded in the cementitious grout.
- Flexibility of polyethylene sheathing is dependent upon temperature. When polyethylene sheathing is coiled
or uncoiled at low temperatures, it may crack. Therefore, coiling and uncoiling operations should have temperature limitations. Steel sheathing is typically protected from corrosion by coating. If corrosion-perforates the steel sheathing, or if the welds on the steel sheathing are defective, the effectiveness of the corrosion protection system will be greatly reduced.

- It is difficult to install and maintain completely moisture- and gas-tight sheathing. The functions of the cementitious grout for the stay cable are to protect bare steel tension elements from corrosion by passivating the steel and to provide a second barrier to the outside environment. The cementitious grout is permeable because it is very thin and it is subject to cracking under dynamic loading, thus offering only limited protection from the outside environment. Therefore, it is recommended that new grout materials that provide better corrosion protection be developed.

- Training the project inspector and contractor is a critical factor to ensuring the long-term durability of the corrosion protection system. The inspector should be familiar with the specifications, inspection techniques, proper installation, and critical problems that can affect long-term durability. This program should be specified as part of the design and construction of a new cable-stayed bridge.

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