# Implications of Test Results from Full-Scale Fatigue Tests of Stay Cables Composed of Seven-Wire Prestressing Strand

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Since 1990 14 full-scale axial and combined axial/flexural fatigue tests of parallel-strand cable specimens representing three recently constructed U.S. cable-stayed bridges have been conducted. Stay cable specimens ranged in size from 17 to 85 strands 15.2 mm (0.6 in.) in diameter with lengths between 4,570 and 14 600 mm (15 and 48 ft) and nominal capacities between 4430 and 22 157 kN (996 and 4,981 kips). The specimens represented the variety of parallel-strand cable anchorage designs in use worldwide, namely, the wedge anchorage, combination wedge/conical socket anchorage, and conical anchorage; they also incorporated uncoated, epoxy-coated, and grit-impregnated epoxy-coated seven-wire strand. The primary goal of each test series was the validation of the as-designed cable system's fatigue performance for each bridge. However, test results indicate that these specification-required tests effectively identified endurance- and durability-impairing features of certain cable components, prompting the system's refinement and validation during test series. The intent of the review is to synthesize test results for a highly diverse sample of stay cable designs, installation procedures, and test criteria, emphasizing fatigue performance enhancements resulting from specific cable configuration refinements. Measured fatigue test data are compared with Post-Tensioning Institute cable testing criteria.

Laboratory structural testing was conducted to evaluate the performance of as-designed stay cable systems when subjected to fatigue and static load conditions. Specimen components were provided and assembled by cable suppliers. The test regimes incorporated axial fatigue and combined axial/flexural fatigue loading, depending on bridge design. Table 1 presents pertinent test data. In general, the stay cable specimens were subjected to 2 million cycles of fatigue loading ranging from 36.5 to 45 percent of guaranteed ultimate tensile strength (GUTS) in accordance with bridge specifications and on the basis of recommendations of the Post-Tensioning Institute (PTI) Committee on Cable-Stayed Bridges (*1*). The number of wire breaks allowed during fatigue testing was limited to 2 percent. Depending on bridge specification requirements, axial fatigue test specimens were required to withstand a static load of 95 percent of either nominal or actual (determined by tests to failure of representative strands) ultimate tensile strength. All test specimens were dissected after the strength tests to assess the condition and performance of various cable components. Most fatigue tests were performed at an approximate frequency of 2 Hz; some tests were performed at lower frequencies (between 1 and 2 Hz).

TABLE 1 Project-Specific Stay Cable Test Parameters

| Test Designation(1) | Cable(4) Length mm | Cable Nominal Tensile Capacity (GUTS) kN | Fatigue Load Range Minimum kN | Fatigue Load Range Maximum kN | Static Proof Load Requirement, kN |
|---|---|---|---|---|---|
| A31 | 6,183 | 8,079 | 2,949 | 3,636 | 8,074 |
| A31R(2) | 6,116 | 8,079 | 2,949 | 3,636 | 8,065 |
| A49 | 7,675 | 12,770 | 4,661 | 5,747 | 12,753 |
| A73 | 7,879 | 19,025 | 6,944 | 8,561 | 19,003 |
| B46 | 5,512 | 11,989 | 4,376 | 5,395 | 11,387 |
| B37(3) | 13,614 | 9,643 | 3,519 | 4,083 | N/A |
| B17 | 4,877 | 4,431 | 1,617 | 1,994 | 4,200 |
| B46R | 5,487 | 11,989 | 4,376 | 5,395 | 11,387 |
| C85 | 5,725 | 22,153 | 8,086 | 9,969 | 21,520 |
| C79 | 5,707 | 20,589 | 7,515 | 9,265 | 19,995 |
| C85R | 5,736 | 22,153 | 8,086 | 9,969 | 21,907 |
| C85U | 5,685 | 22,153 | 8,086 | 9,969 | 21,045 |
| C79U | 5,693 | 20,589 | 7,515 | 9,295 | 19,559 |
| C82U(5) | 14,595 | 21,371 | 7,913 | 9,275 | N/A |

(1) Denotes test identifier, including test series (A, B or C), cable size expressed as number of 15.2-mm strand, U denotes uncoated strand cable, R denotes retest.

(2) Ungrouted specimen.

(3) Combined axial/flexural fatigue test incorporated 23 ksi fatigue stress range including 5 ksi flexural stress range. Test geometry incorporated 2,743 mm saddle radius, 23° anchorage angle and 175-mm saddle pipe diameter.

(4) Length between ends of strand anchorages.

(5) Saddle test geometry incorporated 3,505 mm saddle radius, 27° anchorage angle, and 219-mm diameter saddle pipe.

METRIC CONVERSIONS: 1 mm = 0.039 in., 1 kN = 0.2248 kip

## Cable System Configurations

The principal load-carrying elements of the tested stay cables were high-strength steel strands. The function, design, and installation of stay cables are discussed by Podolny (2). A number of seven-wire epoxy-coated or uncoated strands were encased in either high-density polyethylene (HDPE) or steel pipe. The coated strands evaluated in these test series incorporated an epoxy coating that encased the outside periphery of the strand and did not fill the interstitial spaces between wires. Spaces between strands and between strands and pipe were filled with cement grout. The primary function of grout was to protect the strands. Some cable designs also use grout as a structural component of anchorage sockets; grout consisted of cement, water, and admixtures. The cables were grouted while they were subjected to a constant load of approximately 39 percent of GUTS. The grout was cured to a specified compressive strength before fatigue testing.

Stay cable anchorage designs vary substantially among bridge projects. In general, strands are splayed outward near anchorages. These strands either terminate in a large socket or are anchored individually with wedges at an anchor plate. In the wedge system, the force in each strand is transferred to the anchorage through a two- or three-piece conical wedge set. Each strand passes through a conical opening in the anchor plate, which constrains the wedges. As the strand force increases, sharp ridges lining the wedge interiors penetrate the surface of the wires and provide a means for transferring force to the anchor plate.

In socket systems, the force transfer occurs over the length of a conical socket. The diameter of the splayed strand bundle decreases with the distance from the anchor plate end of the socket to the location where the nonvariable diameter cable free length begins. Bond between strands and the contents of the socket (epoxy or grout) transfers cable forces to the sockets over their length. Nevertheless, wedges or sewage-type systems are still used at strand ends.

Figure 1 shows the three anchorage systems evaluated in the cable tests discussed here: wedge, socket, and hybrid systems.

Anchorage System A is a prefabricated socket system consisting of a steel socket filled with a mixture of epoxy and steel balls. The strand's epoxy coating is stripped over the strand's length inside the socket and for a relatively short distance adjacent to the socket in the free length of cable. This is done to enhance bond between epoxy-steel ball compound and the strand. A layer of epoxy and a layer of water barrier sealant fill the spaces between strands and HDPE pipe in the area adjacent to the socket. The water barrier sealant was used to prevent penetration of grout bleedwater to unprotected strands. Each strand terminated in a swaged sleeve bearing on a locking plate.

The anchorage used in Test Series B combines features of both the wedge and socket systems. The epoxy coating of the strands is not removed and grout is used to transfer forces from the strands to the socket structure through bond. Unlike the coated strands in Test Series A, the epoxy-coated strands in Series B were manufactured with a grit-impregnated surface to improve bond. All strands pass through a wedge-gripped anchor plate and terminate in a grout cap. To enhance penetration through the epoxy coating, the wedges are manufactured with deeper teeth compared with conventional (uncoated) strand wedges. Since a static load is applied to the cable before grouting, the socket mechanism becomes effective only after grout cure. Therefore, prior to grouting, the entire cable force is carried by the wedges while the subsequent cyclic forces are carried mainly through the socket mechanism.

Anchorage System C relies solely on conical wedges for force transfer between strands and the anchorhead. Steel pipe sheathing was used instead of the HDPE pipe used in the other two systems. The steel transition pipe is bolted to the anchor plate. The strands terminate in a grout cap. This as-designed system used epoxy-coated strands without surface grit. Therefore, bond between strand and grout is comparable to System A.

## Test Fixtures

Construction Technology Laboratories (CTL) operates two separate test facilities for axial fatigue and combined axial/flexural fatigue tests of stay cables. In general, axial fatigue tests are incorporated in the test series for all bridges whereas the axial/flexural fatigue tests are performed only for cable-stayed bridge designs incorporating continuous cables through the pylons or towers. In such designs, the cables are not anchored at the pylons but are supported on a curved "saddle" and anchored at the deck level only.

Figures 2 and 3 show the axial and axial/flexural test fixtures, respectively. The test systems are structurally self-reacting and the forces are balanced within the fixtures. The axial test fixture was fabricated of steel, and the axial/flexural fixture is a post-tensioned segmental concrete beam. In the axial/flexural test fixture, the hydraulic ram is placed under the saddle, and cyclic axial and flexural forces are applied through vertical movements of the ram piston. A description of the axial/flexural test fixture and its use was documented by Tabatabai and Pandya (*3*). A closed-loop servohydraulic system is used to apply cyclic loads to the cables. Both test fixtures incorporate a continuously recording nondestructive wire break detection system for monitoring wire ruptures during cyclic loading.

## Test Results

The following sections present narrative descriptions of the 14 stay cable fatigue tests, incorporating the authors' discussion of specimen dissections and unique test procedures and cable design features. Fatigue performance data for all tests are presented in Table 2.

### Test Series A

Test Series A consisted of a specified total of three axial tension tests for 31-, 49-, and 73-strand epoxy-coated stay cable specimens. There were no combined axial/flexural fatigue test requirements for this project.

#### *31-Strand Cable Test (Specimen A31)*

During 2 million cycles of fatigue loading on the 31-strand cable, the wire break detection system indicated a total of eight wire breaks, or approximately twice the number of breaks allowed by specification (2 percent of total number of wires, or four wires). The maximum load achieved during the subsequent static load test was 7086 kN (1,593 kips), which was less than the acceptance load level of 8074 kN (1,815 kips).

A number of observations were made during the dissection of the cable. Severe corrosion of strands was noted in the area beneath the epoxy-zinc compound near the bottom cable socket. The corresponding area

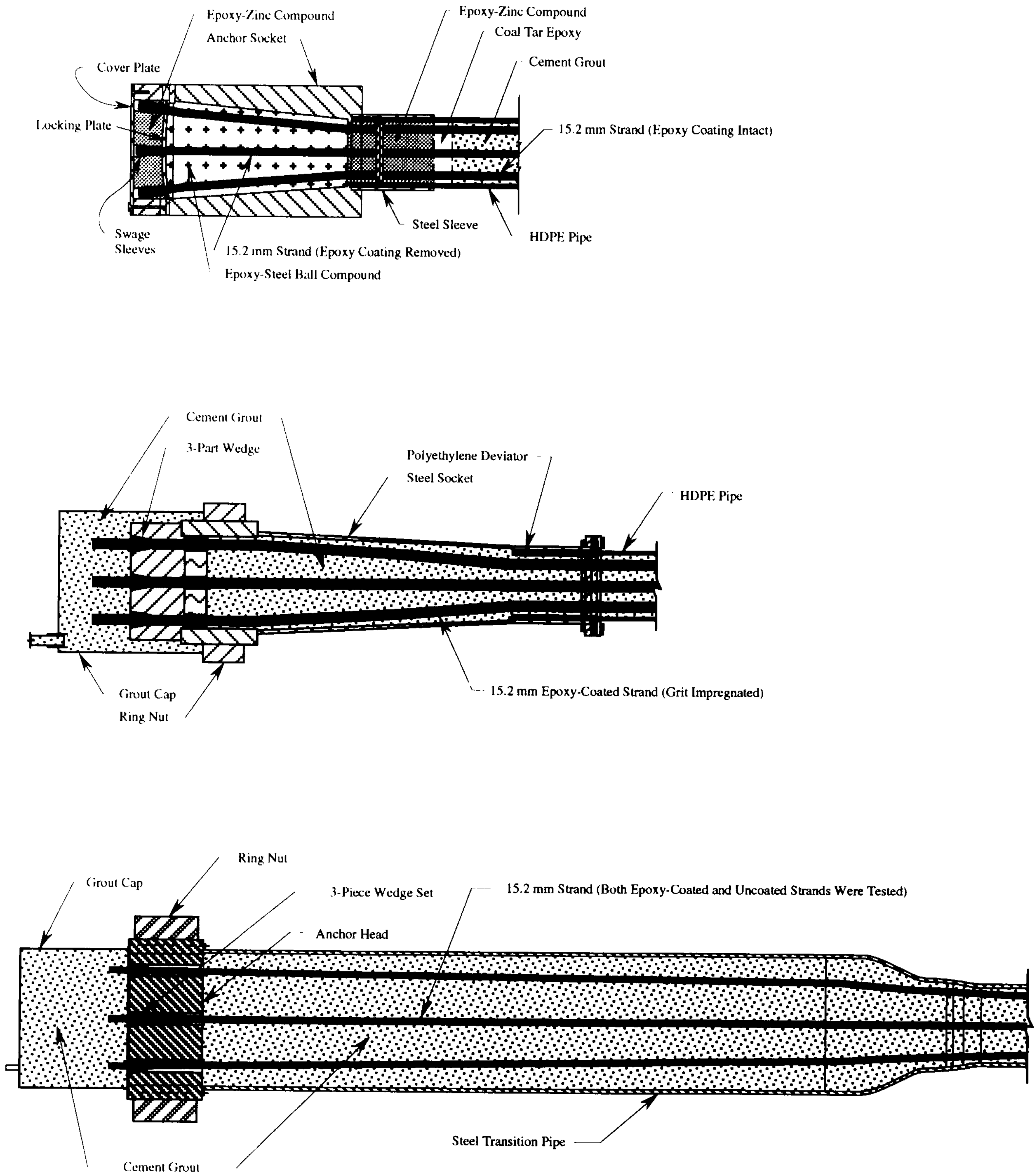


**FIGURE 1** Stay cable anchorage systems: *top*, Series A; *middle*, Series B; *bottom*, Series C.

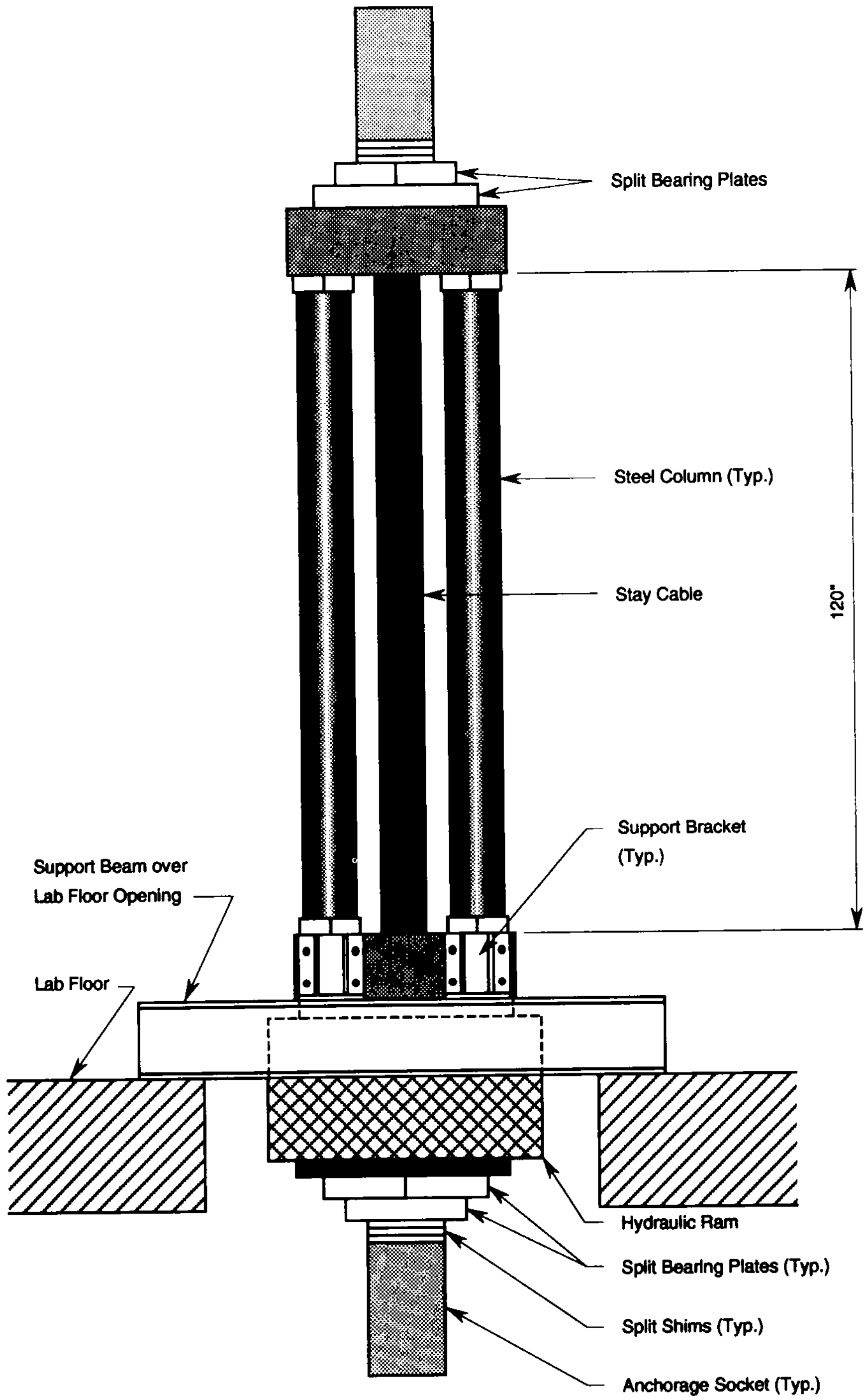


**FIGURE 2** Test fixture for axial fatigue testing.

near the top socket was also corroded, but to a lesser degree. It should be noted that the epoxy coating was removed from these regions during assembly of the cable. Although strand areas under the coal tar epoxy had also been stripped bare, these areas were free of corrosion.

Twenty-six broken wires (including three completely severed strands) were found, almost all of which were located in the severely corroded area within 190 mm (7½ in.) of the bottom socket. Seventeen wire breaks were considered fatigue fractures, and the rest appeared ductile. It is believed that although eight wire ruptures occurred during fatigue testing, the remaining wire breaks observed in dissection were attributable to static fractures at fatigue damage accumulation sites on the wire.

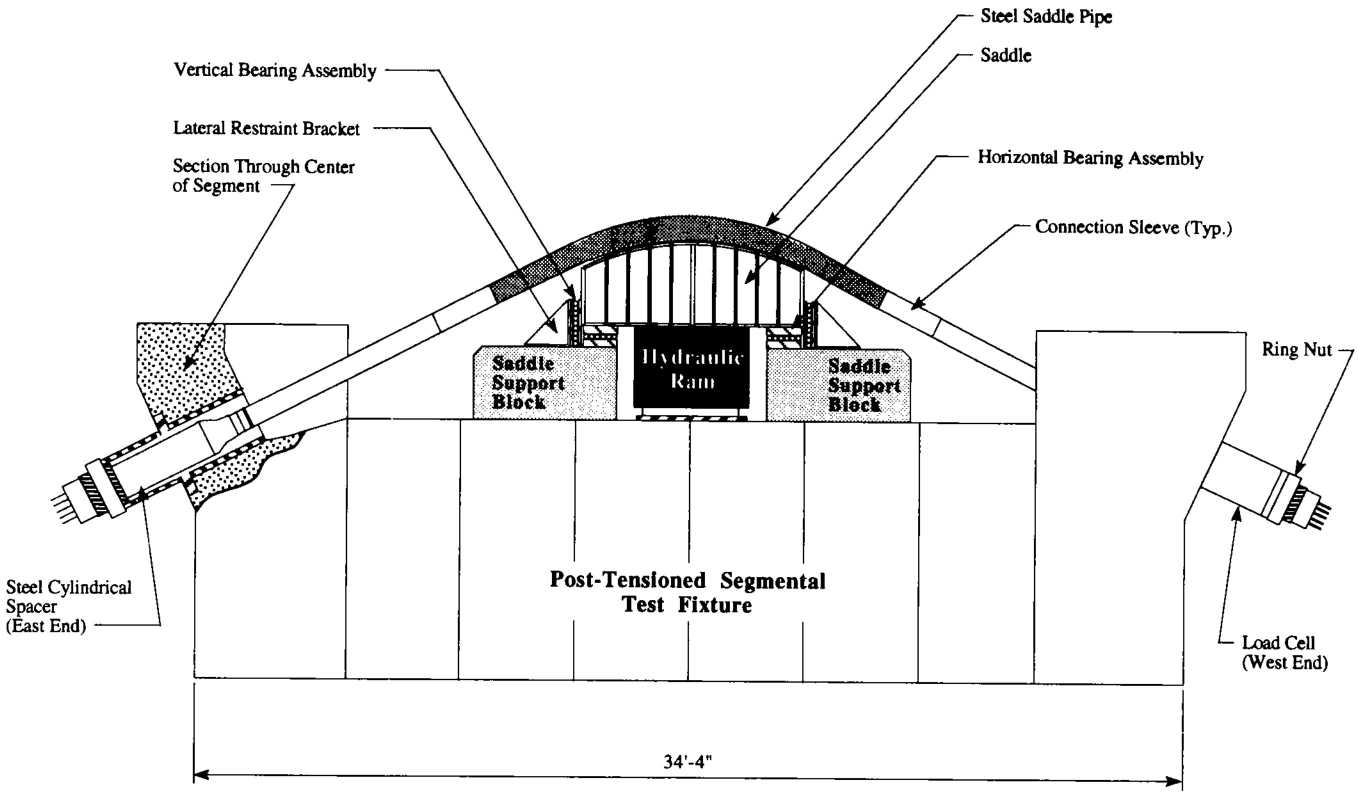


FIGURE 3 Test fixture for combined axial/flexural fatigue testing.

The contents of the bottom socket were forced out in a high-capacity compression testing machine to examine the degree of corrosion inside the socket. Corrosion had extended approximately 178 mm (7 in.) into the epoxy-steel ball compound zone of the bottom socket. It is believed that penetration of grout bleedwater through the boundary between the coal tar epoxy and the HDPE pipe caused the corrosion. The grout bleedwater then reached the bare strands through the closely spaced transverse cracks in the epoxy-zinc compound. The extensive strand corrosion observed occurred during the month between grouting and cable dissection.

### *31-Strand Cable Retest (Specimen A31-R)*

A second 31-strand cable was tested. This cable was similar to the first 31-strand cable, except that in accordance with approved test procedure revisions, it was tested ungrouted. During fatigue testing, three wire breaks were detected. Therefore, the allowable number of wire breaks (4) was not exceeded. However, the maximum load of 7037 kN (1,582 kips) achieved during the subsequent static test did not attain the target load level of 8065 kN (1,813 kips). Several wire and strand breaks were heard, and the testing was discontinued.

The cable was then removed from the test fixture and dissected. A total of 22 broken wires, including three completely severed strands, were found. Seven of the wire breaks were considered fatigue fractures, and the rest were ductile. One broken strand was located near the top socket, one near the bottom socket, and the third approximately 1525 mm (60 in.) from the top socket (in the free length). A closer examination of the immediate area of wire fractures in cable free length indicated presence of localized corrosion on several wires. There were no indications of corrosion observed on the bare strands under the coal tar epoxy and the epoxy-zinc compound.

### *49-Strand Cable Test (Specimen A49)*

The next stay cable specimen tested in Series A was a grouted 49-strand cable. From the results of the first two tests, the cable manufacturer modified the cable design slightly. Revised anchorage details incorporated a polyurethane material in place of coal tar epoxy. The thickness of the water barrier sealant was also increased, and the strand epoxy coating was left intact at least 127 mm (5 in.) from the socket. The wire break detection system indicated four wire breaks during fatigue tests, which conformed with the acceptable breakage limit of 2 percent, or seven wires.

**TABLE 2 Fatigue Test Results**

| Test Designation(1) | Number of Cycles at First Wire Breakage | Number of Broken Wires at 2,000,000 Cycles(4) | Number of Fractured Wires Observed After Static Proof Test |
|---|---|---|---|
| A31 | 1,100,000 | 8 | 26 |
| A31R(2) | 1,029,000 | 3 | 22 |
| A49 | 51,000 | 4 | 21 |
| A73 | 52,000 | 5 | 49 |
| B46 | 600 | 87 | 144 |
| B37(3) | N/A | 0 | N/A(5) |
| B17 | N/A | 0 | 0 |
| B46R | 1,603,000 | 4 | 19 |
| C85 | 1,370,000 | 7 | 7(6) |
| C79 | 1,982,000 | 2 | 32 |
| C85R | 1,490,000 | 12 | 60 |
| C85U | N/A(7) | 0(7) | 8 |
| C79U | 611,000 | 10 | 28 |
| C82U(3) | 78,000 | 148(8) | N/A(5) |

(1) Denotes test identifier, including test series (A, B or C), cable size expressed as number of 15.2-mm strand, U denotes uncoated strand cable, R denotes retest.

(2) Ungrouted specimen.

(3) Combined axial/flexural load regime - see Table 1 for test parameters.

(4) Based on wire break detection system data except for C82U.

(5) Static proof test not required.

(6) Anchorage failure occurred at 57.8% GUTS.

(7) Wire break detection system malfunction noted.

(8) Based on outcome of cable dissection.

The maximum load achieved during the static test was 12 366 kN (2,780 kips), which corresponds to 96.8 percent of GUTS and 92.1 percent of the actual ultimate strength of cable. Several wire and strand breaks were heard during the static test, and the acceptance load level of 12 753 kN (2,867 kips) was not achieved.

Three completely severed strands (21 broken wires) were found inside the cable during dissection. Two strand breaks were near the bottom socket, and one occurred near the top socket. All three breaks occurred on the outside layer of strands. Ten of the broken wires exhibited fatigue fracture features; other breaks were ductile.

### *73-Strand Cable Test (Specimen A73)*

The last stay cable specimen tested in Series A was a grouted 73-strand cable. During fatigue testing, five wire breaks were detected with the wire break detection system. Therefore, the number of breaks conformed with the specification required limit of 2 percent (10 wires). The maximum load achieved during the static test was 17 175 kN (3,861 kips), which corresponded to 90.3 percent of GUTS and 85.9 percent of actual cable strength.

Seven completely severed strands (49 broken wires) were found in the cable during dissection. All breaks were close to the bottom socket and, in general, appeared on the outside layer of strands. Of the total number of broken wires, 36 wires exhibited fatigue fractures and the others were ductile. Two strands showed clear indications of corrosion on the surfaces of the center (king) wire. The surfaces of outside wires in these two strands, which were in contact with the center wire, also showed evidence of corrosion. There was no evidence of grout bleedwater penetration in the area of these strand fractures.

## Test Series B

Cable Test Series B included axial tests of 17- and 46-strand specimens and one axial/flexural test on a 37-strand cable. The anchorage system for this cable is shown in Figure 1.

### *46-Strand Cable Test (Specimen B46)*

The first stay cable specimen in Series B tests was a 46-strand cable. After placement of individual strands inside the test frame and before placement of grout caps, the cable supplier applied epoxy patches at the ends of each strand protruding beyond the wedge plates. The cable was then statically loaded to 65 percent of GUTS to seat the wedges. The load was reduced to grout load (38.6 percent of GUTS), and the cable was grouted. The grout was allowed to cure for 1 week before the fatigue test was begun.

The wire break detection system recorded 87 wire breaks during the fatigue test. A sharp rise in the number and rate of occurrence of wire breaks occurred after approximately 1,400,000 cycles and continued to increase until the end of the test. It should be noted, however, that the stiffness of the cable and the magnitude of its elongation from minimum to maximum load changed very little as a result of all the wire breaks. The maximum load achieved during the subsequent static proof test was 8452 kN (1,900 kips), or 70.5 percent of GUTS. Several wire and strand breaks were heard during the static test, and the acceptance load level of 11 387 kN (2,560 kips) was not achieved.

After the static test, the cable was removed from the test fixture and dissected. The grout near the area of top socket was wet. Fractured wires were evident beneath the cracked and damaged epoxy coating, and extensive corrosion and moisture were evident near most fractures. Corrosion stains were also apparent on the inside surfaces of epoxy coatings. Strands protruding beyond the bottom wedge plate were sawcut a few inches from the wedge plate. Strands were then numbered and individually sawcut at the inside surfaces of top and bottom wedge plates. As strands were being handled, water (of a yellowish brown color) was observed coming out of a number of strands.

A total of 144 broken wires were found in the cable with multiple successive fractures (up to three) on a number of single wires. Some multiple fractures occurred within a few inches of each other. Only 16 of the 144 fractures were clearly ductile while the balance exhibited fatigue or brittle fracture features. All wire fractures occurred within 915 to 2000 mm (36 to 79 in.) from the inside face of top wedge plate. This area corresponded to the wet grout zone observed upon removal of HDPE pipe.

It became clear that grout bleedwater found its way into the interstitial spaces between wires under the epoxy coating and remained there throughout the test as free water. It is believed that water may have penetrated through epoxy-patched strand ends and the wedge areas where the epoxy coating is cut with the wedge teeth. It is not clear what role, if any, that possible holidays in the surface of the epoxy coating may have had on the penetration of water or to what extent preexisting corrosion-induced pitting affected fatigue endurance. However, it is also clear that if grout bleedwater can penetrate inside the strand, then severe corrosion of wires can be expected over a short period. On the basis of the observed lack of change in the stiffness of cable after the occurrence of many wire breaks, it is concluded that wires and strands redeveloped relatively large forces a short distance from a break location, possibly because epoxy-coated strands with grit were used. This may also explain why many wires had multiple fractures.

Investigation of the fatigue test failure by the bridge owner (4) revealed that the poor performance was created by preexistent corrosion of the strand used for cable tests. Additionally, the presence of grout water beneath the epoxy was believed to have contributed to fatigue fractures. As a result, strand coils were screened more carefully for the presence of corrosion and grout pressures were reduced to minimize pressure bleed.

### *37-Strand Cable Test (Specimen B37)*

The axial-flexural fatigue test was performed on a 37-strand cable (Figure 3). Before grouting, the cable manufacturer used plastic caps filled with epoxy to cover the ends of strands on both ends of the cable. The epoxy was then allowed to cure. A few hours after grouting, the cable manufacturer removed the grout caps and their grout contents, thereby exposing the strands protruding beyond the wedge plates. The strand ends (including plastic caps) were sawcut a few inches from the wedge plates on both cable ends. Drops of water were observed coming out of some strands. The cable manufacturer subsequently used demoisturized and pressurized air to remove moisture from the interstitial spaces between wires in all 37 strands.

Approximately 2 million cycles of fatigue loading were then applied to the cable. The wire break detection system did not indicate any breaks. The acceptance requirements did not specify static proof loading after the fatigue test; therefore, a static test was not performed.

The cable was then removed from the test fixture and dissected after the conclusion of fatigue tests. No wire breaks were found during the dissection.

### *17-Strand Cable Test (Specimen B17)*

Another axial test was performed on a 17-strand cable. Again, prior to grouting, the ends of all strands were covered with plastic caps filled with epoxy and allowed to cure. A few hours after grouting, the grout caps and the grout inside the caps were removed and the strand ends were cut near the wedge plates, thereby removing plastic caps. Water was observed coming out of two strands on the bottom. The cable manufacturer used demoisturized and pressurized air to remove moisture from inside all strands.

After the minimum specified grout strength was achieved, fatigue testing began. The detection system indicated no wire breaks. The acceptance load level of 4200 kN (944 kips) was attained during the static test. No wire fractures were found during dissection of this cable.

### *46-Strand Cable Retest (Specimen B46-R)*

The final test performed in this series was a retest of the 46-strand cable. Before grouting, the cable manufacturer covered the ends of all strands with plastic caps filled with an epoxy. A coating of epoxy was also applied over the plastic caps. Prior to the start of fatigue tests, both top and bottom grout caps were removed and plastic caps on the strand ends were exposed. However, strand ends were not sawcut. Plastic caps on four strands were damaged during removal of grout. A few drops of water were observed coming out of the bottom of one strand with a damaged plastic cap. In addition, yellowish residue was found at the bottom of another strand, which indicated water leakage. During fatigue testing, four wires were broken (fewer than the allowable number of six), as indicated by the wire break detection system.

The acceptance load level of 11 387 kN (2,560 kips) was achieved during the subsequent static test. Before the cable was removed from the test fixture, a plastic cap was removed from the bottom of a strand and water was observed coming out of it.

During dissection, cracked and damaged epoxy coatings indicated the presence of fractured wires. Some corrosion was evident in the vicinity of most fractures on the center wire and along the contact lines between wires. Small amounts of water were observed coming out of five strands. Nineteen broken wires were found in the cable, with four wires having two fracture locations for a total of 23 fractures. All 23 fractures exhibited fatigue features.

## Test Series C

Two axial (79- and 85-strand specimens) and one axial/flexural (82-strand specimen) cable tests were originally specified for Series C. When the first manuscript of this paper was submitted for review, three tests of the originally specified epoxy-coated cable and three tests of uncoated strand cable had been completed. The anchorage system for this test series is shown in Figure 1.

### *85-Strand Epoxy-Coated Cable Test (Specimen C85)*

The 85-strand test cable was first statically loaded to 45 percent of GUTS to seat the top wedges. The bottom wedges had been seated to 45 percent of GUTS in the supplier's plant. The load was then reduced to grout load. The strand ends were covered with plastic caps filled with epoxy and the epoxy was allowed to cure. The cable was then grouted. A few hours after grouting, the top and bottom grout caps were removed and the strand ends (both top and bottom) were sawcut to examine whether water had penetrated beneath the epoxy. Water was clearly evident in at least 35 strands. Then, at the direction of the cable supplier, pressurized and demoisturized air was used to remove moisture from inside of all strands.

Very early during cyclic testing, all the bolts 12.7 mm (½ in.) in diameter connecting the steel transition pipes to the top and bottom anchor plates failed (six at each anchor plate). Seven wire breaks (1.2 percent) were detected during the fatigue test.

At the conclusion of the fatigue test, the cable was statically loaded with the target of achieving the acceptance load level of 95 percent of the actual cable strength, or 21 520 kN. At a load of 57.8 percent GUTS, or approximately 12 811 kN (2,880 kips), all strands in the top anchor head simultaneously and unexpectedly slipped through their wedges about 70 mm (2¾ in.). Only the epoxy coating of strands and one broken wire were left standing above the anchor plate.

During dissection of the cable, seven wire fatigue breaks were found. Six breaks occurred on an outer-layer strand approximately 380 mm (15 in.) from the bottom anchor head. Corrosion was observed on this strand in the area of breaks. One wire break occurred on an inner strand approximately 12.7 mm (½ in.) below the end of its wedge at the upper anchorhead. Corrosion was also evident on this strand in the fracture area and at random locations on other exposed strands. The teeth of wedges in the top and bottom anchorheads did not show signs of flattening or bending. The penetration of wedges into the wires was not uniform in the top anchorage. However, wherever penetration was evident, the wire surface was scraped and flattened as a result of strand slippage.

### *79-Strand Epoxy-Coated Cable Test (Specimen C79)*

The second test in Series C incorporated similar preparations to Test C85's, except that anchorage wedges were seated at a load level corresponding to 70 percent GUTS in order to circumvent the previous anchorage difficulty. Following grouting and at the request of the cable supplier, bleedwater that had penetrated beneath the strand epoxy coating was forced out of each strand with compressed demoisturized air. During fatigue testing, the wire break detection system identified two wire ruptures. After fatigue testing, the cable was loaded statically, withstanding a maximum load of 18 994 kN (4,270 kips). The target load level was 19 995 kN (4,495 kips).

During dissection of the cable, 32 broken wires were noted, along with fractured welds between the transition pipe and its anchorhead attachment flange. Residual moisture, most likely consisting of grout bleedwater, was evident in the specimen. Corrosion with pitting of strand was noted beneath the epoxy coating.

### *85-Strand Epoxy-Coated Cable Retest (Specimen C85R)*

In preparation for the third test in Series C, the transition pipe-to-anchorhead attachment details were modified. The number of connecting bolts was increased to 12 on each anchorhead, and welding procedures were revised. The cable was grouted, and, at the direction of the cable supplier, strands were dried internally using compressed demoisturized air.

During fatigue testing, 2 percent wire breakage occurred (12 wires); thus this specimen conformed with fatigue test requirements. However, 22 of the 24 transition pipe-to-anchorhead connecting bolts at both anchorheads fractured during fatigue testing. During the static proof test, the specimen attained a maximum load of 20 044 kN (4,506 kips); the target proof load was 21 907 kN (4,925 kips). Subsequent dissection of the specimen revealed 60 fractured wires, with successive multiple fractures on individual wires. Residual moisture, presumably from grout bleedwater, was evident, as was corrosion ranging in severity from light to moderate beneath the epoxy coating.

### *85-Strand Uncoated Cable Test (Specimen C85U)*

Subsequent to the first three cable tests, the bridge specification was modified to allow an uncoated strand system. Revisions included strand anchorage modification and application of a corrosion inhibitor solution to strands before grouting. This latter measure represents an accepted cable installation practice intended to protect uncoated strands from corrosion prior to cable grouting. Further modifications were made in the transition pipe-to-anchorhead bolted connection details to improve performance.

Fatigue testing indicated acceptable performance with respect to wire breakage, and the cable attained the specified static proof load of 95 percent GUTS. Dissection of the specimen revealed eight fractured wires. Difficulties with suitable performance of the transition pipe-to-anchorhead continued, with cracking occurring in the machined transition pipe flange. Strands exhibited evidence of corrosion with surface pitting at locations of transverse cracks in grout.

### *79-Strand Uncoated Cable Test (Specimen C79U)*

To overcome continuing difficulties in suitable fatigue performance of the steel transition pipe, additional modifications were made to this component. Specimen assembly and grouting procedures were similar to Specimen C85U.

This specimen performed adequately in fatigue, with 10 wire breaks (1.8 percent) occurring through the cyclic load application interval. During static proof loading, the specified maximum load of 19 559 kN (4,397 kips), or 95 percent GUTS, was achieved.

Dissection of the specimen revealed the presence of 28 broken wires in the specimen. Locally severe corrosion was noted at several wire fractures. Areas of corrosion coincided with transverse cracks in the cementitious grout. Weld cracks occurred in the machined flange at the anchorhead end of the transition pipe.

### *82-Strand Uncoated Cable Test (Specimen C82U)*

A combined axial/flexural fatigue test was conducted on the 82-strand uncoated specimen. Test criteria and specimen geometry data are presented in Table 1. The test specimen was fabricated atop CTL's axial flexural test fixture (Figure 3). Strands were installed and wedges were preseated individually. Grouting load was attained by extending the hydraulic actuator positioned beneath the apex of the saddle pipe.

Two million cycles of fatigue load were applied to the specimen. The repetitive load applied to the cable (measured axially) ranged from 7913 to 9275 kN (1,779 to 2,085 kips). Acceptance criteria required that no more than 12 wires rupture during the fatigue test. No static proof loading of the specimen was required.

From the start of the test, the wire break detection system noted an unusually large number of events that suggested wire breaks. Commencing at approximately 78,000 cycles, a very large number of wire breaks were detected in the cable. Therefore, the specimen did not conform with wire breakage criteria. Subsequent dissection of the specimen revealed 148 fractured wires on 40 individual strands. These fractures were distributed equally between both ends of the saddle (71 and 73 at either end). Ninety-seven percent of the fractures were located in the end regions of the saddle. The remaining four fractures were located in the cable free length. Some corrosion of the specimen was noted at transverse cracks in the grout, and partial penetration weld fatigue fracture was noted at the concentric reducer sections of the transition pipe.

Detailed examination of wire ruptures in the cable indicated that many of the fatigue fractures originated at oval-shaped fretting marks on the wire surface. Brownish staining on fracture faces suggested possible involvement of corrosion in the failure mechanism. The fretting of wire was noted principally at interstrand contact points in high-contact stress regions of the cable over the saddle. Modifications in cable specimen stressing methods, specimen anchorage, and transition pipe details were made in preparation for retest of the specimen, with the intent of improving specimen performance.

## Summary and Conclusions

1. Fourteen fatigue tests of full-scale stay cables were performed to fulfill acceptance testing programs for the construction of three U.S. cable-stayed bridges. The cable specimens ranged from 17 to 85 strands 15.2 mm (0.6 in.) in diameter with nominal tensile capacities of 4430 to 22 157 kN (996 to 4,981 kips).

2. Tested cables were composed of seven-wire uncoated and epoxy-coated parallel strands 15.2 mm (0.6 in.) in diameter. Different cable anchorages were used for the three bridges. One test series used epoxy-coated strand with a grit-impregnated surface to improve bond, and the other incorporated epoxy-coated strand with smooth surfaces and uncoated strand. It should be noted that the reported test series did not evaluate cables constructed of the epoxy-encapsulated (filled) strand.

3. Review of fatigue test results indicates that conformance with the current 2 percent limit on wire breakage during cable fatigue testing can be attained. However, it is apparent that design, materials, and fabrication features that have the potential for impairing fatigue resistance of bridge stay cables affect adequate test performance as well. During the three test series, these features resulted in excessive wire breakage during cyclic load application or wire damage accumulation (transverse cracks) during fatigue testing, which induced wire rupture during static proof loading.

4. Manifestations of wire fatigue fracture during testing occurred principally in cable specimen free length, with few instances of wire fracture in anchorages.

5. Testing revealed that moisture from the cement grouting process can infiltrate the epoxy coating of strands and remain as free water in the cable specimen for the duration of the cable qualification test (1 to 2 months). It is believed that this phenomenon contributed to the premature, corrosion fatigue–related fracture of wires during all three series. Moisture intrusion most likely occurs in the wedge regions where the epoxy coating is breached by wedge teeth. It is possible that holidays in the epoxy coating also promote the penetration of grout bleedwater. It should be noted that grout specification requirements for all three test series contained stringent provisions intended to limit corrosion aggressivity of grout constituents.

6. Test results from an ungrouted cable (A31-R) and investigation of a grouted-cable test failure (B46) indicated that preexistent corrosion of strand beneath the epoxy coating contributed to mechanisms inducing wire fracture during fatigue tests. Preexistent corrosion-induced pitting of strand initiated fatigue cracks.

7. Cement-grouted, uncoated strand cable systems developed localized corrosion activity at transverse grout crack locations during the 1- to 2-month fatigue test duration. These regions near grout cracks acted as sites at which wire fatigue damage accumulated.

8. Extensive fretting-fatigue damage at interstrand contact surfaces within the saddle pipe region was noted during a combined axial/flexural fatigue test of a particularly large cable. Interactions between cable size, saddle radius, saddle pipe diameter, and test methodology were under study at the time this paper was prepared.

9. Cable sheathing consisting of HDPE or steel pipe serves as the primary barrier to passage of deleterious substances to the cable's principal structural element. The sheathing's durability-enhancing function can be disrupted. The sheathing acts compositely (to some extent) with the rest of the cable and is therefore subjected to repetitive stresses and possible failure at connections.

## Recommendations

1. Review of the rest results suggests that the presence of free moisture in cement-grouted stay cable specimens contributes to accelerated wire damage during fatigue testing. This phenomenon was observed in both coated and uncoated strand and occurred in the brief

1- to 2-month duration of the affected tests. Although it is unknown to what extent and for what duration grout bleedwater can function as a corrosion medium in an erected, grouted bridge stay cable, even relatively minor surface pitting of cold drawn wire can reduce the fatigue resistance of strand, thereby reducing the potential service life of a cable. For this reason, the authors recommend that methodical development and enforcement of improved grouting procedures be implemented with the goal of minimizing the liberation of free moisture during stay cable cement grouting. From observed cable test performance, this measure would be an effective advance in stay cable durability. Other measures, such as the use of epoxy-encapsulated (filled) strand, may prove to be beneficial should the encapsulating coating resist infiltration of free moisture liberated during pressure grouting.

2. Preexistent corrosion of coated and uncoated strand for stay cable use should be prohibited in specifications for strand procurement. Currently, the PTI recommendations contain no such provisions.

3. Bridge stays incorporating continuous cables over saddles should be designed with caution and evaluated rigorously for the effects of high-contact stress-induced fretting between strands created by cable curvature. Study of this issue on performance of existing uncoated-strand bridge stay cables is warranted.

4. Acceptance testing programs for bridge stay cables should be conducted as early as practical during the process of fabricating and erecting stay cable. This approach allows ample time for implementing cable detail and execution refinements, if proven necessary by test, and limits the impact of testing difficulties on a bridge construction schedule.

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