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Implementation Program on High Performance Concrete

Guidelines for Instrumentation of Bridges

August 1996

TECHNOLOGY APPLICATIONS

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16. Abstracts

This report provides an outline for the instrumentation of bridges being constructed under the Federal highway Administration's (FHWA's) Strategic Highway Research Program (SHRP) implementation effort in High Performance Concrete (HPC). The report describes the various types of measurements that can be made and the appropriate types of instrumentation that should be used. A basic instrumentation program is described that should be implemented on all demonstration bridges. Optional items that may be included at the discretion of each State are also suggested.

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BACKGROUND

High performance concrete has been used in the building industry for many years. Although its application in highway structures has been limited, it is now receiving increased attention. As part of a program to further the implementation of high performance concrete, the Federal Highway Administration (FHWA) is developing a showcase package. The package will include demonstrations, workshops, and field assistance. Several demonstration high performance concrete bridges will be built and the results described at the workshops. The bridges will have different types of superstructures, will be built in different climatic regions, and will be examples of the practical application of high performance concretes. Construction of these bridges will provide opportunities to learn more about the placement of high performance concrete as well as the actual behavior of high performance concrete bridges. It is anticipated that each bridge will be instrumented to monitor its performance over a period of several years. Similar instrumen-tation will be used on each structure so that performance comparisons can be made among these demonstration bridges.

OBJECTIVE

The objective of this report is to provide an outline for the instrumentation program of the demonstration bridges. The report describes various types of measurements that can be made and the appropriate types of instrumentation that should be used. A basic instrumentation program is described that should be implemented on all demonstration bridges. Optional items that may be included at the discretion of each State are also suggested. The optional items are not intended to restrict the use of innovative ideas and States may want to try other types of instrumentation not described in this report.

TYPES OF MEASUREMENTS

This section of the report describes several types of measurements for which the technology is well established. However, successful instrumentation depends on the abilities and skills of the individuals doing the work. In-plant or on-site installation should not be considered a training ground for students or technicians. Training should be completed prior to any installation and collection of data.

Temperatures

Temperatures are measured to determine:

- Heat of hydration.
- Temperature for match-cured cylinders.
- Temperature of quality control cylinders.
- Temperature gradients.
- Temperature corrections for other measurements.

Temperatures are measured using thermocouples that can be purchased assembled or can be made from thermocouple wire. They are best positioned prior to concrete placement by attachment to either the reinforcement or a special fixture that is then tied to the reinforcement. The latter method is preferred when temperature gradients over a short distance such as a slab thickness are required. Thermocouple wires must be carefully positioned to avoid damage during concrete placement and vibration. The lead wires from a group of thermocouples should be bundled together and tied to the reinforcement so that they exit the concrete at a single and convenient location. Whenever possible, the wires should be tied to the underside of reinforcement to protect the wires from falling concrete. Wires may also be protected by using plastic sheathing.

When strains are measured with electrical resistance strain gages or mechanical strain gages, temperatures should be measured at the gage locations. When strains are measured with Carlson strain meters or vibrating wire gages, the gages include a built-in system for determining temperatures at the gage.

Strains

For purposes of instrumentation, strains can be divided into two types—short-term and long-term strains. Short-term strains are those changes that occur over a period of hours whereas long-term strains are those occurring over months or years. Short-term strains are generally caused by changes in dead and live loads, daily temperature cycles, or wind loading. Long-term strains are caused by seasonal temperature changes and creep and shrinkage in concrete structures.

Short-Term Strains

Short-term strains should be measured using electrical resistance strain gages. Although these gages can be attached directly to reinforcing steel in the field, this method requires attachment under field conditions and is very difficult. Consequently, the gages should be attached to separate lengths of reinforcement such as a 10- or 15-mm diameter bar about 600 mm long. This allows the gages to be attached to the bars under laboratory conditions and permits proper attachment of leads and waterproofing. Waterproofing should be done according to the manufacturer's recommendations and should be verified before gages are cast in concrete. The gaged bars can be tied directly to the reinforcement cage in the plant or at the site with minimum interruption to construction. Lead wires from groups of strain gages should be bundled together and tied to the reinforcement so that they exit the concrete at a single and convenient location. Whenever possible, the wires should be protected from damage from falling concrete by tieing to the underside of the reinforcement and, if necessary, protecting them in plastic sheathing. Electrical resistance strain gages should not be attached to prestressing strands, as this requires a special technique of attaching the gages along the spiral of individual wires and is difficult to accomplish. It is also likely that the gages will be damaged during stressing.

Electrical resistance strain gages can be applied to hardened concrete surfaces. For surfaces cast against steel forms, this is relatively easy provided access to the surface is possible and the weather is suitable. For troweled or grooved surfaces, special techniques are needed to prepare the surface prior to application of the gages.

Weldable electrical resistance strain gages are available for use on steel structures and large size reinforcing bars. These gages are produced with leads and waterproofing attached and only require spot welding to the steel. With practice, they can be installed under adverse site conditions.

Electrical resistance strain gages are available as temperature-compensated gages. These gages are designed so that when attached to a material with the specified coefficient of thermal expansion, the measured strain will not change as a result of temperature changes when length changes of the material are unrestrained. However, it must be remembered that the temperature compensation is not perfect because of the following:

- The coefficient of expansion of the material will not exactly match the specified coefficient of expansion of the gage.
- Any restraint to the free expansion or contraction of the material will result in an apparent strain.

Interpretation of measured strains under varying temperature conditions should consider the above factors.

Long-Term Strains

Long-term strains should be measured with gages designed specifically for this purpose. Two types are available for measurements inside concrete.

- Carlson strain meters.
- Vibrating wire gages.

These two types operate on different principles. However, they are both designed to have long-term stability, are robust for installation on site, and are provided with leads already attached. The lead wires are durable and may be tied directly to the underside of reinforcement for protection. Additional protection is not, generally, needed. The gages can be attached directly to the reinforcement although the vibrating wire gage may require a special mounting fixture. It is also possible to cast these gages in concrete blocks and then cast the blocks in the concretestructure. Use of this method is discouraged because of doubts about the effect of differential creep and shrinkage between the block and the concrete.

Output from these gages is affected by temperature changes, and the output data need to be corrected for both temperature changes of the gage and temperature changes of the structure. In most cases, the temperature of the gage and structure will be the same though the coefficients of thermal expansion will be different.

Long-term strain measurements are generally used to determine prestress losses. For this purpose, the gages are best positioned at the centroid of the prestressing force. Since strands are often draped or debonded in prestressed girders, the measurements are best made near midspan of the girders. If measurements near the ends of girders are required, the gages should be placed to avoid any effect on the strand transfer length.

Long-term strains have been measured using electrical resistance strain gages. However, attachment of the gages requires special care and this technique is not recommended.

Mechanical Strain Gage Measurements

Both short-term and long-term surface strains can be measured using mechanical strain gages. In this method, the distance between two points on the concrete surface is compared with the length of a standard invar reference bar. This approach requires the installation of special points on the concrete surface, is labor intensive, and cannot be used easily with an automated data acquisition system. It is particularly suitable for measurements of strand transfer length and as back up for long-term strain measurements by other means. In some applications, the sensitivity of the mechanical strain gage measurements will not be sufficient to provide reliable data. Measurements of concrete surface temperatures and standard reference bar temperatures are also needed when using a mechanical strain gage. To maintain the accuracy of this method, frequent comparisons with the reference bar are needed.

Length Changes

Measurements of overall length changes of a bridge or portions of a bridge can be comparedwith calculated length changes from creep and shrinkage or seasonal temperature changes. Length change measurements require a reference rod with a very low coefficient of thermal expansion. The rod must be fixed to the bridge at one end and relative movement between the rod and the bridge measured at the other end with a dial gage, linear potentiometer, or linear variable differential transformer. Care must be taken to ensure that the rod is protected from damage or changes in alignment. When electrical transducers are used to measure length changes, they must be electrically stable over the duration and temperature range of the observation period.

Deflections

No simple automated method exists for measuring vertical deflections of long-span girders. However, two simple manual methods are available. The first method involves the use of precise surveying equipment to measure the deflection at various points along the span relative to the ends of the girder. Reference pins can be located in the tops of girders for this purpose. The reference pins need to be relocated to the top of the slab when the deck is placed.

In the second method, a taut wire is stretched between two reference locations at the ends of a girder and the relative movement measured at locations along the span. The reference locations may be two bolts fixed rigidly to the sides of the girder, and the taut wire may be removed when not in use. However, it is important that the same tension be applied to the wire each time by using a pulley and weights at one end. A fixed reference, such as a scale on the side of the girder, is needed at each measurement location. Parallax errors can be eliminated by mounting a mirror adjacent to the scale. On box girders with easy access to the inside, deflections relative to the wire can be measured on the underside of the top slab inside the box. Non-corroding steel plates can be attached to the slab and measurements made with a digital sliding ruler on a magnetic base.

In some situations, a combination of the taut wire and surveying methods may be needed depending on plant and site conditions and the construction timing.

Vertical deflections can be measured with electrical transducers such as potentiometers and linear variable differential transformers. This method requires a stable accessible reference location for each measurement and, for most bridges, is not practical.

When monitoring deflections, it is important to remember that temperature gradients can have a large effect on camber changes. Ideally, all deflection measurements should be taken just before sunrise when the temperature gradient is a minimum.

Slopes

Changes in slope can be measured with tiltmeters. Both uniaxial and biaxial tiltmeters are available. Biaxial tiltmeters measure rotations in two orthogonal directions. Tiltmeters can be mounted on either vertical or horizontal surfaces and can be read manually or with an automated data acquisition system. They may be used for both short-term and long-term measurements.

Prestressing Forces

The most accurate method to determine prestressing forces prior to transfer is with load cells. Load cells can be positioned on strand at either the dead end or jacking end in the prestressing bed. Although calibrated hydraulic jacks are used to stress strands, they only provide the force before their release. For pretensioned members, load cells provide the force after release of the jack, during curing, and immediately prior to detensioning of the strand.

Load cells may also be used on the ends of unbonded post-tensioning tendons and stay cables to measure the changes of force with time. In this application, a means to verify the “zero” reading of the load cell is needed. This is generally done using a lift-off procedure where the force in the load cell is removed by pulling on the end of the tendons and reacting directly against the concrete member. The load cell “zero” reading is verified when all the load is carried by the jack. Load cells are available as stock items from several manufacturers or can be custom built.

Strand End Slip

Slip of strand at the ends of girders can be measured using a technique developed by FHWA andillustrated in Appendix A. A small channel-shaped fixture is attached to a strand at the end of the member. Holes in the legs of the fixture accept a digital depth gage or caliper which measures the distance from the outer leg of the fixture to the concrete surface. An initial measurement must be made prior to detensioning. Subsequent changes in the distance correspond to strand slip. Strand slip can be measured at detensioning, during the subsequent life of the girder, and during load tests. If it is necessary to cut the strand flush with the end of the girder, subsequent slip can be determined by measuring the relative movement between the end of strand and the end of the girder using a depth gage.

DATA ACQUISITION

Output from the sensing elements described in the previous sections can generally be measured using manual-read-out boxes or automated data-acquisition systems (ADAS). The two exceptions are deflections and mechanical strain gages, which can only be measured manually.

For instrumentation of precast girders, it is recommended that measurements prior to erection of the girders be measured manually. An ADAS may be necessary to facilitate frequent temperature measurements during the curing process. After erection, measurements may be taken manually or with an ADAS depending on the frequency of measurements. An ADAS requires an investment in equipment and installation time but greatly facilitates data acquisition particularly where a lot of readings are required in a short time. Data reduction is also a lot easier and more timely. Manual readings are labor intensive to obtain and still require input into a computer for data reduction and analysis.

For instrumentation of cast-in-place construction, the measurements may be taken manually or with an ADAS. For cast-in-place construction, installation of an ADAS is much easier and the sensing elements can be connected to the ADAS prior to concrete placement. Manual readout boxes will still be necessary in case the ADAS cannot be connected in time or in the event of failure of the ADAS. It should be noted that, with instrumentation during construction, there is no opportunity to put the experiment "on-hold" while the instrumentation is fixed. It is, therefore, essential to have a back-up plan particularly as it relates to obtaining "initialreadings."

DATA INTERPRETATION

Installation of sensing elements and data acquisition is only the start of monitoring field performance. Interpretation of data is equally important. Measurements of strains must be corrected for the coefficient of thermal expansion of the gages and the concrete if measurement of long-term strains is the objective. This requires a determination of the coefficient of thermal expansion of the concrete and, in some cases, the coefficient of thermal expansion of the gage. Determination of stresses from short-term strains requires a determination of the modulus of elasticity of the concrete or steel. Determination of stresses from long-term strains is considerably more complex and requires information about creep and shrinkage of the concrete. The determination of creep properties requires special loading equipment.

Consequently, accurate interpretation of the measured data requires information about the coefficients of thermal expansion of the gages and concrete, moduli of elasticity of concrete and steel, and creep and shrinkage of concrete. These data can be calculated or may be available from previous projects. However, it is recommended that the properties be determined from measurements on the actual concretes used in the instrumented portions of the structure. This requires the manufacturing of separate test specimens—usually 150- by 300-mm cylinders. These specimens should be cured and stored as long as practical with the actual structure prior to test.

SAMPLE INSTRUMENTATION PROGRAM

Many variations of instrumentation programs are possible depending on the specific interest of individual States. However, it is recommended that all States implement the basic program described in the next section. This will provide a basis for comparison between bridges in the different States. An optional program is also provided for States that wish to obtain additional information. It should be noted that the incremental costs for some parts of the optional program will be small compared to the extra information obtained.

Basic Instrumentation Program

The basic program consists of measurements of temperatures, long-term strains, and long-term deflections.

Temperatures

Temperature measurements are required to determine:

- Effects of heat of hydration on the properties of high performance concretes.

- Temperature gradients for superstructures at different locations in the United States.

- Number of freeze-thaw cycles experienced by the bridges at each location.
- Temperature correction for other measurements.

Measurements of temperature to determine the effects of the heat of hydration, must be made during the concrete curing period. Measurements of temperature gradients are only needed for the completed bridge. However, one set of thermocouples can be used for both measurements.

For measurements of thermal gradients, thermocouples should be placed along the vertical center line of the girder at the following depths:

- Top surface of the deck.
- 100 mm below top surface of the deck.
- 200 mm below top surface of the deck if deck is greater than 200 mm thick.
- Bottom surface of the deck.
- Approximate location of center of gravity of the top flange of the girder.
- Mid-depth of the girder.
- Approximate location of center of gravity of the bottom flange of the girder.
- Bottom surface of girder.
- Outside girder for measurement of air shade temperature.

At least three girders of each structure should be instrumented. The instrumentation should be placed near midspan in each girder. For measurements of heat of hydration, additionalthermocouples at the same depths but near the concrete surface may be included to determine transverse thermal gradients. Thermocouples should be placed near each end of the girders to measure the variation of temperature along the girders. Temperatures of match-cured cylinders and quality control cylinders cured in the prestressing bed should also be measured.

Data acquisition for heat of hydration requires that measurements must begin as soon as the concrete is placed and continue until the concrete temperatures fall to near ambient. Temperatures should be recorded at 30-minute intervals during the first 24 hours to ensure measurement of the maximum temperature. Data acquisition for temperature gradients need not begin until the bridge is complete and need only be made in summer and winter. Temperature readings at hourly intervals will provide sufficient information. Data acquisition for freeze-thaw cycles need only be made from late fall to early spring depending on geographic location. Temperature readings at 30-minute intervals should provide sufficient information.

Long-Term Strains

Long-term strains are required to determine prestress losses from elastic shortening, creep and shrinkage. Gages should be placed at the center of gravity of the prestressing force close to midspan and parallel to the strand. At least three gages should be provided in at least three girders. The three gages in each girder may be spaced longitudinally along the center line or transversely at one longitudinal section. The use of three gages provides some redundancy in case a gage is damaged and provides an indication of scatter in the data.

Measurements of long-term strains should begin as soon as the concrete is placed although readings in fresh concrete may not be appropriate for the “initial readings” for data reduction. Initial readings should be taken before and after every significant event that affects the stress in the girder (such as before and after detensioning). After completion of the structure, it may only be necessary to obtain data every few months. Sufficient readings should be obtained so that trends in the data are clearly discernable. Readings should continue for the duration of the project.

Deflections

Measurements of deflection are necessary to determine changes of camber with time. Since high performance concrete is likely to be used in longer span bridges, absolute camber will be greater than in shorter span structures. However, changes in camber may not be as significant due to the higher modulus of elasticity and lower creep properties of the high performance concrete. At least three girders in every structure should be monitored although measurements on more girders are desirable. Mid-span deflection relative to the ends of the girder is the minimum amount of information needed. Measurements of deflection must begin prior to detensioning and be obtained before and after every significant event that affects the girder. Frequency of readings after completion of the structure should be selected so that trends in the data are clearly discernable. Readings should continue for the duration of the project.

Since changes in temperature gradients and live loads influence measured deflections, it is important to eliminate or minimize their effects. The effect of temperature gradients can be minimized by taking readings early in the morning just before sunrise. Temperature gradients should be measured at the same time, and if necessary, a correction can be made for the temperature induced deflections. Live load effects can be eliminated or minimized by closing the bridge to traffic, if practical, or taking readings when the traffic volume is light. Failure to minimize these extraneous effects will increase scatter in the data.

Optional Additional Instrumentation Program

The basic program described above included the instrumentation of three girders to measure temperatures, long-term strains and deflections. This program can be extended as described in Option No 1. Option No 2 describes additional types of measurements that can be made to supplement the basic program. Option No 3 discusses instrumentation for use with live load tests.

Option No 1 - Extension of Basic Instrumentation Program

Additional girders and additional cross sections of the same girder can be instrumented to measure temperatures, long-term strains, and deflections. Additional thermocouples can beplaced to measure the variations of concrete temperatures along individual girders and along the prestressing bed during curing. Since previous research has shown that temperature gradients in completed bridges do not vary much along the length of a bridge, a smaller array of thermocouples can be located at the ends and quarter points of the girders at the following depths:

- Approximate location of center of gravity of the top flange of the girder.
- Mid-depth of the girder.

- Approximate location of center of gravity of the bottom flange of the girder.

Temperature gradients in the deck can be measured at locations midway between girders. Due to the exposed underside of the deck, gradients at these locations will be different from those at locations directly above girders.

Strains can be measured at the quarter or third points of girder. The vertical distribution of longitudinal strain can also be measured to verify a linear strain gradient.

Deflection profiles along individual girders can be determined from measurements at 8 to 10 locations.

Option No 2 - Additional Types of Measurements

End slip of prestressing strands can be measured using the technique described previously. If feasible, the slip of all strands at both ends of three girders should be measured. For girders with a large number of strands, at least 20 strands should be instrumented. Access to the ends of girders will be needed prior to detensioning.

Strand transfer lengths at the ends of girders can be determined from the variation of strains along the length of girders. These strains are generally measured with a mechanical strain gage. Access to the outside faces of the girders is needed prior to detensioning for installation of strain gage points and initial readings. The alignment of strain gage points must be parallel to the prestressing strand. Special techniques are needed to ensure rapid installation of strain gage points.

Longitudinal slopes at the ends of simply supported girders can be measured for comparison with calculated values. Longitudinal slopes of continuous girders can be measured at the section of maximum rotation. It is recommended that not more than three girders be instrumented in this manner. The instrumentation may be installed prior to detensioning or after the girders are erected.

For precise measurement of prestressing force prior to release, several prestressing strands at the end of the prestressing bed can be instrumented with load cells. It is recommended that at least three strands be instrumented at one end of the bed. As a minimum, readings should be taken before and after stressing every strand and before and after detensioning every strand. Readings at other times will indicate how the forces vary during concrete placement and curing.

Measurements of length changes are appropriate for long bridges without joints. However, little benefit will be obtained by measuring length changes of individual girders because of the complications of installing the reference rod.

In addition to the well established and proven types of instrumentation, States should consider including instrumentation that might be considered “experimental” in nature. For example, the use of fiber optic sensors has been identified as a new technique for instrumentation of civil engineering structures. The technique may offer several advantages over conventional type sensors and has the potential for establishment of “smart” structures. Lasers might also be used for measurement of deflections.

Option No 3 - Instrumentation for Live Load Tests

Many of the design provisions in the AASHTO Standard Specifications for Highway Bridges are based on knowledge and experience with normal concretes. With the introduction of high performance concrete, the applicability of these provisions needs to be reassessed. Items that can be investigated with live load tests include impact factors, lateral load distribution, shear lag, and vertical deflections.

Since a live load test is essentially designed to investigate a bridge response under short-termloading, instrumentation should be selected that will respond accordingly. In addition, strains from live loads are likely to be relatively small (less than 100 microstrain) and the instrumentation must have the required sensitivity.

For static load tests, manual reading of data is possible provided all instrumentation can be read in a time that is short enough to eliminate strain changes caused by temperature changes and creep. For dynamic load tests, a data acquisition system with a very short scanning time is required.

Depending on the objectives of the live load test, some of the instrumentation described under the Basic Instrumentation Program will be appropriate. However, it is likely that additional instrumentation in the form of strain gages will be needed. As discussed previously, it is recommended that the majority of short-term strains be measured with electrical resistance gages attached to reinforcing bars cast in the concrete. Surface mounted strain gages can also be used to measure live load response and may be necessary to achieve certain objectives. The number and layout of gages will be dependent on the objectives of the load test. Specific types of gages for these measurements are given in Appendix B.

APPENDIX A
PHOTOGRAPHS OF ACTUAL INSTALLATIONS

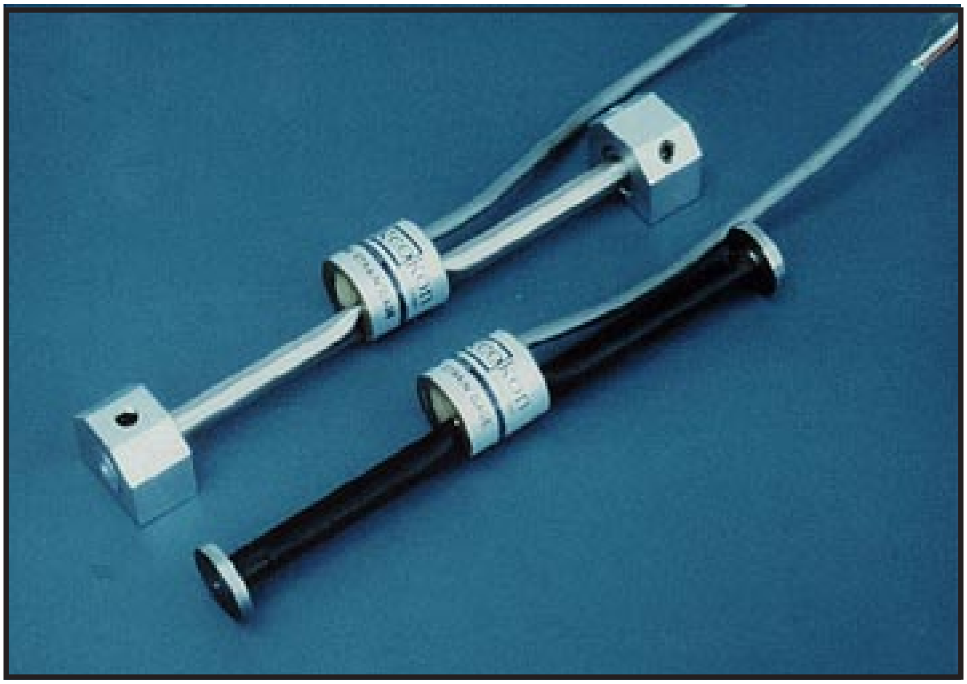

Figure 1. Vibrating wire strain gages prior to installation.

Figure 2. Carlson Strain Meter.
The gage is located in the bottom flange of a prestressed concrete girder.

Figure 3. Electrical resistance strain gage on reinforcement. The gage is attached to a short length of steel reinforcement and located in the web of a prestressed concrete girder.

Figure 4. Electrical resistance strain gage and Carlson Strain Meter. Both gages are located in the deck slab above a prestressed concrete girder.

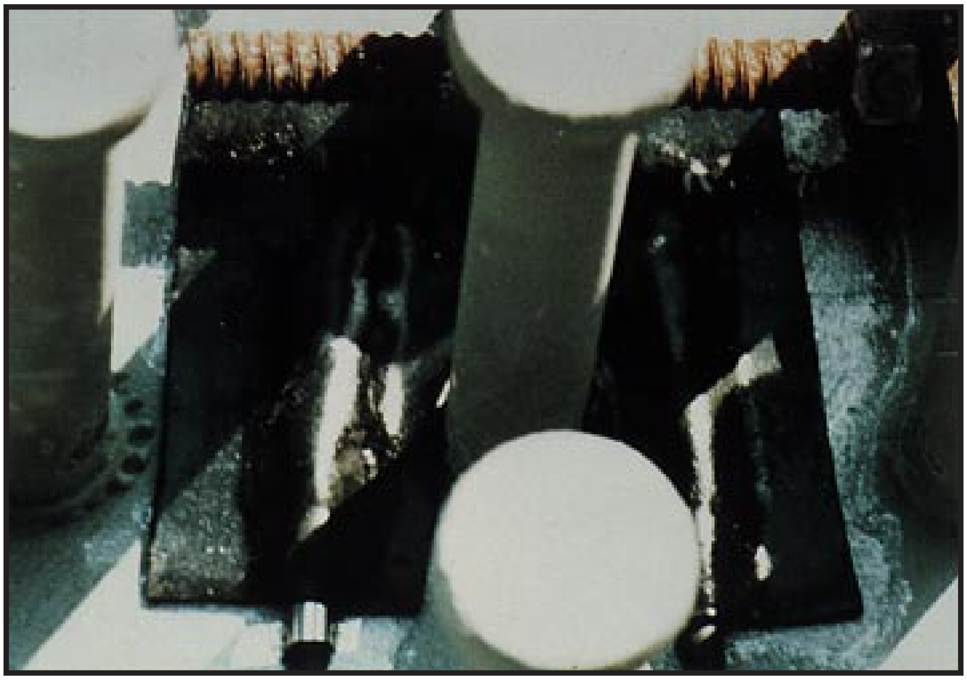

Figure 5. Weldable electrical resistance gages on a steel girder. The gages are located on the top flange between the studs.

Figure 6. Electrical resistance strain gage on concrete surface. Special preparation on the surface was needed prior to application of the gage.

Figure 7. Surface strains.
A Whittemore mechanical strain gage is being used to measure transfer length in a prestressed concrete girder.

Figure 8. Deflection measurement relative to a taut wire.

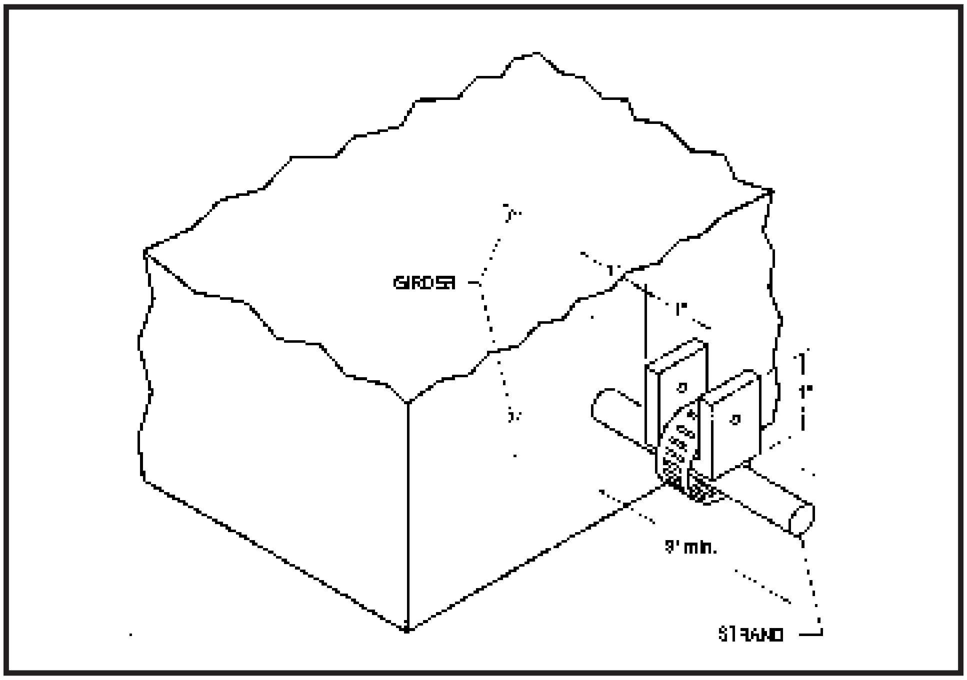

Figure 9. End slip instrumentation.

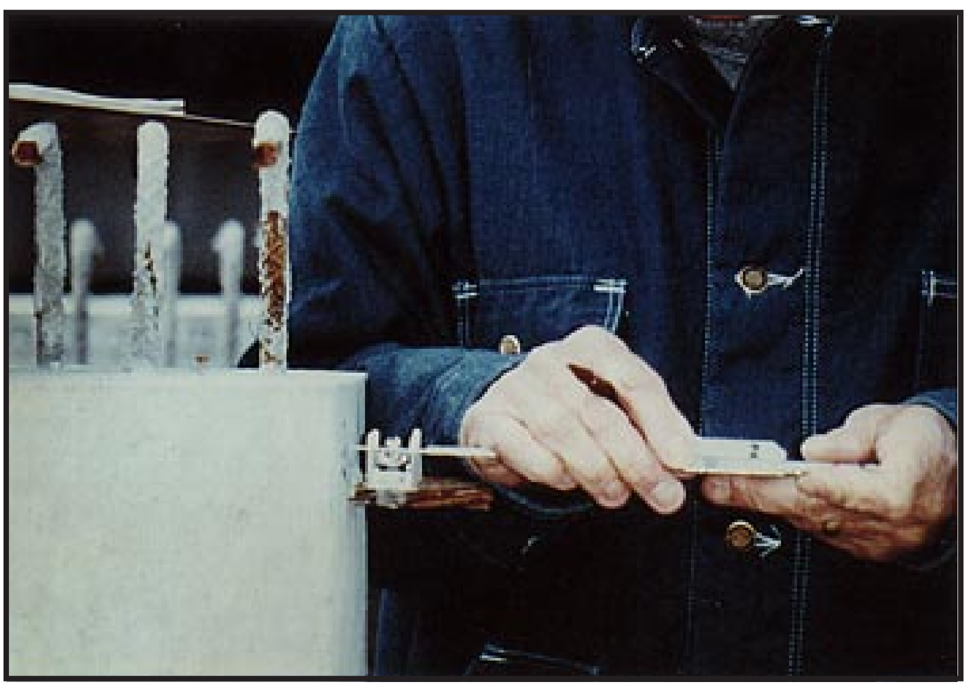

Figure 10. Measurement of strand end slip using a caliper.

Figure 11. Tiltmeters.
The meters are arranged to measure changes in slope in two orthogonal directions.

APPENDIX B - TYPES OF INSTRUMENTATION

This appendix identifies specific sensors that can be used for bridge instrumentation. Although alternatives are available from different suppliers, the listed sensors have been used in the past and have worked successfully. The use of these sensors should be verified with the manufacturer to ensure that they are appropriate for the specific applications.

Thermocouples

- Copper-Constantan Type T (Minimum temperature range (-50° F to +250° F)

Electrical Resistance Strain Gages

For reinforcing bars:

- Designation CEA - 06 - 250UW - 350
- Designation CEA - 06 - 250UW - 120
- Designation EA - 06 - 250AE - 350

  The CEA series features large, rugged copper-coated tabs for ease in soldering leadwires directly to the gage. The above three designations indicate a gage length of 0.25 in. (6.4 mm), self temperature compensation of 6.0 ppm /°F and a resistance of either 350 or 120 ohms. The gages are available from Measurements Group, Inc.

For concrete surfaces:

- Designation EA - 05 - 20CBW - 120
- Designation EA - 06 - 20CBW - 120
- Designation EA - 05 - 40CBY - 120
- Designation EA - 06 - 40CBY - 120

  The above gages are self temperature compensated for either 5.0 or 6.0 ppm /°F and have a gage length of either 2 or 4 in. (51 or 102 mm). The gages are available from Measurements Group, Inc.

For structural steel:

- TML AWC - 8B

  This weldable gage is available from Texas Measurements, Inc.

Vibrating Wire Gages

- Model VCE - 4200 with a 6-in (152-mm) gage length.
- Model VCE - 4210 with a 10-in (254-mm) gage length.

The Model VCE - 4210 is more rugged to resist bending. Both gages are available from Geokon, Incorporated.

- Model EM-5 with a 168 mm gage length.

  The gage is available from Roctest, Inc.

Carlson Strain Meters

- Model No. A8 with a gage length of 8 in. (203 mm).
- Model No. A10 with a gage length of 10 in. (254 mm).

  The A8 and A10 models have resolutions of 3.6 and 2.9 x 10^{6} respectively. Both meters are available from Carlson/R. S. T. Instruments, Inc.

Mechanical Strain Gages

- Demec mechanical strain gage with a gage length of 8 in. (203 mm).

  The gage is available from Mayes Instruments Limited.

- Model No. C 6981 (English) or C 6991 (Metric) plus accessories and spare parts.

  The gage is available from Hogentogler & Co., Inc.

- Model No. H-3230 (English) or H-3231 (Metric) plus replacement parts.

  The gage is available from Humboldt Mfg. Co.

- Model No. CT-171 (English) or CT-171M (Metric) plus accessories and replacement parts.

  The gage is available from ELE International, Soiltest Products Division.

- Whittemore mechanical strain gage with a gage length of 10 in. (254 mm).

  Although this gage is no longer produced, it is available at several testing facilities.

Tiltmeters

- Model 800

  This uniaxial tiltmeter has a resolution of 0.0001 degrees and an angular range of ± 0.5 degrees. The model is available from Applied Geomechanics, Incorporated.

Caliper for Strand Slip

- Digit-Cal plus Model No. 599-571-3

The caliper is manufactured by Brown & Sharpe and is available from McMaster-Carr Supply Company.

Data Acquisition Systems

Data acquisition systems need to be selected based on the types and quantity of sensors. Manual readout boxes are generally available from the sensor suppliers. Automated data acquisition systems are available from a variety of suppliers including Geokon, Incorporated; Campbell Scientific; Measurements Group; Roctest, Inc; and Texas Measurements, Inc.

APPENDIX C - INFORMATION SOURCES

Applied Geomechanics, Incorporated
1336 Brommer Street
Santa Cruz, CA 95062
Tel: (408) 462-2801
Fax: (408) 462-4418

Brown & Sharpe
1701 Howard Street, Suite F
Elk Grove Village, IL 60007-2447
Tel: (847) 593-5950
Fax: (847) 593-6619

Campbell Scientific, Inc.
815 W 1800 N.
Logan, UT 84321-1784
Tel: (801) 753-2342
Fax: (801) 752-3268

Carlton/R. S. T. Instruments, Inc.
241 Lynch Road
Yakima, WA 98908
Tel: (509) 966-1254
Fax: (509) 965-0857

ELE International, Inc.
Soiltest Products Division
P. O. Box 8004
Lake Bluff, IL 60044-8004
Tel: (800) 323-1242
Fax: (847) 295-9414

Geokon, Incorporated
48 Spencer Street
Lebanon, NH 03766
Tel: (603) 448-1562
Fax: (603) 448-3216

Hogentogler & Co., Inc.
P. O. Box 2219
Columbia, MD 21045
Tel: (800) 638-8582
Fax: (410) 381-2398

Humboldt Mfg. Co.
7300 W. Agatite Ave.
Norridge, IL 60656
Tel: (800) 544-7220
Fax: (708) 456-0137

Mayes Instruments Limited
Vansittart Estate
Arthur Road
Windsor, Berkshire SL4 1SD
UK
Tel: 011-44-1753-620237
Fax: 011-44-1753-832430

McMaster-Carr Supply Company
P. O. Box 4355
Chicago, IL 60680-4355
Tel: (708) 833-0300
Fax: (708) 834-9427

Measurements Group, Inc.
P. O. Box 27777
Raleigh, NC 27611
Tel: (919) 365-3800
Fax: (919) 365-3945

Roctest, Inc.
94 Industrial Blvd.,
Plattsburgh, NY 12901-2016
Tel: (518) 561-3300
Fax: (518) 561-1192

Texas Measurements, Inc.
P. O. Box 2618
College Station, TX 77841
Tel: (409) 764-0442
Fax: (409) 696-2390