

Instrumentation of a Prestressed Concrete Containment Vessel Model¹

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Abstract

A series of static overpressurization tests of scale models of nuclear containment structures is being conducted by Sandia National Laboratories for the Nuclear Power Engineering Corporation of Japan and the U. S. Nuclear Regulatory Commission. At present, two tests are being planned: a test of a model of a steel containment vessel (SCV) that is representative of an improved, boiling water reactor (BWR) Mark II design; and a test of a model of a prestressed concrete containment vessel (PCCV). This paper discusses plans and the results of a preliminary investigation of the instrumentation of the PCCV model. The instrumentation suite for this model will consist of approximately 2000 channels of data to record displacements, strains in the reinforcing steel, prestressing tendons, concrete, steel liner and liner anchors, as well as pressure and temperature. The instrumentation is being designed to monitor the response of the model during prestressing operations, during Structural Integrity and Integrated Leak Rate testing, and during test to failure of the model. Particular emphasis has been placed on instrumentation of the prestressing system in order to understand the behavior of the prestressing strands at design and beyond design pressure levels. Current plans are to place load cells at both ends of one third of the tendons in addition to placing strain measurement devices along the length of selected tendons. Strain measurements will be made using conventional bonded foil resistance gages and a wire resistance gage, known as a "Tensmeg"[®] gage, specifically designed for use with seven-wire strand. The results of preliminary tests of both types of gages, in the laboratory and in a simulated model configuration, are reported and plans for instrumentation of the model are discussed.

¹ This work is jointly sponsored by the Nuclear Power Engineering Corporation and the U.S. Nuclear Regulatory Commission. The work of the Nuclear Power Engineering Corporation is performed under the auspices of the Ministry of International Trade and Industry, Japan. Sandia National Laboratories is operated for the U.S. Department of Energy under Contract Number DE-AC04-94AL85000.

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Instrumentation of a Prestressed Concrete Containment Vessel

Background

A series of static overpressurization tests of scale models of nuclear containment structures is being conducted by Sandia National Laboratories for the Nuclear Power Engineering Corporation (NUPEC) of Japan and the U. S. Nuclear Regulatory Commission. At present, two tests are being planned: a test of a model of a steel containment vessel (SCV) that is representative of an improved boiling water reactor (BWR) Mark II design, and a test of a model of a prestressed concrete containment vessel (PCCV). These tests and the details of the models are described in detail in Ref. 1.

This paper discusses test plans and the results of a preliminary investigation of instrumentation for the PCCV model. Particular emphasis is placed on the instrumentation of the prestressing system, since this element of the model distinguishes it from previous reinforced concrete containments tested at Sandia. Previous attempts to test large-scale models of prestressed containments have resulted in mixed interpretations of tendon behavior. Both NUPEC and the U.S. NRC have identified the characterization of tendon behavior, from prestressing through loading to failure of the vessel, as a key objective of this test program.

Previous Testing of Prestressed Containment Models

Several tests of large-scale models of containment vessels have been conducted in the past. A test of a 1:10-scale model of a prestressed containment vessel was conducted in Poland in the late 1970s. The report of this test (Ref. 2) does not indicate the details of the prestressing system or whether it was instrumented.

A 1:14-scale model of a prestressed containment vessel was tested in Canada in the 1970s (Ref. 3). This model was tested hydrostatically and utilized a plastic liner. The prestressing tendons in this model, consisting of 1/2" and 5/8" seven-wire strand, were instrumented using weldable strain gages on individual wire strands. The tendons were placed in lightly corrugated metal ducts and grouted. Unfortunately, of the 13 gages applied to the tendons, 5 were damaged before the wall was prestressed and 5 were damaged during prestressing and grouting operations. This left only 3 functional gages for data gathering during the test-two on dome tendons and the other on a horizontal wall tendon.

The most recent test was a 1:10-scale model of a prestressed concrete containment vessel tested in Great Britain in July, 1989 (Ref. 4). This model was also tested hydrostatically and did not include a steel liner. A membrane was included in the model to prevent leakage of the pressurization medium. The tendons in this model consisted of single, seven-wire strands which were greased and encased in a plastic sheath. The model tendons were intended to exhibit unbonded behavior. Fifty-seven strain gages were placed on the tendons at 19 locations and 14 load cells were also used. Similar to the Canadian test, the strain gages exhibited a high mortality rate, both during prestressing operations and during load testing, when some of the gages debonded at or near the ultimate load. While the output of those gages which survived appeared to correlate well with the other instrumentation, the results of the strain measurements were inconclusive. One major area of uncertainty which remains is whether the tendons behaved as unbonded tendons, as intended, or more like bonded tendons. A comparison of pre- and post-test analyses with the test data appears to indicate that the tendons may have behaved more like bonded tendons. It was not possible to resolve this issue through post-test inspections of the tendons.

Instrumentation of a Prestressed Concrete Containment Vessel

Current Test

The current test will consist of a uniform 1:4-scale model of an actual prestressed concrete containment vessel in Japan. The model will include a steel liner and scaled representations of the equipment hatch, personnel airlock, and main steam and feedwater line penetrations. The overall geometry of the model is shown in Figure 1. The model will be tested pneumatically, using nitrogen, through a series of low-level tests, including an integrated leak rate test (ILRT) and a structural integrity test (SIT), and finally pressurized to failure. Failure, for the purposes of this test, is the inability to maintain containment integrity. Construction of the model at Sandia National Laboratories is scheduled to begin in the middle of 1996 and the tests are scheduled to occur in late 1999.

The model will be constructed of normal concrete and will include both conventional and prestressed reinforcing. The area of the conventional reinforcing is based on the scaled area of the reinforcing in the actual plant. There is a one-to-one correlation between the prestressing tendons in the model and the tendons in the actual plant. The model includes 90 vertical, "hairpin" tendons, which cross the dome in an orthogonal pattern and are anchored at the tendon gallery inside the basemat. Ninety (90) hoop tendons, each spanning 360°, are alternately anchored in two vertical buttresses. Each tendon consists of three, seven-wire strands, with each strand having a nominal diameter of 13.7 mm. These strands are being specially manufactured to match the scaled area of the tendons in the actual plant. The tendons will be placed inside lightly corrugated metal ducts of the same type used in the actual plant and will not be grouted or greased except for a light coating of a corrosion inhibitor.

Model Instrumentation

The objectives of this test program include validation or improvement of numerical simulation methods for predicting the response of containment structures to loadings beyond the design basis accident. As such, it is necessary to obtain data on the behavior of the various elements of the structure in order to gain insight into the general behavior of these elements and to compare this behavior with predicted responses.

To meet this objective, an extensive suite of instrumentation will be incorporated into the model. While the details of this instrumentation suite have not been finalized, a preliminary plan has been developed and is being refined. This plan currently includes approximately 2000 channels of data consisting of displacement transducers, both linear variable displacement transformers (LVDTs) and cable potentiometers, to measure global and local model movements; strain transducers for liner, liner anchor, rebar, tendon, and concrete measurements; load cells for tendon anchor loads; pressure sensors to monitor the load; and temperature sensors to monitor the gas temperature for leak rate calculations and for strain gage compensation.

One important aspect of the instrumentation plan is that we are planning to obtain data on the model response during construction, beginning with the prestressing operations, and will continue to monitor the response of the model for approximately 18 months until the pressurization tests occur. At present, we are planning to use a separate suite of high-resolution, low-range transducers for these low-level measurements, including the ILRT and SIT tests.

Instrumentation of a Prestressed Concrete Containment Vessel

Prestressing System Instrumentation

As noted previously, the feature that distinguishes this test from previous large-scale containment tests in the United States and Japan is the prestressing system. For this reason and because the behavior of the prestressing system is not well understood at high load levels, the prestressing system itself may be the critical element in determining the ultimate (structural) capacity of the containment vessel.

A great deal of emphasis has therefore been placed on gaining reliable and accurate data on the behavior of the prestressing system. The nature of the data desired is twofold:

- First, we wish to understand the global behavior of the prestressing system, and,
- second, we wish to understand the behavior of individual tendons in terms of the variation of stress along the length of the tendon.

To achieve the first of these objectives, we are planning to place up to 120 load cells on the tendons, one each at both ends of one third of the tendons in the model. (Note: this number may be reduced in the final test plan.) This is being done to monitor the effective prestress in the model for comparison with the design conditions and to monitor the change in prestress, both temporally and spatially, as a function of the internal pressure. We are planning to use a through-hole type load cell which has been integrated with the tendon anchor system. A sketch of the load cell/anchor arrangement is shown in Figure 2.

The second of these objectives is more difficult to achieve, as reflected by the attempts to measure tendon stress levels in the earlier containment tests. The requirements of the tendon instrumentation are that it provide reliable measurements of the total force on the cross section of the tendon without having the transducer alter the behavior of the tendon. Even if gage mortality is reduced to near zero, the meaning of strain gage data is uncertain owing to the complex geometry of the tendons. As a result, a separate tendon instrumentation development effort was undertaken as part of the test program.

Development of Tendon Instrumentation

Instrumentation Survey

Initially, an attempt was made to identify previous attempts to measure the total force or average strain in tendons composed of twisted, seven-wire strand. An extensive survey was conducted at the University of Texas at Austin as part of a study of instrumentation for segmental box girder bridges. This survey, which was summarized in an unpublished report, identified the following types of strain measurement devices which had been used for monitoring loads in seven-wire strand.

Strain Measuring Devices:

- **Electrical Resistance Strain Gages.** In addition to the problems with gage mortality noted previously, the primary difficulty is that the typical application consists of bonding the gage to an exterior wire whose axis is not parallel to the axis of the strand. Secondary effects due to nonuniform loading of all the wires and local interactions between the wires may further affect the data. The advantage of using conventional strain gages is their proven reliability and low cost, and methods have

Instrumentation of a Prestressed Concrete Containment Vessel

been developed (such as mounting multiple gages on alternating wires at a given location) which can reduce the effects of some of the deficiencies.

- Extensometers. Extensometers can provide very accurate information on average strand strain and thereby load; however, their use on tendons within ducts is impractical.
- Optical Fiber Strain Gages. Several reports have been published on the use of optical fiber strain gages (Ref. 5, 6); however, at present, devices based on light attenuation in optical fibers have only been used in fiberglass tendons in Germany in research applications.

Load Measuring Devices:

- Load Cells. In addition to electrical resistance load cells, hydraulic load cells are also available, but both types are limited to measurements at the tendon ends.

Cable Tensiometers:

- Tensiomag[®]. This device was reported to be offered by Freysinette International. It consists of an AC-powered magnetic coil which is placed around the tendon to measure inductance variations in the strand. It operates on the principle that elongation of the strand will create corresponding variations in the total inductance of the strand. This concept is very attractive, since it seems to provide a means of directly measuring the tendon stress without altering tendon behavior. Unfortunately this device is no longer marketed by Freysinette. (Sandia conducted a series of tests using a similar device to demonstrate the elongation/inductance relationship. The results appeared to indicate nonlinear behavior and the device was deemed too complex for the needs of this project. This test is described in more detail in Reference 7.)
- Dyna-Tension[®], Cable Tensiometer[®], Fulmer Tension Meter[®]. These devices all measure tension in an individual strand with varying degrees of accuracy but are not suitable for testing multiple-strand tendons because they require access to individual strands.

In addition to these devices, two other options for instrumenting the tendons in the PCCV model were considered:

- Development of a prototype load cell which could be incorporated into the tendon itself. While several viable concepts were identified, this option was abandoned due to the cost and uncertainty of developing a new type of transducer and the intrusive nature of such a device on the tendon behavior.
- Tensmeg[®]. This device, manufactured by Roctest Inc., is a spiral strain gage consisting of a Teflon-sheathed resistance wire extending between two hard rubber end blocks which are chemically bonded to the strand. While this device is limited to application on a single strand, it appears to provide a more direct measurement of strain than conventional bonded resistance gages. Uncertainties exist regarding its effect on tendon behavior because of the frictional resistance of the rubber end blocks as well as the interpretation of the data from curved tendons. The Tensmeg gage is shown in Figure 3.

Instrumentation of a Prestressed Concrete Containment Vessel

After we considered all these options, we decided to continue investigating both the electrical resistance strain gages and the Tensmeg as potential devices for instrumenting the tendons in the PCCV model. A series of tests were planned and are being conducted to calibrate and demonstrate gage performance on individual strands and on a full-scale mock-up of the tendons in the PCCV model.

Testing

Single-Strand Tests

A series of tests were conducted at Sandia's Material Testing Laboratory to investigate the performance of conventional strain gages and Tensmeg gages on seven-wire strand. These tests were performed to obtain a correction factor for the wire-mounted strain gages and to verify the performance of both the wire-mounted and Tensmeg gages up to the ultimate capacity of the strand.

One initial difficulty which had to be overcome was the method of gripping the seven-wire strand. The strand material itself (JIS G3536, equivalent to ASTM 416) is notch sensitive and the geometry of the specimen is not compatible with the grips of most testing machines. The difficulty lies in the ability to grip the strand in such a way that all the wires are stressed uniformly without causing a premature failure (well below the specified ultimate strength) at the grips. A detailed summary of testing of seven-wire strand is provided in Ref. 8. According to the reference, if the strand is not gripped properly, premature failure may occur, invalidating the tensile test of the specimen. A number of methods of testing seven-wire strand are discussed.

A 220,000 pound tensile testing machine equipped with hydraulic grips was used for these tests. The chucks in this machine are V-notched with serrated teeth. Initial tests conducted by gripping the bare strand directly with the hydraulic grips resulted in premature failure of the strand, as expected. Through a trial-and-error process and through consultation with the machine's manufacturer, a gripping method was developed which allowed us to develop the full strength of the strand. This method consisted of placing a stainless steel tube, with an inside diameter approximately equal to the nominal strand diameter, over a short length of the strand at each end. This tube was also split in half longitudinally (to eliminate any hoop strength), and the interior surface coated with a thin layer of silicon carbide grit which was bonded to the tube with an epoxy cement. The results of the tests using this 'split-sleeve' grip are shown in Figure 4. This figure also shows the results using a 'solid-sleeve' grip.

Several types of strain gages and mounting methods were also investigated in conjunction with these grip tests to address premature "debonding" of the gages at near-ultimate loads. A weldable strain gage and bondable gages, using two types of bonding agents, were tested. Both a high-elongation, heat-cured adhesive (20% rated) and a standard room temperature-cured adhesive (6% rated) were tested. The weldable gages were rated to 2% elongation, although past experience indicates that strains of 6% are readily achievable. All gages were felt to be adequate for these tests since the specified minimum elongation for the strand is 4.5%. Each test specimen was instrumented with three strain gages mounted on alternating exterior wires at a single axial location.

The results of these tests indicated that all of the attempted adhesion methods were acceptable for eventual application in the PCCV. No debonding events occurred. The test data also confirmed that the relative strain levels in the helical wires were roughly uniform from wire to wire (<10% maximum strain difference above the low-load anchoring error

Instrumentation of a Prestressed Concrete Containment Vessel

region). Considering cost and ease of future field installations on the model tendons, bondable strain gages (room temperature cure) were used for all subsequent tests.

Next a series of three calibration tests on specimens which included three wire-mounted, bondable strain gages and one Tensmeg gage were conducted. The calibration standard for these tests was a long gage length (24") extensometer manufactured by Tinius-Olsen Co. which is specially designed for testing seven-wire strand. The gage length was such that the Tensmeg gage and the wire-mounted strain gages could be mounted within the reference points of the extensometer. The test configuration is shown in Figure 5.

The results of these calibration tests are shown in Figure 6. Since failure of the strand can be quite energetic, the extensometer was removed during a pause in the loading sequence at approximately 2% strain. While this strain level is below the minimum ultimate elongation, it was felt that this was far enough beyond the yield strain to calibrate the gages for both elastic and plastic strains. The tests were continued up to the failure of one or more wires. The full load cycle for one test is shown in Figure 7.

The test data indicate that the Tensmeg gage provides a direct reading of the average strain in the strand. The data also indicate that a correction factor must be applied to the wire-mounted strain gage readings to account for the geometry of the strand wires. A correction factor of 1.32 for the wire-mounted strain gages was obtained from these tests. The results indicate that both the Tensmeg gage and the wire-mounted strain gages are capable of providing accurate information on average strand strain from which the total tendon load can be derived. The next question to be addressed was whether these gages would perform as well for multiple-strand tendons under the conditions of the PCCV model.

1:4-Scale Tendon Tests

As noted above, while both the wire-mounted strain gages and the Tensmeg gage performed well for laboratory tests of single, straight strands, the ultimate standard of performance requires that the tendon instrumentation provide reliable and accurate data on the average strain or total load for multiple-strand, curved tendons placed inside metal ducts within the model.

An opportunity presented itself to investigate the performance of the instrumentation on prototype model tendons. As part of the ancillary test program, friction and setting loss tests were to be conducted by Taisei Corporation, the constructor of the PCCV model, at their research center in Yokohama. These tests were to be conducted on two sets of prototype tendons constructed at the radius of the cylinder wall hoop tendons and at the minimum radius for tendons deflected around penetrations. Three tendons would be included in each set for a total of six tendons. In order to allow a test of the tendon instrumentation, an additional tendon at each radius was added, for a total of eight tendons. Two semicircular, reinforced concrete rings were constructed, containing the two sets of four tendons. The resulting test configuration is shown in Figure 8.

Only one tendon at each radius was installed with instrumentation on the tendon strands. (The "uninstrumented" tendons were monitored at each end for load and displacement data.) The configuration of the tendon instrumentation is shown in Figure 9. The uninstrumented tendons would provide a control on the instrumented tendons and address any concerns about the additional friction caused by the tendon instrumentation (as well as providing the data to resolve the original goals of the ancillary test program).

The configuration of the tendon instrumentation was designed to answer two fundamental questions about tendon behavior:

Instrumentation of a Prestressed Concrete Containment Vessel

- How does the strain or force in the tendon vary along the length?
- Is the strain in the individual strands the same at a given location?

The gage layout for the small radius tendon was designed to address the first question. One of the difficulties with the tendon instrumentation, particularly with the Tensmeg gages, is the size of the gage installation relative to the size of the duct. For the purposes of the instrumented tendons in the ancillary tests, the tendon duct is 40 mm in diameter while the Tensmeg gage end blocks are 27 mm in diameter (as installed). While the manufacturer of the Tensmeg gage has indicated it will be possible to reduce the diameter of the end blocks for the PCCV test installations, only off-the-shelf gages were available at this time. This required that the gages at a given measurement point be staggered, along the length of the tendon to avoid overlap and interference with the duct wall. The amount of stagger required, approximately twice the gage length or 40 cm, was judged to be insignificant in terms of addressing the uniformity of the tendon strain.

It was determined that the second question could be addressed by instrumenting only a single strand at multiple locations, resulting in the configuration shown for the large radius tendon.

At each location where a Tensmeg gage was mounted on the strand, three wire-mounted (bondable) strain gages were installed adjacent to the end block. The lead wires for all the gages were bundled and looped inside the duct and routed through a hole in the duct which was then sealed. After the tendons were installed in the forms, concrete was placed around the ducts and the exiting lead wires. (For one measurement location, flexible plastic conduit was used to protect the lead wires from contact with the concrete. The exits of the conduit were sealed to keep moisture from migrating to the tendons.)

After concrete curing, all the instrumented tendons were tested on May 24, 1995. Each tendon was loaded twice to 85% of the nominal yield force and once to the yield force, using the prestressing jacks to apply the load at one end. A jack at the opposite end measured the anchor load. Elongation at both ends was measured using LVDTs. Load cells of the type proposed for the PCCV model were installed on both ends to demonstrate their operation and compatibility and to confirm the load measurements made with the prestressing system.

At this time all of the test results have not been reduced and analyzed, however, some general observations can be made.

- The gage signal was lost on all but one of the Tensmeg gages and three of the wire-mounted strain gages during the prestressing operations. It appears from the nature of the signal received that this was due to a failure of the lead wire or lead wire to the gage connection. Given the highly congested nature of the gage and lead wire installations, plus the lack of "travel" for the lead wire, this is not unexpected. It appears that this is an engineering problem which can be remedied for the actual PCCV installation.
- Up to the point where the gages failed, the results appeared to be reasonable and exhibited the expected behavior. It also appears that some of the Tensmeg gages may have slipped during the load test.

Instrumentation of a Prestressed Concrete Containment Vessel

- It does not appear that the presence of the Tensmeg or wire-mounted strain gages altered the friction coefficient for the tendon.

Future Plans

The data from the ancillary tests will be analyzed after they have been released. With this information and the results of the previously mentioned post-mortem of the test structure, a decision will be made among NUPEC, the NRC, and Sandia regarding the use of Tensmeg and wire-mounted strain gages in the PCCV model. Further investigation and design will be needed to improve the survivability of the lead wires if it is determined that this is the primary cause for the signal loss during the test. Ways to reduce the diameter of the Tensmeg gages, improve their resistance to crushing, and reduce their friction coefficient are also being explored.

Pending the outcome of these activities, the detailed instrumentation plan for the PCCV model will clearly identify the types and locations for measurement of load and/or strain.

Acknowledgments

The authors of this paper wish to acknowledge the support and cooperation of Mr. Yasuyuki Murazumi and Mr. Yutaka Kobayashi, Taisei Corporation, Tokyo; and Dr. Jun Kobayashi, Taisei Research Center, Yokohama in the conduct of the ancillary tendon tests.

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Instrumentation of a Prestressed Concrete Containment Vessel

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Instrumentation of a Prestressed Concrete Containment Vessel

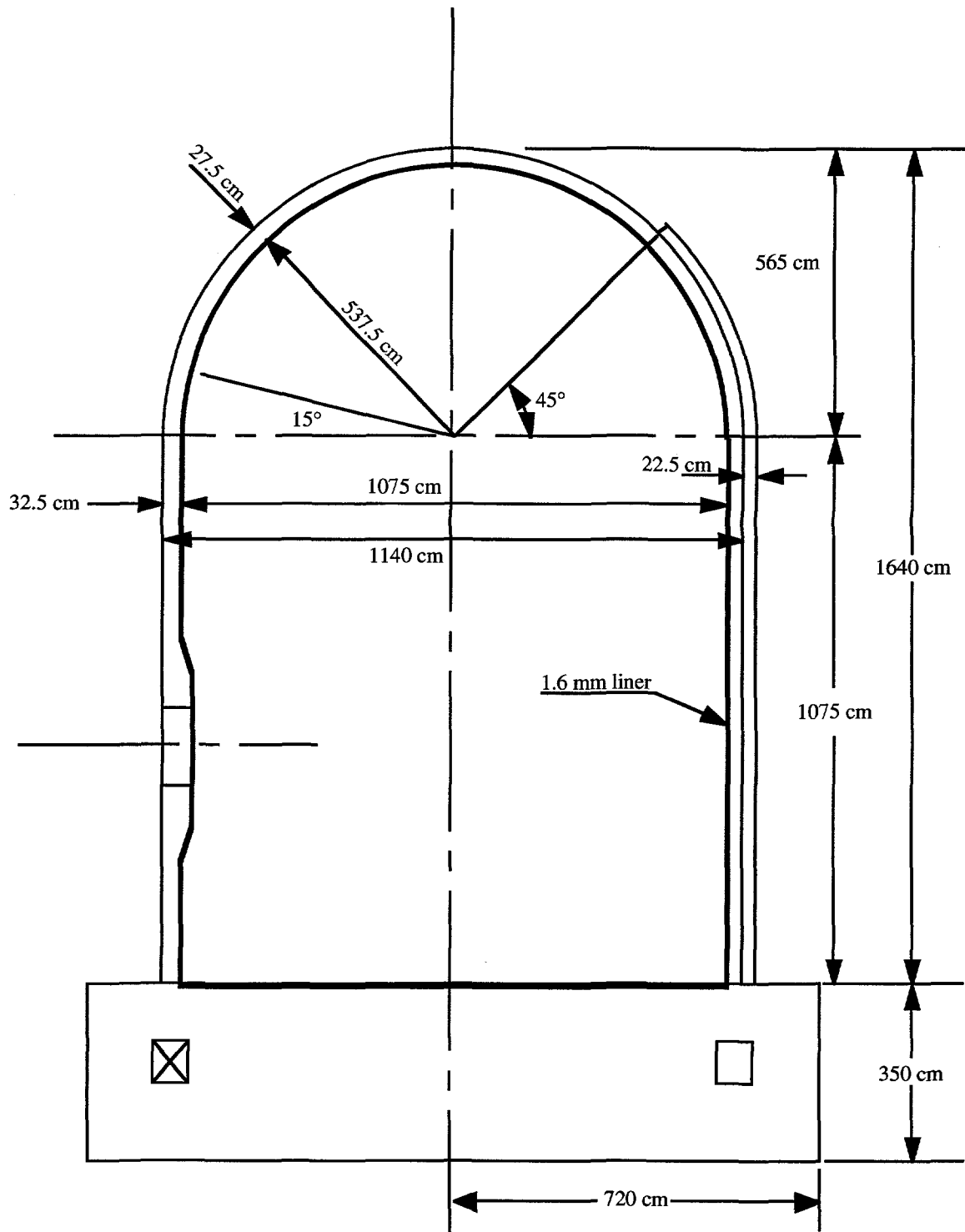


Figure 1. Geometry of 1:4-scale Prestressed Containment Vessel Model

Instrumentation of a Prestressed Concrete Containment Vessel

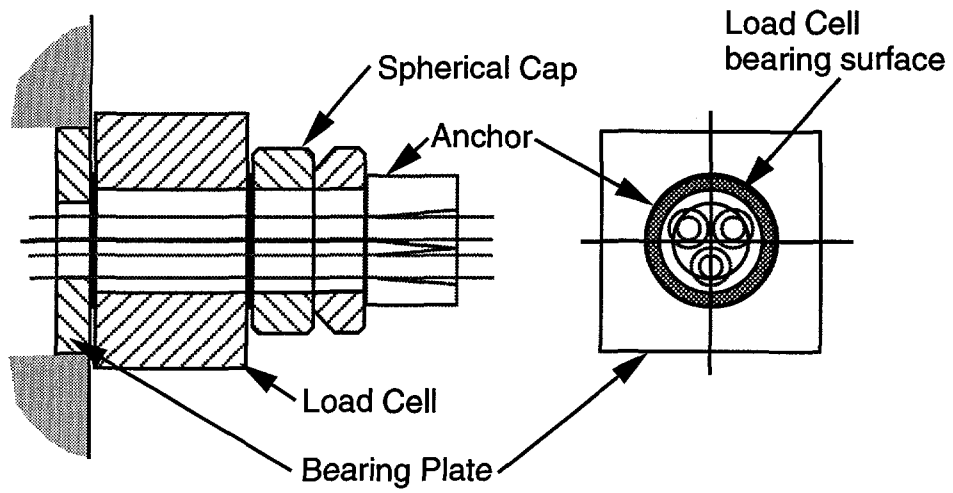


Figure 2. Tendon Anchor/Load Cell Arrangement

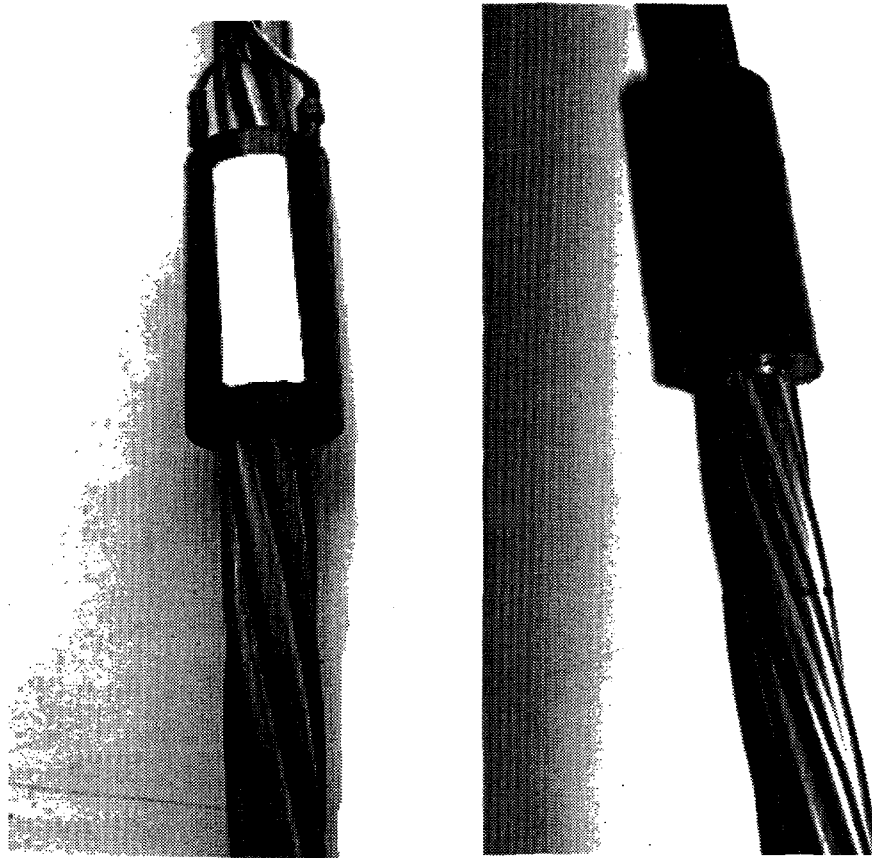


Figure 3. Tensmeg Tension Measuring Gage by Roctest, Inc.

Instrumentation of a Prestressed Concrete Containment Vessel

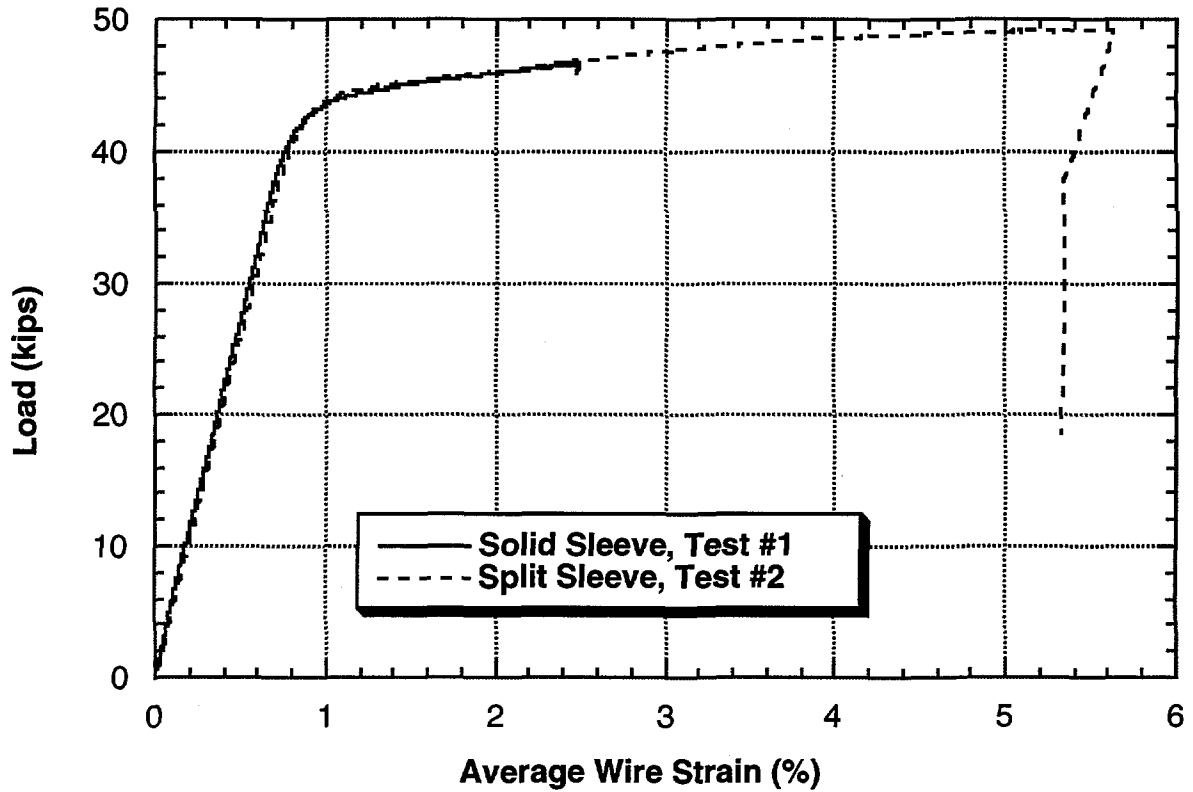


Figure 4. Wire Strain vs. Load for Single-Strand Test (Bonded Gages with both Split and Solid Sleeve Grip).

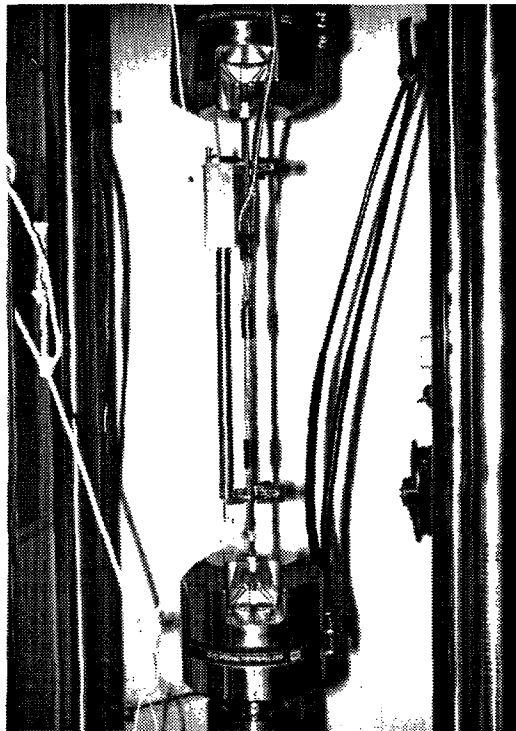


Figure 5. Calibration Test Configuration for Tensmeg and Wire-Mounted Strain Gages.

Instrumentation of a Prestressed Concrete Containment Vessel

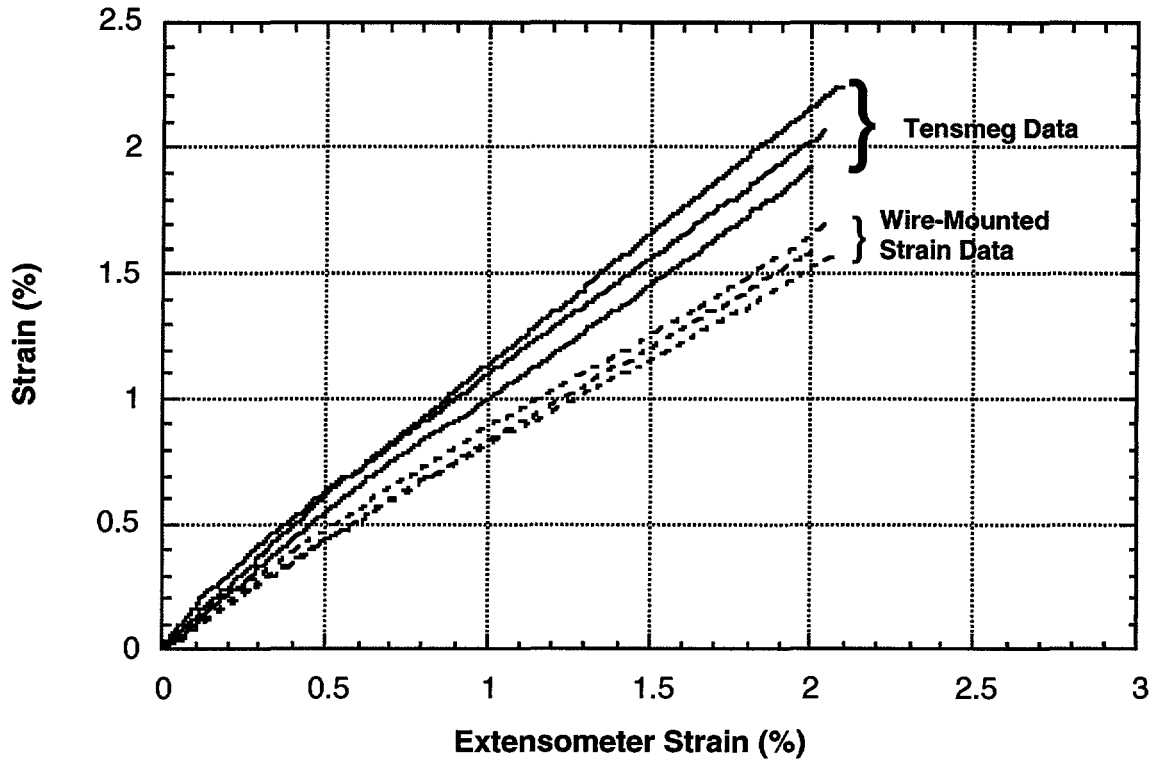


Figure 6. Calibration Test Results for Tensmeg and Wire-Mounted Strain Gages.

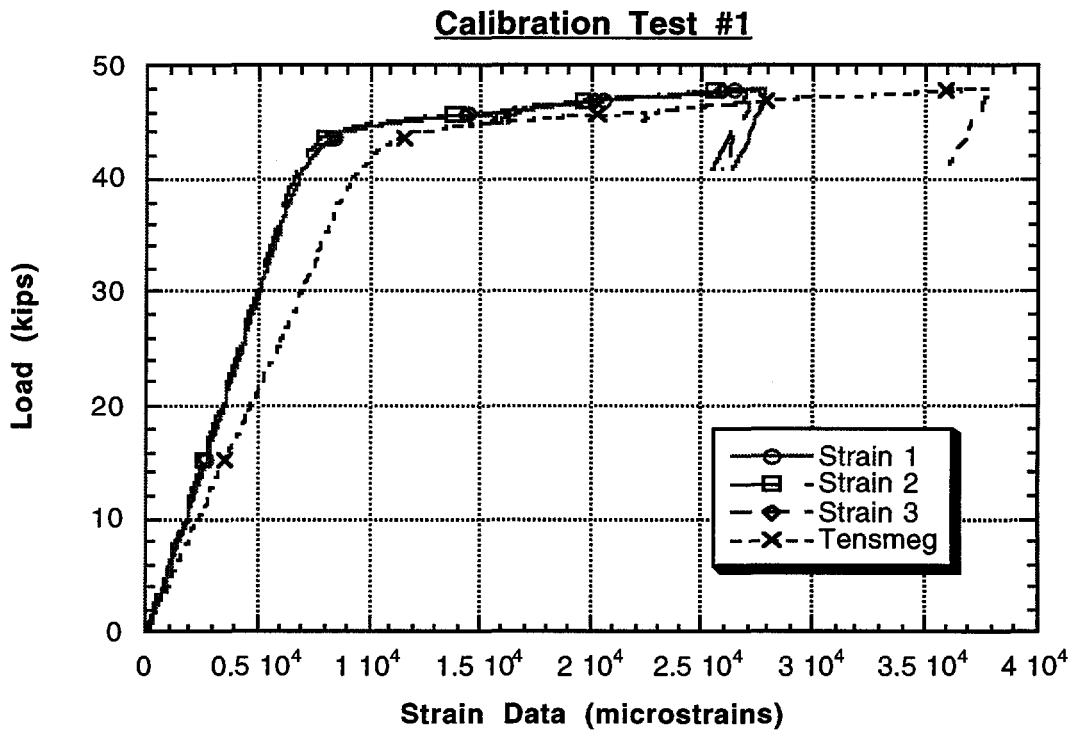


Figure 7. Load vs. Strain (uncorrected) for Calibration Test #1.

Instrumentation of a Prestressed Concrete Containment Vessel

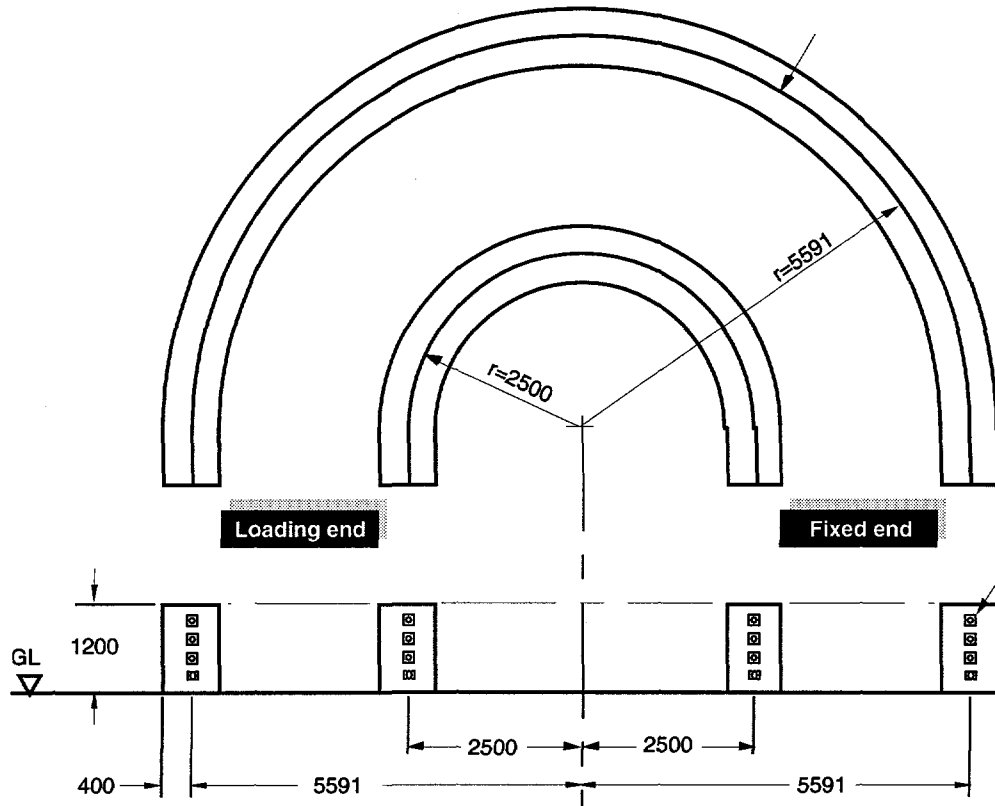
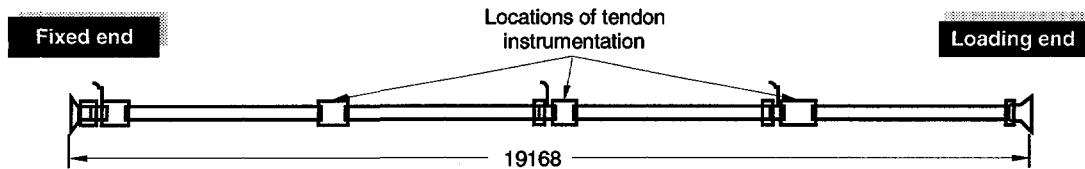


Figure 8. Test Configuration for Prestressing System Friction and Setting Loss Tests.

Large Radius Tendon



Small Radius Tendon

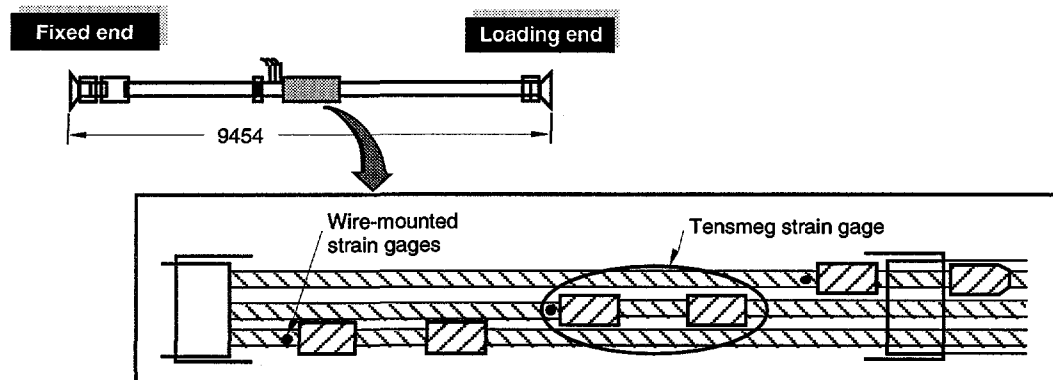


Figure 9. Tendon Instrumentation Layout for Ancillary Tests.

Instrumentation of a Prestressed Concrete Containment Vessel Model

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Background

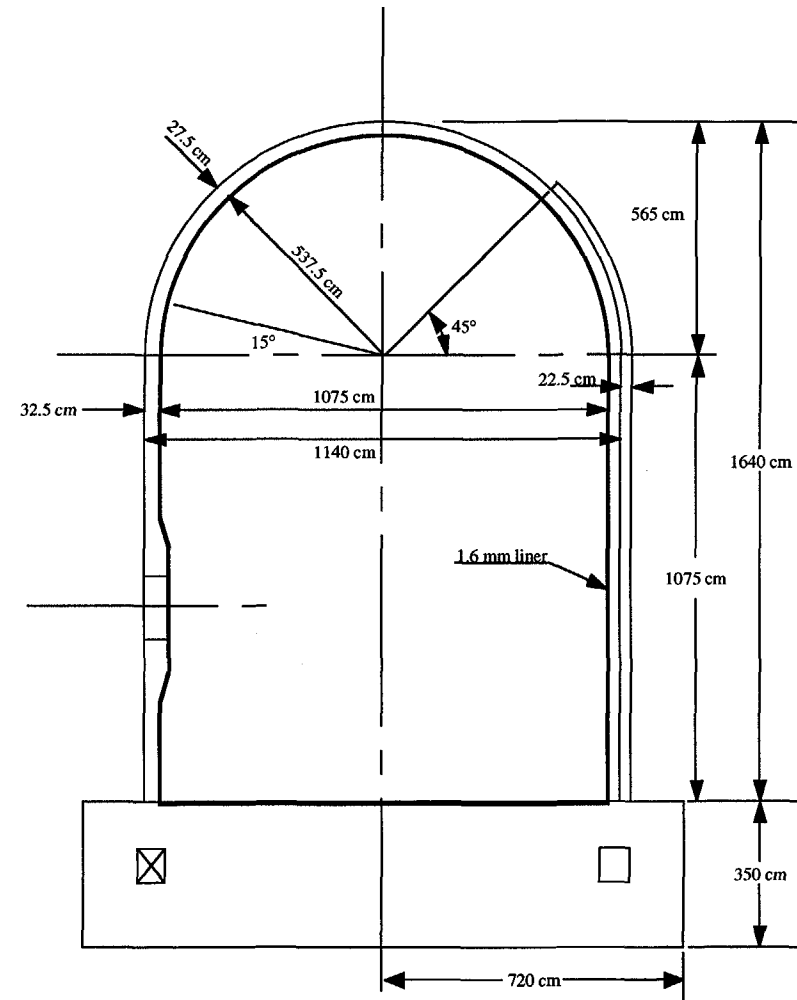
- **Cooperative Program between Nuclear Power Engineering Corporation (NUPEC) of Japan and United States Nuclear Regulatory Commission (NRC).**
- **Static Overpressurization Tests to 'Failure' at Ambient Temperature**
- **Two Models are being Tested:**
 - **Steel Containment Vessel (SCV) Model ~ end of 1996**
 - **Prestressed Concrete Containment Vessel (PCCV) Model ~ end of 1999**

Previous Tests of PCCV Models

- **1:10-Scale Model**
 - Poland, late 1970s
- **1:14-Scale Model**
 - Canada, late 1970's
 - tested hydrostatically, no liner
 - wire-mounted strain gages on prestressing strand
 - high gage mortality
- **1:10-Scale Model**
 - Great Britain, 1989
 - tested hydrostatically, no liner
 - wire-mounted strain gages on prestressing strand
 - high gage mortality

PCCV Model

- **1:4-Scale Model of Actual Containment**
- **Steel Liner, Functional Equipment Hatch, Airlock and Small Penetrations**
- **Will be tested Pneumatically (Nitrogen)**
- **2-Buttress Design**
- **90 Hairpin Vertical Tendons**
- **90 Hoop Tendons (360°)**
- **Tendons: 3, 13.7mm 7-wire strand**



Instrumentation

- **Almost 2000 channels of data**
 - **Displacement (LVDTs, cable potentiometers)** 280 channels
 - **Reinforcement Strains** 280 channels
 - **Concrete Strains** 480 channels
 - **Liner Strains** 600 channels
 - **Tendon Strains** 120 channels
 - **Tendon Forces** 120 channels
 - **Pressure** 5 channels
 - **Temperature (for gage compensation and leak rate)** 40 channels
 - **Video**

Tendon Instrumentation

- **Objectives**

- Understand global behavior of prestressing system.
- Understand behavior of individual tendons in terms of variation of stress along the length of the tendon.

- **Requirements**

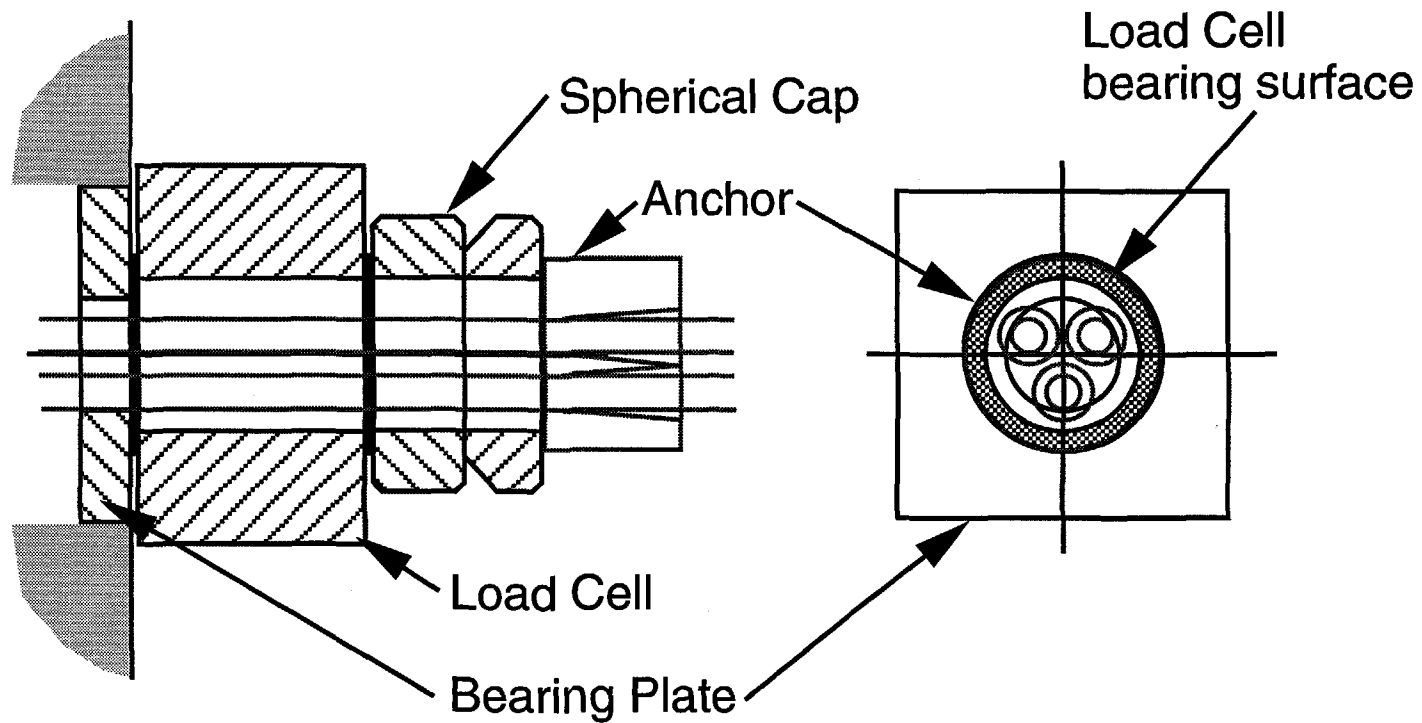
- Reliable measurement of total force on tendon cross-section (low mortality).
- Presence of transducer does not alter tendon behavior.

Tendon Instrumentation

- **Existing Devices**
 - **Strain Measuring Devices**
 - **Electrical Resistance Strain Gages**
 - **Extensometers**
 - **Optical Fiber Strain Gages**
 - **Load Measuring Devices**
 - **Load Cells**
 - **Cable Tensiometers**
 - **Tensiomag, Dyna-Tension, Cable Tensiometer, Fulmer Tension Meter**
- **New Devices**
 - **Development of new prototype**
 - **Tensmeg**

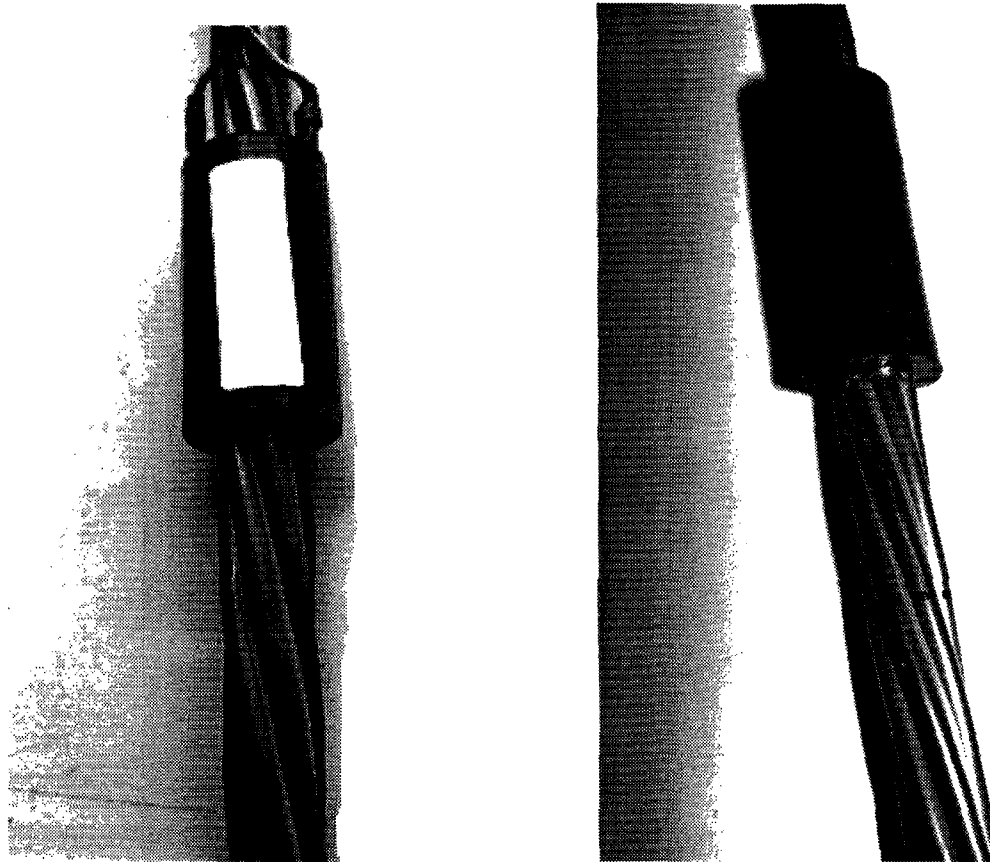
Tendon Instrumentation

- Tendon Anchor/Load Cell Arrangement



Tendon Instrumentation

- Tensmeg Gage

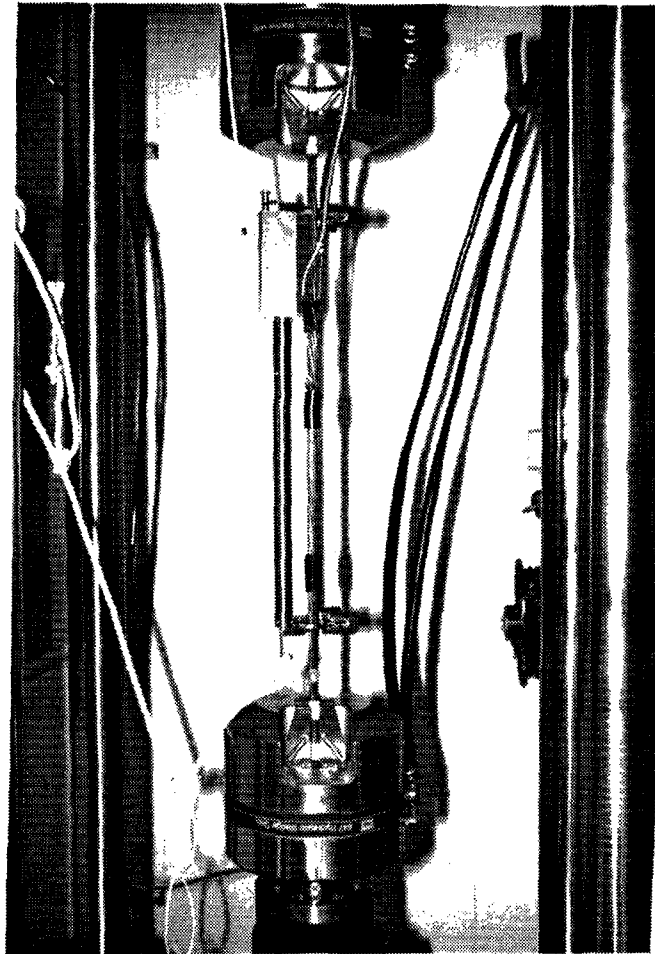


Tendon Instrumentation

- **Single Strand Tests**
 - Investigate wire-mounted strain gage and Tensmeg performance.
 - Calibrate gages.

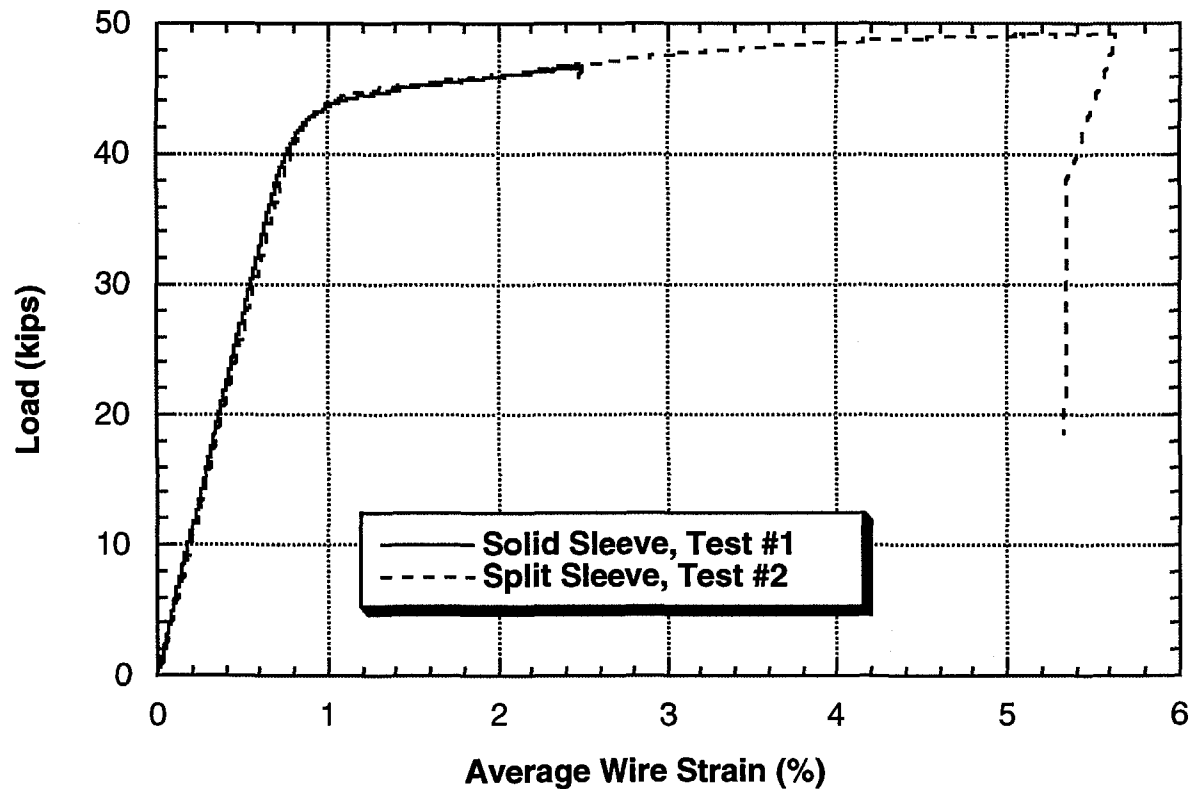
Tendon Instrumentation

- **Single-Strand Test Set-up**



Tendon Instrumentation

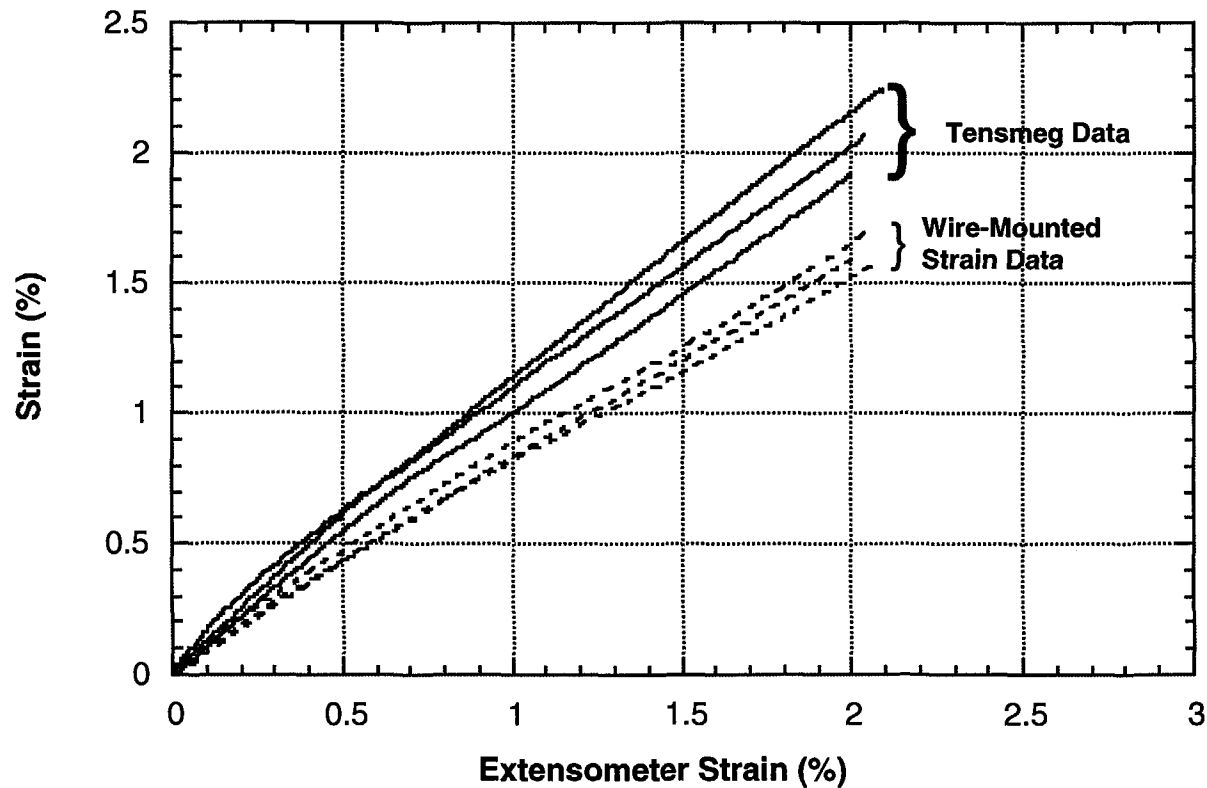
- Single Strand Tests



Tendon Instrumentation

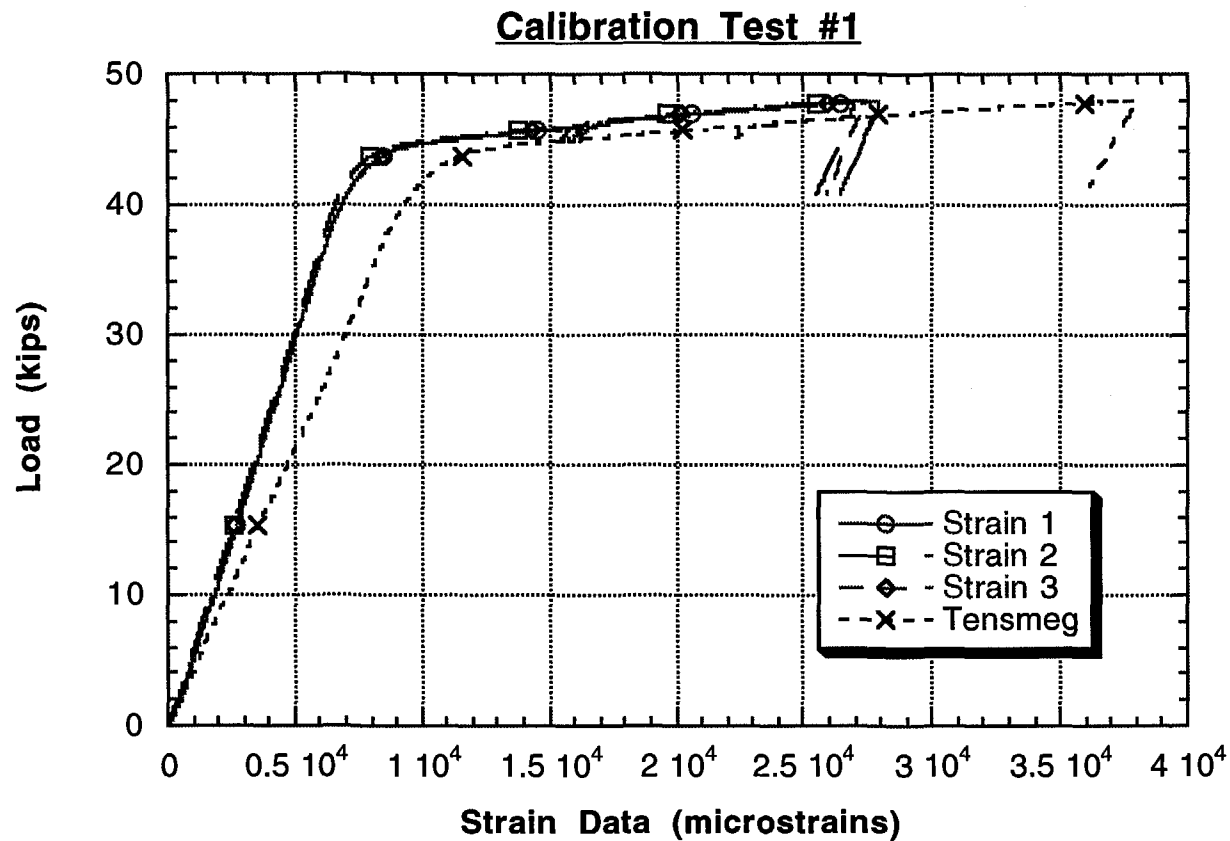
- **Calibration Results**

- **Tensmeg Correction Factor = 1**
- **Wire-mounted Strain Gage Correction Factor = 1.32**



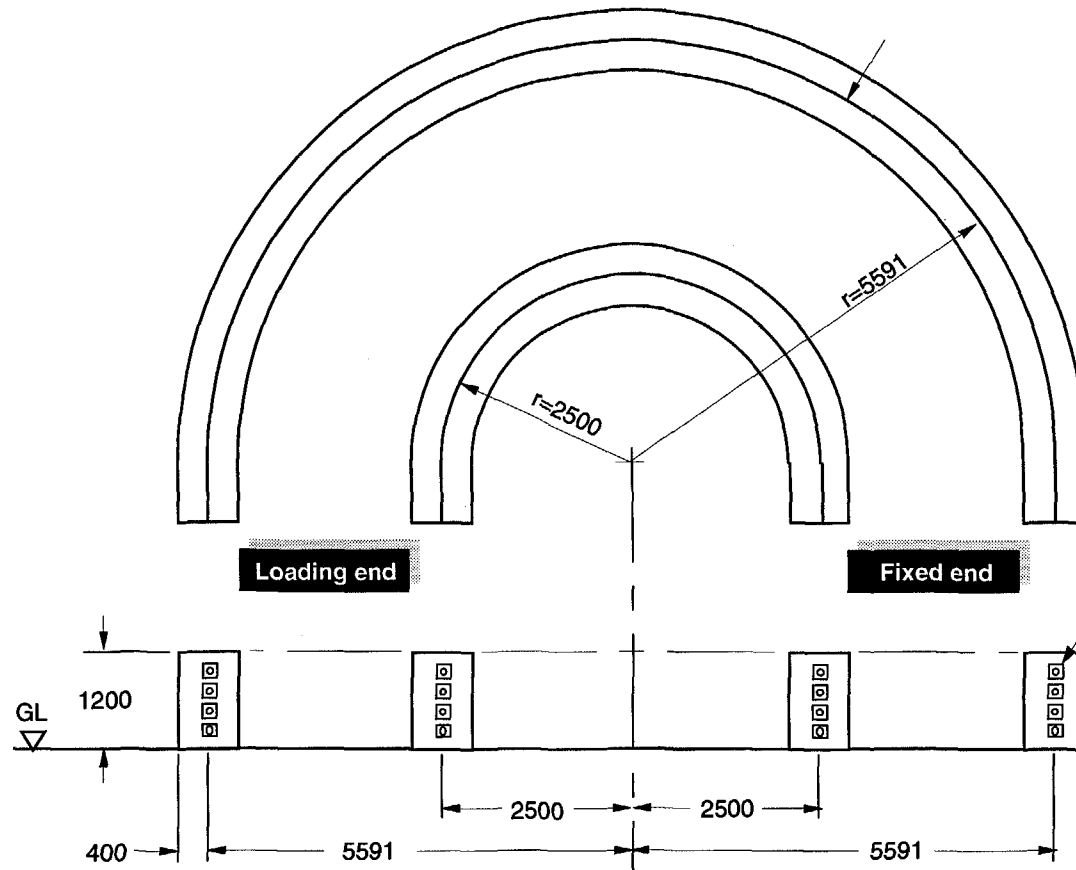
Tendon Instrumentation

- Calibration Results



Tendon Instrumentation

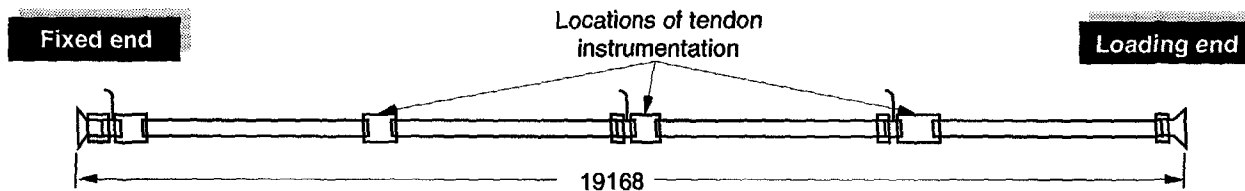
- Tendon Test Configuration



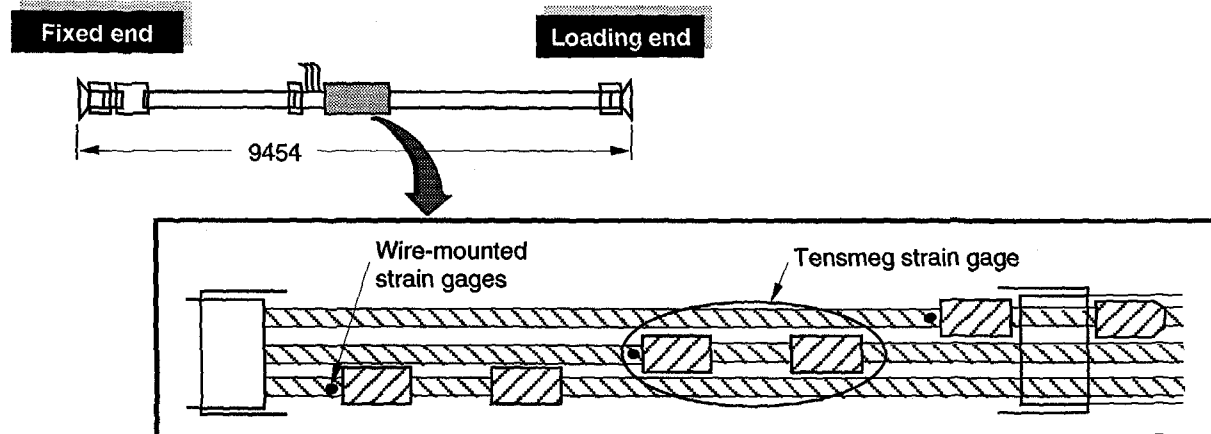
Tendon Instrumentation

- **Layout**

Large Radius Tendon

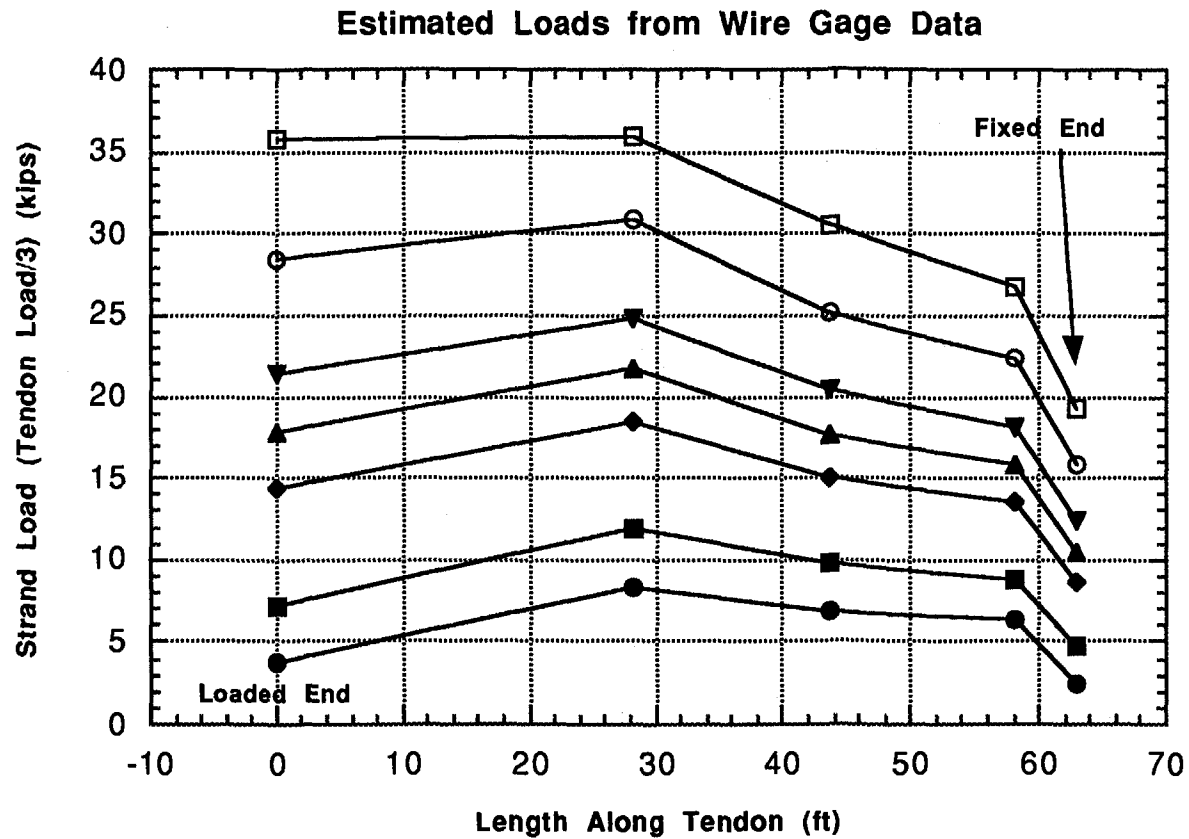


Small Radius Tendon



Tendon Instrumentation

- Results (preliminary)



Tendon Instrumentation

- **Future Plans**

- **Complete detailed analysis of tendon test data.**
- **Modify Tensmeg design to improve survivability.**
- **Investigate methods to improve lead wire survivability.**