Monitoring of a Prestressed Segmental Box Girder Bridge During Strengthening

Bruno Massicotte Ph.D., P.E.
Associate Professor
Department of Civil Engineering
École Polytechnique de Montréal
Montréal, Québec, Canada
Formerly, Bridge Design Engineer at the Québec Ministry of Transportation

André Picard, Ph.D., P.E.
Professor
Department of Civil Engineering
Université Laval
Québec City, Québec, Canada

The Grand-Mère Bridge, a 285 m (935 ft) long cast-in-place segmental box girder bridge, experienced some distress which required strengthening by adding external prestressing equivalent to 30 percent of the remaining internal prestressing. Considering the importance of this undertaking, the Québec Ministry of Transportation supported an extensive research program with the objectives of measuring the external prestressing effects on the existing bridge and validating several design assumptions. The testing program comprised various measurements. Instrumentation included electrical strain gauges, mechanical strain gauges, thermocouples, and surface and embedded vibrating wire gauges. One mobile and two permanent data acquisition systems were used, together with manual reading devices. This paper presents details of the instrumentation program. Some field measurements are presented and comparisons with several design assumptions are discussed. The technology gained from this project is also applicable to precast, prestressed concrete bridges.

The Grand-Mère Bridge is a 285 m (935 ft) long cast-in-place post-tensioned box girder bridge built in 1977 and located 200 km (125 miles) northeast of Montréal, Québec, Canada (see Fig. 1). This bridge experienced various problems and distress that resulted in significant deflection in the 181.4 m (595 ft) central span. After numerous independent studies, and considering the importance of the bridge, the owner, the Québec Ministry of Transportation (QMT), made the decision to strengthen the bridge by installing additional prestress corresponding to 30 percent of the remaining amount.[1]

To better understand the behavior of the bridge during and after strengthening, the QMT engaged École Polytechnique de Montréal to plan and execute a testing program with the collaboration of Laval University and Sherbrooke University. The objectives of the program were to:

- Determine the short- and long-term efficiency of the additional prestressing.
- Understand the behavior of the anchorage blocks.
- Measure the thermal gradients.
- Study the dynamic response of the bridge.

The planned research program called for numerous types of instruments, suitable for short-term and/or long-term measurements, installed on the bridge during the summer of 1991.

To fulfill the first three objectives, École Polytechnique collaborated with Laval University and the QMT Bridge Testing Branch. The dynamic part of the experimental program, performed entirely by Sherbrooke University, is not described in this paper. The measuring devices were installed from June to August 1991, and data have been collected continuously since then. The bridge strengthening procedure took place in November 1991, and was completed over a two-week period during which a large part of the field measurement program took place.

Fig. 1. The Grand-Mère Bridge.

SCOPE OF THE PAPER

This paper is the second of two companion papers. The first paper[1] describes the various problems experienced with the Grand-Mère Bridge and the strengthening actions undertaken to rectify the bridge state of stress. This second paper describes an extensive testing program carried out during and after the bridge strengthening process.

Bridge designers and bridge owners may be interested in considering such an experiment or learning from the experience regarding design assumptions gained in the Grand-Mère Bridge project. To the authors' knowledge, it is the first time such an extensive field instrumentation and monitoring program, with a wide variety of instruments, has been carried out in North America during the strengthening of a major bridge. The field testing experience gained from this project can be applied to any precast or cast-in-place concrete structure, existing or new.

This paper contains a brief description of the bridge and its structural problems. The objectives of the field testing program and its various aspects are presented. The instruments used in the testing program are described and the experience gained during the strengthening process is discussed. Finally, test results are compared with the assumptions made in the strengthening design.

BRIDGE DESCRIPTION

A description of the bridge, its problems and the ensuing strengthening program are discussed in detail in Ref. 1. A summary is presented here.

Geometry

The Grand-Mère Bridge, located on Highway 55 over the St. Maurice River, is 285 m (935 ft) long. The bridge has three continuous spans of 39.6, 181.4 and 39.6 m (130, 595 and 130 ft) with a wedge-shaped solid cantilever span of 12.2 m (40 ft) at each end acting as counterweights (see Figs. 1 and 2).

In the central span, the depth of the box girder varies parabolically from 9.75 m (32 ft) over the interior piers to 2.90 m (9.5 ft) at the center. The depth of the cross section in the end spans varies slightly from 9.75 m (32 ft) at the interior piers to 8.53 m (28 ft) at the exterior piers. The total width of the bridge deck is 12.8 m (42 ft), including a 6.7 m (22 ft) wide single-cell box and two 3.05 m (10 ft) cantilevers.

Observed Distress

Shortly after its completion, the central span of the bridge showed signs of unexpected deflection. Measurements were then taken regularly and by 1986 the average midspan deflection, fluctuating with seasonal temperature variation, had reached over 300 mm (12 in.) without showing any sign of stabilization. This was considered sufficiently abnormal to warrant extensive studies.

Despite this unusual deflection, a careful inspection of the bridge in 1988 did not reveal any evidence of significant distress; cracking was observed in only two areas. The first set of cracks, at the third points of the central span, was attributed to the anchorage of continuity prestressing bars. The second set of cracks, in the top flange of the east end span, was probably due to differential shrinkage between the webs and top flange of the box girder.[2]

From studies on the current state of the bridge, it was concluded that the integrity and safety of the bridge were acceptable in the short-term period. However, most studies stated that a lack of sufficient prestressing was causing excessive tensile stresses in

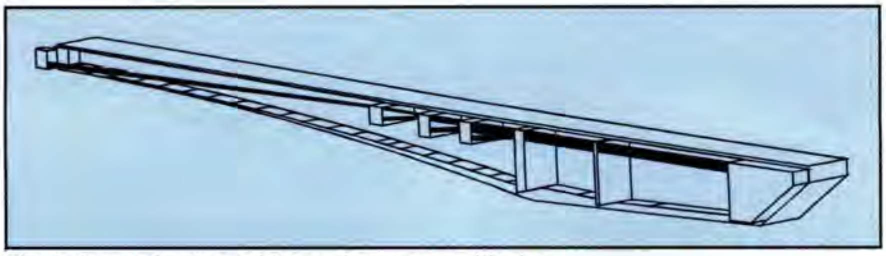

Fig. 2. Strengthening cables and anchorage blocks.

some areas of the top deck. These stresses exceeded the allowable limits by more than three times. This condition could lead to more serious cracking and corrosion problems in the future and impair the bridge's safety in the long-term period. The importance of the bridge dictated corrective action, so the QMT strengthened the structure in 1991.

Strengthening

The strengthening was achieved with prestressing cables, external to the concrete but located inside the box girder. A total of 32 cables, 16 from each end, was added (Fig. 2). These straight cables were placed just underneath the top slab near the webs, eight on each side. This additional prestress corresponds to 30 percent of the original remaining prestressing force.

Each of the 32 cables, made up of 12 or 15 individually lubricated sheathed strands, was encased in a PVC duct running from the dead-end anchorage zone to the 14 anchorage blocks distributed along the bridge's central span. The dead-end cable anchorage was located in the two solid cantilever end spans. Tension was applied, strand by strand, at each anchorage block.

OBJECTIVES OF THE EXPERIMENTAL PROGRAM

Technical Considerations

The Grand-Mère Bridge, with its slender central span, is an important structure requiring special consideration. The importance of the strengthening work justified the extensive experimental project. The primary research objective was to measure the strengthening efficiency; beyond this first objective, the experimental program was directed toward validation and improvement of some of the assumptions used in the strengthening design.

In a broader sense, the program was aimed at improving, through field monitoring, the general engineering knowledge applicable to new bridge design and to structural behavior of existing bridges. The assumptions directly associated with the strengthening design concern thermal gradients in the bridge, behavior of the anchorage blocks, prestress transfer mechanism to an existing structure, and dynamic behavior of the bridge before and after strengthening.

Moreover, although bridge strengthening by prestressing is an attractive remedy for deficient reinforced and prestressed concrete bridges, the engineering knowledge on the efficiency of this strengthening technique is scarce. Specifically, the testing program was expected to provide information on the following topics:

- Bridge response and prestressing force distribution in the structure compared to predicted behavior
- Variation of the added prestressing force with time
- Force transfer mechanism from the anchorage blocks to the webs and flanges of the box girder
- Validity of the assumptions used for the design of the anchorage blocks
- Adequacy of a linear vertical thermal gradient to compute thermal stresses
- Effect of the strengthening on the dynamic behavior of the bridge
- Actual support behavior
- Strengthening effect on the cracking level of the bridge

Only a large scale testing program combined with subsequent refined analyses can possibly answer these questions.

Large Scale Testing of Bridges

Field testing of bridges is growing, the primary reason being economics. Because the bridge infrastructure is aging, it is important that the actual behavior of structures be monitored. In some instances, significant increases in load capacity of bridges have been reported.[3] This feedback is valuable to bridge engineers.

Although numerous field tests of bridges have been described, comprehensive bridge testing programs are not yet common in North America. In Europe, bridge testing is more common and has been used for several decades, often as proof load testing. Recently, however, several testing programs on existing bridges have been initiated in the United States.[4] In Canada, the Ontario Ministry of Transportation has been conducting tests on existing bridges since 1969;[5] in Québec, the QMT started bridge testing programs in 1990.[6] However, in North America very few tests have been performed on existing prestressed concrete box girder bridges.

Recent problems with segmental prestressed concrete bridges have forced many agencies to strengthen their deficient bridges. Québec is the site of the first segmental bridges built in North America: the St. Adèle Bridge, built in 1964, was the first post-tensioned segmental box girder bridge;[7] the Lièvre River Bridge was the first precast segmental box girder bridge.[8] Deficiencies in these two bridges required strengthening procedures.[9]

In recent years in France, the Bridge and Roadway Central Laboratory (LCPC) has conducted several tests on prestressed concrete bridges, both on new construction and on strengthened existing bridges. To the authors' knowledge, monitoring of a segmental prestressed concrete bridge during strengthening has never been done in North America. Consequently, the testing program carried out during the Grand-Mère Bridge strengthening program is of prime interest.

Research Program

An important aspect of the instrumentation and testing program on the Grand-Mère Bridge was the collabora-

Table 1. Types and locations of measuring and recording devices.

Section (see Fig. 9)	Vibrating wire gauges	Electrical strain gauges	Thermo-couples	Readings*	Pairs of mechanical strain gauges
E1	6S	5	23 (1991)	DAS-p	5
			35 (1992)	DAS-p	
E2	4S			DAS-p	
E3	1S			DAS-p	5
		11		M	
Block 1-NE	6S			M	72
Block 1-NE	12E			M	2
E4	1S			DAS-p	2
E5	1S			DAS-p	2
E6	1S			DAS-p	
E7			19 (1991)	M	8
	5S		51 (1992)	DAS-p	24
Block 4-NC				M	13
W1		17		DAS-m	
W2		3		DAS-m	
Block 1-NW		33		DAS-m	
W3		3		DAS-m	
W4		3		DAS-m	
W5		3		DAS-m	
Total	25 S-type 12 E-type	78	42 (1991) 86 (1992)		133

*DAS = data acquisition systems: permanent (p) and mobile (m)

M = manual readings with portable units (for electrical strain gauges, vibrating wire gauges and thermocouples)

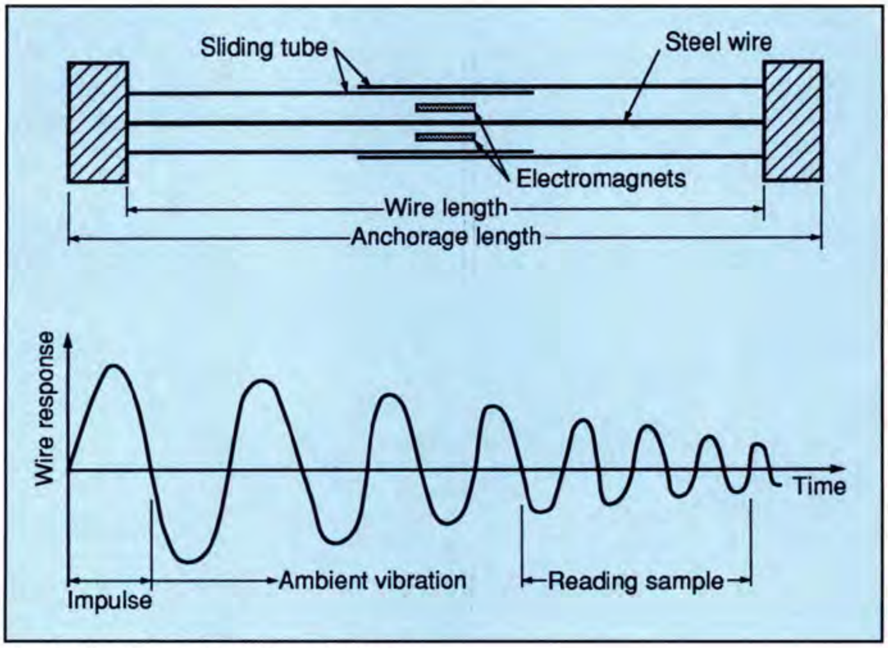

Fig. 3. Vibrating wire gauge principle.

tion of three universities, the QMT Bridge Department, the QMT Bridge Testing Branch, practicing engineers and contractors. In addition to the information gained through the experimentation program and the subsequent analyses, the knowledge transfer among these groups was a key factor in obtaining the financial support of the QMT. The instrumentation program, led by École Polytechnique, was split into five independent research projects defined as follows:

1. Short-term efficiency of the additional prestressing

2. Behavior of the anchorage zones

3. Dynamic behavior of the bridge, before and after the strengthening process

4. Thermal behavior of the bridge

5. Long-term efficiency of the additional prestressing

INSTRUMENTATION

Measuring Instruments

A summary of the measuring instruments used in the 1991 testing program is given in Table 1, along with the additional instruments added in 1992. Two data acquisition systems, one permanent and one mobile, and various portable reading devices gathered the data during the strengthening process.

All the instruments used (except those related to the dynamic aspect of the testing program) along with their advantages and disadvantages are described in this section. Refs. 10 and 11 provide more details on field testing of structures and on this experimental project.

Electrical strain gauges — Electrical strain gauges are widely used for accurate short-term strain measurements. On concrete surfaces, their long-term reliability under field conditions is uncertain. Moreover, wire length difficulties associated with electrical strain gauges limit their use in locations too distant from data acquisition systems.

For these reasons, the long-term strain measurements planned in this experimental program were not taken with electrical strain gauges. However, their use was considered appropriate during the strengthening process and 78 gauges 100 mm (4 in.) long were installed at various locations inside the box girder.

Vibrating wire gauges — A vibrating wire gauge is a strain measuring device consisting of a free vibrating steel wire located inside a steel tube anchored at both ends (see Fig. 3). Set to an initial tension, any modification in tube length results in a modification of the wire's first natural frequency, which is then converted into strains.

To measure the initial natural frequency, the wire is excited by electromagnets located within the steel casing.

Once the vibration is induced, these electromagnets measure the wire's ambient vibrating frequency. This takes about one second. Although not often used in structural engineering applications, these devices are common in geotechnical applications. Their main advantage is their long-term stability, enabling the planning of long-term measurements — an important aspect of this experimental project.

Two types of gauges are available: those anchored to the concrete for surface measurements (S-type) and those embedded in the concrete for internal measurements (E-type). When properly anchored, the S-type gauges displayed an accuracy comparable to electrical strain gauges, according to laboratory tests at École Polytechnique.[12] The accuracy of E-type gauges is more difficult to establish.

The relationship between frequency and strain is obtained from basic physics. The first natural frequency of a wire of length, L, and density, ρ, subject to a tensile stress, σ_0, is given by:

$$f_0 = \frac{1}{2L_0}\sqrt{\frac{\sigma_0}{\rho}} \qquad (1)$$

If L_0 and f_0 are base values for the initial wire length and the initial frequency, and f_1 is the modified frequency corresponding to a wire elongation ΔL_1, the frequency-strain relationship is given by:

$$\begin{aligned}\varepsilon_1 &= \frac{\Delta L_1}{L_0}\\ &= \frac{4L_0^2\rho}{E}\left(f_1^2 - f_0^2\right) \qquad (2)\\ &= K\left(f_1^2 - f_0^2\right)\end{aligned}$$

The difference between the wire length and the anchorage spacing must be accounted for in computing the average strains. Characteristics of the Telemac® vibrating wire gauges that were used are given in Table 2. In this table, the K factor in Eq. (2) is given as $6.25 \times 10^{-6} K_0$, where K_0 is a constant associated with each type of gauge.

Table 2. Vibrating wire characteristics.

Parameter	SC2 (surface)	C110 (embedded)
Length	300 mm	142 mm
K_0	0.5	0.3
Range	3000 $\mu\varepsilon$	3500 $\mu\varepsilon$
Accuracy	0.5 $\mu\varepsilon$	0.3 $\mu\varepsilon$

Note: 1 mm = 0.03937 in.

In addition to their long-term reliability, vibrating wire gauges are not affected by the connecting wire length. Also, remote data acquisition is possible without difficulty because only wire frequencies are read. Moreover, surface gauges are reusable. However, these devices are expensive and need special acquisition or reading systems that can induce the wire vibration and read its frequency.

For their long-term measurement capability and for strain measurements inside an anchorage block, both types of gauges (see Fig. 4) were used: 25 Telemac SC2 (S-type) gauges were mounted on the concrete surface and 12 Telemac C110 (E-type) gauges were embedded in one anchorage block.

Mechanical strain gauges — Mechanical strain gauges (Demec®) are reasonably accurate devices, with an accuracy of about 6.5 microstrains ($\mu\varepsilon$) for a 250 mm (10 in.) long Demec gauge and a reading range of ± 2 mm (0.08 in.). Although manual readings with these gauges are cumbersome, they were used extensively on this project because of the limitation in location of the data acquisition systems.

Moreover, because the testing could not be repeated, they acted as backup devices in several locations in case of any malfunction in the other systems. In total, 133 pairs of mechanical gauges were installed. Many of them were located on anchorage blocks and surrounding areas (see Fig. 5), and also on diaphragms between adjacent blocks.

Thermocouples — Thermocouples were used to measure the temperature distribution in the bridge. In North America, most temperature measurements in box girder bridges have been taken in constant depth structures, and only a few bridges with depths varying from 3 to 10 m (10 to 33 ft) have been part of extensive temperature measurement programs.[13] Moreover, due to the east-west orientation of this bridge, the south web of the box girder is exposed to the sun and direct solar radiation significantly more than the north web.

The amount of solar radiation on the south web is influenced by two factors on this bridge. First, the shadow of the

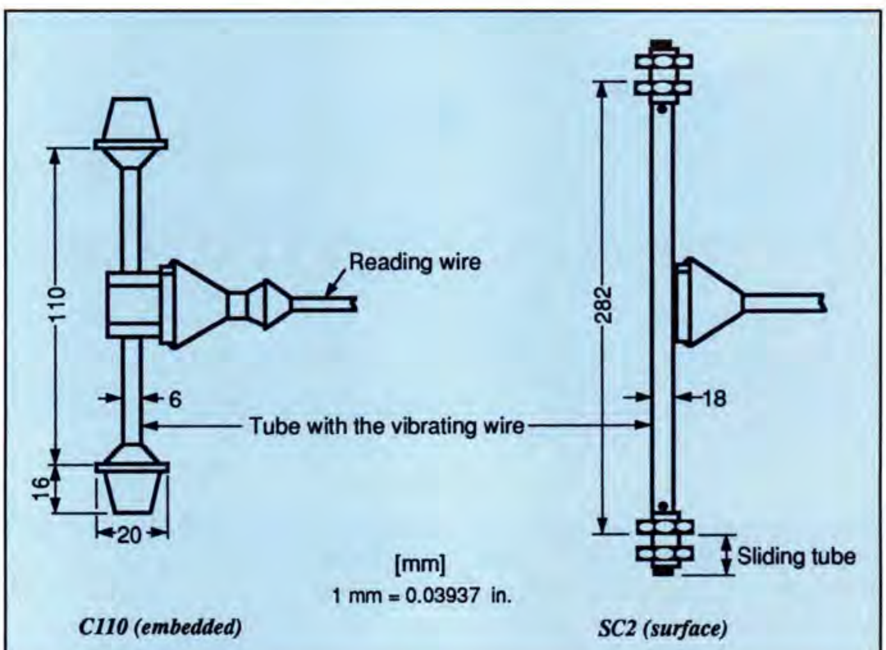

Fig. 4. Vibrating wire gauges.

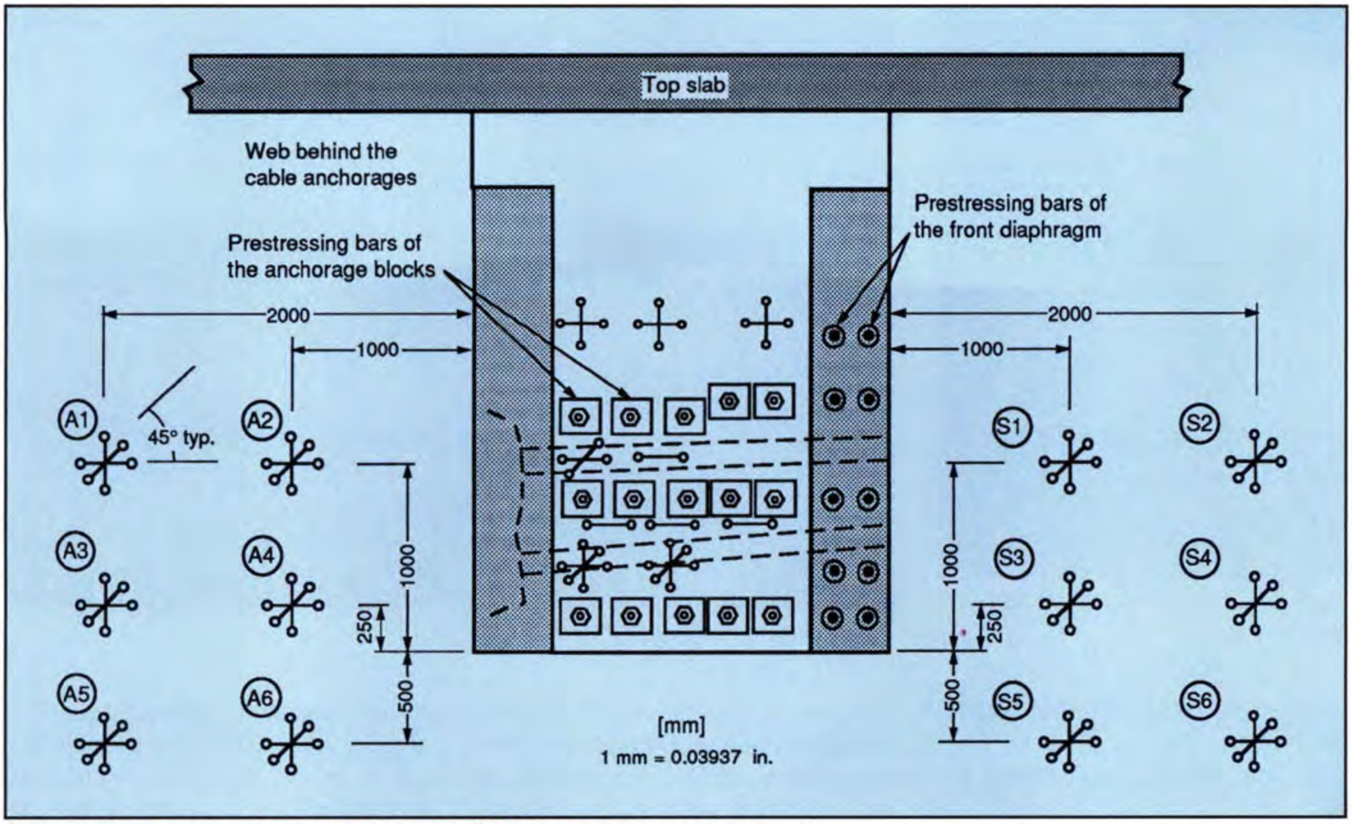

Fig. 5. Demec mechanical strain gauges on the face and around Block No. 1.

top deck on the box girder web varies considerably between midspan and end spans. This aspect is not considered in any thermal gradient specifications. Second, due to the northern location of the bridge at a latitude of 46° 37', the sun is low during relatively hot spring and fall days and the daily transverse temperature gradient is more pronounced. Again, the transverse temperature gradient is not quantified in any specification.

Forty-two T-type [copper-constantan (a nickel-copper alloy)] thermocouples were used in 1991, increased by another 44 in 1992. These thermocouples are reliable, inexpensive, easy to install and well-adapted to measuring temperature variations in normal environmental conditions.

Fig. 6. Mobile bridge testing vehicle.

Displacements and deflections — To measure horizontal displacements at piers, a micrometer and a mechanical dial gauge, with an accuracy of ± 0.01 mm (0.0004 in.) and reading ranges of 200 and 50 mm (8 and 2 in.), respectively, were used. They were installed at the two horizontally free supports on the east side of the bridge.

Also, a high accuracy surveying level (± 0.2 mm or ± 0.008 in.) was utilized to measure the relative deflection, due to the strengthening, at 10 bench marks located on both sides of the roadway along the bridge's eastern half. Although these devices were theoretically of high accuracy, confidence in the readings under field conditions was about 0.1 and 1 mm (0.004 and 0.04 in.) for horizontal displacements and vertical deflections, respectively.

Data acquisition systems and portable reading units — The selection of the acquisition and reading systems for the various data to be gathered was an important aspect of the experimental program because it dictated the location of the instruments. Ideally, as many data acquisition systems as required would have been used. During strengthening, it was

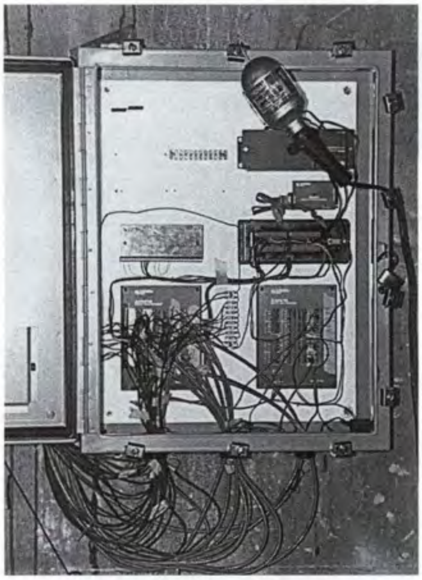

Fig. 7. Permanent data acquisition system.

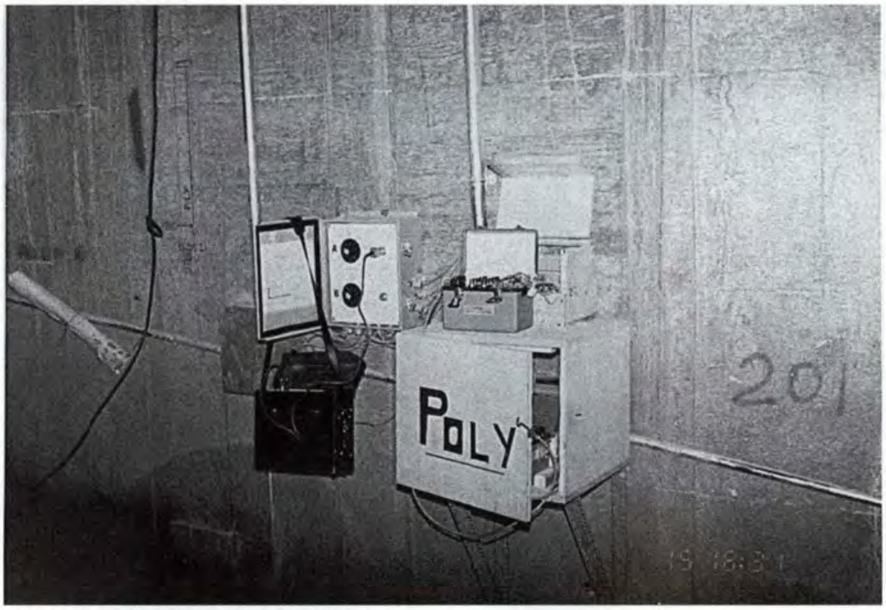

Fig. 8. Junction boxes and metal ducts.

possible to use only two data acquisition systems.

The first, a mobile bridge testing vehicle owned by the QMT, has the capacity to simultaneously handle 60 electrical strain gauges located at a maximum distance of 45 m (150 ft). This mobile data acquisition system, used only during the strengthening process, was positioned on the bridge deck above the anchorage Block No. 1 on the west side (see Fig. 6).

The second data acquisition system, bought specifically for this experimental program and designed to operate automatically for long periods, can read electrical strain gauges, thermocouples and vibrating wire gauges (see Fig. 7). The system includes a controlling recording unit connected to two multiplexers. With its current configuration, this system has a total capacity of 16 electrical strain gauges, 24 thermocouples and 20 vibrating wire gauges.

Despite the remote location of the bridge, continuous automatic acquisition for long periods was possible because electric power was available at the bridge. The computer memory is sufficient to store data for a 40-day period when readings are taken every four hours. To clear the memory, a portable computer, through a RS-232 connection, is required.

During the strengthening process, readings were taken at shorter intervals according to the rate of application of the strengthening prestress.

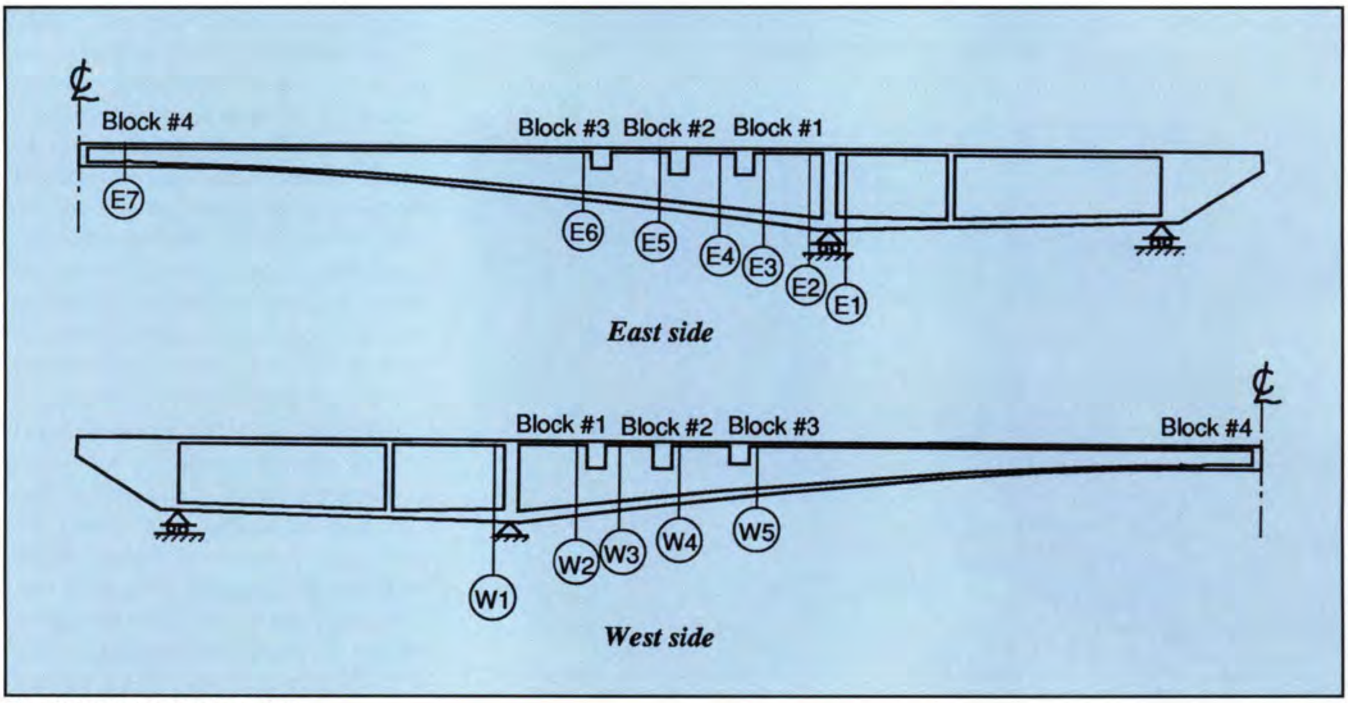

Fig. 9. Instrumented sections.

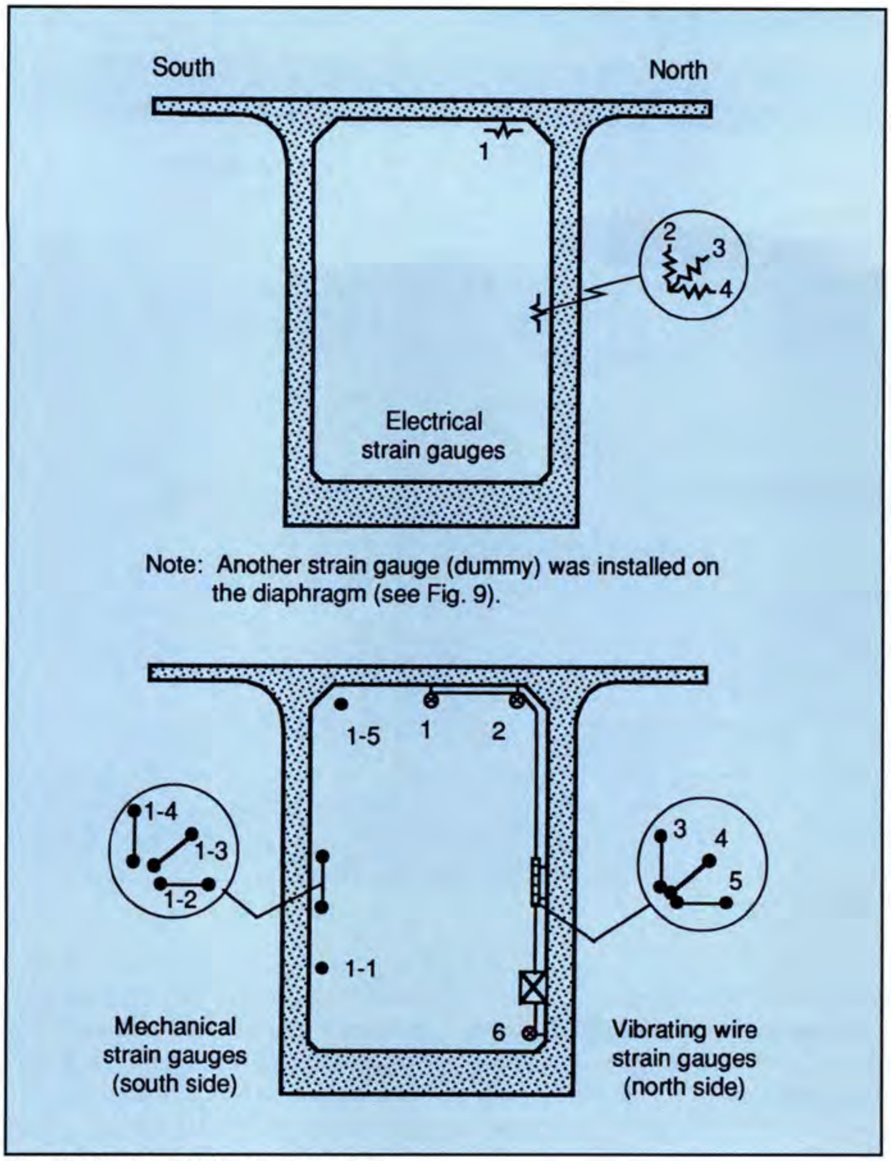

Fig. 10. Section E1 instrumentation.

The permanent data acquisition system was fixed to the box girder's north web in the east end span, close to the interior pier diaphragm.

In addition to these two automatic data acquisition systems, several portable manual reading units were used for strain gauge, vibrating wire gauge and thermocouple measurements. Displacements and mechanical strain gauges were also read manually. Reading of the instruments not connected to the data acquisition systems was facilitated by four junction boxes, grouping together similar instruments at various locations along the bridge (see Fig. 8).

In the summer of 1992, after the addition of 44 thermocouples at Sections 1 and 7, a second permanent data acquisition system, identical to the first one, was installed at Section 7 at midspan (see Fig. 9).

Selection of the Instrumented Sections

The selection of the instrumented sections was dictated by the prevailing field and construction conditions, the proximity of data acquisition systems and the accessibility when scaffolding was required. Twelve sections and three anchorage blocks, attached to the north web, were instrumented (see Fig. 9), as shown in Table 1.

On the west side of the bridge, only electrical strain gauges connected to the QMT mobile data acquisition system were used. Five sections, the north side Block No. 1 and its surrounding area were instrumented with a total of 62 electrical strain gauges. The east side of the bridge had six instrumented sections with a combination of electrical strain gauges, mechanical strain gauges, vibrating wire gauges and thermocouples.

The north side Block No. 1, on the east side of the bridge, had mechanical strain gauges, and both surface and embedded vibrating wire gauges. At the center of the bridge, one section and the north side anchorage Block No. 4 were instrumented with various measurement devices: surface vibrating wire gauges, thermocouples and mechanical strain gauges.

Selection of the Instruments

The reasons for selecting the measuring devices used at the twelve instrumented sections and at the three anchorage blocks are:

Strain measurements — To study the global prestressing effects on the structure, Sections E1 (see Fig. 10), E2, E7 and W1 were instrumented with longitudinal gauges and gauge rosettes. These sections were selected to adequately measure the prestressing normal forces and bending moments where the magnitude of these effects was expected to be more important.

The remaining sections (E3 to E6 and W2 to W5) had gauges located underneath the upper deck only for comparison with calculated values. Also, these positions were selected to determine any restraining effect due to friction at the theoretically free supports and any possible shear lag of prestressing force distribution in the upper slab.

Strains induced by the prestressing force applied at three anchorage blocks were monitored with gauges on the blocks and on the webs in the surrounding areas. Also, strain measurement inside Block No. 1 on the east side was done with two spatial rosettes of vibrating wire gauges, made of six gauges each, embedded in the block. Fig. 11 shows the electrical strain gauge arrangement for Block No. 1 on the west side. Also, mechanical strain gauges were used to measure the response of the two diaphragms linking adjacent blocks.

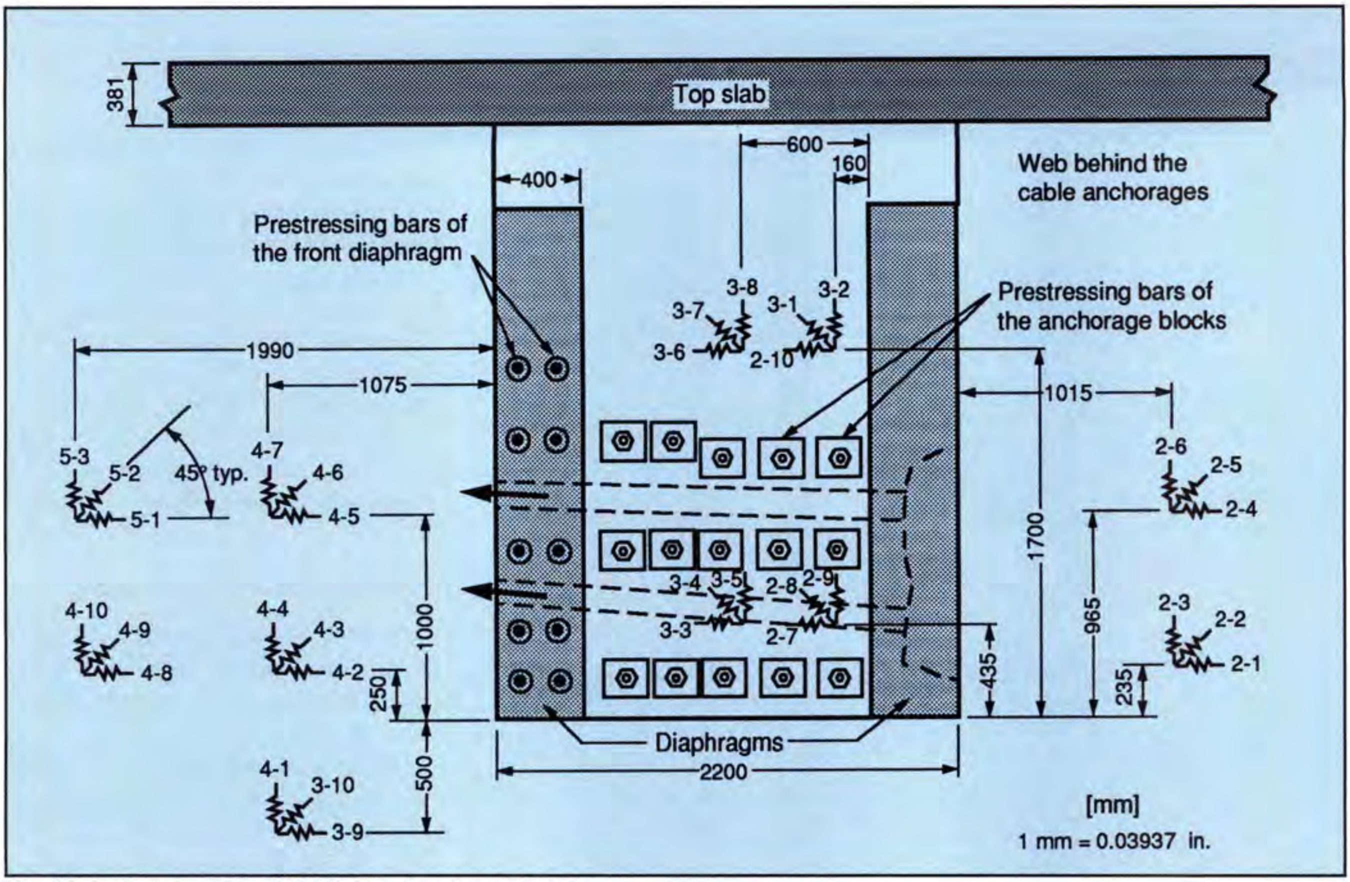

Fig. 11. Instrumentation of Block No. 1 on the west side.

Temperature — Considering the variation in the cross section, thermocouples were placed in Sections E1 and E7 (see Fig. 12). Their purpose was to study the temperature distribution in two very different sections of the same bridge, a shallow and a deep cross section. Local thermal gradients in the top slab and webs, together with global vertical and transverse gradients, are of interest in this study.

INSTALLATION

Field instrumentation of this scale in a remote area during construction is difficult. The tight construction time schedule initially established required the collaboration of several people: technicians, graduate and undergraduate students, and QMT staff. The working schedule was carefully planned to meet the mid-August deadline.

To install all the measuring instruments, a total of 162 man-days was required. The planning required, the installation of the various devices, the methodology adopted and the difficulties met on the construction site are described in this section.

Strain gauges — For the 78 strain gauges installed, two types of adhesive were used. The 62 gauges of the west side (Sections W1 to W5 and Block No. 1-NW) were installed with a fast curing adhesive. The 16 gauges on the east side were installed with a conventional epoxy bond requiring a longer curing time with pressure. The latter technique, well-adapted to laboratory experiments, was not practical in field conditions; the former technique is highly preferred. Gauges were protected against moisture with coating and waterproof tape. Wooden plate caps were installed over each gauge to prevent any accidental damage from the ongoing construction work.

Vibrating wire gauges — Surface vibrating wire gauges were anchored to concrete by means of two steel inserts (see Fig 13). Two holes, 20 mm in diameter by 75 mm deep (3/4 in. x 3 in.), were drilled using a template for alignment. Inserts were installed and held in place with the template during the curing of the injected epoxy gel.

When the inserts were correctly anchored to concrete, the vibrating wire gauges were put in place and end screws were tightened to set the initial wire tension. An initial frequency of approximately 800 Hz, in the middle of the reading range, allows tension and compression strain measurements. Steel caps were added as protection against impacts.

Two spatial rosettes of embedded vibrating wire gauges were installed in Block No. 1-NE. Six gauges were required for each rosette (see Fig. 14). Each gauge was carefully and firmly attached to the reinforcing bars before the wooden forms of the block were erected. The initial frequency of each gauge was set at the factory at about 1000 Hz. Careful concrete pouring and limited vibration ensured proper installation and operation.

Thermocouples — The thermocouples were placed in 10 mm (3/8 in.) diameter drilled holes that were injected with low viscosity epoxy. Injection was done with a medical syringe (see Fig. 15); a caulking compound was used around the hole and a rubber tube was placed for air expulsion.

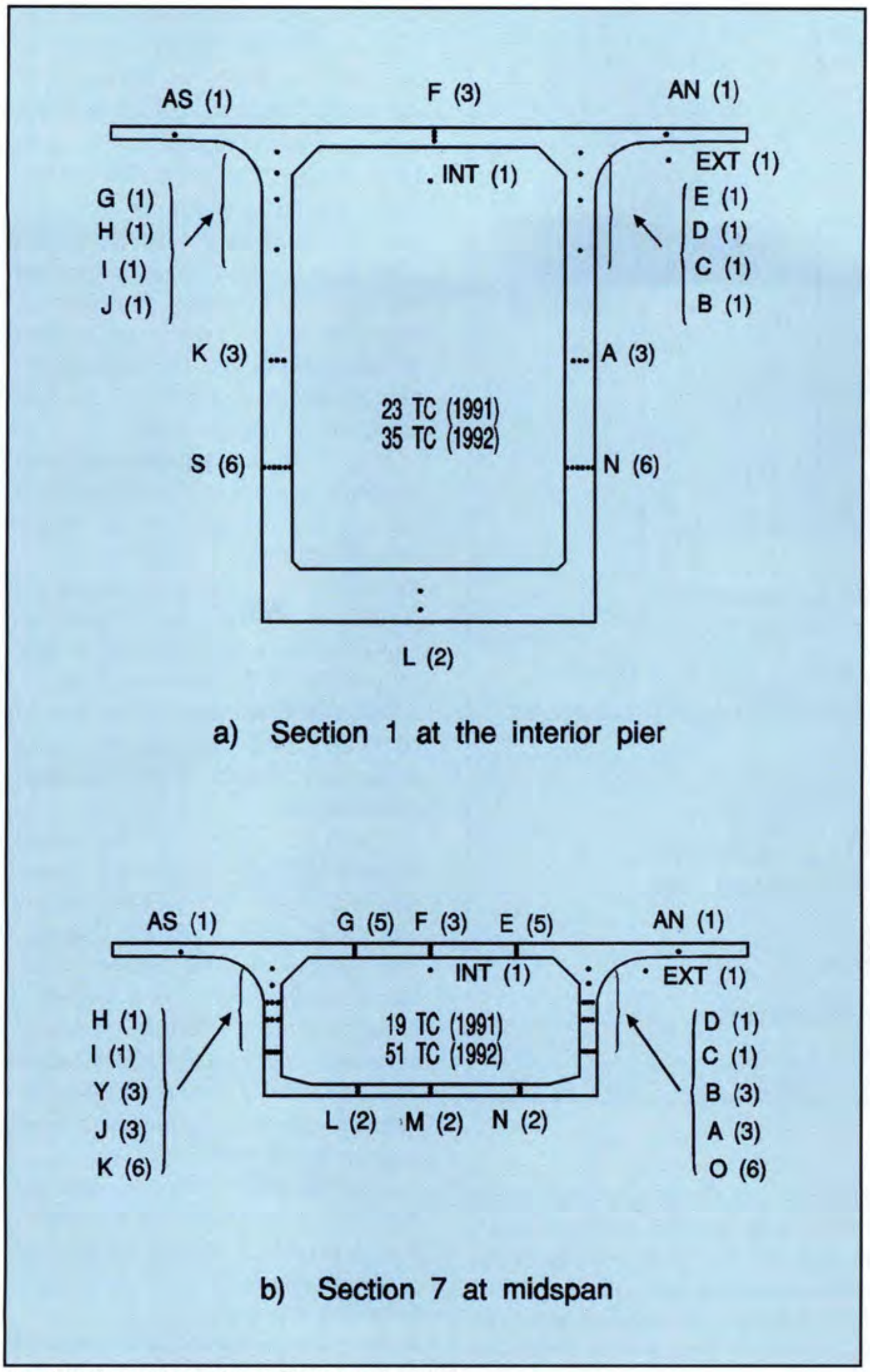

Fig. 12. Thermocouples in Sections 1 and 7.

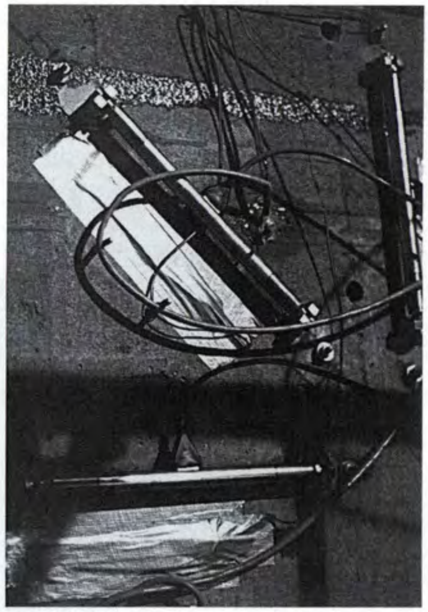

Fig. 13. Vibrating wire gauges.

Wire protection — A total of 100 m (350 ft) of flexible electrical metal ducts, 25 and 50 mm (1 and 2 in.) diameters, was used to protect the wires at the center of the bridge and on the east side (see Fig. 8). Construction site conditions necessitated such care. Although the workers and the contractor were exceptionally cooperative, high voltage electrical ducts inhibited any inquisitiveness during the absence of the university crews. The strain gauges connected to the mobile laboratory on the west side required no special wire protection because they were installed temporarily just before the strengthening process, when construction work was almost complete (see Fig. 16).

Construction site requirements and difficulties — The field testing program was planned and executed under difficult conditions. First, it was required that all measuring devices be installed within a six-week period. The strengthening work had already begun and it was essential to interfere as little as possible with the on-going construction. Also, due to the inside height of the box girder at many instrumented sections, scaffolding was necessary. This equipment was shared with the workers, who had first priority.

The most difficult aspect of the job was certainly the very high dust content of the air during the drilling and chipping of existing concrete. The technical crew had to work evening shifts to install sensitive instruments, such as the electrical strain gauges, in relatively clean conditions. The success of the instrumentation was due largely to excellent planning and an innovative staff.

RESULTS OF THE MONITORING PROGRAM

The success of the monitoring program is discussed here, along with results related to three of the five topics identified previously: strengthening efficiency, anchorage block design and thermal behavior.

Instrumentation

Due to some difficulties faced by the contractor, the strengthening operation was postponed until November 1991, three months after the initially scheduled date. The temperature was stable at just around freezing during the two-week period needed to

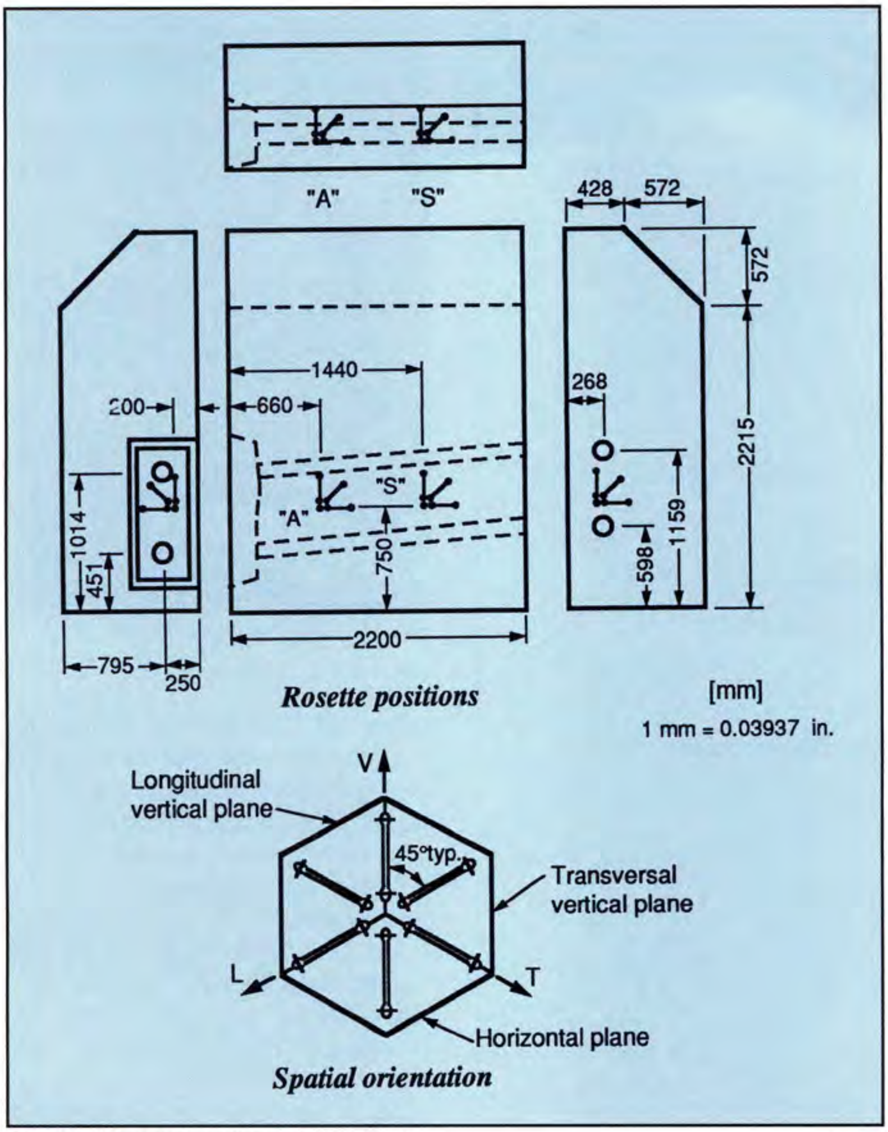

Fig. 14. 3D rosettes at an anchor block.

strengthen the bridge. Due to the low temperature, the work was difficult for the university staff. However, the stable temperature reduced the corrections needed on strain measurements.

Although some adjustments were required at the beginning of the strengthening, the data collecting went as planned. Of all the instruments installed, only three electrical strain gauges malfunctioned at the time of strengthening. Later analysis of the results indicated that three surface vibrating wire gauges also did not function properly, their frequency remaining constant under axial deformation. Manual strain measurements with the Demec gauge were successful, allowing the identification of adequate behavior of the other strain measuring instruments.

In planning the experimental program, it was thought that the use of many instrumented sections would provide the best picture of the bridge response to the strengthening. With the experience gained, it is clear that using more instruments at fewer sections is more advisable than monitoring many sections with a few instruments in each one. For this project, monitoring one section in each span, with more instruments in each section, would have simplified the interpretation of the results. Duplication of various instruments at the same location is strongly recommended.

Strengthening Efficiency

The actual strengthening efficiency is of prime interest in this experimental study. As a first indication in quantifying efficiency, two displacement measurements are considered. In Fig. 17, the vertical displacement at midspan, measured after the prestressing application at each group of Block Nos. 1 to 4, is compared to the calculated values. The estimated deflections, computed assuming an elastic module based on specified strength which is smaller than the actual strength, and assuming an uncracked structure, are 35 percent larger than the measured values. This indicates either a stiffer structure or reduced efficiency of the strengthening.

Fig. 18 shows the measured and computed horizontal displacements at the east side interior bearing. In this case, if bearings are functioning well, the stiffness of the structure should not significantly affect the comparison. However, the measured value is only 60 percent of the theoretical figure. This could indicate a certain amount of friction at the Teflon bearing which is partially restraining the horizontal displacement.

A refined study[12] on this aspect showed the friction coefficient at bearings is at least 6 percent. This quantity was derived from strain and displacement measurements compared to analytical results obtained with a sophisticated nonlinear structural analysis computer program, CPF[14] (for Cracked Plane Frame). The program was developed especially for the analysis of segmental construction.

Analyses with CPF determined that the most probable source of distress was repetitively occurring thermal gradients, causing the bridge to crack. From this study, the strengthening efficiency was estimated to be about 85 percent. It was also concluded that strengthening by external prestressing was the most appropriate way to improve the bridge behavior and to extend its useful life.

Anchorage Block Design

Fig. 19 shows the stress distribution in the anchorage Block No. 1, east side, in which two spatial vibrating wire gauge rosettes were embedded at "A" and "S." The stress distribution was obtained using a combination of analysis calibrated on experimental values. It appears clearly on this figure

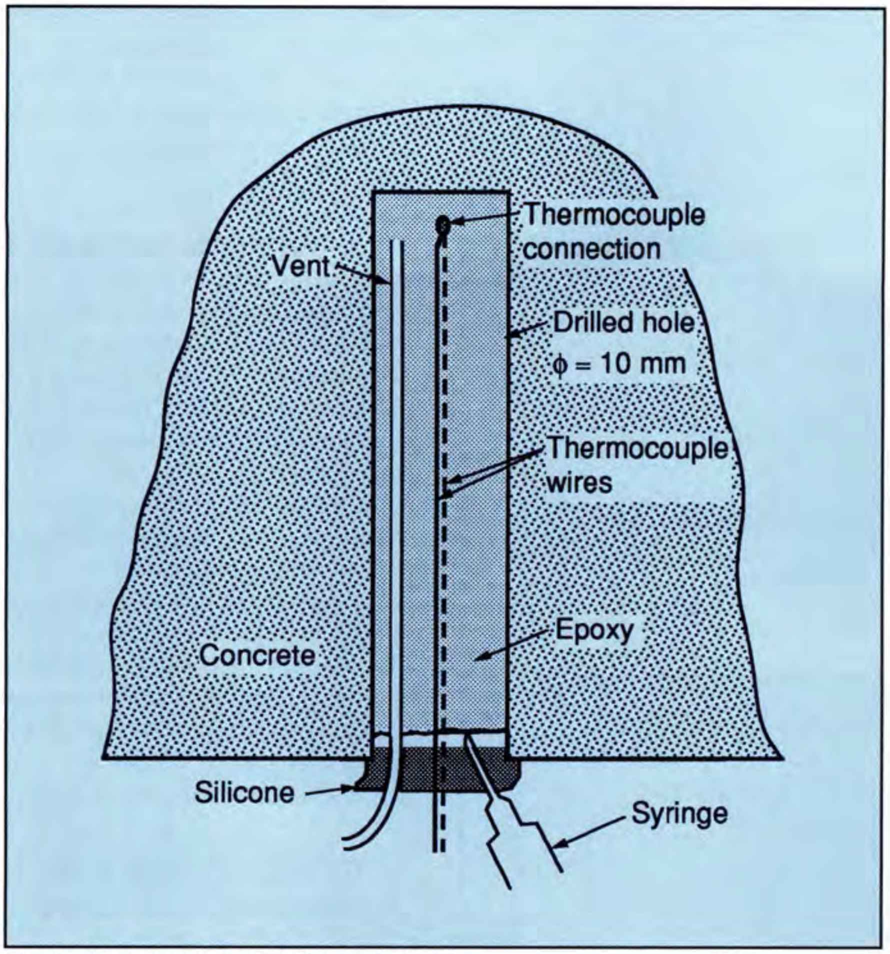

Fig. 15. Thermocouple injection technique.

that the prestressing force dissipates rapidly from the block to the web. A more detailed study[15] indicates that 50 percent smaller anchorage blocks would have been sufficient. However, the front and back diaphragms are essential components in avoiding any bending moment in the webs.

Rational anchorage block design recommendations are not currently available. With the current knowledge, computing the reinforcing steel as in the design of beam end zones is suggested. The amount of reinforcement is then calculated assuming an independent behavior in both vertical and horizontal planes.

Strain measurements in the webs on the front side of the blocks indicate a rapid diffusion of the prestressing force. On the back side, very small strains were measured and the dragging stresses behind the block are not as significant as anticipated.

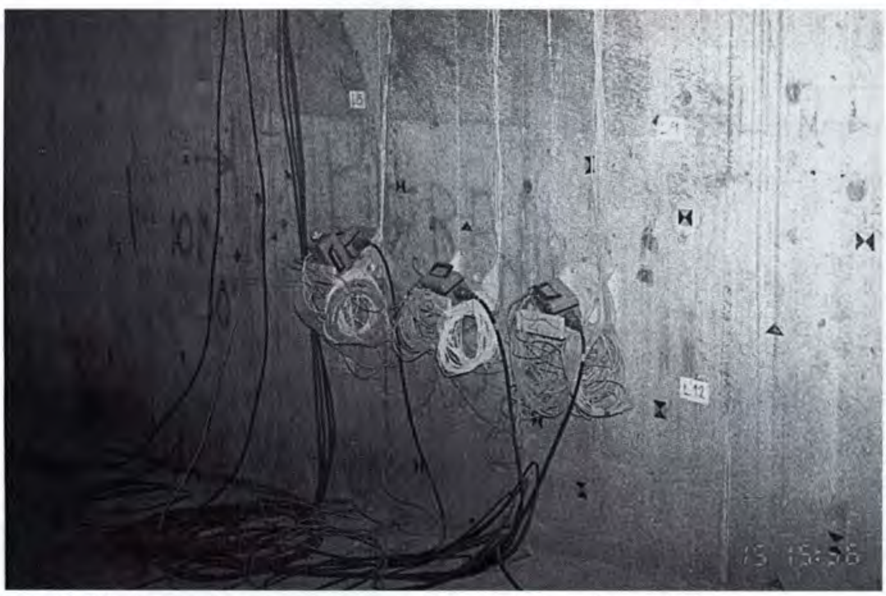
Fig. 16. Strain gauge connection wires to the mobile testing vehicle.

Thermal Behavior

Temperature measurements allowed the calibration and utilization of a finite element program (FETAB-2) adapted to the thermal analysis of a box girder cross section.[16] Excellent correlation between measured and computed temperature is shown in Fig. 20. During the first year of temperature measurements, the temperature distributions observed were closer to a bilinear gradient than the initially adopted linear variation. Also, due to the cross section variation and the landscape of the surrounding area, temperatures at midspan are less than those observed closer to the shore.

Analysis with FETAB-2 allowed continuous transient modeling of the thermal response of the bridge subjected to weather conditions. Actual air temperatures measured at the bridge, combined with data on wind speed and cloudiness, were input in FETAB-2 to determine temperature distributions in Sections 1 and 7 over a one-year period. From these analyses, three temperature components were extracted: an average temperature, a linear gradient and residual temperatures (see Fig. 21).

The first component governs the longitudinal expansion and contraction of the bridge and does not generate stresses; the second gives rise to bending moments in an indeterminate structure; the third creates eigenstresses necessary for plane sections to remain plane. In the strengthening design,[1] only a linear thermal gradient of 12°C (21°F) was considered. From the analysis,[17] it was found that, for a 50-year return period in Section 1, an extreme 11.4°C (20.5°F) linear thermal gradient would be appropriate —

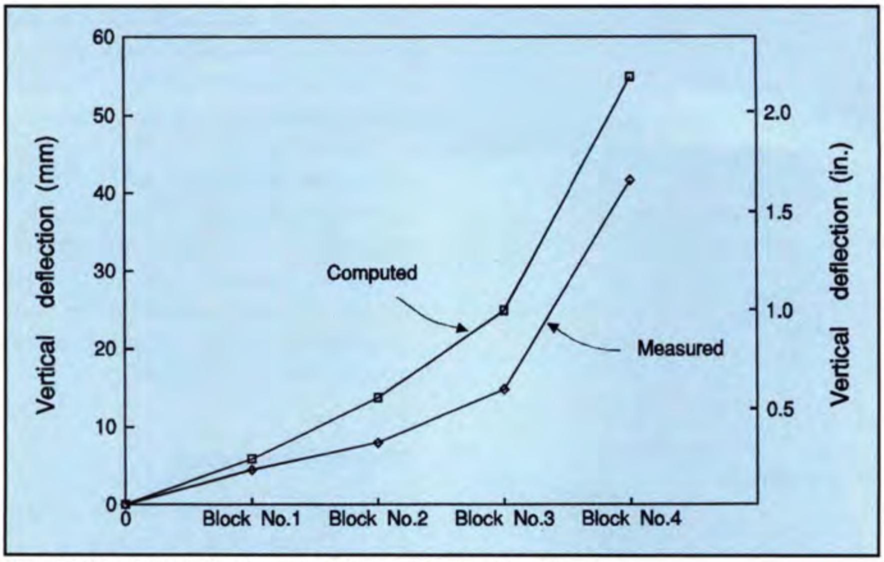

Fig. 17. Vertical deflection at midspan due to strengthening.

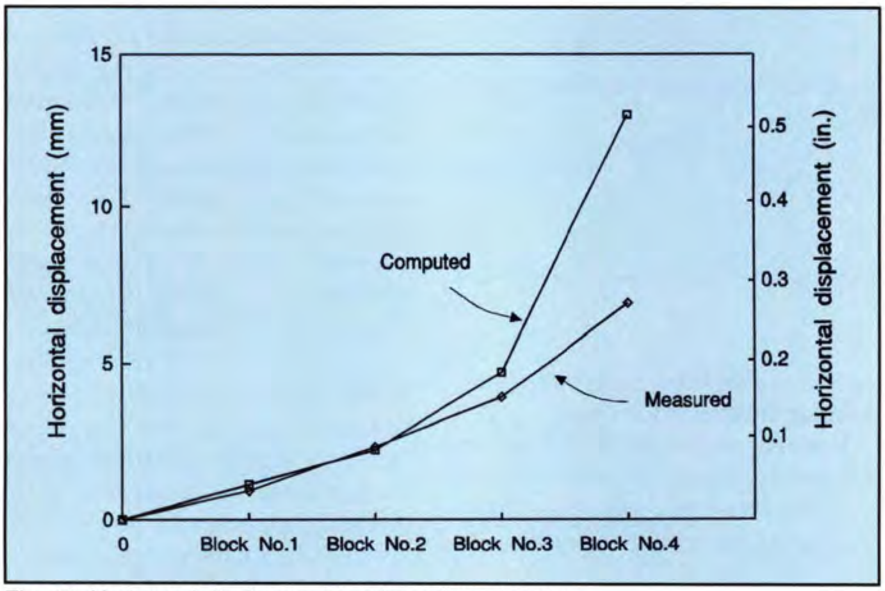

Fig. 18. Horizontal displacement at free sliding bearing.

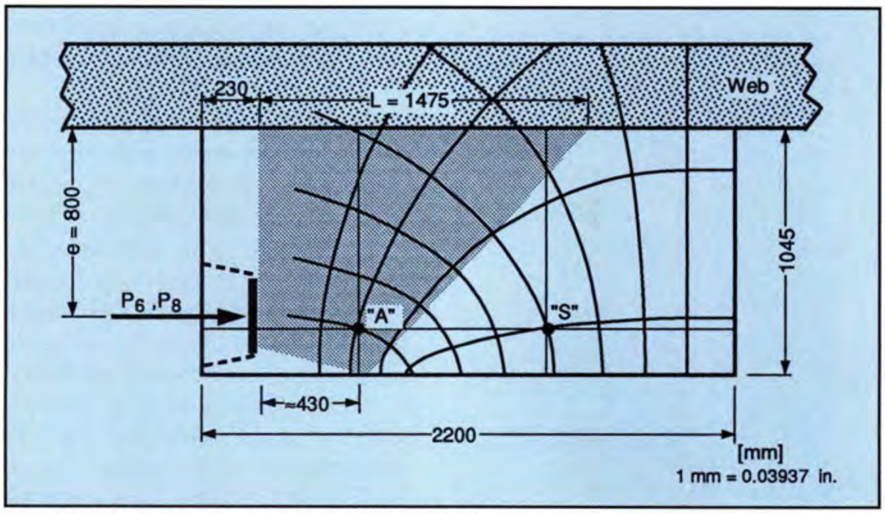

Fig. 19. Stress transfer in an anchorage block.

whereas residual temperatures in some extreme fibers could generate tensile stresses in the order of 4 MPa (600 psi). The corresponding values found at Section 7 were slightly less than at Section 1.

In this study,[17] design thermal gradients are proposed for the Grand-Mère Bridge. However, they cannot yet be generalized to other structures of the same kind built elsewhere in North America. More research is being carried out on this subject. Nevertheless, it is recommended, in the design process of major box girder bridges, to carry out a steady-state thermal analysis of the cross section with the anticipated extreme temperature conditions. Such an analysis can be done easily with advanced computer programs such as FETAB[18] or FETAB-2.[16] Thermal stresses are not secondary effects and their importance suggests they should be considered in an appropriate manner, especially for box girder bridges.

CONCLUSIONS AND RECOMMENDATIONS

The experience gained in field monitoring can be applied to any type of concrete structure — bridges, buildings or dams. The analytical studies[12,15,16,17] that followed the experimental program improved the knowledge of the behavior of this segmental bridge. The major findings, applicable to both post-tensioned and precast, prestressed concrete bridges, are summarized here:

1. Fast curing adhesive for electrical strain gauges is recommended in any field testing program.

2. Surface vibrating wire gauges are reliable and accurate strain-measuring devices. Their use is recommended for both short- and long-term monitoring programs for several reasons: their accuracy, the possibility of remote automatic data acquisition without wire length problems, a gauge length well adapted to measurement on concrete, and their stability over very long periods.

3. Local thermal gradients are better measured with a minimum of four to five thermocouples used through the thickness of flanges and webs. Global vertical thermal gradients vary rapidly

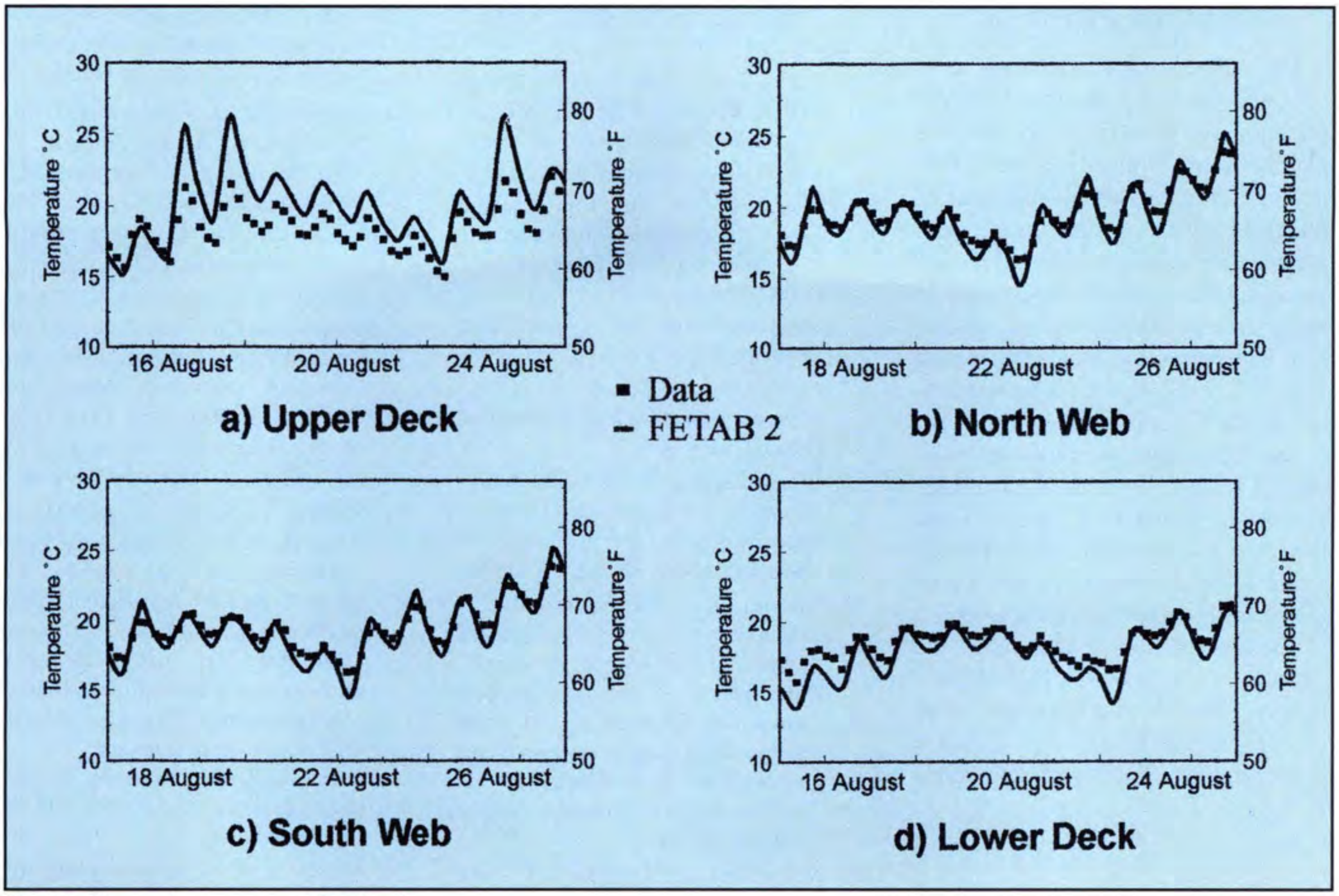

Fig. 20. Thermal response at Section 7.

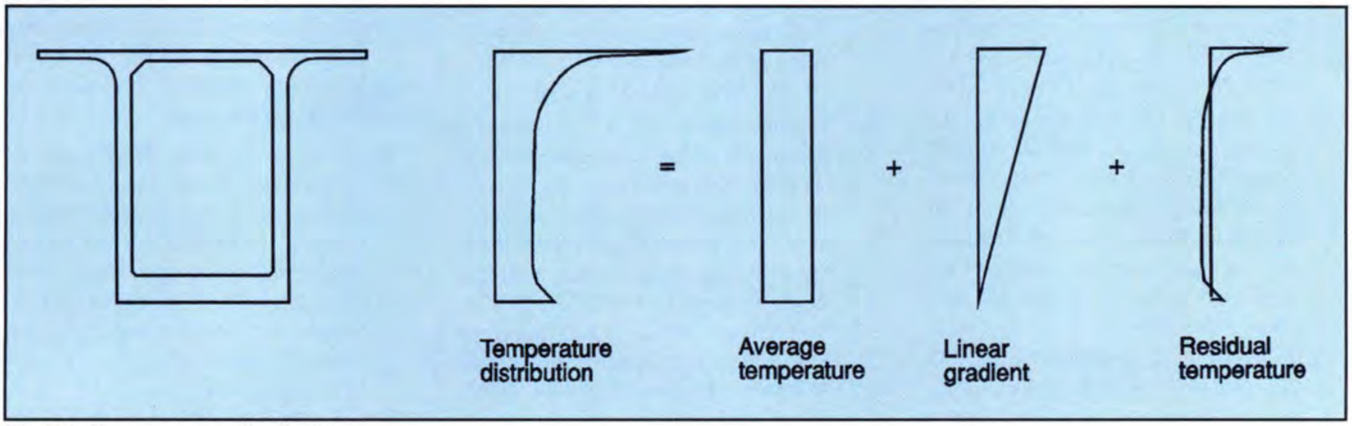

Fig. 21. Temperature distribution.

from the top fiber through the upper region of webs. Closely spaced thermocouples are recommended in these regions.

4. Redundancy in measurements and measuring devices at a given section is strongly advised. It is preferable to have a few fully instrumented sections rather than many sections with few instruments.

5. Strengthening design should account for friction at bearings in establishing the prestressing level. A friction coefficient of 6 percent was measured for Teflon bearings in this project.

6. The transfer of the prestressing force from the prestressing blocks to the webs occurs rapidly so the anchorage blocks could have been reduced safely to half of their size. However, the diaphragms are essential in reducing, as much as possible, the introduction of local bending moments in the webs. Further studies on these components have just been initiated.

7. Thermal gradients were more pronounced than originally anticipated in the design for strengthening. They were identified as the most probable cause of distress observed in the bridge. For major prestressed concrete box girder bridges, it would be advisable to carry out a steady-state thermal analysis of bridge sections. This could be done easily using advanced finite element programs.

ACKNOWLEDGMENT

The authors would like to acknowledge the Québec Ministry of Transportation and its officials for their financial support and interest in this research project. The collaboration of the QMT Bridge Testing Branch and Shawinigan District is also greatly appreciated. The authors would like to recognize the excellent work, leadership and professionalism of Stéphane Tremblay, in charge of the experimental aspects of the project.

The collaboration of the undergraduate and graduate students of Laval University and Sherbrooke University and the support of the technical staff of the École Polytechnique Structural Laboratory are gratefully acknowledged.

The authors also acknowledge the financial support of the Natural Science and Engineering Research Council of Canada and the Québec Fund for the Promotion of Research (Le Fonds FCAR).

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