PROTOTYPE
FACULTY OF ENGINEERING AND APPLIED SCIENCE
Journal of Undergraduate Engineering Research and Scholarship

PT-2013: Coastal and Ocean Engineering ENGI.8751 Undergraduate Student Forum
Faculty of Engineering and Applied Science, Memorial University, St. john's, NL, Canada March, 2013

Paper Code. (PT-2013 -Doyle)

Field Monitoring of Ice Forces, Temperature Effects and Deformations on the Confederation Bridge

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ABSTRACT

The Confederation Bridge was built to provide a highway traffic link across the Northumberland Strait between Cape Tormentine, New Brunswick, and Borden, Prince Edward Island. It is currently the world's longest prestressed concrete box girder bridge built over salt water, consisting of 45 main spans of 250 meters each and a 100 year design life. Due to the design criteria of the bridge it is not currently covered by any engineering code or standard in the world. It is for this reason that a comprehensive monitoring program is necessary to study the behaviour of the bridge under initially assumed loadings.

Several monitoring programs aim to determine the performance of the bridge under temperature effects, short and long term deformations, and ice forces as well as to gain information that engineers currently lack in these areas of design. This report will outline the necessary measurement equipment, and they're placement required to acquire this data.

The monitored data received from the research results will also be very valuable to engineers with respect to the design and construction of other complex long-span bridges and structures in the future. The information provided from this research will be used in the improvement of computer modeling and simulation, as well as contributing to the development of new design standards and guidelines for long-span bridges.

1 INTRODUCTION

The Confederation Bride was completed in 1997 and provided a much needed traffic link across the Northumberland Strait in Eastern Canada. More specifically, the bridge connects Borden, Prince Edward Island, with Cape Tormentine, New Brunswick. Currently, the Confederation Bridge is the world's longest continuous prestressed concrete box girder bridge built over salt water. Due to its long span and required design life of 100 years (twice as long as expected of a typical structure), the bridges design is not governed by any specific code or standard in the world. Also, the bridge is expected to operate under extreme environmental conditions. The location of the bridge can be seen below in Figure 1.

Considering the long design life and harsh environmental conditions expected, it was decided that a complete and detailed understanding of the bridges behaviour would be necessary to review and accurately predict the bridges performance. To achieve this goal a joint monitoring and research partnership was created, including membership of Canadian Universities, Strait Crossing Development Inc. (SCDI), and Public Works and Government Services Canada (PWGSC).

Using many different methods of Instrumentation, the following environmental loads and effects were required to be monitored to review the short and long term performance of the bridge: short and long term deformation, temperature effects, and ice forces.

Another goal of this monitoring and research partnership was to verify design assumptions related to load and resistance parameters used in initial design and analyses of the bridge. This data will also be useful in the development of a comprehensive database on the bridges performance, assisting in the creation of effective maintenance and management strategies.

This report will outline the types of instrumentation used for each loading effect, as well as their placement on the structure. Insight into the research required on each of these effects will also be included.

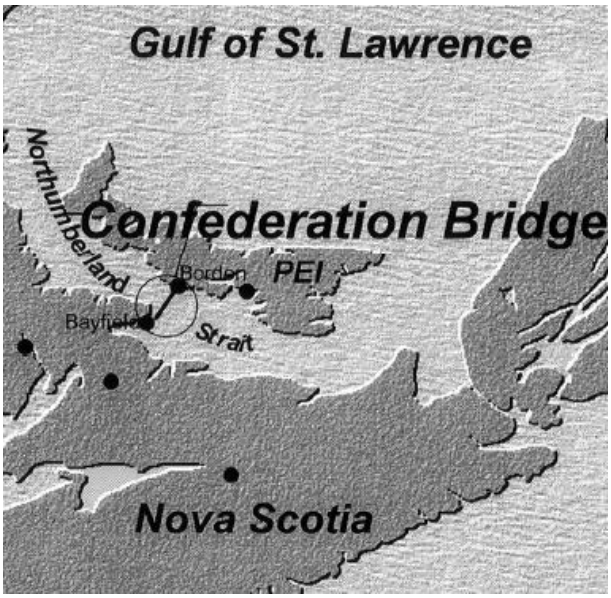

Figure 1: Location of The Confederation Bridge

2 CONFEDERATION BRIDGE DESIGN

The Confederation Bridge is currently the world's longest continuous prestressed concrete box girder bridge built over salt water. The bridge consists of 11 approach spans and 45 main spans, each at a typical height above sea level of 40m (60m at the navigation span). The bridge has a total length of 12.9 km. A cross-section of the bridges deck structure reveals a single prestressed concrete box of 11m width and a depth that varies with each span. The bridge pier designs specify a hollow shaft with an octagonal shape for the upper portion, a conical ice shield at the midpoint, and a conical shell with a ring shaped footing on the seabed. Externally and Internally bonded post tensioned prestressing tendons were used in the construction of the bridge. For analysis, two consecutive spans, one drop in span and one rigid frame span, as well as four piers were instrumented for monitoring.

3 INSTRUMENTATION

In order to properly monitor all of the desired loading effects a detailed instrumentation scheme was required. This instrumentation scheme will monitor both short and long term performance and behaviour of the bridge structure. The loading effects to be monitored include, short and long term deformation, temperature effects, and ice forces. As with any instrumentation scheme the primary design concern is the required high degree of reliability in the system operation and data collection. To obtain correlated data and minimize the cost of monitoring the instrumentation was installed in the same two consecutive spans, one rigid span and one drop-in span, at the deep sea level of the strait.

3.1 Short and Long Term Deformations

The factors that influence short and long term deformation include the change of modulus of elasticity with age, creep and shrinkage of concrete, relaxation of prestressed steel, and foundation movements. Usually these factors have been accounted for in earlier analyses and design, however due to the unique nature of the confederation bridge the initially assumed values will need to be verified. To verify the assumptions the received monitored data will be compared with the recommendations in the various codes that apply. The data for this comparison will be yielded from concrete cylinder tests and instrumentation of the structure.

A test for the change in modulus of elasticity (Ec) and strength of concrete (fc) is necessary as both of these factors are known to vary significantly with time. These tests are performed using three arbitrary concrete casts. The casts will consist of 3 x 6 cylinders, which will be stored and tested at six selected ages within the range of interest for the confederation bridge. Through these tests expressions for Ec(t) and fc(t) at different values of time (t) can be determined and used in the verification of initially assumed values.

The test for creep and shrinkage of the concrete will also be performed on three arbitrarily chosen concrete casts. The concrete casts will also be subject to the same weather and curing of the prefabricated bridge elements. These concrete cylinders will be loaded to determine the shrinkage plus creep values. The device used for this test can be seen on the following page in Figure 2.

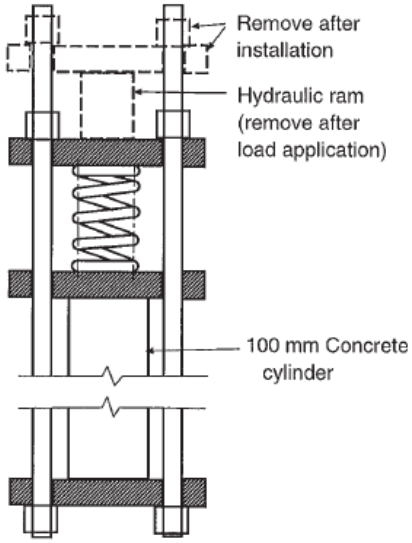

Figure 2: Device used for creep and shrinkage tests

Other non-loaded specimens of the same number will also be monitored for their shrinkage values for comparison.

Tests for the steel relaxation are also performed using three samples of steel; which will be taken from the three different prestressing stages subjected to three levels of initial stress. The tests will be performed in a temperature controlled environment. The loading device used for testing can be seen in Figure 3 below.

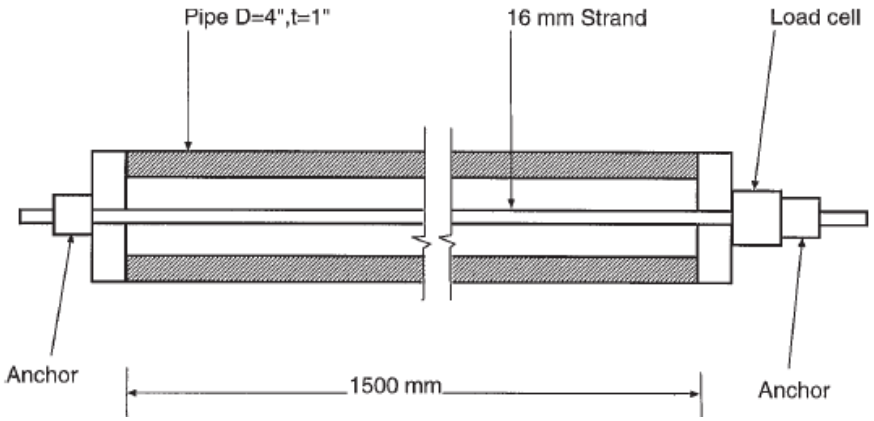

Figure 3: Steel Relaxation Test Device

The foundation settlements are determined by measuring the displacements at the junction of the pier base with the pier shaft (at 4m sea level). The vertical displacement is also measured and compared with onshore stable benchmarks by precise leveling technique.

Monitoring the displacement of the superstructure is performed by precise levelling to measure the vertical deflections of 17 benchmarks within the box girder. Auto reflection is used to determine horizontal displacement at 4 points located at 11 different cross sections. Mechanical strain gauges and vibrating wire gauges will also be used and installed at specific locations, which are outlined in Figure 4, on the following page. These will measure strain in the bridge at crucial points.

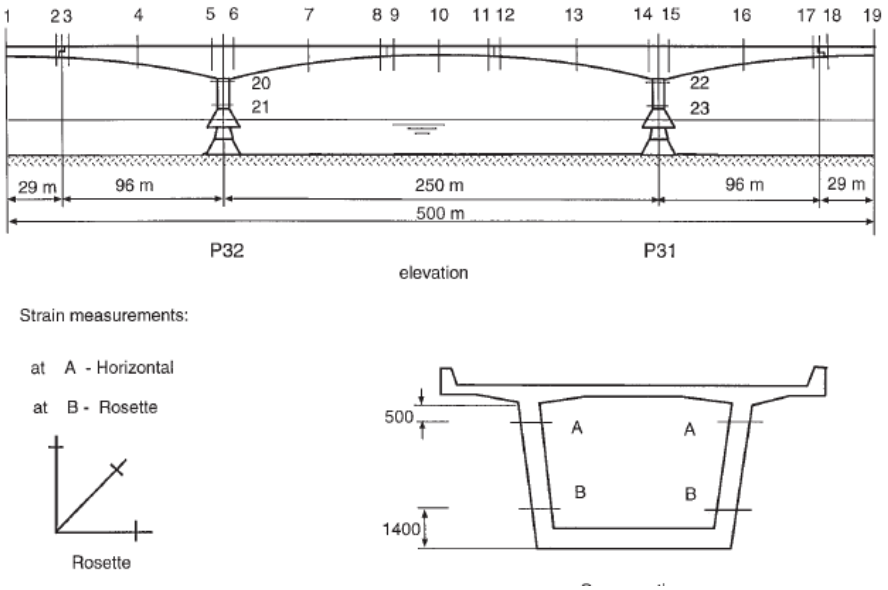

Figure 4: Strain Gauge Locations

3.2 Temperature Effects

The monitoring of temperature effects and how they will affect a structure is particularly important to the Confederation Bridge, as its stiff piers will resist temperature deformations. Therefore information on the daily and seasonal temperature variations are crucial. The primary concern for the monitoring of the temperature changes within the structure is the effective prediction of thermal cracking and thermal stresses, as well as determining their importance as a design issue.

For concrete bridges the main source of temperature change during construction is the heat of hydration, which is caused by the chemical reaction of cement and water. The resulting rise in temperature is known to cause non-uniform cooling, leading to a decrease in strength, as well as high thermal stresses, leading to potential cracks. Therefore it is necessary to monitor the bridge during construction for maximum temperature as well as maximum temperature gradient, especially where high and high performance concrete is used, as they yield the highest heat of hydration values.

The temperature effects are monitored using thermocouples placed at seven sections along the bridge. These sections can be seen below in Figure 5.

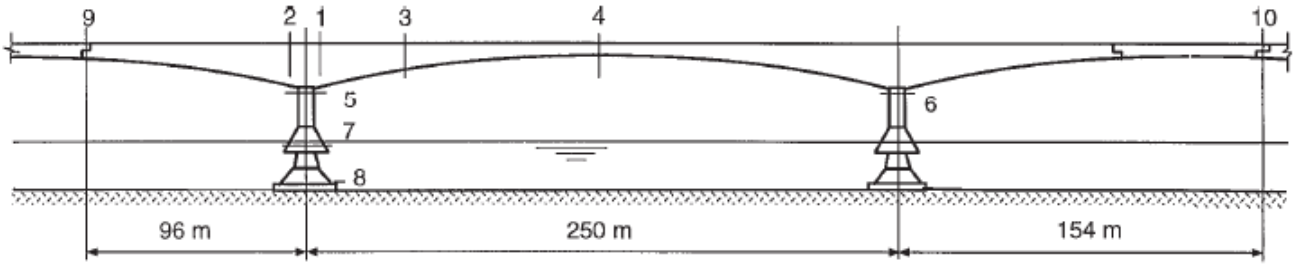

Figure 5: Areas of Interest for Temperature Effects

At each of these sections thermocouples are arranged in the thickness direction along with vibrating wire gauges to monitor the contribution to strain distribution. A Typical arrangement for the

thermocouples and strain gauges can be seen below in Figure 6. This is an example of the arrangement expected in the box girder, sections 1 and 2.

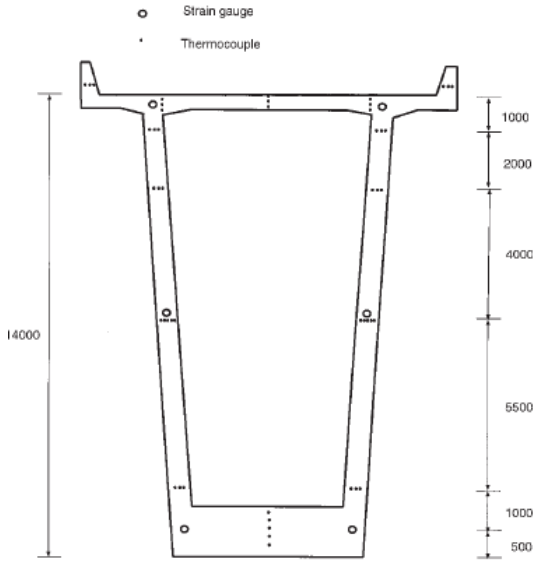

Figure 6: Thermocouple and Strain Gauge Placement in Concrete Box Girder

For a complete analysis of the temperature effects on the bridge, the changes due to solar radiation were required to be recorded. This information is collected by pyranometers placed strategically throughout the bridge. The placement is as follows, one above the top surface of the bridge and one on each web of the box girder. Thermocouples will also be added to measure the ambient temperature, as well as the temperature along the inside of the box girder.

Testing in the laboratory will be required to determine the specific thermal properties of the concrete used in the bridge. These thermal properties are themselves required to determine the thermal stresses acting in the bridge from the measured values of temperature and strain. The tests to be performed will be relaxation tests, preformed by subjecting axially restrained concrete prisms to varying degrees of temperature change.

3.3 Ice Forces

Due to the Northumberland Strait being ice covered for 4 months every winter it is necessary to monitor the effects of ice loading on the bridge. The floe size expected in the area can reach diameters of up to 3 to 4 km, with ice thicknesses of up to 1 m. However the embedded ridges can have keel depths of up to 18 m. The interaction of the ice with the conical ice shield causes the ice to slide up the shield face. This will result in a bending moment within the ice sheet causing it to fail in flexure. These ice pieces are then continually pushed up the shields face by the advance of the ice floe where they fall down eventually leading to large amounts of ice debris around the piers. This leads to further issues if the embedded ridge of the ice floe is to interact with the bridge pier, as the accumulated broken ice in the keel and sail will also need to clear the pier, adding to the total expected load.

Considering the complexity of the ice pier interactions, there are many theories for how to properly determine the expected design loads. As a result of this, the monitoring program will measure both local and global ice forces acting on the bridge piers, as well as prevailing ice conditions.

The ice forces monitoring program will consist of three different components; the direct measurement of local ice loads; the indirect measurement of global ice loads; and the ice interaction kinematics, and prevailing ice conditions.

The measurement of the global ice load is determined indirectly as there is no technology currently available that could accurately measure the total load with the bridge piers design. Therefore the global load is determined by measuring the structural response of the two instrumented piers. This response is measured using two biaxial tiltmeters placed at two locations within the shafts of the pier. To supplement this measurement and provide dynamic resolution of the response, these biaxial tiltmeters are coupled with accelerometers, which will measure the corresponding lateral accelerations. The combination of these two devices will result in the ability to measure ice forces as low as 30 kN with frequencies to 3 Hz.

The local ice loads are more easily measured, requiring 56 m^2 of ice load panels to be installedon a pier. These panels are thin, double-walled panels that contain internally strain gauged load sensors. These sensorscan measure loads on areas of 0.25 m^2. The panels are installed with the majority on the conical ice shield (40 m^2) with the remaining installed on the pier barrel below the cone (16 m^2). The objective of the lower panels is to measure the loads caused by interactions with ridge keels, while the cone panels measure loads from the sheet ice. The data from these panels is used to determine the distribution of ice loads on the pier, which can be used to validate ice load algorithms, or help in the development of new ice load algorithms. The placement of the ice load panels can be seen on the following page in Figure 7.

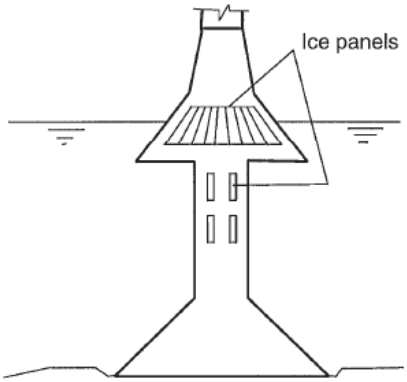

Figure 7: Ice Panel Placement

The observation system that is in place consists of two sonar devices, a laser, and four time lapse video cameras. One of the video cameras is used to record the prevailing ice, while the remaining three cameras record the kinematics of the ice interacting with the two instrumented piers. These cameras are all linked by a digital multiplexer to a 24 hr time lapse recorder. The sonar are placed on the seabed, 40 m west of one of the instrumented piers. These sonar are pointed up, and used to measure the keel depth of the ridges interacting with the lower part of the bridge pier. The laser is installed such that it measures the freeboard of the ice at the same location that the sonar are measuring the draft.

The accuracy of the indirect global load measurement system is dependent on reliable observations of the structural response of the instrumented piers. However, in determining the actual forces, the transfer functions relating the measured responses to the applied force are required. These have been quantified using the following methods: analysis of deformations during construction, numerical modeling, and a full scale pull test on one of the instrumented piers. The pull test involved the application of 1.5 MN by a Canadian Coast Guard vessel (Terry Fox), which added to the reliability of the calibration of the ice load measurement system.

4 DATA ACQUISITION

In order to acquire, process and store all the data to be received from the monitoring components, an advanced data acquisition system was required. The current system consists of many low and high speed data loggers with a total of 750 channels. These data loggers are then connected to the computer system using fibre optic cables. The sensors for ice forces are connected to the high speed data loggers, while the deformation and temperatures effects are handled by the low speed system.

These data loggers have been programmed to operate in two very distinct modes; time-averaged and event triggered burst mode. During time-averaged mode the data logger will store data only for time averaged statistical data (ex. mean, variance, min/max) over a specified length of time. It is only when a threshold value in one of the preselected set of triggering sensors (ex. strain, load, acceleration) is exceeded during a significant event does the event triggered burst mode activate. In this mode the data logger will collect data at an increased rate and store time history data for detailed analysis of the bridges structural response to the event. These events could be cause by storms, the impact of a large ice floe, an earthquake, or a heavy vehicle.

5 CONCLUSION

With the application of this detailed monitoring program with respect to ice forces, temperature effects, and short and long term deformations, crucial information on the behaviour and performance of the Confederation Bridge can be recovered. This information can also be used to either validate or invalidate any assumptions made during its design, as well as help with the development of strategic maintenance and management strategies.

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