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Safety Assessment of Brooklyn Bridge Masonry Vaults Based on Real Time Monitoring and Laboratory Tests

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ABSTRACT: The Brooklyn Bridge, one of the oldest suspension bridges in the United States, was completed in 1883. Spanning over the Hudson River, it connects the New York City boroughs of Manhattan and Brooklyn. The approach structure of the bridge includes several brick masonry vaults. The two largest vaults have longitudinal cracks at the vault crest. An all fiber optic system was employed to monitor the performance of the structure under ambient loadings. Fiber optic crack sensors, tiltmeters, accelerometers and displacement sensors were installed on the vaults and walls of the vault structure. Sensor readings, recorded for a year, were used to monitor the cracks openings, wall tilt and temperature change of the structure. Concurrently, a scaled model of the masonry vault was tested in the laboratory to assess the crack formation and deflection of the structure. Fiber optic crack sensors similar to those mounted on the real structure were used to measure the crack opening of the scaled model. Vertical deflection of the arch model, measured by a Laser Doppler Vibrometer, was employed to tune the finite element model of the arch. In this article, some of the field data are presented and discussed in detail. The laboratory test plan and instrumentation are also summarized. Further studies are being carried out to relate the laboratory test results and field data with the aim of service life estimation and safety assessment of the structure.

1 INTRODUCTION

Health monitoring of the civil infrastructures has attracted much attention in recent years. Condition evaluation of structures based on routine visual inspections does not allow precise assessment of the structural safety. This brings an urgent need to continuously monitor the response of the structure under service loading (Ansari 2007). The Brooklyn Bridge, connecting Manhattan to Brooklyn, opened to the public in 1883. It spans over Hudson River with the total length of 1825m. With its monumental masonry towers supporting a unique hybrid suspension/ cable-stay system, the bridge immediately imposed itself as the most distinctive city landmark. The approach structures on both Brooklyn and Manhattan sides of the bridge consist of several brick masonry vaults. The approach span on the Manhattan side is an impressive 476.1m in length; nearly as long as the main span (Abrams Inc. 1983). The two largest vault spans on the Manhattan side, shown in figure 1, are the subject of this study. The vaults are semicircular with span lengths of 10m and 10.4m. There is a steel truss structure to the west of these vaults (left side in Figure 1) and on the east is the bridge abutment. The bridge abutment is essentially a masonry counterweight constructed on top of the steel anchorage for the main bridge cables. The west vault has slight skew as it tapers toward the north end. The thickness of the masonry forming the vault is 0.91m at the ends of the vault and at the center drops to 0.61m. The fill above the vault is granite and rubble stone fill without mortar.

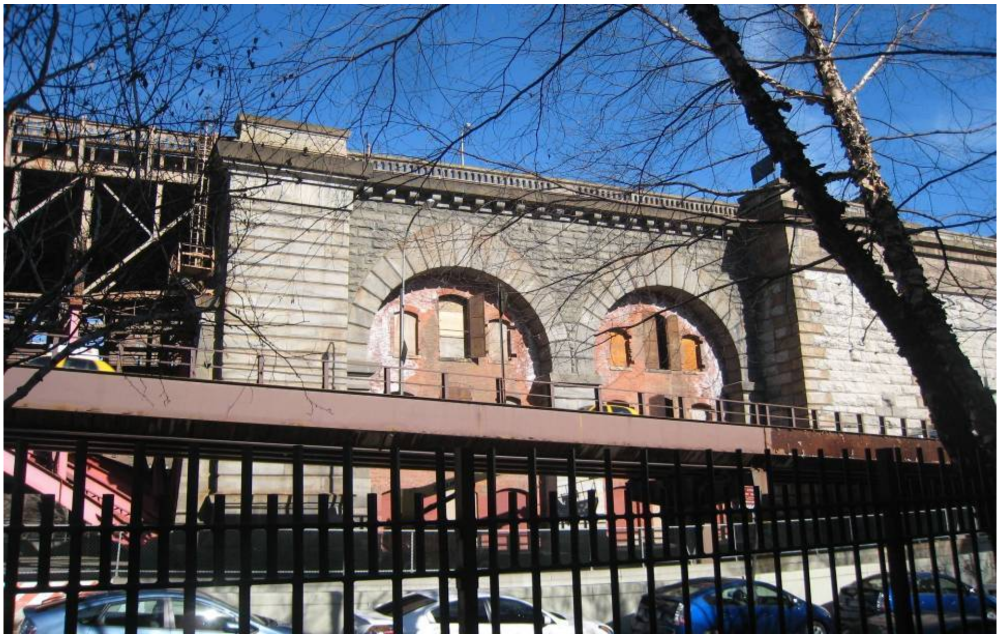

Figure 1. Approach Structure of the Brooklyn Bridge.

Longitudinal cracks along the length of both of vaults were observed during regularly scheduled bridge inspections. These cracks have been documented in bridge inspection reports and there are spray paint markings noting their existence in 1996. The vertical masonry walls supporting the vaults are also cracked. Some of the wall cracks could be traced continuously down to the exposed portion of the foundation. In the following, the feasibility of using the developed fiber optic sensors for structural health monitoring of masonry vaults, via monitoring the crack openings, wall tilting and temperature fluctuations within the structure is investigated. Recorded sensors readings were employed to evaluate the global behavior of the structure under service loading. Laboratory test plans and instrumentation are briefly described. Further studies are being carried out to assess the safety of the structure based on field data and laboratory test results.

2 FIELD INSTRUMENTATION AND SENSOR LOCATIONS

A real time monitoring program designed for the approach structure included fiber optic sensors, a data acquisition system, and wireless internet for remote communication. Fiber optic sensors have the advantages of immunity to electrical and electromagnetic interferences and the capability of serial multiplexing. They have a high resolution with limited noise and are relatively small in size (Majumder et. al. 2008). Fiber optic sensors including crack sensors, tiltmeters, displacement sensors, temperature sensors, and accelerometers were strategically mounted on the approach structure as shown in Figures 2 and 3. Fiber optic crack sensors, designed and fabricated at University of Illinois at Chicago, were installed on the vaults of the structure as well as the walls. The crack sensors have a gauge capacity to measure a wide range of openings (20 microns to 10 mm range).

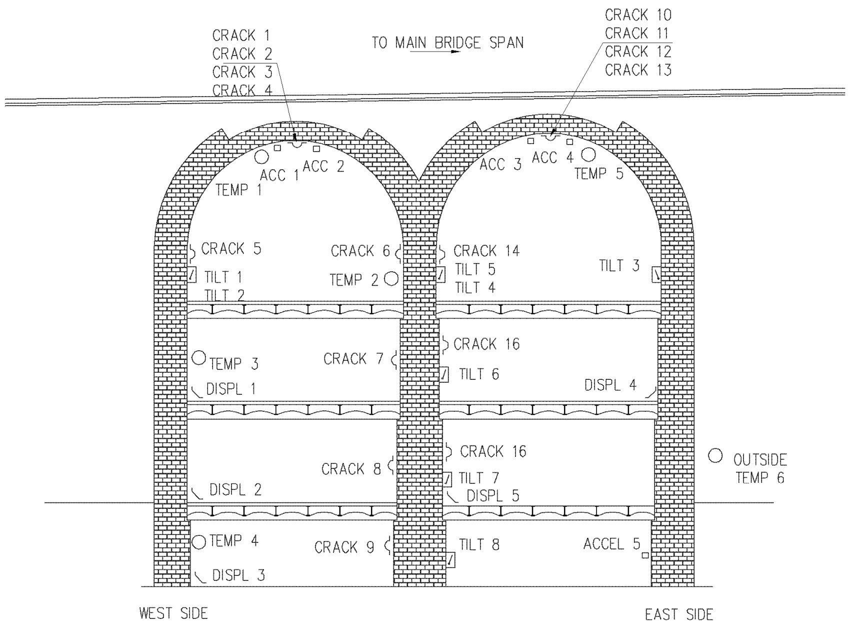

Figure 2. Sensors Locations (Section View, Not to Scale).

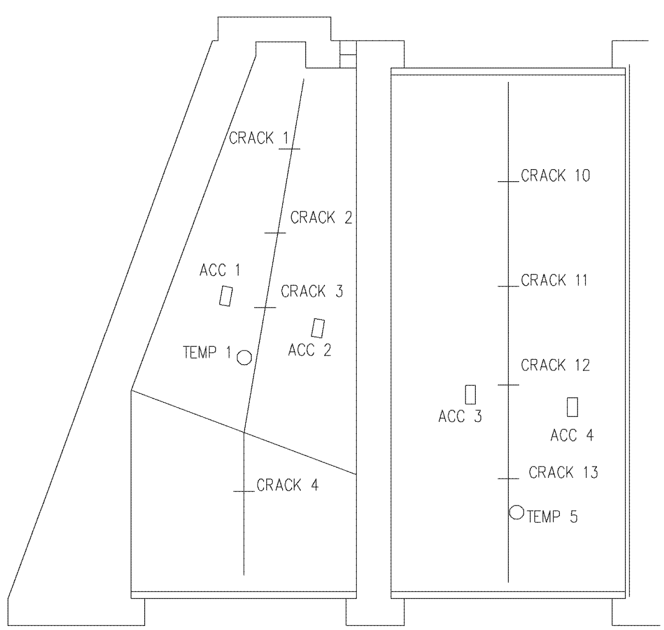

Figure 3. Sensors Locations (Plan View of Arches, East direction is to the right). Crack sensors placed along longitudinal crack at the peak of each arch.

Each of the crack sensors was individually calibrated in the laboratory prior to installation. Displacement sensors were similar to crack sensors but modified to a quarter-circle shape in order to allow relative displacement to be measured between two perpendicular surfaces. Displacement sensors were attached to the wall and floor. Fiber optic accelerometers (Talebinejad et al. 2009) were installed on each side of the vault cracks to record a possible relative vibration difference. An accelerometer was also mounted in the basement adjacent to the bridge abutment to detect any significant vibration due to adjacent cable anchorage. Temperature sensors were mounted at locations throughout the inside of the building. The data from these sensors were used to compensate any recorded changes in the sensors that were due to temperature effects. Tiltmeter sensors were mounted on the walls of the structure to measure wall tilting. They were located to detect if there was any spread of the arches or the settlement of the supports. The tiltmeters had an internal temperature compensation capability and an accuracy of +/- 0.01 degrees. The fiber optic sensors are controlled by a computer and interrogator system that is housed in a metal cabinet within the vault structure. Electrical power was available at the bridge site. A cellular modem was used for internet access. However, an external antenna with a high performance coaxial cable was used to improve the signal performance and connection stability. For continuous structural health monitoring, the on-site computer constantly reads data from the fiber optic interrogator. Due to hard drive size limits, the real time data were not continuously saved to the on-site computer. Instead, the sensor data was recorded at various selected time intervals and saved to the on-site computer. Then, the data sets were downloaded via an FTP server for further detailed analysis. Data sets were recorded and downloaded to analyze daily, weekly and monthly changes.

3 FIELD DATA ANALYSIS

Data recorded at regular intervals showed little change during a day. Figure 4 shows typical data for the crack sensor #3 recorded at different time on April, 4^{th} 2009. Sensor readings showed insignificant change during the day. The maximum daily change was approximately ± 25 micrometer.

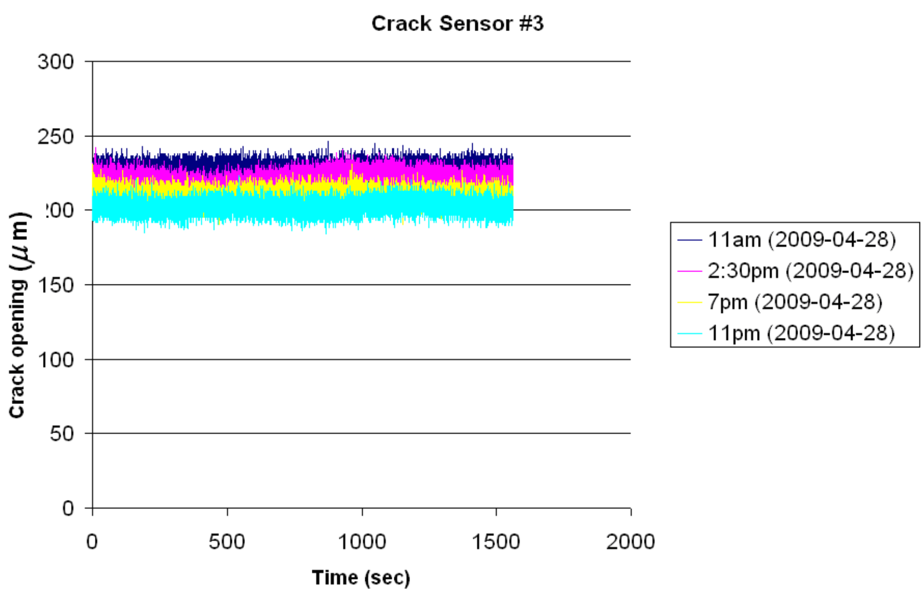

Figure 4. Daily Recorded Data for Crack Sensor 3.

For the weekly analysis, data were recorded on five days starting from Monday, April 27, 2009 and ending on Saturday, May 01, 2009 as shown in figure 5. Data were recorded at the same time each day, between 6pm and 8pm. The maximum difference between readings was approximately ±27 micrometer.

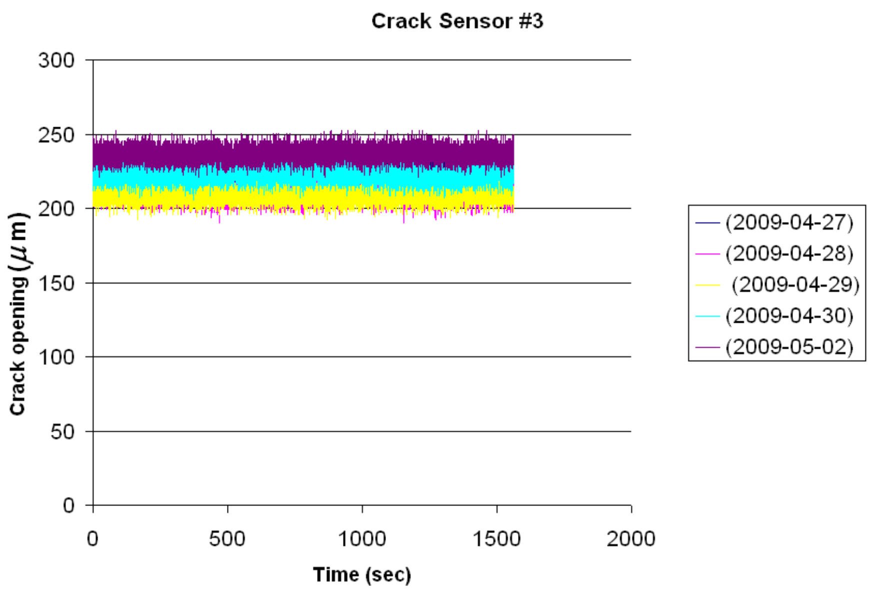

Figure 5. Weekly Recorded Data for Crack Sensor 3.

As there was little change in the short term, i.e. daily and weekly, monitoring of the cracks, the focus shifted to the long term performance of the crack openings. Monthly analysis of the sensor data was performed on the data to show the longer term history of the crack movements. The most critical sensors were those specifically monitoring the longitudinal cracks along the vaults, namely crack sensors #1, #2, #3, #4, #10, #11, #12, and #13. The tiltmeters on the third floor were also of particular interest as a way of monitoring the support conditions of the vaults. Figures 6 and 7 show recorded data for crack sensors from March 2009 until May 2010. The data were offset to zero for March 09, 2009 for the west vault and July 27, 2009 for the east vault as the reference points. The later reference point was used for the east vault due to an earlier sensor error.

Crack sensor #3 and # 11 mounted on the middle of east and west vault show more movement than those closer to the spandrel walls. This was likely due to the additional stiffness provided by the spandrel walls at the ends of the vaults. Figure 8 shows data recorded by temperature sensors # 1 and # 5 mounted on the east and west vault respectively. Comparing Figure 8 and Figures 6 and 7, crack sensor #3 follows the same trend as temperature sensor #1 while crack sensor #11 shows an inverse trend.

The fiber optic accelerometers showed negligible amounts of vibration in both the short term and long term. The masonry vaults and supporting walls form a very rigid structure. No significant or differential vibrations on opposing sides of the longitudinal vault cracks were

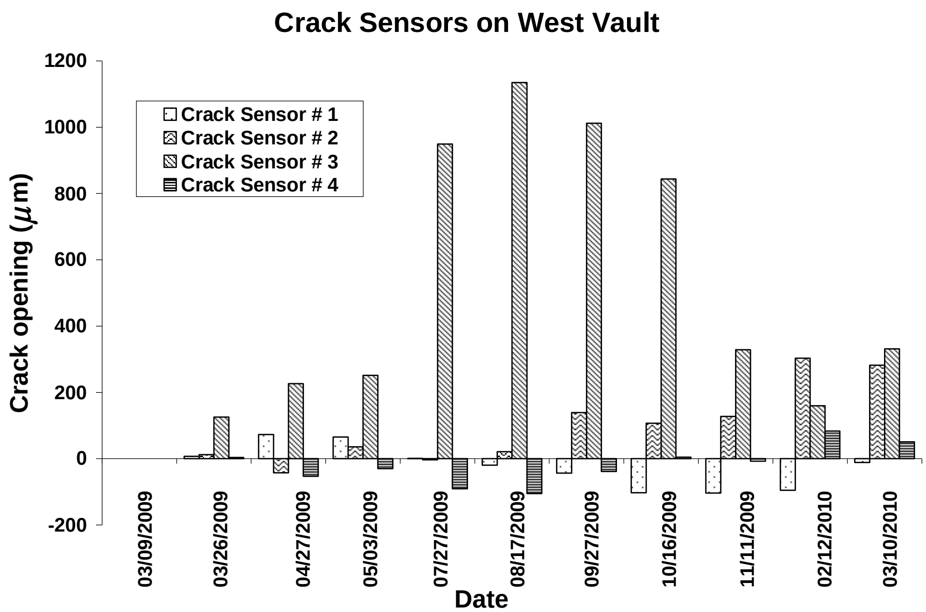

Figure 6. Recorded Data for Crack Sensors on West Vault.

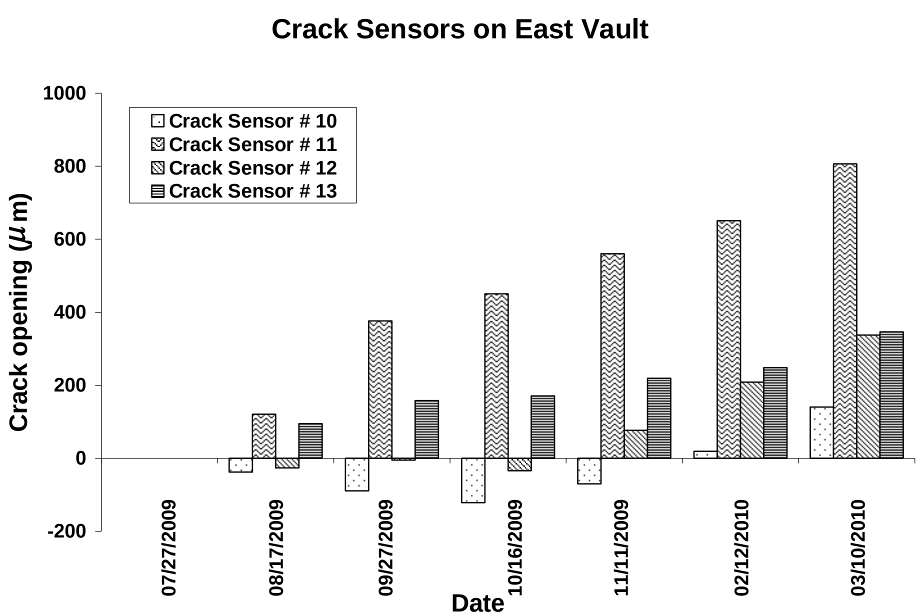

Figure 7. Recorded Data for Crack Sensors on East Vault.

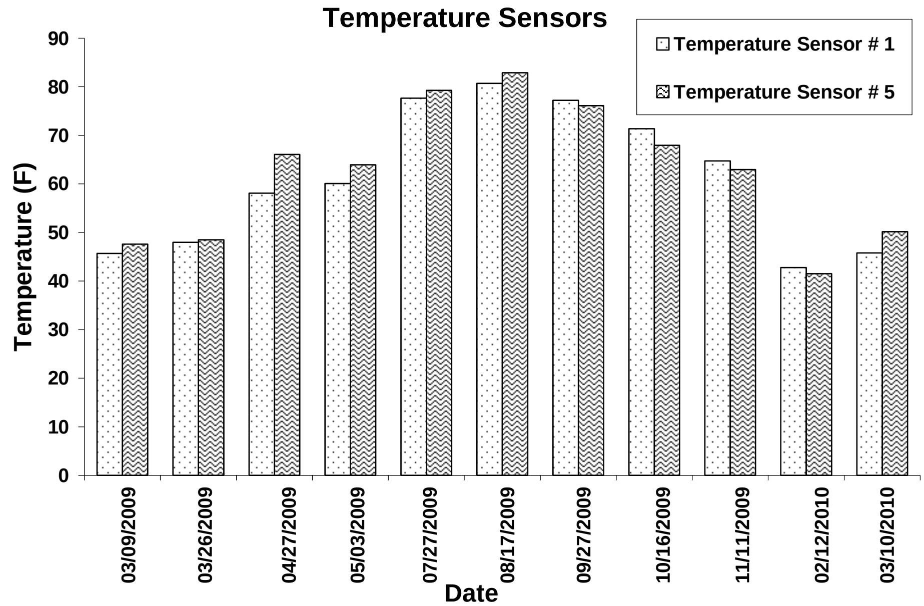

Figure 8. Recorded Data for Temperature Sensors.

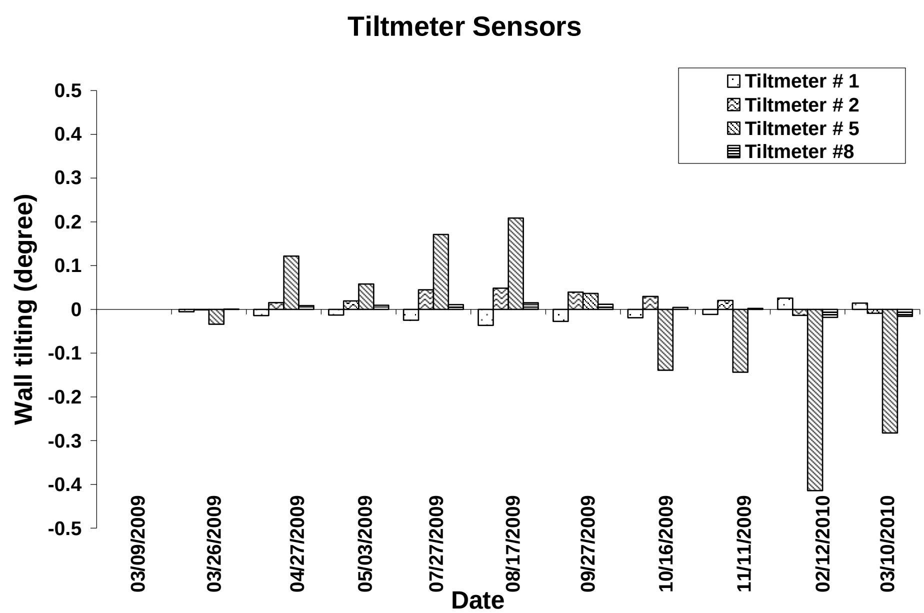

Figure 9. Recorded Data for Tiltmeter Sensors.

occurring. Figure 9 shows recorded data for some of tiltmeter sensors. Tiltmeter #5, located directly under the vaults, shows the most movement. The wall tilt recorded by tiltmeter #5 tends to follow the temperature fluctuations. The maximum and minimum peaks of tiltmeter 5 correspond to the temperature peaks. Thus the tilt can be attributed to thermal expansion and contraction in the vaults. Tiltmeters #1 and #2, located on the west wall of the third floor, show negligible activity. This wall is restrained on the outside edge by masonry counterforts supporting the steel trusses spanning over the adjacent roadway. In other words, the data confirm that this wall is rigidly constrained.

4 LABORATORY TESTS PLAN AND INSTRUMENTATION

Crack sensors mounted on the vault of the structure, particularly crack sensor # 3 and # 11, showed some movement in terms of crack opening. As a result, a limit should be set for the readings of the crack sensors to assure the safety of the structure in the future. In order to find a margin of safety for the structure, a set of laboratory tests was designed. The laboratory testing program comprised of testing a series of brick masonry arches, with 1.83 m spans subjected to horizontal displacements at the support. The thickness of the masonry arch was 0.2 m at the supports and 0.14 m at the crown. The arch was constructed on a wooden framework comprising a 7 mm-thick curved plywood sheet attached to the 12 mm-thick semicircular plywood sheet as shown in Figure 10.

The purpose of the test program was to monitor crack opening of the arch as well as arch deflection until the whole section was cracked. Fiber optic sensors similar to those mounted on the real structure were used to measure crack opening. Horizontal displacement of the support and resisting force were recorded by the MTS software. Laser Doppler Vibrometer was used to measure vertical deflection of the arch. Figure 11 shows the laboratory test set up and instrumentation. Further research is being carried out to set up a margin of safety for the structure based on laboratory test results and field data.

Figure 10. Wooden Frame for Masonry Arch Fabrication.

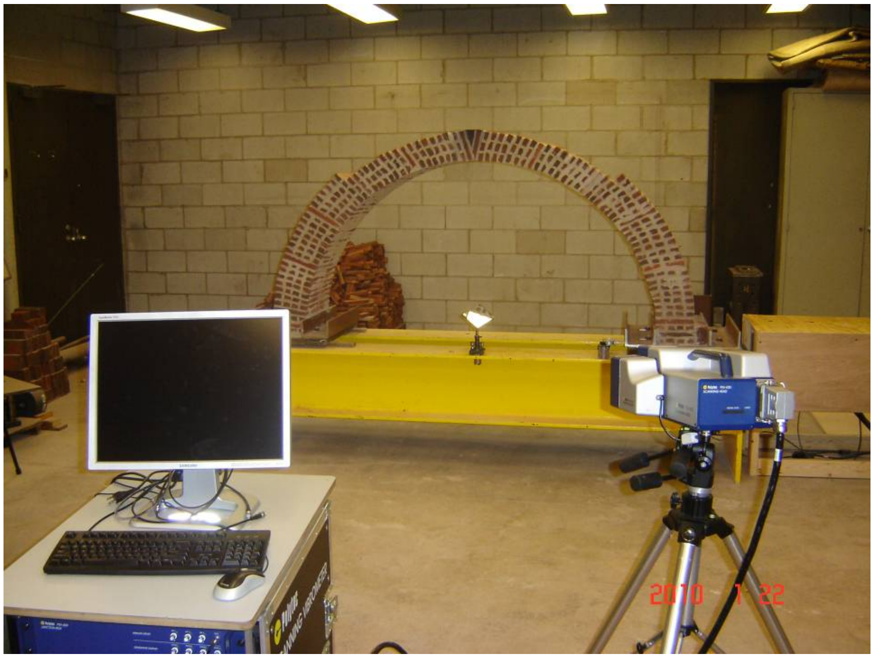

Figure 11. Laboratory Test Set Up.

5 CONCLUSIONS

A fiber optic system was employed to monitor the structural behavior of the Brooklyn Bridge approach structure. The monitoring set-up included fiber optic sensors, a data acquisition system, wireless modem and external antenna. Fiber optic crack sensors, displacement sensors, tiltmeters, accelerometers and temperature sensors were installed on the masonry vaults and walls of the structure. The crack sensors of greatest importance were those monitoring the longitudinal crack at the crest of each vault. These sensors showed negligible changes in the crack width over short periods of time such as days or weeks. However, there was a slight drift in the crack openings and wall tilting over a longer period of time namely a year. In general, crack sensors located on the middle of the vaults showed more activity in comparison to those mounted close to the ends. Tiltmeter sensors located adjacent to these crack sensors also showed more activity than other sensors mounted on the east and west walls of the structure. Visual inspections, preceding the sensor verification presented in this paper, were correct in establishing that the crack movement is primarily due to thermal expansion and contraction. The monitoring plan confirmed that the bridge is currently safe for the traveling public. However, a set of laboratory tests was designed to set a margin of safety for the structure. Several scaled models of the structure were fabricated and tested under support movement. The purpose was to monitor the crack formation and crack opening of the model until the whole section was cracked. This information along with field data is being analyzed to quantify the current damage of the structure and estimate its level of safety.

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