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MONITORING OF CFRP PRESTRESSED MASONRY WALLS

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Abstract

In July 2002, after a series of preliminary laboratory tests, two Carbon FRP (CFRP) prestressed masonry diaphragm retaining walls were constructed on the University of Calgary campus. A considerable amount of research has been carried out to study the behaviour of CFRP prestressing tendons in combination with masonry. New CFRP tendon anchors used in these walls were designed and tested in the Department of Civil Engineering. A number of sensors were installed in the walls to monitor their behaviour. Tendon strains, masonry strains, and temperatures have been monitored during the past year and a half.

The wall design and the long term monitoring program are briefly described. The results from the first year and a half of monitoring are also briefly discussed. The results from the first year of long term monitoring indicated that temperature effects and exposure to solar radiation were the most significant loading conditions for these walls. Thus, short-term continuous monitoring was conducted in order to gain a better understanding of these effects. The future of the monitoring program is also discussed.

Key Words

Masonry, Prestressed structures, Post-tensioning, Retaining walls, CFRP, Monitoring

1 Introduction

Fiber Reinforced Polymers (FRP) offer many advantages over traditional steel prestressing materials. These relatively new materials are light weight, have high strength, high durability and are corrosion free. These advantageous properties have driven many researchers around the world to investigate various applications for FRPs in different areas of civil engineering. For example, retrofitting, strengthening, seismic performance improvement, and reinforcing are some of applications of FRPs in masonry structures (Lissel and Gayevoy 2003).

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Laboratory testing has indicated that the behaviour of CFRP prestressed masonry structures can be predicted from fundamental engineering principles and that this structural form is very robust (Lissel 2001). In July 2002, two Carbon FRP (CFRP) post-tensioned masonry diaphragm retaining walls were constructed on the University of Calgary campus and prestressed using anchors developed at the Department of Civil Engineering (Sayed-Ahmed and Shrive 1998) as a demonstration project. One wall is straight, 3.2 m long, 2.3 m high and retains soil over its entire height. This wall is eccentrically prestressed. The other wall is 7.5 m long, 2.6 m high, has a 7.5 m radius curvature in plan, and retains soil only over half its height. This wall is concentrically prestressed. The location of the walls governs the environmental conditions that the walls are subjected to. The locations are shown in Figure 1 and the design and construction are described in more detail elsewhere (Lissel et al. 2002, Lissel and Shrive 2003). The straight wall retains soil on its south side over its entire height and remains in the shade all the time except in the early evening (~17:00) in the summer. The east and west ends of the wall butt up against the building and a wheelchair access ramp, respectively. The curved wall is subjected to more variable and interesting conditions. The north face is usually shaded throughout the winter and until early afternoon in the summer. The wall also retains soil on its south side, but only over half of its height, therefore the top of the wall is exposed to solar radiation effects earlier in the day when they are more intense. A number of sensors were installed in the walls to monitor their behaviour and since it was expected to see more "interesting" temperature effects in the curved wall, more strain-gauges and thermocouples were installed. The monitoring of the walls should provide insight into real structure behaviour under real loading conditions.

The data presented and discussed here is only for the larger, curved wall since it is exposed to more variable environmental conditions.

Figure 1 - View towards the southwest showing the location of both demonstration walls

2 Monitoring Programme

Strain gauges were installed on the masonry surfaces (only on the interior of the wall) and on the tendons. Both 30 mm and 100 mm strain gauges were installed, the former being placed on the brick surface only, the latter being attached to the surface such that two mortar joints were crossed. Since the masonry strain gauges were installed in a ¼ bridge configuration, temperature effects resulting from the difference in coefficients of thermal expansion (CTEs) are not automatically taken into account and therefore thermocouples were installed at every masonry strain gauge location so that these effects could be determined later. Tendon strain gauges were installed in a ½ bridge configuration so that the strains read are the strains in the tendons with no influence from the differing CTEs of the tendons and the gauges. Control masonry prisms instrumented with thermocouples and strain gauges were placed in the cavities of the walls to obtain readings from unloaded masonry.

In addition to strains and temperatures, humidity in the wall cavities is measured regularly by inserting a humidity probe into the cavities through the weep holes. The cavity humidity is usually 20-30% higher then ambient environmental humidity and varies from 60% to 95%, depending on the day's weather. The humidity seems to vary greatly even over relatively short periods of time and additional investigation is required to identify the reason for this instability and find some reasonable solution to this problem. Reflective targets have been placed on the north faces of the walls to monitor deflections with a total station. Measurements to date indicate that deflections are extremely small and within the error or the measuring equipment.

Strain and deflection readings taken prior to post-tensioning, prior to backfilling, and after backfilling, indicated that no significant loading effects could be detected. Once the walls were at service conditions it wasn't expected to see significant changes in the readings in the short term. Prestressing losses due to creep are expected to be observed over the long term and the reaction of the structures to the real environmental loads are also expected to be revealed over time. The data taking technique was improved during the first year to minimise errors in the measurement process.

The data collected in the first year revealed some of the expected effects due to temperature changes, however, some unexpected variations in the data were also observed. More detailed discussion of the first year's data is presented elsewhere (Gayevoy and Lissel 2003). New, short-term, continuous monitoring tests were planned and carried out based on the initial analysis of the data. The installation of a more advanced monitoring system that would allow more frequent (even continuous) readings over a longer term, and in all weather conditions, is being considered and should be implemented soon. Such a system should provide more informative data for further processing.

3 Long Term Data Collection

Following the prestressing and backfilling of the walls, readings were being taken about once a month in various weather conditions. After monitoring through the first winter season, the first data charts were reviewed. Figure 2 shows the variation in the masonry strains in the curved wall over the first year. Due to the infrequent nature of the readings, the lines do not necessarily indicate trends in the data but aid in clarity of the data. It was after this first year that the short term continuous monitoring was implemented and changes in the wiring prevented long term readings from being taken. For clarity, only data from a few representative gauges are shown, and the data has

also not been corrected to account for the initial strain (if this were done, many of the lines would appear on top of each other). In Figure 2, two peaks, abnormal relative to the other readings, were observed. A closer look at the data revealed that these peaks occurred for the gauges located on the south face in the upper, exposed portion of the wall. Figure 3 shows the temperatures corresponding to the locations of the gauges in Figure 2 and the ambient temperature. On the day where the peak is observed, there was a bit of a weather irregularity in that it was cloudy and snowing and Calgary is normally very sunny, even on cold days. Thus, on this particular day, the two gauges located on the south face were the only ones to respond to this weather irregularity because of the lack of solar radiation and their exposed location. Most of the readings were taken in the afternoon on clear-sky days when the masonry had been exposed to direct solar radiation resulting in quite warm temperatures compared to the ambient conditions (see Figure 3).

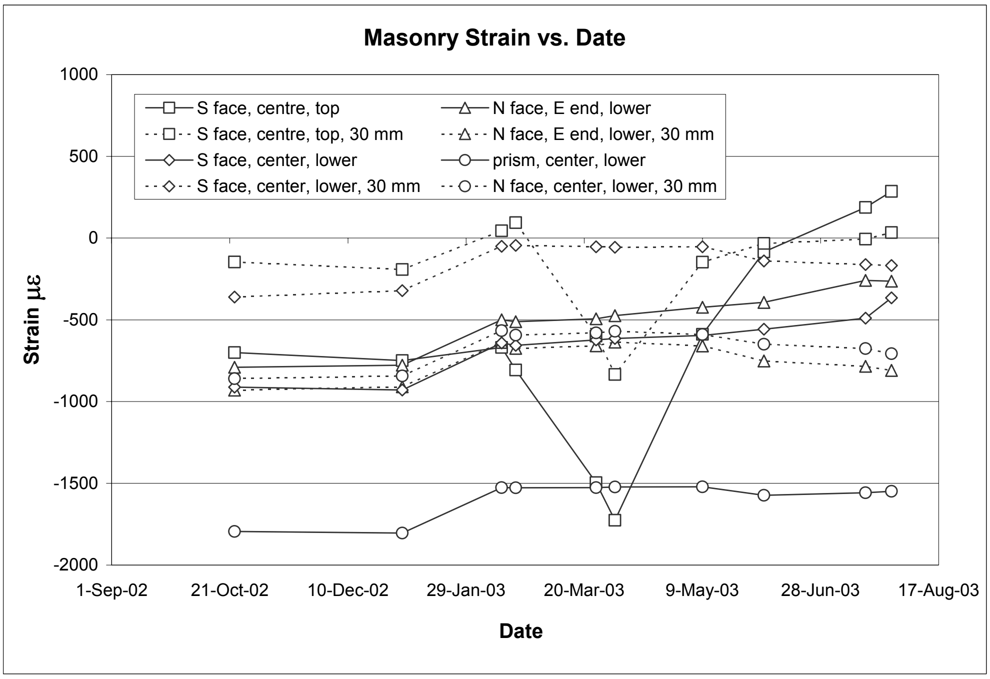

Figure 2 – First year masonry strain readings.

4 Short Term Data Collection

This observed peak in Figure 2 indicated that the solar radiation effects in the curved wall are quite significant. Thus, new, short term, continuous monitoring sessions were implemented. Those took place in the late summer, and were organized so that readings from all thermocouples and strain gauges could be taken simultaneously using a more sophisticated data acquisition system. In order to obtain a more in depth picture of the diurnal effects readings were taken every 2 minutes over a 2 day period, and every 5 minutes over a 4 day period, for the 1st and 2nd sessions, respectively. The continuous monitoring system cannot be used in cold weather; however, another system which would function in harsh conditions is being evaluated for use.

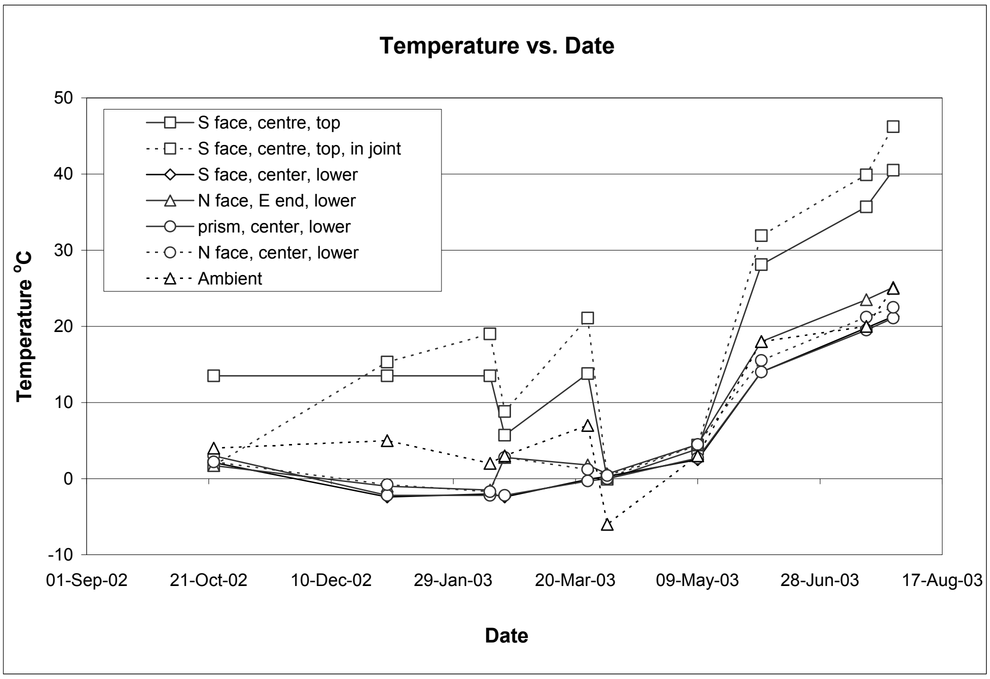

Figure 3 – First year temperature readings.
Source for ambient temperature data: The Weather Network

The results of the first short term session are presented in Figure 4 and Figure 5. Note that the data acquisition system automatically sets initial strain readings to zero so that only changes in strain are measured. These figures show that throughout the diurnal cycle, the change in strain for the south face top gauge is about -250 με for a drop in temperature of about 20 ^{o}C. For a smaller drop in temperature of about 6 ^{o}C, the change in strain for the lower east end on the north face is about +48 με, and about +70 με for the 100 mm and 30 mm gauges, respectively. There are negligible changes in temperature and strain in the cavity (prism) and on the lower part of the south face (insulated by soil backfill). Several observations can be made from these charts:

1. 30 mm strain gauges show a more significant reaction with temperature change than the 100 mm ones which is related to the fact that they are attached to the brick only, while the 100 mm gauges cross over 2 bed joints reading an average strain in brick and mortar.
2. The change in strain is insignificant for the part of the wall which is isolated from environmental effects like the lower part of the south face
3. The most interesting and currently inexplicable effect is that for a decrease in temperature, the south face centre top gauge shows a negative change in strain (compression) while the other gauges show an increase in strain (tension). This effect is discussed further below.

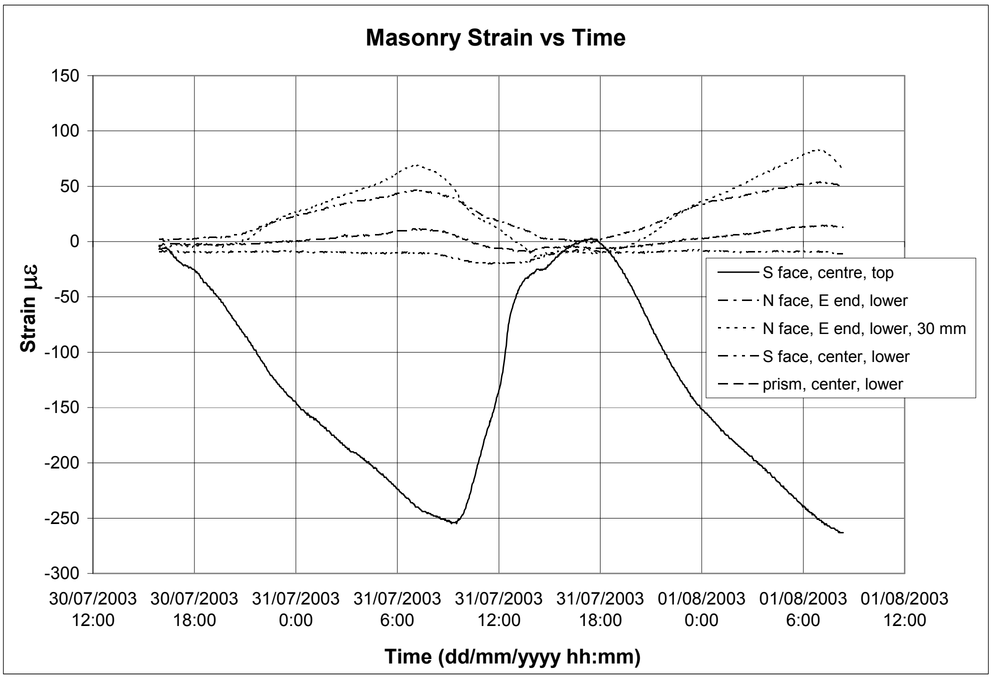

Figure 4 – Two day monitoring of changes in masonry strain.

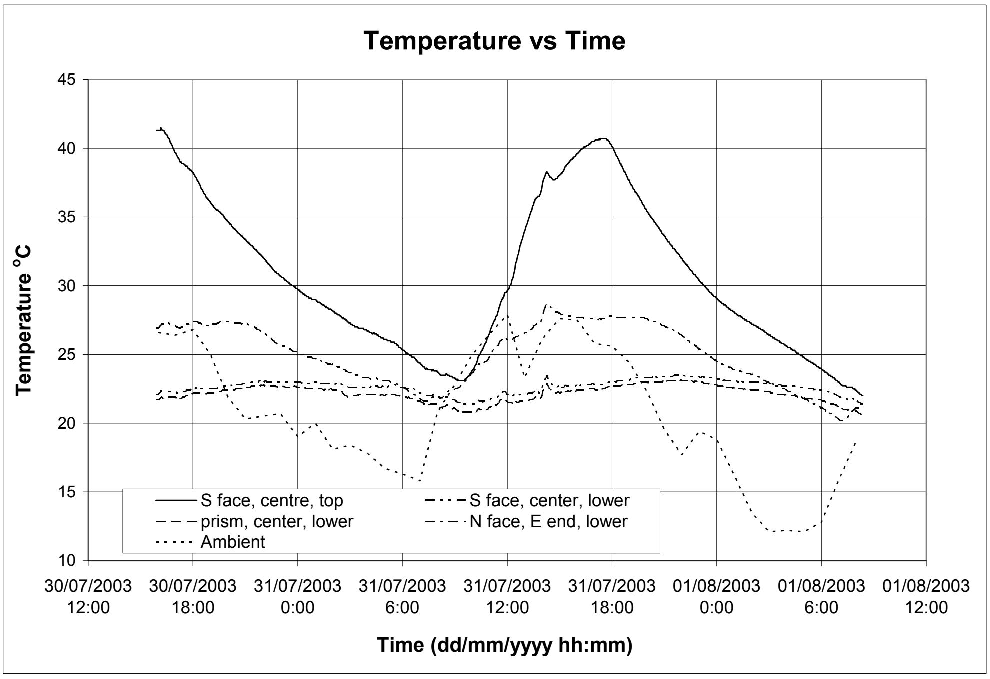

Figure 5 – Two day monitoring of temperature.
Source for ambient temperature data: Environment Canada

For masonry subjected to a temperature decrease, shortening is expected and as a result, a decrease in strain (compression) should be measured from the gauge. However, as mentioned earlier, the strain gauges attached to the masonry have a ¼ bridge configuration and therefore differences in the CTEs of the masonry and the gauges need to be accounted for. The technical information from the strain gauge manufacturer indicates that the CTE for the gauges is approximately 11.7 x $10^{-6}/^{o}C$. The CTE for brick and brickwork has been reported to vary between 3.1 and 12.4 x $10^{-6}/^{o}C$ for brick and between 6 and 8 x $10^{-6}/^{o}C$ for brickwork (Drysdale, et al. 1999, Shrive

1988). If the CTE of masonry is less than that of the gauges then for a given temperature decrease, the gauge would tend to experience more shortening than the masonry. However, since the gauge is attached to the masonry surface, it is restrained and the gauge will read tension. So those gauges that show an increase in strain (tension) as a result of temperature decrease are correct as we see from computing the expected change in strain due to a temperature decrease:

For the 100 mm gauges attached to the masonry:

$$(6-11.7)\text{x } 10^{-6}/^{o}\text{C } *(-6^{o}\text{C}) = +34.2\mu\varepsilon \ \approx 48\ \mu\varepsilon$$

and for the 30 mm gauges attached to the brick:

$$(3.1-11.7)\text{x } 10^{-6}/^{o}\text{C}*(-6^{o}\text{C}) = +51.6\mu\varepsilon \ \approx 70\ \mu\varepsilon$$

The predicted change in strain is slightly less than that measured, however, the calculations are based on assumed CTEs for the masonry and gauges. So the problem remains that two of the gauges (south face top) are reading decreases in strain with decreasing temperature, opposite to what they should be. There are a few possible causes for this unexpected behaviour:

a) The gauges in question could possibly have a CTE smaller than masonry. This would only be possible if the gauges used in this location were of a different type than the ones installed lower down on the wall. These two gauges were installed at a different time than the majority placed lower down, however, only one kind of gauge is usually purchased so the chances of this are slim.
b) Though the strains due to the prestressing force are small, changes in the prestressing forces could be affecting this area through elastic deformations of the masonry. Changes in the prestressing force with the diurnal cycle can be determined from the change in strain in the tendon which was approximately - 50 με (for the CFRP tendons, E_p= 142 GPa and A_p = 46 mm^2):

$$\Delta P = \Delta\varepsilon_p * E_p * A_p = -50\mu\varepsilon * 142000MPa * 46mm^2 = -327N$$

This loss in prestressing force results in a change in strain in the masonry at the bottom of the wall equal to:

$$\Delta\varepsilon_m = \frac{\Delta P}{E_m * A_m} = \frac{327N}{8312.8MPa * 126900mm^2} = 0.310\mu\varepsilon$$

where A_m is the area of masonry for one cell and E_m = 8312.8 MPa and was determined experimentally. Finite element modelling of a similar diaphragm wall section (without temperature loading consideration) shows that a small amount of tension can appear in the top part of the wall due to the prestressing force transferred to the wall through the capping beam. The tension predicted by the model at the top is about 0.02 MPa versus -0.57 MPa stress (compression -ve) at the bottom. A decrease in prestressing force will cause the stresses to decrease in that location leading to a negative strain change. However, as we can see, the resulting change in strain is extremely small and obviously does not appear to be the cause of the 250 με decrease in strain that was measured.
c) The temperature of the masonry could be different than that of the gauge. This is somehow possible since the masonry is directly exposed to environmental conditions and the temperature of the gauges is affected by conduction through the masonry surface. However, with the exception of one thermocouple place in the

masonry joint (closer to the outside surface), the thermocouples are located on the same surface as the gauges so this also does not seem to be a logical explanation.

The second short term session confirmed and illustrated further the expected solar radiation effect on the wall. As can be seen from Figure 6 and Figure 7, the strain in the wall in the south face at the top is very closely related to the temperature of the wall which does not follow the ambient temperature pattern exactly.

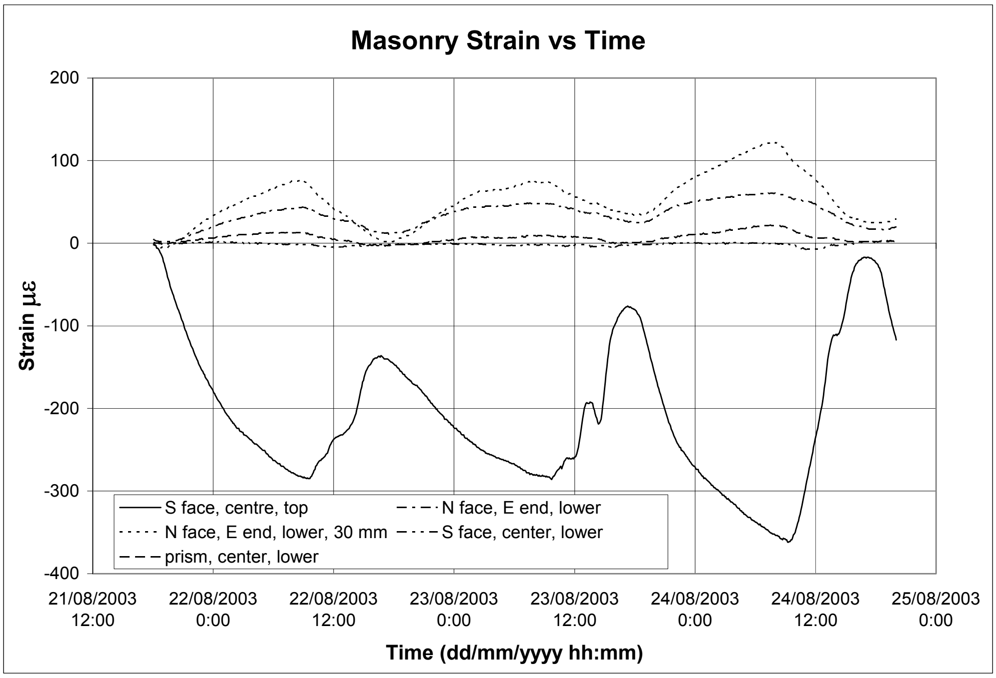

Figure 6 – Four day monitoring of changes in masonry strain.

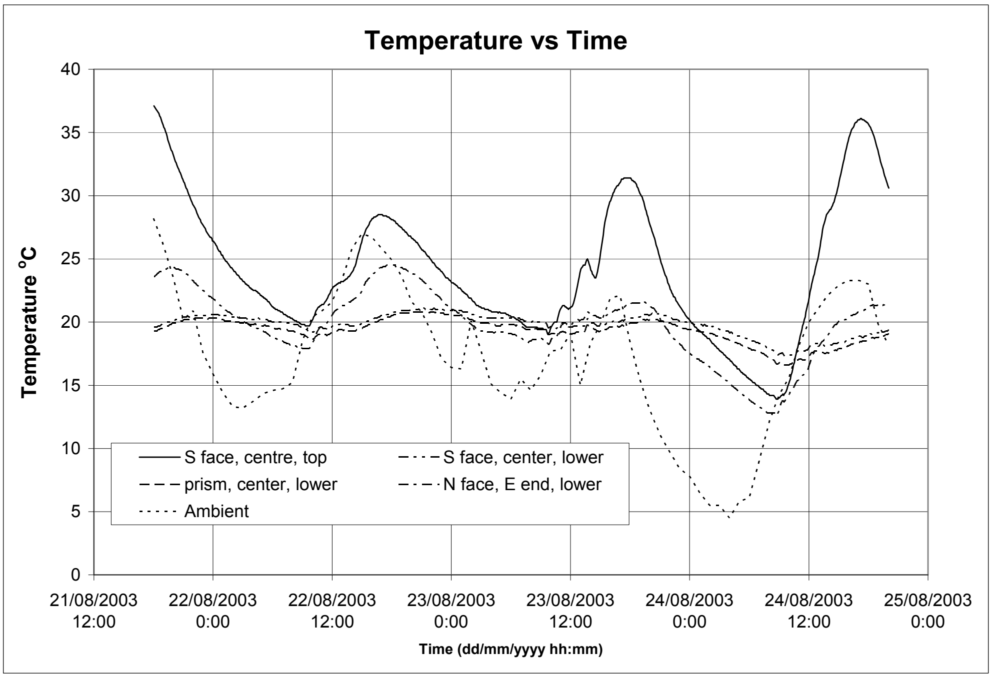

Figure 7 – four day monitoring of temperature.
Source for ambient temperature data: Environment Canada

The difference in strains at the top of the south face on the afternoons of August 21st and 22nd is about 140 με while the peak ambient temperatures differ by only 3 – 4 ^{o}C. Comparing the afternoon peaks on August 21st and 23rd we observe about a 75 με difference in strain at the top of the south face for an 8 ^{o}C difference in ambient temperature. The maximum observed strain change is about 350 με for about 25 ^{o}C variation in the wall temperature. The readings obtained in this short term session confirmed the main observations made in the first short term session (discussed earlier) and confirmed the need for further investigation of the temperature effects.

5 Further testing and analysis

An explanation for the unexpected observation mentioned previously (#3) is not easy to find since the temperature conditions on the curved wall are quite complex. There is an obvious necessity to investigate the thermal properties of the masonry used and the influence of the different CTEs of the masonry and gauges through a simple laboratory test. For such a test, two sets of instrumentation, each of one 30 mm gauge, one 100 mm gauge, and one thermocouple will be installed on a masonry prism specimen and on special glass which has a zero coefficient of thermal expansion. The specimen and the glass will be placed in a thermally controlled environment and subjected to temperature changes. It will allow the CTE for the masonry, brick, and gauges to be determined. Using this data it will be possible to calibrate the strain gauge readings to remove the thermal effects due to differences in the CTEs.

In order to examine more closely the complex temperature loading effects, a Finite Element Model has been developed, though at this time thermal loading has not been implemented in the model. Work on the model will continue in an effort to verify the observed thermal effects on strain.

6 Conclusions

It is important to understand and to be able to predict losses in prestress for efficient, economical, and safe design of prestressed structures. The use of FRP as a prestressing material has emphasized temperature dependent losses as a new subject for research and scientific investigation. The presented research was conducted with one goal being to investigate these and other types of losses. The first year of long term monitoring called our attention to the effect of solar radiation on the masonry strain. Therefore, two short term reading sessions were implemented, the results of which have confirmed some of our expectations but have also raised new issues for further investigation. As expected, the temperature dependent effects are very significant in the masonry exposed to solar radiation; however, new tests are required to fully explain the data obtained from monitoring.

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