Long-Term Wireless Structural Health Monitoring of the Ferriby Road Bridge

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Abstract: As part of an effective bridge management system, sensor networks can provide data to support both inspection and assessment. Wireless sensor networks (WSNs) have the potential to offer significant advantages over traditional wired monitoring systems in terms of sensor, cabling, and installation costs as well as expandability. However, there are drawbacks with WSNs relating to power, data bandwidth, and robustness. To evaluate the potential of WSNs for use in bridge management, a network of seven sensor nodes was installed on the Ferriby Road Bridge, a three-span reinforced concrete bridge. Three displacement transducer nodes were placed across cracks on the soffit of the bridge to measure the change in crack width. Three inclinometer sensor nodes were mounted on two of the elastomeric bearing pads to measure the change in inclination of the bearing pads while a final node monitored temperature in the box that contained the gateway. The installation of the WSN is discussed and data from this network is analyzed. Finally, the use of sensor networks to support inspection and assessment is discussed.

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Introduction

Around the world, aging civil infrastructure is becoming a growing concern as material deterioration causes unknown reductions in the load carrying capacity of these structures. Often, especially in the case of bridge infrastructure, this decreasing capacity is juxtaposed against higher live loading requirements both in terms of magnitude and frequency. One solution to this problem is to rebuild these critical structures. However the cost of this solution both in terms of capital investment and user delay times often makes this option infeasible. Instead, a maintenance strategy that allows the service life of each structure to be optimized while still decommissioning structures before they become unsafe is required. To facilitate such a maintenance strategy, engineers and bridge managers must be provided with the necessary data about each structure to make well-informed decisions about their operation.

One possible tool that can be used to acquire this critical data is a wireless sensor network (WSN). WSNs are similar to traditional monitoring systems in that a series of sensors are connected to a data logger, and this logger can then either be accessed on site or remotely via an Internet connection. However, unlike more traditional systems, WSNs do not require that the sensors be attached with wires for data and/or power transmission. This eliminates the time and expense of cable installation resulting in potentially inexpensive and rapidly deployable monitoring systems. Also, because wiring is not required, additional sensors can be quickly added to the system as and when they are required. There are also four primary drawbacks with these WSNs: (1) power; (2) data transmission bandwidth; (3) reliability; and (4) time synchronization. First, since the sensors are usually battery-powered, careful consideration needs to be given to the type and amount of data to be acquired to minimize power consumption. One such approach to this problem is to monitor long-term changes in the structure by taking sensor readings infrequently as will be described in this paper. A second drawback is that wireless data transmission limits the volume of data that can be transferred while the third drawback is the reliability of the wireless connection, which can result in some data not being transmitting or connection to individual sensors being lost. There are a number of factors that can affect the reliability of this connection including the type of antenna used, the distance between individual nodes, the material composition of the structure, and whether there is line of sight between nodes. Here again, the sensor and how it is applied have to be chosen carefully so that these limitations can be overcome. If all the data being monitored is critical, such as would be the case for acoustic emission monitoring of prestressing wire breaks for example, the transmission protocol must ensure that each data packet transmission is received at the database. Time synchronization between nodes is also important, especially in applications such as vibration monitoring where the results from all the nodes must have a common time datum so that they can be compared. While many researchers have investigated the use of WSNs to monitor bridges for short periods of time (e.g.,

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Fig. 1. Humber Bridge

Lynch et al. 2006; Kim et al. 2007) to date limited research has been conducted on the use of WSNs for long-term monitoring applications (Feltrin et al. 2007).

As part of a larger project investigating the use of WSNs for monitoring civil infrastructure, a WSN has been installed on both the Humber Bridge and also an adjacent reinforced concrete approach bridge. The first WSN was installed to monitor the environmental conditions within the north anchorage chambers of the main suspension cables of the Humber Bridge and has been described elsewhere (Hoult et al. 2008). The second WSN, which is the focus of this paper, was installed on the Ferriby Road Bridge located on the approach road immediately to the north of the main suspension bridge as illustrated in Fig. 1. This paper will present details of the WSN that was installed on this structure, introduce some of the issues related to network connectivity, and present some of the data and how it is visualized. This will be followed by a brief discussion of the role sensor networks can play in the management of reinforced concrete bridges.

Ferriby Road Bridge

The Ferriby Road Bridge, as illustrated in Fig. 2, was completed in 1979 and provides access to the north end of the main suspension span of the Humber Bridge. It is a three-span skew reinforced concrete slab bridge with expansion joints at each abutment and a variable width as illustrated in Fig. 3. The central span is 16.7 m and the two side spans are 13.8 m. The average slab depth is 750 mm. The end spans are supported on elastomeric pad bearings at each abutment while the two interior pier supports are formed by RC columns spaced at approximately 7 m centers. Elastomeric pad bearings are also provided at the top of the outermost columns in each line of piers. All other internal columns are cast integrally with the bridge deck.

During the bridge's last visual inspection in 2002 several defects were noted which may require maintenance in the future. The first was the presence of cracks on the soffit of the slab. These cracks run both transverse to the longitudinal axis of the bridge at midspan of the central span and in the longitudinal

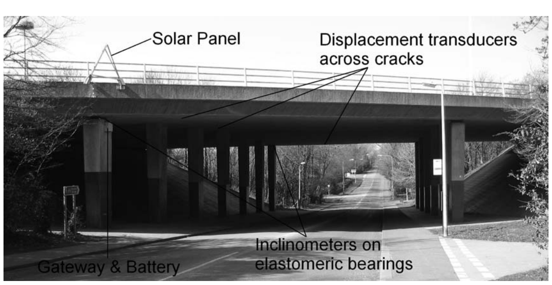

Fig. 2. Ferriby Road Bridge

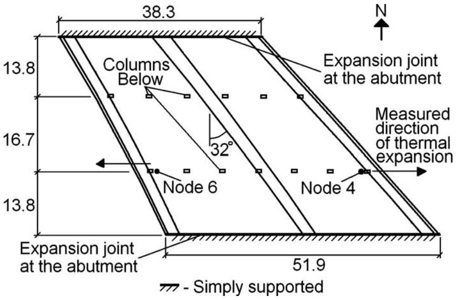

Fig. 3. Plan view of the Ferriby Road Bridge

direction in the region near the columns. At present these cracks are quite small (0.1 to 0.2 mm) but during wet weather, moisture accumulates in their vicinity on the slab soffit suggesting that there is the potential for long-term deterioration. Also noted during the inspection was the transverse inclination or tilting of many of the bearings at both abutments. This could mean that the bridge is slowly moving in the transverse direction with time. It is also possible that this inclination is the result of action at the time of construction. In the case of both the cracks and the inclined bearings, the magnitude of movement to date is not significant enough to require maintenance. However it is also possible that these defects will get worse with time and that a threshold will be crossed when maintenance to correct these defects will be required. Unfortunately, one of the drawbacks of visual inspection is that observations about the level of deterioration, such as crack widths, can vary from inspector to inspector and even from inspection to inspection by the same inspector (Moore et al. 2001). Thus, a more accurate method of quantifying the extent and rate of deterioration at the Ferriby Road Bridge was sought.

Wireless Sensor Network

One possible method for measuring the change in crack widths and bearing inclination is to install a sensor network. Because the Ferriby Road Bridge crosses the Ferriby Road, installing sensors on the underside of the bridge at midspan requires partial closure of the road, which could result in road user delays. Minimizing these delay times, will reduce the associated delay costs. This makes the use of a WSN, which does not require the installation of cables and the associated installation time, an appealing option. In addition, the network can easily be expanded to measure other parameters elsewhere on the bridge at some later date as required, without the need for installing new wires or physically altering the data logging devices.

A WSN is typically composed of nodes and a data acquisition system or gateway. The nodes combine sensors, a computer processor and wireless communication functionality. The nodes take readings from their sensors at a predetermined interval (every three minutes in the case of the current network) and transmit this data back to the gateway. The nodes can either transmit the data back to the gateway directly or via other nodes in the network, which is referred to as a "multihop" network. The gateway, as the name suggests, is the portal by which the data can be accessed from the outside world either by directly connecting to it or by an Internet connection. The gateway may also store the database of sensor results or a copy of that database.

In the case of the Ferriby Road Bridge installation Crossbow MICAzs were used to provide the computer processor and wireless communication components at each node in the network.

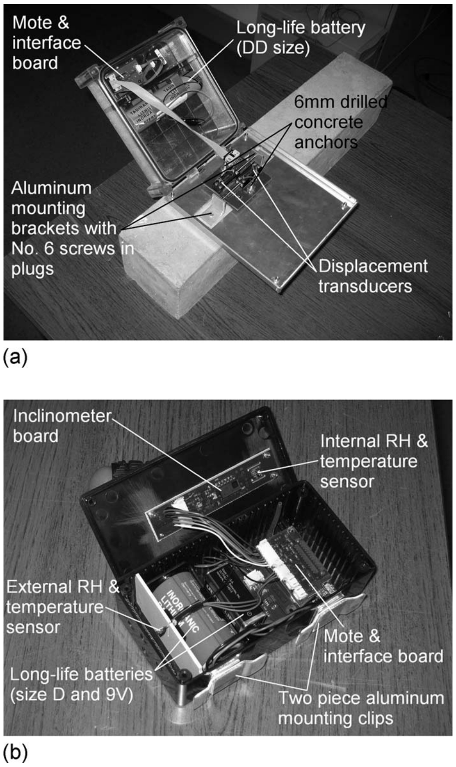

Fig. 4. Nodes used at Ferriby Road Bridge: (a) crack displacement node; (b) inclinometer node

This WSN consists of seven sensor nodes, three of which measure crack displacements as well as temperature and relative humidity (RH), three which measure bearing inclination and temperature and RH, and one that measures temperature inside the gateway box. Temperature and RH are measured so that results from the other sensors can be properly calibrated against environmental conditions, although these values could also be useful on their own as discussed later. For the node in the gateway box a sensor board (the MTS300 manufactured by Crossbow) that attaches to the MICAz was used to measure the temperature. For the other six nodes, bespoke circuit boards were manufactured to interface the required crack displacement and inclination sensors with the MICAz.

To measure the crack displacement two linear potentiometric displacement transducers (LPDTs) were interfaced with the 10-bit analog to digital converter (ADC) on the MICAz processor with a resulting displacement measurement resolution of 0.01 mm. The LPDTs were model number S13FLP12A from Caldaro AB and had a range of 12.5 mm. One of the LPDTs was placed across a crack on the deck soffit and the other was placed across an uncracked region of concrete for temperature compensation. Each crack displacement sensor node was placed inside a bespoke box that protected the unit from the surrounding environment as illustrated in Fig. 4(a). Two temperature and RH sensors were attached to each unit; one sensor measured these values inside the box while the second measured the same parameters external to the box. The inclination of the bearings was measured using a microelectromechanical systems (MEMS) inclinometer. In this case, the 10-bit resolution of the MICAz ADC did not provide sufficient resolution for the inclination measurements so another bespoke circuit board was created with a 16-bit ADC which allowed the inclination to be measured with a resolution of approximately 0.001°. The inclinometer node was placed in a box to protect it from the environment and two temperature and RH sensors were also provided as shown in Fig. 4(b).

As outlined in the introduction, one of the potential drawbacks of WSNs is that the sensor nodes are battery powered and therefore changing the batteries will have to be factored into the maintenance budget for the system. However, the length of time between battery changes can be increased by decreasing the interval at which the sensor data are transmitted and by using long-life batteries. Both of these strategies were implemented in the current system. Sensor readings are taken and transmitted every three minutes although these three-minute cycles are not synchronized between nodes. The nodes are then programmed to "sleep" in between these transmissions to conserve power. However to ensure that data from other nodes intended for the gateway gets retransmitted as required, in sleep mode each node "wakes up" for a brief interval eight times a second to listen for radio traffic intended for them. If action is required the node stays awake to complete the required action before going back to sleep whereas otherwise the node goes back to sleep immediately. The crack displacement sensors are powered by a 35Ah–3.6V lithium battery which should theoretically allow them to operate (including powering the sensor, sampling the data, and transmitting that data back to the gateway) for four years between battery changes. Similarly, the inclinometer nodes are powered by 19Ah–3.6V lithium batteries that will allow them to operate for approximately 1.5 years between battery changes.

The gateway used in the Ferriby Road Bridge network is a low-power computer that logs the data that is transmitted from all the nodes in the network and then stores this data in text files on a compact flash memory card. At preset time intervals the gateway uses its High-Speed Downlink Packet Access (HSDPA) modem to create a connection via the mobile phone network and the Internet to a server based in the University of Cambridge. It then uploads any additional data that has been acquired since the last time it established a connection to the server, which is then logged in a database on the server. Because the gateway must listen to all the radio traffic, unlike the nodes, it does not sleep and thus has higher power consumption than the nodes. Due to its isolated location, it was not possible to attach the gateway to a main power supply at the Ferriby Road Bridge, so the solution to this problem was to power the gateway using a 120Ah–12V battery, which was in turn charged by a 64-W solar panel attached to the side of the bridge shown in Fig. 5. This power system, coupled with the use of a mobile phone Internet connection, means that this WSN setup can be used in remote locations where a mains power supply is unavailable.

The layout of the nodes is illustrated in Fig. 6. Node 1 measures the displacement of a transverse crack at midspan of the bridge. Nodes 2 and 3 monitor the displacement of longitudinal cracks. Nodes 4 and 6 measure the transverse inclination of the elastomeric bearings on top of the two outer columns on the south side of Ferriby Road. Node 5 measures the bearing inclination along the longitudinal axis of the bridge on the same column as node 6. It should be noted that the inclination of the bearings was observed at the abutments in the 2002 visual inspection not at the tops of the outer columns. However, since the bearings at the abutments are easily accessible to the general public, it was decided to place the sensors on the column bearings instead to reduce their susceptibility to vandalism. The column bearings were also inclined in the transverse direction although this was not as pronounced as the inclination of some of the abutment bearings.

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Fig. 5. Solar panel

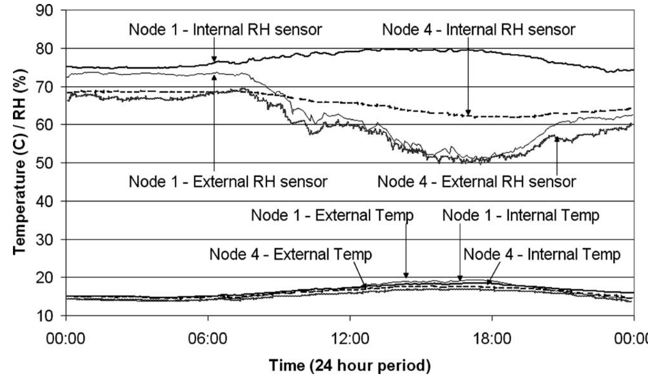

Fig. 7. RH and temperature for nodes 1 and 4 over 24 h

Installation

The first stage of the installation occurred over two days in March and April 2008. The crack displacement gauges were attached to the soffit of the bridge using drilled concrete anchors. Anchors were used because they provided a fixed point of reference for measurement and ensured that the sensors did not fall onto the road below. The inclination sensors were attached to the side of the elastomeric bearings atop the outer columns using aluminum mounting brackets, glued to both the bearing and the sensor node box, which allowed the inclinometers to be removed easily for testing and repairs.

The gateway, along with the HSDPA modem, node 7 and the 12 V battery were placed in a polycarbonate box. This box was then mounted on a bespoke steel shelf that was attached using drilled concrete anchors near the top of the eastern-most column on the south side of Ferriby Road. Wires were run between the gateway box and the solar panel which was mounted on a custom-made steel frame on the east side of the bridge facing south. The angle of the solar panel (64° to the horizontal) was chosen to optimize the amount of solar power generated by the panel over the course of a year, especially during the winter months (Hui 2002).

Fig. 6. Node layout at the Ferriby Road Bridge

Connectivity Issues

After the initial installation of the network it was discovered that the gateway was only receiving transmissions from three of seven nodes (1, 4, and 7). One of the reasons for this lack of total network connectivity was thought to be the small offset of the antennas from the flat soffit of the bridge. If antennas are placed relatively close to a flat surface (<50 mm) the radio waves tend to propagate perpendicular to the surface but not parallel to it (Wu and Wassell 2008). This can result in very poor radio transmission range along the soffit of a bridge deck. To establish complete network connectivity external antennas were added to nodes 3, 5, and 6 as well as the gateway (connection to node 2 was achieved through the use of an external antenna on the gateway). These antennas had larger offsets from the soffit as well as improved performance over the small antennas that were supplied with the MICAz motes. The new antennas had gains between 2 and 5 dBi (decibels isotropic—indicates the gain of an antenna relative to an isotropic antenna) compared with essentially no gain for the original antennas. Because of these issues, the WSN was not fully operational until June 2008. Interestingly, node 1 was able to transmit to the gateway from approximately 35 m away, whereas nodes 2 and 3, which were the same type of node, could not transmit to the gateway despite being approximately 8 and 18 m away from the gateway, respectively. As mentioned in the introduction, radio connectivity can be affected by a number of factors which also include the node hardware and software used (MICAz nodes and TinyOS, respectively, in this case) and it goes beyond the scope of this paper to discuss them all. However, this example illustrates that radio connectivity issues can be difficult to predict and that they, along with battery life, are one of the major potential problems standing in the way of greater acceptance of WSN technology. Although the initial installation of this network took only two days, the subsequent trips required to bring the system fully online meant that a wired sensor network could probably have been installed in less time in this instance.

Results and Data Visualization

RH and Temperature. Fig. 7 illustrates the variation in temperature and RH for nodes 1 and 4 over a 24-h period. The temperature read by both the sensor internal to the box and the sensor external to it are in good agreement, which is to be expected since the thin plastic boxes offer little thermal insulation. On the other hand, the RH readings from the internal sensors tend not to change as significantly as the external ones. This is a result of the high resistance to moisture penetration of the boxes. The data from these sensors not only allow for temperature compensation

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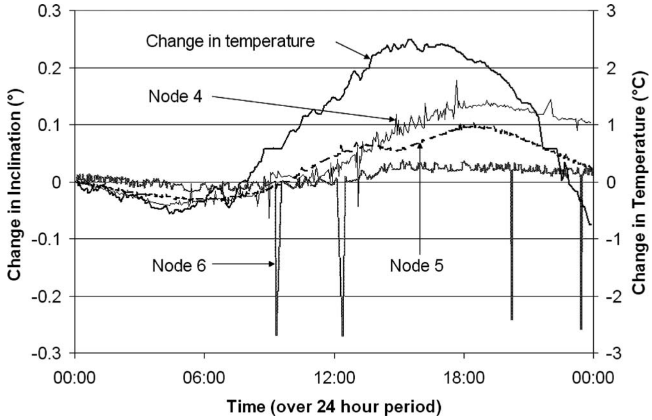

Fig. 8. Change in bearing inclination for nodes 4, 5, and 6 with change in temperature over 24 h

of the other sensor readings (e.g., crack sensors) but could also be used in deterioration models where accurate knowledge of the environmental conditions would result in more accurate predictions (e.g., Saetta 2005).

Crack Widths. The *maximum* increases in crack width recorded since the network was installed 5 months ago for nodes 1, 2, and 3 were 0.01, −0.03, and 0.02 mm, respectively, while the *latest* readings were 0.01, −0.02, and 0 mm respectively. These results suggest that there is very little, if any, crack growth as displacements this small are not significantly above the noise threshold of the ADC (0.01 mm). This is to be expected as crack growth, if indeed it is occurring, will happen over a period of years and not months if it is being caused by a long-term deterioration mechanism such as corrosion or very suddenly if the cause is overloading. It should also be noted that because of the aforementioned connectivity issues there are only a few months of data for node 3 for comparison. Perhaps of greater interest is the consistency of the readings which suggests that the LPDTs are not drifting with time, which bodes well for their use in a long-term WSN.

Bearing Pad Inclination. The change in inclination for nodes 4, 5, and 6 over a 24-h period is plotted against the change in temperature in Fig. 8. One can see that the measured inclination of each bearing correlates well with the change in temperature. In this case, it is believed that the inclinometers are measuring the expansion and contraction of the elastomeric bearings with temperature. While the top and bottom of each bearing is fixed against the soffit of the slab and the column, respectively, the center of the bearing is free to expand and contract with changes in temperature. The difference in measurements between the three nodes is believed to be largely due to the position of the aluminum mounting clips on the bearing as illustrated by the three possible positions in Fig. 9(a). In position 1, the inclinometer would be where the slope of the bearing reaches a minimum and thus it would measure no change in inclination despite being at the point of maximum expansion. In position 2, the inclinometer would measure the maximum change in inclination due to the expansion of the bearing. While in position 3, the fixity between the bearing and the column would again reduce the inclination observed. The results indicate that while node 4 is in position 2, nodes 5 and 6 are in position 3. It should also be noted that while these values appear large due to the scale of the plot, the maximum change in angle measured by node 4 of 0.177° equates to an expansion of the bearing at midheight of just 0.125 mm. Interestingly, there are small spikes in the inclination data for node 4, which may well be due to the passage of heavy vehicles squashing the bearings slightly at the time the readings were taken and causing an increase in inclination. A future modification to this network for checking the correlation between live loads and the readings from other sensors such as the inclinometers could be the addition of a camera to record the type of vehicles that passed over the bridge along with the time. It also seems that node 6 is producing spurious inclination readings occasionally which are evident from the large spikes on the graph in Fig. 8. While it appears to be capturing the overall trend of the data well, these spikes in the data are cause for concern. Over the long term, this sensor node will be replaced to ensure the quality of the data but this problem serves to illustrate one of the current impediments to the use of WSNs for long-term monitoring and that is the robustness of the sensor node hardware. However, if the data from these systems proves to be useful for bridge managers, the quality control issues that occur when electronics are produced on a small experimental scale will be largely eliminated with large-scale commercial production.

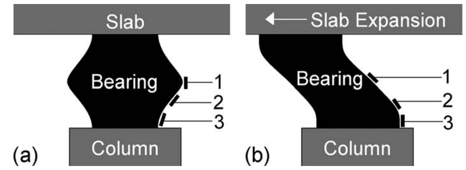

Fig. 9. Effect of inclinometer location on inclination change measurement: (a) diurnal measurements; (b) long-term measurements

The change in inclination of the elastomeric bearings and the change in temperature with time are plotted in Fig. 10 for nodes 4 and 6. The long-term change in inclination as measured by node 4 during the last five months of the deployment is approximately 1.46°. One can see that, as with the diurnal inclination changes, the long-term inclination changes for node 4 are highly correlated to temperature. However the cause of this long-term behavior is believed to be different than the cause of the diurnal behavior. While the diurnal behavior was driven by expansion and contraction of the bearing, the long-term behavior is considered to be the result of expansion of the bridge deck causing the bearing to tilt in only one direction. The direction of deck expansion/contraction that correlates to the readings obtained from nodes 4 and 6 is

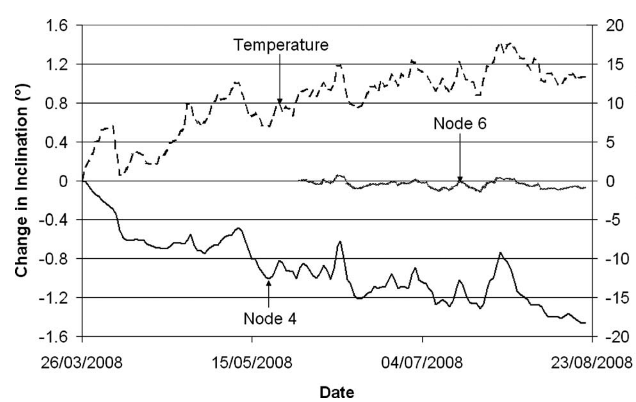

Fig. 10. Long-term change in bearing inclination for nodes 4 and 6 with change in temperature

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illustrated in Fig. 3. As a result, the diurnal behavior is cyclic whereas the long-term inclination trend measured to date is all in one direction due to the continual warming from spring to summer. One can see from Fig. 10 that while the same trends in the data exist, the effect of temperature on the change in inclination measured by node 4 is one order of magnitude greater than node 6. This is the same result as seen in Fig. 8 where node 6 measured considerably smaller changes in inclination over the course of a day than node 4. However, this difference in performance could again be due to the placement of the inclinometer on the bearing as illustrated by the three possible inclinometer positions in Fig. 9(b). In this case, if the inclinometers were placed in position 1, they would measure a maximum value for the change in inclination, in position 2 they would read a slightly reduced value and in position 3 they would register almost no change in inclination. Thus the data indicates that node 4 was once again in position 2 and nodes 5 and 6 were in position 3.

To determine whether the inclination values measured by node 4 are reasonable an estimate of the expected bearing movement can be made. One can assume that the slab expands and contracts due to temperature in the transverse direction symmetrically about the centerline of the bridge. The distance from the centerline of the bridge to the center of the elastomeric bearing at the top of the outer column that node 4 is attached to is approximately 20 m. Taking the coefficient of thermal expansion for concrete as $10\times10^{-6}/{}^\circ\mathrm{C}$ (Collins and Mitchell 1997) and the change in temperature as $13^\circ\mathrm{C}$ (taken from Fig. 9) one would expect the slab to expand toward the bearing by 2.6 mm. If one uses the full bearing height of 80 mm then the resulting change in angle would be 1.86°, which is slightly more than the value of 1.46° measured by node 4. This is only an estimate of the inclination as a number of factors will affect the expansion of the slab including the coefficient of thermal expansion which can vary between 6 and $12\times10^{-6}/{}^\circ\mathrm{C}$ depending on the aggregate type and the restraint provided by the columns. Hence the long-term results from the inclinometers seem reasonable although placement of the inclinometer for these types of measurements clearly needs to be given careful consideration.

Potential Use of Sensor Networks

Effective bridge management programs require both the inspection and assessment of bridges. Inspection focuses on observing the bridge for potential areas of deterioration and so in this regard sensor networks (both wired and wireless) provide a useful tool for supporting this process. For example, as demonstrated in this study, once a possible area of deterioration has been identified sensors can be installed to track this deterioration. Another option is to use sensor networks to identify possible areas of deterioration. Grosse (2008) has employed wireless acoustic emission sensors to identify and localize areas of potential damage. It is important to note that sensor networks can be used to supplement inspections but they should not be considered as a replacement for visual inspections for several reasons some of which are discussed in the following.

Despite their potential usefulness for monitoring deterioration there are several limitations to sensor networks that users should be aware of including: (1) the localized nature of sensor measurements; (2) the sensors available; (3) the choice of appropriate measurements; and (4) cost. A sensor can typically only monitor the local conditions where it has been mounted and therefore may not be monitoring the critical area in terms of deterioration. For example, the crack displacement sensors used in this study measure the crack width across a specific crack; however it is possible that due to localized corrosion other cracks in the same area are increasing at a more significant rate. This would mean that a potentially significant problem would not be recorded by this monitoring system. If this system were used in conjunction with a comprehensive inspection program, then it is hoped that this deterioration could be identified visually. There are other sensors that potentially allow for problems to be detected over a larger area, rather than at discrete locations, such as acoustic emission transducers and digital cameras. However, it is important that engineers who design monitoring systems as well as those who use the results from these systems are aware of the limitations of the individual sensors used.

While the advent of MEMS technology has meant that an increasing array of inexpensive sensors are available for use with monitoring systems, there still exist deterioration mechanisms that cannot be measured accurately with available sensors. The most important example of this for reinforced concrete structures is reinforcement corrosion. While engineers would like to be able to know the extent, rate, and location of corrosion, current sensor technologies cannot provide all these parameters accurately. A corrosion ladder for example may provide an estimate of the rate of corrosion but not the extent. Also, the corrosion ladder will only provide measurements where it is located, which could mean that other areas of critical corrosion are not identified.

Careful consideration also needs to be given to what should be monitored. A popular approach to structural damage detection is vibration-based monitoring (e.g., Zhou et al. 2007). This technique measures changes in stiffness of the bridge and aims to use these values to locate areas of damage. However, in cases where damage will have very little influence on the overall stiffness of the bridge (such as localized corrosion) vibration monitoring may not be able to detect this damage. Thus while vibration monitoring has potential for certain applications, it may not be appropriate for measuring corrosion of a RC slab. Very careful consideration needs to be given to the selection of sensors and the data that these sensors can supply if they are to be effective for identifying and monitoring deterioration within a structure.

At this time, monitoring does not seem to offer the solutions required to support the second element of a bridge management program: assessment. There are three essential pieces of information that are required to perform an assessment of a reinforced concrete bridge: (1) the strength of the materials used; (2) the area of steel reinforcement present at every location; and (3) a conservative but accurate structural analysis technique. Currently, it is difficult to gather information about points 1 and 2 using any available nondestructive testing techniques, let alone a monitoring system. In addition, as pointed out earlier, it is currently not possible to provide an accurate estimate of the extent, rate, and location of corrosion using monitoring. Future technological developments may make the use of a monitoring system to support assessment feasible but at this time it would seem that sensor networks are best used to supplement inspection.

Finally, minimizing the cost of sensor networks is vital, especially if their use is to become pervasive. While it goes beyond the scope of this paper to address all the factors that affect the economic viability of monitoring it is worth noting that each MICAz node costs approximately \$100 while the accompanying sensor boards cost approximately \$200. At \$300 a sensor node, pervasive systems with hundreds or thousands of nodes would likely be prohibitively expensive. However, the \$100 cost of each node is likely to decrease significantly due to economies of scale

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and continued technological development. Some of the sensor board components will also become cheaper with mass production, although these costs are likely to remain higher as sensor production, especially of displacement transducers, is a more mature market. That being said, when compared to the cost of the structure itself, which in the case of a bridge similar to the Ferriby Road Bridge would be over $1 million, the cost of a WSN is relatively small when evaluated against the potential benefits. The current project has been focused on evaluating the feasibility and robustness of WSNs rather than attempting to develop the most cost effective hardware.

Conclusions

Two WSNs have been installed at the Humber Bridge site as part of a larger project investigating the use of WSNs for civil infrastructure. One of these networks has been installed on a three-span reinforced concrete bridge known as the Ferriby Road Bridge that provides access to the northern end of the main suspension bridge. Based on the 2002 inspection report for this bridge, two potential deficiencies were chosen for long-term monitoring: cracks in the soffit of the slab and transverse inclination of the elastomeric bearings. A WSN consisting of seven nodes and a gateway was installed. Three of the nodes measure crack displacement on the soffit of the slab, while three other nodes measure bearing pad inclination. All of these nodes measure temperature and RH. A seventh node inside the gateway box measures temperature. The gateway stores the data from the nodes in text files, which are then downloaded to an off-site server. The data can then be accessed anywhere in the world via a webpage. Initially, not every node in the network was able to transmit to the gateway, a problem which was resolved through the use of external higher gain antennas. These connectivity issues are a potential stumbling block for wider acceptance of WSNs as they may cause significant delays during installation and commissioning. The deterioration data from the network so far has shown little variation, which is to be expected since changes in these values are more likely to occur over a period of years rather than months. However, the data suggests that the sensors are stable enough for long-term use. Sensor networks represent a useful tool that can be used to supplement, but not replace, visual inspection. However, care needs to be taken as there are limitations to their use including the localized nature of the data, the limited types of sensors available, the correct choice of data to be monitored and cost. At the present time, the use of sensor network data in the assessment of reinforced concrete bridges has limited applications but as technologies develop this problem may be overcome.

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