Field monitoring of reinforced concrete structures under cyclic loading

Zachary E Broth\textsuperscript{1} and Neil A Hoult\textsuperscript{1}

\textsuperscript{1} Dept. of Civil Engineering, Queen’s University, Kingston, Canada, 12zb6@queensu.ca

Abstract

To meet changing demands, existing reinforced concrete structures are often required to carry more frequent and heavier loads than they were designed to support. When assessing these complex and heavily redundant structures, engineers are often forced to make conservative assumptions. To avoid costly rehabilitation or unnecessary reconstruction, the need exists for monitoring technologies that can be applied to existing reinforced concrete structures and that provide the type of quantitative data required to make more refined assessments. Current monitoring technologies are generally restricted to discrete sensors. These sensors provide a limited representation of the behaviour of the structure. Dynamic distributed fibre optic sensing (DDFOS) provides continuous strain data throughout the fibre optic cable length at frequencies high enough to measure the response of a structure to cyclic loading. This paper introduces a field test that was conducted on an in-service reinforced concrete building. A discrete displacement transducer and fibre optic strain sensors were installed on a beam that was then subjected to cyclic loading. The results of this load test will be presented and the sensor results compared. Insights into the behaviour of the structure will be taken from comparisons between the measurements and expected values.

1. Introduction

As infrastructure around the world ages, the burden has been placed on the engineering community to decide whether these structures are able to support existing or increased demands, or adequately fulfil a new purpose. These decisions require an assessment of the existing structure to approximate its current condition and its ability to carry existing or increased loads. With reinforced concrete structures, this task becomes more difficult due to the complexity of the structural behaviour. Engineers are often required to make generalizing assumptions that are commonly overly conservative. Consequently, the need exists for monitoring and assessment methods that can be used to accurately decipher this complex behaviour.

To date, structural assessment and health monitoring has taken a variety of forms, including non-destructive testing (NDT), computer aided modelling (CAD), and various monitoring techniques. New technologies have improved the ability to gather important data to update existing models and provide insight into the behaviour of the structure. For example, linear potentiometers (LP) and electrical resistance-based strain gauges are both commonly used monitoring tools that provide the engineer with information about the structure’s behaviour. However, many traditional sensors such as these provide only discrete measurements, which fail to provide sufficient data to fully understand the performance of these heavily redundant structures. Distributed fibre optic sensors (DFOS) allow the engineer to obtain strain measurements throughout the length of the fibre optic cable, at a predefined gauge length. Although an improvement on discrete sensors, static DFOS can only provide a static snapshot of the structure’s behaviour, which is not ideal...
for monitoring existing structures that experience dynamic or cyclic loading. The ability to record distributed-dynamic strain data would provide new insights into many structures’ behaviour.

Dynamic fibre optic sensing options are available, varying in gauge length, accuracy and cost. Fibre Bragg gratings (FBG), for example, can provide accurate dynamic strain data (±5 microstrain) (1), but only at discrete points throughout a fibre length. Dynamic distributed fibre optic sensing (DDFOS) is a new technology that has the ability to record strain measurements using small gauge length (< 10 mm), at rates up to 250 Hz depending on the fibre length (2). Research into the use of DDFOS, however, is limited, and its ability to monitor reinforced concrete structures is yet to be tested.

To evaluate this technology, a field test will be conducted on an existing reinforced concrete structure. Specifically, a 6.4 m section of a reinforced concrete beam located in a university building was instrumented. To simulate a cyclic load, a class of 150 students was asked to jump, in unison, on the floor directly above the beam.

The objectives of this research project were to:

1. Monitor a reinforced concrete element under maximum expected cyclic loading using discrete and distributed sensors,
2. Compare the response of the two sensor systems to evaluate their suitability for monitoring the response to this loading, and
3. Evaluate the response of the structure against typical metrics for structural performance.

The next section of the paper will provide a brief background on structural assessment methods and FOS technologies, followed by details of the field study. The results of these tests will then be presented and discussed.

2. Background

2.1 Existing structural assessment techniques

In recent years, health monitoring of reinforced concrete structures has emerged as an important research topic within the field of civil engineering (3). The advancement of technology and methods in this area has focused mainly on the determination and monitoring of load, strain, and displacements as well as detecting the presence and size of cracks (3). Deformations are commonly determined using displacement transducers, such as Linear Variable Differential Transformers (LVDT) and Linear Potentiometers (LP), which provide discrete measurements at the point of installation (4). These devices are only useful when fixed to a known point of reference, reducing their usability in large scale assessments (4). Non-contact displacement measurement methods have been studied, such as Digital Image Correlation (DIC) (5), vision-based systems (4) and Global Positioning Systems (GPS) (6), each with their own advantages and disadvantages. DIC, for example, has also been proven as an effective method to locate and monitor cracks in reinforced concrete beams (7) but requires line of sight between the camera and the element being monitored.
Strain monitoring is most commonly done with electrical based strain gauges. Like displacement transducers, these gauges provide discrete measurements. The use of electrical based strain gauges is often limited due to environmental conditions, project scale, and installation restrictions (8). Advances in wireless and smart sensing technologies have improved on the traditional strain gauge by simplifying sensor installation and allowing for remote monitoring of a structure (9). However, the discrete nature of these measurements still reduces the assessment capabilities of these methods for heavily redundant structures where a variety of loading scenarios can produce the same set of point measurements.

As such, distributed sensors that are capable of providing thousands of unique data points are an appealing option for the assessment of heavily redundant and complex structural systems.

2.2 Assessment with fibre optic sensing

In recent years, research into fibre optic sensors has shone a light on the various capabilities that the technology has to offer in the field of structural health monitoring. Fibre optic sensors come in two main forms: discrete and distributed (10). Discrete fibre optic sensing, like traditional strain gauges, allow strain data to be captured at a limited number of points along a fibre optic cable. Fibre Bragg Gratings (FBG), for example, offer accurate strain data at etched points along a fibre length, which are less affected by environmental conditions than traditional strain gauges and more easily applied to large scale monitoring projects (11). FBG sensors however, can be expensive compared to electrical based strain gauges and are ultimately limited by the number of discrete measurements that they can provide (10).

Distributed strain measurement technologies, including Brillouin and Rayleigh fibre optic sensors, have the ability to measure strains at a series of points distributed along a fibre optic cable. Brillouin optical time domain reflectometry (BOTDR) has been used in large scale assessments due to its ability to monitor several kilometres of fibre with an accuracy of approximately 30 microstrain (12). Rayleigh backscatter measurement technologies can measure strain at a higher accuracy and smaller gauge length than BOTDR, however the total sensing length is limited to less than 100 meters of fibre to achieve high strain accuracy (13).

Although distributed sensors improve on traditional discrete measurements, most of these technologies can only provide a static “snapshot” of the strain throughout the structure, and are therefore unable to capture the behaviour due to cyclic loading.

2.3 Dynamic fibre optic sensing

The ability to measure strain induced by cyclic loading is provided by dynamic fibre optic sensors. Dynamic fibre optic sensors, similar to the static options, exist in two forms: discrete and distributed. To date, research has focused primarily on the dynamic capabilities of FBG sensors. FBG sensors can provide long-gauge (i.e. discrete) strain measurements along a fibre at acquisition rates as high as several thousand samples per second (14). Dynamic FBG can be applied to large scale assessment projects, as seen with
the Horsetail Falls Bridge, where 26 FBG sensors were applied to the exterior of the bridge to monitor the strengthening effect of composite wrapping (14). Despite the speed and accuracy of the strain data received during this test, FBG sensors are again limited by their discrete nature.

Dynamic distributed fibre optic sensing (DDFOS) is a new technology that surpasses the limitations of the previously described methods by providing dynamic strain measurements continuously throughout an optical fibre. Early research into the use of DDFOS has shown that this option can be applied to a wide range of dynamic sensing applications due to its ability to provide high resolution strain sensing, at high acquisition rates (15). The versatility of DDFOS is directly related to the capabilities of the data acquisition technology. One available DDFOS-capable system is the Optical Distributed Sensor Interrogator, the LUNA ODiSI-B. The ODiSI-B is a Rayleigh-based distributed dynamic analyser that utilizes optical frequency domain reflectometry (OFDR), which had been previously limited to static measurements (15).

The acquisition rate of the analyser used in the current study, i.e. the ODiSI-B system, is dependent on the total sensing fibre length, up to 20 m. For example, for a sensing length of 20 m, the acquisition rate is 50 Hz, while the gauge spacing is 2.61 mm, with an accuracy of ±25 microstrain. Reducing the sensing length can increase the acquisition rate (i.e. 250 Hz with a 2 m fibre), however the accuracy is relatively unaffected (±30 microstrain) (2).

To date, applications of the ODiSI-B system have been limited to small scale, laboratory-based tests. As seen in the work by Kreger et al., the dynamic behaviour of a swinging golf club has been analysed to show the high-resolution strain measurement capabilities of the system and the ability to calculate shape profiles (15). Kreger et al. concluded that the ability to measure dynamic responses of a structure is applicable for many industries, including structural health monitoring, where high speed measurements are beneficial (i.e. cyclic loading) (15). Additional applications of the ODiSI-B system have been seen in the aerospace field, including the monitoring of strain and temperature within the fuselage of an airplane (16). Studies have also been undertaken using the OBiSI-B to measure strains in rails during the passage of trains (17).

Limitations of DDFOS have also been identified. The measurement length and spatial resolution of the system is affected by the acquisition speed (16). Compared to other DFOS systems, DDFOS is currently not applicable for large scale assessments, as the maximum measurement length is only 20 m. Additionally, data post-processing is increasingly more time consuming due to the large data files produced by the combination of high acquisition rates and long-term testing (16).

3. Experimental Procedures

3.1 Field testing site

Ellis Hall, located on the Queen’s University campus in Kingston, Ontario, Canada, was designed and constructed in the late 1950s. The reinforced concrete structure includes a series of cast-in-place T-beam sections tied into rectangular columns. The focus of the
testing is a single T-beam located directly below the Ellis Hall auditorium. The beam spans 11 m between two columns. Due to the limited beam access and the measurement length restrictions of the DDFOS system (i.e. 20 m for the 50 Hz acquisition rate), only the first 6.4 m was instrumented along both the top and bottom of the beam. A section and profile view of the beam can be seen in Figure 1.

3.2 Instrumentation setup

A total of 16 m of nylon coated fibre optic sensing cable (18) was applied to the exterior of the beam as shown in Figure 1. Starting from the column, the first 6.4 m of the beam was instrumented along both the bottom and then the top using a single fibre. The application process included the sanding of the beam to remove the paint and expose the concrete surface. The surface was then cleaned using 99% isopropyl alcohol before the fibre was applied using a two-part epoxy (Loctite E-20HP). The fibre was installed leaving a 50 mm space below the slab and above the bottom edge of the beam. Additionally, the bonding of the fibre started and ended 60 mm away from the column face. An electrical transfer box was installed to protect the loose ends of the fibres when not in use. In addition to the fibre optics, a linear potentiometer (LP) was installed at the midspan of the beam in order to monitor the vertical deflections.

![Figure 1. Schematic of beam instrumentation and set-up](image)

3.3 Loading and monitoring

The location of the beam allowed easy access to the supported tributary area above, within the Ellis Hall auditorium. In order to test the dynamic capabilities of DDFOS, cyclic loading was applied to the beam in the form of students jumping at a constant rate. A class
of 150 first year engineering students (Figure 2) were asked to jump, in unison, within the
centre region of the auditorium above the instrumented beam. To reduce file sizes and
allow for repeatability, the tests were conducted in short bursts of 20 jumps within a 30
second period. The data acquisition for both the fibre optics (ODiSI-B) and LPs were run
for 1 minute in order to capture initial strains and displacements before jumping.

Figure 2. Student volunteers before jumping test began

4. Results and Discussion

Displacement measurements with time from the LP, presented in Figure 3, were recorded
throughout the duration of the testing. The displacement data was zeroed when the
auditorium above the beam was fully occupied, therefore the zero-line shown represents
the loaded condition while the students were at rest.

Figure 3. Beam displacement data from the LP throughout the duration of the testing period
The displacement data in Figure 3 includes a total of 19 jump cycles. The positive peaks represent the time when the students have left the ground, allowing the beam to return to an “unloaded” position at approximately +0.2 mm. When compared to the zero position of the data, it can be concluded that the initial midspan deflection of the beam, caused by the weight of the students at rest, is approximately -0.2 mm. Overall, the beam experienced a maximum deflection of -0.37 mm, as shown in Figure 3, or -0.57 mm when considered from the unloaded position. The Canadian Standards Association (CSA) in Table 9.3 of their concrete design code provides a deflection limit defined as the length of a reinforced concrete member divided by 360 for live loading on a beam (19). When applied to the assessed beam, the maximum allowable deflection is determined to be approximately 30 mm, which is much greater than the observed deflection of approximately 0.6 mm.

Each jump cycle follows a repeating pattern as seen in Figure 4, which gives a close up of two complete jump cycles. There is an initial negative deflection caused by the “push-off” force of the students. As the students leave the ground, an “unloaded” peak is observed as noted previously. When the students make contact with the floor, an “impact” deflection peak occurs, immediately followed by the beam’s response while the students are at rest.

![Figure 4. Two complete “jump cycles” from the LP displacement data](image)

The inconsistency in the shape of the unloaded and impact peaks, shown in Figure 4, is likely due to the irregularity of the students’ jumping pattern. Although asked to jump in unison, it was observed that some participants were out of sync. The beam response (when the students have landed and are at rest) follows a sinusoidal pattern, which potentially follows the natural frequency of the beam system.

The DDFOS system was used to determine the points in time at which the maximum and minimum strains occurred within the bottom fibre optic cable. At these times, the strains throughout the fibre were captured and are provided in Figure 5. The maximum strain (Figure 5(a)) occurs as the impact force of the students is applied to the beam, causing a peak deflection and therefore a maximum strain. Since the tare of the ODiSI-B system was made while the auditorium was occupied (similar to the LP displacement data),
negative strains occur as the students leave the ground, causing the minimum strain (Figure 5(b)).

![Graph showing strain data along the bottom of the beam at the point when the (a) maximum and (b) minimum strains occur](image)

**Figure 5.** Strain data along the bottom of the beam at the point when the (a) maximum and (b) minimum strains occur

In Figure 5(a) compressive strains are observed toward the column end of the bottom fibre (the left side of the figure), between the column and the inflection point at approximately 2 m. Similarly, positive tensile strains are seen in this region in Figure 5(b) before switching to negative compressive strains at the inflection point. This behaviour near the support suggests that there is partial fixity at the column-beam connection.

Figure 5(a) shows that the largest tensile strains, including the maximum strain, are at the midspan of the beam. This is expected, as this is the location of the maximum moment for the beam under this loading condition. Similar to the maximum displacement results, the maximum tensile strains can be compared to the yield strain of the reinforcement provided by the CSA. The Canadian Highway Bridge Design Code states that for reinforcing steel produced between 1914-1972, the minimum yield strength is 275 MPa (20) resulting in a yield strain of 1375 microstrain, which is much greater than the strains observed. The individual peaks within the strain plot represent the location of cracks, which cross the fibre along the bottom of the beam. The presence of these flexural cracks is also expected since the bottom of the beam experiences large tensile stresses, forcing cracks to open. It is interesting to note that the strains as measured do not exceed the cracking strain of the concrete (~100 microstrain), however one must remember that the strain measurements were zeroed with the beam already under load and that the strains due to self-weight are also not included in these measurements. The negative strain peaks in Figure 5(b) represent the closing of the cracks as the beam is unloaded while the students are in the air.
Figure 5 is one example of the advantage of DDFOS in terms of providing distributed data. However, DDFOS can also provide this information at a rate of 50 times per second. The strain data can thus be plotted as a three dimensional surface (i.e. time versus fibre length and strain) as shown in Figure 6 allowing for greater insights into the structure’s behaviour.

![Figure 6. Three-dimensional strain surface](image)

Displayed within Figure 6 are 1985 strain data samples taken throughout the 39.7 seconds of testing from 2823 gauge locations along the 6.4 meters of fibre optic cable. Similar to Figure 5, which was a snapshot of strain along the length of the fibre (strain vs. length), the strain can also be observed for a single gauge location with time (strain vs. time). Figure 7 provides an example of the strain versus time data for a gauge location in the fibre close to the position of the LP at midspan. A similar pattern to the displacement data at midspan can also be seen with the strain data at the midspan location (Figure 7).

![Figure 7. Bottom fibre DDFOS strain data over time at the midspan of the beam](image)
The same 19 jump cycles observed in the LP displacement data can also be seen as negative strain peaks in Figure 7. As noted previously, the negative peaks indicate periods when the beam is unloaded (i.e. students leaving the ground) causing the cracks due to the initial loading to close.

5. Conclusions

The need for proper structural assessment has provided an opportunity to explore new sensing technologies that will improve an engineer’s ability to investigate the performance of existing structures. Advancements in fibre optic sensing technology allow for both distributed and dynamic strain measurements to be made, which can effectively monitor the behaviour of a structure under a variety of different load cases. To test the abilities of DDFOS, a load test was performed on an existing reinforced concrete beam. In addition to an LP located at midspan, fibre optic cables were applied to the beam and monitored using DDFOS as 150 students applied cyclic loading by jumping on the floor above. Both the displacement and strain data were analysed, and the following conclusions were made:

- The use of DDFOS to monitor strain with time and capture the behaviour of an existing reinforced concrete beam under cyclic loading was a success as critical performance indicators such as maximum strains and support conditions could be observed,
- The trends in both the discrete and distributed sensor data sets were in agreement, suggesting that the DDFOS was accurately capturing the behaviour of the beam, and
- The maximum displacement and strain values experienced by the beam due to the maximum cyclic loading expected on the beam were well under the limiting values provided by Canadian design codes.

Acknowledgements

The authors would like to acknowledge the Natural Sciences and Engineering Research Council of Canada for their financial support. The authors would also like to thank Sara Nurmi, Eric Pannese, and Andre Brault from Queen’s University. Finally, the authors would like to thank the 2021 Queen's University class of Engineering and Applied Science students, as well as their professor Colin MacDougall.

References

13. ST Kreger et al., "High-resolution extended distance distributed fiber-optic sensing using rayleigh backscatter", 2007, 6530, p. 65301R,.
15. ST Kreger, AK Sang, N Garg, and J Michel, "High resolution, high sensitivity, dynamic distributed structural monitoring using optical frequency domain reflectometry", 2013, 8722, p. 87220D,.