Distributed strain measurements for culvert assessment

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Abstract

Corrugated steel pipes (CSPs), frequently used for culverts and other drainage structures, are susceptible to corrosion. Current assessment methods for culverts are largely based on the results of a visual inspection, however, these visual observations are not correlated to strength. Additionally, initial lab-based studies have shown that the level of corrosion may not be the only factor that should be considered. Furthermore, the design models available to estimate the structural demands in these highly redundant systems are very approximate. Distributed fibre optic strain sensors have the potential to be a useful tool for these assessments as they can provide thousands of strain readings around the pipe's circumference. This paper reports on a load test conducted on a CSP culvert that was monitored using distributed fibre optic strain sensors. The culvert was monitored under known static vehicle loading as well as while the same vehicle was driven across the culvert at varying speeds. The response of the culvert under static and dynamic loading will be examined to highlight the potential use of these sensors for CSP assessment. Conclusions will be drawn about the potential of these sensors for use in culvert assessment.

1. Introduction

Corrugated steel pipes (CSPs) have played a major role in modern drainage systems since they were first developed in 1896 (1). In recent years, these structures have become more popular in the form of culverts, storm sewers, highway and railway bridges, and underpasses, because of their rapid installation times, low cost, and high strength-to-weight ratio. However, CSPs are susceptible to corrosion and those installed in the mid-20\textsuperscript{th} century are reaching the end of their design service lives. Currently, the assessment of culverts is highly dependent on visual inspection to determine whether rehabilitation or replacement is required (2), which is usually subjective and not correlated to structural strength. Therefore, quantitative assessment approaches are needed to get a better understanding of culvert behaviour.

Experiments have been conducted to study pipe performance in both the laboratory and the field. Meegoda et al. investigated 10 culverts and estimated their service life based on field inspection results (2). Brachman et al. assessed the ultimate limit state of a large-span box culvert in the laboratory (Error! Reference source not found.Error! Reference source not found.). Yeau et al. conducted static and dynamic load tests on 39 in-service highway culverts with a wide range of sizes and geometries (4). And Flener et al. tested a long-span railway culvert during backfilling and in service (5). However, in all these cases, the assessments of these culverts relied on either visual inspection or conventional strain gauges. Strain gauges can only be installed at specific locations around the pipe’s circumference, where the most critical responses are...
predicted to occur. But peak strains and stresses will be missed if they do not occur at those locations, a situation which is possible if the pipe is deteriorated or the models do not capture correct behaviour or address complex geometry (e.g. skewed orientation).

In order to overcome the limitations of discrete strain sensors, fibre optic sensors (FOSs) are employed in the current research. Distributed fibre optic sensing technologies enable the measurement of strain along the entire fibre optic cable, providing a strain profile around the culvert circumference. Compared with strain gauges, FOS systems have many advantages such as lower installation time, lower sensor costs, water resistance, inherent safety since they do not transmit electrical current, immunity to electromagnetic interference, and most importantly, no requirement for accurately predicting critical behaviour locations prior to testing (6). While static FOS measurements have been used in buried infrastructure monitoring (6), bridge assessment (7), and laboratory material tests (8), dynamic FOS systems have never been used for culvert monitoring to the authors’ knowledge. As such, there is a need to investigate whether distributed FOS can be used to monitor a culvert’s response to dynamic loading. Especially since compared to static loads, dynamic loads may have a different impact on pipe response (4). In this paper, dynamic fibre optic measurements for culvert monitoring in the field will be explored for the first time.

The objectives of the current study are: (a) to investigate the feasibility of using static and dynamic FOS measurements for culvert assessment in the field and (b) to study the impact of static and dynamic loading on a culvert.

2. Background

Up until now, discrete measurement techniques have been the predominant method for strain monitoring of CSPs during field tests. Yeau et al. (4) tested 39 in-service corrugated steel highway culverts in Ohio under both static and dynamic loadings. The tested culverts had a wide range of shapes, skew angles, cover depths, ages, and conditions. Strains were monitored using 14 strain gauges and deflections were measured by 6 displacement transducers. According to their results, deflections and strains decreased nonlinearly with increasing backfill height and in most cases, maximum deflections in dynamic tests were lower than those in static tests. Flener et al. (5) assessed a corrugated steel railway culvert with an 11.12 m span in Sweden, using 6 strain gauges and a linear variable differential transformer (LVDT). The strains and deflections were recorded during backfilling and the passage of a cargo train. It was reported that theoretical moments and axial forces during compaction showed good agreement with test results, while theoretical moments due to live load were conservative. However, these results may not be conservative if the strains do not reach peak values at the discrete sensor locations due to influences such as heterogeneous soil properties, skew angles, and localized deterioration.

In the current research, a Rayleigh optical backscatter reflectometer (OBR) distributed FOS technology is used for both static and dynamic tests. An optical fibre is composed of a central core with a unique refractive index, a cladding with a lower refractive index to reflect the light waves back in to the core, and a coating to protect the fibre (9). The Rayleigh backscatter system takes advantage of imperfections in the fibre core that
reflect light back down the core. The frequency of the reflected light changes when the cable is strained, and the change in reflected light frequency measured by the analyser can be linearly converted to a strain change measurement. Compared to Brillouin-based distributed strain sensors, which are commonly used in civil engineering, Rayleigh backscatter-based systems provide better spatial and strain resolutions (8). More discussion on the Rayleigh FOS system can be found in Hoult et al. (8). While the same fibre optic cables can be used for both static and dynamic measurements, different analysers are required. In this research, static tests were conducted using the Luna OBR 4600. The gauge length and sensor spacing is adjustable but was set to 20 mm and 20 mm, respectively, in the current static tests. The maximum sensing length is 70 m. In the dynamic tests, the Luna ODiSI-B was employed to measure strains. The gauge length and sensor spacing of this system is pre-set at 5.2 mm and 2.6 mm, respectively. The maximum sensing length is 10 m at a frequency of 100 Hz or 20 m at 50 Hz.

The Rayleigh technology has already been applied in laboratory CSP experiments. Simpson et al. (6) explored applications of fibre optics for buried infrastructure in a bespoke testing facility. Details about the testing facility can be found in Regier et al. (10). Both nylon-coated and polyimide-coated fibres were attached on a deteriorated 1.8 m diameter CSP. Surface live loads were applied on a pair of steel pads to simulate vehicle loads. The results from both the nylon and polyimide fibres showed agreement with strain gauges but were able to capture the distributed strain profile around the circumference, which was not obtainable from discrete strain gauges. The polyimide fibres offer the benefit of improved accuracy over the nylon fibres, but have limitations in terms of durability and the ability to measure across cracks. Regier et al. (10) performed live load and ultimate load tests on a horizontal-ellipse corrugated steel culvert using distributed strain measurement. Those measurements captured the pipe behaviour during backfilling as well as during service and ultimate load testing. However, it is still crucial to obtain field test data using fibre optic sensing because of the difference between field and laboratory conditions, such as variable soil characteristics, real vehicle loadings, deterioration etc. Furthermore, tests with the dynamic FOS system have not yet been conducted on culverts.

3. Experimental methods

3.1 Test site

The tested culvert is a semi-circular arch sitting on concrete footings (see Figure 1) located under Cordukes Road in Kingston, ON, Canada (44°17'42.5"N, 76°34'33.8"W). The span is 2.75 m and the rise is 1.75 m including the 0.35 m footing. The average cover depth is about 0.6 m, which is shallow enough to capture responses under live loads. The culvert is made of corrugated steel plates which are bolted together. The corrugation has a standard profile of 152 x 51 mm (6 x 2 in) with plate thickness of 3 mm. According to the Corrugated Steel Pipe Institute (CSPI) Handbook of Steel Drainage and Highway Construction Products (1), this cross section has a moment of inertia (I) of 1057.25 mm⁴/mm and an area (A) of 3.522 mm²/mm. The steel is assumed to have a Young’s modulus (E) of 200,000 MPa. There is a skew angle of about 45° between the road and the culvert. The culvert is usually empty and only filled with water in rainy seasons. The water level is normally lower than the footing level and no
obvious corrosion was observed above the concrete footings in the pipe, though some corrosion was observed near the seams and bolts.

![Image](image_url)

**Figure 1. The field site showing the corrugated steel culvert**

### 3.2 Instrumentation

Fibre optic strain sensors, total station prisms, a displacement transducer and particle image velocimetry targets were installed prior to testing to measure strains and displacements. But only the fibre optic sensor results will be presented in this paper.

As mentioned before, nylon fibres have the advantage of greater durability versus polyimide fibres, which is an important factor in field tests. Therefore, nylon-coated fibres were chosen in the current research. Two fibre optic cables were glued on the internal wall along both the crest and valley of the corrugation around the circumference (Figure 2(a)). Fibres were glued with an adhesive (Loctite 4861) after the surface had been cleaned using sandpaper, wipes, and alcohol. More details about the fibre installation procedures can be found in previous studies (6, 8). In order to prevent future deterioration of the tested culvert, none of the galvanizing coating was removed when installing the fibres. As shown in Figure 2(b), the fibres were not glued across the bolted seam, they were left loose in this area due to concerns about potential signal loss in the measurements caused by bending the fibres around the sharp edge of the seam.
3.3 Testing procedure

Tests were conducted on the 23rd of September, 2017. A dump truck (Figure 3) loaded at a local facility was used in both the static and dynamic tests. The truck had 4 axles, but the middle axle was raised during testing as seen in Figure 3. According to the Canadian Highway Bridge Design Code (CHBDC) S6-14 (11), the contact tire area of the rear wheels (including middle and back wheels) is assumed to be 0.25 x 0.6 m, while the contact area of front wheels is 0.25 x 0.25 m. The measured wheel loads for the truck are given in Table 1.

In Figure 4, the black squares are the truck wheels, the red lines represent the pair of fibre optic sensors, and the blue line represents the truck route for the dynamic tests. In the static test, the truck was heading south as pictured in Figure 3. The right back wheel of the truck was located over the crown of the culvert, where the fibre optic cables were installed (Figure 4). The westbound lane was closed to traffic during the static test. In the dynamic tests, the truck was driven across the culvert at speeds of 10, 20, 30, 40, and 50 km/h. Measurements were started several seconds before the truck arrived and ended several seconds after the truck passed. Since the total length of fibre optic cables was approximately 13 m, the measurement frequency was taken as 50 Hz (the maximum available for that fibre length).
Figure 3. The dump truck during static testing

Table 1. Wheel loadings of the truck

<table>
<thead>
<tr>
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<th>Front Wheel (kN)</th>
<th>Middle Wheel (kN)</th>
<th>Back Wheel (kN)</th>
</tr>
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<tbody>
<tr>
<td>Left</td>
<td>48.1</td>
<td>37.6</td>
<td>41.2</td>
</tr>
<tr>
<td>Right</td>
<td>51.6</td>
<td>44.7</td>
<td>37.7</td>
</tr>
</tbody>
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Figure 4. Top view of the culvert, the road, fibres, and the truck route
4. Results and discussion

4.1 Static test results

The distributions of incremental strains (due to truck loading) around the circumference measured by the fibre optic sensors at the valley and crest of the corrugation for the truck position in Figure 4 are shown in Figure 5. The results are plotted using a polar coordinate system in a semicircle so that they follow the circumference of the culvert. While the tested culvert is not a perfect semicircle, it is clearer to illustrate the results this way. Strain distributions are recorded from the south footing, through the crown, to the north footing. The gaps in the curves represent the locations of seams, where no valid data were obtained and so are left blank. The strains in Figure 5 are due to live load only. One can see that the strains vary around the circumference but are largely compressive as would be expected for an arch structure.

![Figure 5. Strain distributions from the static test at: (a) valley; (b) crest](image)

The thrust and bending moments in the culvert due to the static truck load are given in Figure 6 and Figure 7, respectively. The calculation method for getting these values from measured strain is discussed in detail in Regier et al. (10). In Figure 6, it can be seen that the entire culvert is in compression, even though tension strains were measured at some locations (see Figure 5). The thrust forces are distributed unevenly around the circumference and the maximum thrust force (-30.4 kN/m) is observed at about a 30° offset from the crown to the north. This result is inconsistent with the CHBDC (11) and the American Association of State Highway and Transportation Officials (AASHTO) (12) codes, in which the thrusts at the springlines are assumed to be the maximum thrusts. Moreover, this critical response would probably be missed if traditional strain gauges were used to monitor this culvert since it is not at either the crown or the springlines. Therefore, a distributed fibre optic sensing technology can provide a better understanding of pipe behaviour. The thrust forces at both springlines have different magnitudes. The thrust at the south footing is nearly zero, however, the thrust at the north footing is about 15 kN/m. Meanwhile, the maximum thrust position is closer to the north. Hoop stresses can be calculated by dividing the thrusts by the wall area resulting in a maximum hoop stress of -8.6 MPa, which is less than the yield stress of the steel (assumed as 230 MPa according to the CSPI Handbook (1)).

Figure 7 shows the bending moment profile around the circumference in the static test. Herein, the moment is defined as positive when the outside of the pipe wall is in tension and the inside wall is in compression. It can be seen that the culvert has a sagging
moment near the crown and a hogging moment near both shoulders. The absolute value of the minimum negative moment (0.58 kNm/m) is higher than that of the maximum positive moment (0.40 kNm/m). The moments decrease near springlines, however, while there is a near zero reading at the south springline, there is still a moment at the north springline. It was noted in the field that the connection details between the culvert and the footing were different on both sides of the culvert, which may have led to the difference in support reactions. As with the thrust force results, the critical values of bending moments are also not obtained at predictable locations, which makes it difficult to capture these values using strain gauges. In both the CHBDC (11) and AASHTO (12) codes, bending moments are not taken into account when designing culverts with shallow corrugations (with a pitch between 150 and 230 mm and a depth between 50 and 65 mm). However, the maximum calculated bending stress is 14.8 MPa, which is larger than the maximum normal stress due to thrust (8.6 MPa). Therefore, for a culvert with a shallow cover depth, bending moments are possibly just as important as thrust forces and potentially should be considered in standards.

![Figure 6. Thrust forces around the circumference in the static test](image1)

![Figure 7. Bending moments around the circumference in the static test](image2)

4.2 Dynamic test results

Strains were measured every 0.02 s during the dynamic tests. Thrusts and moments can be subsequently calculated with the same method as used in the static post-processing. As the dynamic results have lower accuracy than the static ones (±25 microstrain (13) versus ±1 microstrain (6), respectively), every 20 readings around the circumference were averaged together to increase the measurement accuracy (at the expense of spatial
resolution) when processing the dynamic data, providing an equivalent sensor gauge length and spacing of 52 mm.

At most positions around the circumference, the culvert response to the front wheel is higher than the response to the rear wheels. However, in order to compare the dynamic results to the static test results, only the responses to the rear wheels are discussed here. Figure 8 shows the thrust force distributions at 10 km/h at the moment when the maximum thrust due to the rear wheels is achieved. Generally, the dynamic results (Figure 8) have a similar pattern to the static results (Figure 6). Thrust forces on the south side are smaller than those on the north side and reach zero at the south springline. On the north side, the thrusts near the springline are around -20 kN/m. The maximum thrust (-34.1 kN/m) in Figure 8 is larger than the static test and is offset from the maximum static location by about 15° to the north. Compared with Figure 6, thrusts in Figure 8 are larger near the north springline and lower near the crown, so the truck was possibly closer to the north footing at the moment the data for Figure 8 was captured. This may be because the results in Figure 8 were obtained at the peak thrust value during the passage of the rear wheels and the truck location was not exactly the same as in the static test. Therefore, peak responses due to moving vehicle loading can be measured with the dynamic FOS system and their locations may be different from the locations observed in static tests.

Maximum and minimum bending moments obtained during the 10 km/h test during the passage of the rear wheels are shown in Figure 9. The profiles of both figures are similar to moment results for the static test (Figure 7). The minimum and maximum moments at 10 km/h (-0.50 kNm/m in Figure 9(a) and 0.39 kNm/m in Figure 9(b)) are lower than the minimum and maximum static moments. Compared with static results, the minimum negative moment occurs at almost the same location near the crown, while the maximum positive moment occurs closer to the crown. Moments near the south springline in both figures are zero and those at the north springline are about 0.20 kNm/m. Furthermore, the minimum negative and maximum positive moments were not achieved at the same time, which meant the truck was at different locations when they occurred.

![Figure 8. Max thrust forces around the circumference at 10 km/h for the rear wheels, t = 6.00 s](image)
Figure 9. Bending moments around the circumference at 10 km/h for the rear wheels: (a) minimum negative moment, $t = 5.74$ s; (b) maximum positive moment, $t = 5.68$ s

Figure 10 presents the thrust changes over time at 10 km/h at the location of the maximum thrust in Figure 8 (i.e. the north shoulder). The three peaks represent the passing of the three truck axles. Measurement noise of ±1kN/m can be seen before and after the truck drove over the culvert. At this point in the pipe, the front wheel has almost the same impact on the culvert as rear wheels, even though it has a higher impact at most other locations. The thrust forces between the last two peaks do not return to zero, because the distance between the middle and back wheels is small enough that they can influence the culvert simultaneously. From the times given in Figure 8 and Figure 9 ($t = 6.00$, 5.74, and 5.68 s, respectively), it is found that the maximum thrusts occurred under the back wheel and the maximum moments peaked under the middle wheel.

Figure 10. Thrust force changes over time at 10 km/h at the maximum rear wheel thrust location

4.3 Comparisons between static and dynamic test results
Comparisons of bending moments between the static and dynamic tests are shown in Figure 11. Curves at varying speeds are plotted at the time of the minimum negative moments due to the rear wheels. All the profiles have a similar pattern. The minimum negative moment occurred during the static test, followed by the 20, 30, and 10 km/h, respectively. It is observed that the measurement noise increases as the speed increases, and that data points are not recorded at 30 km/h near the northern shoulder.

![Figure 11. Comparisons of bending moments between the static test and dynamic tests](image)

5. Conclusions

Distributed fibre optic sensing systems were used to monitor a corrugated steel culvert in the field under static and dynamic truck loads. Distributed strain profiles around the circumference of the culvert were successfully captured in both static and dynamic tests. Dynamic measurements were possible and provided useful structural response results. Data collected enabled thrust and moment calculations for further assessments.

In the static test, the entire culvert was subjected to compression thrust forces. The maximum thrust occurred near the north shoulder, which was inconsistent with the expected location (springline) from the CHBDC and AASHTO design codes. Thus, peak values might be missed using discrete strain gauges. The minimum negative moment was larger than the maximum positive moment. And the bending stress was higher than the thrust induced hoop stress, which meant moment could also be a critical factor when designing a culvert under a shallow cover depth.

In the dynamic tests, the overall behaviour of the culvert was recorded during the passage of the truck at different speeds. The dynamic sensors had lower accuracy than the static ones. Patterns of thrust and moment were both similar to static test results. While the maximum thrust force at 10 km/h was higher than that in the static test, the minimum and maximum moments were lower. Moreover, the peak values of thrusts and moments were not achieved at the same time.

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