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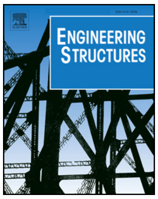

Assessment of a steel model truss using distributed fibre optic strain sensing

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ABSTRACT

Steel truss bridges are a critical part of the North American rail bridge inventory, with many being over a century old. Current assessment techniques are often based on visual inspections, which do not provide quantitative data to assess critical areas of the bridge with damage or deterioration. Distributed fibre optic strain sensors may be able to provide quantitative data to assess the effects of damaged members, different connection types, or deterioration. As a first step towards developing this technology for truss bridge assessment, a model truss bridge with three types of joint conditions and two types of simulated deterioration was monitored using two types of distributed fibre optic strain sensors while under static and cyclic loading. Although the impact of the changing joint conditions was clearly evident from displacement measurements, it was only possible to explain the difference in displacement measurements with the aid of the distributed strain data. At model scale, member continuity and joint movement played a significant role in the truss behaviour, which was evident from the strain data. Localized deterioration was detectable using dynamic distributed strain measurements although proximity to the deterioration and choice of sensing fibre influenced the accuracy of the measurements. Based on the results of the lab scale testing, distributed strain monitoring shows promise for steel railway truss bridge assessments although field trials of the monitoring technology are a required next step.

1. Introduction

The failure of the I-35W Bridge in Minneapolis, Minnesota, USA, was a result of inadequate design and inspection of the gusset plate connections that resulted in the deaths of 13 people and an additional 145 injuries [1]. One of the most common monitoring solutions for bridges involves visual inspection, however shortcomings of this monitoring approach include differences in accuracy, reliability, and quality based on which inspector performs the inspection [2]. Using a monitoring technology that can provide distributed quantitative data, which can be used to assess structural integrity and locate damage over time, would help to supplement the results of a visual inspection.

There have been many different ways in which steel truss bridges have been monitored for both damage and structural performance. Artificial neural networks have been used, however they require significant computational effort, inputting known parameters such as mode shapes and natural frequencies, and back propagating based on known outputs in order to be effective at locating damage [3]. Yu et al. [4] were able to perform a structural damage assessment using frequencies measured with accelerometers to detect damage due to loosened bolts on a fabricated truss structure. DelGreco et al. [5] instrumented a century-old steel railway truss bridge with 372 weldable strain gauges, and found unexpected behaviour in the truss such as non-uniform load distribution and out-of-plane bending. Moreu et al. [6] used a wireless sensor network consisting of strain gauges and accelerometers to monitor bridge behaviour under in service train loading. However, since these sensors were discrete in all these cases, it was difficult to accurately assess and locate damage using this data. A distributed strain sensor could potentially overcome the limitations of discrete sensors and provide insight into the structural performance of both damaged and undamaged trusses.

Fibre optic sensors (FOS) are a technology that have the capability to measure distributed strains based on the backscattered properties of light. Two types of backscatter can be used to measure distributed strains: Brillouin and Rayleigh. Rayleigh backscatter provides higher spatial and strain resolution readings, which is ideal for localized damage detection, when compared to Brillouin Optical Time Domain Reflectometry [7]. There have been several implementations of Rayleigh backscatter based distributed strain sensing in reinforced concrete [7,8]. However, the only application of this technique for damage detection in steel was on steel plate specimens [9]. To the authors' knowledge, no one has yet used distributed strain sensing on a steel truss bridge, and more specifically to evaluate whether the strains can be used to assess the behaviour of different types of joint conditions and for the detection of deterioration, which is the purpose of the current investigation.

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Fig. 1. The Mile 17.7 Grimsby-sub CN Rail Bridge in Jordan, Ontario: (a) Full bridge, (b) modelled span.

In order to explore the use of distributed sensing for assessing the impact of joint conditions and deterioration detection, a model truss was constructed, instrumented with FOS, and tested under static and cyclic loading. The first set of experiments consisted of monitoring the truss under pseudo-static loading using both displacement and distributed static strain measurements under three varying joint conditions. The second set of experiments involved the use of distributed dynamic strain measurements to detect varying degrees of simulated corrosion, and to detect cracking in the outer diagonals of the truss under cyclic loading.

The objectives of this research are to: (i) assess the impact of joint condition on truss deflection, (ii) use distributed strain data to assess the impact of joint condition on truss behaviour, (iii) compare the performance of two fibre optic sensing cables in terms of their ability to capture local changes in strain, and (iv) evaluate whether dynamic distributed strain sensors can detect the presence of simulated corrosion and cracking damage. The next section introduces background information on FOS, the model truss, and the experimental campaign. The experimental results will then be presented and discussed, followed by some final concluding remarks.

2. Fibre optic sensing background

There are many advantages to using FOS, such as their resistance to electromagnetic interference, large data transmission bandwidth, resistance to corrosion, and small size and weight. There are two main types of FOS: discrete and distributed. Discrete sensors, such as fibre Bragg gratings (FBGs), are point sensors that have been implemented on steel bridge structures, as demonstrated by the work of Tam et al. [10] who used FBGs to monitor the Tsing Ma Bridge. That particular study required the installation of 40 sensors to obtain measurements across various members, yet did not obtain distributed measurements of the structural behaviour.

Distributed FOS make use of three types of light scattering: Raman, Brillouin, and Rayleigh. Raman is used to measure temperature and cannot be used to directly measure strain. The sensing range of Raman sensors can vary. For example, for a spatial resolution of 10 mm, they can have a sensing range of 1 km, or for a spatial resolution of 17 m, they can be used up to 37 km [11,12]. This makes these sensors ideal for long-scale temperature sensing applications. Brillouin backscatter sensors work by measuring the frequency of light that is reflected back along the fibre. One of the most commonly used technologies is Brillouin Optical Time Domain Reflectometry (BOTDR), which has sensing range of kilometres. This sensing range is ideal for large-scale geotechnical and structural applications, however the spatial resolution (~1 m) and strain accuracy (~30 $\mu\varepsilon$) [13] is an issue for structures with localized variations in strain, such as would be seen in a damage detection application. Rayleigh backscatter occurs due to the interaction between a light pulse sent into the fibre core from the analyzer, and imperfections distributed along the full length of the fibre due to subtle variations in glass density. Systems based on Rayleigh backscatter have spatial resolutions on the order of millimetres and strain accuracies of approximately 1 $\mu\varepsilon$ [14]. However, the systems used in the current research have maximum sensing lengths of 70 m for static measurements and 20 m for 50 Hz dynamic measurements.

Fibre optic cables require a coating to increase the durability of the fibre for civil engineering applications. There are many types of coatings that can be used, however the two fibres that will be used throughout the current testing campaign have a nylon and a polyimide coating. The nylon coating is more durable at a considerably lower cost than the polyimide fibre (~$0.15/m for nylon versus ~$2.50/m for polyimide), however it has been shown to be less effective at measuring localized changes in strain due to slip between the cladding and the coating [9]. The fragile nature of polyimide coated fibre optic sensors present challenges for field monitoring, and therefore have been limited to laboratory testing despite their advantage over nylon fibres in strain sensitivity.

3. Experimental set up

The model truss constructed was based on the Mile 17.7 Grimsby-sub CN Rail Bridge in Jordan, ON. The bridge has 8 spans that are Warren trusses with verticals, which is the second most common truss type for railway bridges after the Pratt truss. The two end spans of the bridge, one of which was modelled in this study, have a pin and a rocker support while the six interior spans have a fixed and a rocker support. The whole bridge is shown in Fig. 1(a) with the modelled span indicated, and a close-up of the modelled span is shown in Fig. 1(b).

3.1. Model truss

Only one of the eight truss spans was constructed for the model. Also, the Mile 17.7 Bridge truss consisted of a series of built-up sections whereas the model truss was constructed using commercially available angles and channels of 50W and 44W steel as listed in Table 1. The top and bottom chords consisted of two back to back channels, and all diagonals and verticals consisted of two back to back angles. The top and

Table 1
Properties of the truss members.

Member	Member designations	Area (mm^2)	Second moment of area (mm^4)	Length (mm)
Top Chord	2 – C75 × 6	1526	1.34×10^6	3063
Bottom Chord	1 – C75 × 6, 1 – C75 × 5	1456	1.30×10^6	1822
Vertical	2 – L32 × 32 × 3.2	384	3.68×10^4	386
Diagonal	2 – L32 × 32 × 3.2	384	3.68×10^4	514