Longitudinal strain monitoring of rails using distributed and discrete sensors

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Abstract

With one of the most extensive rail networks in the world (48,000 km of track), rail transportation is vital to Canada. Newer, more powerful locomotives hauling heavier freight at higher operating speeds are capable of producing twice the tractive effort of older locomotives. This has raised concerns regarding the risks associated with exceeding the longitudinal load carrying capacity of in-service rail support systems (e.g. bridges). There is now a growing need to investigate the longitudinal stresses that rails are being subjected to and to evaluate the potential requirement for rail rehabilitation. Past studies exploring structural health monitoring (SHM) techniques for rail infrastructure have focused on the application of discrete strain sensor technologies making it difficult to understand the rail’s full strain profile under locomotive loading. This paper introduces a series of dynamic field tests conducted to assess the suitability of both distributed and discrete sensors to measure longitudinal rail strain under locomotive braking. A distributed fibre optic sensor (FOS) based on Rayleigh backscatter in addition to electrical resistance strain gauges were used. Conclusions will be drawn as to the most applicable rail monitoring technology and future research directions will be outlined.

1.0 Introduction

Railway bridges are being exposed to greater longitudinal forces than their original design intended and, consequently, are becoming a growing concern as their conditions worsen with age (1). With over 100,000 bridges, more than half predating 1920, North America’s rail network is expected to exceed its freight tonnage capacity over the next 20 years as today’s locomotives are hauling heavier freights at higher operating speeds (2). A study by Foutch et al. conducted to measure longitudinal forces in railway bridge decks under the operating limits of new locomotives at the time measured forces 30 times greater than those used to design the original structure (1). Therefore, it is imperative that condition assessment of rail infrastructure accounts for longitudinal forces so that actions may be taken to ensure these bridges are performing adequately under these increasing loads.
Condition assessment of rail infrastructure typically consists of periodic visual inspections made by trained personnel walking along the railway network (3). However, this method is only effective at identifying surface damage (3) and thus has limited value in longitudinal force monitoring. Instead, more novel strain sensing technologies have been utilized in recent years as methods of measuring longitudinal rail forces. Srinivas et al. bonded electrical resistance strain gauges at discrete locations on a railway bridge and were successful in quantifying the longitudinal force at several locations in the rail and bridge members due to the weight of a passing locomotive (4). Wang et al. used bi-directional fibre Bragg grating (FBG) strain sensors to accurately measure longitudinal force at a single location on a rail (5). A limitation of these systems is that discrete strain sensors cannot produce the full strain profile along the entire length of a rail or structural member without using a prohibitively expensive number of sensors. This has led to the use of distributed fibre optic sensors as an improved strain sensing technology for rail applications. Minardo et al. measured static and dynamic strain under an in-service train on a 60 m section of rail using a fibre optic sensor based on Brillouin optical time-domain analysis (BOTDA) (6). This practical sensing length, coupled with the high accuracy of the BOTDA system was still limited by its 1 m spatial resolution. This resolution may be too large to measure significant changes in strain over short distances, which is a possibility as wheel loads cause strain variation between ties, which typically have a maximum spacing of 610 mm (7). Yoon et al. achieved a more practical spatial resolution of 36 mm, in the measurement of longitudinal rail strain, using a distributed fibre-optic sensor based on Brillouin optical correlation domain analysis (BOCDA) (8). However, this system was not tested under field conditions with an in-service locomotive and the sensing length was only 2.8 m. The optimal solution for longitudinal force measurement in rail applications would be a fully distributed fibre optic strain sensor with a high spatial resolution and practical sensing length proven under field conditions.

Distributed fibre optic sensing based on Rayleigh backscatter could offer such a solution as this technology possesses a gauge length of 5.22 mm, sensor spacing of 2.61 mm and a dynamic sensing range of 20 m (9). While this range limits its usefulness for large-scale railway monitoring, it is still a practical length for condition assessment of shorter, more critical rail sections and bridge members. Distributed sensors based on Rayleigh backscatter have been used in the past for various structural monitoring applications. Regier and Hoult used this fibre optic sensing system on the surface of four beams of a reinforced concrete bridge in Madoc, Canada (10). A series of electrical resistance strain gauges were also installed on the beams at locations directly adjacent to the fibres in order to assess the correlation of strain data between the two technologies under a moving truck load. Results showed good agreement between the two types of sensors proving the usefulness of this fibre optic system in providing accurate and meaningful results in bridge monitoring. In the context of rail applications, Wheeler et al. demonstrated the effectiveness of this fibre optic system in measuring high resolution, dynamic rail strain through a series of lab and field tests in Kingston, Canada (11). However, it was concluded that vibration-induced noise in the strain data due to high locomotive speeds limited the overall applicability of this system.

A distributed fibre optic sensing system based on Rayleigh backscatter has been used with success in both bridge and rail monitoring. Thus, an opportunity exists to combine these applications by assessing the effectiveness of this system in measuring longitudinal strain in railway bridges. This information would lead to new knowledge regarding how
longitudinal forces transfer through railway bridges and will give further insight into their condition under today’s heavier train loads. The current investigation is a preliminary step in this research aimed at conducting a series of field tests to assess the correlation of longitudinal rail strain data between distributed and discrete sensors. The objectives are threefold: (i) to measure discrete and distributed strains under locomotive braking, (ii) compare discrete and distributed strain measurements, and (iii) to better understand longitudinal force transfer in a rail. The sections that follow will provide a background on fibre optic sensor technologies and a description of the test site, instrumentation, and testing procedure. Results will be presented and discussed, followed by conclusions outlining the major findings of the research.

2.0 Background

Fibre optic sensors can be classified based on the distribution of sensors along the length of the fibre and the light scattering process that is observed in the core. Discrete, or point, sensors have a single measurement point located at the end of the fibre. Integrated, or long-base, sensors also have a single sensor at the end of the fibre, however, integrated over a longer measurement base. Quasi-distributed, or multiplexed, sensors contain multiple sensor points at regular intervals along the length of the fibre. Distributed sensors are capable of sensing at any point along the fibre (12,13,14). For applications in the rail industry, quasi- and fully-distributed sensors have widely been used taking advantage of FBG techniques and Brillouin scattering.

2.1 Fibre Bragg Grating

Fibre Bragg Grating sensors are the most widely used fibre optic technique for continuous measurement applications, as 2/3 of monitoring projects to date, using fibre optics, have employed this quasi-distributed technology (15). Bragg gratings are density alterations in the optical core facilitating the reflection of light and are made at regular intervals by exposing the fiber to high-intensity ultraviolet light (16). FBG sensors can be used to perform simultaneous measurement of temperature and strain (16) and can achieve a spatial resolution of 2 mm (15). However, the main limitation of FBG sensors lies in their sensing range, which is commonly limited to 100 gratings (17).

2.2 Brillouin

Brillouin-based fibre optic sensors are often used for long-distance sensing applications. When a pulse of light is sent along an optical fibre, counter propagating “Brillouin scattering” waves, produced by stimulated acoustic vibrations, act to weaken this forward-moving pulse (18). The frequency shift between with the original pulsed light and these Brillouin scattering waves can be measured and related to physical perturbations affecting the fibre (19). Sensing techniques relying on this process, such as BOTDA systems, can monitor up to 200 km (20). However, the practicality of this method for short-range monitoring (up to 1 km (21)) is limited by the technologies’ 100 mm spatial resolution (22).
2.3 Rayleigh

Systems based on Rayleigh backscatter offer a potentially optimal solution for short-range strain measurement applications as they possess the highest potential spatial resolution of the distributed fibre optic sensor techniques. Rayleigh scattering is produced by the inherent and random microscopic variations in the optical core’s refractive index (23). Variations in the intensity of these backscattered waves is measured to detect attenuation in the signal, which will drop due to external events acting on the fibre (24). These systems can achieve a sensor spacing of 2.61 mm while sampling at 50 Hz, at the expense of a limited dynamic sensing range of 20 m (9). This technique was used in conducting the current investigation.

3.0 Experimental Procedures

A series of field tests, in which a locomotive braked over various instrumented sections of rail, was conducted to assess the correlation between dynamic strain measured by discrete and distributed sensing technologies. The collected data was then used to calculate the distribution of longitudinal force in the rail in an attempt to determine the force transfer mechanism between the axle load and the underlying rail system.

3.1 Test Site

The field tests were conducted at National Research Council Canada’s (NRC) Rail Research Laboratory in Ottawa, Canada. A 152 m section of 100lbs RE jointed rail was chosen for the tests, as shown in Figure 1. Each jointed rail section measured approximately 11.8 m in length.

Figure 1. View of the 100lbs RE rail used at the test site.
3.2 Instrumentation

The outer side of two adjacent sections of rail was instrumented for these tests. Optical fibre, with an 8.2 μm diameter core and nylon coating, was used in conjunction with a LUNA Innovations ODiSI-B dynamic analyzer which possesses a maximum dynamic sensing range of 20 m, gauge length of 5.22 mm, sensor spacing of 2.61 mm and a strain accuracy of +/- 10 µε (9). The instrumented surface of the rail was cleaned using water and a degreasing agent prior to bonding the fibres using a cyanoacrylate adhesive (Loctite 4861). The complete instrumentation plan is illustrated in Figure 2.

Two adjacent segments of the same rail were instrumented. Rail 1 consisted of a 3.0 m long section of fibre running along the rail’s flange and head at a height of 18 mm and 135 mm, respectively, above the bottom of the rail. Looping the fibre in this orientation enables the measurement of strain at two heights at every point in the rail, allowing a complete strain profile to be derived at each sensing point. Rail 2 was instrumented in a similar orientation, however, over a longer length of 7.5 m. Rail 2 was also instrumented with a pair of electrical resistance strain gauges bonded at elevations of 50 mm and 90 mm in the same longitudinal location. The gauges were placed equidistance between two adjacent ties situated within the length of the rail containing fibres, as shown in Figure 3. Uniaxial strain gauges, from Tokyo Sokki Kenkyujo Co., Ltd., with a 5 mm gauge length and 350 Ω impedance were used (25).
3.3 Testing Procedure

The braking tests were conducted using the CSTX 1003 locomotive shown in Figure 4.

For each test, the locomotive started from rest away from the instrumented section and accelerated so that its speed approaching the section would be less than 16 km/hour to limit noise in the fibre data. The locomotive then applied its brakes just before its front wheel axle reached the instrumented section and so that it would come to a complete stop with the front wheel axle directly over the fibres. Sensor data was recorded once the locomotive was within 3 m of the instrumented section.
4.0 Results and Discussion

4.1 Strain Gauge Data

Figure 5 shows the strain measured by the two electrical resistance gauges during a braking test in which only the locomotive’s front bogie passed over the gauged section of rail before coming to a complete stop. The red and blue data curves represent the strain measured by the gauges bonded at a height of 50 mm and 90 mm, respectively, above the bottom of the rail.

![Figure 5. Discrete strain gauge data from a locomotive braking test.](image)

The sharp spikes in the strain measurements (circled in Figure 5) correspond to points during the test in which one of the locomotive’s wheels passed directly over the vertical pair of strain gauges. The equal and opposite nature of the data indicates that the gauges were bonded on either side of the rail’s neutral axis. It should also be noted that the blue curve shows an abrupt positive peak in strain, indicated on Figure 5, when the locomotive’s wheel is directly over top of the gauges suggesting the occurrence of localized stress concentrations.

4.2 Distributed FOS Data

Figure 6 shows the strain measured along the 3 metre length of fibre bonded to Rail 1 and at the point in the test when the locomotive had come to a complete stop. The red and blue curves correspond to the fibre bonded to the rail at heights of 18 mm and 135 mm, respectively, above the bottom of the rail. It should be mentioned that when looking at Figure 6, the locomotive had been travelling from the right side to the left side of the figure prior to the readings being taken.
As seen on Figure 6 and suggested by the spikes in the strain curves at 2.5 m, the locomotive came to a complete stop with only its front wheel reaching the rail segment instrumented with the fibre. The data presented in Figure 6 illustrates the important advantage that a distributed FOS based on Rayleigh backscatter has over conventional strain gauges: that the high spatial resolution of the sensor allows it to capture the complete strain response of the rail due to locomotive loading.

4.3 Comparison between Strain Gauge and FOS Data

A comparison between the strain measured by the distributed and discrete sensors is shown in Figure 7. It should be noted that the strain gauge and FOS data was collected from separately conducted tests. The solid red curve displays a strain spike measured by the electrical resistance gauge bonded to Rail 2 at a height of 50 mm above the bottom of the rail. The solid blue curve displays a similar spike measured by the fibre optic sensor at the same discrete location as the electrical resistance gauge on Rail 2, but at a height of 18 mm above the bottom of the rail. The red-dashed curve is the strain calculated by extrapolating the total strain profile formed by the two electrical resistance gauges to the elevation of the fibre on the rail.
The results displayed in Figure 7 indicate that the FOS experiences more noise than the electrical resistance gauge. Additionally, the maximum fibre optic strain is lower than the maximum adjusted strain as this data was collected from separately conducted tests. These results also indicate that the FOS is less effective than the strain gauges at capturing strain peaks, which may be resolved in future tests by using a higher sampling rate with the FOS.

4.4 Understanding Rail Behaviour

Knowing the strain at two elevations on the same section of rail permits the calculation of curvature, which can be used to calculate axial force at this location if the geometric centroid of the rail is assumed (11). Figure 8 shows the axial force calculated from the strain data in Figure 5.
As indicated on Figure 8, the rail experiences tension immediately before the locomotive’s wheel passes the gauges and compression immediately after. Figure 8 also shows that the rail experiences tension when it is between adjacent wheel sets of the same bogie but is in compression when between adjacent bogies. It should be noted that the effects of localized stress concentrations on the peaks of the measured strain gauge data, as seen in Figure 5, were replaced by linearly interpolating between the points of strain immediately before and after the positive strain spikes to permit the calculation of axial force at these critical points in the tests.

This same concept was applied to the FOS data. Figure 9 displays the results of calculating the axial force along the entire length of fibre using the distributed strain data shown in Figure 6. A side view of the instrumented rail is included in Figure 9 to illustrate the orientation of the fibres. As seen on Figure 9, the rail experiences a maximum axial compression at the location of the locomotive’s wheel. Additionally, Figure 9 shows that points of strain inflection, labelled IP on the strain curve, correspond to sudden transitions in the sign of the axial force at that location on the rail. While Figure 8 presents interesting information regarding the axial force in the rail at a single location, the results from Figure 9 demonstrate the advantage that the distributed FOS has over discrete sensor technologies in that the axial force distribution can be obtained with time.

![Distributed axial force calculated along the length of the rail.](image)

**Figure 9.** Distributed axial force calculated along the length of the rail.
5. Conclusions

A series of field tests was conducted in which a locomotive braked to a complete stop over various segments of rail instrumented with electrical resistance strain gauges and fibre optic strain sensors. The objectives of this research were to investigate the suitability of discrete and distributed sensors to measure dynamic rail strain and to assess their correlation. The collected data was also used to determine the distribution of axial force in the rail under locomotive braking to better understand axial force transfer between the wheels and the underlying rail system. The results of these tests led to the following conclusions:

- Electrical resistance strain gauges experience less noise than the FOS and are more effective at measuring strain peaks.
- The distributed nature of the FOS provides a more complete understanding of the response of the rail under locomotive loading, as compared to the strain gauges.
- The rail experiences a maximum axial compression at the wheel location and axial tension between adjacent bogie wheels.

The insight gained from these tests will aid in future research which should include full-scale longitudinal strain monitoring of an in-service railway bridge.

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