U.S. Department
of Transportation
**Federal Railroad
Administration**

RESEARCH RESULTS
FRA OFFICE OF RESEARCH, DEVELOPMENT & TECHNOLOGY

RR 23-21 | **November** 2023

RAIL-MOUNTED OPTICAL FIBER SENSORS FOR MONITORING TRACK TRANSITIONS

SUMMARY

Track transitions, including bridge approaches, grade crossings, tunnels, and special trackwork locations, are challenging to maintain due to rapid degradation. Transitions experience impact loads due to variations in the track stiffness and settlement between the adjacent track support types. Abrupt changes in the dynamic response of the track structure as well as the time-dependent settlement of track substructure layers can result in significant track degradation requiring frequent maintenance and resurfacing. Effective monitoring of these transitions is important to ensure track safety and to evaluate the effectiveness of maintenance.

The Federal Railroad Administration (FRA) sponsored a research team from Oklahoma State University (OSU) to assess how well Optical Fiber Sensors (OFS), specifically Fiber Bragg Grating (FBG) sensors, can monitor railroad track transitions. The initial laboratory work focused on comparing the strains and deflections in a section of statically-loaded rail. The team collected strain gage and linear transducer data for comparison to FBG sensors and numerical modelling predictions. The results show good agreement between the methods, providing confidence in this new measurement technique. Additional planned research includes dynamic load tests and experiments to determine the best way to mount the FBG-sensor to the rail.

BACKGROUND

Track geometry defects arising from differential settlement and sudden stiffness variations at track transitions lead to increased dynamic loads, which can be a safety concern for train operation (Indraratna et al., 2019). The length of a transition zone can vary widely depending on the transition geometry, the properties of track substructure layers, and the train operating speed. Traditional track condition monitoring methods, such as strain gauges, provide spot-based measurements of the track response and are not suitable for measuring the performance of longer track segments.

Advancements in sensor and communication technologies led to the development of sensor systems that can continuously monitor and report the performance of a length of track. Recent research studies have employed a distributed type of OFS technology to measure track deflection and stiffness (Wheeler et al., 2017, 2018, 2019; Milne et al., 2020). In this project, OSU researchers investigated the use of a network of OFSs to continuously monitor key track response parameters at transition zones.

OBJECTIVES

In the first phase of this project, researchers experimented with a specific type of OFS based on FBG technology. The research team carried out tests to compare rail-mounted FBG sensor measurements with those from conventional sensors and finite element-based numerical models. The primary research questions of interest were:

1. How accurately can rail-mounted FBG sensors measure the rail response under loading?

2. How sensitive are the FBG sensor measurements to their position along the rail section being monitored?

METHODS

FBG sensors track changes in the wavelength of a reflected light spectrum along a length of optical fiber. In FBG sensors, the fiber core is marked with a periodic grating pattern. These gratings have a specific average refractive index and reflect the light corresponding to a specific wavelength called the Bragg wavelength (λ_B) (see Eq. 1). When the FBG sensor is subjected to axial strain, the spacing between the grating changes, thereby resulting in a shift in the Bragg wavelength ($\Delta\lambda_B$) (Eq. 2):

$$\lambda_B = 2n_{eff}\Delta \qquad \text{Eq. 1}$$

$$\Delta\lambda_B = (1+\rho)\lambda_B \qquad \text{Eq. 2}$$

where n_{eff} is the average effective refractive index of the gratings, Δ is the grating distance, and ρ is the effective coefficient of photoelasticity of the fiber core material.

Single FBG sensors were connected in series to create an array of sensors. OSU researchers mounted this array on a rail web at pre-defined locations to measure rail strains under static loading. The team studied five commercially available FBG sensors with different Bragg wavelengths. Figure 1 shows a photograph and schematic of a FBG sensor used in the study.

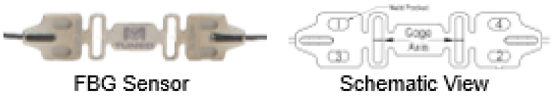
FBG Sensor Schematic View

Figure 1: FBG Sensors

The laboratory test plan included three-point bending tests on a section of AREMA 141 RE rail with a free span of 2.16 m (7.08ft) (Figure 2).

The team used a hydraulic actuator to apply a static load of 89 kN (20k lb) at the mid-length of the rail. Figure 3 illustrates the test setup showing the different sensor types and their respective positions along the rail.

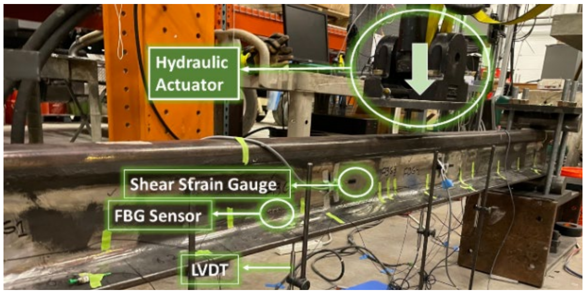

Figure 2: Laboratory Test Setup

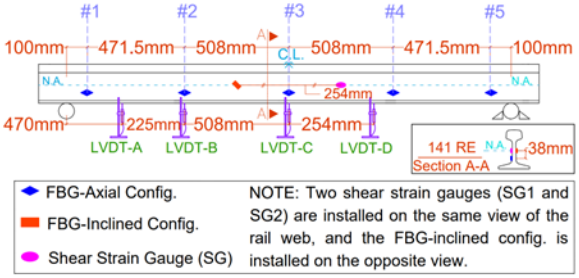

Figure 3: Different Sensors Used During Laboratory Testing and Their Positions Along the Rail

The test setup included two types of conventional sensors: Linear Variable Differential Transformers (LVDTs) and dual-element shear strain gauges (SG). FBG sensors were mounted parallel to the rail's neutral axis and at 45 degrees to the neutral axis to quantify the axial and shear strains, respectively. Sensors were mounted at different positions along the rail length to determine whether the measurement accuracy changed with position along the rail.

The team developed a three-dimensional finite element model of the laboratory test setup using ABAQUS. The model was validated through comparison with conventional sensors. Researchers used this model as reference to assess the accuracy of FBG-based strain measurements. Figure 4 compares the numerically predicted rail vertical deflection values with those measured using the LVDTs. The results indicate a good match between the two sets, with an average difference of ~4 percent.

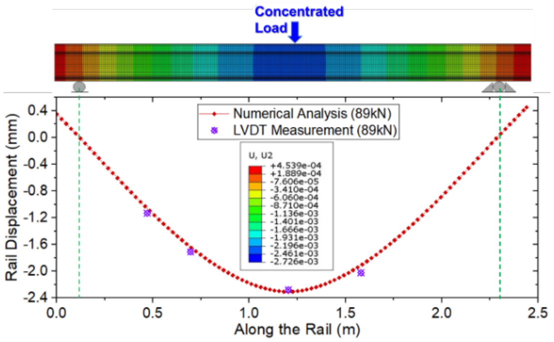

Figure 4: Comparing Model-Predicted and LVDT-Measured Rail Vertical Deflections

RESULTS

The team compared shear rail strains measured by a FBG sensor and a dual element shear strain gauge. These data were also compared to numerical modeling results. As shown in Figure 5, the maximum absolute difference between the strain gauge data (SG in Figure 5) and model-predicted strain values was 23 $\mu\varepsilon$; the difference between the FBG- and SG-measured values was 40 $\mu\varepsilon$. Some differences in values were expected as the FBG sensor measures axial strain which is then converted to shear strain using transformation formulas. The strain data is useful for measuring the rail curvature and calculating rail displacement and internal rail forces. As this project continues, these data will be used to characterize the track condition.

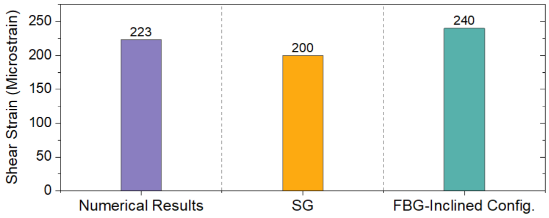

Figure 5: Comparing Shear Strains Measured Using FBG, SG, and Values Predicted by the Numerical Model

The team analyzed a series of five FBG sensors mounted parallel to the rail neutral axis to determine the strain distribution along the rail length. Figure 6 shows that axial strain variations along the rail measured using the FBG sensors were similar to those from the numerical model. Figure 7 shows the percentage difference between the numerical results and the FBG-measured values. The largest difference is near the right-side support location (Location #5). This indicates that the FBG sensors may be influenced by load concentrations in the system. A minimum distance should be established between FBG sensors and support points. Overall, model-predicted and FBG-measured strain values differed by less than 10 percent on average.

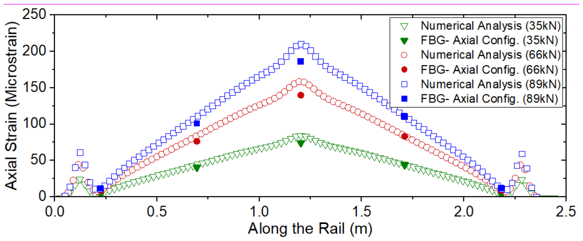

Figure 6: Axial Strain Distribution Along the Rail Length

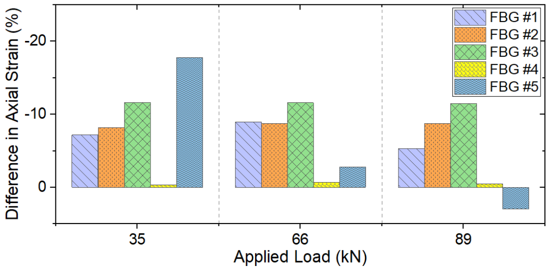

Figure 7: Difference Between Model-Predicted and FBG-Measured Strain Values

CONCLUSIONS

The OSU team successfully collected data to demonstrate the accuracy of the FBG sensors compared to strain gauges and numerical modelling predictions.

Shear and axial strain measurements differed by approximately 20 percent at maximum. This difference may be attributed to errors in strain gauge placement, model construction, and support point influences.

The test results established that FBG sensors can be arranged in an array to track the variation of axial strain along the rail with reasonable accuracy. This result shows a good level of confidence in the efficacy of this method to measure track performance over extended lengths and provides momentum to continue the research.

FUTURE ACTION

Future tasks in this research study include assessing performance of the FBG sensors under repeated loading. Axial strain values measured at different positions along the rail will be used along with classical beam theory to calculate rail deflections. Different mounting approaches will be evaluated to establish how the optical fiber sensors can be adequately mounted to the rail to ensure accurate measurements under harsh operating conditions. Different OFS types will also be studied to assess their suitability for railroad applications.

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ACKNOWLEDGEMENTS

Mahsa Gharizadehvarnosefaderani and Md. Fazle Rabbi of Oklahoma State University worked on all project tasks.

CONTACT

Cameron D. Stuart
Project Manager
Federal Railroad Administration
Office of Research and Development
1200 New Jersey Avenue, SE
Washington, DC 20590
(202) 493-6384
cameron.stuart@dot.gov

Debakanta Mishra
Associate Professor
Oklahoma State University
238 Engineering North, Stillwater, OK 74078
(405) 744-3332
deb.mishra@okstate.edu

KEYWORDS

Optical Fiber Sensors, Fiber Bragg Grating, Track Monitoring, Rail Strain

CONTRACT NUMBER

693JJ6-22-C-000039