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Fiber Optic Sensors for Bridge Monitoring.

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Abstract
This paper presents the data obtained from monitoring a steel Struss bridge using Fiber Bragg Grating (FBG) sensors before and after a proposed repair for crack propagation in the end plates. This paper details the operating mechanism behind the FBG sensors and the advantages of using FBG sensors over resistive foil strain gauges for bridge structural health monitoring and also details how cracks on the outer web's end plate originated and then provides a step-by-step guide to the completed repair. This technology can be used in other practical applications where structural health monitoring is needed.

Keywords: Fiber Bragg gratings, strain gauges, structural health monitoring

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Introduction

Fiber Bragg Grating (FBG) sensors are extremely responsive to changes in the strain [1]. With the increase in innovations in the optoelectronic field, the cost of manufacturing FBGs is very low [2]. As a result of this, FBG sensors moved from laboratory research to industrial applications [2]. FBGs have been used for a wide variety of sensing applications including monitoring of civil structures (highways, bridges, buildings, dams, etc.), smart manufacturing and non-destructive testing (composites, laminates, etc.), remote sensing (oil wells, power cables, pipelines, space stations, etc.), smart structures (airplane wings, ship hulls, buildings, sports equipment, etc.), as well as traditional strain, pressure, and temperature sensing [3-8]. The basic principle of FBG interrogation generally is wavelength scanning [9-10]. Using a broadband light source to illuminate the FBG, part of the light that obeys the Bragg condition is reflected, and the rest of the light is transmitted [9-8]. When an FBG undergoes a uniform strain along the grating, the FBG sensing principle becomes simply tracking the peak Bragg wavelength which shifts proportionally to the strain and temperature [9-10].

Above mentioned FBG sensors were used to analyze the effectiveness of a repair done on a steel Struss bridge. The steel spans of the bridge were approximately 1000m. The orthotropic deck of this portion of bridge included crossbeams at 3m centers for its full length. The portion of the crossbeam in the outer cell spanned between the outer web and inner web of the box girder. The connection to the outer web comprised an end plate which was welded to the crossbeam and bolted to the outer web. This detail had a history of fatigue cracking, and there appeared to be a correlation between the incidence of this fatigue cracking and distortion of the crossbeam end plate that had given rise to a gap between the outer face of the end plate and the mating face of the box girder outer web. When live loads produce negative bending moments in the crossbeam at its connection to the outer web, the flexural compressive stresses at the bottom of the crossbeam, particularly the crossbeam flange, tend to close the gap, thereby causing cyclic flexural stresses in the end plate. Due to residual tensile stresses of a high magnitude associated with the welding process, the cyclic stresses caused fatigue cracking in the welds of the end plate. A three-stage repair was proposed to overcome the above-mentioned problem. As a result, FBG sensors were used to analyze the strain of the end plate before and after the proposed repair.

Experimental Materials and Methods

Steel Struss Bridge:

In order to provide a substantial improvement in the fatigue performance of the detail, a remedial treatment was proposed, which included the following steps:

- Remove corners of cracked end plate as shown in Figure 1.
- Weld repair of cracks in the end plate
- Insertion of shims to fill the gap between the end plate and the outer web, to the extent reasonably possible.
- Sealing around the interface in preparation for injection of epoxy
- Injection of epoxy
- Heating the joint until the epoxy achieves the required strength.

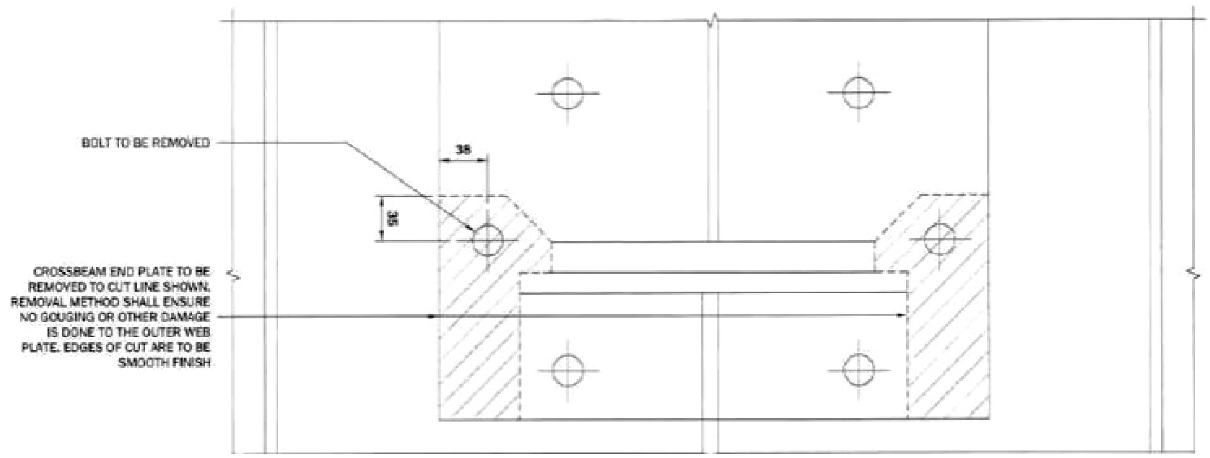

Figure 1. Engineering drawing of the end plate with instructions on how to remove it safely.

To assess the effectiveness of the proposed repair, it was recommended that the strain in the end plate be monitored, and the fatigue performance of the repaired detail be assessed using FBG sensors. FBG sensors will be used as strain gauges. Strain/stress measurement is proposed to be conducted at four locations as schematically shown in Figure 2. Gauges 1 and 2 were installed to measure the surface stress component in Y-direction at 4 mm and 10 mm away from the weld toe line of the fillet weld above the bottom flange of the crossbeam as shown in figure 3. The stresses measured by Gauges 1 and 2 were used to obtain the Hot Spot Stress at the weld toe by extrapolation method, and their locations at 0.4 t and 1.0 t (t, thickness of end plate, 10 mm) away from the weld toe line are pursuant to the suggestions of the International Institute of Welding [11]. Horizontally, the gauges were in between the two epoxy injection holes and 60 mm away from the crossbeam web. Inspections were made to make sure that there are no fatigue cracks along weld toe of the fillet weld before installing G1 and G2.

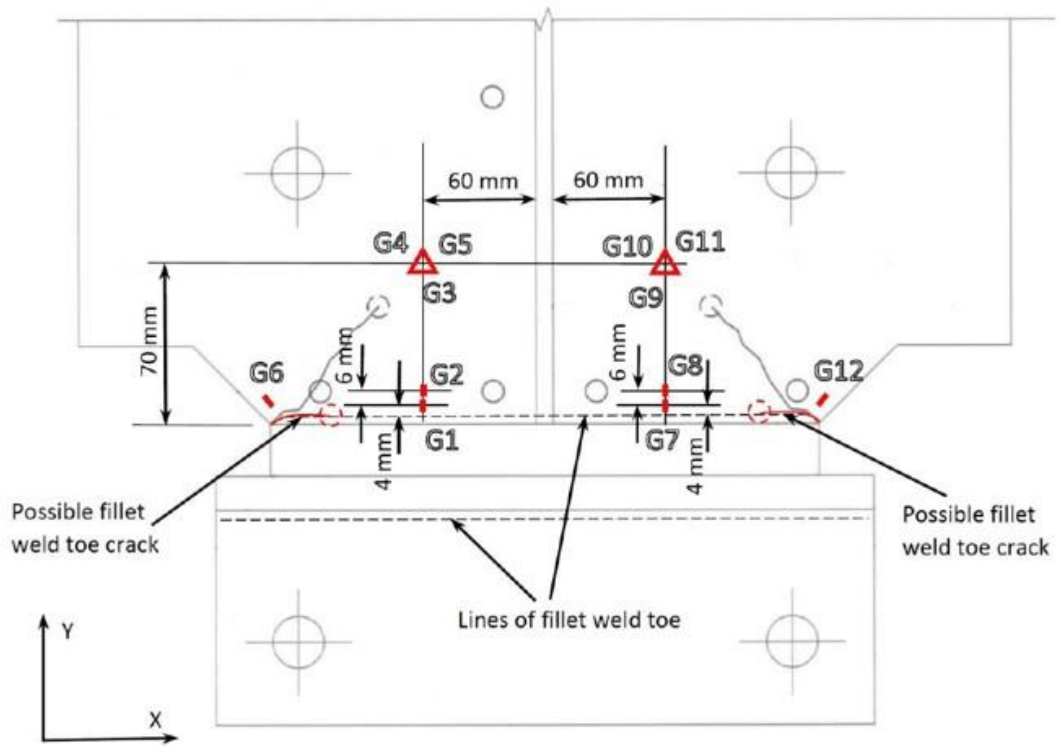

Figure 2. Detailed engineering drawing showing the placement of twelve FBG sensors.

To get a better understanding of principal stresses at the central part of the end plate, a rosette FBG sensor consisting of G3, G4 and G5 were attached to the surface of the end plate in the central area where the plate was subjected to less constraint from the web and the bottom flange of the crossbeam and the nearest bolt. The orientation of G3 was along the X-direction. The rosette sensor was placed at least 20-30 mm away from the edge of the stop hole drilled at the end of the butt-weld repaired crack. G5 in the rosette was at 45 degrees to the horizontal line (x-axis). The stress component in this direction was approximately perpendicular to the crack repaired with partial penetration butt weld and may cause it to re-crack. Furthermore, in order to provide some redundancy in strain gauging, a duplicate set of gauges G7-G12 were installed on the opposite site of the crossbeam web, Figures 2 and 3.

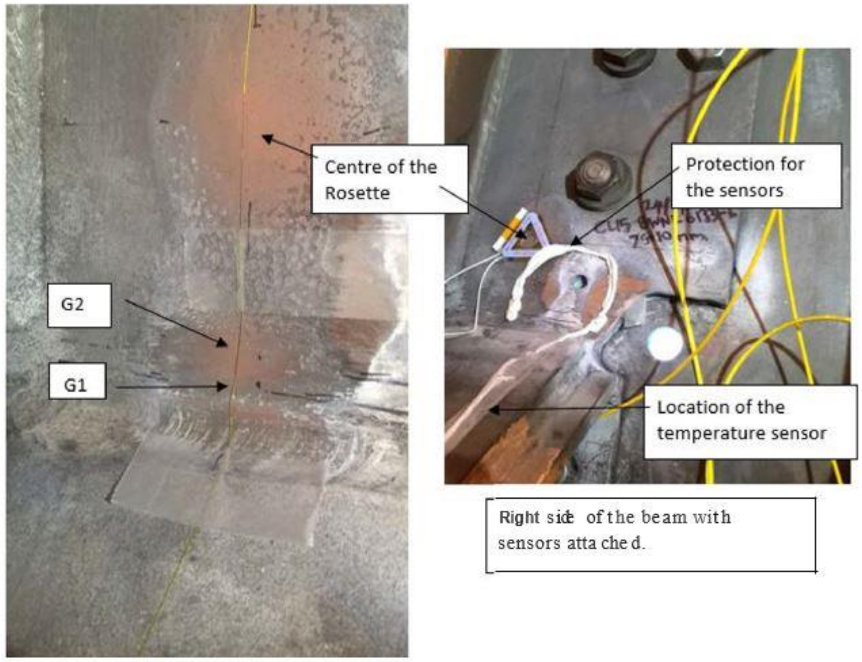

Figure 3. Placement of G1, G2, temperature sensor and a rosette on the end plate.

Results and Discussion

A Steel Truss Bridge

The strain was recorded using the FBG sensors G1- G12 at the sampling rate of 100Hz. This sample rate was adequate to capture spike loading due to moving traffic. Data was recorded for 3 stages, after the weld repair, after insertion of shims and after epoxy injection. For each stage data was recorded for 1 weekday of the week as shown in figure 4.

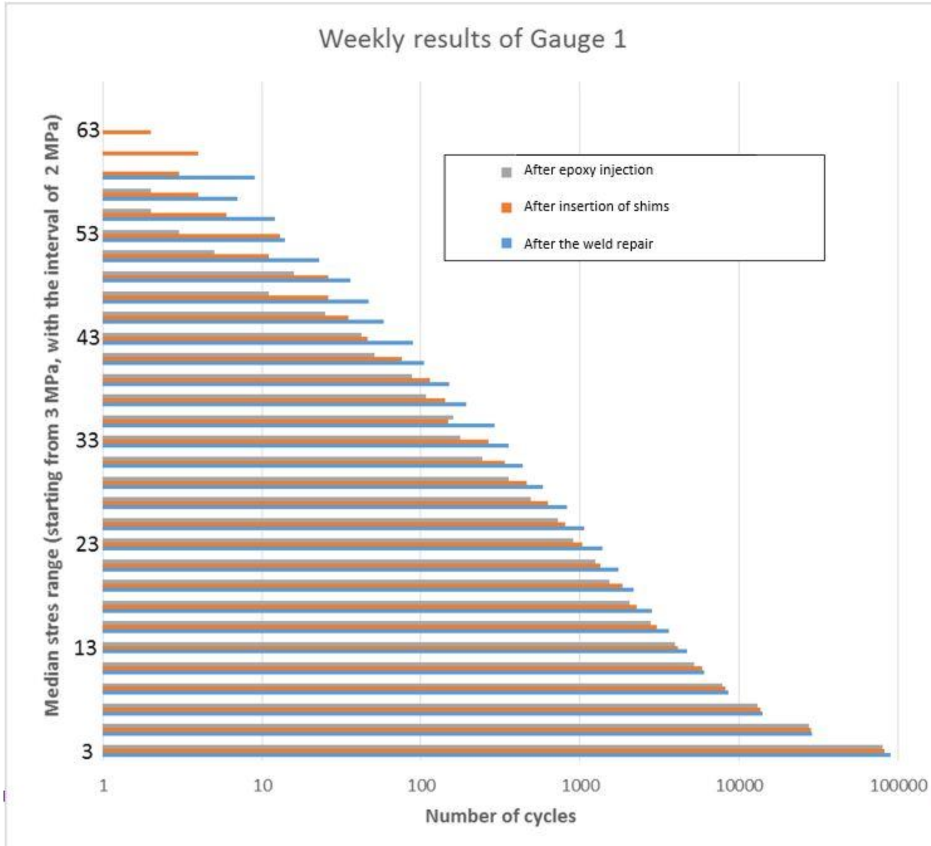

Figure 4. Median stress range for after the weld repair, after insertion of shims and after epoxy injection for Gauge 1.

Data were stored and processed using the rain flow method. The rain flow method gave the option to group the output data that was produced, into fewer cycles. This was performed in two different ways, depending on the grouping method; bandwidth percentage or absolute bandwidth. The algorithm itself calculated the maximum and minimum from the input dataset to determine a range for both spectrums. Once the range was determined, either a percentage value or an absolute value was used to calculate a constant interval throughout the range.

Then the maximum and the minimum values were used to calculate the range of the dataset and then applied to the absolute value or percentage. The interval was used to create the 'boxes' for grouping, each interval would be a maximum and minimum for a box using the bandwidth percentage. This method generated a number of loading cycles with similar amplitudes which were used for comparison of stress levels in three stages of the analysis. Proposed repair decreased the median stress range in the end plate. The end plate experienced 3 MPa median stress as well as 63 MPa median stress depending on the live traffic on the bridge. At 43 MPa median stress, the number of stress cycles decreased from 100 to 65 cycles after the stage 3 repair. Not only that but also at 55 MPa median stress, the number of cycles decreased from 11 to 4. A shown in figure 4, the median stress of Gauge 1 decreased substantially after the stage 3 repair, which was epoxy injection.

Conclusion

FBG sensors are one of the best options that can be used to monitor structural health and can be used for long term monitoring. As FBG sensors are smaller in size, they can be embedded or attached precisely on structures for accurate monitoring of stress locations. They are also non-conductive, therefore, immune to electromagnetic interference and much more environmentally stable for long term monitoring. In this study, FBG sensors have been successfully used in monitoring a bridge structure for the effectiveness of a fatigue crack repair. Results show that the repair reduces the stress levels and thus improved the fatigue life of the bridge structure.

Conflict of Interest

The authors declare no conflict of interest.

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