

Use of Optical Fiber Bragg Grating for Geogrid Strain Measurements

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Abstract

As the use of geosynthetic reinforced earth structures becomes more popular, its safety has gain much attention recently. In a white paper report prepared by Geosynthetic Research Institute (GRI), the use of strain sensing within the geosynthetic was emphasized. Citpo Technologies Co. Ltd. has successfully developed a technique to attach optical fiber Bragg grating (FBG) on the surface of geogrid as a strain sensor. This report describes the principles of FBG as a strain sensor, and a case of using FBG for geogrid strain measurements. Results from laboratory geogrid tensile load tests, field deployment of FBG for strain monitoring of a geogrid reinforced embankment are presented.

Principles of FBG

Optical fibers are made of silica, with a diameter about the same of a human hair, and can transmit light over long distances with very little loss of fidelity. Optical fibers comprise two essential components: a core surrounded by an annular cladding. The core of the optical fiber serves to guide light along the length of the optical fiber. The cladding has a slightly lower index of refraction than the core. Its primary function is to ensure total internal reflection within the core and that very little light is lost as it propagates along the core of the optical fiber. The typical combined diameter of core and cladding is 125 μm . The silica core/cladding is protected by an acrylic coating. The total outside diameter of an optical fiber with the acrylic coating is 250 μm . By adopting technologies from telecommunication, many fiber optic based sensing techniques have been developed. These sensors have been used in medical, defense, aeronautical, and civil engineering industries. Development and application of fiber optic sensors are expanding rapidly as indicated by the well-attended conferences organized by many international societies such as the International Society for Optical Engineering (SPIE). The fiber optic Bragg grating (FBG) is one of the many available forms of optical fiber sensors. An FBG is made by a periodic variation of fiber core refractive index. The typical length of an FBG is 1 to 20 mm long. When the FBG is illuminated by a wideband light source, a fraction of the light is reflected back upon interference by the FBG. When the FBG is illuminated by a wideband light source, a fraction of the light is reflected back upon interference by the FBG. The wavelength of the reflected light, or the Bragg wavelength, λ_B is related to the period of the index modulation, Λ , and effective fiber core index of refractive, n , as expressed by: (Rao, 1998)

$$\lambda_B = 2n\Lambda \quad (1)$$

Longitudinal strains within the Bragg grating, ε_{FBG} , induced by variations in temperature or stress can cause a change in Λ and thus a shifting of λ_B , with the following approximate relationships: (Rao, 1998)

$$\Delta\lambda_B = 0.74\lambda_B\varepsilon_{FBG} \quad (2)$$

and

$$\Delta\lambda_B = 8.9 \times 10^{-6} \lambda_B \Delta C^\circ \quad (3)$$

where ΔC° is the change of temperature in degree Celsius. The constants in Equations 2 and 3 can vary, depending on the photoelastic properties of the optic fiber. For the FBG sensors reported herein, the λ_B ranged from 1520 to 1570 nm (10^{-9} m). A typical commercially available FBG data acquisition system can detect a shifting of λ_B as small as 1pm (10^{-12} m), which corresponds to a strain (ε_B) of the order of 10^{-6} according to Equation 2. This is well above desirable resolution for strain sensors. In addition, the strain ε_B is determined through the change of λ_B which is relatively immune to variations in the strength of light source. This unique feature makes FBG less likely to have signal drifting.

The wavelength of the reflected light, is linearly related to the longitudinal strains of the FBG, thus making FBG an ideal strain gage. The returned signal from every FBG carries a unique domain of wavelength $\lambda_B + \Delta\lambda_B$, making it possible to have multiple FBG elements on the same fiber. The multiplexing among various sensors on a single fiber can be accomplished by wavelength division addressing as conceptually described in Figure 1. The FBG is partially distributive because only those parts of the optical fiber with FBG are used as strain sensors and these sensors can share the same optical fiber transmission line. There is a limited bandwidth of the light source and as the light passes an FBG there is a loss of its intensity, the number of FBG sensors that can be placed on a fiber is not more than 20 with the currently available FBG interrogation systems. By monitoring the temperature induced strain in a loose FBG, it is possible to use FBG as a temperature sensor with a resolution on the order of 0.1°C .

An important disadvantage of FBG and optical fiber in general, is that without protection, the fiber is rather fragile and can be easily damaged. Also, FBG breaks when it is subject to a tensile strain in excess of 1% ($10,000 \mu\varepsilon$). For the relatively flexible material such as geogrid, its reinforcement effects under design conditions are most apparent when the tensile strains within the geogrid are in the range of 3 to 5%. Thus, it is imperative to adjust the FBG so that it can be subject to tensile strains in excess of 5%. Provided the above potential drawbacks are dealt with, the use of FBG as geogrid strain sensors can the following important advantages:

- Signal can be transmitted for over 10 km without the loss of fidelity.
- Optical signals are immune to moisture, electromagnetic interference (EMI) or lightning.
- Optical fiber and FBG are made of silica, the material and thus the sensor is extremely durable.
- The FBG sensors are passive in nature, can be used for 5 to 10 years.
- The optical fiber with Kevlar and stainless steel fiber protection is extremely strong and compact with an outside diameter of 3 mm.
- FBG is partially distributive, multiple sensors can be connected to a common optical fiber.

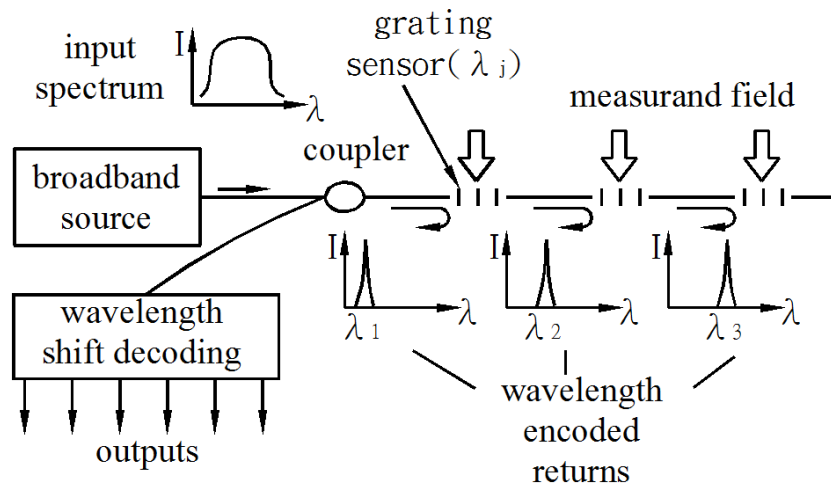


Figure 1. Schematic diagram of Fibre Bragg Grating (after Kersey 2007),

I = light intensity λ =wavelength

Laboratory Tensile Load Tests

Citpo Technologies developed a proprietary technique to mount the FBG on the geogrid, so that the FBG can serve as a strain sensor as the geogrid is subject to a tensile strain over 5%. The tensile load test as shown in Figure 2 was performed on a single rib of geogrid. The geogrid was made of PET with a coating of PVC. The geogrid had a tensile strength over 140 kN/m. During the load test, an LVDT was mounted on the back side of the geogrid specimen to provide the reference displacement readings. Results of three sets of tensile load tests on the same type of geogrid, using three different specimens are shown in Figure 3.

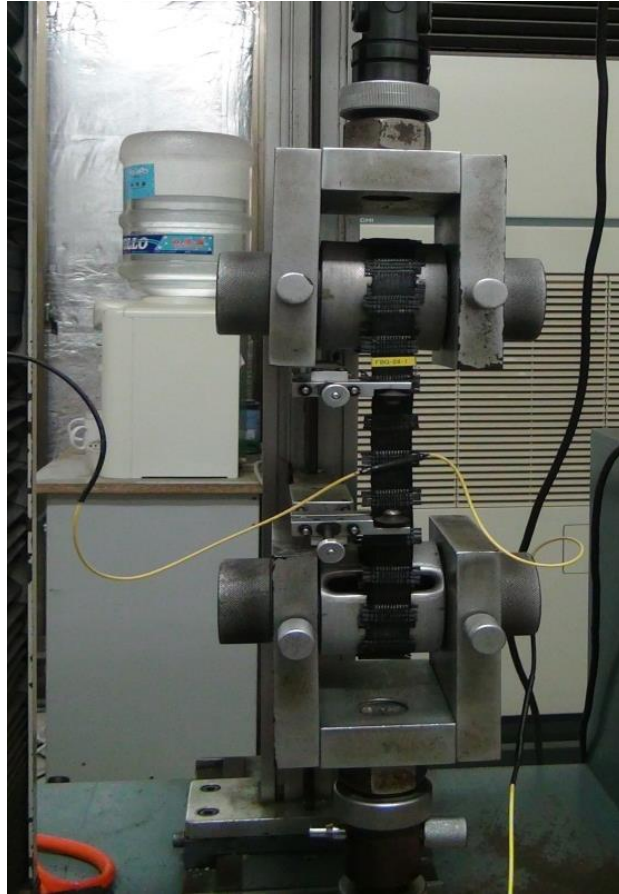


Figure 2. Laboratory set up of the tensile load test.

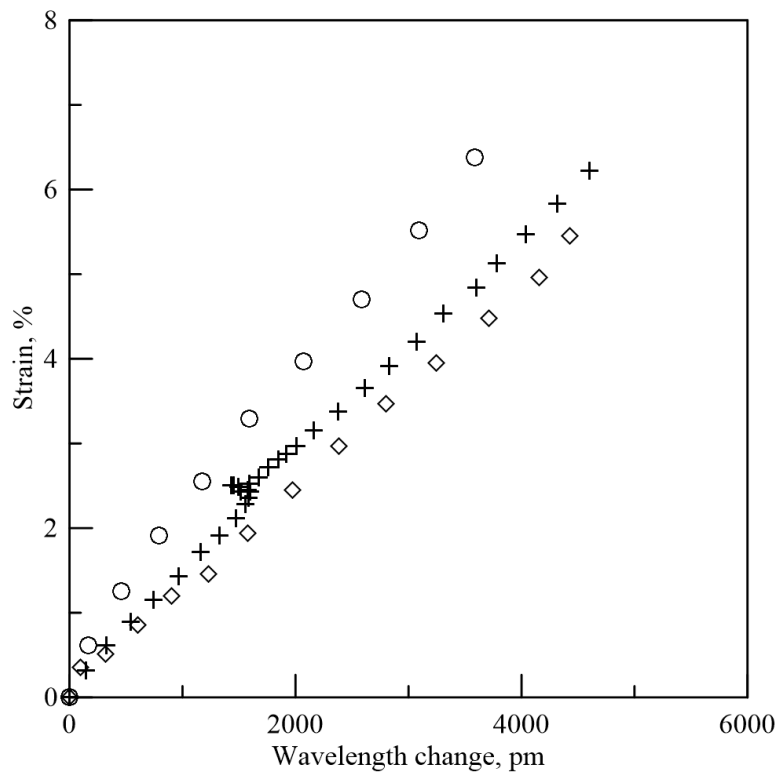


Figure 3. Results of load tests showing strain versus wavelength change.

Field Application of FBG for Geogrid Strain Monitoring

Figure 4 shows a cross sectional view of the geogrid reinforced embankment in Taichung, Taiwan. The FBG's were first mounted on a 25 m long, 1 m wide strip of geogrid. The FBG's were spaced at 1 m apart. Mounting of the FBG's on the geogrid strip was conducted in the laboratory. The embankment had a final height of 23 m. The instrumented strip was placed at approximately 2/3 of the embankment height. The FBG's were aligned at 7 m to 22 m from the front face of the embankment.

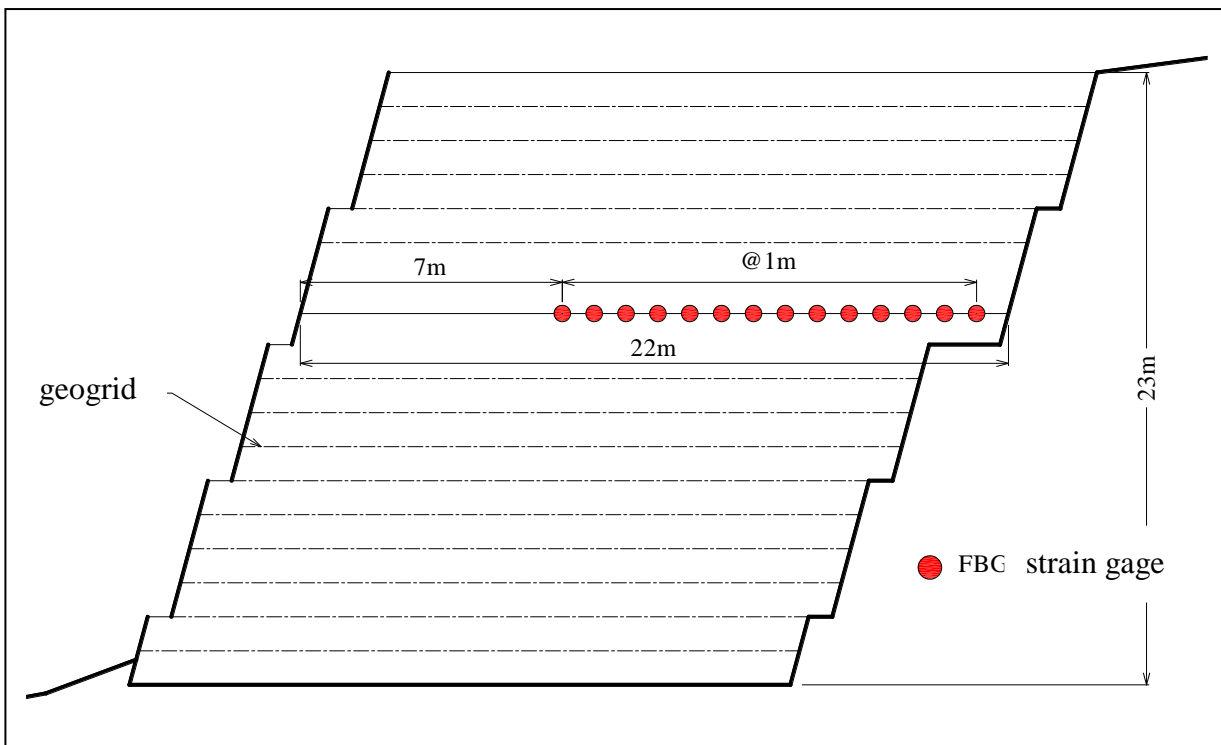


Figure 4. Cross sectional view of the geogrid reinforced embankment and locations of FBG's.

Fine to medium sand created by crushing a poorly cemented sandstone on site, was used as the backfill for the construction of the embankment. The instrumented geogrid was unrolled on top of an existing geogrid as shown in Figure 5. A layer of approximately 50 cm thick soil back fill was then placed to completely cover the instrumented geogrid. This 50 cm thick soil back fill was compacted by a hand operated jumping jack compaction machine. Upon the protective back fill compaction, operation using full size dozer and compaction roller were then resumed for further construction of the embankment. The field installation procedure was compatible with that reported by Rowe and Gnanendran (1994) for monitoring geosynthetic reinforced embankment with electrical strain gages.

Figure 6 shows the available strain readings after the embankment was completed, starting on February 1, 2013 and continued till January 2014.



Figure 5. Unrolling of the instrumented geogrid.

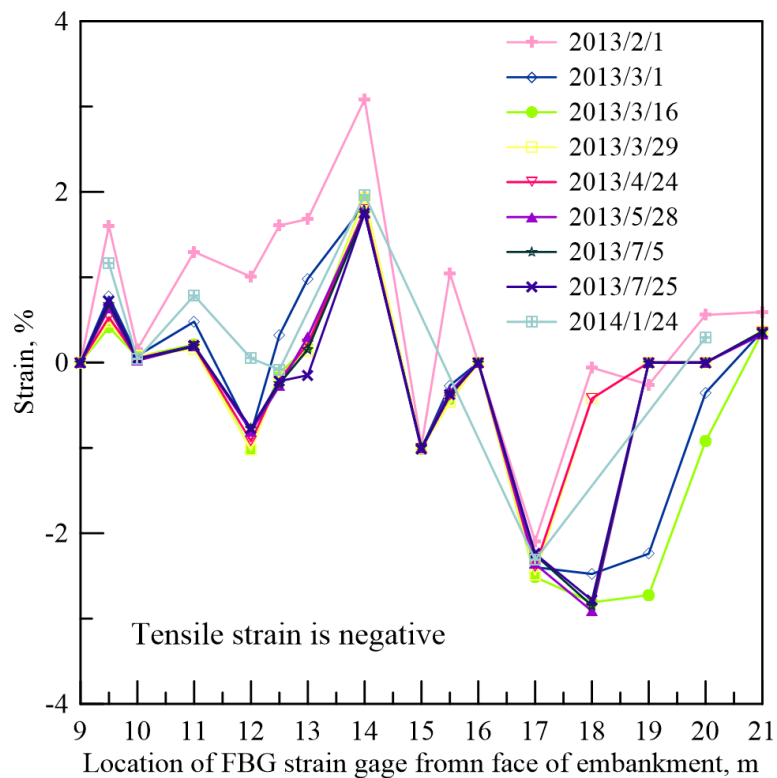


Figure 6. Readings from the FBG sensors.

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