Field Monitoring of Shield Tunnel Lining Using Optical Fiber Bragg Grating Based Sensors

Surveillance de doublure d'un tunnel au bouclier utiliser les capteurs optiques de fibre-Bragg-grating

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ABSTRACT: The design of soft ground shield tunnel lining for Taipei Mass Rapid Transit (MRT) system has been relying on semi-empirical procedures. The earth pressures involved in tunnel lining structural design has been determined based on experience. It is not certain if the design is adequate. Also, occasionally new MRT tunnel or other forms of underground constructions can be located dangerously close to an existing tunnel. An effective means of monitoring the behavior and integrity of the tunnel lining is imperative to the future design and safety of the MRT tunnel system. The authors developed techniques to attach optical fiber Bragg gratings (FBG) in the reinforcement as a means to monitor the strains experienced by the shield tunnel lining. Readings were recorded from pre-cast concrete section production through field installation and continued after field installation. The paper describes the techniques of FBG field monitoring, their available records and discusses implications in the design and safety monitoring of shield tunnel linings.

RÉSUMÉ : Le projet du rêvetement de tunnel bouclier au terrain moule pour la système du Masse Transit Rapide de Taipei (MRT) avait eu en s'appuyant sur les procedures semi-empiriques. Le sol impliqué dans la construction de MRT a été alluvial dans la nature avec l'argile limoneuse et le sable limoneuse intercouché avec le dépôts de gravier occasionel. Les pressions de terre impliqué dans le projet structural du rêvetement de tunnel avait eu détérminées basées sur l'expérience. Il n'est pas certain si le projet est trop conservateur. Également, parfois le tunnel nouveau de MRT ou less autres formes des constructions sousterrain peuvent être situées dangereusement près d'un tunnel existant. Le moyen efficace de surveillance du comportement et l'intégrité du rêvetement de tunnel est impératif du projet avenir et la sécurité de système de tunnel de MRT. Les auteurs ayant développés les techniques à attacher les grilles de Bragg à fibre optique (FBG) dans l'renforcement comme un moyen de surveiller les deformations expérimentées par le rêvetement de tunnel bouclier. Les FBG détectés le rêvetement de tunnel sont instalés dans la ligne Shin-Yi MRT de Cité de Taipei en 2007. Les lectures sont enregistrés de la section de béton pre-contriante pendant l'installation des chantier et continués jusqu'à aujourd'hui. Cet article décrit les techniques de FBG la surveillance de chantier, leur enregistrements disponibles et discute influences dans le projet et la sécurité de surveillance des rêvetements de tunnel bouclier.

KEYWORDS: fiber Bragg grating, shield tunnel lining, monitoring

1 INTRODUCTION

The design of shield tunnel lining has been based on semi-empirical procedure and may be rather conservative. The conservatism is mainly due to lack of field measurement as to the stresses or strains that the tunnel linings are actually experiencing during different stages of construction and operation. For municipal subway tunnels, there may be threats from other construction activities such as those for new building basements or other tunnels in close proximity. Earlier attempts of using electrical strain gauges for field monitoring in shield tunnel had the drawbacks that include the lack of longevity and signals prone to electromagnetic interference (EMI). There have been reports on the use of optical fiber sensors to monitor subway tunnel lining deformation using the fully distributive Brillouin Optical Time Domain Reflectometry (BOTDR) method (Mohamad et al. 2007). In their report, optical fiber was mounted inside the existing tunnel lining. The BOTDR signals are immune to EMI and optical fibers are durable, and thus are clearly more desirable than the conventional electrical sensors. There were no baseline readings when the tunnel lining was completely free of exterior earth pressure. The strain readings were therefore, relative to the post tunnel-construction conditions. While the BOTDR readings serve the purpose of revealing the effects of nearby constructions on the existing tunnel lining, the results had little value in evaluating the current design procedure. For the latter purpose, it is necessary to measure the absolute strains within the tunnel lining.

Optical fibres 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 fibres comprise two essential components: a core surrounded by an annular cladding. The core of the optical fibre serves to guide light along the length of the optical fibre. 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 fibre. 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 fibre with the acrylic coating is 250 μm. By adopting technologies from telecommunication, many fibre optic based sensing techniques have been developed. The fibre optic Bragg grating (FBG) is one of the many available forms of optical fibre sensors. An FBG is made by a periodic variation of fibre 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. The wavelength of the reflected light, is linearly related to the longitudinal strains of the FBG, thus making FBG an ideal strain gage. 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. The returned signal from every FBG carries a unique domain of wavelength, making it possible to have multiple FBG elements on the same fibre. The multiplexing among various sensors on a single fibre 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 fibre with FBG are used as strain sensors and these sensors can share the same optical fibre transmission line.

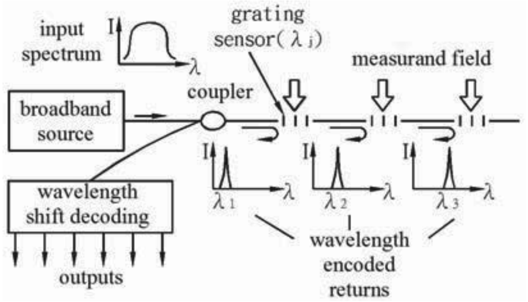

Figure 1. Schematic diagram of Fibre Bragg Grating (Kersey 1992), I = light intensity λ = wavelength.

The authors developed the techniques to install FBG strain sensors on the tunnel lining panel reinforcement prior to concrete casting. FBG strain readings could be recorded during panel concrete curing, shipping, before and after field installation for long term monitoring. The absolute strains experienced by the lining panel could be determined according to baseline readings taken before installation and data recorded following the completion of the tunnel lining. The authors developed the techniques of attaching FBG strain sensors and other FBG based sensors to the reinforcement and/or the tunnel lining panel. The techniques were first applied at Taipei MRT Xinyi line, installation of the first FBG sensored shield tunnel panel was completed on March 24, 2008. Continuous, automated strain readings were recorded from January 1, 2010 to April 26, 2012. The paper describes the techniques of FBG sensor installation, the case of applying this technique to Taipei MRT Xinyi line, presents available records and discusses implications in the design and safety monitoring of shield tunnel linings.

2 FBG STRAIN SENSOR INSTALLATION AND PANEL LOAD TEST

Figure 2 shows a typical cross section of the Taipei MRT Xinyi line tunnel. It has an outside diameter of 6m and a thickness of 200mm. The tunnel lining is fabricated by assembling six, 1m long pre-cast concrete panels. The designations and the dimensions of these panels are shown in Figure 2. For the case reported herein, FBG strain sensors were installed in panels A1, A3 and B. For each panel, an inner (short) and an outer (long), No. 7 reinforcement steel was selected for instrumentation. Three FBG strain sensors were attached to the designated reinforcement steel. The FBG's on the long steel were numbered in the clockwise direction while those on the short steel were numbered in the counter clockwise direction. Figure 3 shows the locations and numbering the FBG strain sensors for the case of A1 panel. An electrical thermo couple and a vibrating wire (VW) strain gage were also installed as shown in Figure 3 to provide reference values. A 4mm wide and 11mm deep channel was milled into the reinforcement steel as schematically shown in Figure 4. The optical fibre along with the FBG's were attached to the bottom of the channel. For strain measurement, the FBG's were epoxied to the surface of a well-polished and cleaned steel surface. A separate FBG, designated as FBG (T) sealed inside a tubing, so that it is not making contact with the steel, was placed next to FBG2(L) and served as a temperature sensor. The empty space of the channel was then filled with epoxy. This arrangement minimizes the effects of local bending of steel on FBG strain readings and provides good protection of the optical fibre during casting and handling of the panel. Figure 5 shows a fully assembled reinforcement steel cage with all FBG sensors included.

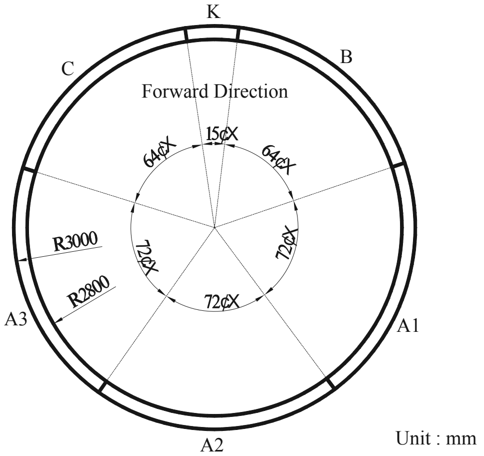

Figure 2. Cross section of the Taipei MRT Xinyi line tunnel.

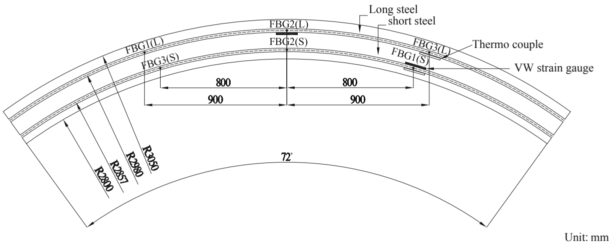

Figure 3. Numbering of FBG strain sensors in A1 panel.

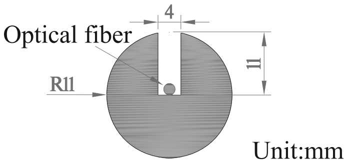

Figure 4. Placement of optical fiber in reinforcement steel.

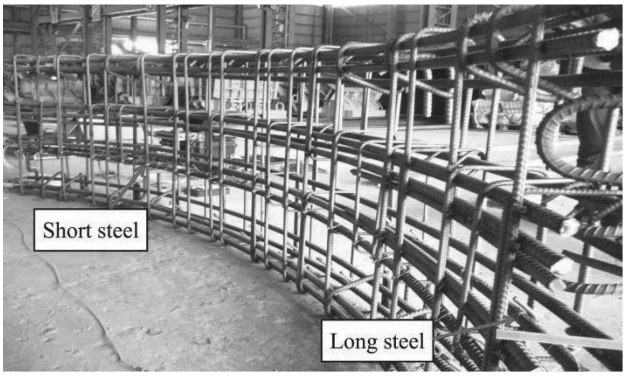

Figure 5. A fully assembled reinforcement steel cage for A1 panel.

The precast concrete panels were manufactured in a factory. The reinforcement steel cage along with low slump concrete were placed in a steel mold and subjected to vibration. Upon initial setting and de-molding, the panel was cured in a steam room and followed by submerging under water for three days before taking out and undergo the rest of the curing in the air. The effects of this harsh environment are reflected in the sharp increase in the FBG wave length during steam curing as shown in Figure 6. Every one pm (10^{-12} m) wavelength change corresponds to approximately 1 $\mu\varepsilon$ of strain. The continued readings assure the integrity and functionality of the FBG's during the curing stage of the panel.

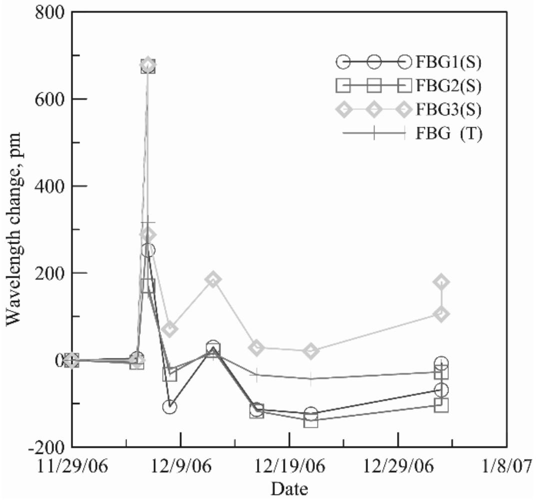

Figure 6. FBG wave length changes during the curing stage.

To verify the effectiveness of the sensors, an A1 panel with the instruments installed as shown in Figure 3 was load tested under compression. As depicted in Figure 7, the vertical load was applied at the crown of the panel. The ends of the test panel were supported on rollers to assure no bending. Figure 8 shows the change of strain (Δμε) from the FBG and VW strain sensors attached to the short steel. All sensors showed tensile strain until breakage of the panel at approximately 43 tons of loading. Being located at either the same or compatible positions due to symmetry, strain readings from FBG1(S) and FBG3(S) are very similar to those from the VW strain gage. FBG2(S) had the most significant tensile strain readings because it was subject to the maximum bending moment in load test. There was a sharp increase in tensile strain in FBG2(S) near failure when cracking started at the bottom of the panel and the stress became concentrated in the steel. FBG sensors on the long steel, for the most part, were located in the compression side during the load test.

Figure 7. Panel load test set up.

The FBG sensors on the long steel showed modest compressive strains in the early stage of the load test. The strain readings in FBG2(L) showed a reversal of strains from compressive to tensile at about the same time when FBG2(S) started to have a sharp increase in its tensile strain. This reversal is apparently also related to the cracking of the panel at the bottom side. The strain readings in FBG2(L) reversed twice towards the end of load test as the final bending of the panel was almost entirely taken by the steel.

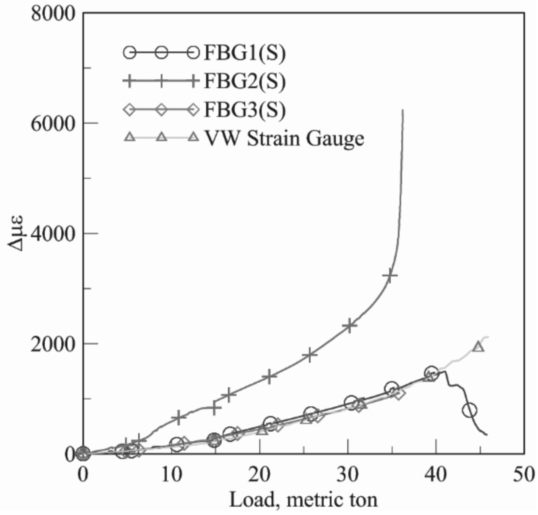

Figure 8. Change of strains from FBG's on short steel.

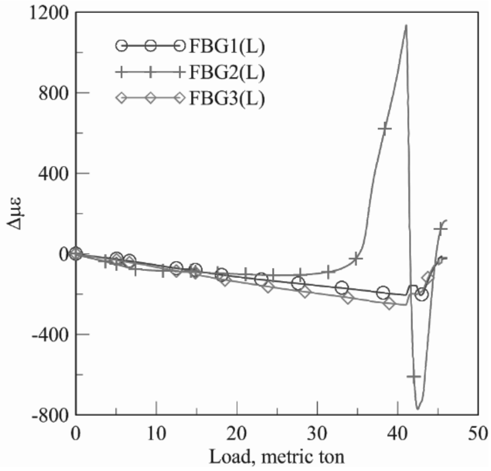

Figure 9. Change of strains from FBG's on long steel.

3 FBG STRAIN READINGS AFTER FIELD INSTALLATIONS

The sensored panel was part of the shield tunnel section at 0k+399m of the Taipei MRT Xinyi line contract CR580A, near the Daan Park station (R9). The tunnel had an overburden of approximately 30m. The shield tunnel boring machine was powered by multiple electric motors. During field installation, the concrete panels were placed near these motors with strong EMI. The fact that FBG signals are immune to EMI is an important advantage, if readings are to be taken during the early stage of panel insertion. Figure 10 presents the change of strains (Δμε) recorded in panel A1 immediately following its field installation on March 24, 2008. Fluctuations of strains were believed to be induced by assembling various panels and back grouting. The readings became relatively stable after one week of installation. FBG1(L) and FBG2(L) showed tensile strains indicating that the tunnel lining was bulging slightly towards the three o'clock direction. The rest of the strain readings were slightly in the compressive side indicating that the tunnel lining was subject to relatively modest earth pressure.

Long term automated data logging started on January 1, 2010 and continued until April 26, 2012. During this period, the monitored section was at least 500m behind the shield tunnel boring machine. The long term strain readings as shown in Figure 11 generally ranged from slightly positive (tensile) to as much as -500 micro strains (compressive). The compressive strains were much more significant than those recorded during the initial stage of panel installation. This is an indication that two years after installation, the earth pressure had exerted on the tunnel lining. Slight bulging remained in panels A1 and B with strains in long steel close to the tensile side, while the reverse is true for panel A3. The strain readings showed consistent fluctuations among the three panels. A comparison with the temperature record as depicted in Figure 12 indicates that the strains registered in the panels appear to be synchronized with that of temperature. As the tunnel near its completion and temperature stabilizes, the strain fluctuation also reduces.

4 CONCLUDING REMARKS

Essentially all FBG sensors installed in this case are still functioning, nearly five years after construction. The experience shows that because FBG is immune to EMI and made of durable material, FBG can be an ideal sensor to provide reference data for future tunnel lining design, as a means for construction quality assurance and for long term safety monitoring against nearby construction activities.

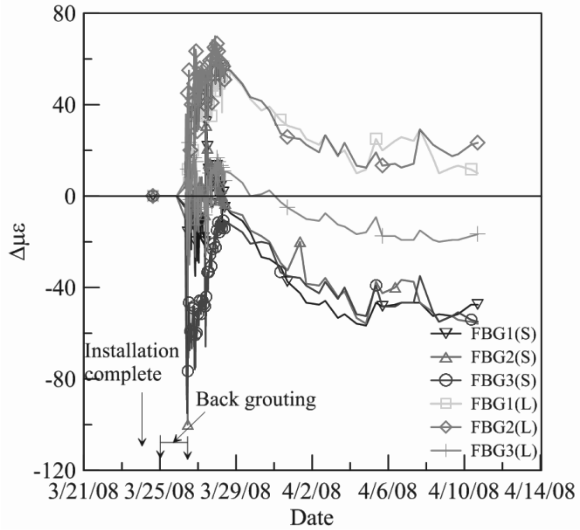

Figure 10. Change of strains in the early stage of A1 panel installation.

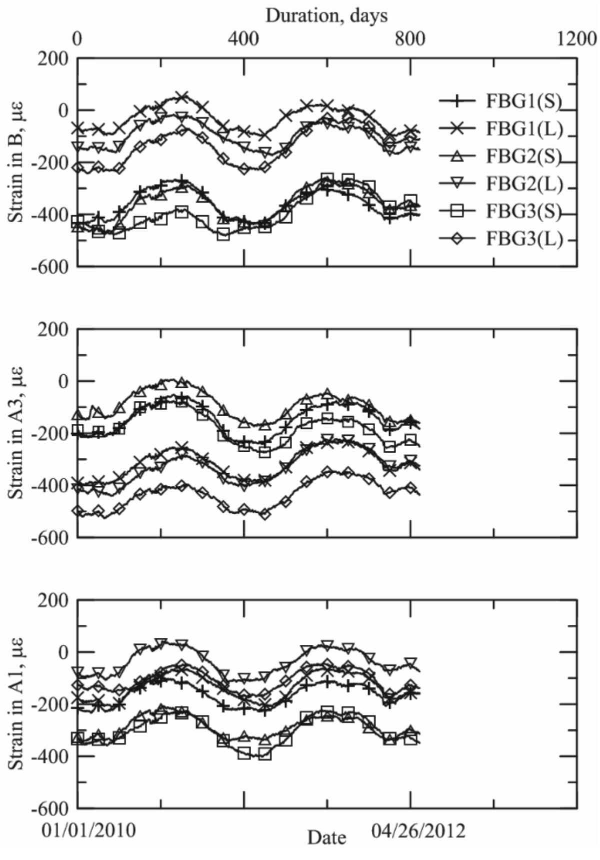

Figure 11. Long term strain readings.

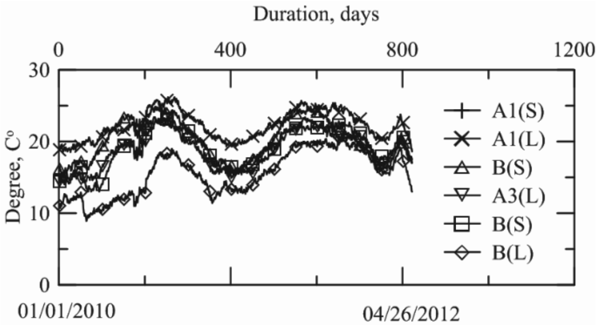

Figure 12. Long term temperature readings.

5 REFERENCES

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