

Fiber Bragg grating arrays for impact damage monitoring in concrete

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ABSTRACT: This paper discusses innovative high-speed, low-cost, remote, real-time monitoring of impact damage, residual strength and penetration resistance in concrete based on embedded optical Fiber Bragg Grating (FBG) sensor networks. FBG sensors are well suited for monitoring dynamic strain in concrete structures due to their small size, low cost, and ability to be embedded internally or surface mounted. For installation, pre-packaging can improve the sensor survivability when subject to rapid placement of concrete. Multiple color-coded FBG sensors can be cascaded along a single fiber to form a natural self-contained sensor network, providing synchronized and correlated sensing. The sequence of impact and timing of penetration can be precisely measured. Following penetrator impact, the technique has potential to provide real-time multipoint monitoring of penetrator progression detecting both slow (typically millisecond) strain transient effects associated failure waves as well as early-time information regarding fast (typically microsecond) transients associated with wave reflections and pulverization.

1 INTRODUCTION

Intelligent Fiber Optic Systems Corporation (IFOS) has developed a novel ultra-high-speed, low-cost real-time monitoring solution for reinforced concrete based on embedded Fiber Bragg Grating (FBG) sensor arrays. FBG sensors are ideally suited for monitoring strain in concrete structures due to their small size providing minimum disturbance to the concrete structure, low cost, widely availability, multiplexing capabilities whereby multiple wavelength-division-multiplexed (WDM), i.e., color coded, FBG sensors can be cascaded along a single optical fiber.

FBG multiplexibility facilitates installation (in comparison with, for example, resistive foil gages which each require multiple wires installation. FBG sensor arrays can be embedded internally in concrete or surface mounted. Pre-packaging can improve the sensor survivability when subject to rapid placement of concrete.

Furthermore, FBG sensors are absolute, linear in response, electromagnetic interference (EMI) immune, relatively robust especially when appropriately packaged, and have the ability to withstand high temperature – the sensors can maintain their capabilities even close to the glass softening point for a short duration. These characteristics have the potential to enhance the survivability of FBG sensor networks embedded in structures subject to impact and ensure delivery of critical information to a remote high-speed FBG interrogator. Smart algorithms can be programmed into the monitoring process to make correction and determine concrete behavior for varying structure densities according to real-time data. FBG sensor systems have the potential to produce significant cost savings, while providing great improvement on the data acquisition capabilities in terms of precision, time resolution and speed.

IFOS has tested the feasibility of measuring the dynamic condition of concrete using FBG sensors with high-speed real-time monitoring through optical fiber cables. Previous work had established the ability of embedded and surface mounted FBG sensor to detect static or low-speed strain in reinforced concrete in laboratory tests. Now, with a high-speed parallel process-

ing WDM interrogator, we can provide synchronized and correlated sensing. The sequence of impact and timing of penetration can be precisely measured. For example, following penetrator impact, the technique has the potential to provide real-time multipoint monitoring of penetrator progression detecting both slow (typically millisecond) strain transient effects associated failure waves as well as early-time information regarding fast (typically approaching microseconds) transients associated with wave reflections and pulverization around the penetrator.

In Section 2, we discuss FBG strain measurement principles and the enabling FBG interrogation technology. Then, in Section 3, we present results for impact tests on a concrete disk containing embedded FBG sensors before concluding in Section 4.

2 FBG SENSING AND FBG INTERROGATION SYSTEM DESIGN

2.1 FBG Strain Measurement Principles & Characterization

FBGs (Hill & Meltz 1997) are sensor elements which are photo-written into germanium doped optical fiber using intense interfering ultra-violet laser beams. Many FBG sensors can be supported on a single strand of optical fiber (Childers et al 2001). They can be used for the measurement of strain (Black et al. 2008c), crack growth (Black et al. 2008b), vibration (Chau et al. 2003), acoustic waves (Perez et al. 2001) and temperature with applications reported including monitoring of concrete dams (Ren et al. 2009), highways, bridges (Chan et al. 2005), aerospace components (Black et al. 2008b), robots (Park et al. 2009), and wind turbines (Sotoudeh et al. 2009) as well as in chemical and biological sensors. They also have potential in monitoring and recording of seismic responses of underground structures including rock mass, etc.

The basic principle of an FBG-based sensor system lies in the monitoring of the wavelength shift of the returned Bragg-signal, as a function of the measurands (e.g., strain and temperature). The Bragg wavelength is related to the refractive index of the material and the grating pitch. Sensor systems involving such gratings work by injecting light from a spectrally broadband source into the fiber, with the grating reflecting a narrow spectral component at the Bragg wavelength, or in transmission this component is missing from the observed spectrum (see Fig. 1).

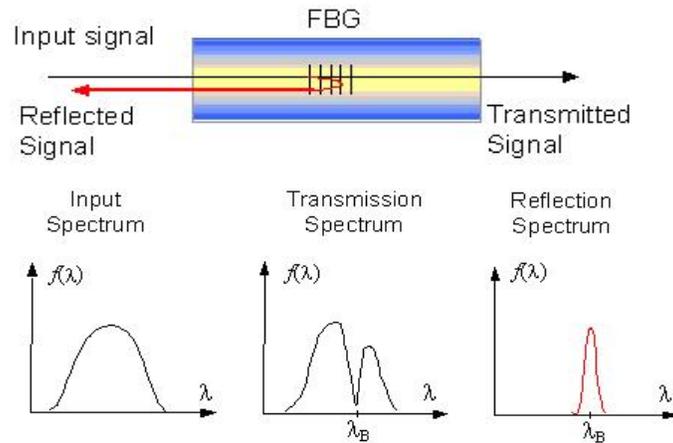


Figure 1. Functional principle of an optical fiber Bragg grating (FBG)

FBG sensor systems can exhibit a resolution of $\text{sub-nanostrain}/\sqrt{\text{Hz}}$. Bragg gratings operate by acting as a wavelength selective filter that reflects a single wavelength, called the Bragg wavelength, λ_B . The Bragg wavelength is related to the grating pitch, Λ , and the mean refractive index of the core, n , by $\lambda_B = 2\Lambda n$. Both the fiber refractive index (n) and the grating pitch (Λ) vary with changes in strain (ϵ) and temperature (ΔT), such that the Bragg wavelength shifts in response to longitudinal deformations in response to mechanical or thermal effects. This means that FBGs can be used as sensing elements. In a FBG sensor, the measurand causes a shift in the Bragg wavelength, $\Delta\lambda_B$. The relative shifts in the Bragg wavelengths due to an applied strain (ϵ)

and a change in temperature (ΔT) are approximately given by the relationships (Black et al. 2008c):

$$\Delta\lambda_{BS} = \lambda_B(1 - \rho_\alpha) \Delta\varepsilon \quad (1)$$

$$\Delta\lambda_{BT} = \lambda_B(\alpha + \zeta) \Delta T \quad (2)$$

where $\Delta\lambda_{BS}$ and $\Delta\lambda_{BT}$ are the strain and temperature induced Bragg wavelength shifts, λ_B is the Bragg wavelength, ρ_α is the photoelastic coefficient of the fiber (~ 0.22), α is the coefficient of thermal expansion and ζ is the thermo-optic coefficient. Operation as a sensor relies upon the measurement of the measurand induced shift in the Bragg wavelength. For FBGs written with Bragg wavelengths at 1550 nm, the sensitivities to strain and temperature, measured at room temperature, are ~ 1.2 pm/ μ strain and ~ 10 pm/ $^\circ$ C respectively.

Figure 2 plots the peak reflected wavelength versus strain for a typical grating.

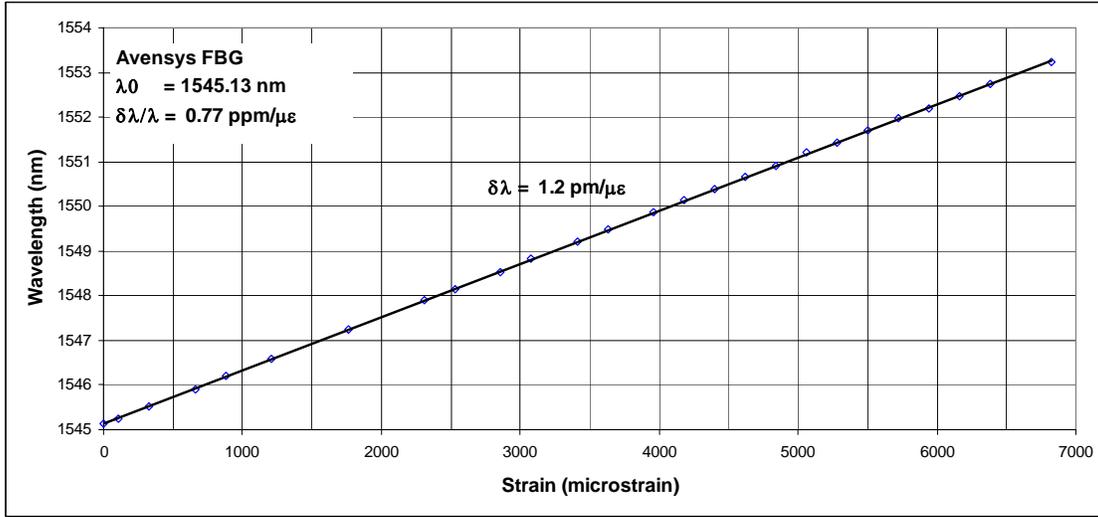


Figure 2. IFOS measurement of conversion between wavelength shift and strain change for an example grating (Black et al. 2008c)

2.2 FBG Interrogation

The strain measurements discussed in this paper rely on a sensor network comprised of FBG sensors embedded in concrete. In order to determine the strain on each of the networked FBG sensors, an FBG interrogator (Black & Moslehi, 2008a, Moslehi et al. 2003) is needed to collect data from the individual FBGs in the form of strain-induced wavelength changes. This interrogator can be located remotely from the FBG sensors with connection via a fiber optic cable.

The IFOS high-speed parallel-processing interrogator is based on sending broadband light to the FBG sensors, and then dividing the reflected light (multiple wavelength peaks, each corresponding to a different FBG) into multiple DWDM (Dense Wavelength Division Multiplexed) optical channels each separated by 0.8 nm in wavelength (100 GHz in frequency). Next channels are simultaneously examined with post-detection signal processing algorithms providing synchronized and correlated wavelength sensing for each FBG.

3 IMPACT TESTS AND RESULTS ON CIRCULAR CONCRETE SLAB

A set of tests were run on a concrete disk structure shown in Figure 3. IFOS research team fabricated the concrete disk test structure. The markings in Figure 3 show the positions of the fiber and sensors embedded at a depth of approximately 2.5 inches into the 5-inch thick disk.

Three independent impact tests were carried out and their results are shown in Figures 4 through 9. Only one FBG was used to measure the outputs. This time, instead of simply taking

the quasi-static measurements of the FBG spectra after each series of impacts, for these tests, the sensor outputs were measured for 5 seconds by a DWDM-based FBG interrogator with a sampling rate of 1 kHz.

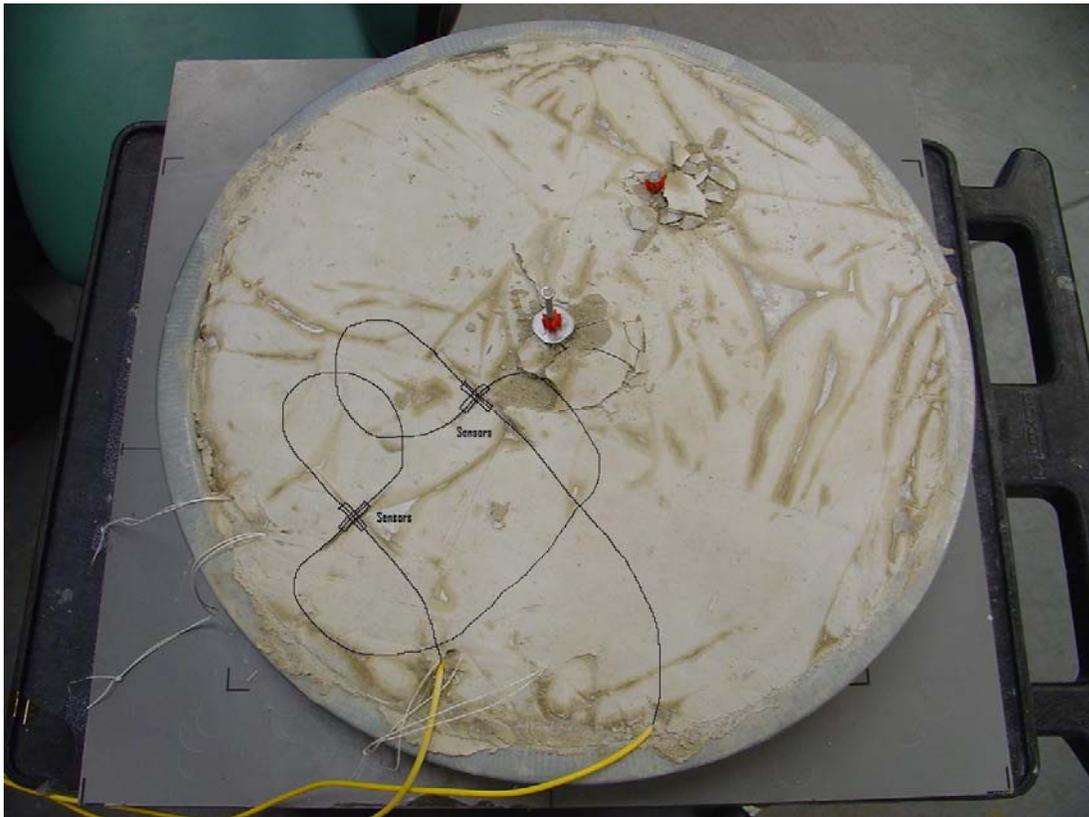


Figure 3. Fabricated concrete disk test structure – The markings show the positions of the fiber and sensors which were embedded at a depth of approximately 2.5 inches into the 5-inch thick disk.

3.1 *Test 1*

Two impacts were applied to the concrete slab by hammering. Figure 4 shows the raw data of sensor channel outputs (the voltage in each channel is related to the how close the FBG wavelength is to the center wavelength of the channel), and Figure 5 shows the wavelength shift determined from the raw data. The two impacts were detected clearly, and the wavelength shifts are also shown. The wavelength shifted approximately 0.03 nm on each impact. This wavelength shift corresponds to approximately 25 μ strain (given a gage factor for the FBGs of 1.21 pm per μ strain (Black et al. 2008c)).

3.2 *Tests 2 and 3*

Single impact was applied to the concrete slab in the same way of Test 1. Figures 6 and 8 show the raw data of two sensor channel outputs, and Figures 7 and 9 show their wavelength shifts respectively. The wavelength shifted approximately 0.011 nm on each hit (corresponding to approximately 9 μ strain).

We were able to see the transient strain changes in all the tests. However, higher sampling rate will provide more information at the moment of the impact. Also, the results show the sensor takes a certain period of time to stabilize after impacts.

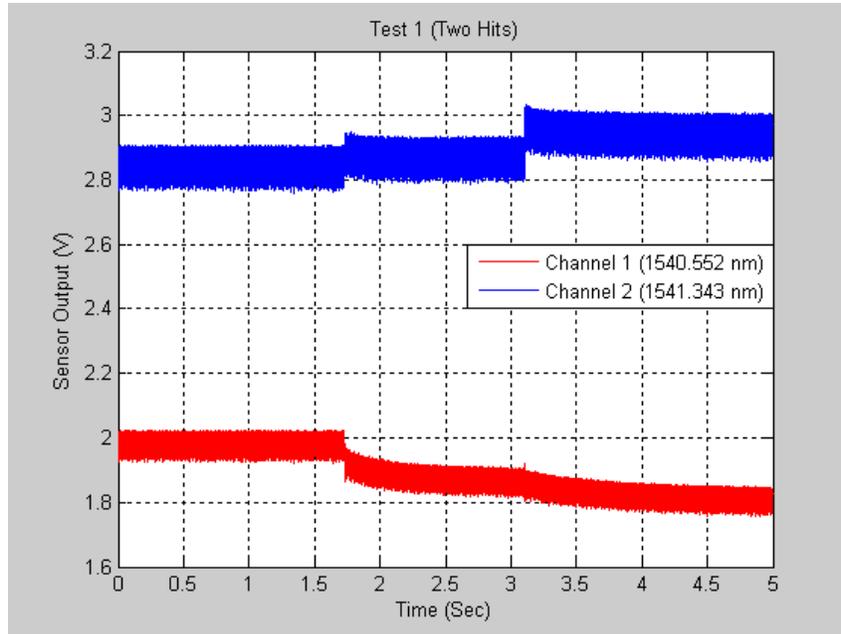


Figure 4. Sensor output changes from double impacts (Test 1)

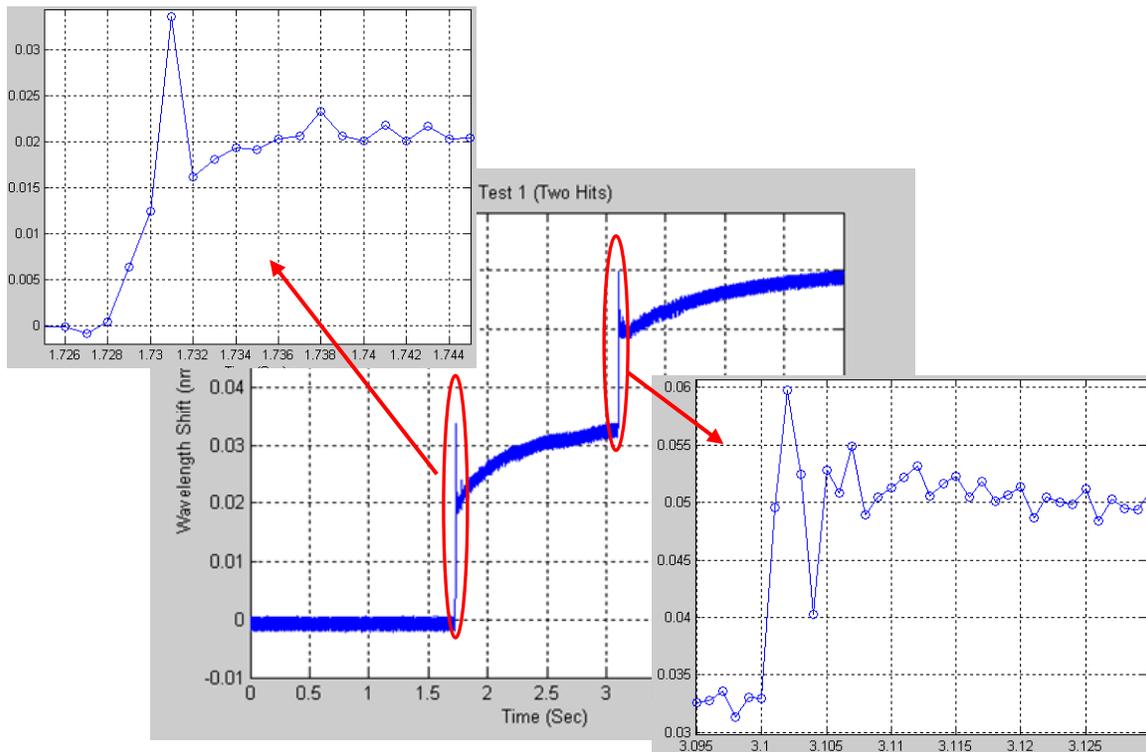


Figure 5. Wavelength shift from double impacts (Test 1)

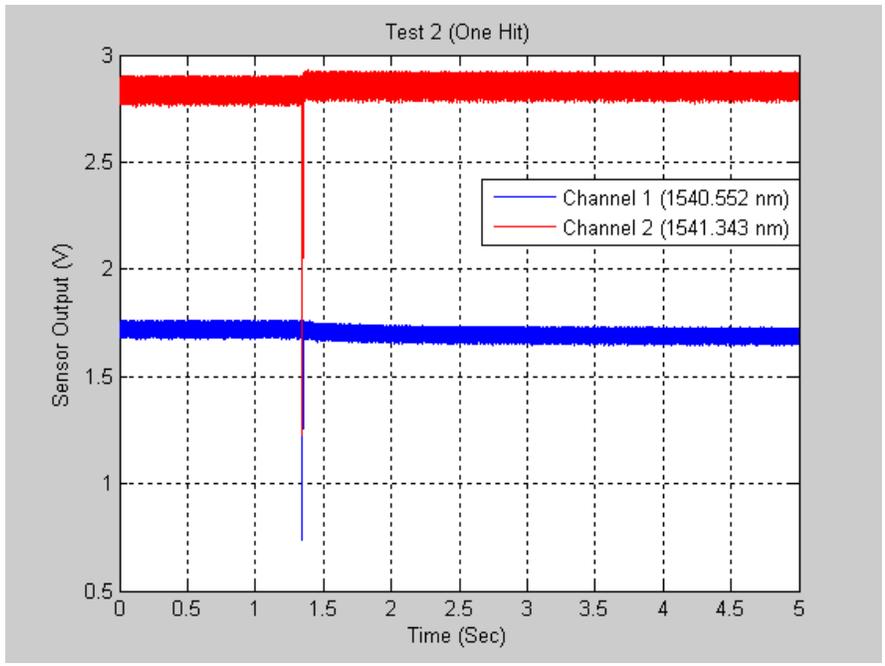


Figure 6. Sensor output change from single impact (Test 2)

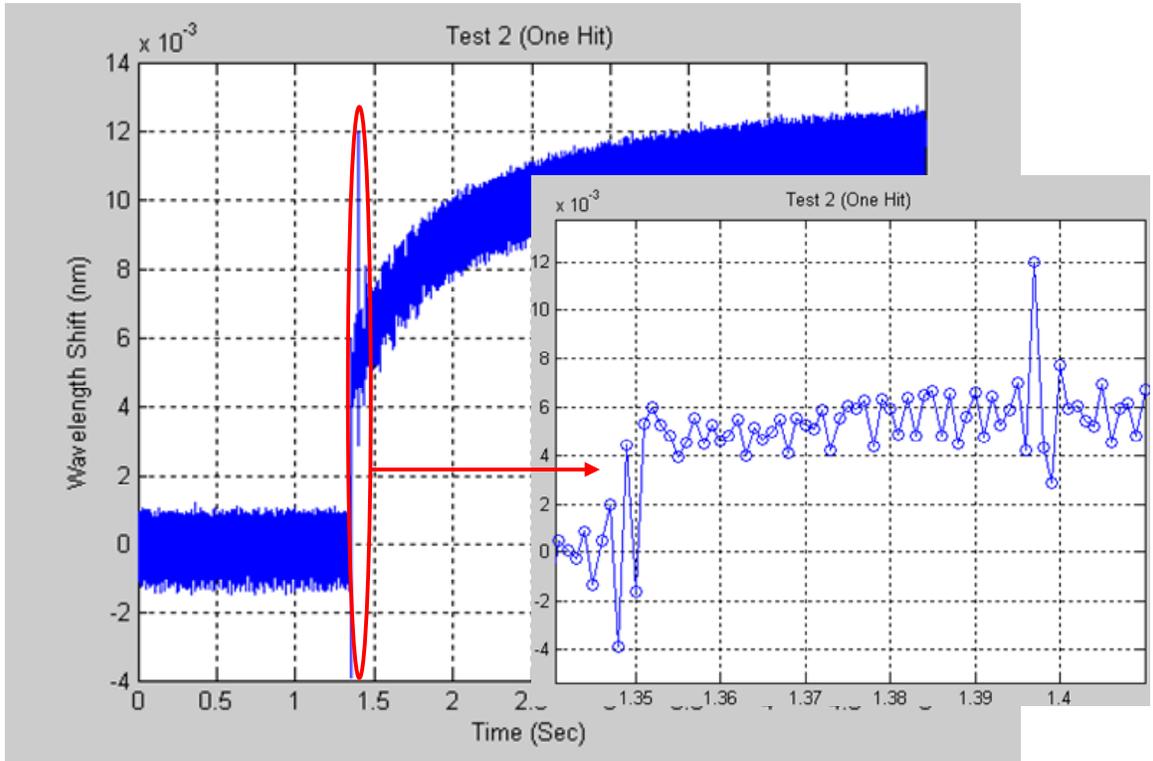


Figure 7. Wavelength shift from single impact (Test 2)

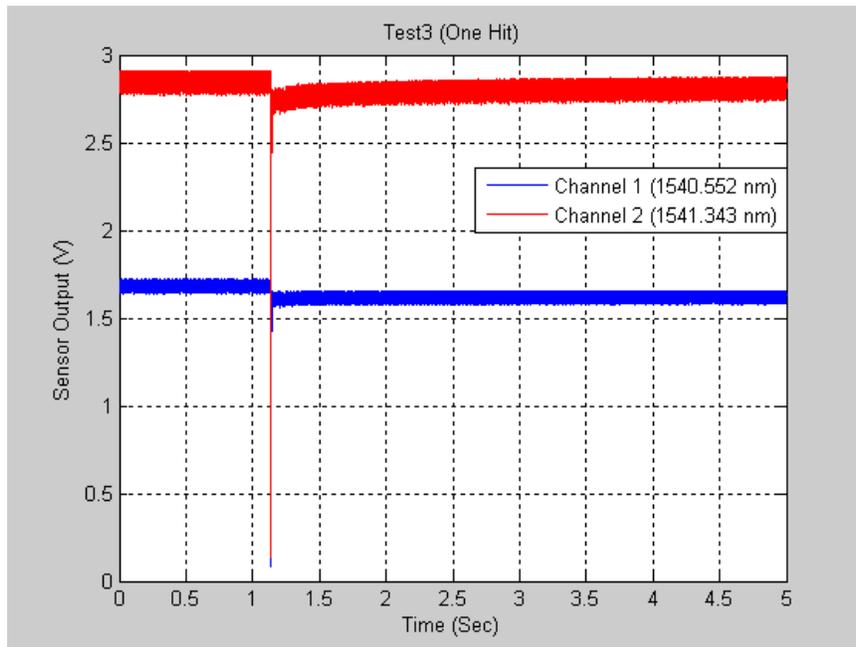


Figure 8. Sensor output change from single impact (Test 3)

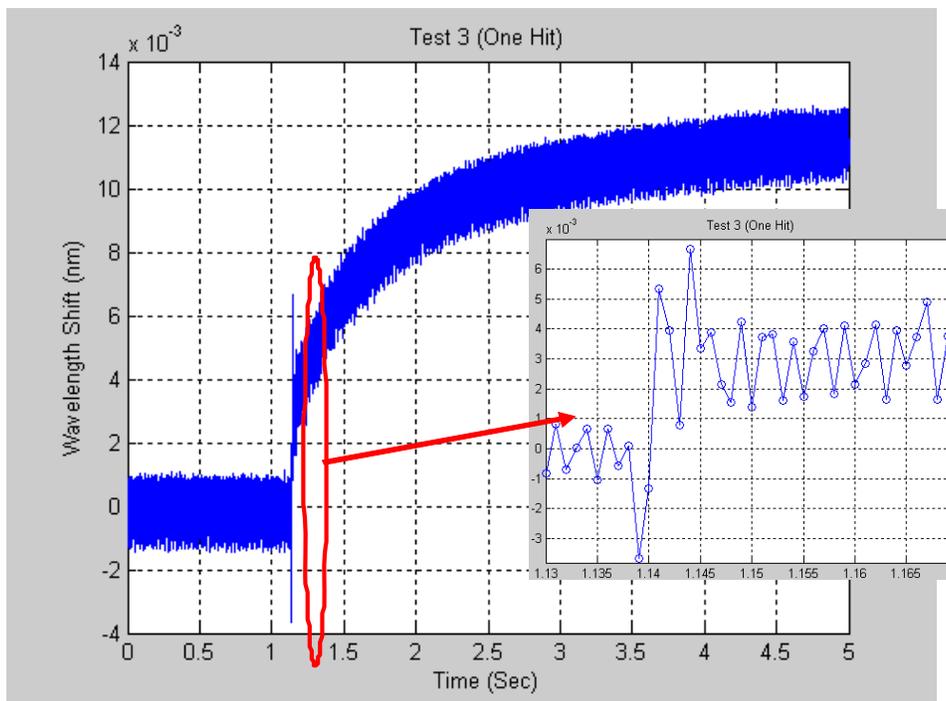


Figure 9. Wavelength shift from single impact (Test 3)

4 CONCLUSION

IFOS has clearly demonstrated the feasibility of FBG sensor arrays for providing information regarding high speed dynamic strains in concrete. This includes providing a measure of the residual strength of the concrete. Quantifying damage in solid materials, which may be described in terms of their residual strength such that future response will be well-characterized, is a problem that is not easily or quickly solved. However, this research work involved measurements that bear on this problem. In this work, we aimed to perform impact experiments and provide a preliminary explanation of the relationship between our dynamic strain measurements and the nonlinear specimen response associated with the failure mechanisms.

5 ACKNOWLEDGEMENT

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