Fiber Bragg Grating Arrays for Impact Damage Monitoring in Concrete

V. Sotoudeh *, B. Moslehi, R.J. Black, L. Oblea, G. Chen
Intelligent Fiber Optic Systems Corporation (IFOS), Santa Clara, CA 95054, USA

P. Randles
Defense Threat Reduction Agency (DTRA), NM, USA

ABSTRACT: This paper discusses an innovative high-speed, low-cost, real-time monitoring solution for impact damage, residual strength and penetration resistance monitoring in concrete based on embedded Fiber Bragg Grating (FBG) sensor networks. The concrete condition can be directly measured and remotely monitored in real time through optical fiber. FBG sensors are well suited for monitoring dynamic strain in concrete structures due to their multiplexing capabilities for increasing the number of sensors, small size which provides minimum disturbance to the concrete structure, 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 wavelength-multiplexed (color-coded) FBG sensors can be cascaded in 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. 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. FBG sensors have the advantage of being absolute, linear in response and EMI immune as well as the ability to withstand high temperature, capable of maintaining their sensing capabilities even close to the glass melting point for a short period of time. These characteristics enhance the sensor network survivability during impact to deliver the critical information to a remote high-speed interrogator.

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, low cost, ability to be either embedded internally or mounted on the surface; and multiplexing capabilities of increasing the number of sensors by Wavelength Division Multiplexing (WDM).

Furthermore, FBG sensors have the advantage of being absolute, linear in response and EMI immune, as well as the ability to withstand high temperature – the sensors can maintain their capabilities 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 FBG interrogator.

IFOS has tested the feasibility of measuring the dynamic condition of concrete using FBG sensors and remotely monitored in real time through fiber cables. Previous work had established the ability of embedded and surface mounted FBG sensor to detect static of low-speed strain in reinforced concrete in several laboratory tests.

FBG sensors provide an absolute, linear response, are EMI immune (electrically passive) and have the ability to withstand high temperature. These characteristics enhance the sensor network survivability during impact to deliver the critical information to the remote 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 sensors are low-cost, widely available and can easily be embedded in concrete. Such systems produce significant cost savings, while providing great improvement on the data acquisition capabilities in terms of precision, time resolution and speed.

2 FBG INTERROGATION SYSTEM DESIGN

2.1 *FBG Strain Measurement Principles & Characterization*

FBGs [1]-[13] are sensor elements which are photo-written into germanium doped optical fiber using intense ultra-violet laser beams and as a consequence records nanometer spaced diffraction gratings into the fiber. They can be used for the measurement of strain/deformation and temperature with applications reported including monitoring of concrete dams, highways, bridges, aerospace components and robotics [6] 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 Figure 1).

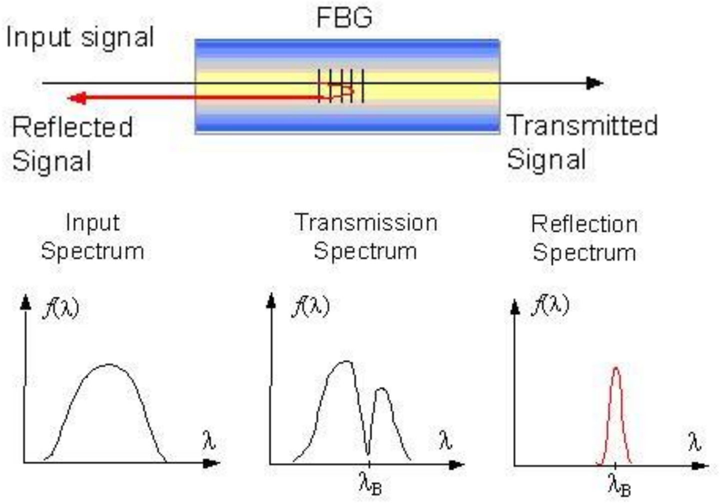

Figure 1. Functional principle of an optical fiber Bragg grating (FBG)

FBG sensor systems can exhibit a resolution of sub-$nanostrain/\sqrt{Hz}$. 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 [3]

$$\Delta\lambda_{BS} = \lambda_B(1-\rho_\alpha)\Delta\varepsilon \qquad \Delta\lambda_{BT} = \lambda_B(\alpha+\xi)\Delta T \tag{1}$$

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 ξ 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/μstrain and ~10 pm/°C respectively.

Figure 2 shows an IFOS measurement of the peak reflected wavelength versus strain for a typical grating.

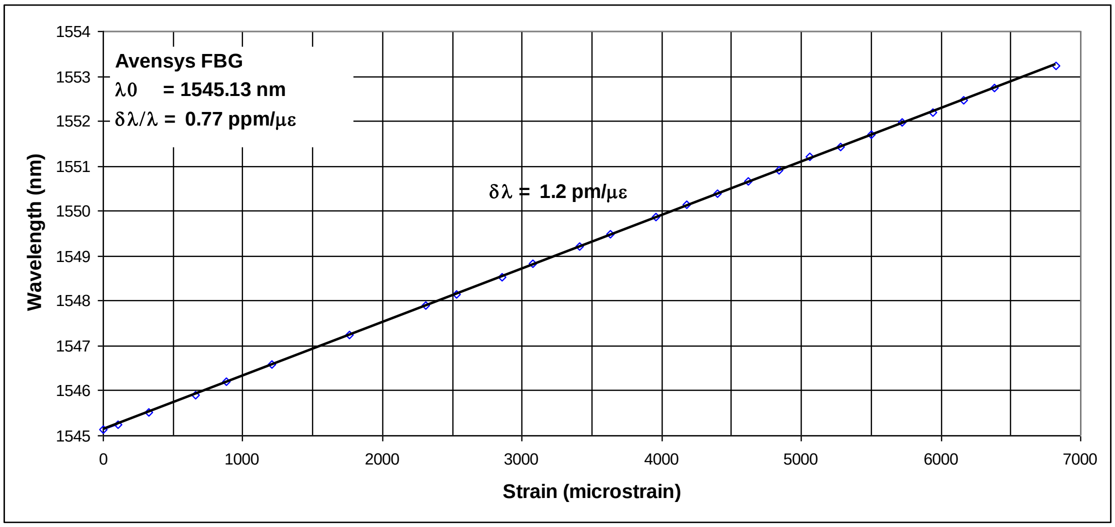

Figure 2. IFOS measurement of conversion between wavelength shift and strain change for an example grating [3]

2.2 *FBG Interrogation*

The strain measurements rely on a sensor network comprised of Fiber Bragg Grating (FBG) sensors embedded into concrete. In order to determine the strain on each of the networked FBG sensors, an FBG interrogator [1] is needed to collect data from the individual FBGs in the form of strain-induced wavelength changes. FBG sensors have great potential to address the need for embedded sensors and interrogation systems for real-time high-speed determination of system health in a number of military and commercial applications. This is, in part, due to their small size, lightweight, immunity to electromagnetic interference (EMI), multiplexability and minimal power consumption.

The high-speed IFOS interrogator is based on interrogating a number of DWDM (Dense Wavelength Division Multiplexed) wavelength-addressed optical channels separated by 0.8 nm.

2.3 *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 makings 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 Figure 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.

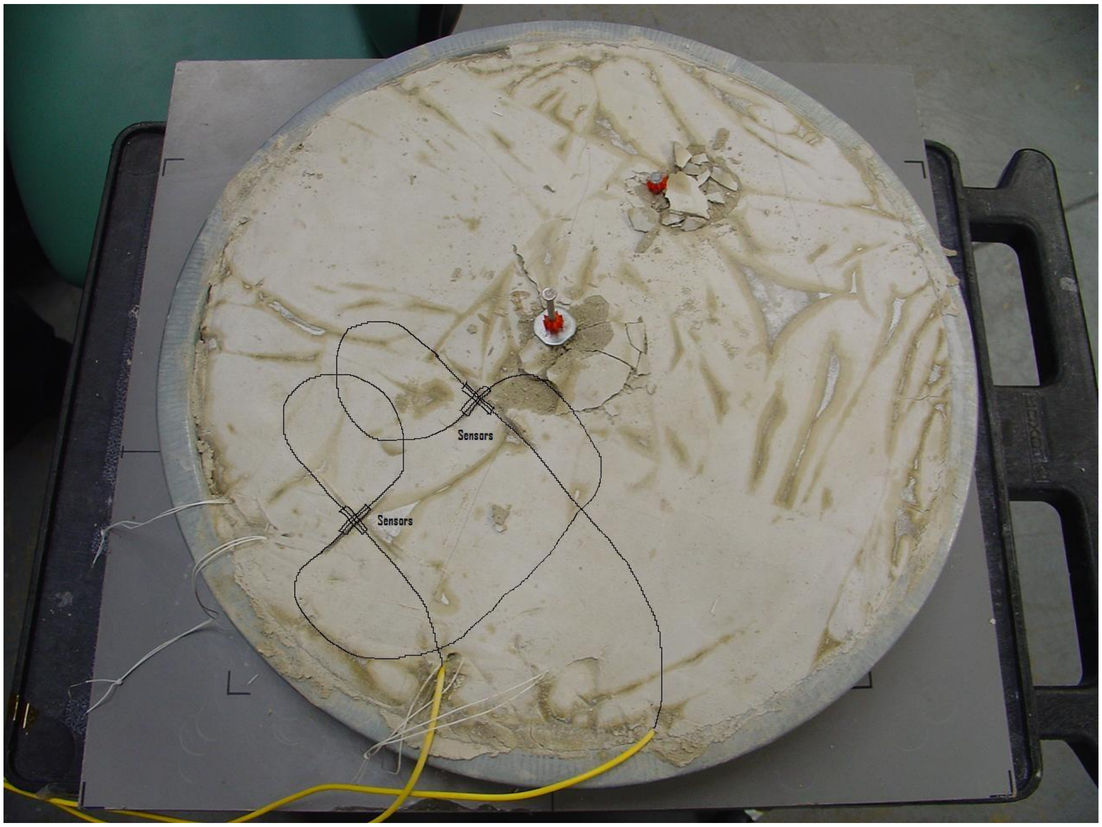

Figure 3. Fabricated concrete disk test structure – The makings show the positions of the fiber and sensors which were embedded at a depth of approximately 2.5 inches into the 5-inch thick disk.

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 μstrain (given a gage factor for the FBGs of 1.21 pm per μstrain [3]).

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 μstrain).

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.

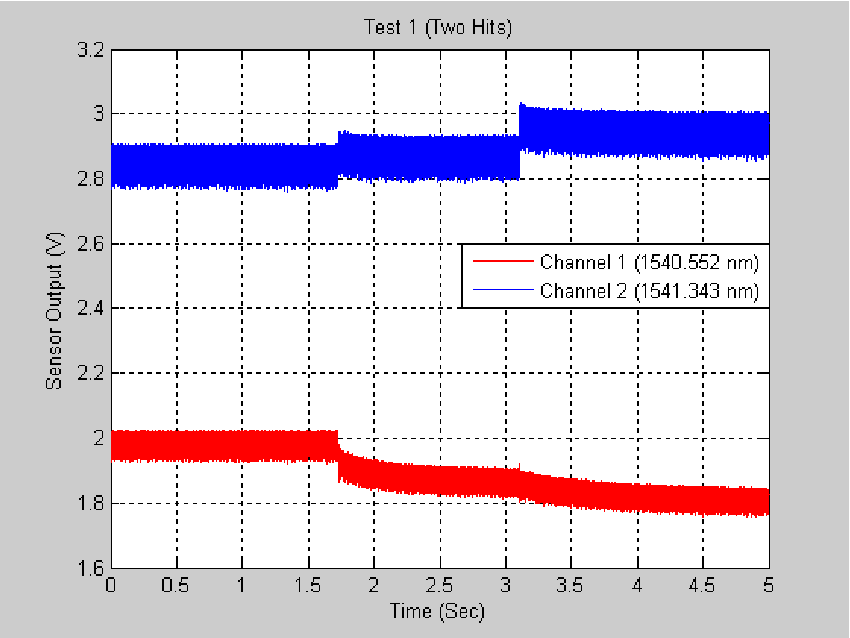

Figure 4. Sensor output changes from double impacts (Test 1)

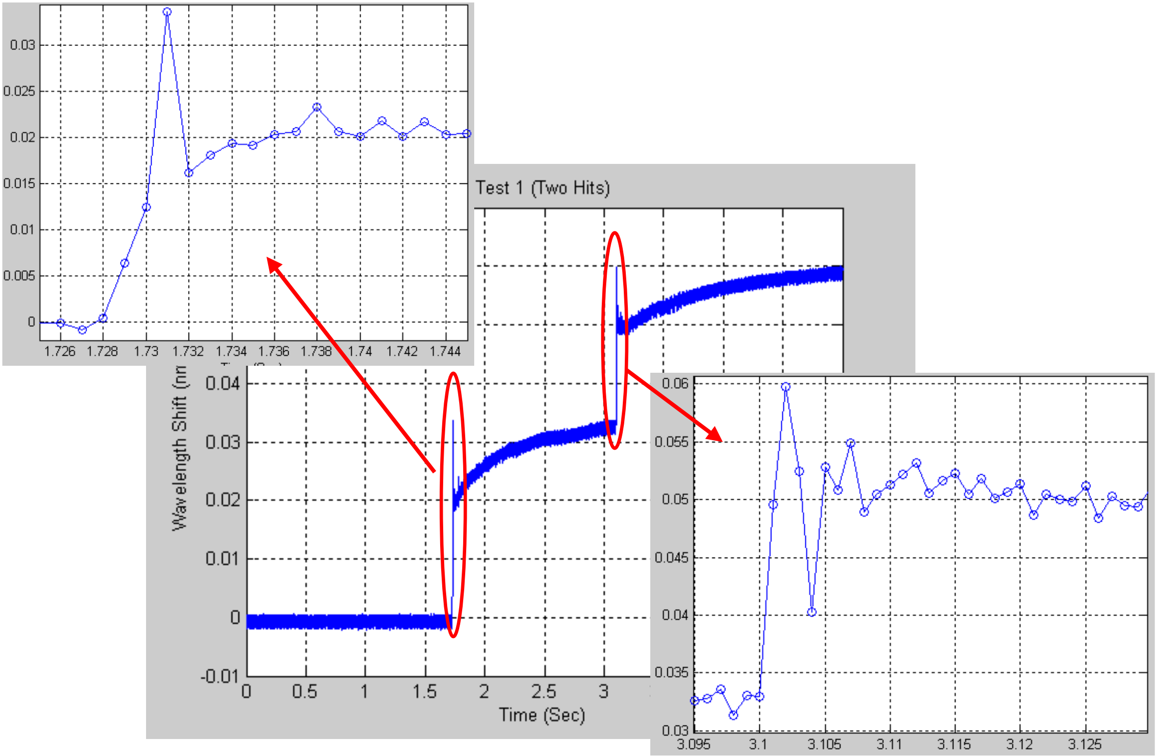

Figure 5. Wavelength shift from double impacts (Test 1)

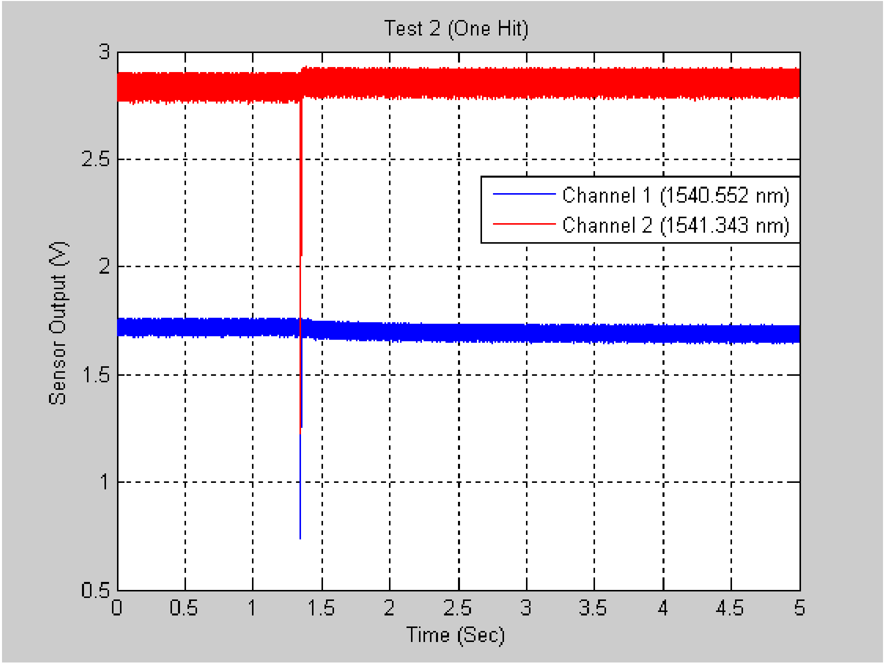

Figure 6. Sensor output change from single impact (Test 2)

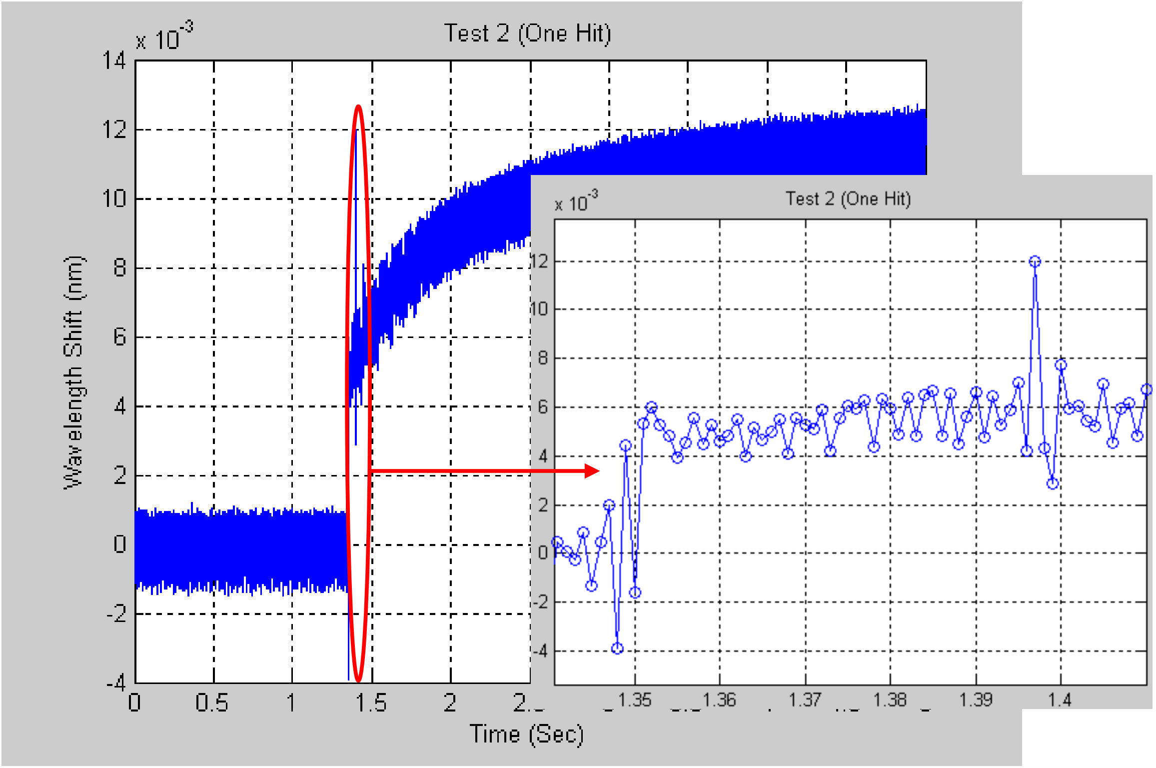

Figure 7. Wavelength shift from single impact (Test 2)

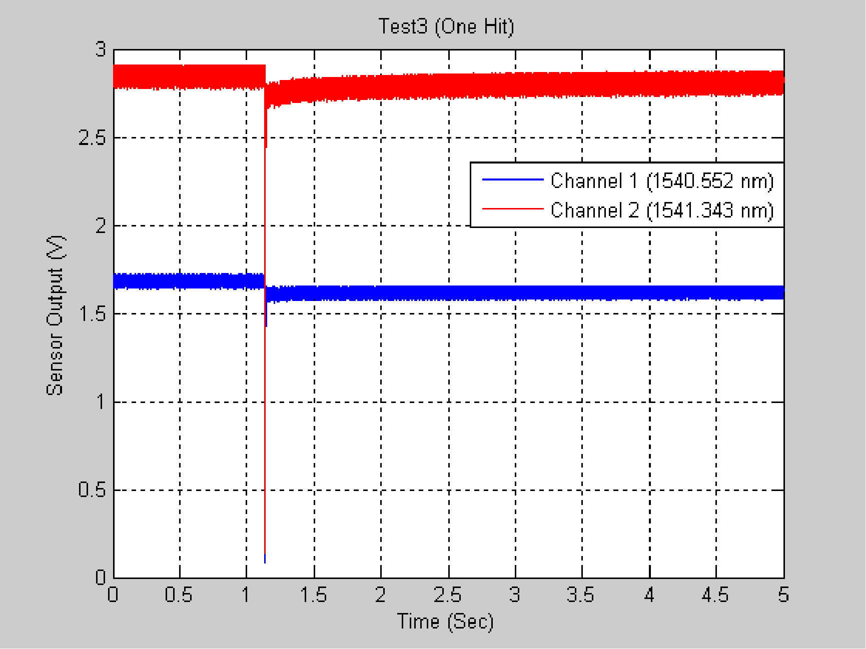

Figure 8. Sensor output change from single impact (Test 3)

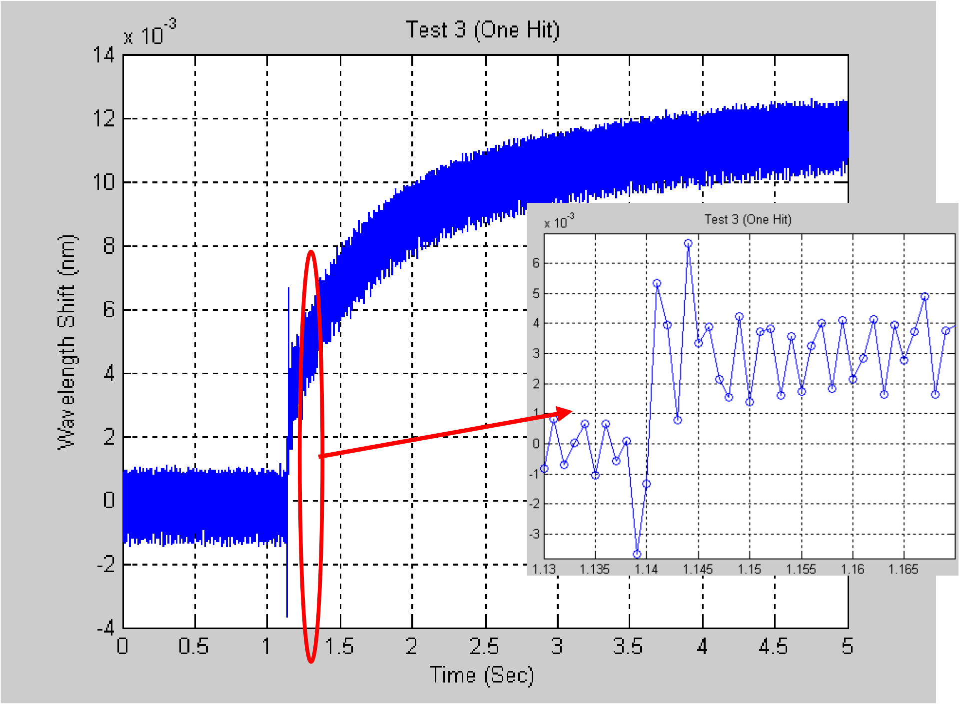

Figure 9. Wavelength shift from single impact (Test 3)

3 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.

4 ACKNOWLEDGEMENT

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