25 Years of Structural Monitoring Using Fiber Optic Sensors

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ABSTRACT

This paper describes selected work in the area of fiber optic smart structures performed by the author and his colleagues at McDonnell Douglas, Blue Road Research and Columbia Gorge Research over the past 25 years. It is intended to provide an overview of some of the developments in the field and how it evolved over this time span. Application areas that will be addressed include aerospace, civil structures and composite materials.

Keywords: Fiber gratings, Sagnac interferometer, smart structures, fiber optics, health monitoring

1. Innovations at McDonnell Douglas

Early work at McDonnell Douglas on fiber optic sensors began with the development of fiber optic rotation sensors based on the Sagnac interferometer [1-2] and fiber optic acoustic sensors utilizing the Mach-Zehnder interferometer. It was quickly realized that these interferometers could be used to sense a wide variety of environmental effects. Importantly a fiber optic strain sensor based on the Sagnac interferometer [3-4] was invented in the early 1980s as a derivative of the closed loop fiber optic gyro utilizing an acousto-optic modulator as a frequency shifter. The offset frequency of the acousto-optic modulator made the entire fiber loop sensitive to strain and the closed loop support electronics allowed changes in length of as little as 1 part in 10^8 to be sensed. Immediate applications of this strain sensor involved measurements of composite parts for aircraft and potential structural assemblies of the space station. These early demonstrations of composite material included the realization that conventional acrylate coatings did not provide reliable strain transfer and that polyimide coatings worked very well. In 1985 the US Air Force was conducting Project Forecast II and asking for suggestions for topics that would be of high interest. Eric Udd suggested two topics, fiber optic smart structures and secure fiber optic communication. Both were accepted and allotted an hour of time for each briefing. The smart structures title was actually derived from another Air Force topic involving smart sensors that were for a very different application. The Air Force adopted “smart structures” into their plans for future funding and for the next two years Eric Udd spent a considerable amount of time at various Air Force bases explaining what that meant. While early demonstrations involved organic composite materials there was interest in expanding structural sensing to very high temperatures. This resulted in demonstrations that optical fibers could be successfully embedded in titanium using a variety of coating materials that included aluminum and gold.

Figure 1 shows in block diagram form the basic elements of a smart structure as conceived at McDonnell Douglas in the mid 1980s.

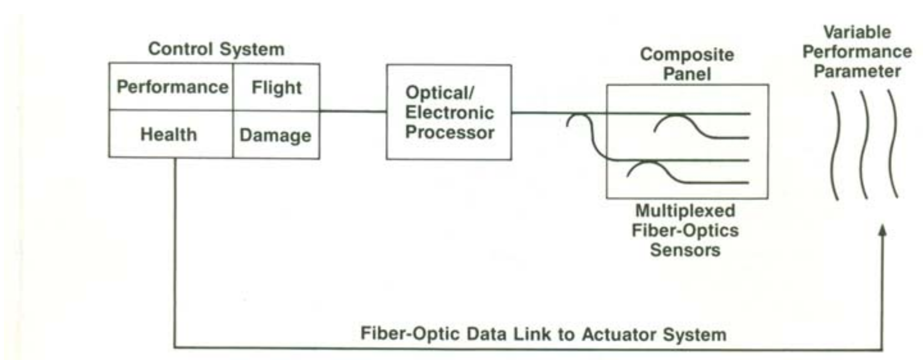

Figure 1 Block diagram of a smart structure system circa 1985.

The principle applications were directed toward aircraft and space based applications, including early designs associated with the space station, as shown in Figure 2. Examples of aircraft applications involved measurements of strain in light weight composite parts to identify and localize damage. On the space station there was concern about monitoring the integrity of struts and identifying and localizing micro-meteorite strikes.

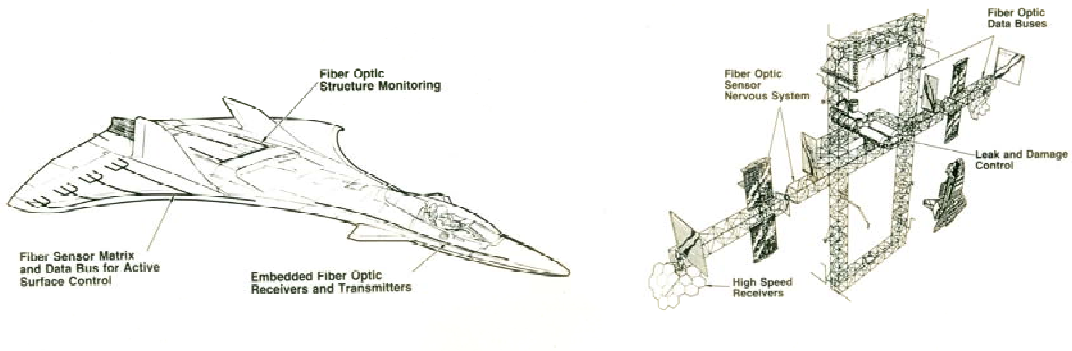

Figure 2 Applications of smart structures at McDonnell Douglas in 1985

The first demonstrations of strain measurements using optical fibers were conducted at McDonnell Douglas using the Sagnac strain sensor which was a derivative invention of the closed loop fiber gyro. Figure 3 shows a photo and the layout of the Sagnac strain sensor. Figure 4 shows this sensor being used to measure strain in a carbon epoxy coupon.

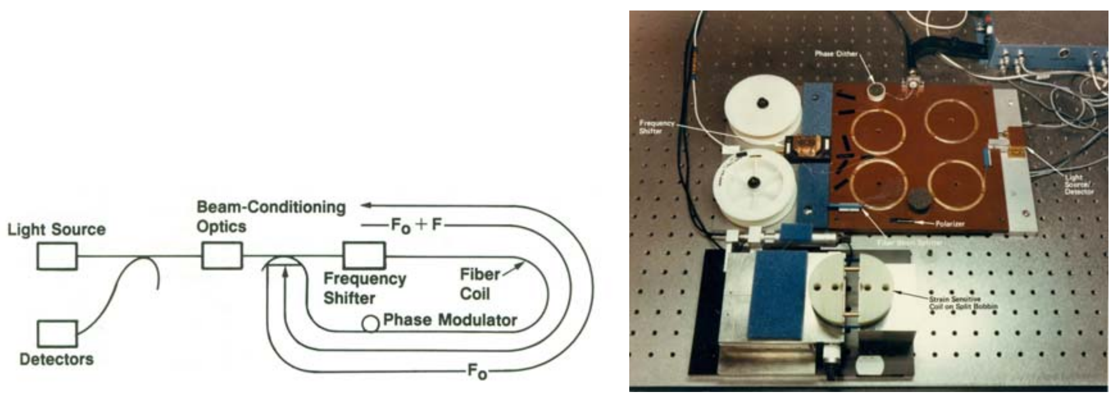

Figure 3 The Sagnac strain sensor was used for the first demonstrations of strain measurements with embedded fiber optic sensors in composites

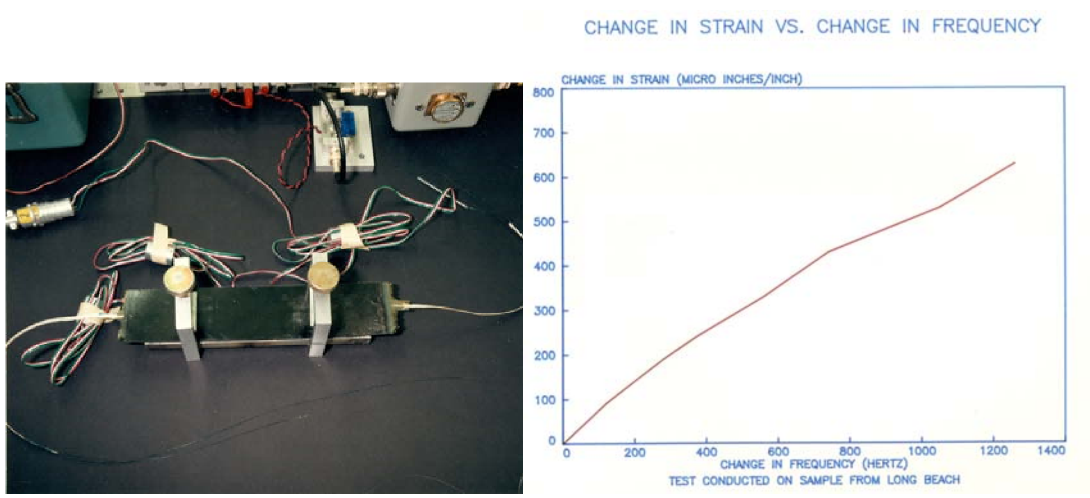

Figure 4 Embedded fibers being used to measure strain in a carbon epoxy coupon in 1985

The early interferometer tests were used to support testing of carbon epoxy, thermoplastic and titanium composite structures. For organic composite materials these served to identify polyimide coatings on optical fibers as having good adhesion and reproducible strain results. The first attempts were made using epoxy acrylate coated optical fiber and slippage of occurred. For the titanium structures it was found that aluminum and gold coatings would allow the optical fibers to survive the manufacturing process with temperatures up to 1000 C and pressures up to 1000 psi. Long duration testing at elevated temperatures also established temperature limits for successful operation of the optical fibers before softening and core diffusion limited performance.

The early configurations of the Sagnac interferometer were responsive to strain and temperature. They had much longer gauge lengths than those associated with electrical strain gauges that were commonly employed by structural engineers. In the late 1980s fiber gratings became available and McDonnell Douglas developed a series of fiber grating read out units that included the usage of fiber gratings for filters and scanning Fabry-Perot etalons. Both open and closed loop methods were developed in analogy to those employed to support fiber optic rotation sensors.

One major issue that remained was to deal with isolating strain from temperature. This was addressed in two ways. The first was a simple isolation method where fiber sensors were packaged or mounted mechanically to sense only temperature or strain. The second was to use two fiber gratings written at two different wavelengths superposed on the same area of the optical fiber. By monitoring both wavelengths two equations in two unknowns could be established allowing strain and temperature measurements to be made simultaneously at the same location.

The usage of fiber grating sensors at McDonnell Douglas for structural health monitoring moved in the late 1980s and early 1990s toward two major demonstration projects. The first involved making measurements on very thick composite parts that were several cm thick. When fiber grating sensors were place into this type of composite material transverse forces become increasingly important with depth of placement. Investigations were conducted looking at fiber gratings that had tilted fiber gratings and more than two superposed wavelengths to look at multi-dimensional strain fields associated the interior of thick composites.

As a result of these efforts, fiber grating sensors were selected to measure strain and temperature on an advanced composite hydrogen tank on the Delta Clipper, a one third scale single stage to orbit vehicle that was demonstrated under Air Force funding in the early 1990s through a series of flight tests. After successfully performing all required test flights on the program for the Air Force, NASA sponsored a series of additional flights. Eventually one of the landing pads did not deploy properly and the Delta Clipper tipped over and exploded. Before the flight tests there were some engineers who were used to electrical strain and did not want to use fiber grating sensors. When the tests were completed the fiber grating strain sensors had performed successfully throughout the tests while the electrical gauges had failed. The same engineers who had complained said they would never use an electrical strain gauge on a cryogenic composite tank again. A scanning etalon approach was used with elements similar to the block diagram on Figure 5 which also shows the Delta Clipper.

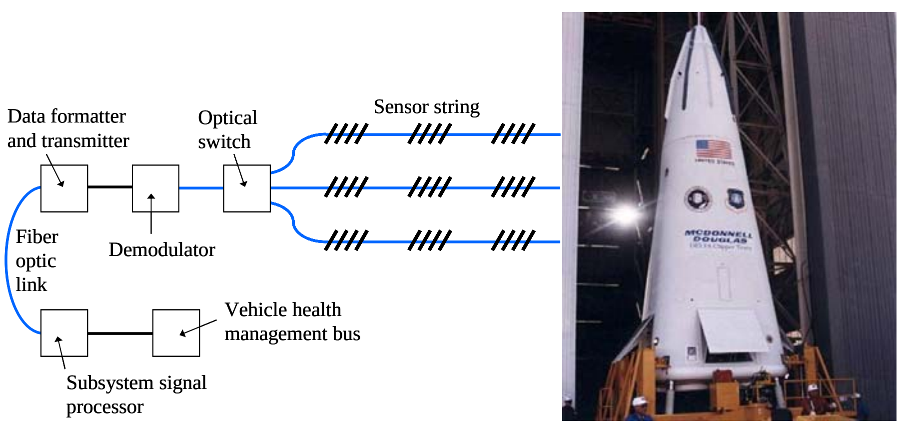

Figure 5 Block diagram of a fiber grating sensor system similar to that employed to monitor strain and temperature on the composite hydrogen tank of the Delta Clipper flown in the early 1990s.

2. Innovations at Blue Road Research

Very early in the development of fiber grating sensor systems it was realized that a high speed fiber grating sensor system could be realized by placing an optical filter that might be a fiber grating in front of a detector so that spectral changes in the reflection from a fiber grating were amplitude modulated [5-7]. In principal the only limitation on this type of system involved the speed of the output detector which with the development of high speed communication links moved from the regime of 10s of MHz toward 10s of GHz. The earliest deployed systems involved civil structures including measurements of the strain fields on composite utility poles and missile bodies during break tests [8-12], bridges and freeways [13-19, 21-23, 25, 27]. This was followed by a series of developments that included high speed fiber grating sensors to support nondestructive testing via ultrasonic wave detection [20], high speed machining [24] and monitoring ship hulls [26]. Each of these applications involved monitoring mechanical motion of structures and thus interest was in speeds up to a few 10s of MHz. Most recently there has been interest in using fiber grating to monitor the very high speed events such as detonations [28-30] and this has led to utilization of fiber gratings that are consumed during an event that may require detection speeds of hundreds of MHz and in the future multiple GHz.

Through arrangements with McDonnell Douglas, Eric Udd and Blue Road Research obtained licenses to all McDonnell Douglas patents by Eric Udd that were not related to fiber optic gyros or secure fiber optic communication which were licensed to other companies. This largely involved patents related to the read out and operation of fiber optic gratings sensors and configurations of the Sagnac interferometer that were used for physical measurements other than rotation.

One of the first issues faced was the need to be able to monitor high speed strain events associated with the failure of large composite structures. Three different types of high speed measurement systems were investigated including an overcoupled coupler configuration, a miniature Mach-Zehnder interferometer filter and finally stabilized fiber grating filters. The overcoupled coupler used had a coupling region that was approximately 10 cm in length and transitioned between complete transmission and cross coupling over a wavelength range of 20 nm in the 1300 nm band. By positioning the fiber gratings at a wavelength between peak transmission and peak cross coupling a highly sensitive fiber grating sensor read out unit was realized whose speed was limited only by the speed of the output detectors. A pair of New Focus receivers was used during initial experiments with variable bandwidth and gains that could be operated up to 1 MHz. An early application involved monitoring composite utility poles to failure.

Figure 6 High speed fiber grating system based on overcoupled coupler and testing of 20 m fiber glass utility pole through failure

The first pole tested was approximately 8 m in length and 30 cm in diameter. Larger utility poles were later manufactured and tested that were a little less than 20 m in length (see Figure 6). The poles were loaded to failure with several fiber grating sensors in place to monitor the composite near the bonded junctions. The recording electronics used had a bandwidth of 10 kHz. The overcoupled coupler was replaced in later systems by the miniature Mach-Zehnder because it had better temperature stability and less polarization dependence. This later was replaced by chirped gratings mounted on thermally stabilized substructures. This approach had better thermal stability than the miniature Mach-Zehnder and was lower cost. The miniature Mach-Zehnder did have the advantage of a very smooth transfer function. This high speed system was used later to monitor acoustic signals in composite pressure vessels and during ultrasonic tests at speeds up to 1 MHz. It was also used to monitor strain fields induced by high speed impacts on thick composites up to 30 MHz.

In the early years at Blue Road Research all sponsors of research programs were out of state and in an effort to find a sponsor in Oregon a series of discussions were held with the Oregon Department of Transportation. These efforts resulted in the construction of fiber grating strain sensors that were mounted in tubes of lengths up to 1 m. The first involved monitoring the Horsetail Falls Bridge in the Columbia River Gorge National Scenic Area. Sixty fiber grating sensors were constructed and mounted into 5 full scale concrete beams with composite overwraps that were tested to failure at the civil engineering department of Oregon State University. These tests demonstrated the ability of the sensors to measure strain fields in both the concrete beams and the composite overwrap allowing successful modeling of the performance of the beams. This was followed by installation of 28 fiber grating strain sensor assemblies into the Horsetail Falls Bridge as it was being refurbished with composite overwrap procedures. Fiber grating sensors were selected because they could be embedded into the structure without altering the appearance of the historic bridge and because they could be put in place for long duration monitoring. After two years of monitoring the bridge for seasonal changes the bridge strengthening program was considered a success and the bridge safe for likely the next 100 years. The same sensors were then used to demonstrate the potential to measure the weight and speed of traffic on the bridge by using fiber grating filter read out systems operating at 5 kHz (see Figure 7). By improving the sensitivity of the read out system and developing sensors with lengths up to 1.5 m a series of installations were made into concrete and asphalt test pads to demonstrate that the weight distribution of cars could be measured. This in turn lead to two installations on the I 84 freeway near exit 14 during 2000 and 2001. These demonstrated that freeway traffic could be monitored, trailer types identified and relative weight distributions determined.

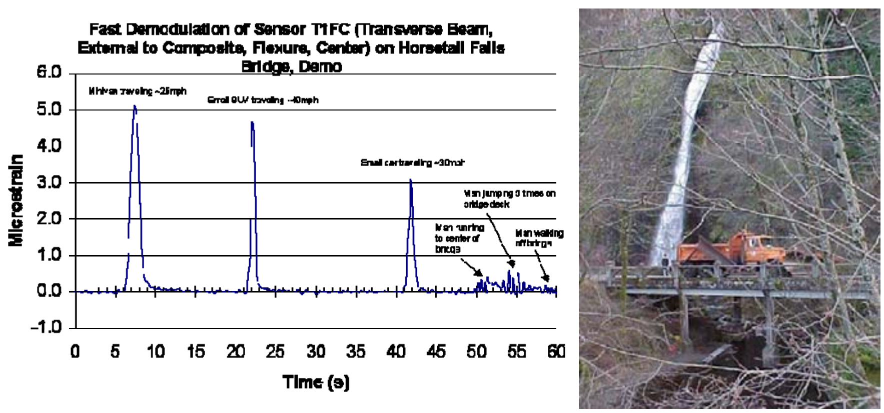

Figure 7   28 fiber grating sensors were installed into the Horsetails Falls bridge in the Columbia Gorge National Scenic Area, one was used to monitor traffic weight and speed…including a jogger

One of the major innovations of Blue Road Research was the introduction of multi-axis strain sensors based on writing fiber gratings onto birefringent optical fiber that may be commercial polarization preserving optical fiber. By writing a single fiber grating two strain components can be measured or axial strain plus temperature. With two overlaid fiber gratings all three axes of strain and temperature may be measured. By properly orienting these fibers grating sensors into composite material the direction and extent of damage could be monitored and the principle of "strain imaging" for damage assessment was born [28-30]. Demonstrations were performed on a series of composite pressure vessels under sponsorship from the Air Force. Later a variant of the system was used to requalify composite fuel tanks on the Space Shuttle.

The fundamental concept associated with "strain imaging" is that by measuring changes in the strain gradients associated with fiber gratings embedded into composite structures damage may be localized and assessed. This process is further aided when multi-axis fiber grating sensors are used that can be aligned with transverse axes in the plane of the part and orthogonal to it. Figure 8 shows the concept in general form. An array of fiber grating sensors that may be multi-axis fiber grating sensors are placed into a composite structure. The initial state of the fiber gratings are recorded and then when damage occurs, that may as an example be due to an impact, the change in strain gradients is then used to localize the damage and assess the type of damage. Figure 9 shows a comparison of a strain imaging result to an ultrasonic survey.

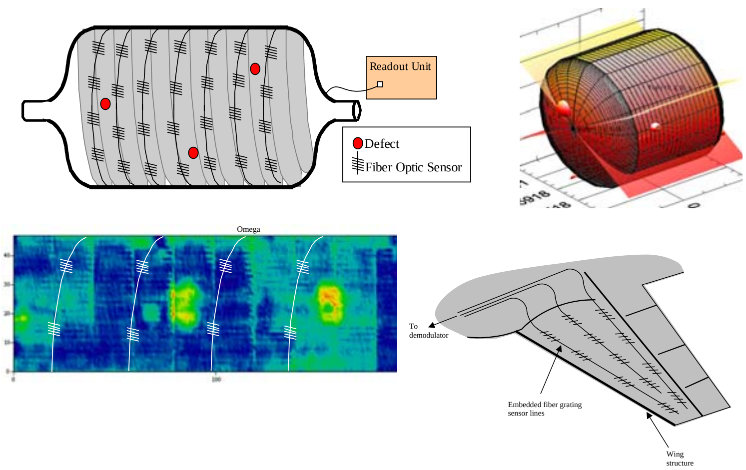

Figure 8 Arrays of fiber grating sensors may be embedded into composites and strain gradients used to localize and assess damage via "strain imaging"

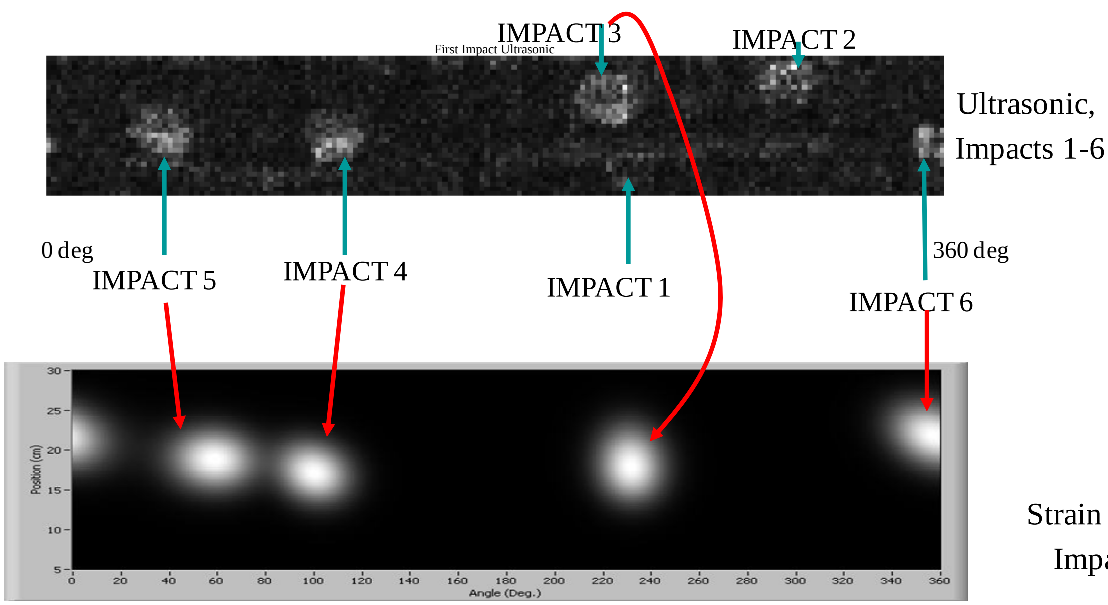

Figure 9 Comparison of impact damage to a composite pressure vessel using ultrasonic and strain imaging techniques….the ultrasonic scan took hours the strain imaging scan seconds

Strain imaging using fiber grating sensors has a number of advantages. The sensors are passive and electromagnetic interference problems are eliminated. The complete array of fiber gratings sensors can be scanned very quickly. While the data shown in Figure 9 was taken at a 2 Hz rate there are now solid state spectrometers that can operate in the 500 to 1000 kHz range with similar resolution. The state of the structure can be interrogated on demand when the information is needed. It is also important to note that ultrasonic techniques generally miss damaged tow material but are good at detecting disbands. Eddy current techniques are good at detecting damaged tow but miss disbands. Strain imaging has sensitivity to both.

3. Innovations at Columbia Gorge Research

Columbia Gorge Research has royalty free licenses to all the US Patents of Blue Road Research and certain patents of Schlumberger involving Eric Udd. It is continuing to work on "strain imaging" and branching into new areas involving very high speed and in some cases very high temperature events. In particular Columbia Gorge Research has been working with Lawrence Livermore to demonstrate the ability of fiber grating sensors to measure the velocity and position of blast waves during detonation. It has also been investigating the properties of different types of fiber gratings up to and beyond the melting temperature of quartz.

A very high speed system involves placing chirped fiber gratings into highly energetic material [28-30]. As the blast wave consumes the fiber grating its velocity and position may be measured to high accuracy. To show the utility of the system a chirped fiber grating was mounted in the center of a test article shown in Figure 10 that consists of PBX. Conventional piezoelectric pins are used to identify the position and velocity of the blast wave and compared to the high speed fiber grating sensor system that is operating at about 500 MHz. Raw data from this test is shown in Figure 11.

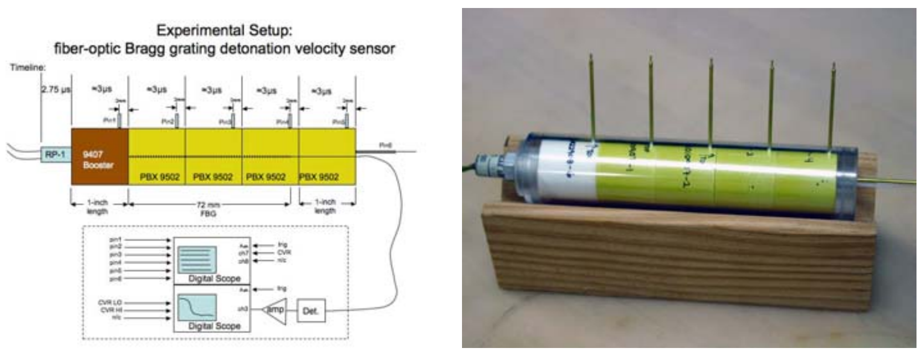

Figure 10 Experimental setup where a CFBG is embedded in a 4 inch column of PBX-9502 (left). The detonation was initiated with a commercial RP-1 detonator followed by a 1 inch PBX-9407 booster. Five piezo timing pins were placed at 1 inch intervals along the length of the PBX-9502 column (right).

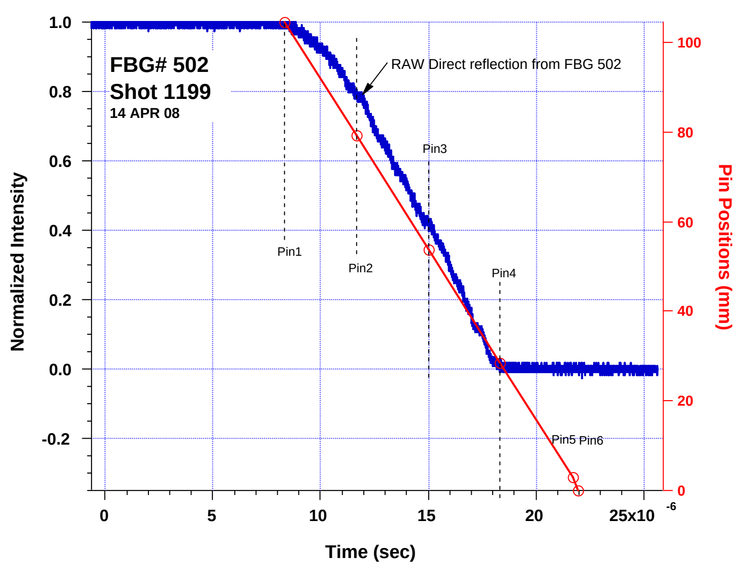

Figure 11 Raw data from test-firing PBX-9502. Raw pin data PBX-9502 average velocity is 7.65 mm/μsec. Raw CFBG sensor data had good signal-to-noise ratio compared to earlier test done in 2007.

Summary

This paper provides a short summary of some of the work performed by McDonnell Douglas, Blue Road Research and Columbia Gorge Research during the 1985 to 2010 time frame on structural monitoring. The author would like to thank the many people he has worked with on these projects as well as the many sponsoring organizations including the US Air Force, US Navy, US Army, DARPA and the Oregon Department of Transportation.

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