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FIBER BRAGG GRATINGS FOR DETONATION VELOCITY AND POSITION

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER

Munitions Engineering Technology Center

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14. ABSTRACT

With ever increasing demands for more detailed and accurate data in the energetics community, it is of significant importance to utilize new techniques to expand the testing capabilities to meet the demands imposed by program requirements and modeling and simulation needs. In this series of experiments, fiber Bragg gratings (FBG) were used as a detonation wave position sensor. Testing allowed for verification of system functionality, establishment of best practices, and the creation of analytical techniques to properly transform the captured voltage data to the corresponding distance data. These experiments yielded important pretest procedures and discovery of sources of noises in the system. Additionally, "edge effects" of the FBG spectrum response were accounted for. Verification of FBG system performance was achieved through comparison of the FBG methodology against a piezoelectric pin array to estimate system accuracy.

15. SUBJECT TERMS

Fiber Bragg FBG Detonation wave measurement Detonation position
Flexible detonation position sensor

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INTRODUCTION

For energetics testing, there is a broad and rich field that encompasses a significant number of tests and techniques to characterize the dynamic properties of materials as well as their response to specific external stimuli. The range of characterization tests can be broken out into more specific areas of interest such as sensitivity testing, material performance, end item reliability/performance, etc. While techniques have been established and improved upon over time as they relate to individual material characteristics, there is still a drive to provide more accurate and detailed information to support ever increasing program needs or for more accurate modeling efforts. One such technique of interest is in the use of fiber Bragg gratings (FBG) as detonation wave position sensors.

As the detonation velocity of a material is a critical material property that is used in many modeling efforts, it is of considerable interest to accurately capture. This material property is typically measured via signals from piezoelectric pins that are spaced at known intervals, though other techniques such as fiber optic probes, break wires, or streak camera can also be used. However, these techniques are moderately limited in terms of resolution as to increase resolution would require a greater number of sensors to be applied to the sample that, in turn, would increase both the cost of the test and likelihood to interfere with the reaction of the material as the sensors are in contact with the sample material. A potential solution to this was introduced with the use of FBG as a detonation wave position sensor (ref. 1). This system is relatively unique in that it can provide a continuous measurement of the detonation wave as a function of position and time in a manner more accommodating for complex geometries via a single thin fiber.

While not operating on the same first principles as photonic Doppler velocity systems used in high-speed velocimetry, an FBG system is similar in that both are optical systems that leverage commercial off-the-shelf components from the telecommunications industry to reduce testing costs and apply these systems to energetics community interests. The FBG system uses a broadband light source that emits a range of wavelengths centered on the C-band for infrared communications (1,530 to 1,565 nm). This light source is then fed into a three-port circulator that runs from the source to the fiber and then back from the fiber to a digitizer. Along this fiber is a linearly chirped FBG set across a specific distance of the fiber. As the shock passes through the fiber (from the detonation event), the measured reflected wavelengths will change as the shock induces a change in the index of refraction. As the fiber is linearly chirped along this set distance, the change in amount of reflected light can then be related to position of the detonation wave as a function of time via an output voltage from a digitization of the fiber response.

While this technology has been already used in various projects and programs (refs. 2 through 4), there is the potential to leverage such capability to support testing of more complicated geometries that are not amenable to typical measurement techniques. This would ideally allow for more accurate modeling of end item performance due the greater resolution of the positional data. However, prior to this, some basic tests were performed to establish and verify the FBG system for use at the U.S. Army Combat Capabilities Development Command Armaments Center, Picatinny Arsenal, NJ.

TEST SETUP

As the goal of this testing series was the establishment and verification of the use of FBG as a detonation position measurement tool, a basic setup with a characterized energetic material was utilized. As Composition C4 is a material that is easily workable and readily available, it was selected to provide the energetic stimulus to test the system and prove out the necessary analysis techniques. An overview of the primary test setup is shown in figure 1, though it is noted that the piezoelectric pins were only implemented for the final test shot. All shots prior to the final test shot used only the FBG sensor.

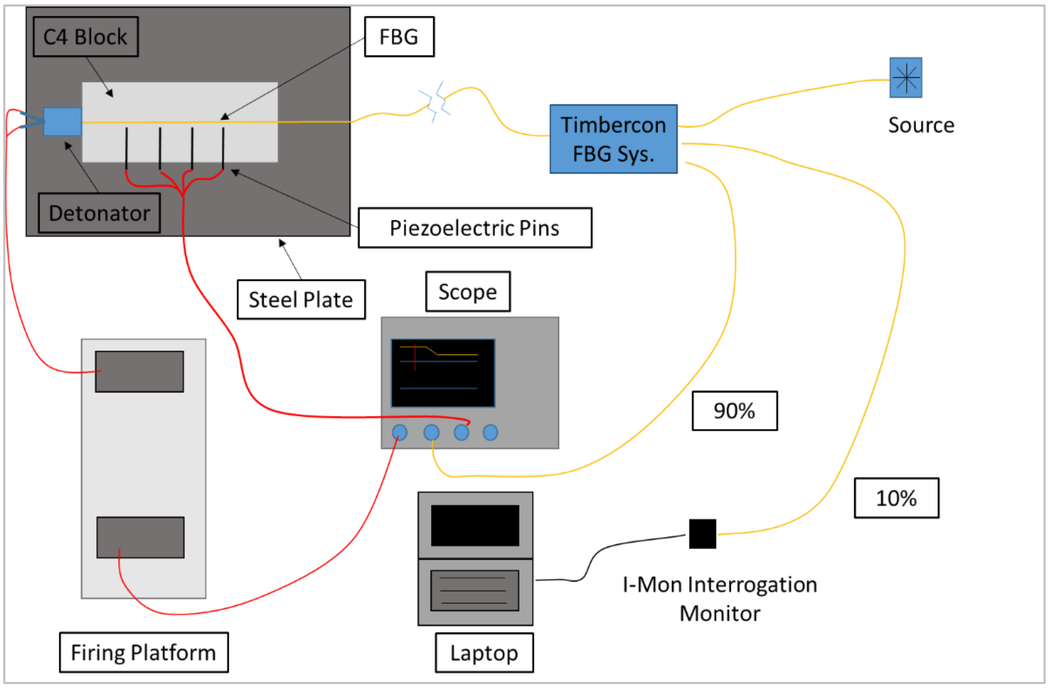

Figure 1
Test setup for FBG verification shots

When conducting shots with only the FBG sensor, the sensor was secured with electrical tape to the polycarbonate plate after verifying the location of the FBG via an I-Mon 512 Interrogation Monitor. By using the interrogation monitor and applying light pressure onto the FBG, the physical location and limits of the FBG sensor on the fiber could be determined. While markings on the fiber are present, the physical location should be confirmed with the aforementioned monitor and application of pressure to the fiber with a rubber (or other similar yielding material) tipped object. To illustrate, pressing down with a standard pencil eraser tip was sufficient to yield a measurable response via the monitor. The point at which a response was first recorded and last noted was marked on the fiber and the distance between the two points recorded. This step is also necessary to later analyze the sensor data, as the recorded response must be related to the position of the FBG. A picture of the FBG with markings is shown in figure 2. It is noted that there are multiple methodologies to locate the FBG with much greater positional accuracy; for example, utilizing a traversing stage and more precise tip or laser system are also viable alternatives.

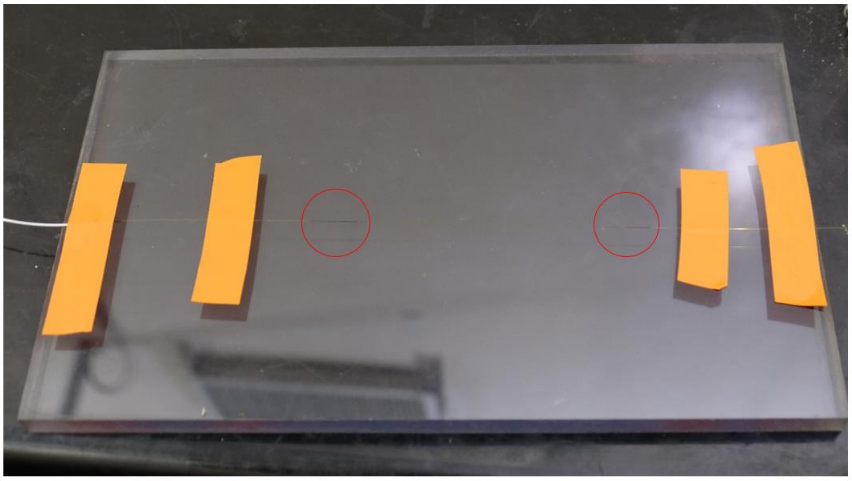

Figure 2
FBG taped to polycarbonate baseplate prior to testing

After the location of the FBG was determined and the fiber secured to the test plate, the C4 was pressed onto the FBG. Additionally, a “ball” of C4 was added to the initiation end of the line of energetic material in order to ensure that the material properly detonated. An exploding bridgewire detonator was pressed into the aforementioned “ball” of C4. The test fixture was then moved into the testing chambers, and the fiber connections between the FBG system and test item were completed. The final configuration of the test item without piezoelectric pins is shown in figure 3. Since greater positional accuracy was required when using the piezoelectric pins in conjunction with the FBG sensor, an additional polycarbonate plate was necessary. The piezoelectric pins were placed to ensure that all of the pins were inside of the region measured by the FBG. The setup is shown in figure 4, and the technical drawings for the experiment are provided in the appendix. .

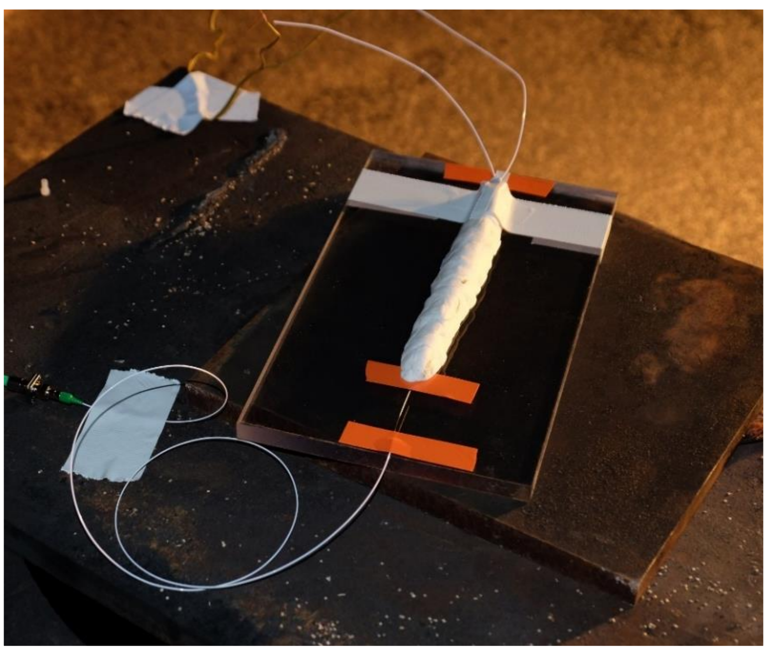

Figure 3
Typical test setup

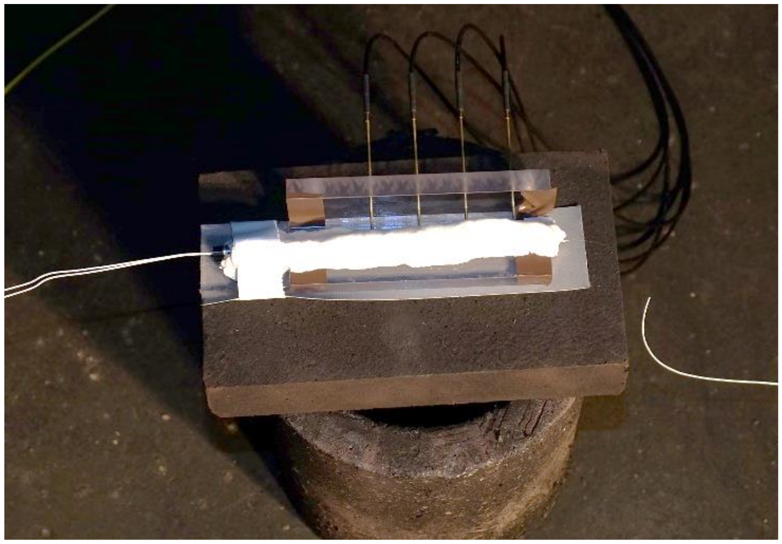

Figure 4
Piezoelectric pin verification test

The FBG system for all shots for this test series was composed of a BaySpec amplified spontaneous emission (ASE) light source, a 4-channel Timbercon 125 MHz FBG Interrogation Monitor, and an I-Mon 512 Interrogation Monitor. The output from the Timbercon system was then connected to an oscilloscope that recorded the detonation event. When using piezoelectric pins, an additional channel on the oscilloscope was used to ensure the same timescale between data channels for the experiment.

RESULTS

The FBG technique is a useful method of obtaining detonation position as a function of time, but it requires the use of various analytical techniques to yield the desired distance and time data. As such, this testing series provided an opportunity to improve on the data quality of each shot through experience and also improve upon the analysis techniques used to transform the oscilloscope voltage data into positional data. Throughout the testing, there were some difficulties in addressing noise, accuracy, and various other challenges that were necessary to address.

While the voltage data is the primary output for any FBG test, the data requires a degree of analysis and post-processing in order to properly transform the raw voltage data. As was mentioned in the previous section, the spectrum response of the FBGs were recorded using an I-Mon 512 Interrogation Monitor to provide a relation between the voltage drop and distance traveled. A normalized graph of the spectrum response of each FBG is shown in figure 5. For each curve, the units on the left are arbitrary as the sampling time for the monitor greatly influences the recorded results. However, care should be taken to not saturate the monitor, which would reduce the accuracy of the measurement and any subsequent analysis.

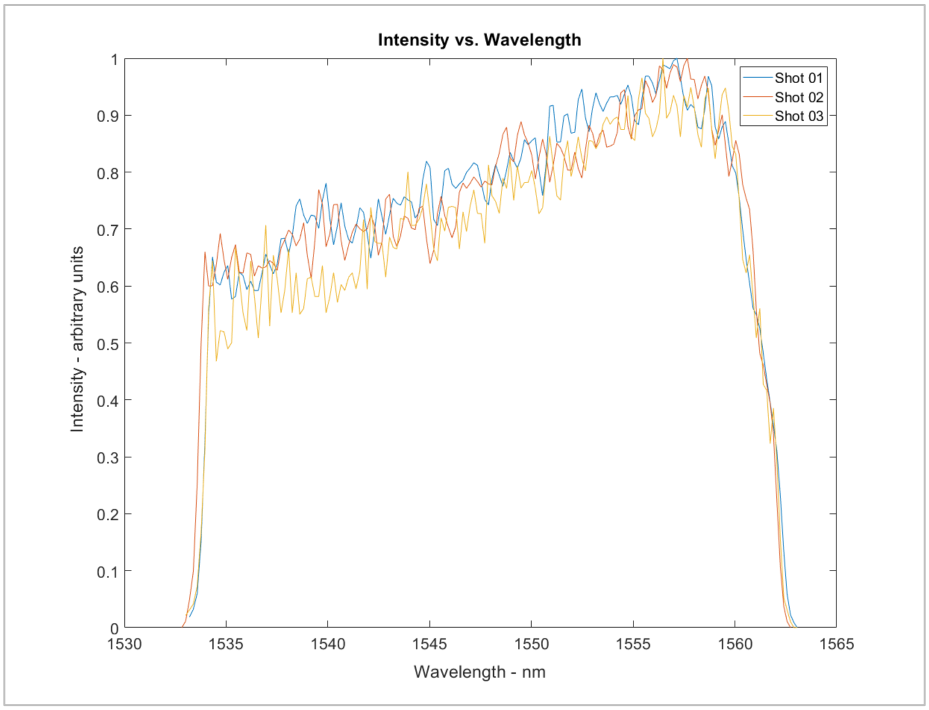

Figure 5
Normalized spectrum for the FBG sensors

When looking at the spectrum response of each FBG sensor in figure 5, there is a lack of flat-topped region, which would lend itself to idealized analysis to directly correlate the length of the FBG to the voltage drop. Due to this nonideal spectrum response, an integral of the intensity as a function of wavelength is necessary. A simple trapezoidal integration of adjacent individual data points divided by the cumulative integral across the domain will yield a proportion respective to those points. This is spelled out by equation 1 as it is necessary to construct the aforementioned proportion function $P(\lambda)$ that would be the integration of the spectrum function, $S(\lambda)$, of current wavelength over the total cumulative integral of the spectrum function. Due to the coarse, discrete points of the monitor relative to the sensitivity of the oscilloscope, interpolation is necessary to increase the resolution.

$$P(\lambda) = \frac{\int_{\lambda_0}^{\lambda} S(\lambda)}{\int_{\lambda_0}^{\lambda_f} S(\lambda)} \quad (1)$$

With $P(\lambda)$ determined, the voltage ratio would be next to calculate. The voltage ratio would theoretically be the maximum voltage divided by the measured voltage as a function of time; however, this simplistic approach would allow for sampling error to unduly influence the ratio values (as it would shift this maximum and minimum value). Thus an “average” maximum voltage value must be calculated (prior to the decrease associated with the start of the test) to avoid using the limits of the noise as boundary conditions. When the voltage data is converted to a ratio, it can then be compared to the spectrum response integral ratio that was previously discussed. By matching the voltage ratio to the calculated cumulative integral ratio, the position of the detonation wave as a function of time may be determined.

While the methodology to translate the raw voltage data into a distance measurement is not particularly complex, there are some considerations and factors that inhibit a straightforward analysis. For example, there are multiple sources of noise that cause variation from a single consistent voltage value, such as sampling error of the scope and noise from the firing pulse. Due to the presence of these nonidealized conditions, there is some additional difficulty in determining the specific start and stop time of the FBG data. While the decrease is distinct, the variations in the voltage data can obscure the exact start time, which will then require a closer examination of the data to determine the experiment time limits.

Somewhat separate from the noise-related issues, there is also the nature of the spectrum response as the edges of the spectrum curves that warrant some discussion. While the edges of the curve still have a physical representation of some distance, this will be associated with relatively small voltage changes. These small changes in voltage representing a physical distance will be masked due to the sampling error of the oscilloscope. As a result, consideration should be given to the accuracy of the data at the edges of the fiber. To reduce the magnitude of this effect, the beginning and end of the spectrum response less than a set cutoff value relative to the normalized intensity could be used.

In performing this testing, there were some system and procedures discovered that isolated sources of interference and assisted in collecting more ideal voltage data from the FBG system. To illustrate with an example, in the first shot, which is shown in figure 6, there is a significant amount of noise prior to the FBG response to the detonation event that obfuscates the data and the starting point of the experiment (no piezoelectric pins were used in this shot). After investigating the issue, it was found that the firing pulse was interfering with the oscilloscope as both shared a common ground. To mitigate this effect, another layer of insulation from the grounding system of the control room and firing system was added. This was accomplished via a separate backup power supply that was disconnected from the grounding system of the building. The result of change, which can be seen in figure 7, shows that firing pulse noise was eliminated and the results were more within the expected system variation.

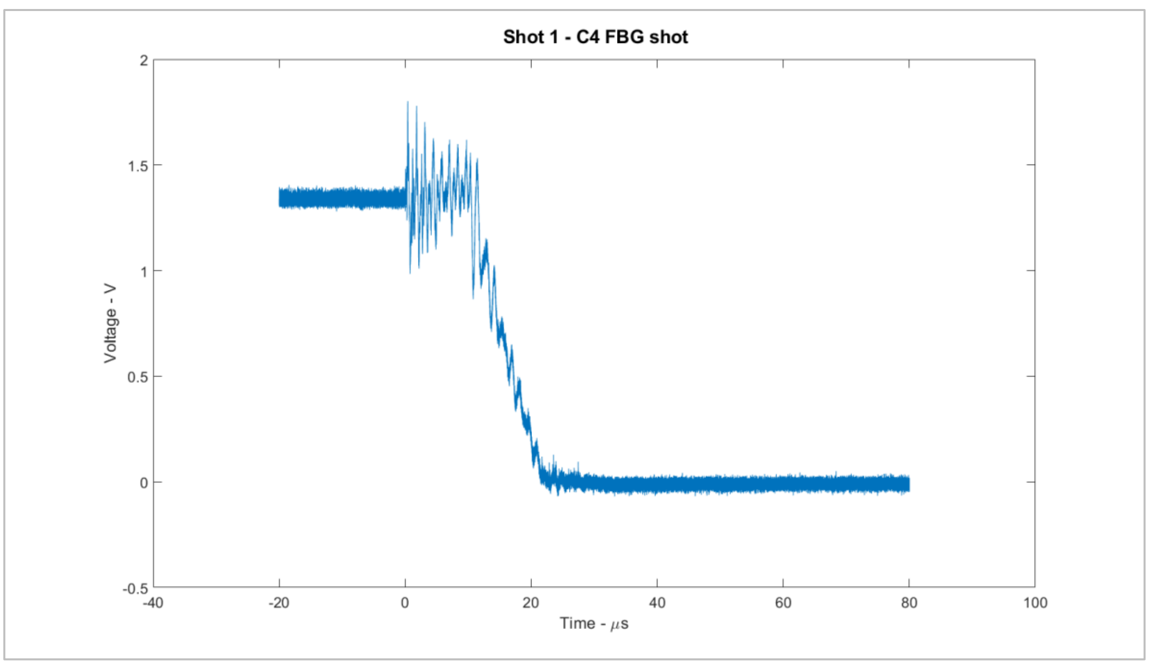

Figure 6
Shot 1- raw voltage versus time

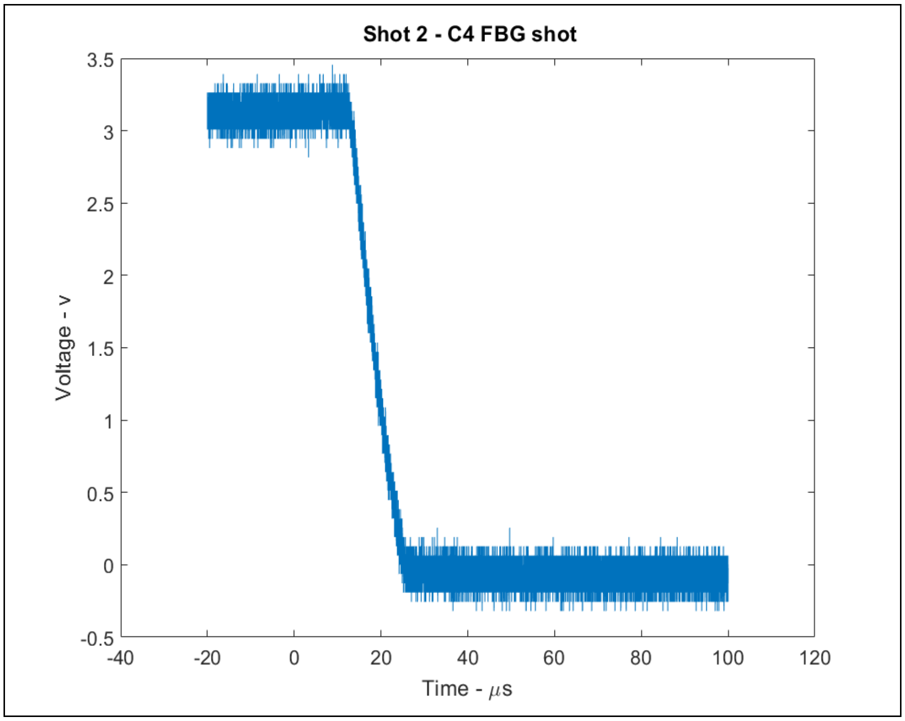

Figure 7
Shot 2 - raw voltage versus time

The final test shot in this series introduced piezoelectric pins to independently verify the FBG measurements with a typical methodology to ensure agreement between the two techniques. However, the addition of the piezoelectric pins unintentionally reintroduced firing pulse noise into the system. As the same oscilloscope was used to sample both the FBG voltage data and the piezoelectric pin data so that each would share a common time zero, the oscilloscope was therefore susceptible to coupling via the firing lines onto the cabling carrying the piezoelectric pin signal. Fortunately, this accidental injection of noise was possible to filter out using various signal processing tools, which are shown in figure 8. While this noise was possible to remove using numerical methods, removal of the source is a more optimal solution. In-house testing (apart from this FBG testing series) showed introducing an opto-isolator was sufficient to remove the firing pulse noise and was capable of resetting in enough time should multiple pulses be necessary.

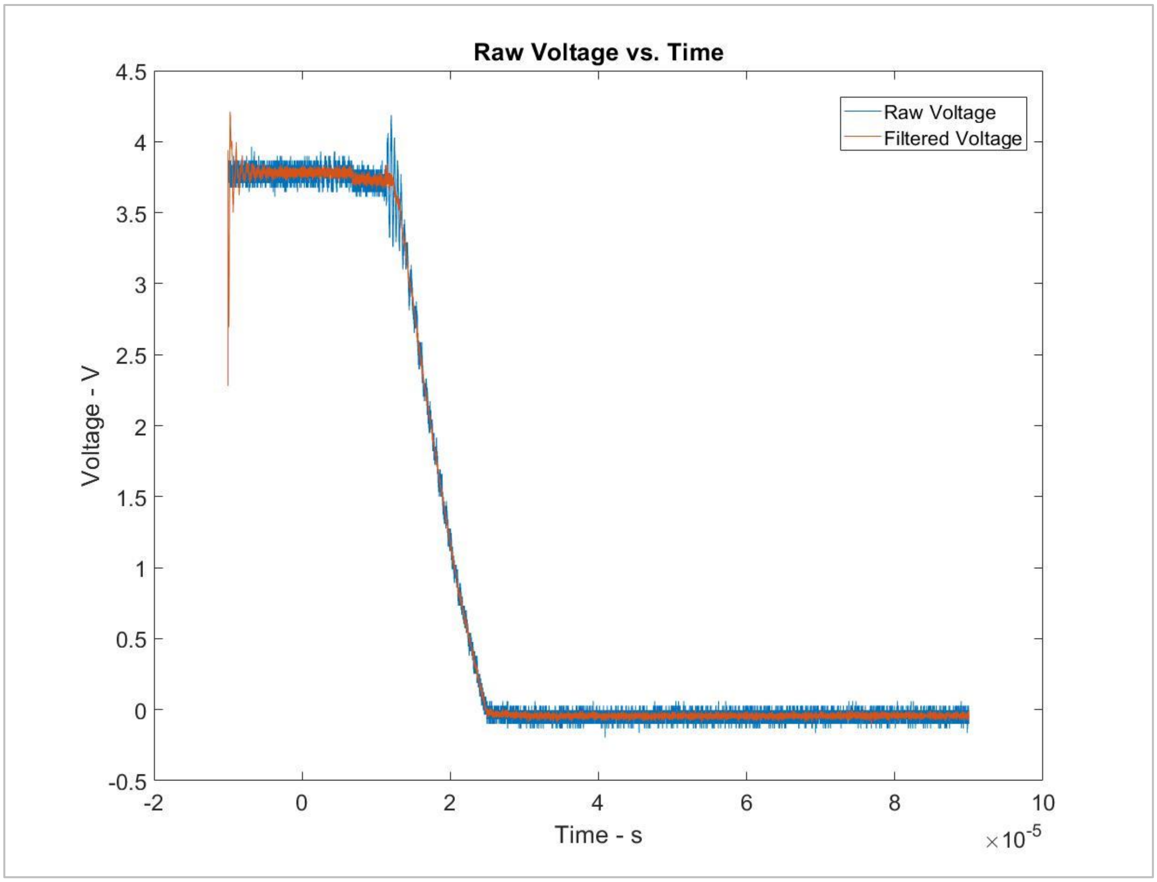

Figure 8
Shot 3 - C4 FBG shot, raw versus filtered data overlay

After isolating the data from the noise in the third shot and normalizing the second and third shot for data visualization purposes, the resultant plot is shown in figure 9. Unfortunately, the first shot is not included in this analysis due to the firing pulse noise that proved difficult to filter out. However, shots 2 and 3 were numerically similar to one another, which is not unexpected due to similar test setup and utilization of the same energetic material. However, the expected shot-to-shot variation and noise remaining from the filtering prevented a more complete overlay.

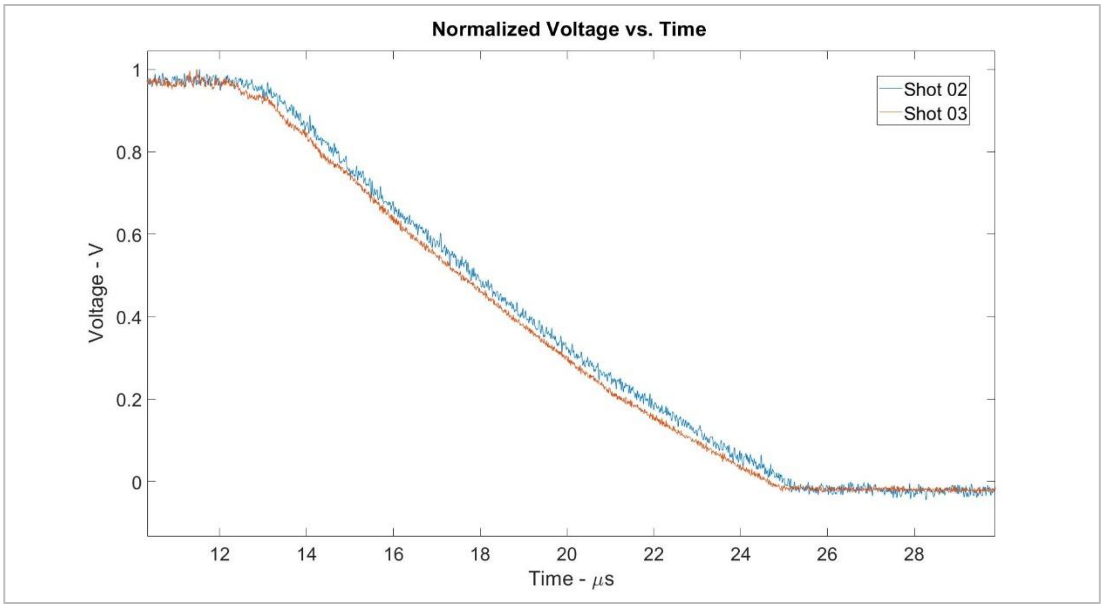

Figure 9
Normalized voltage versus time

With the voltage data filtered of the worst of the noise, the data can then be transformed into positional data as shown in figure 10. As an overall trend of the data is desired, a linear least square fit to the data may be applied to find an appropriate overall slope of the data, which would be a rough measure of the velocity (in mm/µs) of the two shots. It is important to note that there would be some artifacts at the limits of the data due to normalization as unfiltered noise variation would then be measured as above the maximum value that it could not physically represent. Additionally, as was mentioned earlier, the edges of the spectrum response correlating to small changes in voltage would artificially inflate values at the edge of the measurement (beginning and end). Both of these issues can be resolved by clipping a portion of the data away and primarily relying on the central region.

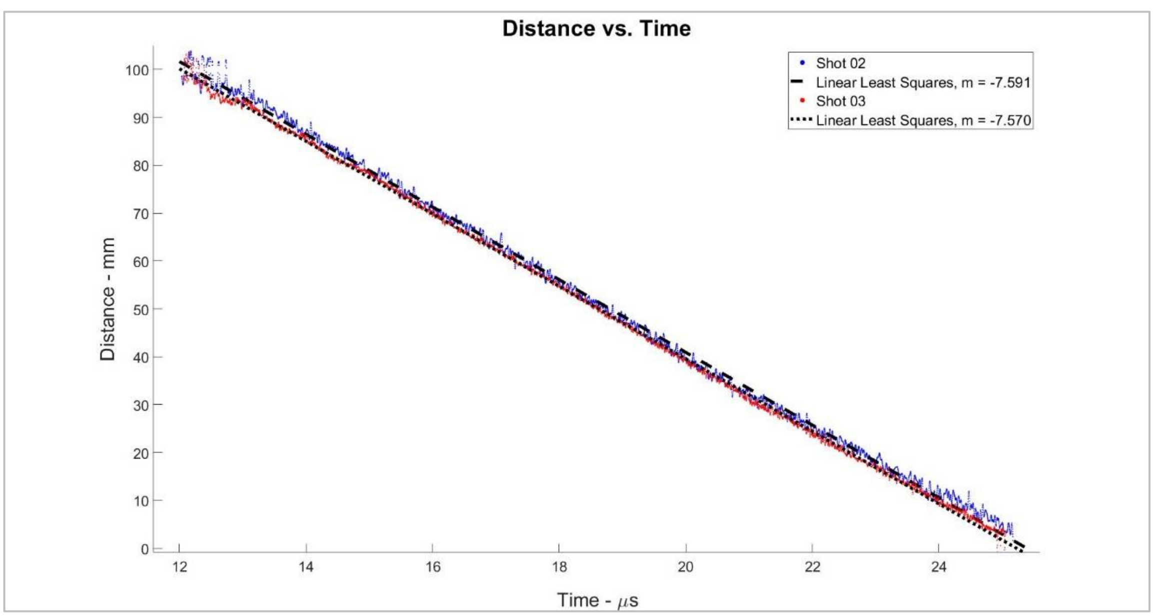

Figure 10
Distance versus time conversion of voltage data

In clipping the end and start of the data by 10%, there is an immediate shift of the fit slope to the data. In this case, it raises the overall measured velocity by roughly 0.08 to 0.09 mm/µs, which is closer to the expected value of C4, but, due to inconsistencies in packing density, some variation is to be expected. The results of the abbreviated data set are visualized in figure 11. In order to verify the accuracy of the FBG measurement, an independent technique was added.

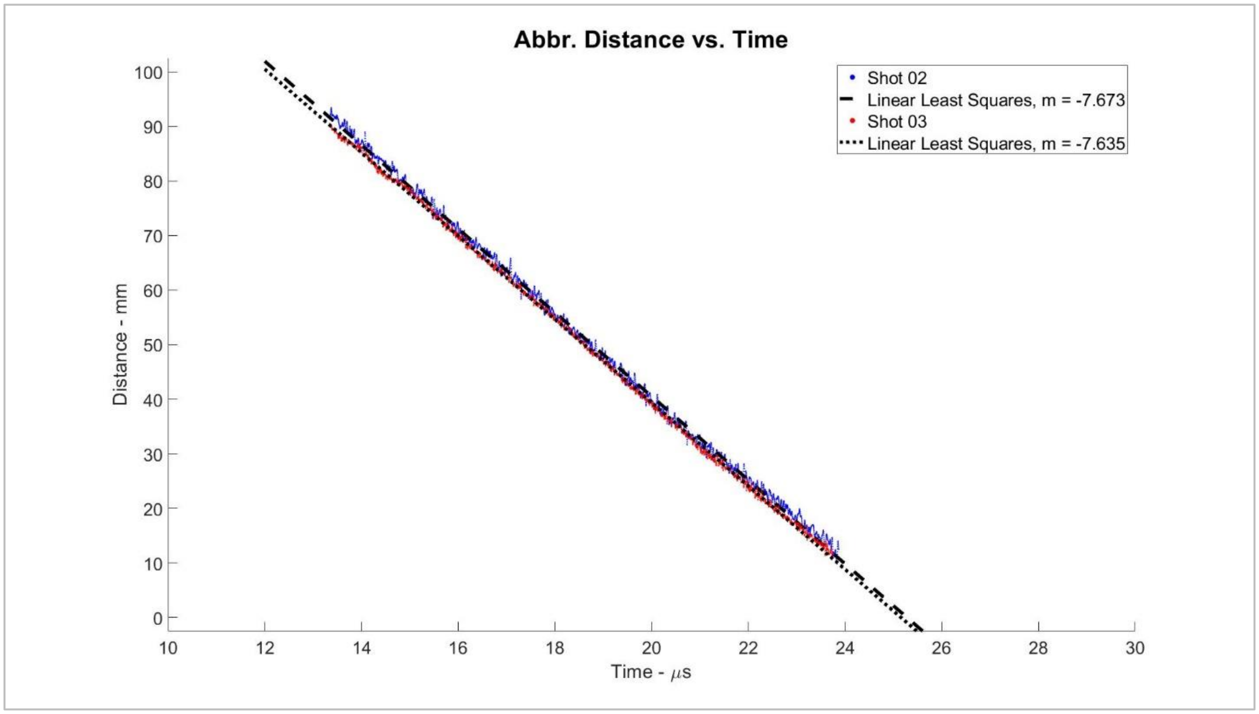

Figure 11
Abbreviated distance versus time dataset

Unfortunately, only one shot had the independent verification/validation of the piezoelectric pins and did so with a limited number of pins. As there were four pins with a spacing of roughly 1 in. (25.4 mm) between each, each set of pins could be used to create velocity averages over the measured range that could then be compared to the measured FBG velocity. Since there are tolerance values associated with the manufacture of the side plate holding the piezoelectric pins, a visualization of this error band is plotted against the FBG data to provide reference values. The data is displayed in figure 12.

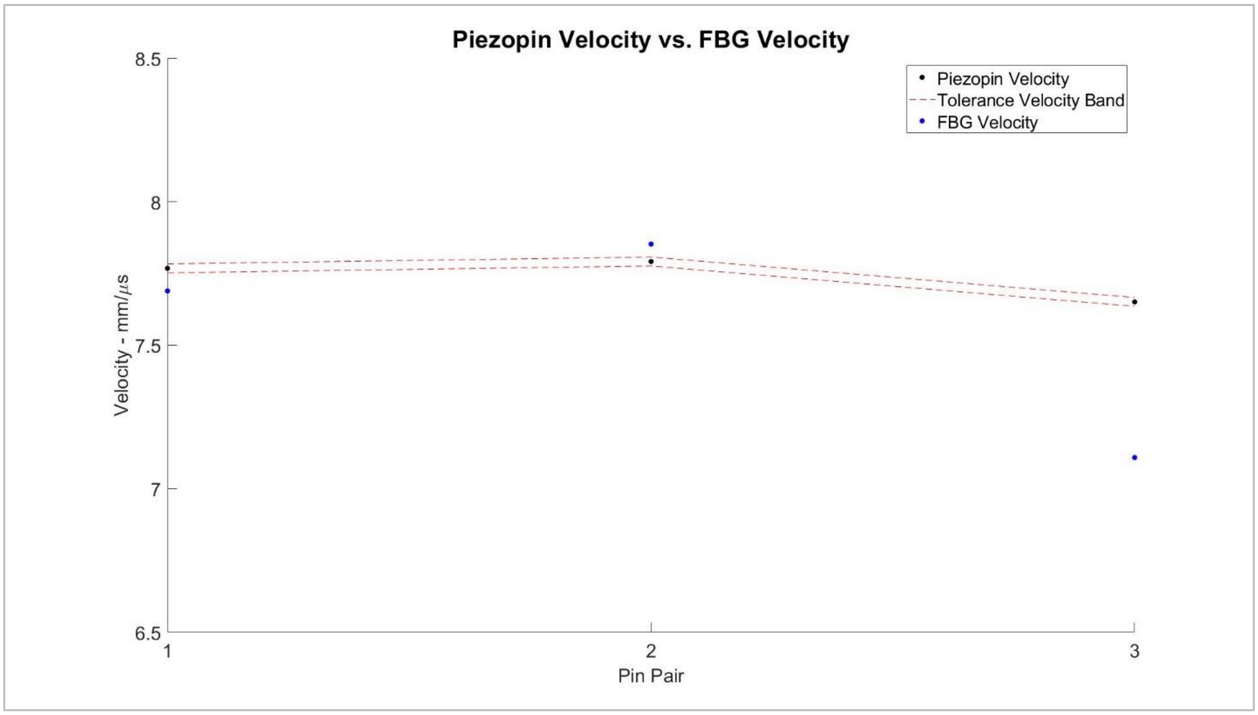

Figure 12
Piezoelectric pin velocity verification

The data was broken out into pin pairs to allow for averaging of the data over a region such as between pins 1 and 2. This then allowed for the velocity data measured via FBG data to be compared to the known time differences between the pins (and thus velocity using the known distance between pins). Referencing the data, it can be seen that there is some discrepancy between the measured velocities from pins 1 to 2 and pins 2 to 3, though this value is low. However, the last piezoelectric pin pair (pins 3 to 4) does present an outlier as the difference between the two methods at this data point is approximately 7%. The values are recorded in table 1.

Table 1
Measurement velocity comparisons

Piezoelectric pin pair	Pin measured velocity (mm/μs)	FBG comparison (mm/μs)	Percent error (%)
1	7.7676	7.6887	1.02
2	7.7914	7.8523	0.78
3	7.6506	7.1084	7.09

With the unexpected discrepancy in measured velocity for the last pin set, the fiber data associated with the final piezoelectric pin pair was plotted in figure 13 for the purposes of looking for a skewed or a systematic error in the data. Inspection of the data does not yield an obvious answer as no outliers appear to be skewing the data as to interfere with any of the calculations or various transforms. This implies that the fit is appropriate to the data and, thus, another issue may be influencing the lower than expected reading. It is noted that the piezoelectric pins and FBG were located in slightly different positions and the C4 was molded by hand. This may have introduced an uneven amount of material that influenced the measured results. Additionally, though perhaps not verifiable for this particular shot, there may be an issue in the spectrum response due to the interrogation monitor. However, additional shots would be required in order to verify or dismiss any problems with the monitor.

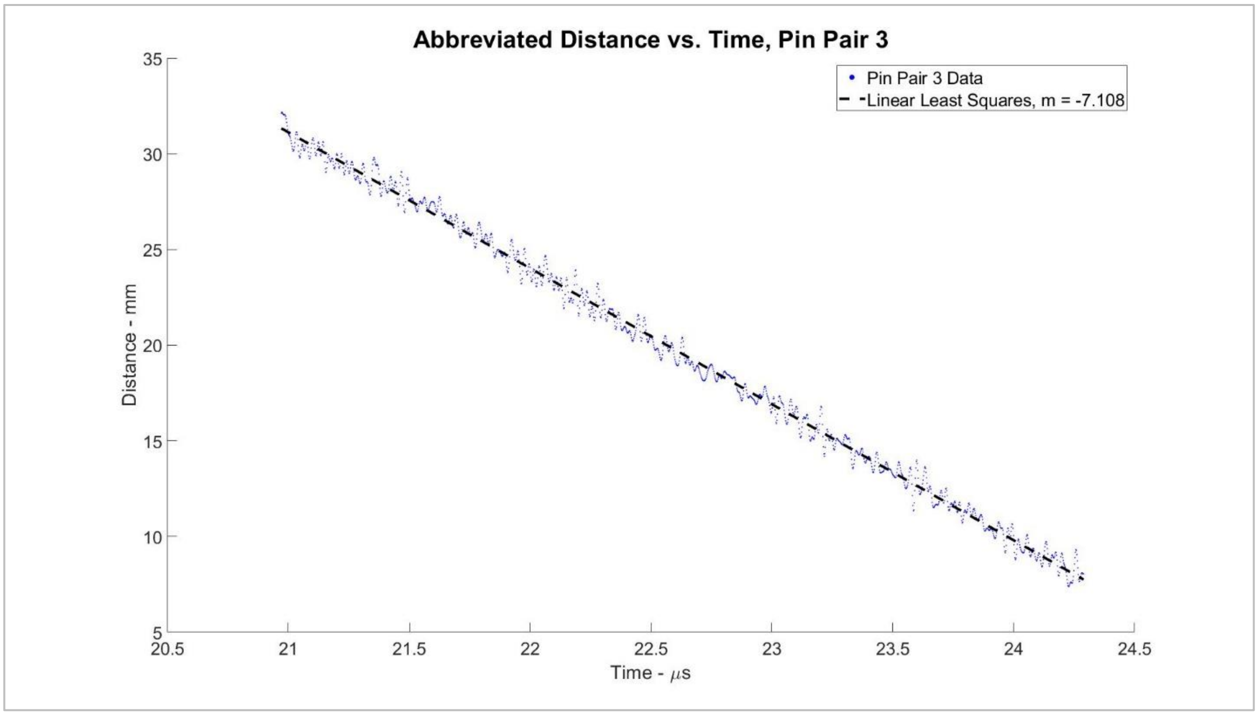

Figure 13
FBG data for final pin pair

CONCLUSIONS

In utilizing past projects and papers detailing the processes and systems necessary to use fiber Bragg gratings (FBG) as a detonation wave position sensor, this technique was implemented at the U.S. Army Combat Capabilities Development Command Armaments Center, Picatinny Arsenal, NJ. This measurement technique was used and verified on multiple shots using Composition C4 as the energetic material in order to refine the process and analytical techniques to capture the desired data. As noise in the data was a considerable issue in this testing series, these sources were identified and controls were implemented to mitigate their effect.

The results of the testing were overall positive but did have some issues to follow up on in future testing. The measured overall velocities were in line with expectations and, when breaking the fiber into “regions” that corresponded with piezoelectric pin coverage, the results were within approximately 1% of each other with one notable exception. This discrepancy resulted in a difference of approximately 7%, which did not have a readily apparent explanation outside of potential issues with the recording of the spectrum response of the specific FBG. Due to the flexibility of this experimental technique for complex geometries and providing a less intrusive and more continuous measurement of detonation velocity, this technique may present opportunities for velocity capture that would be unfeasible for piezoelectric pins and other traditional measures.

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APPENDIX
TECHNICAL DRAWINGS

DRAWING SIZE C

NOTES:

1. APPLICABLE SPECS/STANDARDS:
   A. ANSI Y14M.5M-1982

REVISIONS				
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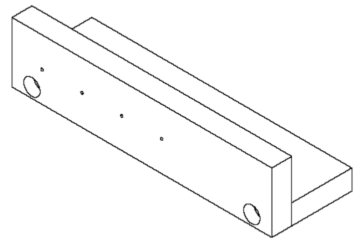

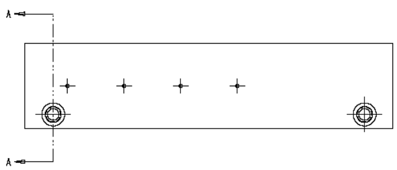

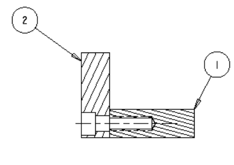

SECTION A-A

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1	1	19200	FBVG003	FIBER BRAGG, BOTTOM PLATE	

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PART NO. FBGV001

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APPLICATION

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TOLERANCE ON ANGLES ± °
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3 PLACE DECIMALS ±

THIRD ANGLE PROJECTION

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CONTRACT NUMBER

CONTRACTOR

DRAWN BY: DAVID RYDZEWSKI | DATE(YEAR-MO-DA)

CHECKER | ENGINEER: DAVID RYDZEWSKI

ENGINEER | QUALITY ENGINEER

DRAWING APPROVAL

DESIGN APPROVAL

DESIGN ACTIVITY
US ARMY
ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
PICATINNY ARSENAL, NEW JERSEY 07806-5000

FBG TEST ASSEMBLY

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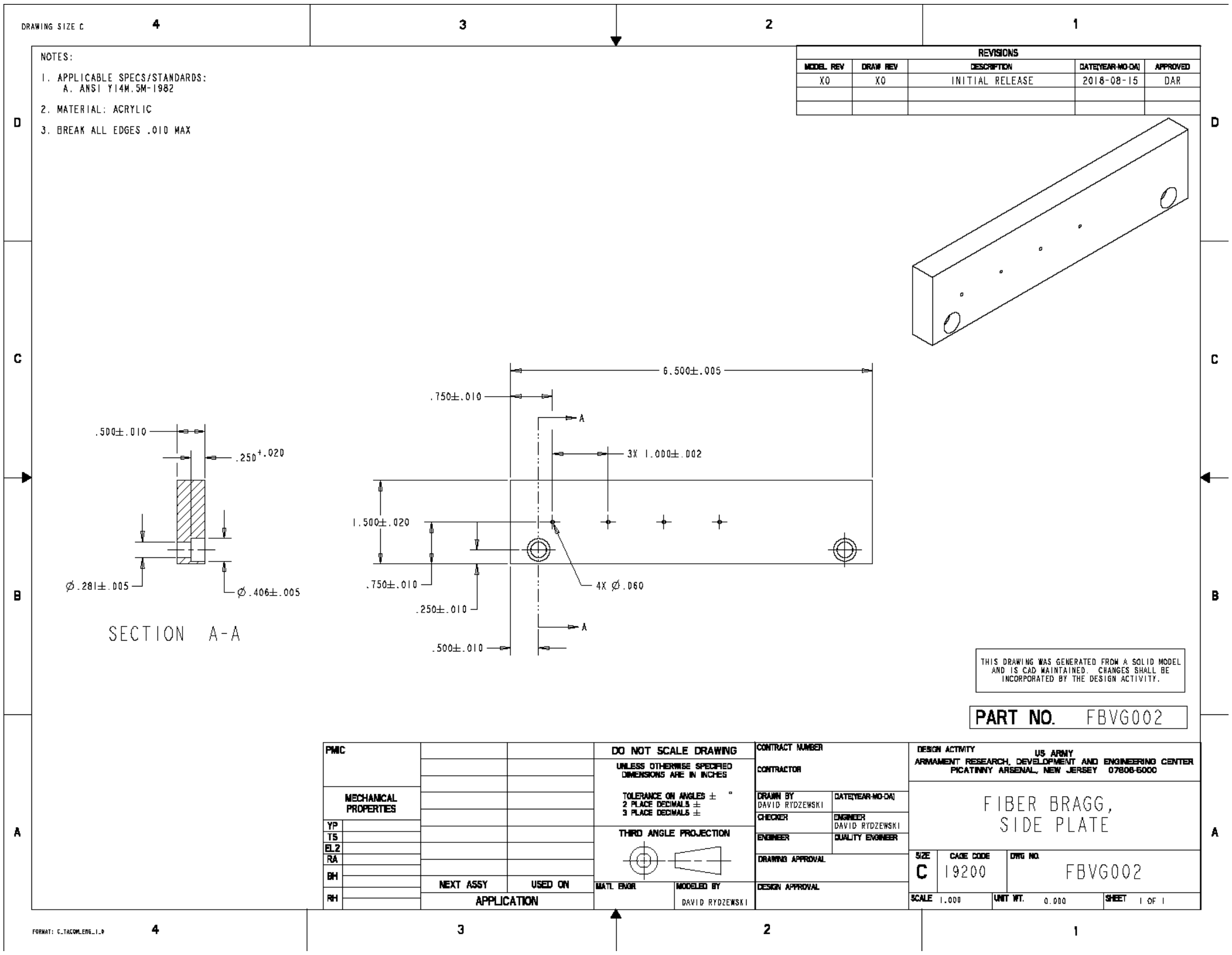
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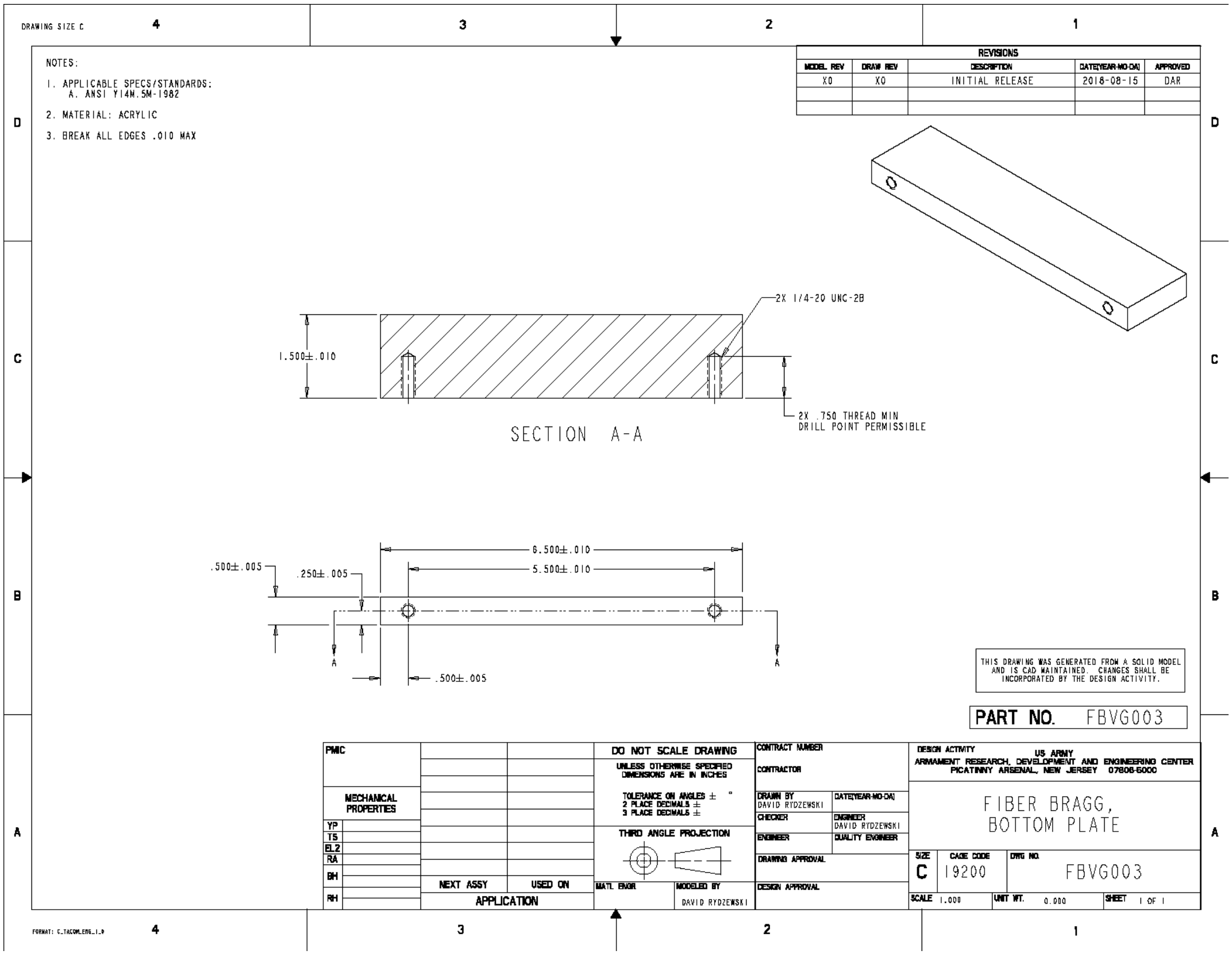

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Author/Project Engineer

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