CARBON FIBER / THERMOPLASTIC OVERWRAPPED GUN TUBE

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ABSTRACT

The emphasis on lightweight large caliber weapons systems has placed the focus on the use of advanced composite materials. Using composite materials not only directly removes weight from the gun tube, but by better balancing the tube, allows the use of smaller gun stabilization drive systems, thus further enhancing system weight loss. Additionally the use of high stiffness composites helps with pointing accuracy and alleviating the dynamic strain phenomenon encountered with high velocity projectiles.

Traditionally though, using composites has been difficult due to the coefficient of thermal expansion mismatch between the steel substrate and the composite jacket, which causes a gap after manufacturing. Dealing with this mismatch has greatly complicated the manufacturing process in the past to the point where mass-producing the barrels would be problematic at best. By using a thermoplastic resin and a cure on the fly process the manufacturability of the barrels has been greatly improved and the gap has been eliminated. This is the first time that this approach has been applied to a large caliber gun tube.

A 120mm barrel has been manufactured using this process with IM7 fibers in a PEEK matrix and successfully test fired. This paper will present the design, manufacturing, and test firing of this barrel.

INTRODUCTION

Previous composite wrapped gun tube efforts have been under taken by Benét Laboratories during the late 1980's and early 1990's. These efforts led to the fabrication and test of several 105mm and 120mm gun tubes. One of the outcomes from this work was the need for a methodology to prevent or eliminate the formation of a gap, on the order of 0.1 mm (0.004 in), between the composite overwrap and gun steel liner during the composite curing process. The gap was formed due to the coefficient of thermal expansion (CTE) mismatch between steel and composite. This gap effectively prevented or reduced the load carrying capability of the composite. To overcome the gap problem, the gun tube was autofrettaged after the application of the composite wrap. The autofrettage effectively closed the gap, and also imparted some favorable residual stresses to the gun tube structure. There were, however, three problems with this methodology; first, the thermal soak treatment used to stabilize the residual stresses in the tube after autofrettage could not be conducted. The thermal soak is done at temperatures of 650 to 700 ^{o}F which is well above the maximum temperature the composite can handle. The second problem was that the tube could not be chrome plated since the chrome plate process requires the tube to be immersed in chromic acid, which would destroy the composite and also contaminate the chrome plating bath. The third problem is the creation of extremely high radial stresses at the steel / composite overwrap which may be higher than firing stresses [1].

One novel approach to getting around these problems was the 105mm Multi-Role Armament and Ammunition System (MRAAS) Swing Chamber Launcher [2]. In this case the CTE mismatch was handled by tailoring the lay-up. A combination of fiberglass and graphite was used with the ply angles being adjusted such that the lay-up's CTE matched that of the steel. This resulted in no gap forming between the composite and the steel but the performance of the composite was degraded.

The composites being used at that time were all thermoset materials; therefore the curing process took place after composite wrapping. For the current ATD effort, thermoplastic composites will be used on a large caliber gun tube for the first time. The advantage of thermoplastics is the "curing in place" fabrication technique. In this fabrication methodology, the composite is cured immediately after it is placed on the gun tube. Heating of the composite is localized, minimizing heat input to the composite and gun tube. This process mitigates thermal expansion effects and effectively eliminates the gap problem. The composite can therefore be placed onto the gun tube after the autofrettage thermal soak and chrome plate application.

One of the challenges of the composite wrapped gun tube will be to handle the dynamic loading environment of a gun tube. Measurements of gun tube strain on 120mm tank cannons have, in the past, shown that the measured strains are typically higher than expected from static ballistic pressure alone. This increase in tube strain is attributed to both the loading condition, which is effectively a square wave, as well as high speed dynamic loading of the gun tube during projectile passage. In most cases, this strain is typically 8-10% above the statically predicted (open ended cylinder, Lame equations) values. In situations where thin walled gun tubes and high velocity projectiles are used, the strains can be significantly higher, on the order of 300-400%. This phenomenon is known as gun tube dynamic strain and has been an area of study for many years by Benét Laboratories [3,4,5]. In the development of the Light Weight 120mm (LW120) cannon, this phenomenon will be of special interest since the LW120 will have a thinner tube wall than the current 120mm M256 cannon and thus it will be more prevalent.

The 120mm Line of Sight (LOS) / Beyond Line of Sight (BLOS) Advanced Technology Demonstration (ATD) is tasked to design, develop & demonstrate new armament & ammunition technologies for use in the Army’s Future Combat System (FCS). The specific role the ATD will play is to support the development of the main armament for the Mounted Combat System (MCS), which will be equipped with a 120mm main armament and will provide LOS and BLOS firing capabilities.

One of the tasks assigned to the 120mm LOS/BLOS Gun Assembly Team was to provide a light weight 120mm gun assembly for the MCS vehicle. The focus of this report is the use of an organic composite overwrap to lighten the weight and reduce the imbalance of the gun tube. The ATD is scheduled to deliver two prototype composite wrapped gun tubes. This report will focus on the 1st of these tubes, Serial No. ATD-1.

DESIGN AND ANALYSIS

Initially a lightweight all steel 120mm gun tube was designed using traditional methods. The steel design had a weight of 889 kg and was 5460 mm in length. The goal of the composite design was to match or exceed the frequency of the first bending mode of the steel design while saving weight.

As mentioned previously, for the first time in a large caliber gun tube, thermoplastic composites were used instead of thermosets in order to take advantage of the cure in place fabrication technique. Besides this manufacturing consideration the composite overwind had to be able to withstand the significant forces and heat fluctuations associated with firing the weapon.

IM7 fiber with a polyetheretherketone (PEEK) matrix was the material selected for this project for several reasons. The first is the superior strength (2.07 GPa (300 ksi) in the fiber direction), modulus (138 GPa (20 msi) in the fiber direction) and toughness of the composite when compared to the majority of thermoset and other thermoplastic materials. The second reason for the selection of this material was its high melt point (653 °F / 345 °C). The final reason for the selection of this material was its excellent chemical resistance; in particular, its resistance to petrochemical fluids that would be encountered in the day to day operation of a large machine. The cost of thermoplastics, while in general higher than thermoset counterparts (~20%), was offset by the fact that there would be no autoclave post cure required. With a shape as complex and large as this, bagging and autoclaving add significant expense (up to 20%) to thermoset processing, plus the capital investment in a large autoclave (approx $300,000 for one large enough to process this gun tube), making thermoplastics a competitive alternative.

With the fiber/matrix selected the lay-up itself had to be designed. The two main design goals for the gun tube were to match or exceed the frequency of the first bending mode of the all steel design as well as match the residual hoop stress distribution through the gun tube wall. The tubes natural frequency (especially the first bending mode) affects the gun aiming and stabilization system. Maintaining the same natural frequency as the current gun tube minimizes changes to these systems. In addition, if the tube natural frequency gets too low, it may approach the natural frequency of the riding loads of the vehicle. Excitation of the gun tubes natural frequency may then occur leading to a condition in which stabilization of the gun tube becomes impossible.

Large caliber gun tubes often use autofrettage to impart favorable residual stresses into the gun tube structure. Since some of the steel is replaced with composites, it was vital that the composite provide the same residual stress distribution as the original steel. To accomplish this, the residual stress distribution through the tube wall, including autofrettage and the composite wrap, was modeled using the WIND Composite Cylinder Design Software Tool developed by the University of Delaware Center for Composite Materials.

With the WIND software the geometry of the steel tube and the composite lay-up are entered. The code then generates the strains and stresses in each ply in the radial, hoop, and axial directions under an applied pressure loading. The autofrettage parameters, winding tension, ply start, ply stop, material and orientation, can be changed for each ply. Using this code, a candidate lay-up was designed and then sent to Abaqus for a dynamic finite element analysis (FEA).

Previous work at Benét Labs [6] was employed to properly model the dynamic effects of a pressure wave moving down a gun tube and to ensure the correct high frequency data was captured. An axisymmetric FEA model was created using 8-node biquadratic axisymmetric quadrilateral reduced integration elements (CAX8R).

The steel tube and composite jacket were modeled as separate parts and then joined together. To insure the FEA model was accurately run the composite to steel interface was modeled three different ways. The first was a “tied” contact whereby the composite was

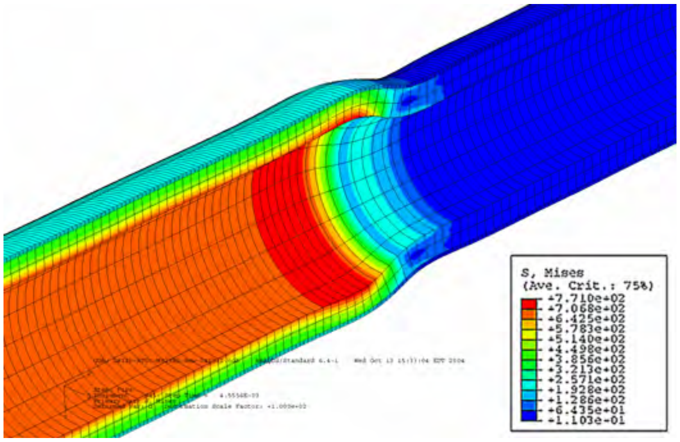

Figure 1–Dynamic FEA Analysis of Steel Tube with Composite Jacket – Mises Stress, 100x magnification

considered to be perfectly glued to the steel. The 2nd model permitted the composite to separate or slide along the steel. The 3rd model allowed sliding, but not separation. The results of these models yielded results which were within <<5% of each other. This indicated frictional and bending forces were low enough such that the composite and steel interface never separated or slipped relative to each other, so tie constraints were used for the final models.

Smeared orthotropic properties were used for the composite. Additional runs were performed with ply by ply and grouped ply properties but the results were similar (<<5% difference) to the smeared ones so smeared properties were used in order to decrease computational time.

Static, normal mode and dynamic analyses were all performed. For the dynamic analysis, a pressure load was moved down the bore of the tube to simulate a projectile. The maximum time increment allowed was kept small to ensure that all dynamic strains and high frequency vibrations were recorded. A graphical result of this analysis can be seen in Figure 1.

These analyses were repeated until a lay-up was arrived at that met or exceeded all of the metrics. The final lay up consisted of 50 layers with a mixture of hoop and axial plies. The muzzle end of the lay-up wound up having almost twice as many plies as the breech end. This lay-up resulted in 56.7 kg (125 lbs) of steel being removed and 11.3 kg (25 lbs) of composite being added for a net weight savings of 45.4 kg (100 lbs). A schematic of the lay-up can be seen in Figure 2.

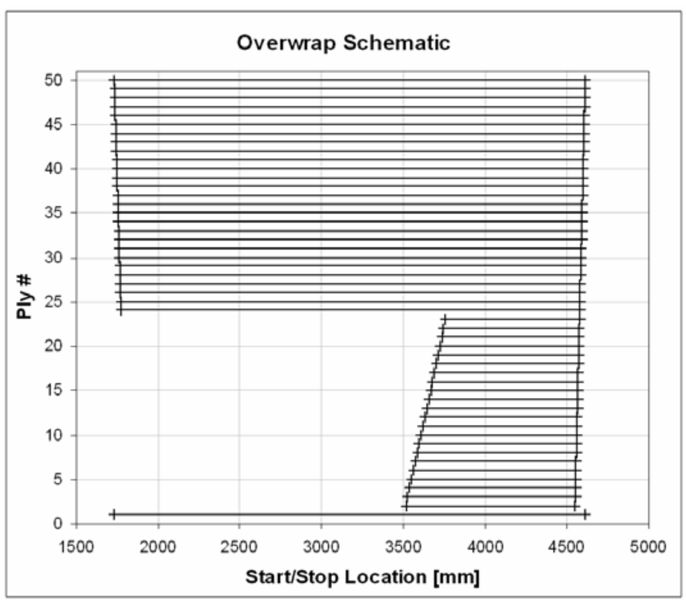

Figure 2–Composite Lay-up Schematic

MANUFACTURE

The steel portion of the gun barrel was manufactured according to the normal process, except that an area was undercut for the composite. Additionally, this area was not painted. Prior to shipping the barrel to Automated Dynamics Corporation (ADC) for application of the composite the bore of the gun tube was checked for straightness and a maximum bend of 0.21 mm was recorded.

ADC utilizes robotics and fiber placement heads to precisely place and consolidate strips of thermoplastic prepreg tape. With this procedure, wind angles of 180 degrees to –180 degrees can be achieved. The thermoplastic prepreg is melted with a hot gas torch and then consolidated with a pressure roller.

There were three major issues that needed to be overcome in order to fabricate the overwind:

1. Making sure that the overwind was extremely tight on the metal barrel at the completion of fabrication.

2. Galvanic corrosion between the overwind, the barrel and other components had to be avoided.

3. The OD of the composite had to meet a precise, predetermined specification.

The gun barrel develops significant burst pressure when fired. To help offset this it was determined that the composite overwind should be fabricated in such a way that it would exert a residual compressive force on the barrel, i.e. the composite would be squeezing the steel when at room temperature. Several options were explored. It was determined that the best way to achieve this was to wind on the barrel when it was cold. The cold would shrink the barrel. The composite would be placed when the barrel was in its cold/smaller state. As the barrel warmed to room temperature, the metal would try to expand and the composite would resist this expansion and therefore exert a compressive force on the steel. It should be stated at this point that the CTE of carbon fiber is essentially zero. So regardless of the processing temperature or the temperature of the barrel, the dimensions of the composite (in the fiber direction) would not change. So, the composite material placed with the fibers running circumferentially around the barrel would exert the compressive force that we desired. Additionally, since the fibers have a near zero CTE, their dimensions would not change under the extreme heat generated when firing the weapon.

The fiber placement process used by ADC locally generates a lot of heat. Therefore an object that starts cold will quickly heat to 140 to 150 °F. Before processing started, the gun barrel was pre-cooled to sub-zero. The temperature of the barrel was monitored during and after each ply to maintain it below a predetermined threshold value throughout the winding process. As noted, this helped achieve the desired fit between the metal and the composite and also provided a consistent heat sink for “freezing” the molten tape onto the substrate. Though the exact temperature the barrel was cooled to can not be released it was within the operational temperature of the gun system so it will not adversely affect the mechanical properties of the steel.

The carbon fiber in the composite is a conductive/"metallic" material. Therefore, if brought into intimate, prolonged contact with another, dissimilar metallic surface, galvanic corrosion would take place. This was avoided by covering the barrel with a thin (2 plies) non-conductive layer of S2 fiberglass/PEEK. This S2/PEEK layer acts as an insulator between the two conductive materials and prevents galvanic corrosion. Since the matrix is the same (PEEK), the bond between the graphite composite and the insulating layer is excellent. The CTE of this layer is higher than the carbon layer but still lower than the steel so it will not adversely effect the tightness of the steel/composite fit. This layer was accounted for in the FEA model.

Figure 3–An Axial Ply Being Applied to the Gun Barrel

The lay-up had varying wall thicknesses. Over some sections of the gun barrel the composite wall thickness called for required winding 23 plies and over other sections the desired wall thickness required that we wind 42 plies. Some areas (specifically, the short tapers at each end) end up with only a couple of plies of composite coverage. Creating this variation is relatively simple with ADC's in-situ fiber placement technology. Before fabrication began, each ply had a start and a stop point determined. Some plies were as short as 1,039 mm while others were the full length of the desired overwind, 2,878 mm. By controlling the length and location of each ply, the desired wall thicknesses were achieved.

Due to some standard variation in raw material thickness (spec for the material allows a +/-0.0127 mm variation in tape thickness), close attention was paid to the OD during fabrication. Modifications to ply lengths and locations were made to maintain the desired final OD.

Figure 3 shows an axial ply being applied to the gun barrel. The white area is frost that develops on the part due to the sub-zero chilling of the barrel. The hot gas torch vaporizes this as it applies the tape, so that none of the moisture finds it way into the part.

After the wrap was completed the barrel was returned to Benét Laboratories and another straightness measurement was conducted. This time the maximum bend was found to be 0.19 mm. The 0.02 mm difference is within the uncertainty of the machine so it was determined that the wrapping process had no effect on tube straightness.

NON-DESTRUCTIVE EVALUATION

Besides checking tube straightness modal impact, pressure, and acoustic emission (AE) testing were all performed to assess the state of the composite overwrap. Additionally ultrasonic inspection was planned if any of the other tests uncovered possible areas of damage.

Figure 4–Modal Testing Setup

Modal impact testing was performed prior to applying the composite, after applying the composite, and after firing. This way the effect of the overwind on tube stiffness and any detrimental effects of the test firing could be determined. In all cases the tube was hung from springs to simulate free-free boundary conditions. This setup can be seen in Figure 4.

Accelerometers were placed at the muzzle and every foot (304.8 mm) down the length of the composite. The tube was then impacted 219 mm from the muzzle and the response of the accelerometers was recorded. After this, all but the muzzle accelerometer were removed and the tube was then impacted at each location where there had been an accelerometer.

The results of this testing for the first three modes can be seen in Table 1 and Figure 5. The composite wrap slightly increased the stiffness of the gun and firing had a minor effect on the level of response but no effect on the location of the modes. These results were compared to the FEA analysis and were found to be in good agreement. Not only did this result help to validate the FEA models but also ensured that energy was being transferred from the composite to the steel and vice versa.

The pressure test was a means of ensuring that the composite and the steel were in good contact. If there was a gap between the steel and composite there would be a delay in the composite picking up the pressure load applied to the bore.

Table 1–Modal Impact Testing Results

	Mode (Hz)		
	First	Second	Third
Before Wrap	30.25	85.50	176
After Wrap	30.75	87.00	177.75
After Firing	30.75	87.00	177.75

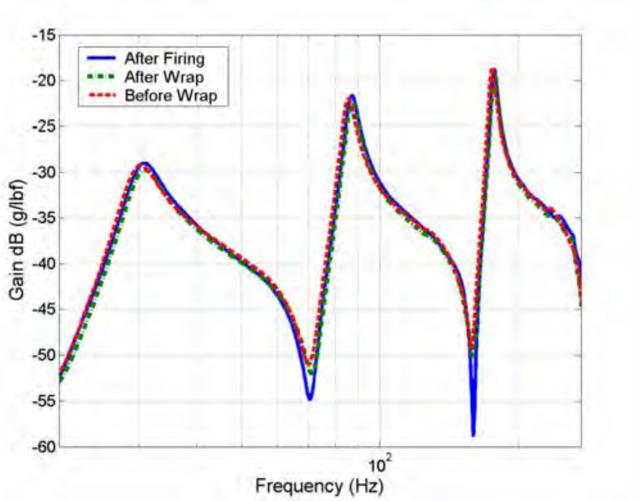

Figure 5–Frequency Response

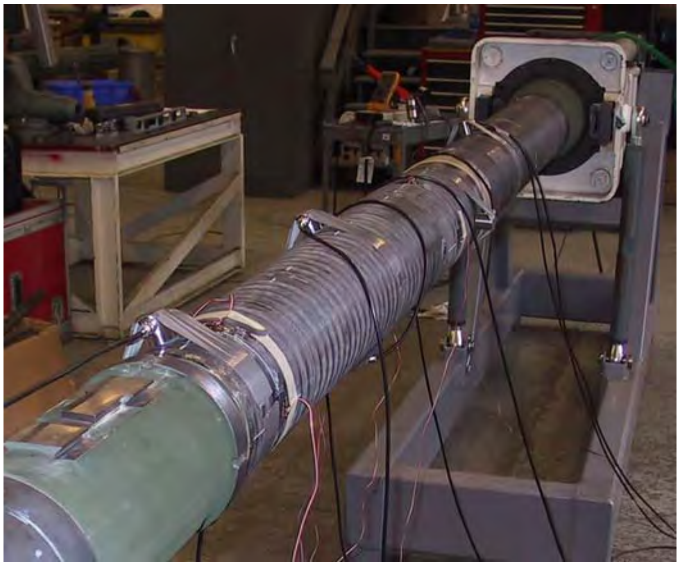

Figure 6–Acoustic Emission Test Setup

For this test standard rosette strain gages were placed at 3500mm, 4500mm and 5000mm from the rear face of the tube. At each location a gage was placed at the 12, 3, 6 and 9 O'clock positions. These same gauges were later used in the firing test. A mandrel was then inserted into the bore under the composite and was pressurized to 68.9 MPa (10 ksi). The strain readings were recorded every 6.89 MPa (1000 psi).

The acoustic emission (AE) and pressure test were conducted at the same time as they both required pressurizing the gun tube. For the AE test the tube is pressure cycled twice. The first time there will be some fiber and matrix cracking as this is the first time it has seen any load and any defects need to work themselves out. When the pressure is applied the second time there should be no noise. If any noise events are encountered on the second loading they could be an indication of real damage and need to be investigated. A total of eight AE sensors set up in an array were used so that the location of any suspected damage could be located.

The mandrel used to pressurize the tube was only 1828.8 mm (72”) in length so the pressure/AE test had to be conducted twice to cover the entire length of the composite. Figure 6 shows the setup of the AE sensors for the second test area. The pressure data that was collected were within 3% of the FEA predictions. For the AE test a couple of small suspect areas were noted. These were close to strain gauge locations so it was assumed that the noise was the glue on the strain gauges cracking.

These suspect areas were supposed to be investigated further during the repeat of the pressure/AE test after firing. However that test has not yet been conducted as of the writing of this report.

FIRING RESULTS

In July 2004 the gun was taken to Aberdeen Proving Ground (APG), MD for test firing. The gun was fired in direct and indirect fire modes though strain data was only taken for the first 20 direct fire shots. During these shots a series of M831A1, M865, M829A2 and M829A3 rounds were fired.

The test instrumentation used was standard rosette strain gauges. Gauges were placed at five axial locations, 390mm, 470mm, 3500mm, 4500mm and 5000mm from the rear face of the tube. At each axial location a gage was placed at the 12, 3, 6 and 9 O'clock positions. Measurements of axial and circumferential (hoop) strain were recorded throughout the first 20 rounds of the test. Note only the 3500mm & 4500mm locations were on the composite wrap zones, the other locations were on non-composite areas.

Figure 7–Test Firing at APG

Table 2–Experimental and Theoretical Strains

Round Type	M829A2	M829A3
390 mm Experimental Hoop Strain (με)	Mean 2180 Std Dev 31	Mean 2174 Std Dev 36
390 mm Theoretical (με)	2060	2114
470 mm Experimental Hoop Strain (με)	Mean 1878 Std Dev 43	Mean 1874 Std Dev 16
470 mm Theoretical (με)	1741	1788
3500 mm Experimental Hoop Strain (με)	Mean 1531 Std Dev 71	Mean 1586 Std Dev 114
3500 mm Theoretical (με)	1462	1606
4500 mm Experimental Hoop Strain (με)	Mean 3064 Std Dev 1079	Mean 2982 Std Dev 1475
4500 mm Theoretical (με)	2246	2035
5000 mm Experimental Hoop Strain (με)	Mean 1353 Std Dev 247	Mean 1507 Std Dev 390
5000 mm Theoretical (με)	1264	1531

Table 2 gives both the theoretical and experimental strains for the M829A2 and M829A3 rounds that were fired. By the time the M831A1 and M865 rounds were fired most of the strain gauges were no longer reliable. Given the firing environment it is not unusual to loose several gauges during the test. Looking at the table it can be seen that there is good qualitative and quantitative agreement between theoretical and measured strain levels. The first rounds fired were the M829A2's and the difference between theoretical and experimental is less than 5% at 3500mm. For later rounds this difference increased as the gauges degraded.

Figure 8 and Figure 9 show the experimental and theoretical strains vs. time at 3500 mm and 4500 mm respectively. The experimental traces have been time shifted by 0.2 and 1.5 msec respectively, so that they do not fall directly on the theoretical prediction. This allows for an easier comparison between the traces. Looking at the figures it can be seen again that there is good agreement between theoretical and experimental results, though at 4500 mm the model damps out quicker than reality and just the opposite at 3500 mm. At present the reason for this behavior has not been looked into as it does not present a problem with performance.

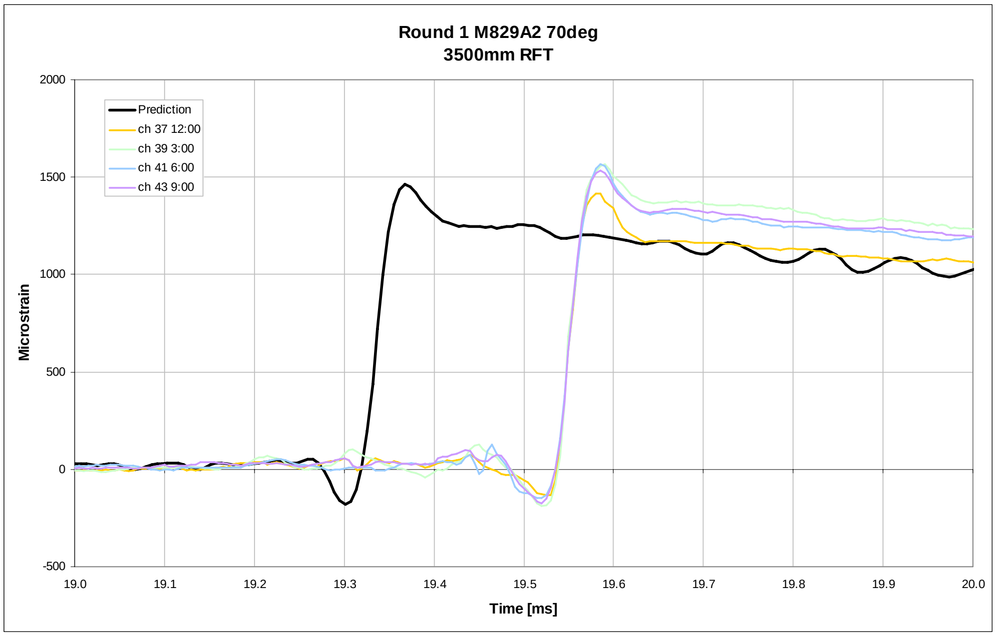

Figure 8–Experimental & Theoretical Strain vs. Time

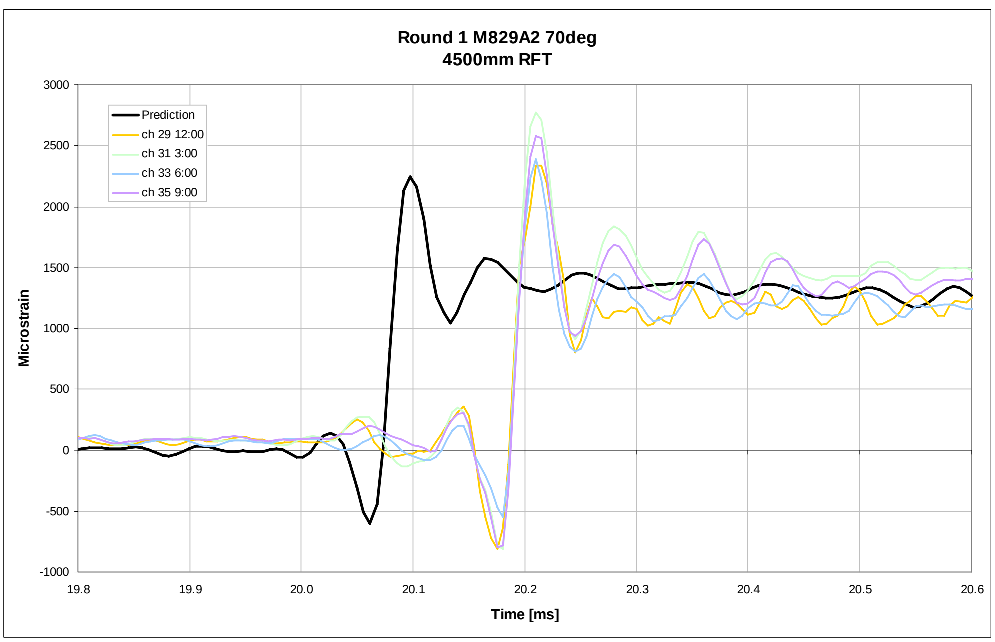

Figure 9–Experimental & Theoretical Strain vs. Time

CONCLUSION

A lightweight composite wrapped 120mm gun tube was successfully designed, manufactured, and test fired. For the first time a thermoplastic matrix was used, allowing for cure in place fabrication. This avoided the manufacturing complications due to coefficient of thermal expansion mismatch encountered in previous attempts at composite wrapped gun tubes. The design resulted in a gun tube that was 100 lbs lighter than its all steel counterpart while maintaining the same first bending mode and cross sectional profile.

Finite element models were used to help predict the response of the gun tube to firing loads. These models were validated through non-destructive testing and later shown to be in good agreement with the firing results.

The composite jacket survived the firing with no apparent damage. The only possible indication of damage was a slight decrease in the magnitude of the frequency response. There was no shifting in the location of the modes so this drop in magnitude could be attributed to the way the accelerometers were mounted on the tube.

Overall, this effort was very successful and the data collected will be very useful in the design of future composite wrapped gun tubes.

ACKNOWLEDGMENTS

The authors would like to thank the entire LOS/BLOS ATD team; the firing range crew at APG; the group at ADC that helped manufacture the tube; and Physical Acoustics for helping to perform the acoustic emission testing. Without the help of all these people this effort could never have been completed.

REFERENCES

[1] Parker, A.P., Troiano, E., and Underwood, J.H., 2005, “Stresses Within Compound Tubes Comprising a Steel Liner and an External Carbon-Fiber Wrapped Laminate”, ASME Journal of Pressure Vessel Technology, 127(1), pp. 26-30

[2] Littlefield, A., Hyland, E., 2002, “Use of Composites on the FCS-MRAAS Swing Chamber Launcher for Reduced System Weight,” Proc. of the 23rd Army Science Conference.

[3] Simkins, T.E., 1987, “Resonance of Flexural Waves in Gun Tubes,” ARCCB-TR 870008, Benét Laboratories, Watervliet, NY.

[4] Hasenbein, R., Gabriele, A., Artus, B., Cunningham, G., Gast, R., 1990, “Dynamic Strain Waves – a Development Perspective,” ARCCB-TR-90030, Benét Laboratories, Watervliet, NY.

[5] Hasenbein, R., and Hyland, E., 1992, “Dynamic Strain Waves and Permanent Bore Enlargement,” ARCCB-TR-92042, Benét Laboratories, Watervliet, NY.

[6] Hasenbein, R., Gabriele, A., and Artus, B., 1991, “Dynamic Strain Study of the M256 Cannon Tube”, Technical Report ARCCB-TR-91015, Benét Laboratories, Watervliet, NY.