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ADVANCED COMPOSITE APPLICATIONS TO LARGE CALIBER WEAPONS SYSTEM--ETC(U)
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ADVANCED COMPOSITE APPLICATIONS TO LARGE CALIBER WEAPONS SYSTEMS (1)

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I. INTRODUCTION

Composite materials are ideal for structural applications where high strength-to-weight and stiffness-to-weight ratios are required. Aircraft, spacecraft, and missiles are typical weight-sensitive structures in which composite materials are utilized.

According to Jones (1) there are three commonly accepted types of composites: (1) Fibrous composites which consist of fibers in a binding matrix, (2) Laminated composites which consist of layers of various materials, and (3) particulate composites which are composed of particles in a binding matrix.

This study deals with composites of the first type--the application of an advanced fibrous composite, graphite/epoxy, to increase the overall performance of the barrel extension used on the 75mm rotating chamber single shot firing fixture. In order to increase accuracy and muzzle velocity, an all-metal barrel extension (Figure 1) had been added to the 75mm gun tube where the muzzle brake had been located. This extension increased the muzzle velocity, but round dispersion was still apparent. This round dispersion was attributed to the initial "droop" of the tube caused by its body forces.

Advanced composites proved to be a good candidate for the solution of this problem. A comparison of specific properties, (Figure 2) where the specific property is defined as that material property divided by the material density, shows that if one takes specimens of steel and graphite-epoxy, both of the same weight, the

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graphite-epoxy would have up to four times the stiffness and five times the strength.

With this in mind, if much of the outer metal were replaced with a graphite/epoxy composite with its fibers oriented uniaxially along the tube direction, the new tube would (1) be

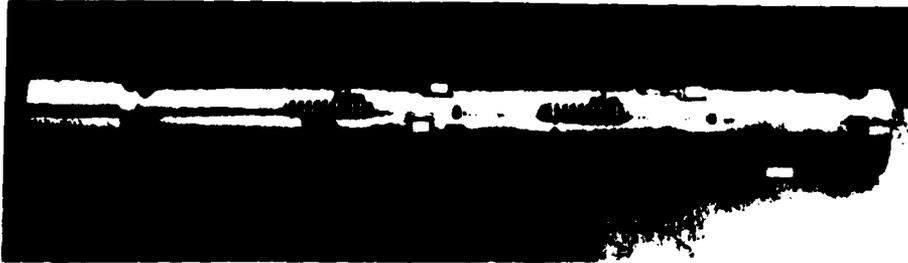


Figure 1. ALL METAL BARREL EXTENSION

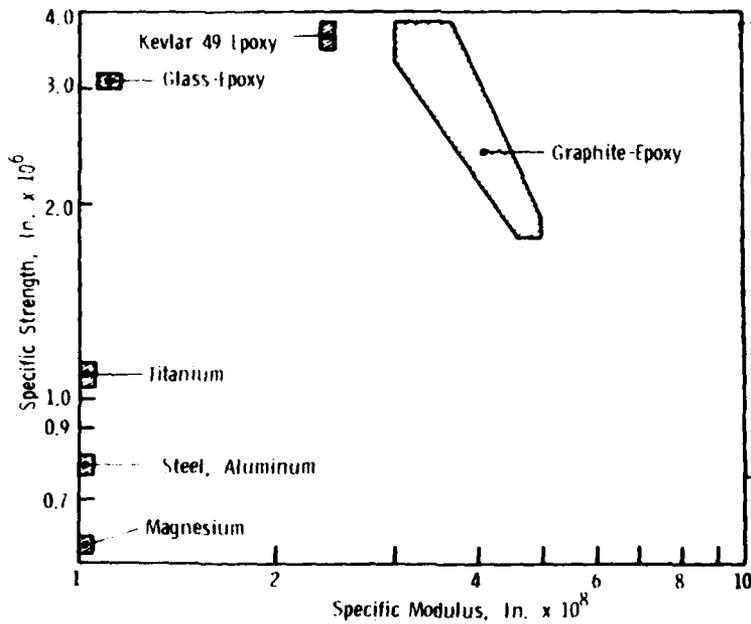


Figure 2. PROPERTY COMPARISON

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lighter in weight; (2) the tube would be stiffer in the longitudinal direction, and (3) with the combination of the above, initial "droop" would be less, and the natural frequency of the extension in the longitudinal sense would be higher, thus combating the well known whip phenomenon that large caliber weapons exhibit.

II. DESIGN APPROACH

The basic design approach was to remove the outer metal of the original extension, and then to replace that removed metal with a composite. Once the metal was removed, the original extension would become both an internal liner to protect against erosion, and a permanent mandrel on to which the composite would be applied.

Figure 3 shows the pressure-history experienced by the chamber. A maximum pressure of 55,000 psi is what the chamber of the gun sees, but this is not what the muzzle extension must withstand. The projectile exits at approximately 7-8 milliseconds after charge ignition. This means that the end of the tube is exposed only to atmospheric pressure up to that time. At exit time, the pressure has already decreased to 15,000 psi in the chamber. Also, there is a pressure gradient along the tube such that the muzzle pressure is 80% that of the chamber pressure. The working pressure, then, seen by the extension is roughly 12,000 psi.

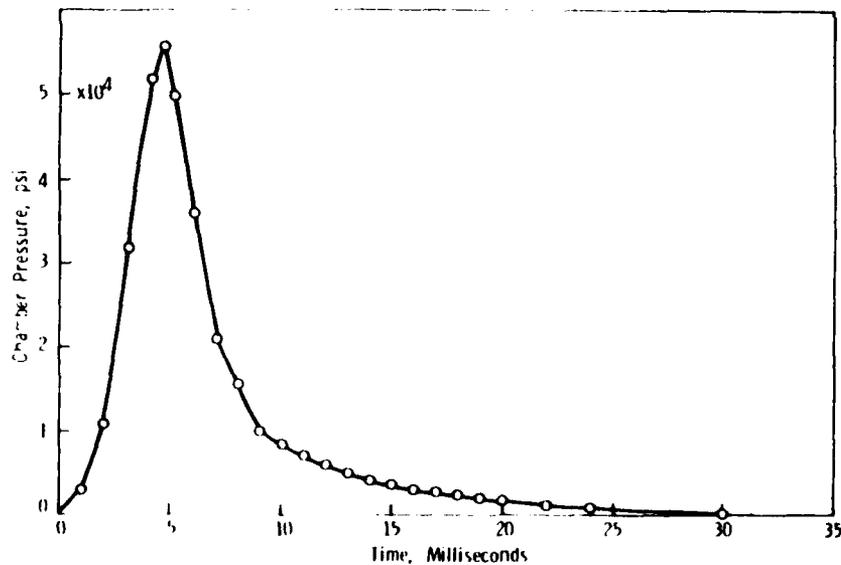


Figure 3. PRESSURE-HISTORY

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The internal heat input per round was experimentally determined to be 68 BTU/ft²/round (2). This caused a temperature rise of 27°F per round at the outer wall of the tube.

After examining these operating conditions, both finite element and classical techniques were used to determine exactly how much metal was to be removed and how much composite would be added, in order to increase the overall performance while staying within material property limits.

An orthotropic finite element code ORFE (3) was used to predict the hoop and radial stresses developed during fire. This code is an interactive substructured routine installed on the AMMRC U-1106 computer. For this particular model isoparametric axisymmetric finite elements were used. Figure 4 shows a sample grid used in the analysis. Classical equations were also developed to analyze the isotropic cylinder overwrapped with an orthotropic composite subjected to an internal pressure pulse. This analysis calculated the radial stress (Figure 5) and the hoop stress (Figure 6) as a function of radius.

To verify that the assumption of a static loading case was valid in the pressure-stress relations, it was necessary to determine the radial and hoop-type ring frequencies and compare their period of oscillation to that of the rise time of the pressure pulse. Calculations showed that these periods of oscillation were sufficiently high so that the internal pressure pulse would not excite the system and cause a dynamic loading case.

A thermal analysis was used to determine the axial stress developed during the cure cycle used for the composite, and also to determine the temperature at the metal/composite interface during fire. The mismatch of coefficients of thermal expansion of the metal and the graphite/epoxy was the reason that the thermal study was needed during cure. Steel has a coefficient of thermal expansion that is approximately 6μin/in/°F while that of the composite is essentially zero (actually, it is slightly negative in the fiber direction).



Figure 4. FINITE-ELEMENT GRID

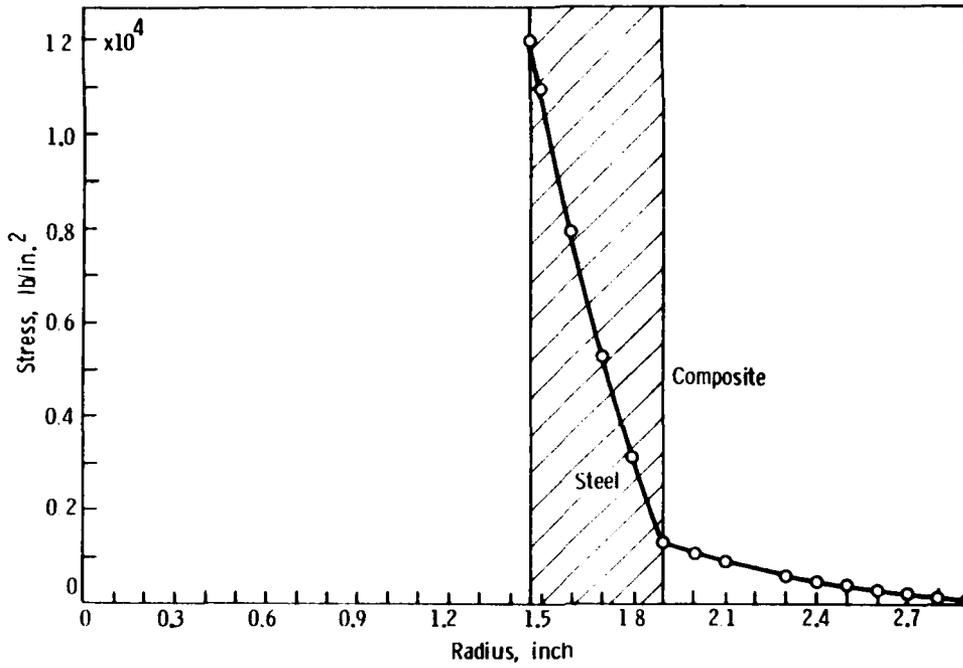


Figure 5. RADIAL STRESS VERSUS RADIUS

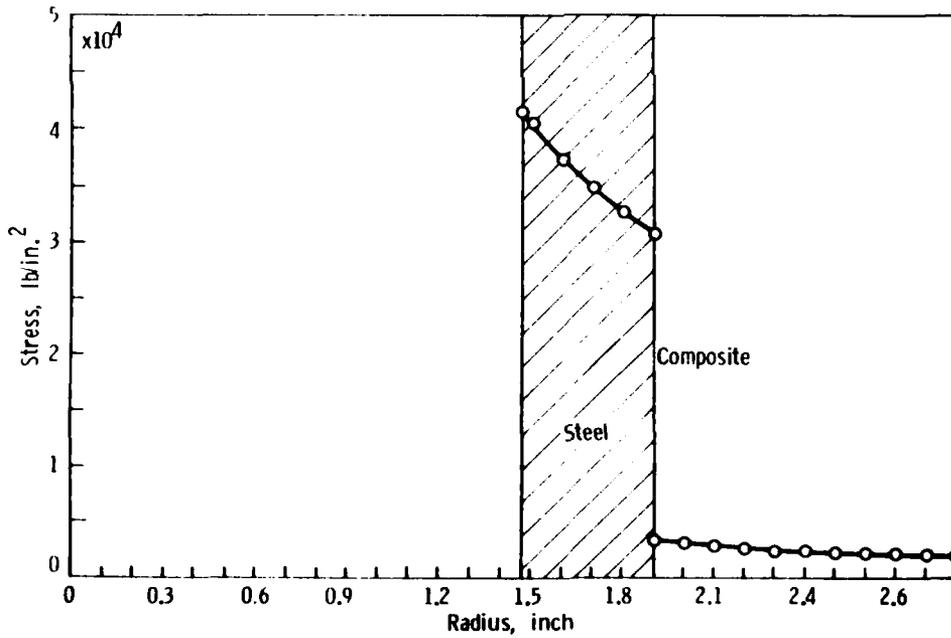


Figure 6. HOOP STRESS VERSUS RADIUS

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When the liner/mandrel with the uncured composite (oriented 0° along the tube axis) is placed in the autoclave and raised to 350°F , which is the cure temperature of the composite, the extension is virtually stress free. At 350°F the composite system cures, thereby restraining the internal steel mandrel in its elongated state. When the extension is cooled, it wants to contract by the amount $\alpha\Delta TL$ (where α is the coefficient of thermal expansion and L is the length of the tube). It is constrained from doing so, however, by the cured composite thus introducing a residual stress field. It is this stress field that had to be determined in order to prevent the composite from buckling during cool-down.

Graphite/epoxy systems tend to lose their structural integrity as the operating temperature approaches that of the cure temperature. Hence it is necessary to assure that the operating temperature does not exceed 350°F . Figure 7 shows the predicted peak temperature above ambient as a function of time for a single shot. In this case where the gun was not fired in a repeating mode, the peak interfacial temperature was determined to be 56°F above that of the ambient, well within the operating range of the composite.

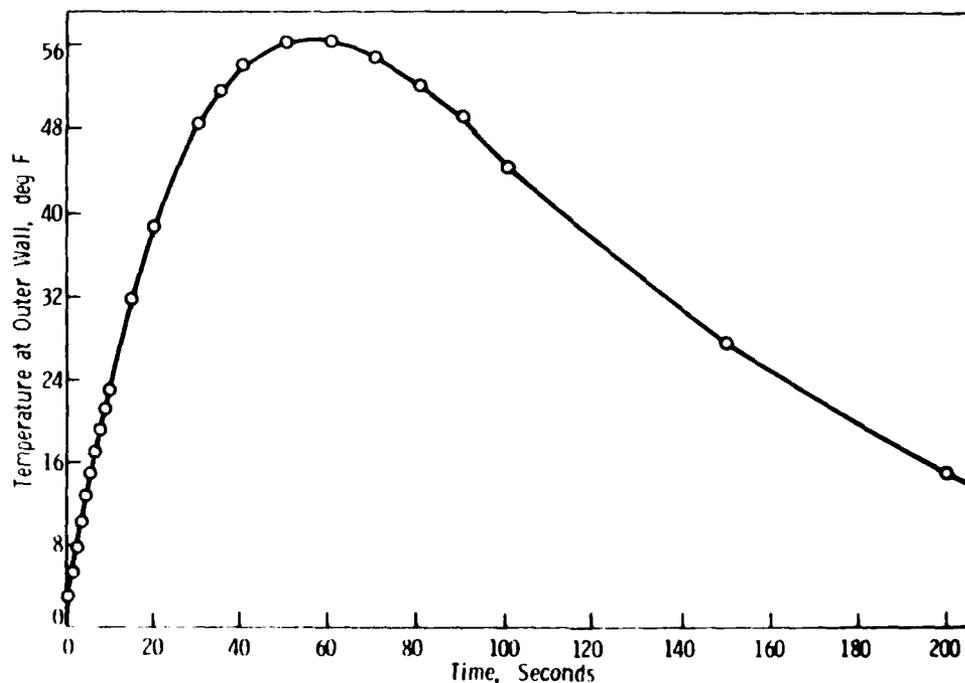


Figure 7. PLOT OF WALL TEMPERATURE VERSUS TIME OF EXIT

III. FABRICATION

Upon converging on a final liner/mandrel design, an original extension was modified as shown in Figures 8 and 9. The surface was then prepared for interfacial instrumentation and composite application.

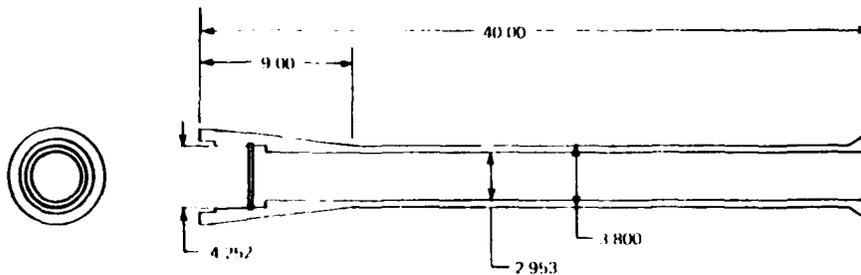


Figure 8. DIMENSIONS OF LINER/MANDREL



Figure 9. LINER/MANDREL READY FOR COMPOSITE APPLICATION

A ten percent solution of hydrochloric acid was used to clean all major dirt and grease left on the part after the machining process. The part was then chucked in a filament winding machine which was used to facilitate part instrumentation and the hand layup of the graphite-epoxy. The filament winding process was not used at this point in the fabrication.

A methanol and subsequent acetone rinse were used to clean the liner/mandrel just prior to instrumenting and composite application. Two strain gages and a thermocouple were applied to the interface. The strain gage orientation was such that longitudinal and hoop stresses could be recorded during fire. The gages and thermocouple were then insulated to prevent the graphite/epoxy from electrically shorting out the gages. The extension was then ready for the first graphite/epoxy application.

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Because the composite was up to an inch thick toward the breech end, the graphite/epoxy had to be applied in three separate operations, with autoclaving between each application; otherwise too much resin "bleedout" would have occurred during cure, resulting in a "dry" composite part. These multiple fabrication steps allowed the application of intracomposite instrumentation to monitor stresses and temperatures through the wall during fire.

After cleaning and instrumentation a film adhesive was applied, and three inch wide prepreg tape (HMS-3501-6) was layed up unidirectionally along the tube axis. Once the composite was at the desired thickness (.33 in) for the first application, a bleeder ply was applied, then a burlap bleeder ply, and finally a vacuum bag and gland. The extension was then autoclaved according to the recommended cure cycle for the 3501-6 epoxy resin--90 minutes at 120°F, followed by 90 minutes at 350°F. When the autoclave cycle was completed the tube was debagged and cleaned. Two more layers of graphite/epoxy were applied in the same manner.

To provide field durability and protect the graphite/epoxy from the "zippering" effect, or splitting along the fiber axis, that could occur with unidirectional composites, a hoop winding of S2 glass/epoxy was applied using a filament winding machine. The extension was then post-cured at 370°F for three hours. Figure 10 shows the composite extension with its final instrumentation ready for firing tests.



Figure 10. COMPLETED LINER/MANDREL

IV. FIRING TESTS

The firing tests were performed at Ares Corporation, Port Clinton, OH. The gun used was their rotating chamber single shot test fixture (RCSSTF). Figure 11 shows the composite extension mounted on the tube.

The firing procedure used was: (1) Ready the RCSSTF in accordance with pre-firing procedures established for proof test of ammunition. (2) Install the all-metal barrel extension. (3) Verify

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barrel bore, breech and barrel insert, barrel extension, and chamber alignment with projectile bore gage. (4) Fire warm-up rounds to insure instrumentation is operating properly. (5) Verify barrel extension bore alignment with bore sight to the center of the target. (6) Fire ten rounds of armor piercing, fin stabilized, discarding sabot (APFSDS) ammunition which has been conditioned at 70°F for at least eight hours. (7) Repeat steps two through six utilizing the composite barrel extension.



Figure 11. COMPOSITE EXTENSION READY FOR FIRING

V. RESULTS

Table 1 shows the data taken from the round locations on the target. The average shot location was significantly closer to the center of the target for the composite extension in the vertical direction and approximately the same in the horizontal direction. This suggests that initial barrel droop was indeed less with the composite extension.

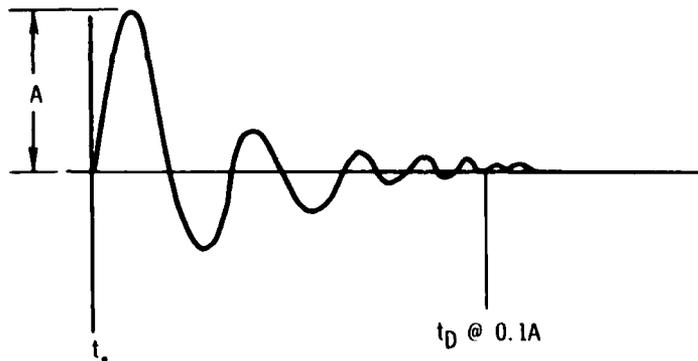
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Table 1. ROUND DISPERSION RESULTS

• FIRING RANGE = 80 METERS

	METAL EXTENSION		COMPOSITE EXTENSION	
	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL
LOCATION	1.448 MRAD	-0.820 MRAD	0.346 MRAD	-0.806 MRAD
VARIANCE	0.131 MRAD	0.198 MRAD	0.072 MRAD	0.370 MRAD

Longitudinal and hoop strain data showed a definite advantage in using the composite extension. From the longitudinal strains recorded during the fire, it was found that the composite extension had a natural frequency that was 22% higher than the metal extension. The damping time (Figure 12) for the composite extension was almost 45% lower than that of the metal extension, where the time to damp, t_D , is that time at which the amplitude of vibration is 0.10 that of the original input.



Composite Extension $t_{Davg} = 29$ msec

Metal Extension $t_{Davg} = 51$ msec

Figure 12. DAMPING HISTORY

Hoop strain data agreed well with the finite element predictions. It was predicted that the hoop strain during fire would reach a value of $870\mu\text{in/in}$ and the measured value was $990\mu\text{in/in}$, an error of only 11% in the estimate.

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Thermal data agreed quite well with the predicted value, except for the decay time. The peak temperature predicted was 56°F above ambient, or 106°F, approximately sixty seconds after fire. The actual temperature measured was 112°F at 1.25 minutes after fire. The decay time, however, was almost an order of magnitude greater than the predicted value.

Erosion data taken by standard star gage techniques showed no difference between the two extensions.

Finally, the weights of the composite and metal extension were 82 and 95 pounds respectively. The metal extension was 16% heavier than the composite. Note that the weight of the turned-down barrel was 57 lbs. Thus, 38 pounds of metal were replaced with 25 lbs of graphite/epoxy.

VI. DISCUSSION

The feasibility of using advanced composites in large caliber weapon systems has been demonstrated. The graphite/epoxy barrel extension was found to be more accurate and lighter than the all-metal barrel extension. Barrel whip has been reduced significantly as evidenced by the damping time.

The use of classical and finite element techniques has proven to be an accurate method when used to predict operating quantities such as the dynamic stresses and strains. Experimental data taken during the firing tests were very close to the analytical predictions; however, some error was present. The greatest discrepancy between the predicted and actual values was in the thermal predictions at the metal/composite interface. Although the rise time and peak temperature were very close to the actual, there was almost no correlation in the decay. Classical heat transfer methods predicted an exponential decay that would approach zero within roughly 350 seconds, whereas actually the time required was 1800 sec. The reason for this difference is thought to arise from the calculation of the negative exponent in the decay term of the heat balance equation. This term has as part of it, the internal convective heat transfer coefficient. It is this quantity that was poorly estimated. It is interesting to note, however, that one can actually use the experimentally measured thermal data to modify the solution to the heat balance equation in order to obtain the actual heat transfer coefficient. This could then be used in future studies.

Regarding the hoop strain calculations, the actual strain was only 11% higher than the predicted value. Such a small

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difference could be attributed to many things, e.g. a slight difference in material properties with respect to what was used in the calculations, especially, in the transverse direction of the composite overwrap (which was in the hoop direction of the extension).

These hoop data also verified the assumption that the model--isotropic cylinder overwrapped with an orthotropic composite--could assume a static loading case. Had there been any dynamic overshoot (i.e. greater than 25% that of the steady state case) there would have been a much greater difference between actual and predicted values of hoop strain at the interface. From these data it can be concluded that the metal liner could have been made thinner providing that the hoop strain at the interface did not exceed that of the strain-to-failure of the graphite/epoxy in the transverse direction.

Because of the increased stiffness and decreased weight, the natural frequency of the composite extension was higher than that of the metal. In addition, the damping time of the composite was less. This could lead to an increased rate of fire in that the composite will have already stopped "whipping" when the metal extension would still be in motion.

Probably the most significant aspect of the results was the target data. Overall dispersion area for the composite was one third of that for the metal (Figure 13). The standard deviation of the round dispersion in the vertical direction was much less for the composite. This fact is attributed to the quicker response of the barrel as it is straightened from its initial droop when the projectile approaches the muzzle and also to the fact that the initial droop was less because of the lighter weight.

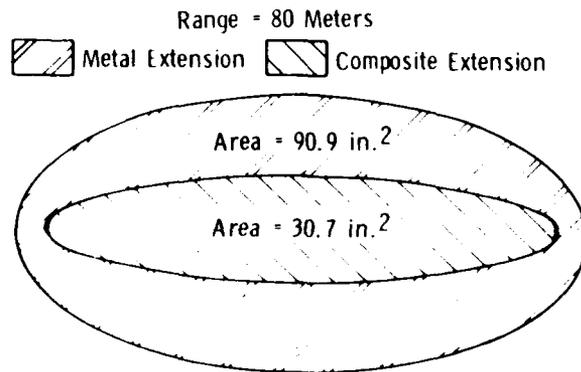


Figure 13. ROUND DISPERSION AREA

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One point that must not be overlooked is that the horizontal variance was higher for the composite even though the average horizontal shot locations were very similar for the two extensions. This phenomenon has not been explained. One suggestion is that because the composite extension was mounted and fired after the metal extension, the test stand might have loosened. It is also interesting to note that on the day of the firing of the metal extension there was essentially no wind, whereas on the day that the composite extension was tested the winds were gusting up to 15 mph. Whether this point is significant or not has not been determined.

VII. RECOMMENDATIONS

Although vertical round dispersion was significantly decreased with the current graphite/epoxy system, and the accuracy of the gun increased, further addition of composites would result in still better overall performance.

At the breech end of the tube, where the highest bending stresses occur, is where the composite would be most needed. To implement this, more detailed analyses would be needed, especially with respect to the thermal problems.

Finally, there are other components used in large caliber weapons systems such as suspension components, trails, hydraulic accumulators etc. that would be candidates for the use of composite materials, and further investigation could be beneficial in many aspects such as cost, performance, and weight savings.

VIII. CONCLUSION

An advanced composite barrel extension for a 75mm gun to replace an all-metal extension has been designed, fabricated and tested. Test firings verified the thermal and structural behavior predicted by the computer codes. Round dispersion, muzzle deflections, and "time-to-damp" were markedly decreased, accompanied by a 16% weight savings and an increased natural frequency. The work serves as a base for a complete composite gun barrel to be designed, fabricated and field tested next year.

Weight savings, while modest at 16% in this first design, can be substantial. Taking into consideration the amount of steel that was replaced by graphite/epoxy, 37% weight savings resulted.

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Other applications where graphite/epoxy has replaced steel have demonstrated weight savings up to 70%. This magnitude of weight savings augurs the development of highly mobile, lightweight vehicles capable of bearing large caliber weapons at a fraction of current systems weight.

IX. REFERENCES

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