1 Introduction

Since gun powder was discovered, guns have been changed and developed in terms of their overall configuration and firing mechanism with their performance over a period of several centuries. The most principal requirements have been mobility and firepower. However, these two characteristics are never compatible. Weapon systems must be light for high mobility, but wall-thickness of gun tube should be thick enough to resist required firepower. In the viewpoint of operation, light weight for mobility is a key factor as well as firepower. SAFE is the abbreviation of operational procedure of weapon systems; see, aim, fire and eliminate.[1] Adequate firepower is required to eliminate targets effectively. However, weight reduction of weapon systems helps obtain better performance on the steps of ‘aim’ and ‘fire’ out of the four steps. Steel, iron or bronze were normally used for monobloc tubes until the middle of the nineteenth century. The use of the barrels as monobloc tubes is limited by the fact that the strain due to enlargement caused by internal pressure during firing, and thereby also the stress at the bore surface, is substantially greater than at the outer surface. Fig.1(a) shows stress curve in the tube wall of a monobloc tube going from the inside to the outside. The difference between the stresses at the inner and outer surfaces of the tube increases with increasing wall thickness, so that the interior part of the tube cross section has reached the permissible stress, while the exterior portion is only slightly loaded. In order to achieve greater tube resistance to gas pressure, an effort is thus to be made to distribute the stress more uniformly over the wall thickness during firing. This is accomplished by using multilayer tubes or monobloc tubes with autofrettage. Multilayer tubes were introduced around 1870.[2] Here, the wall of the tube is composed of several layers, where, in one method, tube rings, or jackets, or both are shrunk onto the liner. In another design, many layers of steel bands or composite plies are wound onto the liner with tensile stress. In either case, the tensile stresses arising in the exterior layers, because of the shrink fitting or winding, result in compressive stresses on the interior layers of the tube. The Compressive stresses present in the interior region of the wall of the tube, even in the unloaded state, compensate to a great extent the loading during firing, while the tensile stresses in the exterior portion of the tube wall are insignificantly increased by the loading. In this way the stress is distributed over the entire tube cross section, so that the material is well utilized. The stresses in a multilayer tube are pictured in Fig.1(b) in the state of rest and when firing.

There are some problems to be overcome for composite wrapped gun tubes; the gap developed
between steel and composite due to the coefficient of thermal expansion (CTE) mismatch of the two materials, lack of pre-stress on the composite, poor manufacturability for mass production, and so on.[3]

The gap issue could be solved by autofrettage after winding process. This process also helps achieve residual stress. However, the thermal soak treatment process cannot be carried out after autofrettage which is essential and bore surface of gun tubes cannot be chrome-plated that is generally required in these days.[4]

Another way to solve these problems could be the lay-up tailoring. Using both fiberglass and graphite together with the ply angles being adjusted such that the lay-up’s CTE matched that of the steel avoids forming the gap. However, it can degrade the performance of the composite.[5]

In this study, IM7/PEEK tape is consolidated onto a steel thick-walled cylinder, in situ, using the robotic equipment for tape placement and this equipment can apply the requested tension during winding. This process is expected to decrease the thermal expansion effect and prevent the gap formed between the steel and the composite effectively. Since this process can be done after both autofrettage and chrome-plating processes, it is suitable for the gun barrel application. In addition, the post cure cycle for thermoplastic composite is not necessary due to the ‘cure in place’ method with the thermoplastic composite.

2 Composite overwrapped thick-walled cylinders

2.1 Plane strain cylinder theory

The generalized plane deformation analysis presented by Hyer [6] is the basis of this work. However, instead of formulating a problem in terms of a scaling variable \( \zeta = \Omega r \). This scaling is done to avoid numerical problems, which is explained later.

It is desired to determine the response of a laminated cylinder subjected to both mechanical and thermal loading. The geometry is defined in the cylindrical x-\( \theta \)-r coordinate system as shown in Fig.2. Since only axi-symmetric loading is considered, the displacements, stresses and strains are independent of the circumferential coordinate \( \theta \). Attention is focused on the response of the cylinder away from the ends and therefore the stresses and strains are independent of the axial coordinate \( x \).

The composite overwrapped thick-walled cylinder can be described as an n-layer cylinder, which the steel mandrel being referred to as the first layer. The outer radius of the cylinder is \( r_o \) and the inner radius is \( r_i \). The interface between the \( k \)th layer and the \((k+1)\)th layer is denoted as \( r_{k+1} \). The inner pressure and the outer pressure are \( P_i \) and \( P_o \) respectively. The cylinder is subjected to a torsion load \( \tau_o \) and an axial force \( F_{axial} \). Each layer may also be subjected to a thermal loading \( \Delta T^{(k)} \), where the superscript \((k)\) denotes the \( k \)th layer.

In the x-\( \theta \)-r coordinate system, the constitutive behavior of each layer is expressed as:

\[
\begin{bmatrix}
\sigma_x^{(1)} \\
\sigma_y^{(1)} \\
\sigma_\theta^{(1)} \\
\varepsilon_{\theta\theta} \\
\varepsilon_{\theta\theta} \\
\end{bmatrix}
= \begin{bmatrix}
\bar{C}_{11} & \bar{C}_{12} & \bar{C}_{13} & 0 & 0 & \bar{C}_{16}^{(1)} \\
\bar{C}_{12} & \bar{C}_{22} & \bar{C}_{23} & 0 & 0 & \bar{C}_{26}^{(1)} \\
\bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & 0 & 0 & \bar{C}_{36}^{(1)} \\
0 & 0 & 0 & \bar{C}_{44} & \bar{C}_{45} & 0 & \gamma_{60}^{(1)} \\
0 & 0 & 0 & \bar{C}_{45} & \bar{C}_{55} & 0 & \gamma_{55}^{(1)} \\
\bar{C}_{16}^{(1)} & \bar{C}_{26}^{(1)} & \bar{C}_{36}^{(1)} & 0 & 0 & \bar{C}_{66}^{(1)} & \gamma_{66}^{(1)} - \alpha_{66}^{(1)} \Delta T \\
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_\theta \\
\gamma_{60} \\
\gamma_{55} \\
\gamma_{66} - \alpha_{66} \Delta T \\
\end{bmatrix}
\]

The \( \bar{C}_{ij} \) terms are the elastic constants and the \( \alpha_j \) terms are the coefficients of thermal expansion of the \( k \)th layer in the global x-\( \theta \)-r system, which are obtained by rotating the lamina properties in the principle 1-2-3 material system by the winding angle \( \Phi \) as shown in Fig.2. The problem is formulated in terms of scaled variable \( \zeta \) as mentioned earlier. Based on the axi-symmetric and plane deformation assumptions, the components of strain for each layer can be expressed in terms of the axial displacement
u(x, $\zeta$), the circumferential displacement $v(x, \zeta)$, and the radial displacement $w(\zeta)$ as follows:

$$
\varepsilon_x = \frac{\partial u}{\partial x}; \quad \varepsilon_\theta = \frac{w}{\zeta}; \quad \varepsilon_r = \frac{d w}{d \zeta};
$$

$$
\gamma_{\theta r} = \left( \frac{\partial v}{\partial \zeta} - \frac{v}{\zeta} \right) \Omega; \quad \gamma_{sx} = \frac{\partial u}{\partial \zeta} \Omega; \quad \gamma_{sx} = \frac{dv}{dx} \Omega \tag{2}
$$

The displacements of the kth layer as shown by Hyer [6] can be obtained as:

$$
u(x, \zeta) = u(x, \zeta) = \varepsilon_\theta x \tag{3}
$$

$$
v(x, r) = \varepsilon_\theta x \left( \frac{\zeta}{\Omega} \right) \tag{4}
$$

$$
\varepsilon_\theta = \frac{1}{\zeta}; \quad \varepsilon_r = \frac{d w}{d \zeta}; \quad \gamma_{\theta r} = \frac{\partial v}{\partial \zeta} \Omega; \quad \gamma_{sx} = \frac{\partial u}{\partial \zeta} \Omega \tag{2}
$$

The solution to this equation is:

$$
\sigma_r(\zeta_o) = \frac{P_o}{\Omega}; \quad \sigma_r^{(1)}(\zeta_i) = \frac{-P_i}{\Omega} \tag{11}
$$

where $\lambda^{(k)} = \sqrt{\overline{C}_{22} / \overline{C}_{33}} \tag{7}$

and

$$
\lambda^{(k)} = (\overline{C}_{13} - \overline{C}_{12}) \alpha_\varepsilon + \overline{C}_{23} - \overline{C}_{22} \alpha_\sigma \tag{8}
$$

If $\overline{C}_{22} \neq \overline{C}_{33}$, the above equations are valid. For a material that is transversely isotropic in the 2-3 plane ($\overline{C}_{22} = \overline{C}_{33}; \overline{C}_{12} = \overline{C}_{13}; \overline{C}_{16} = \overline{C}_{26} = \overline{C}_{36} = 0$; $
\alpha_\sigma = \alpha_r$), the governing differential equation for the radial displacement simplifies to:

$$
\overline{C}_{22} \left( \frac{d^2 w}{d \zeta^2} + \frac{1}{\zeta} \frac{dw}{d \zeta} \right) - \overline{C}_{22} \frac{w}{\zeta^2} = 0 \tag{9}
$$

whose solution is:

$$
w(\zeta) = A^{(k)}_1 \zeta + A^{(k)}_2 \zeta^{-1} \tag{10}
$$

$A_1$ and $A_2$ vary between layers, while $\varepsilon_\theta$ and $\gamma_\theta$ have been shown to be constant for all layers. Therefore, for a laminated cylinder consisting of n layers, 2n+2 constants need to be determined. These constants are determined by enforcing the traction boundary conditions at the outer and inner radii, by enforcing continuity of displacements and tractions at the interfaces between layers, and by enforcing equilibrium of forces on the cylinder. The applicable boundary conditions at the outer and inner radii of the cylinder are:

$$
\sigma_r(\zeta_o) = -P_o; \quad \sigma_r^{(1)}(\zeta_i) = -P_i \tag{11}
$$

The external pressure $P_o$ is positive in the direction of the inward normal, while internal pressure $P_i$ is positive in the direction of the outward normal. Continuity of displacements at the (n+1) layer interface results in:

$$
\sigma_r^{(k)}(\zeta_{k+1}) = \sigma_r^{(k+1)}(\zeta_{k+1}) \tag{12}
$$

The solution to this equation is:

$$
\sigma_r^{(k)}(\zeta_{k+1}) = \frac{P_o}{\Omega} + \overline{C}_{13} - \overline{C}_{12} \alpha_\varepsilon + \overline{C}_{23} - \overline{C}_{22} \alpha_\sigma \tag{12}
$$

Application of the condition of equilibrium of forces in the axial direction results in:

$$
\int_A \sigma_x(r) dA = F_{axial} \tag{13}
$$

$F_{axial}$ represents the total axial force resulting from the applied traction $F_a$ in the axial direction, as well as the axial forces due to the internal and external hydrostatic pressures on the end fittings of a closed-ended cylinder. For the laminated cylinder under consideration, Eq. 13 can be written in terms of $\zeta$ as follows:

$$
\frac{2\pi}{\Omega^2} \sum_{k=1}^{n-1} \sigma_x^{(k)}(\zeta) \zeta d\zeta = F_a + \pi r_i^2 P_i - \pi r_o^2 P_o \tag{14}
$$
The axial forces due to the hydrostatic pressures are absent and only the first term on the right hand side of Eq. 14 is retained, if the cylinder is open-ended. The integral condition representing the applied torsion $\tau_o$ can be written as:

$$\int_0^\infty \tau_{\theta\theta}(r) r dA = \tau_o$$  \hspace{1cm} (15)

Or in terms of $\zeta$ as:

$$\frac{2\pi}{\Omega} \sum_{k=1}^n \int_0^{\zeta_k} \tau_{\theta\theta}^{(k)}(\zeta) \zeta^2 d\zeta = \tau_o$$  \hspace{1cm} (16)

Eq. 11, 12, 14 and 16 provide the necessary $2n+2$ conditions required to determine the $n*(A_1)'s$ and $n*(A_2)'s$ and $\epsilon^o$ and $\gamma^o$ terms, and therefore the displacements, strains and stresses in each layer.[7]

2.2 Design and analysis

Polyetheretherketone (PEEK) that is a thermoplastic polymer was chosen due to its high strength, high stiffness, high impact resistance, high thermal stability, and good chemical resistance. PEEK is used with IM7 that is a high performance carbon fiber. IM7 fiber with a PEEK matrix was the material selected for this study.

First, two S2-Glass/PEEK plies were overwrapped on to the high strength steel thick-walled cylinder in the hoop direction to avoid galvanic corrosion. Second, ten IM7/PEEK plies were overwrapped. Then, ten four-ply set of IM7/PEEK were overwrapped. Each four-ply set has three hoop direction plies and one axial direction ply. Finally, five IM7/PEEK plies were overwrapped in the hoop direction.

Axial and hoop strains on the surface of the composite overwrapped cylinder at six locations were theoretically calculated under certain inner pressure condition.

2.3 Manufacturing

First of all, a high strength steel bar is machined for mandrel as an inner cylinder with the conventional gun tube manufacturing method. S2-Glass/PEEK and IM7/PEEK tapes were consolidated onto the steel mandrel, in situ, as already explained in the 1 section. Fig. 3 shows the automated process of tape placement. During the winding process, the desired tension is applied with the robotic tape placement equipment.

2.4 Nondestructive tests

The pressure and acoustic emission (AE) tests were conducted at six locations along the composite overwrapped cylinder. Strain data of the surface of the cylinder were obtained at six locations. Standard rosette strain gages and Physical Acoustic R-151 AE sensors were placed for the tests. The cylinder was pressure tested to a peak pressure of 138 MPa (20 kpsi). The strain readings were recorded every 34 MPa (5 kpsi) up to peak pressure. Fig. 4 shows the non-destructive test set-up.
Fig. 5 shows the AE test result at a certain location of the cylinder. As the number of pressure loading cycle increases, the number of fiber and matrix cracking hits counted with the AE sensor decreases. This is the Kaiser effect.

![AE test result showing the Kaiser effect.](image)

For the composite wrapped gun tube without winding tension, the strain data that were collected were within 13% of the analytic predictions as shown in Table 1. However, there is quite a bit of error between theoretically calculated strain and experimental results for the composite wrapped cylinder with winding tension as shown in Table 2. Additional studies are required for this case.

### Table 1. Theoretical and experimental strain for the case without winding tension.

<table>
<thead>
<tr>
<th>Strain</th>
<th>$\varepsilon_a(0^\circ)$</th>
<th>$\varepsilon_b(45^\circ)$</th>
<th>$\varepsilon_c(90^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>-0.001005</td>
<td>0.001159</td>
<td>0.003323</td>
</tr>
<tr>
<td>Experimental (mean value)</td>
<td>-0.000912</td>
<td>0.001006</td>
<td>0.002908</td>
</tr>
<tr>
<td>Error (%)</td>
<td>9%</td>
<td>13%</td>
<td>12%</td>
</tr>
</tbody>
</table>

### Table 2. Theoretical and experimental strain for the case with winding tension.

<table>
<thead>
<tr>
<th>Strain</th>
<th>$\varepsilon_a(0^\circ)$</th>
<th>$\varepsilon_b(45^\circ)$</th>
<th>$\varepsilon_c(90^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>-0.001436</td>
<td>0.001663</td>
<td>0.004762</td>
</tr>
<tr>
<td>Experimental (mean value)</td>
<td>-0.000871</td>
<td>0.001103</td>
<td>0.003274</td>
</tr>
<tr>
<td>Error (%)</td>
<td>39%</td>
<td>34%</td>
<td>31%</td>
</tr>
</tbody>
</table>

Fig. 6 shows a specimen of the composite wrapped cylinder for X-ray CT scan and the cross-sectional view image of X-ray CT scan of the specimen. The bright inner ring is the steel tube and the gray outer ring is the composite. However, due to the shadow effect by the steel caused by the density difference between steel (7.8 g/cm$^3$) and carbon (1.6 g/cm$^3$), it was difficult to analyze both the composite zone in detail and the interface between the steel and the composite.

![A specimen (left) and X-ray CT image (right).](image)

### 3 Conclusions

S2-Glass/PEEK and IM7/PEEK tapes were consolidated onto a steel thick-walled cylinder, in situ, using the automated tape placement equipment. The strain data collected was fairly good agreement with predictions for the composite overwrapped gun tube without winding tension. However, the strain data collected was not closed to the theoretical calculated values for the case with winding tension. The AE test under cyclic pressure loading and the X-ray CT scan were also conducted. Some sub-scale tests with theoretical analysis and non-destructive test will be carried out. Finally, live firing tests of the composite overwrapped gun tube will be conducted in the future.

### References


