OPTIMAL DESIGN OF CYLINDRICAL STEEL/COMPOSITE HYBRID STRUCTURES FOR GUN BARREL APPLICATIONS

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Advances in composites design and manufacturing have increased the feasibility of the use of composites into gun tube designs that enable weight reduction, shift the center of gravity and increase the overall natural frequency. In recent years, the design and performance of composite overwrapped gun tubes has been revisited. This work has led to the successful design, manufacture, and firing of a lightweight 105mm hybrid composite gun tube. This barrel can function at temperatures ranging from -50°F to 400°F while still maintaining interface compression between the composite and steel liner.

This work was successful in part due to UD-CCM’s ongoing development of in-house user friendly generic software tools such as CCDS (Composite Cylinder Design Software). This software package incorporates stresses due to manufacture, interior ballistic pressures, autofrettage stresses, loads due to muzzle brakes, and thermal flux during firing. CCDS also incorporates a number of common failure theories for anisotropic materials and a barrel profiler that can be used for end-to-end design of composite overwrapped gun tubes based on variation in internal pressures and temperatures along the length of the tube. Static internal pressure tests and live firing data from the 105mm barrel gave results within 2% of CCDS model predictions.

Keywords: Filament Winding, Structural Analysis, Pressure Vessels/Tanks/Storage vessels.

Introduction

In recent years, use of composite materials as a primary structural component for military applications has increased the need for strong lightweight materials. The use of composite materials as a structural element allows for optimal design using both analytical and finite element models that can readily predict the structural response for a wide variety of static and dynamic loading conditions. Using these models to find an optimal solution for a complex design problem can be difficult due to the large variety of variables involved in the design process. This paper presents a generic analytical solution to a cylindrical steel/composite overwrapped structure, called Composite Cylinder Design Software (CCDS), that incorporates the ability to optimize composite hybrid structures through an intuitive design process. Effects of process temperatures, winding tension and mechanical external loads on final internal stresses in composite hybrid structures are presented and compared with FEA and experimental data for the 105 mm barrel as a case study.
Theoretical Development

Over the years, several investigators have developed theoretical models of the filament winding and curing of composite cylinder structures [1-13]. These models have been shown to successfully predict residual strains during processing. The model used in this work is based on the work of Hyer et al. [7-9] and is a generalized plane deformation model for filament wound structures used to predict the thermoelastic response of a post- and insitu- consolidated laminated cylinder. The theory also models the effects of winding tension in the insitu-process and the redistribution of stresses resulting from composite-steel separation. Both the post- and insitu-consolidation models incorporate the temperature dependence of the thermoelastic response of the material [6].

The post-consolidation process assumes that the cylinder is initially stress free at the processing temperature and is cooled down uniformly to the final operational temperature. The ply-by-ply residual stresses and strains resulting from the application of thermal loads, as well as the ply-by-ply strains and stresses resulting from the application of mechanical loads are determined. Insitu-consolidation assumes an ‘onion skin’ model, in which the cylinder geometry is built up in an incremental manner, layer by layer. The model can be used to investigate the interaction between the cylindrical part and the tool (mandrel), and also the effect of winding tension on the residual stresses in the cylinder.

The geometry is defined in the cylindrical x-ϕ-r coordinate system as shown in Figure 1. Since only axisymmetric loading is considered, the stresses, strains and displacements are independent of the circumferential coordinate \( θ \). 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 \( x \).

![Figure 1. Definition of the Coordinate axes.](image)

The cylinder is comprised of \( N \) layers, with the innermost layer being referred to as the first layer. The inner radius of the cylinder is \( r_i \) and the outer radius is \( r_o \). The interface between the \( k^{th} \) and the \( (k+1)^{th} \) is denoted as \( r_{k+1} \). The hydrostatic pressure acting on the outer
radius is $p_o$ while the hydrostatic pressure acting on the inner radius is $p_i$. The cylinder is subjected to an axial force $F_{axial}$ and a torsional load $\tau_o$. Each layer may also be subjected to a thermal loading $\Delta T^{(k)}$, where the superscript $(k)$ denotes the $k$th layer. The response of the cylinder is determined from the interaction of individual layers that comprise the thickness. The response of each layer is written in terms of constants obtained from the integration of the elasticity equations for that layer. In general, the set of constants vary from layer to layer. These constants are determined by enforcing the traction boundary conditions at the inner and outer radii, by enforcing continuity of displacements and tractions at the interfaces between layers, and by enforcing equilibrium of forces on the cylinder.

The constitutive behavior of each layer is determined by a rotational transformation of elastic constants of that layer. The ply by ply strains are then found and summed to find the total cylinder stresses and strains. A flowchart of the program methodology is shown in Figure 2 below. Details of these formulations are found in Eduljee et al. [5].

**Figure 2.** Flow Chart for the filament winding model.

**Autofrettage**

Autofrettage, a process that induces a favorable distribution of initial or residual stress in a tube, is commonly used in the manufacture of gun barrels. The word autofrettage literally means "self-hooping" and the process involves expanding a partially machined barrel or liner by applying hydraulic pressure to the interior surface. The elastic limit is increased while the less strained outer part applies a compressive force to the inner as if a hoop or tube had been shrunk on. An autofrettage model is included in this analysis as it is a standard process for obtaining a
higher effective strength for gun tube applications. The theoretical solution for applying autofrettage to a steel bore is omitted here but can be found in numerous sources [14, 15].

For a hybrid composite, the autofrettage process is carried out prior to composite overwrap as this technique involves exposing the barrel to high temperatures which will degrade the composite. Ideally this process should be carried out after overwrap to impart a radial compression strain on the steel thus reducing the maximum stresses during firing and maximizing the use of the composite overwrap.

**CCDS Interface**

In this work, the CCDS (a graphical user interface of the plane deformation model) was developed to aid in optimal design and analysis of composite hybrid cylinders. Additional features of CCDS include a barrel profiler used to design entire composite overwrapped tubes based on variation in internal pressures and temperature along the length of the barrel, a number of common failure models for anisotropic structural analysis, and a model to predict the dynamic strain critical velocity based on effective tube stiffness and density [16].

![CCDS Interface](image)

**Figure 3. CCDS Composite Cylinder Design Software (Part of the CDS Suite at UD-CCM)**

A snapshot of this application is shown in Figure 3. The cylinder materials dimensions, individual material properties, ply stacking sequences, thermal and mechanical loads are entered in the top section. The resulting stress, strain and displacements of the tube in the axial, circumferential, radial, and shear directions are plotted in the lower section as a function of radial position. The bore factor of safety, critical velocity, and progressive failures based on maximum stress or strain are also plotted. All results are plotted in real time allowing the design engineer to optimize different materials, stacking sequences and dimensions based on loading conditions.
This software is part of a new software initiative at UD-CCM called Composite Design Software (CDS), a suite of powerful applications for composite design and analysis.

The barrel examined in this study is a generic 105mm gun barrel. The goal of this study is to reduce barrel weight yet maintain or exceed the structural performance of the existing all steel design. The following is a list of existing loading conditions and desired structural characteristics that must be achieved in the hybrid optimal composite overwrap structure:

- Maximum pressure of 90,000 psi at the breech to 16,800 psi at the muzzle location.
- $500,000$lb longitudinal tension muzzle brake load during firing.
- $-50^\circ\text{F}$ to $400^\circ\text{F}$ service temperature.
- No separation between composite and steel for all service temperature and firing conditions.
- Natural frequency must meet or exceed existing baseline barrel frequency.
- Minimum factor of safety of 1.1 for all mechanical and thermal loading.
- No peel or tension failure of composite overwrap at breech or muzzle location for all service temperature and firing conditions.
- Composite overwrap must have no fiber wrinkles and a low final void content.
- Significant weight reduction and center of gravity shift towards the breech must be achieved using current existing composite materials and filament winding technologies with the ability to control winding tension system.

These conditions must be achieved through the optimal selection of materials, stacking sequences, winding tension, autofrettage and processing parameters. The first phase of design, however, must consider whether a composite overwrap should be considered as a feasible design for this structure under these loading conditions. The advantages of using a lightweight composite to replace steel can be offset by the anisotropic characteristics of the composite overwrap, specifically in coefficient of thermal expansion (CTE) mismatch between both materials that can lead to separation between liner and overwrap. Also noteworthy is the higher compliance a composite overwrap exhibits which can reduce the effectiveness in absorbing internal stresses during firing.

Figure 4 is a typical plot of final radial, hoop and axial stresses for a 0.5” [0/90] E-Glass Epoxy composite overwrap on a 105mm barrel with 1” barrel thickness that undergoes a constant $\Delta T$ of $-273^\circ\text{F}$ ($350^\circ\text{F}$ oven temperature to room temperature), mandrel held at a constant temperature of $212^\circ\text{F}$ ($100^\circ\text{C}$), and an internal pressure of 65ksi. Radial compression is achieved if the mandrel can be held at a sufficiently lower temperature than the cure temperature of the resin system. If this controlled temperature cannot be achieved then significant winding tension is required to compensate for the CTE mismatch between composite overwrap and steel barrel.

Based on firing data provided by ARL, the pressure profile during firing varies from 90ksi as the breech to approximately 17ksi at the muzzle. The region considered for overwrap is a 145 inch long section with a maximum internal pressure of 65ksi at the breech end. The existing baseline steel thickness for the 105mm barrel in the area of composite overwrap is 1.4 inch at the start point and 0.53inch at the end point. The effectiveness of applying a composite overwrap is examined by wrapping a number of different composite materials over these two points as they represent the upper and lower bound for internal pressure.

The composites selected for this study were an E-glass/Epoxy, IM7/Epoxy and B4/IM7 Hy-Bor/Epoxy laminate hoop wound at 10lb tension with representative properties given in Table 1 below.
Figure 4 (b) Total radial, hoop and axial stresses for a 0.5” [0/90] E-Glass Epoxy composite overwrap with an internal pressure of 65ksi and ΔT of -273°F.

Table 1. Mechanical Properties for materials used in this study.

<table>
<thead>
<tr>
<th>Property</th>
<th>Steel</th>
<th>E-Glass</th>
<th>Carbon</th>
<th>Hybor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long. Stiffness, ( E_L ), (msi)</td>
<td>29.0</td>
<td>5.7</td>
<td>25.7</td>
<td>41.0</td>
</tr>
<tr>
<td>Trans. Stiffness, ( E_T ), (msi)</td>
<td>29.0</td>
<td>1.24</td>
<td>1.36</td>
<td>2.7</td>
</tr>
<tr>
<td>Poisson’s Ratio, ( v_{LT} )</td>
<td>0.29</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Thermal Exp., ( \alpha_L ) (in/in.°F)</td>
<td>( 6.2 \times 10^{-6} )</td>
<td>( 3.9 \times 10^{-6} )</td>
<td>( -2.257 \times 10^{-6} )</td>
<td>( 2.3 \times 10^{-6} )</td>
</tr>
<tr>
<td>Thermal Exp., ( \alpha_T ) (in/in.°F)</td>
<td>( 6.2 \times 10^{-6} )</td>
<td>( 11.7 \times 10^{-6} )</td>
<td>( 12.0 \times 10^{-6} )</td>
<td>( 13.6 \times 10^{-6} )</td>
</tr>
</tbody>
</table>

Figure 5 is a plot of required composite thickness as a function of steel thickness for the three difference composite overwraps to maintain the steel hoop stresses at a constant value with an internal pressure of 65ksi. The bore is autofrettaged with the plastic radius remaining at a constant ratio of 50% bore thickness. For the E-glass overwrap the required composite thickness to maintain constant stress in the steel increases dramatically with a small reduction in steel wall thickness. The IM7 and Hy-Bor composite performs better but still reaches a limiting thickness where additional overwrap does not help in reducing the baseline steel hoop stress. The reason for this behavior is attributed to the lower stiffness in the composite radial direction that reduces translation of stress to the composite hoop plies.

Figure 6 is a similar plot for the muzzle end of the tube subjected to a significantly lower pressure of approximately 17ksi. This section of the baseline barrel does not require autofrettage as the pressure is low. Here we see that much more steel can be removed and replaced with composite overwrap thus significantly reducing weight at this location of the barrel. Both plots indicate that some steel can be removed and replaced with a light composite overwrap with the
optimal ratio based on pressure, autofrettage conditions and whether a CTE mismatch causes separation between composite and steel liner.

![Graph showing required composite thickness as a function of steel thickness](image)

**Figure 5.** Required composite thickness as a function of steel thickness to maintain the steel hoop stresses at a constant value with an internal pressure of 65ksi. (1.4 inch baseline barrel thickness)

![Graph showing required composite thickness as a function of steel thickness](image)

**Figure 6.** Required composite thickness as a function of steel thickness to maintain the steel hoop stresses at a constant value with an internal pressure of 17ksi. (0.53 inch baseline barrel thickness)

From the previous plots it is easy to see that the carbon or Hy-Bor overwraps are the best materials for replacing the steel liner material. Not only is less composite required but these
composites are lighter than the glass fiber composite. The problem with wrapping steel with these materials is the substantial CTE mismatch that can lead to separation at low temperatures. The -50°F service temperature requirement for this barrel dictates the upper bound of allowable radial tensile stresses between the composite and steel. Figure 7 is a plot of radial stresses for a 0.5 inch steel barrel being wrapped with 0.25 inch [90]_{n} at -50°F with no tension and shows significant tensile stresses between bore and overwrap which can lead to separation. This represents the worst case scenario for separation as it corresponds to the highest ΔT between the process temperature and operating temperature without internal pressure from firing. This can be overcome either by winding under high tension to compensate for this mismatch or by winding off axis to reduce the effective CTE mismatch. Current filament winders are limited in the amount of tension that can be provided during winding but work is ongoing in developing the next generation of high tension machines. For the first generation design we consider a combination of both as a method to minimize these radial stresses.

![Figure 7](image_url)

**Figure 7.** Plot of radial stresses for a 0.5 inch steel barrel being wrapped with 0.25” [90]_{n} at -50°F with zero tension (105mm barrel, 0.5 inch steel, 0.5 inch wrap)

Up to this point the design charts have not considered the axial component of stiffness required to meet or exceed the baseline steel barrel. The natural frequency of the barrel is governed by this stiffness and the 500,000lb load must also be absorbed by the hybrid barrel in this direction. This is incorporated by placing high stiffness fibers in the longitudinal direction of the barrel. Therefore the optimal design incorporates a composite overwrap with hoop or off-axis layers to absorb internal pressure stresses and axial layers to absorb the brake load and maintain or exceed the baseline natural frequency. The interesting point to note here is that incorporation of axial plies in the overwrap reduces the effective CTE mismatch between composite and steel as the hoop CTE of the axial layers is much greater that the CTE of the hoop wound layers. As a result, high strength carbon layers can be placed in the axial direction without an increase in CTE mismatch in the hoop direction.

Figure 8 is a plot of radial stresses for an [0/90]_{n} (0.25x0.005 inch tow) IM7/epoxy overwrap at -50°F with various levels of applied constant winding tension. One can see that radial stresses are reduced significantly with the addition of tension during winding. At a winding tension in excess of 113lb the interface is no longer in tension and will not separate at
this low temperature. Another benefit to winding under high tension is that the composite overwrap places the steel liner under hoop compression and reduces the maximum stresses in the steel during firing. This is demonstrated in Figure 9 which shows the hoop stresses in the barrel with variation in winding tension and zero internal pressure. For the zero tension case the barrel is in hoop tension due to the mismatch in CTE. As tension is increased the bore is placed in compression which reduces the stresses in the barrel. The composite overwrap has the same effect as the autofrettage process, namely placing the steel bore in a state of compression, and thus allowing for the potential for further weight savings. This tension, however, is very high and difficult to apply with current filament winding machinery, but is being examined by a number of researchers.

Figure 8.  Radial stresses for an [0/90]_n (0.25 inch x 0.005 inch tow) IM7/epoxy overwrap at -50°F with increase in constant winding tension (105mm bore, 0.5 inch steel, 0.5 inch wrap)
Based on the results from this study, the first generation barrel was designed using CCDS with a hybrid composite overwrap. Many different materials and layups were studied based on weight, stiffness, CTE mismatch, natural frequency and risk in manufacture. In summary a glass/carbon hybrid overwrap was selected as the materials for the first generation design. Limitation in high tension winding technology required that the hoop wound layers be wound with a compliant CTE material such as a glass fiber composite. The glass layers were wound in off-axis to ensure that the effective CTE would exactly match that of the steel (note that even the all glass [90]
 composite overwrap from Figure 7 resulted in tensile stresses of 700psi) The IM7 carbon is placed axially with the ratio of glass to carbon being 1:1. The composite and steel thickness was optimized along the length of the barrel based on internal pressure and autofrettage conditions using the ‘profiler’ feature of CCDS. The required factor of safety at all locations was 1.1 for the highest loading condition which corresponds to 90,000psi internal pressure at the breech location. The tube also met or exceeded the critical velocities of the all-steel baseline barrel at all locations along the tube length. Figure 10 is a plot showing the barrel profile. It specifies the location and thickness of the composite overwrap and the steel liner thickness as a function of axial location.

Table 2 compares the benefits of the composite overwrap versus the all steel design. Also shown in this table are the specifications of the high tension design. One can see significant benefits to the composite hybrid design over the 9 Hz baseline steel tube. The hybrid tube was found to be 225lb lighter even though heavier glass fiber is used in the low tension design. An important parameter in the design of large caliber gun barrels is the mass*C.G. which is related to the inertial mass of the tube. The lower this figure the easier it is to aim and maintain position on target. A lower mass*C.G. also allows the incorporation of lighter solenoid motors for targeting control. A 29% decrease in mass*C.G. is obtained for the low tension design with a 46% decrease for the all carbon design.
Figure 10. Barrel profile showing composite overwrap for the hybrid glass/carbon design.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>9 Hz Steel Barrel</th>
<th>1st Composite Barrel</th>
<th>High Tension Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1106lb</td>
<td>880.9lb (-225.1lb)</td>
<td>812lbs (-294lb)</td>
</tr>
<tr>
<td>C.G.</td>
<td>75.2in</td>
<td>72.9in (-2.3 in)</td>
<td>69.9 in (-5.3in)</td>
</tr>
<tr>
<td>Mass*C.G.</td>
<td>83171</td>
<td>64217 (-29%)</td>
<td>56759 (-46%)</td>
</tr>
<tr>
<td>Natural Frequency</td>
<td>9Hz</td>
<td>8.42Hz (-0.58Hz)</td>
<td>8.83 Hz (-0.17Hz)</td>
</tr>
</tbody>
</table>

**Tube Manufacture and Testing.**

Based on the optimal dimensions for the barrel found using CCDS, a 105mm tube was manufactured at Benét Laboratories where it underwent autofrettage and surface machining in preparation for placing the hybrid overwrap. Spencer Composites Corporation, based in Sacramento, CA, was selected as the company that would apply the composite overwrap. The resin used was Resolution Performance Product’s (RPP) SU-3/Epon 828 epoxy system. BR-127 primer was used to prepare the steel surface and 3M AF 191 was selected as the film adhesive. The carbon fiber rovings were impregnated with 30% resin by weight resulting in a fiber volume
percentage of approximately sixty percent. The E-glass fiber rovings were impregnated with twenty-three percent resin by weight also resulting in a fiber volume percentage of sixty percent. Figures 11 (a-c) shows various stages of this barrel being wrapped at their plant.

Figures 11a-c Hybrid Barrel being manufactured at Spenser Composites.

The finished barrel was sent to Benét laboratories for static pressure testing. Strain gages were mounted on the composite overwrap at 5 different locations along the length of the barrel. The barrel was then pressure tested to 5ksi in 1ksi increments. Figures 12a and 12b are plots of strain measurements and CCDS model predictions for each pressure at locations 76” inch and 116 inch from the rear face of the tube (RFT). These results also matched the FEA model predictions conducted at Benét labs. In summary, CCDS model predictions were within 2% of all strain and FEA data, successfully demonstrating the accuracy of this program for hybrid tube design.

Figure 12 (a) Strain Measurements and CCDS Predictions at the 76 inch location on the 105mm tube with increasing pressure.
In July 2003 the hybrid tube was test fired at the Aberdeen Proving Grounds. The cannon was fired in both direct (0° elevation) and indirect (30° elevation) fire modes with a mix of kinetic energy simulator and cargo type rounds. Figures 13a and 13b shows the cannon firing in these modes. In the indirect picture, the round can actually be seen in the upper left corner. In total, 11 rounds were fired at pressures ranging from 138 MPa (20 ksi) to 552 MPa (80 ksi).

Strain gages were mounted at multiple locations along the gun tube with data recorded at high acquisition rates. The barrel was tested from 20ksi, 30ksi, 60ksi, 70ksi, 80ksi and 85ksi. Figure 14 is a plot of this data at three of these locations; 116 inch, 152 inch and 177 inch from
RFT, along with CCDS model predictions at these points. Once again, good agreement was obtained between model predictions and experimental test data.

![Graph showing internal pressure at gauge location (psi) vs hoop strain.](image)

**Figure 14. Surface strain at different locations during firing**

**Conclusions and Summary**

The generalized plane deformation model is developed for determining the elastic response of hybrid laminated cylinders. The model was extended to include the effect of winding tension, autofrettage and critical velocity calculations. A graphical user interface, called CCDS (Composite Cylinder Design Software) was developed and used as the primary design tool for the 105mm composite overwrapped gun tube. This tube was designed such that the composite and liner would retain interface compression at temperatures as low as -50°F yet absorb the high stresses and pressures at temperatures up to 400°F. The tube also meets or exceeds the critical velocities of the all-steel baseline barrel at all locations along the tube length. The first generation composite overwrapped tube is 225lb lighter and has a CG shift of 2.3 inches over it steel counterpart which translates in a mass*C.G. reduction of 29%. The 105mm barrel was manufactured, statically tested and successfully fired giving strain results that closely matched CCDS model predictions.

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