Dynamic and stability analysis of prestressed thin-walled filament wound glass fibre composite cylinders with metal liner

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Abstract

High fiber tension can impart sufficient compressive stresses to protect high-speed rotating cylinders from mechanical failures. Therefore, filament-wound metal cylinders with pre-stressed fiber shells are being investigated to provide radial compressive stress. This study proposes an approach to calculate the stress distributions in composite layers and the compressive stresses in the metal liner under various winding tensions. The stresses in the winding layers and metal liner at the end of the filament winding (FW) process under different tensions are determined using both analytical and finite element methods, showing good agreement between the two approaches. During the FW process, a notable stress relaxation phenomenon was observed: both the fiber stress in wound composite layers and the increase in hoop compressive stress of the metal liner decreased. However, this stress relaxation behavior is unaffected by the fiber tension. The residual tension in the fiber during winding not only reduces the stress levels in the metal liner under high-speed rotation but also maintains the stiffness and buckling stability of the pre-stressed fiber composite cylindrical shell with a metal liner (CCS-ML).

Furthermore, as the ratio of winding thickness to diameter increases, the structural stress level gradually decreases and stabilizes under high-speed loads. However, the natural frequency and buckling strength of the structure exhibit significantly different trends. Circumferential winding of the fiber effectively mitigates large deformations of the cylindrical shell under high-speed rotation or external pressure, thereby ensuring safe structural operation.

Keywords: composite cylindrical shells, metal liner, reinforcement, dynamic analysis, stability

1. Introduction

The cylindrical filament wound composite overwrapped shells with a metal liner have been widely used in spaceflight and nuclear fuel centrifuge rotors due to their high strength and low weight. In high speed rotating devices such as thin walled cylinders, these advanced hybrid composite materials combine thin metal layers with fiber/adhesive prepregs, providing good characteristics of metals, such as ductility, impact resistance, and damage tolerance, along with the benefits of fiber composite materials, such as high specific strength, high specific stiffness, and good corrosion and fatigue resistance. This makes them an excellent candidate for various applications. There are several different types of combination of fibre metal materials in the engineering field, as depicted in Figure 1.

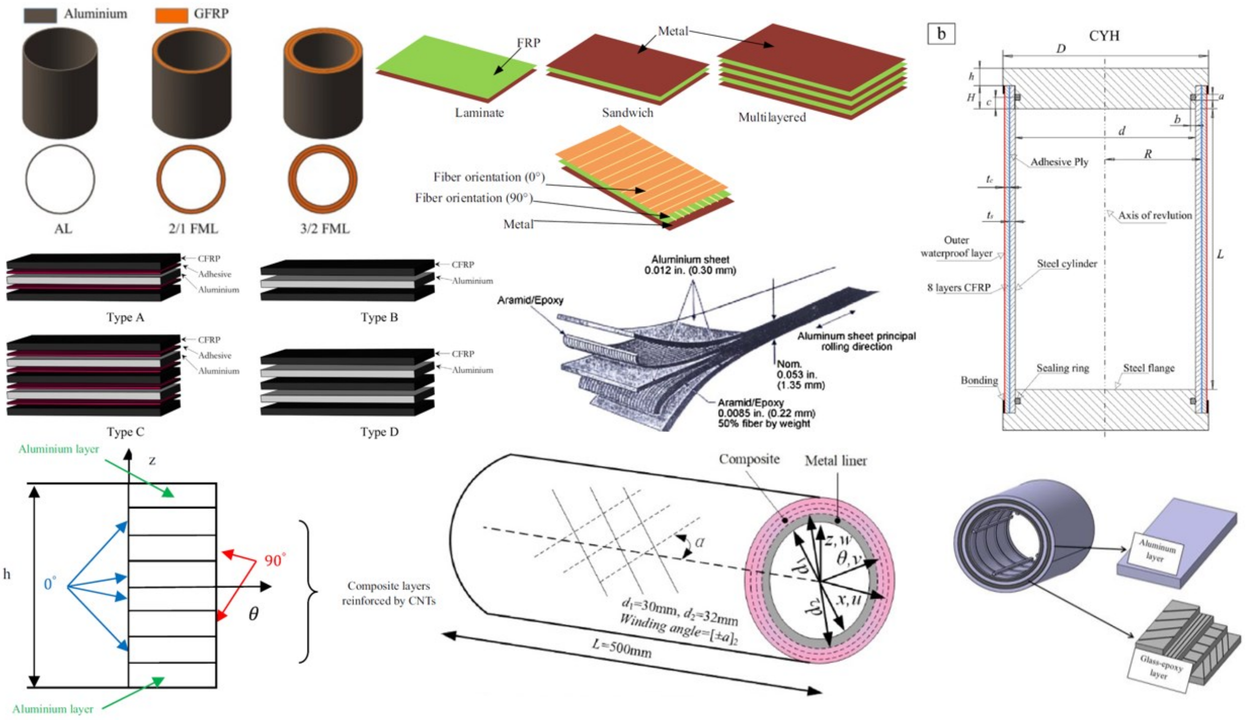


Figure 1 – Schematic representations of fibre metal laminate plates or circular cylindrical shells [1-6].

In these structures, the metal liners, serving as stiffness provider, are thinner than the composite layer and are design to carry the axial stresses up to the working rotating condition. However, optimizing the structure of these high-speed rotating cylinders is more complicated due to the counterbalanced factors of load-bearing capacity, structural stiffness, and servility stability, coupled with dimensional parameters and the filament winding process. For instance, the plastic deformation of metal liner resulting from high-speed rotation is constrained by composite winding layers, which can introduce depressions to the metal liner, causing local buckling. Local buckling can also occur during manufacturing and in service, significantly impacting security and service lifetime. The initial reinforcement effect of the filament winding of GFRP on the metal liner creates both advantages and disadvantages, as it shares a great amount of centrifugal force during high-speed rotation to improve load-bearing capacity but can be detrimental for buckling stability and overall stiffness.

To reveal the mechanism of the initial reinforcement effects of filament winding on metal liner, such as load sharing ability, stiffness and buckling capacity, this study proposes using filament wound GFRP which offers a high strength-to-weight ratio compared to existing metallic material. The 3D finite element model is built using ABAQUS software to predict the dynamic and stability characteristics of circular cylindrical shells with fixed boundary conditions. The computation models are validated by comparing with reported results in previous literatures. The hybrid GFRP cylindrical shells is further studied by varying filament winding process parameters such as winding angle and stacking sequence. The reinforcement effect on the metal liner resulting from the filament wound was achieved by using the equivalent temperature drop method and the element birth and death technology. The critical circumferential stress in composite shell which can protect the metal liner from plastic material failures and keep the minimum tension load inside the GFRP composite material during high-speed rotation condition is determined.

Utilizing a hoop wrap is crucial in increasing the hoop strength of cylindrical shells, as the hoop stresses are twice the magnitude of stresses in the axial direction. To understand the impact of design-related parameters on the cylindrical shells' natural frequencies and linear buckling strength, sensitivity analyses were conducted such as the structural thickness, rotation speed and the pretension force in composite materials. It was found that analyzing the relative contributions from mass and stiffness can offer a reasonable suggestion for determining the structure's thickness. The discrete assumption was employed to depict the critical buckling strength considering the external hydrostatic pressure force and the winding process effect, shedding light on the underlying mechanism principles behind the buckling strength of such hybrid structures.

The entire analysis method can provide valuable suggestions for engineering applications and promoting lightweight design and safety conditions.

2. Model and stresses in CCS-ML

2.1 Equilibrium equation and constitutive model

Consider a thick walled cylinder with an inner radius of *a* and outer radius after alternate-ply FW. Both the generator of the cylinder and the axis of anisotropy lie along the z-axis of a cylindrical coordinate system (r,q,z). Normal stress component in the z direction is zero, the pressure inside the cylinder is zero, and the outside pressure P is constant. The single composite layer is regarded as an orthotropic layer. The cylinder is subjected to uniform rotational body force owning to high speed rotations. Only displacement in radial direction and hoop direction considered.

$$\varepsilon_r = \frac{\partial u_r}{\partial r}\,,\ \varepsilon_\theta = \frac{u_r}{r} \tag{1}$$

The equilibrium equation for each layer is:

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \tag{2}$$

The constitutive equation is:

$$\varepsilon_r = \frac{\sigma_r}{E_r} - \nu_\theta \frac{\sigma_\theta}{E_\theta} + \alpha_r \Delta T \tag{3}$$

$$\varepsilon_\theta = \frac{\sigma_\theta}{E_\theta} - \nu_r \frac{\sigma_r}{E_r} + \alpha_\theta \Delta T \tag{4}$$

The boundary conditions are:

$$\sigma_r^m |_{r=a} = 0\,,\ \sigma_r^m |_{r=b} = \Delta P \tag{5}$$

2.2 Model parameters and material properties

The CCS-ML is composed of an aluminum alloy metal liner, serving as the main structural component. The metal liner is covered by carbon fiver composite materials to achieving lightweight design and protect the internal structures from mechanical failure under high-speed rotation.

The three-dimensional finite element model of the composite body tube structure was established using ABAQUS software. The contact between the composite fiber wound shell and the body tube lining is assumed to be an ideal bond. The geometric parameters and material properties were provided in Tables below.

Table 1 Geometry parameters for the metal liner.

Length (L) / mm	Diameter (D) / mm	Thickness (t_m) /mm
500	140	1.5

Table 2 Material properties for metal liner.

E / GPa	υ	$\sigma_{0.2}$ / MPa
70	0.3	600

Table 3 Material properties for composite layers.

E_1/ GPa	E_2/ GPa	G_{12}/ GPa	υ_{12}	t /mm	α_1 / ℃$^{-1}$	α_2 / ℃$^{-1}$
100	6	5	0.3	0.15	1×10^{-6}/℃	0

3. Numeric results and discussion

3.1 Winding stress

Stresses of winding layers at the end of winding process under various winding tensions are calculated using the analytical method and finite element method, respectively. The filament winding process was simulated by using the thermal parameter method, as shown in Figure 2. To simplify the analysis, here only the circumferential stress variations of the metal liner and composite winding layers within the first three winding layers are considered. It can be observed that with an increasing number of winding layers, the inner metal liner experiences external compressive stress, leading to a gradual increase in circumferential stress, albeit with diminishing increments. Meanwhile, the internal tensile stresses inherent in the composite layers due to their winding process gradually decrease with the influence of additional winding layers, and the magnitude of this reduction also diminishes over time. This indicates the presence of an optimal winding thickness for such hybrid CCS-ML structures, ensuring structural strength while achieving lightweight design.

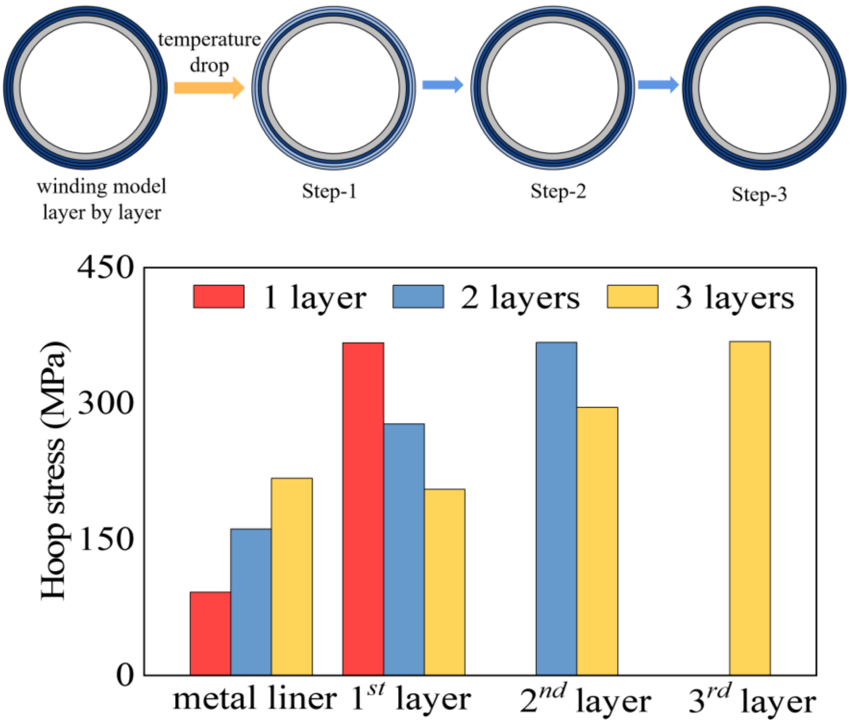
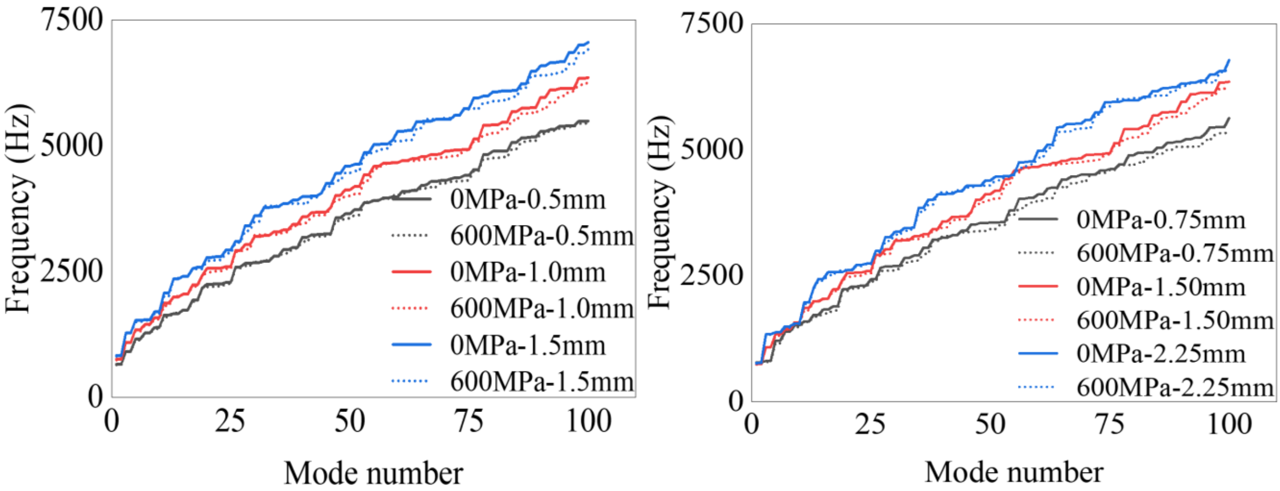


Figure 2 – Winding process simulation and variations of hoop stress.

3.2 Natural frequency

Furthermore, we analyzed the influence of different winding stresses and wall thicknesses on the structural stiffness, as depicted in Figure 3. It can be observed that increasing the thickness of either the metal liner or the composite winding layers enhance the overall stiffness (natural frequency) of the structure significantly. Additionally, due to the pre-stress effect of winding filament, the natural frequency of the structure tends to decrease; however, the extent of this stiffness reduction is relatively unaffected by changes in structural wall thickness. Simultaneously considering the effects of wall thickness and winding prestress can effectively guide the optimization design of practical structures.

Subsequently, we will further explore the contributions of increasing the composite winding layers and increasing the internal metal liner thickness to the overall structural stiffness, thereby providing better insights for lightweight design.



(a) Metal liner (b) Composite layer

Figure 3 – Mode analysis for CCS-ML considering the filament winding stress and structural thickness.

3.3 Buckling analysis

Based on linear buckling analysis, the metal liner undergoes buckling instability under very small compressive stresses. However, structural instability of metal components under significant winding stresses has not been observed in practical engineering applications. Therefore, this section considers a discretized winding process to elucidate this phenomenon.

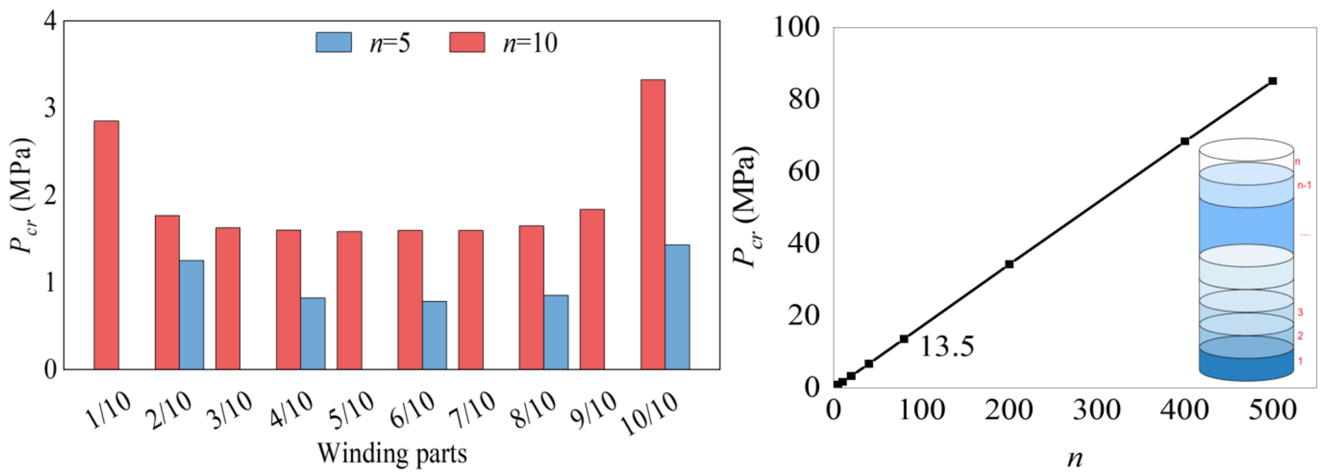


Figure 4 – Buckling stability analysis considering the winding process.

Based on the linear buckling analysis, the metal liner undergoes buckling instability under very small compressive stresses. However, practical engineering applications have not observed structural instability in metal components under significant winding stresses. Therefore, a discretized winding process is used to explain this phenomenon. As shown in Figure 4, we discretize the winding of each layer into segments wound from bottom to top. This means compressive stress is gradually applied to the hybrid CCS-ML structure in segments, where the instability load borne by the structure differs from the effect under overall circumferential compression. Analysis reveals that dividing the layers from 5 to 10 significantly increases the critical buckling strength of the hybrid CCS-ML structure. Further refinement of the discretization process shows a nearly linear correlation between critical buckling load and the degree of discretization. This explains why, in practical scenarios, the structure does not exhibit initial buckling under significant winding stresses.

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