

Research Article

Designing and Fabrication of Double Omega Cross-section Carbon Fiber Thin-walled Boom

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Abstract

With the rapid development of aerospace fields such as deep space exploration, satellite communication, and remote sensing, increasingly stringent performance requirements have been imposed on spacecraft platforms and their payloads. On one hand, there is a demand for deploying large-scale, high-precision, and multi-functional structures in harsh space environments (e.g., large antennas, solar arrays, telescope shields, and truss platforms). On the other hand, constrained by the fairing space and payload mass limitations of launch vehicles, these large structures must be kept in a highly compact folded or rolled state during launch, then reliably and accurately deployed in orbit while maintaining required stiffness and surface stability. Traditional metal structures face bottlenecks in achieving high storage ratios (storage volume/unfolded volume) and large-scale lightweight design. In this context, the deployable structure of composite materials has emerged as a promising solution, with the double omega-section carbon fiber thin-walled boom gaining attention as a novel space deployable structure. In this study, the geometric dimensions of the double omega cross-section were optimized, and the relationship between the cross-sectional moment of inertia and geometric parameters was established through geometric parameter transformation. Additionally, three distinct fabrication processes for the double omega-section carbon fiber thin-walled booms were proposed and discussed.

Keywords

Double Omega Cross-section, Co Curing of Prepreg for Positive Mould, Carbon Fiber Thin-walled Boom

1. Introduction

Thin-ply composite materials enable compact stowage within the limited volume of launch vehicles, facilitating the deployment of critical space structures such as solar arrays, solar sails, payload booms, and antennas [1, 2]. Owing to their superior stowage efficiency, deployable composite booms have emerged as a promising cross-cutting technology candidate for a broad range of deployable space systems in small satellite applications [3-5]. Notably, NASA has prioritized the development of various Collapsible Tubular Mast (CTM) boom designs fabricated from thin-ply composite materials. These designs enable the utiliza-

tion of multi-layer laminates, thereby facilitating enhanced structural design optimization [6, 7]. Among diverse thin-shell deployable boom configurations, closed-section tubular masts with interconnected omega-shaped walls have stood out as the most extensively studied rollable boom design since their inception in the United States during the 1960s, attributed to their superior structural performance [8]. In the late 1990s, DLR revitalized this boom concept for solar sail applications, leveraging more advanced composite materials and analysis software packages [9]. Subsequently, DLR has developed both scaled-up

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[10] and scaled-down [11] iterations of the early designs; however, to date, none of these variants have been validated in on-orbit missions.

The double omega cross-section carbon fiber thin-walled boom [12, 13] exhibits purely elastic deformation during the unconstrained folding process. Upon release of constraints, it automatically releases stored strain energy to return to its straight configuration, characterizing it as a bistable structure. Moreover, its critical buckling moment significantly exceeds the bending moment required for unfolding, enabling robust resistance to external disturbances and maintaining structural stability without significant deformation. Given its reliability, lightweight characteristics, and high packaging efficiency, this boom holds significant potential as a supporting framework for deployable space structures. In recent years, research on the double omega cross-section carbon fiber thin-walled boom has predominantly focused on theoretical derivation and mechanical analysis [14, 15]. However, there remains a significant gap in research regarding its fabrication processes and experimental investigations.

This study presents three processing routes for preparing

carbon fiber thin-walled booms with a double omega cross-section, namely: (i) "Prepreg forming+Post bonding" process, (ii) "Co curing of prepreg for negative mould" process and (iii) "Co curing of prepreg for positive mould" process. Among these approaches, structural components fabricated via the positive mould co-curing route exhibit superior overall performance, and their fatigue properties were systematically evaluated through curling experiments.

2. Parametric Analyses

The double omega cross-section consists of an inner shell and an outer shell, where the inner shell is composed of geometric parameters R_{i1} , R_{i2} , α_{i1} , α_{i2} , and w , while the outer shell is composed of geometric parameters R_{o1} , R_{o2} , α_{o1} , α_{o2} , and w . To satisfy geometric coordination, with the subtended angle $\alpha_{i1}=\alpha_{i2}$ and $\alpha_{o1}=\alpha_{o2}$. The inner shell and outer shell arc lengths are specified as H , which was calculated using the following equation (1). All the geometric relationships were shown in Figure 1.

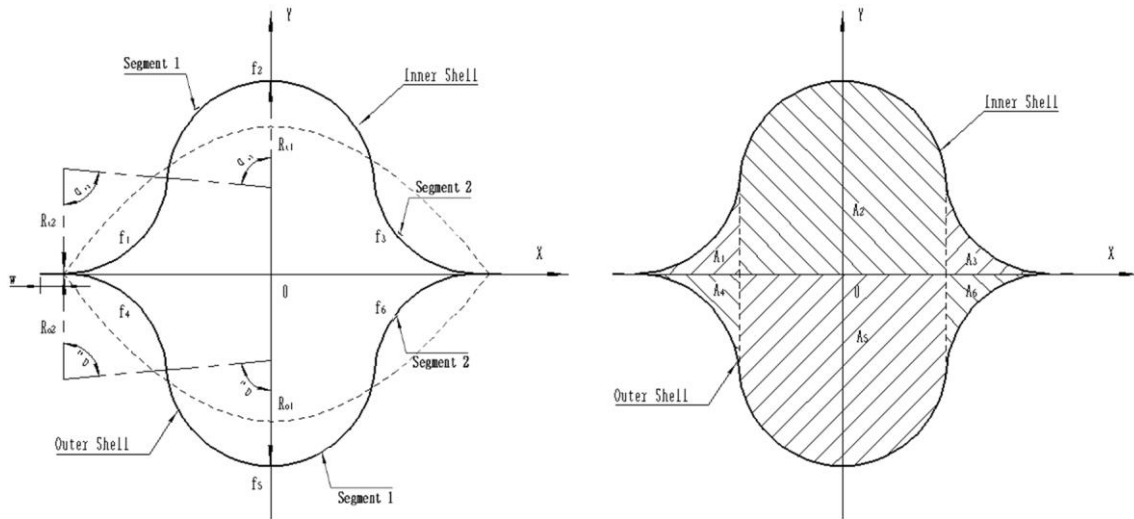


Figure 1. Geometric parameters of the cross-section of the double omega cross-section carbon fiber thin-walled tube structure.

$$H = 2(w + R_{i1}\alpha_1 + R_{i2}\alpha_2) \quad (1)$$

Inner Shell can be expressed by piecewise functions f_1 , f_2 , f_3 , Outer Shell can be expressed by piecewise functions f_4 , f_5 , f_6 as well, which were calculated using the following equation (2).

$$f = \begin{cases} f_1 : [x + (R_{i1} + R_{i2})\sin\alpha]^2 + (y - R_{i2})^2 = R_{i2}^2, & x \in (-(R_{i1} + R_{i2})\sin\alpha, -R_{i1}\sin\alpha] \\ f_2 : x^2 + [y - R_{i2}(1 - \cos\alpha) + R_{i1}\cos\alpha]^2 = R_{i1}^2, & x \in (-R_{i1}\sin\alpha, R_{i1}\sin\alpha] \\ f_3 : [x - (R_{i1} + R_{i2})\sin\alpha]^2 + (y - R_{i2})^2 = R_{i2}^2, & x \in (R_{i1}\sin\alpha, (R_{i1} + R_{i2})\sin\alpha] \\ f_4 : [x + (R_{o1} + R_{o2})\sin\alpha]^2 + (y + R_{o2})^2 = R_{o2}^2, & x \in (-(R_{o1} + R_{o2})\sin\alpha, -R_{o1}\sin\alpha] \\ f_5 : x^2 + [y - R_{o2}(1 - \cos\alpha) + R_{o1}\cos\alpha]^2 = R_{o1}^2, & x \in (-R_{o1}\sin\alpha, R_{o1}\sin\alpha] \\ f_6 : [x - (R_{o1} + R_{o2})\sin\alpha]^2 + (y + R_{o2})^2 = R_{o2}^2, & x \in (R_{o1}\sin\alpha, (R_{o1} + R_{o2})\sin\alpha] \end{cases} \quad (2)$$

Meanwhile, area moment of inertia I_x and I_y were calculated using the following equations (3) and (4) respectively.

$$I_x = \int_{A1} y^2 dA + \int_{A2} y^2 dA + \int_{A3} y^2 dA + \int_{A4} y^2 dA \quad (3)$$

$$I_y = \int_{A1} x^2 dA + \int_{A2} x^2 dA + \int_{A3} x^2 dA + \int_{A4} x^2 dA \quad (4)$$

With the analytical model derived for the structure, a series of geometrical parameter studies were conducted to evaluate how geometric designs influence area moment of inertia I_x and I_y . Each shell of the section had two independent geometric parameters that could be varied, the subtended angle of both circular segments and the radius of either segment. To prevent kinks between the arcs and maintain tangent continuity, the subtended angle of both segments had to be identical. According to the arc length $H=130$ mm, the radius R_{i1} , R_{i2} , R_{o1} , R_{o2} of segments remain equal on one hand.

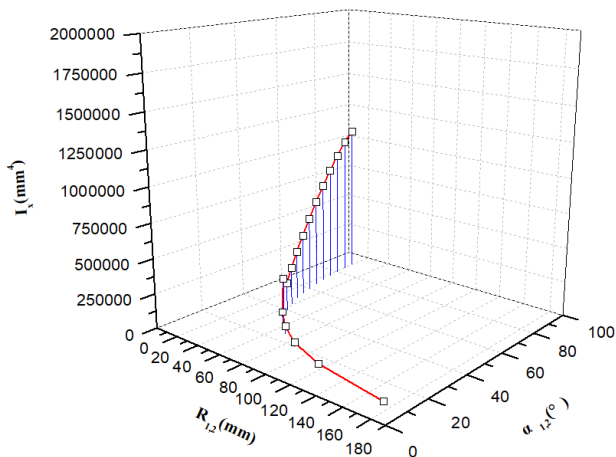


Figure 2. The area moment of Inertia I_x of symmetric section with equal radius with subtended angle varying.

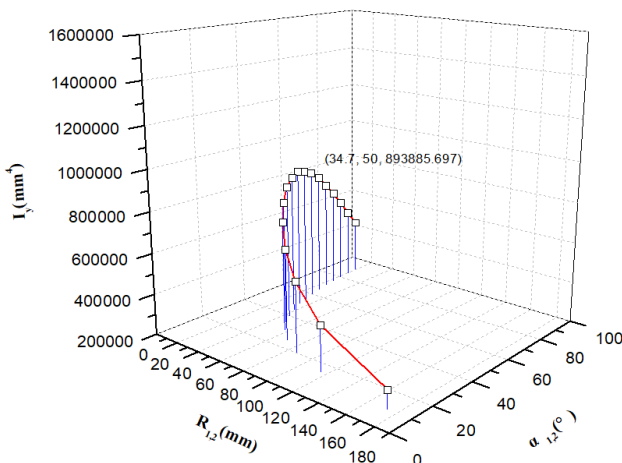


Figure 3. The area moment of Inertia I_y of symmetric section with equal radius with subtended angle varying.

As the subtended angle was varied from 5° to 90° , the radius $R_{i1,2}$, $R_{o1,2}$ of the inner shell and outer shell gradually decreased, and the cross-sectional moment of inertia I_x gradually increased. The area moment of inertia I_x reached a maximum when subtended angle was 90° ; $R_{i1,2}=R_{o1,2}=19.25$ mm. The moment of inertia I_y of the cross-section increased firstly and then decreased. The area moment of inertia I_x reached a maximum when the subtended angle was 50° ; $R_{i1,2}=R_{o1,2}=34.7$ mm; I_x and I_y were approximately equal when the subtended angle was 50° ; $R_{i1,2}=R_{o1,2}=24.75$ mm; As shown in Figures 2 and 3.

According to the arc length $H=130$ mm, the radius R_{i1} , R_{o1} of segments remain equal, while the radius R_{i2} , R_{o2} of segments remain unequal on the other hand.

As the radius R_{i1} and R_{o1} of the inner shell and outer shell increased, the radius R_{i2} and R_{o2} decreased, and the cross-sectional moments of inertia I_x and I_y gradually increased. The cross-sectional moments of inertia $I_x > I_y$, and the rate at which the cross-sectional moments of inertia I_y increased was greater than the rate at which I_x increased. As shown in Figures 4 and 5.

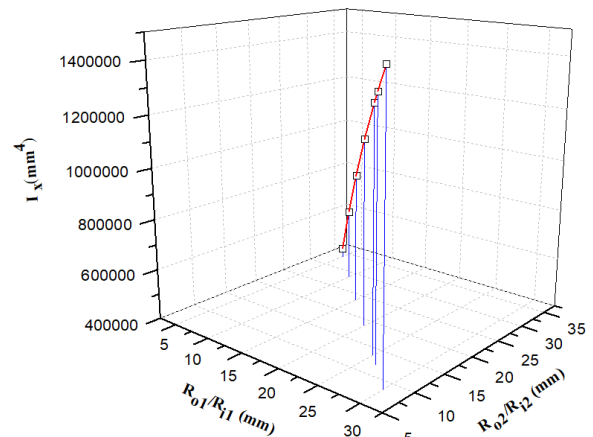


Figure 4. The area moment of Inertia I_x of symmetric section with unequal radius with subtended angle varying.

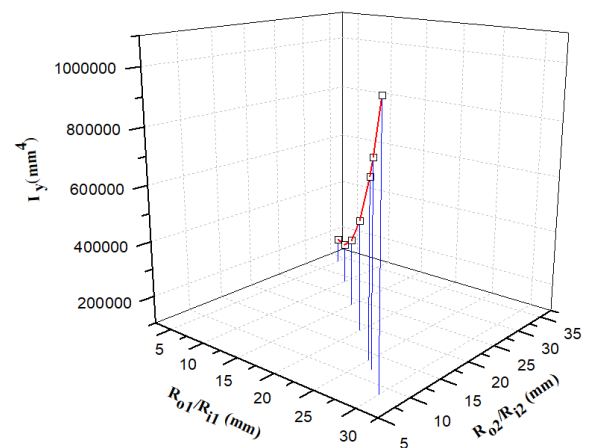


Figure 5. The area moment of Inertia I_y of symmetric section with unequal radius with subtended angle varying.

Optimal cross-sections were obtained by maximizing the area moments of inertia and torsional constants while maintaining bistability and satisfying volume requirements.

The geometric parameters of the carbon fiber thin-walled boom prepared are given as follows: $H=130$ mm, $R_{o1}=R_{i1}=26.5$ mm, $R_{o2}=R_{i2}=12$ mm, $\alpha=90^\circ$, $w=4.5$ mm.

Table 1. Geometric parameters of symmetrical radius section.

No	R_{o1} (mm)	R_{o2} (mm)	R_{i1} (mm)	R_{i2} (mm)	α (°)	w (mm)
1	26.5	12	26.5	12	90	4.5

3. Material and Methods

T300 level plain weave carbon fiber and E2314 epoxy resin were used to fabricate double omega carbon fiber thin-walled boom in this article. Table 1 shows the material description and properties of the thin-ply composites and adhesive that were used for the parametric analysis and boom fabrication. The shell layup and geometry were evaluated in the parametric analysis and are summarized in Table 2.

Table 2. Material properties of thin-ply composites and adhesive.

Label	Material Description	Fiber/ Resin	Lamina AW (g/m^2)	Thickness t(mm)
PWc	Plain Weave Carbon Fiber	T300/ E2314	135	0.19
A	E2314 Film Epoxy	N/A	90	0.1

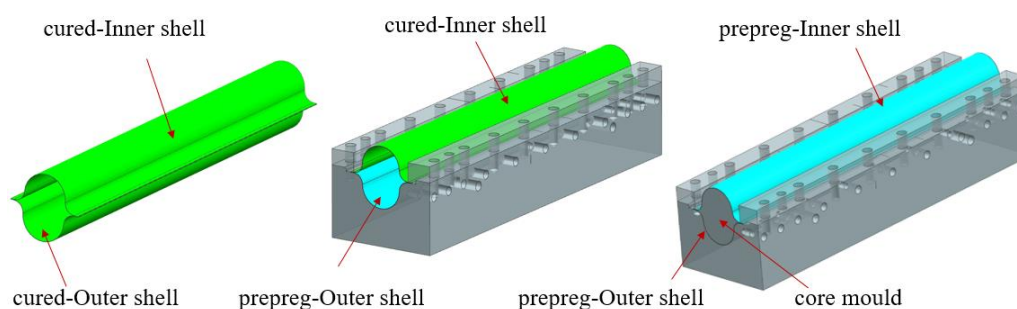
Table 3. Structure evaluated in parametric analysis.

Outer Shell Segment1	Outer Shell Segment2 and Web	Inner Shell Segment1	Inner Shell Segment2 and Web	h (mm)	w (mm)
[45 PWc]	[45 PWc]	[0/90 PWc]	[0/90 PWc]	130	4.5

Figure 6 shows three different process methods to preparing the double omega cross-section carbon fiber thin-walled tube structure, the methods include "Prepreg forming+ Post bonding" (PPD), "Co curing of prepreg for negative mould" (CPNM), "Co curing of prepreg for positive mould" (CPPM).

In terms of Prepreg forming+Post bonding ", inner shell and outer shell were cured by prepreg vacuum bagging technique (PVBT) separately first, and then the two shells were

bonded together using same resin system adhesive without core mould. With regard to "Co curing of prepreg for negative mould", inner shell was cured by PVBT first, and then prepreg-outer shell was curing at the same time the two shells were bonded together using prepreg resin without core mould. For "Co curing of prepreg for positive mould", inner shell and outer shell were curing and bonded together at the same time using prepreg resin with core mould.



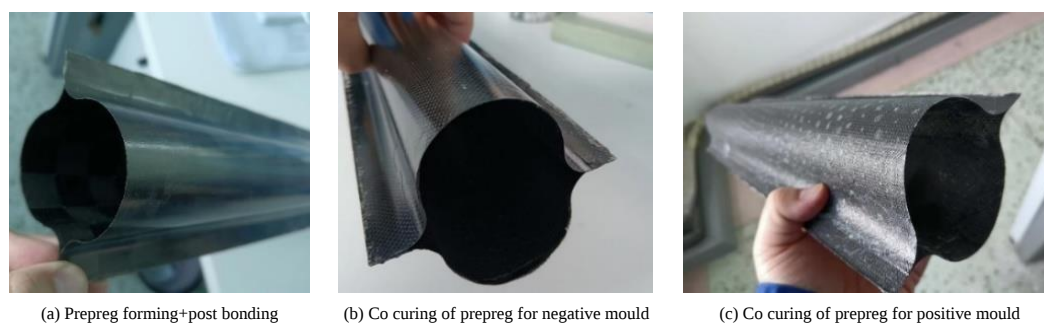


Figure 6. Schematic diagram of three different processes for double omega cross-section thin-walled boom fabricated.

4. Results and Discussion

Figure 6 shows three structural components fabricated by three processes, looking from the appearance, there are no obvious differences.

However the mechanical properties of carbon fiber structural component fabricated by "Co curing of prepreg for positive mould" is superior to those fabricated by the other two processes. The structural components fabricated by "Prepreg forming+Post bonding", "Co curing of prepreg for negative mould" processes have high curling stiffness. During the curling, the cross-sections of them display quasi-circular. Micro cracks first appear in the bonding area, and the cracks propagate and brittle fracture occurs. The structural components can be curled even once. Compared with the structural components fabricated by "co curing of positive mould prepreg" process, have low curling stiffness. During the curling, the cross-sections of them display circular, there were no microcracks in the entire structural area. They can be curled multiple times and display good fatigue performance, as shown in the following Figure 7.

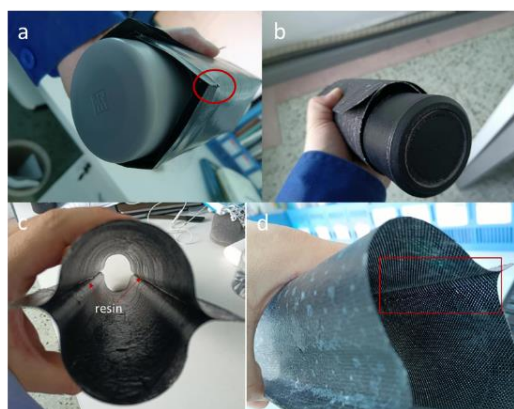


Figure 7. (a) Cracks occur in components fabricated by "Prepreg forming+ Post bonding " and "Co curing of prepreg for negative mould" while curling. (b) Curled component fabricated by "co curing of positive mould prepreg".(c) Resin rod occur inside the components fabricated by "Prepreg forming+ Post bonding " and "Co curing of prepreg for negative mould" along the bonding transition area (d) No resin rod occur inside the components fabricated by Co curing of prepreg for positive mould".

First, Inner shell and outer shell were fabricated at the beginning of "Prepreg forming+Post bonding", and then the two shells were bonded to form double omega carbon fiber thin-walled booms. Due to the pre curing of the inner shell and outer shell, the local stiffness of the bonding area is high. The bonding area of the inner shell and outer shell have poor adhesion with the core mould, resulting in forming gaps and adhesive columns easily. Additionally, the resin system of the prepreg is different from that of the adhesive, which can easily cause stiffness discontinuity of the component.

The structural components fabricated by "Co curing of prepreg for negative mould" are similar to those fabricated by "Prepreg forming+Post bonding". There is resin in the transition area of the inner shell and outer shell bonded, forming adhesive columns on the inner wall that cannot be completely removed, causing a sudden change in local stiffness. During the curling process, the local stress level exceeds the allowable stress of the material, resulting in cracks until failure.

As for "Co curing of prepreg for positive mould", a metal core mould is used to occupy the bonding transition area between the inner shell and the outer shell. Under the condition of prepreg state, inner shell and outer shell are fully bonded to the core mould without any gaps, preventing the resin in the cured layer from flowing into the bonding transition area between inner shell and outer shell, and no adhesive column is formed. There is no sudden change in stiffness and no cracks and abnormal sounds during curling, as shown in the following Figure 8.

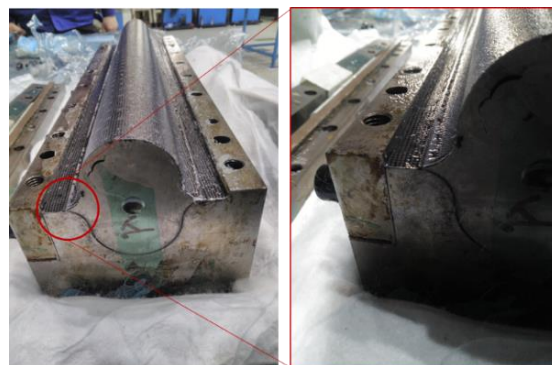


Figure 8. Close-up for inner shell and outer shell bonded during "co curing of positive mould prepreg".

In summary, the structural components fabricated by "Co curing of prepreg for positive mould" have good mechanical and curling performance.

5. Conclusion

- 1) Assuming that the arc length H remains constant and $R_{i1,2}=R_{o1,2}$, subtended angle increases, while the cross-sectional moment of inertia I_x gradually increases, I_y increases firstly and then decreases. As R_{i1} & R_{o1} increase and R_{i2} & R_{o2} decrease, the cross-sectional moments of inertia I_x and I_y gradually increase.
- 2) The mechanical properties of carbon fiber structural component fabricated by "Co curing of prepreg for positive mould" is superior to those fabricated by "Prepreg forming+Post bonding" and "Co curing of prepreg for negative mould".
- 3) Subsequently, curling experiments and researches will be conducted on the structural components fabricated by "co curing of positive mould".

Abbreviations

PVBT	Prepreg Vacuum Bagging Technique
PPD	Prepreg Forming+ Post Bonding
CPNM	Co Curing of Prepreg for Negative Mould
CPPM	Co Curing of Prepreg for Positive Mould

Author Contributions

Fanyi Meng: Data curation, Project administration, Validation, Writing – original draft, Writing – review & editing

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Conflicts of Interest

No potential competing interest was reported by the authors.

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