Load-Carrying Capacity of AFP-Manufactured Hybrid Aluminum/Thermoplastic Composite Tubes under Bending

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1. Abstract

Hybrid aluminum/thermoplastic composite tubes manufactured by automated fiber placement (AFP) are promising lightweight tubular structures for bending-dominated applications such as helicopter ski-landing gear. However, their load-carrying capacity is strongly influenced by the aluminum-composite interface, where limited bonding and interfacial looseness can reduce stress transfer. This study evaluates the quasi-static four-point bending response of an AFP-manufactured hybrid aluminum/PEEK composite tube. A glass/PEEK interfacial layer and adjusted AFP deposition conditions were used to improve interface interaction and reduce looseness caused by thermal-expansion mismatch. The experimental force-displacement response was compared with finite element predictions using full-bonding and no-bonding interface conditions as upper and lower bounds. The measured response fell between these limits, indicating improved load transfer compared with the no-bonding case, but still below the ideal fully bonded condition. Finite element damage predictions further showed that compressive damage was concentrated in the low-angle load-bearing plies, particularly the ±20° sub-laminate. These results indicate that the bending load-carrying capacity is controlled by both interface bonding condition and compressive damage development in the angled composite plies.

2. Introduction

Tubular composite structures are widely used in lightweight engineering applications. Their bending behavior has been studied through analytical, numerical, and experimental approaches, including works on orthotropic tube analysis, flexural stiffness prediction, and the effect of lay-up configuration on structural response [1–5]. For helicopter ski-landing gear, the cross-piece is subjected to severe bending loads; therefore, high load-carrying capacity and a stable force–displacement response are key design requirements.

Hybrid aluminum/composite tubes have been investigated as a way to combine the ductility and damage tolerance of aluminum with the stiffness and strength of composite overwraps. Previous studies on aluminum/CFRP and other hybrid tube configurations have shown that hybridization can improve load-carrying capacity, crashworthiness, and energy absorption [6–8]. However, in aluminum/thermoplastic composite tubes manufactured by automated fiber placement (AFP), the interface between the aluminum liner and the PEEK-based composite overwrap is especially important because strong bonding does not naturally form during processing. Interfacial gaps or looseness can reduce load transfer between the liner and the composite, leading to lower stiffness and peak load under bending.

This study investigates the load-carrying capacity of an AFP-manufactured hybrid aluminum/PEEK composite tube under four-point bending. A glass/PEEK layer is introduced at the aluminum-composite interface to improve interfacial interaction and avoid direct carbon–aluminum contact. The experimental force-displacement response is compared with finite element modeling (FEM) predictions for fully bonded and no-bond interface conditions to assess the influence of the achieved interface condition on bending stiffness, maximum load, and overall load-carrying performance.

3. Experiment Methods

3.1. Manufacturing

The hybrid aluminum/thermoplastic composite tubes were manufactured using AFP process. In this case, the aluminum tube served both as the structural inner tube in the final hybrid tube and as the mandrel during composite tape deposition. As shown in Figure 1(a), the aluminum mandrel was mounted on the rotating mandrel system of the AFP machine. Thermoplastic composite tape was then placed directly onto the aluminum surface at the prescribed fiber orientations, as shown in Figure 1(b). For each ply, complete surface coverage was achieved by depositing multiple bands around the tube. The number of bands required to complete each ply depended on the layup angle; lower fiber angles required more bands, whereas higher angles approaching the hoop direction required fewer bands.

Because the AFP process does not inherently create a bond between the thermoplastic composite and the aluminum mandrel, minimizing interfacial gaps and looseness was essential for preserving contact and promoting load transfer in the hybrid tube. One of the main manufacturing challenges was the mismatch in coefficient of thermal expansion between the aluminum mandrel and the thermoplastic composite overwrap. During heating, the aluminum mandrel expands more than the composite, improving contact during deposition; however, during cooling, its greater contraction can reduce the interfacial fit and lead to relative movement between the mandrel and the first deposited composite layers, especially in the initial hoop-oriented plies. To mitigate this issue, a staged AFP deposition schedule was adopted, as summarized in Table 1. Lower heat input and compaction force were used for the initial layers, followed by higher processing conditions for the remaining laminate. Compressed air cooling was also applied ahead of the torch during deposition of the first four layers to limit heat transfer to the aluminum mandrel and improve dimensional stability during manufacturing. The hybrid aluminum/PEEK composite tube tested in this study had the lay-up sequence

$[\text{Aluminum}/90°_{\text{Glass-PEEK}}\ /90°_{\text{Carbon-PEEK}}\ /(\pm 20°)_5/90°_2/(\pm 30°)_4/90°_2/(\pm 45°)_4]$.

It should be noted that a glass/PEEK layer was introduced between the aluminum mandrel and the carbon/PEEK laminate as the first composite layer. This interfacial glass layer was used to reduce the likelihood of interfacial gaps or looseness reported previously [9], while also acting as an insulating interfacial layer between the carbon fibers and aluminum, thereby reducing the risk of galvanic corrosion. The overall tube geometry, including the aluminum mandrel and composite overwrap dimensions, is shown in Figure 2.

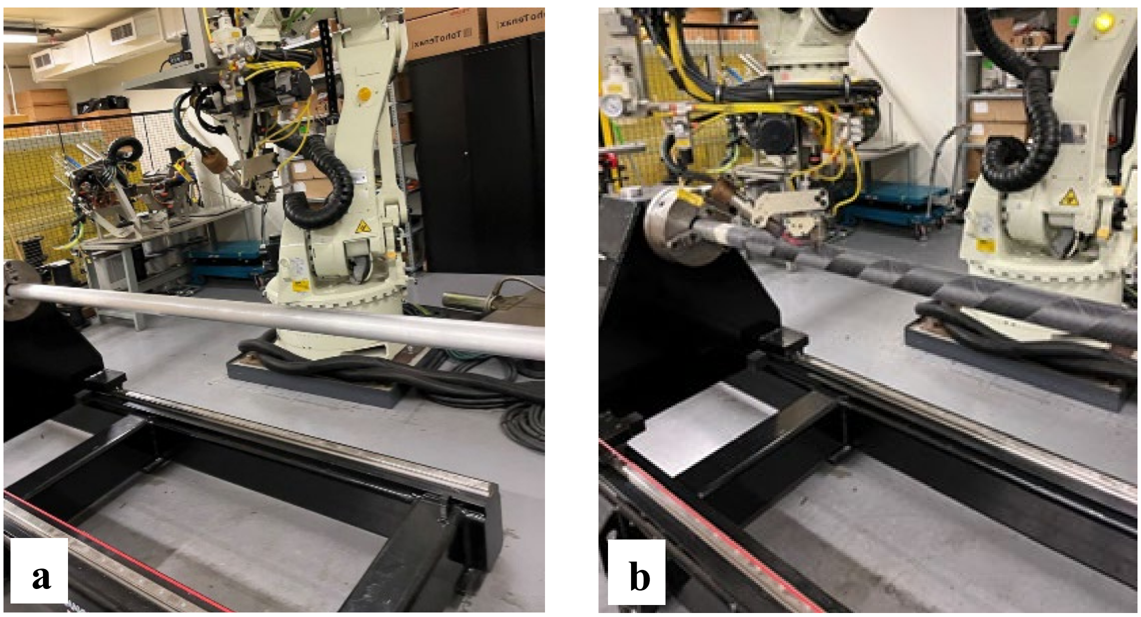

Figure 1. AFP manufacturing of hybrid aluminum/thermoplastic composite tubes: (a) aluminum tube mounted on the AFP system and used as the mandrel; (b) thermoplastic composite tape deposition over the aluminum tube during hybrid tube manufacturing.

Table 1. AFP processing parameters used for manufacturing the hybrid aluminum/thermoplastic composite tubes.

Layer(s)	Torch temperature (°C)	Compaction force (lbf)	Nitrogen flow rate (SLPM)
1	650	30	60
2	800	30	60
3	875	40	60
4–32	875	60	80

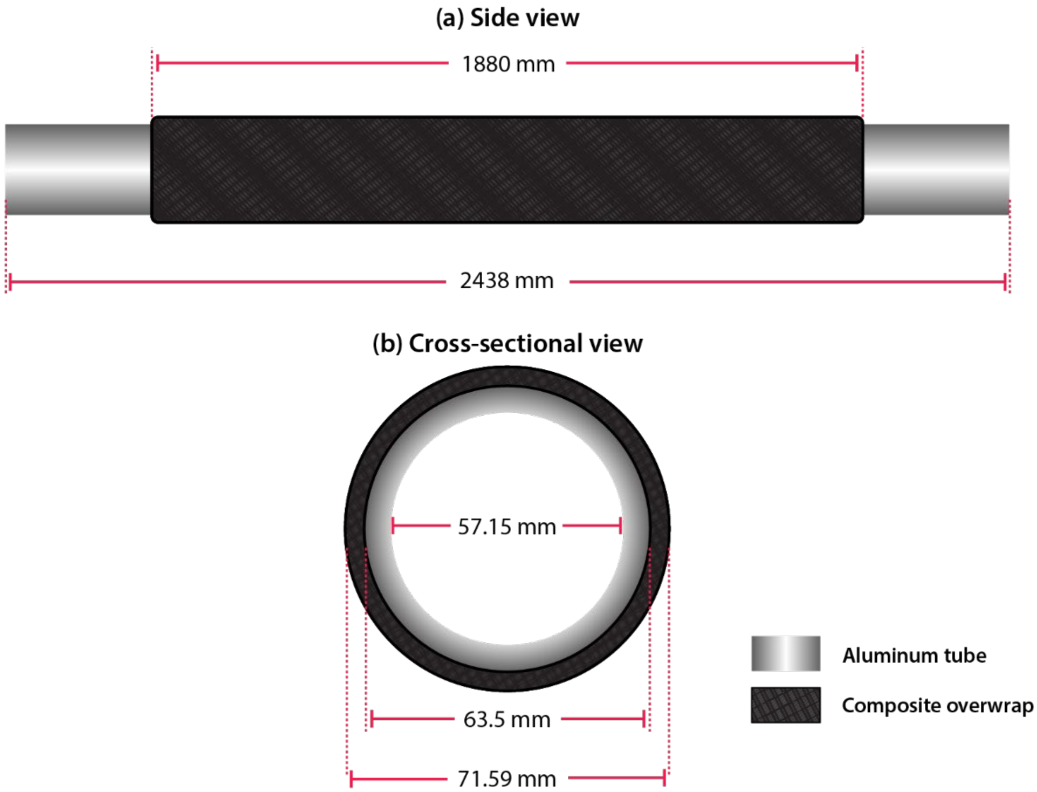

Figure 2. Dimensions of the hybrid tube.

3.2. Four-point bending test

The load-carrying capacity of the hybrid aluminum/thermoplastic composite tubes was evaluated using a four-point bending test. Fiber glass/epoxy pads were bonded to the tube at the loading and support locations to reduce local stress concentration and contact damage during testing. The specimen was positioned symmetrically in a custom four-point bending fixture mounted on a servo-hydraulic test frame. The test configuration is shown in Figure 3. The tests were performed under quasi-static displacement control at a crosshead rate of 6 mm/min, while the applied load and displacement were continuously recorded to obtain the load–displacement response.

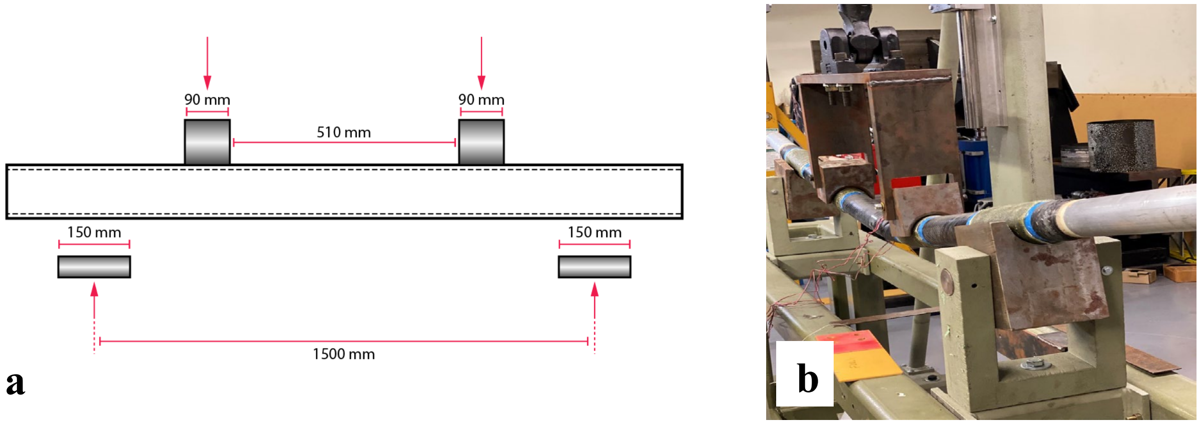

Figure 3. Four-point bending test configuration: (a) schematic of the loading and support arrangement for the tube (b) experimental setup used for testing the hybrid aluminum/thermoplastic composite tube.

4. Numerical simulation

FEM was developed to reproduce the four-point bending test and to evaluate the sensitivity of the hybrid tube load-carrying capacity to the aluminum-composite interface condition. Based on a previous study showing the strong influence of interfacial gaps and bonding quality on the bending response of hybrid aluminum/thermoplastic composite tubes, two limiting interface conditions were considered in this work: full bonding and no bonding. These two cases were used to provide upper and lower numerical bounds for the structural response. In the full-bonding case, the aluminum tube and composite overwrap were assumed to be perfectly connected at the interface, preventing relative displacement between the two materials. In the no-bonding case, the interface was modeled as a contact-only condition, where no adhesive or cohesive traction was transferred and relative sliding/separation between the aluminum tube and the composite overwrap was allowed. For the no-bond interface condition, contact with a Coulomb friction coefficient of 0.2 was used, consistent with the interface modeling strategy adopted from the previously developed and validated numerical framework [9].

The aluminum tube was modeled using elastoplastic behavior with a von Mises yield criterion, while the composite plies were modeled as orthotropic laminae with their prescribed fiber orientations. The experimental four-point bending configuration was reproduced numerically by applying support and loading regions consistent with the test setup. A quasi-static displacement-controlled analysis was performed, and the predicted load–displacement response was extracted for comparison with the experimental results. Composite damage was evaluated using the Puck failure criterion to identify the critical ply groups and damage-prone regions under bending. The present model used the same geometry, meshing strategy, material definitions, and loading/support regions as the validated framework, while the damage evaluation was performed using the Puck criterion. The hybrid tube was modeled with 20-node solid elements. The mesh used 643 axial divisions, 60 circumferential divisions, and one through-thickness element for the aluminum tube and for each of the 32 composite plies, resulting in 1,273,140 elements. This discretization followed the validated mesh strategy reported in [9].

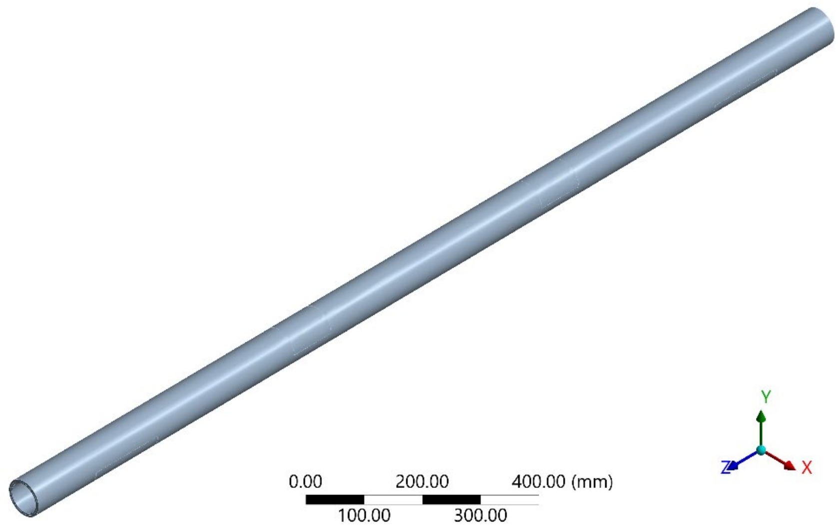

Figure 4. Finite-element model of the hybrid aluminum/thermoplastic composite tube under four-point bending.

5. Results and discussion

5.1. Load-Carrying Capacity: Experimental and FEM Comparison

Figure 5 compares the experimental load-displacement response of the AFP-manufactured hybrid aluminum/thermoplastic composite tube [9] with finite-element predictions obtained using the Puck failure criterion for two limiting interfacial conditions: full bonding and no bonding. These simulations provide upper and lower bounds for the load-carrying capacity of the hybrid tube under bending. The fully bonded model predicted the highest stiffness and maximum load because of more effective stress transfer between the aluminum and the composite overwrap, whereas the no-bonding model showed a reduced bending capacity due to limited interfacial load transfer. The experimental curve falls between these two numerical limits, indicating that the manufactured tube achieved improved load-carrying capacity compared with the no-bonding case. This improvement can be attributed to the manufacturing strategy, including the use of a glass-based interfacial layer and the modified AFP deposition conditions, which were intended to enhance contact stability and reduce interfacial looseness during processing. However, the experimental maximum load remained below the full-bonding prediction, suggesting that the interface did not reach an ideal continuous bond. Therefore, the measured bending response suggests enhanced load transfer at the aluminum-composite interface relative to the no-bonding condition, while residual interfacial imperfections still limit the load-carrying capacity.

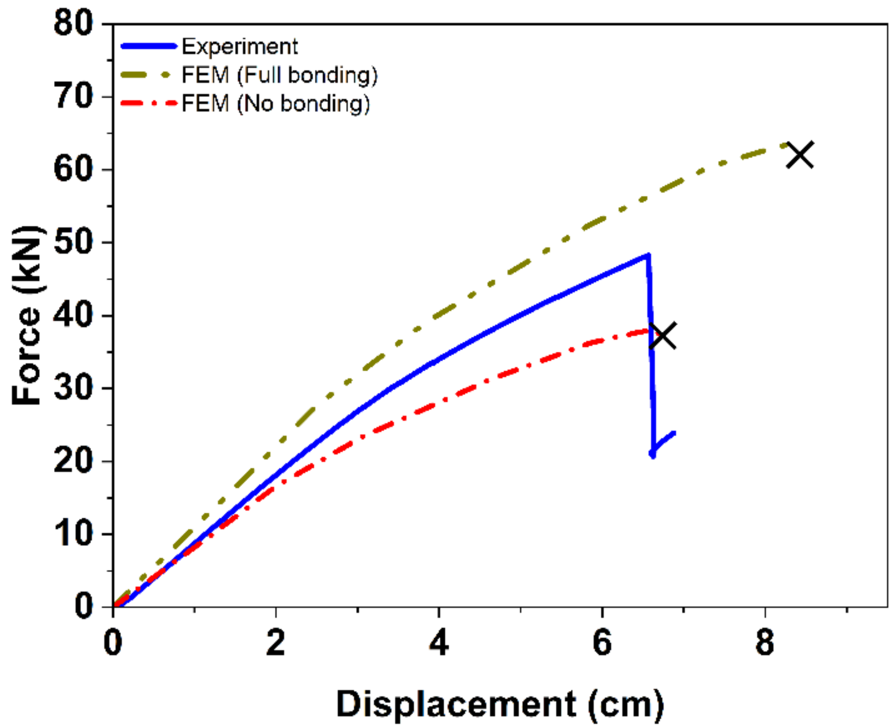

Figure 5. Experimental and numerical load-displacement responses of the hybrid aluminum/thermoplastic composite tube under four-point bending, comparing full-bonding and no-bonding interfacial conditions using the Puck failure criterion.

5.2. FEM Damage-Status Prediction

Figure 6 shows the FEM-predicted damage-status distribution in different composite ply groups under four-point bending. The damage is mainly concentrated on the compressive side of the tube within the constant high-moment region, where the maximum bending stresses are expected. The most severe damage is predicted in the low-angle load-bearing plies, particularly the ±20° and ±30° layers, as shown in Figures 6(a) and 6(b). These plies are more aligned with the tube axis and therefore contribute significantly to carrying the bending-induced axial compressive stresses. As a result, damage development in these low-angle plies directly affects the load-carrying capacity of the hybrid tube.

In contrast, the ±45° plies show a smaller and more localized damaged region, Figure 6(c), indicating a lower contribution to the dominant compressive bending failure compared with the ±20° and ±30° ply groups. The 90° hoop plies remain largely undamaged, Figure 6(d), suggesting that the hoop-oriented layers are not the primary limiting plies under this bending condition. Overall, the FEM results indicate that the bending load-carrying capacity of the hybrid tube is mainly controlled by compressive damage development in the low-angle composite plies, especially the ±20° and ±30° sub-laminates, rather than by the hoop-oriented layers.

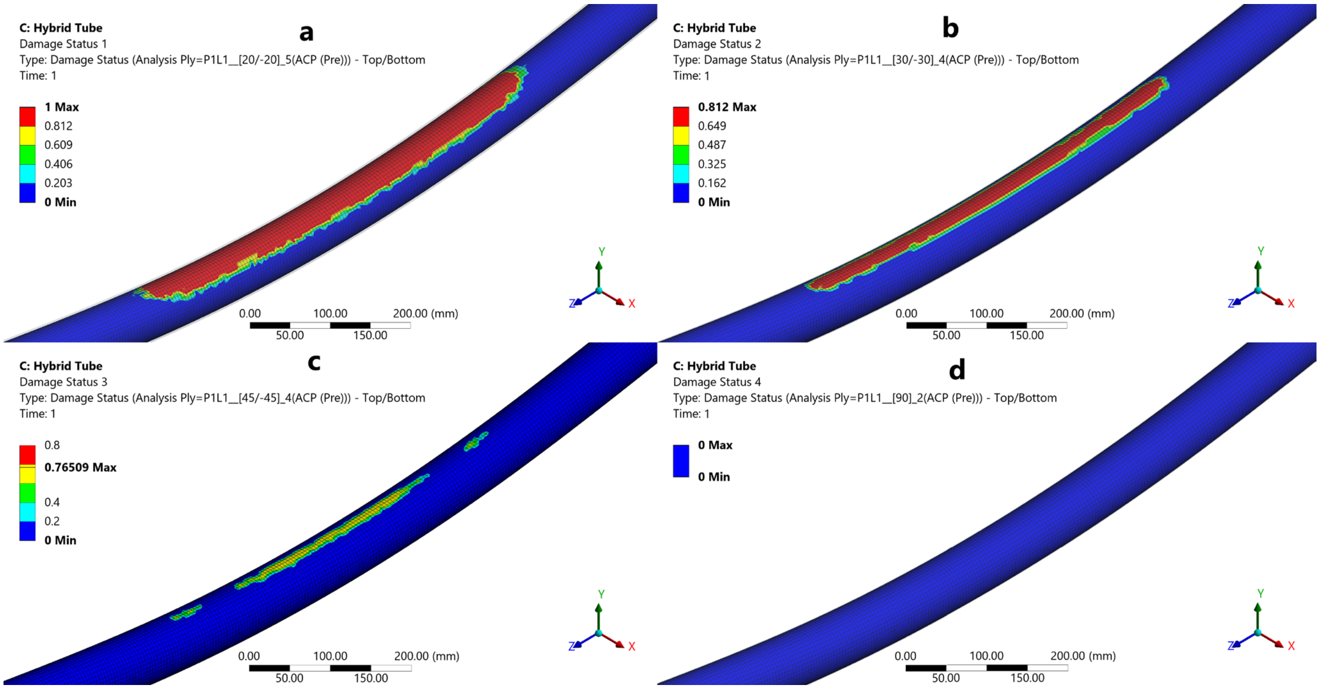

Figure 6. FEM damage-status predictions for different ply groups of the hybrid aluminum/thermoplastic composite tube under four-point bending: (a) ±20° plies, (b) ±30° plies, (c) ±45° plies, and (d) 90° hoop plies

6. Conclusions

The load-carrying capacity of an AFP-manufactured hybrid aluminum/PEEK composite tube was investigated under quasi-static four-point bending. A glass/PEEK interfacial layer and adjusted AFP deposition conditions were used to improve interaction between the aluminum and composite tubes and to reduce interfacial looseness associated with thermal-expansion mismatch during manufacturing.

The experimental force-displacement diagram showed higher load-carrying capacity than the no-bonding numerical case, indicating improved load transfer at the aluminum-composite interface. However, the experimental maximum load remained below the full-bonding prediction, showing that the manufactured tube did not reach the ideal fully bonded condition. Therefore, the measured response suggests enhanced interfacial interaction relative to the no-bonding case, while residual interfacial imperfections still limited the load-carrying capacity.

The FEM damage-status predictions showed that damage was mainly concentrated on the compressive side of the tube within the high-moment region. The most severe damage occurred in the low-angle load-bearing plies, particularly the ±20° and ±30° sub-laminates, while the 90° hoop layer remained largely undamaged. Overall, the results indicate that the bending load-carrying capacity of hybrid aluminum/thermoplastic composite tubes is governed by both the aluminum-composite interface condition and compressive damage development in the low-angle composite plies.

7. References

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