

Design, Testing and Validation of a Cost Effective and Sustainable Bamboo Prosthetic Foot

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Abstract

This study proposes an approach to design and develop a prosthetic foot using bamboo laminate, a sustainable and cost-effective material. The proposed design method is an alternative to the current prosthetic foot design methods developed mainly for carbon-fiber reinforced polymer. This design solution entails significant economic and environmental costs. The research is structured into three main phases: an experimental campaign to characterize the reference prosthesis and select materials for the prototype; a dimensional design and prototyping phase using the new materials; and finally, a phase dedicated to testing and comparative evaluation of the results. Static tests, conducted in accordance with ISO 22675 on both the bamboo prototype and a commercial reference model, revealed comparable static performance between the two solutions. The laminated bamboo prosthetic foot exhibits a strength-to-weight ratio comparable to that of carbon fiber laminates. Its stiffness deviates by less than 15%, with an 8% reduction in weight and a 7% increase in volume compared to the carbon fiber counterpart. Therefore, these results confirm the feasibility of laminated bamboo as a viable material for prosthetic foot design.

Keywords: prosthetic foot; sustainable; bamboo; design; testing



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1. Introduction

A prosthesis is an artificial device designed to replace a missing body part—such as a limb, organ, or tissue—or to support and integrate a damaged one [1]. The prosthetic foot belongs to the category of orthopedic prostheses and plays a critical role, as it serves as the primary interface between the amputee and the ground [2]. For this reason, it must ensure reliability, stability, durability, and adequate biomechanical functionality.

A wide variety of prosthetic foot models are available on the market to meet diverse user needs and to accommodate different lifestyles. Some designs prioritize stability and lightweight construction for elderly users [3], while others are tailored to younger, more active individuals who require greater responsiveness and dynamic movement capabilities.

Based on these functional demands, commercially available prosthetic feet can be broadly categorized into three main groups: active, quasi-passive, and passive devices [4]. These classifications are based on variations in intended use, user morphology, mobility levels, and age [5].

A relevant subclass of passive prostheses is represented by Energy Storage and Return (ESAR) devices. These prosthetic systems are designed to store elastic energy during the

loading phase of gait, through controlled deformation of their geometry and/or flexible components [6]. During the unloading phase, the prosthesis recovers its original shape, releasing the stored energy and thereby actively contributing to the propulsion of the user's gait [7]. Compared to other design approaches, the ESAR concept provides a longer roll-over shape (RoS) in the forefoot region. This extended rocker behavior can reduce the "drop-off" effect of the prosthesis and result in lower loading on the sound limb [8].

Carbon fiber-reinforced polymer (CFRP) composites currently represent the primary material used in the fabrication of prosthetic feet [9], owing to their high strength-to-weight ratio, which ensures both structural integrity and long-term durability [10]. However, despite their excellent mechanical performance, carbon laminates present significant limitations in terms of both economic cost and environmental impact. The price of a commercially available CFRP-based prosthetic foot typically ranges from \$7000 to \$12,000, and even under moderate activity levels and proper maintenance, replacement is often required every 3–5 years [11]. Environmentally, CFRP is non-recyclable, and its manufacturing process is characterized by high energy consumption and substantial emissions, contributing to a considerable ecological footprint [12].

In response to these drawbacks, the present study aims to develop a prosthetic foot with mechanical properties comparable to those of existing ESAR devices on the market but utilizing a more sustainable material alternative. Various studies in the literature have explored the use of polymer-based materials combined with different manufacturing methods, such as injection molding [13–17], and have investigated alternative prosthetic geometries. While these approaches have generally resulted in lower-cost solutions, achieving sufficient mechanical performance often required a significant increase in the prosthesis thickness, leading to greater overall dimensions and weight [18,19].

In this project, laminated bamboo was selected as a sustainable alternative material due to its ability to withstand high mechanical loads, its suitability for shaping into complex forms, its low production cost, and its environmental compatibility [20]. Bamboo, in both raw and laminated forms, is widely available worldwide and commonly used in the construction industry [21], making it an accessible and cost-effective resource. The main advantage of bamboo over CFRP composites, in addition to its lower cost, lies in its nature as a natural, renewable, and biodegradable material, which results in a significantly reduced environmental impact throughout its lifecycle [22].

The main objective of this study is to evaluate the feasibility of using laminated bamboo in the design and fabrication of a functional, cost-effective, and environmentally friendly prosthetic foot. This solution could provide a viable alternative to current prostheses made from high-impact synthetic composites [23], considering the comparable strength-to-weight ratio of bamboo laminates ($18\text{--}25\text{ GPa}\cdot\text{cm}^3/\text{g}$) [24] and carbon fiber composites ($35\text{--}55\text{ GPa}\cdot\text{cm}^3/\text{g}$) [10].

However, the greater susceptibility of bamboo to weathering compared to carbon fiber must be considered, a factor that limits the service life of the device; without specific treatments, this could be reduced to approximately 15 months [25].

For the fabrication of the prosthesis, it will be necessary to obtain bamboo laminate panels, which will then be carefully bent and glued in a controlled manner to achieve a geometry as close as possible to that of the reference models. This process allows the mechanical properties of the material to be effectively exploited, including static bending strength of $96\text{--}130\text{ MPa}$, a modulus of elasticity (MOE) of $8\text{--}13\text{ GPa}$, and impact bending strength of $20\text{--}30\text{ kJ/m}^2$ [24,25], while maintaining a structural configuration capable of meeting the functional requirements of the prosthetic device.

2. Materials and Methods

2.1. Commercial Reference Model

In the present study, one of the most widely used prosthetic devices, the Vari-Flex model [26] (Figure 1) in its standard configuration, was employed as commercial performance reference model. This prosthetic foot is commonly utilized in the orthotic and prosthetic field due to its versatility, which allows application across a broad range of patients with varying ages and activity levels.



Figure 1. Vari-Flex® reference prosthetic foot made by Össur [23].

According to the manufacturer, the Vari-Flex design is intended to enable natural foot flexion during ground contact, facilitating physiological limb progression while reducing the muscular effort required by the user. The carbon fiber construction contributes to efficient energy management by absorbing impact forces through its elastic properties and partially returning energy during the gait cycle, which improves user comfort and reduces muscle fatigue.

2.2. Bamboo Laminate

The conventional use of bamboo is often constrained by its natural morphology, which limits its application primarily to flat or linear components [27]. However, due to its inherent flexibility, bamboo demonstrates considerable potential for the fabrication of curved elements through bending-based forming techniques [28]. The mechanical properties of bamboo can vary significantly depending on the species and material thickness [22–32]. In this study, 3 mm thick Moso bamboo panels were employed, and their mechanical characteristics are detailed in Table 1.

Table 1. Mechanical properties of the Moso bamboo laminate in the longitudinal (||) and transversal (⊥) directions to the material orientation.

Tensile Modulus	Tensile Modulus ⊥	Flexural Modulus
8.8 GPa	85 GPa	14.8 GPa

2.3. Epoxy Resin DP490 Adhesive

The two-component epoxy adhesive 3M™ Scotch-Weld™ DP490 was used for bonding the curved bamboo layers due to its high-performance structural properties. It provides high tensile and shear strength [33] and an elastic modulus optimal for the ESAR design [34], offering a balanced response that is neither excessively rigid nor overly compliant. This mechanical profile ensures effective load transfer while allowing for slight deformations, making it particularly well-suited for natural materials such as bamboo. Furthermore, its

strong adhesion to fibrous substrates contributes to the long-term stability of the bonded joint. The interaction between the resin and bamboo was investigated to determine the optimal combination that ensures a functional and durable prosthesis [35].

2.4. Prosthetic Testing Setup

In order to investigate the behavior of the reference prosthetic foot under static loads, compression tests were conducted across five distinct gait cycle configurations.

The testing procedures followed the guidelines provided in EN ISO 22675 (2024) [36] and EN ISO 10326 (2016) [37].

These configurations were selected to simulate the key phases of the gait cycle and included: two positions in which only the heel contacts the ground, with inclinations of -15° and -7.5° , respectively; one position in which both heel and toe are in contact with the ground, with the foot held horizontally except for a 6 mm heel lift; and two positions in which only the toe is in contact, with inclinations of 10° and 20° , respectively, as illustrated in Figure 2.

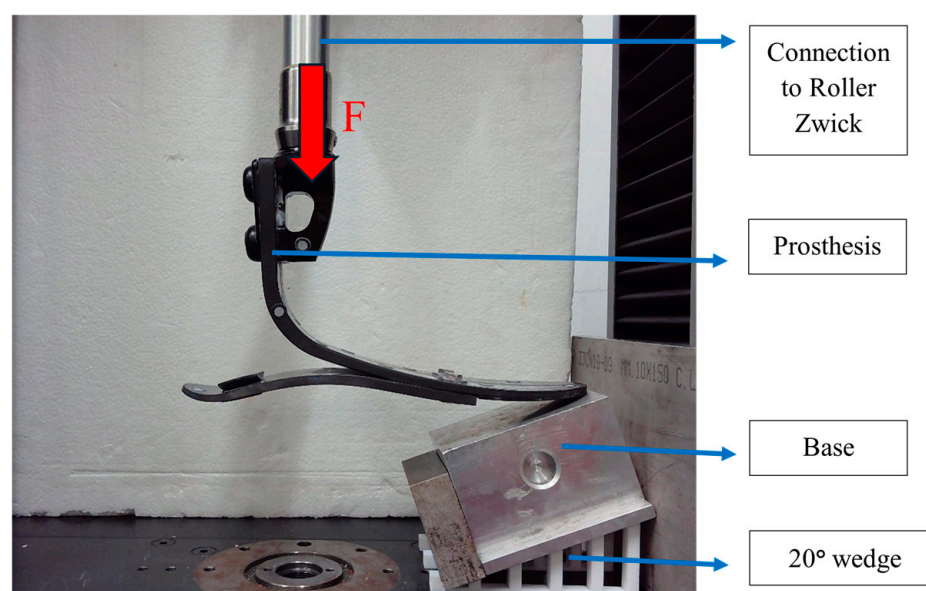


Figure 2. Experimental setup for prosthetic test in 20° configuration.

In accordance with the used standards, a compressive load of 1173 N—corresponding to the force required to characterize the rollover shape—was applied at a displacement rate of 100 mm/min. This standardized force does not cause any damage to the prosthesis; it is applied solely to observe its elastic behavior. All tests were performed using a Zwick ProLine Z010 TN universal testing machine (Zwick, Ulm, Germany).

To achieve the specific inclinations required for each gait phase configuration, custom wedges were designed and fabricated, specifically engineered to prevent deformation under the applied load. These wedges were placed beneath the prosthetic support surface to maintain the appropriate angular orientation during testing.

Following the procedures outlined above, the bamboo prototype was subjected to experimental testing to evaluate its mechanical performance (Figure 3). The tests loading rate was set to 100 mm/min and the maximum target force was 302 N. This force value was selected to reflect the reduced width of the tested prototype, which corresponds to one-quarter of the final design. Consequently, the applied load was scaled proportionally to one-quarter of the original testing force (1173 N). The same wedges previously used were employed to achieve the required inclinations.

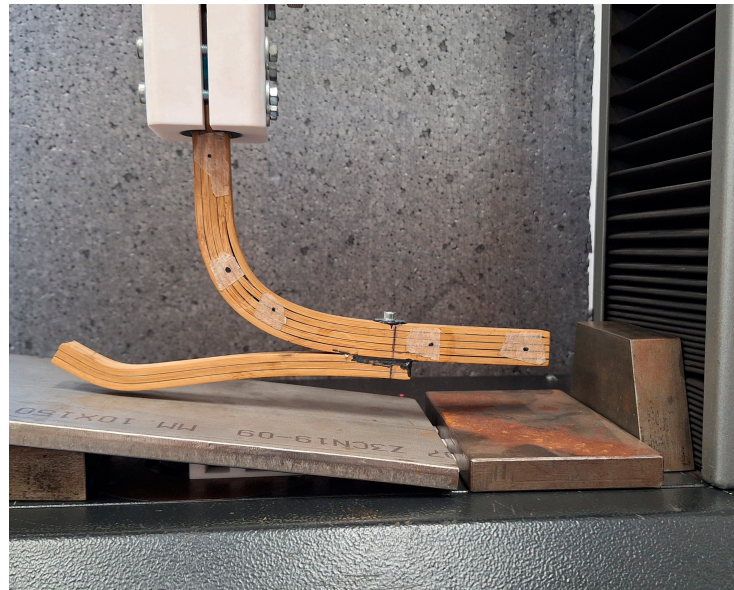


Figure 3. Experimental setup for the bamboo laminate prototype test in -15° configuration.

2.5. Bamboo Laminate Prosthetic Foot Design Method

The objective of this proposed design method is to develop a virtual model of a prosthetic foot made from bamboo laminate, with mechanical properties equivalent to those of the commercial Vari-Flex model.

This phase consists of three main steps. First, a parametric geometry is developed in Software CAD Creo 9.0 from PTC, enabling efficient control of the main design variables. This geometry is then implemented in Ansys Workbench to generate the finite element model, including the boundary conditions consistent with the experimental test setup. Finally, an optimization stage is carried out to adjust the geometry so that the mechanical response of the structure closely reproduces that of the reference prosthesis.

The initial step focus on the design of the two main components of the prosthetic foot: the keel and the sole (Figure 4a,b). For both components, a “sweep” modeling technique was employed, where in a constant cross-sectional profile is extruded along a predefined longitudinal path.

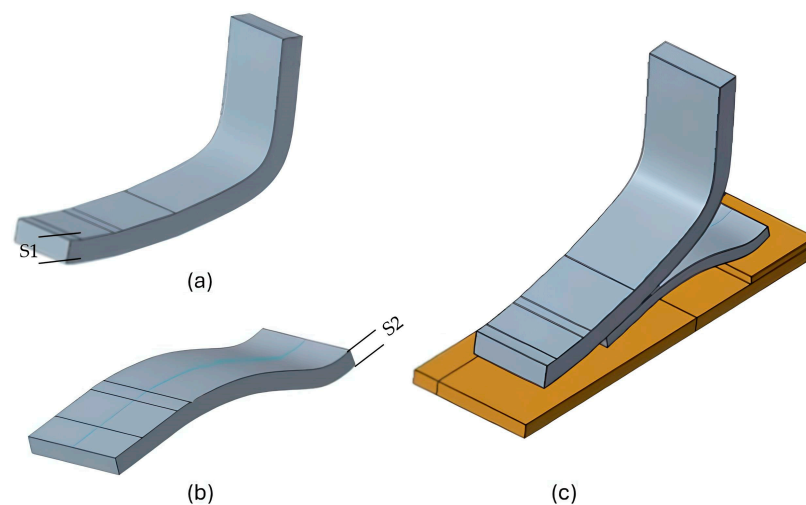


Figure 4. Three-dimensional CAD models of the keel (a), the sole (b), and the assembled prosthetic foot (c), including the support structure. Thicknesses are indicated as $s_1 = 17$ mm (keel) and $s_2 = 10$ mm (sole).

The constant cross-section represents a simplification with respect to the reference geometry, which exhibits a contoured shape. Is it also worth noting that the proposed keel is represented as a single blade rather than the dual-blade configuration found in the reference Vari-Flex design. This modeling choices are made to ease the fabrication process using bamboo laminate panels. In the obtained geometries, thickness was defined as the variable parameter for the optimization integrated in the FEM tools, while the width was kept constant at 60 mm. This decision was driven by two primary considerations: first, variations in width have a limited effect on the overall stiffness of the prosthetic foot unless the increase is substantial; second, maintaining a compact lateral profile is essential to ensure compatibility with standard prosthetic covers and commercial footwear. A significant increase in width would have compromised this requirement. The curvature profile is derived from the reference geometry and is kept constant throughout the simulation, in order to avoid affecting the vertical envelope and to simplify the optimization process.

The prosthetic components were assembled into a complete model by applying a tangency constraint between the sole and the keel, along with longitudinal and transverse alignment constraints based on the dimensions of the physical prototype (Figure 4c). The support plane is constrained to allow the correct inclination of the foot in the five test configurations.

The CAD model was imported in Ansys Workbench and discretized using a mesh of 2 mm elements size after the convergence tests and SOLID186 elements. The material is modeled using a linear elastic orthotropic model and the values are obtained from the bamboo characterization and from a literature review. The local reference systems of the elements were oriented along the bamboo fiber direction to correctly model the bamboo laminate material orthotropy, as shown in Figure 5.

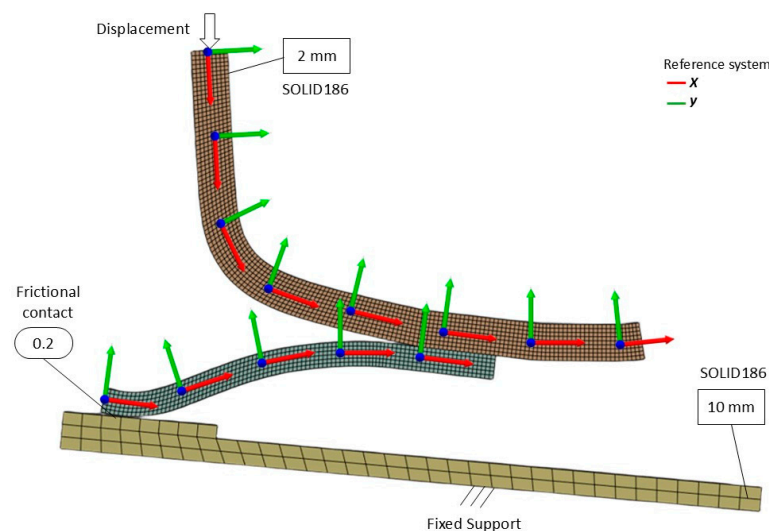


Figure 5. Mesh details of the FEM models, orientation of the elements' local reference systems and boundaries conditions.

The 'large deflection' option was enabled to account for geometrically nonlinear deformations. Finally, vertical displacement is applied to the upper part of the foot, while the support plane is constrained with a fixed boundary condition. The foot is allowed to slide on the plane through a frictional contact with a coefficient of 0.2.

Upon completion of the full models, varying the inclination of the plane according to the five configurations, the optimization phase was initiated. The objective was to evaluate the influence of keel and sole thickness on the structural response, both individually and in combination, followed by an integrated optimization phase.

The optimization process was carried out in Ansys Workbench by performing five static structural analyses, each representing one of the standard loading configurations used in the compression tests (see Section 2.4). From the experimental results, the displacement required to achieve a reaction force of 1173 N was determined for each configuration, in accordance with the regulatory requirements for rollover shape assessment (Table 2).

Table 2. Target for each configuration, derived from experimental tests on reference prosthesis.

Configuration angle	-15°	-7.5°	0°	10°	20°
Displacement [mm]	18	15	6	13.5	30
Force reaction [N]	1173	1173	1173	1173	1173

These displacements were subsequently applied as boundary conditions in the respective simulations. The keel and sole thicknesses were defined as input parameters, while the vertical reaction force was considered as the output parameter. In each optimization iteration, all configuration models shared the same thickness values, reducing the number of independent input variables to two. The optimization target was to obtain reaction forces equal to 1173 N across all five configurations, thereby ensuring consistency between the force–displacement curves from the experimental tests and the numerical models.

A response surface-based multi-objective optimization method was employed [38]. Figure 6 shows a representation of the optimization process scheme.

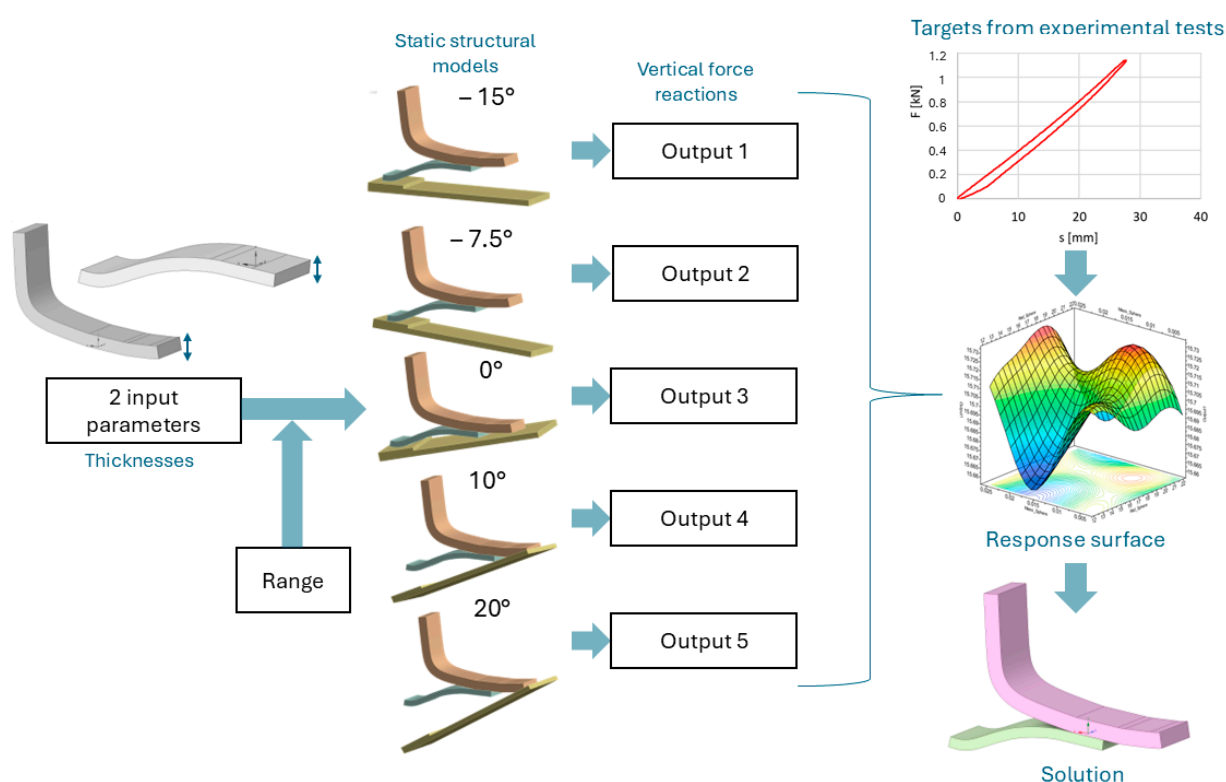


Figure 6. Optimization process scheme.

Based on the optimization outcomes, the final thickness values for both keel and sole components were identified. The optimal configuration corresponds to a sole thickness of 10 mm and a keel thickness of 17 mm. However, two key factors must be considered when translating these values into the actual prototype:

- The thickness of the adhesive resin layers, for a optimal adhesive performance it is suggested to design structural subcomponents using thin adhesive layers, approximately 0.2 mm.
- The thickness of the bamboo laminate panels, commercially available in few thicknesses

It is important to note that the calculated thickness refers exclusively to the bamboo material and does not account for the contribution of the adhesive resin. Depending on the number of layers, the resin may increase the total thickness of each component by approximately 1–2 mm.

2.6. Sole-Keel Hybrid Bonded-Bolted Joint

As shown in Figure 7, a stress distribution analysis was carried out for three different joint configurations: bolted joint, bonded joint, and hybrid bolted–bonded joint. The hybrid configuration was selected as the most suitable solution [39], as it does not induce critical stresses in the bamboo, either in compression (approximately 80 MPa) or in tension (approximately 4 MPa), thereby preserving the structural integrity of the material.

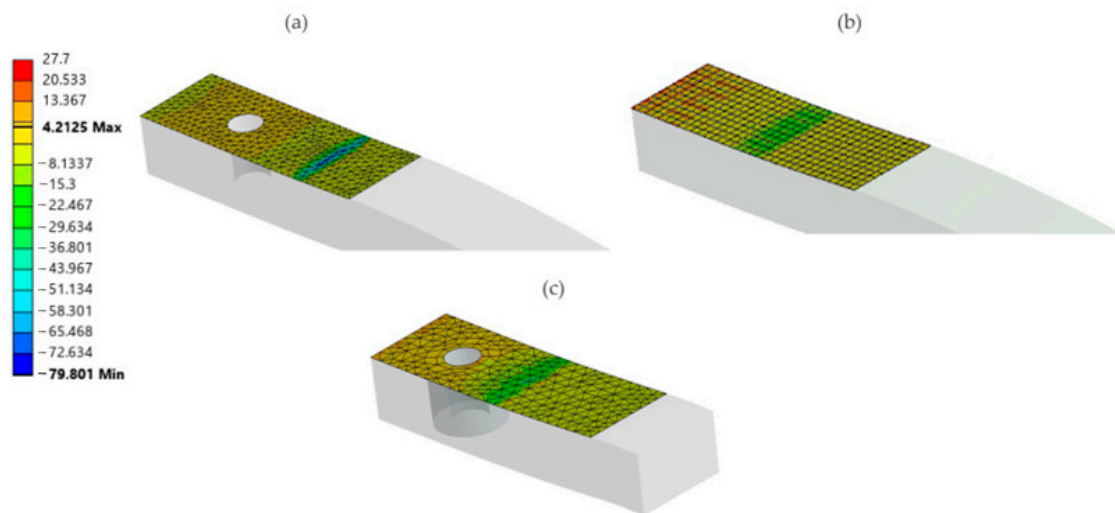


Figure 7. Analysis of mises stress distribution [MPa] in the bamboo interface layer for different joint configurations: bolted (a), bonded (b), and hybrid bonded-bolted joints (c).

In fact, if a purely bolted joint were employed, the clamping force required to prevent relative sliding of the two components would induce notching on the bamboo surface. Conversely, in the case of an adhesive-only joint, the normal stress would lead to delamination failure of the bamboo, as shown in Figure 8.



Figure 8. Detail of delamination failure of bamboo in an adhesive-only joint.

To address this issue, a 0.2 mm thick layer of DP490 adhesive was applied between the keel and the sole, with the aim of ensuring structural continuity between the two components and promoting a more uniform load distribution.

As illustrated in Figure 9, the bolting system consists of an M4 screw threaded into an insert nut, which is securely bonded to the sole using a layer of DP490 adhesive. The hole in the keel was drilled with a diameter larger than that of the screw shaft, to avoid shear load transfer to the screw and ensure that it operates purely under tensile loading.

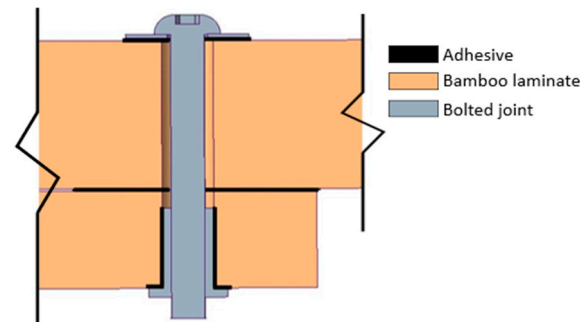


Figure 9. Hybrid joint using bolt and DP490 epoxy resin for high-strength structural bonding (not-to-scale thicknesses).

A steel washer is placed between the screw head and the surface of the keel; this washer is also bonded to the keel using DP490 adhesive. The use of adhesive in this area aims to prevent the washer from inducing localized stress concentrations and to prevent damage in the bamboo due to the bolt preload. A similar approach was adopted for the connection between the insert nut and the sole, to preserve the integrity of the material even in the presence of concentrated loads.

3. Prototype Fabrication

Upon completion of the materials characterization and bamboo laminate prosthetic foot design phases, the bamboo laminate prototype manufacturing process phase was carried out (Figure 10).

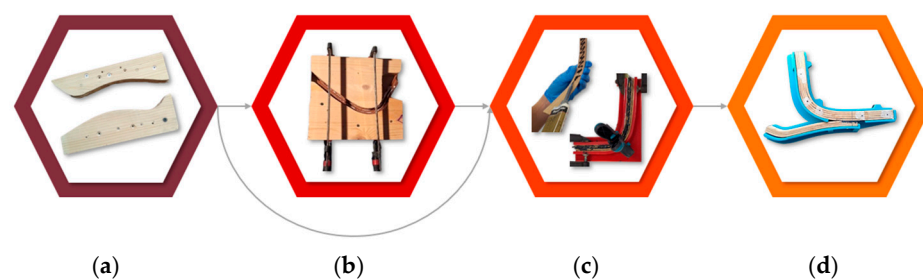


Figure 10. Manufacturing stages of the bamboo laminate prosthetic foot (reduced-scale model): (a) mold preparation, (b) bending process, (c) adhesive bonding, and (d) final polishing.

The initial step is the production of reduced-scale keel and sole components. These components retained the same thickness and length as the FEM optimized design, but featured a narrower width of 20 mm. This downscaling strategy was adopted to evaluate the bending and bonding techniques while easing the manufacturing process. Moreover, this approach limits the material waste in case of unsatisfactory results. For this purpose, bamboo strips with dimensions of $300 \times 20 \times 3.4$ mm were prepared.

This prototype is useful for an initial comparison, based on the resisting cross-section. In the future, it will be necessary to produce a prototype with the correct dimensions to avoid potential scaling effects.

To shape the sole and keel of the prosthetic foot, the bamboo panels were bent using a traditional wood steam-bending technique [40,41]. High-temperature steam (90–100 °C) increases fiber flexibility by reducing intermolecular cohesion, allowing deformation without fracture. After approximately two hours of steaming, the panels were removed and bent under uniform pressure using wooden molds, which maintained the curvature during cooling and setting (Figure 11).

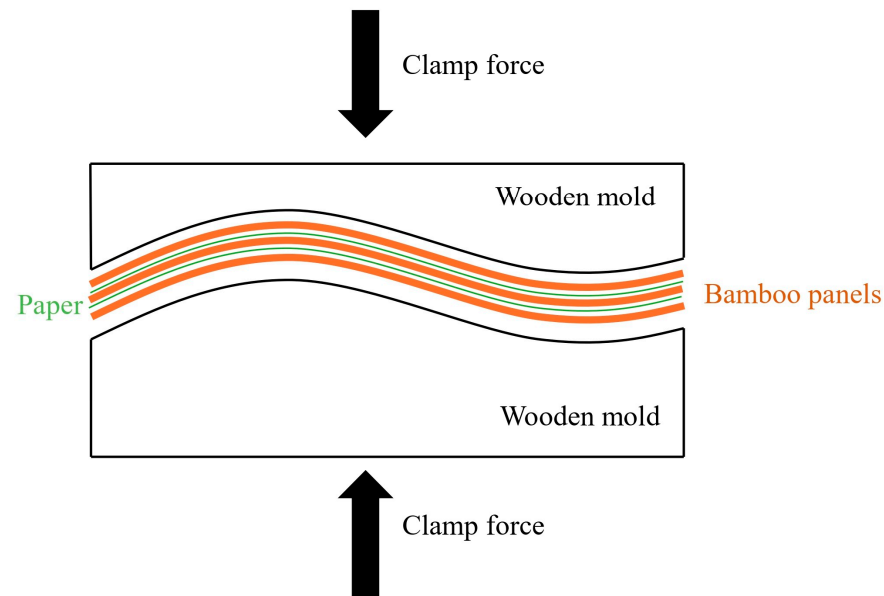


Figure 11. Schematic of the bamboo laminate bending process using a mold and clamps.

For the keel, five pretreated bamboo laminates were stacked and clamped, with 0.25 mm waterproof paper spacers inserted to simulate the adhesive layer thickness, while three laminates were used for the sole. In both components, the layers were stacked with the bamboo fibers kept parallel between consecutive layers, an orientation that was maintained during bonding. A custom clamping jig ensured uniform spacing between the layers, guaranteeing a consistent adhesive joint.

4. Results and Discussion

4.1. Commercial Prosthesis Performance According to the ISO 22675 (2016)

Table 3 reports the displacement along the y-axis of the Variflex prosthetic ankle, recorded for each of the five gait configurations when a reaction force of 1173 N was reached. These displacement values serve as target references to guide the optimization and redesign process of the bamboo-based prosthesis.

Table 3. Y-axis ankle displacement measured at target force for each of the five configurations.

Angle	−15°	−7.5°	0°	10°	20°
Displacement [mm]	18	15	6	13.5	30
Target force [N]	1173	1173	1173	1173	1173

4.2. Final Prototype Geometry and Dimensions Evaluations

Figure 12a,b presents the keel and sole components following the sanding process. The final measured thicknesses of the keel and sole were 17.8 mm and 11 mm, respectively.

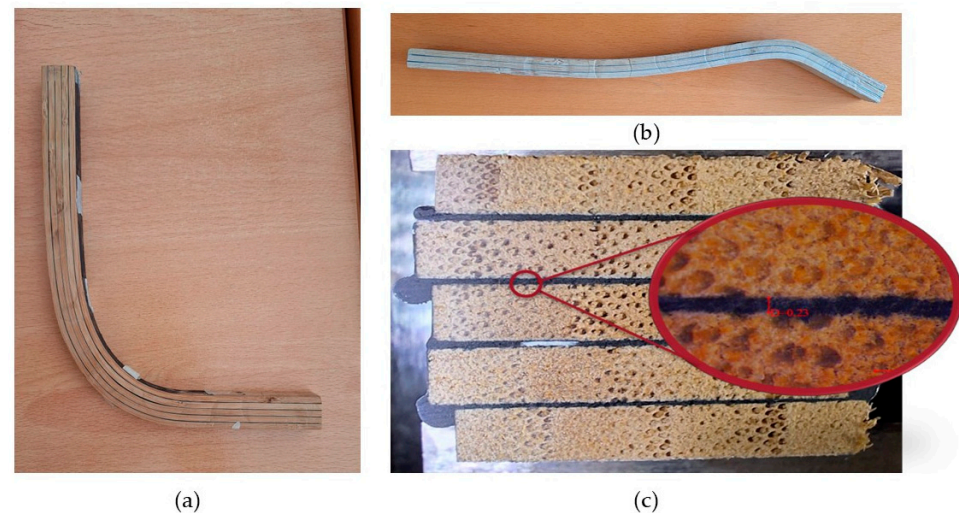


Figure 12. Final prototypes of the keel (a) and the sole (b); in (c), a microscopic view of the adhesive interface between the different layers is shown (before surface leveling and polishing).

As shown in Figure 10c, the resin thickness between the bamboo layers in the sole is consistent with the design specifications, ranging from 0.23 mm to 0.25 mm [28]. These results confirm the effectiveness of the bonding process and the accuracy of the inter-layer separation, achieved using a dedicated bonding jig, calibrated spacers, and precise adhesive application.

In contrast, some areas of the keel exhibit non-uniform adhesive layer thicknesses, with values significantly exceeding 0.25 mm. This irregularity could introduce undesired variations in the structural behavior of the component, potentially affecting the expected performance. Further development will therefore focus on optimizing the bonding process in the keel, with particular attention to the control and regulation of adhesive thickness.

4.3. Bamboo Laminate Prosthetic Foot Prototype Testing and Validation Against the Commercial Model

Following the prototype testing phase, three distinct comparisons were carried out. The first involved a comparison between the experimental results and the FEM simulation of the prototype with optimized thickness and identical width (Figure 13).

This comparison revealed that, in the configuration where the heel is in direct contact with the support surface (Figure 13a,b), the two curves are comparable, exhibiting similar deformation at the point of maximum load. Conversely, in the configurations where the forefoot contacts the support (Figure 13d,e), a marked divergence is observed, indicating increased stiffness in the physical prototype relative to the simulated model.

This behavior can be primarily attributed to two factors:

1. The excessive thickness of the keel, which reduces the flexibility of the anterior portion of the structure.
2. Irregular adhesive layer thicknesses between the bamboo sheets, compromising the overall mechanical uniformity of the component.

In the 0° configuration (Figure 13c), the curves show a noticeable change in slope, which can be attributed to initial contact occurring only at the heel and progressively extending toward the midfoot as the load increases. It is worth noting that the transition point differs between the two graphs, indicating a variation in load distribution. This discrepancy highlights the need to optimize the bonding interface between the keel and the sole to improve structural continuity and achieve a more consistent mechanical response.

The second comparison was conducted between the experimental results of the prototype and those of the commercial reference model, the carbon Variflex (Figure 14). Given the reduced width of the developed prototype (16 mm), the measured forces were normalized per unit width to enable a meaningful and consistent comparison between the two models. This approach allowed for a coherent analysis of the mechanical behavior of the prototype relative to the commercial prosthetic foot.

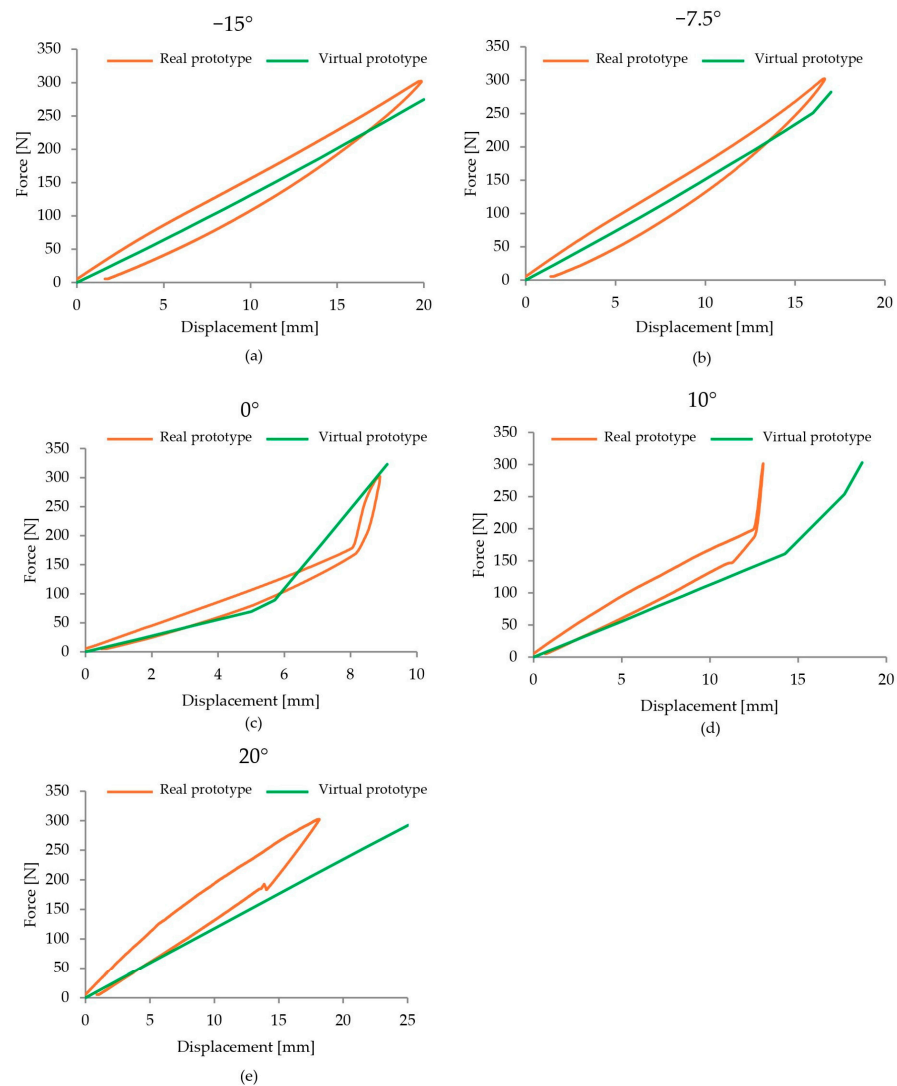


Figure 13. Force per unit width-displacement curves for the real and the virtual bamboo prototype under five gait angle configurations: -15° (a), -7.5° (b), 0° (c), 10° (d), and 20° (e).

As shown in Figure 14, the findings are consistent with the previous observations made for Figure 13 analysis: in the initial stance phase configurations, the curves of the two models are closely aligned, whereas in the remaining three configurations, significant discrepancies are observed, indicating divergent mechanical behavior between the prototype and the reference model.

The third comparison, shown in Figure 15, focused on the analysis of the RoS for the three analyzed models: the virtual bamboo prototype, the physical prototype, and the commercial Variflex foot.

Due to the increased stiffness of the keel, the physical prototype exhibited slightly different behavior compared to the virtual model, displaying a noticeably larger radius of curvature.

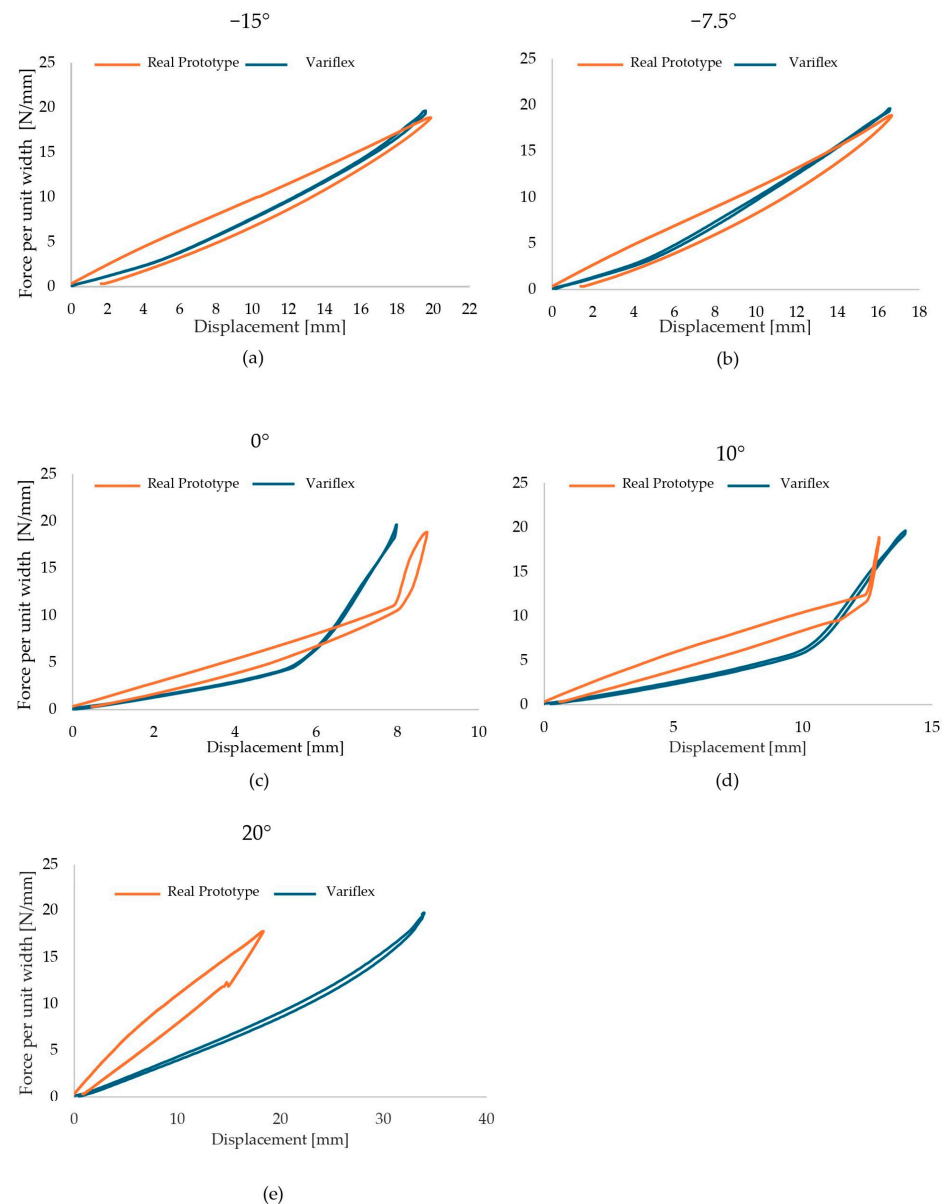


Figure 14. Force per unit width-displacement curves for the carbon Variflex and the real bamboo prototype under five gait angle configurations: -15° (a), -7.5° (b), 0° (c), 10° (d), and 20° (e).

In the comparison between the virtual bamboo model and the Variflex, some localized differences were observed: the forefoot of the bamboo model appears slightly more flexible than the carbon fiber reference, while still maintaining a generally similar mechanical response, whereas the heel exhibits greater stiffness. To further align the two curves, it may be useful to vary the thickness of the sole, particularly in the midfoot area. Overall, the design of the new prosthesis can be considered satisfactory, as the approximated RoS curves show a deviation of less than 15% compared to the commercial model.

A final comparison between the new prosthesis and the reference model was carried out to evaluate differences in weight, vertical clearance, and apparent stiffness. Weight and height were directly measured, and their percentage variations with respect to the reference prosthesis were calculated. Apparent stiffness was determined as the ratio between the applied force in the tests (1173 N) and the corresponding displacement. For each configuration, an average stiffness value was obtained; subsequently, the mean stiffness across all five configurations was calculated. Finally, the percentage variation between the stiffness

of the reference prosthesis and that of the bamboo prosthesis was determined. The results are reported in Table 4.

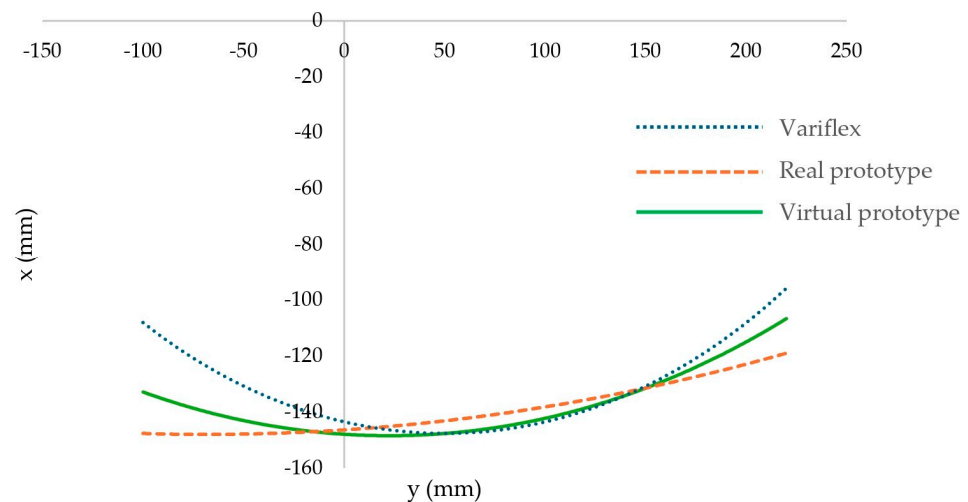


Figure 15. Comparison of RoS curves of the carbon Variflex and the bamboo laminate prototypes (FEM and built).

Table 4. Comparison between the reference prosthesis and the bamboo prosthesis in terms of weight, vertical clearance, and apparent stiffness. Percentage variations are calculated with respect to the reference prosthesis.

	Weight [g]	Height [mm]	Apparent Stiffness [N/mm]
Reference foot	481	152	79.37
Bamboo foot	440	158	76.65
Variation	−8.5%	+3.9%	−7.70%

5. Conclusions

This study explored the feasibility of developing a more cost-effective and sustainable prosthetic device by employing bamboo as an alternative material. Starting from the analysis of existing commercial models, a design method was proposed. Then a prototype was designed and fabricated with the aim of replicating, as closely as possible, the mechanical performance and functional characteristics of reference commercial prosthetic feet.

Experimental tests conducted in accordance with ISO 22675 (2016) standards revealed that the virtual prototype exhibits greater stiffness compared to the physical model. This discrepancy is primarily associated with the increased overall thickness of the keel, partly due to localized regions of thicker adhesive between the laminate layers. These irregularities in the bonding result in a local increase in keel stiffness beyond the intended design. Based on these findings, the main areas for optimization are both the keel thickness and the quality and uniformity of the adhesive bonding between layers.

Similar considerations arise from the analysis of the RoS, which highlights the need to focus on the sole's thickness, particularly in the forefoot region. The observed differences in curvature radii can be mainly attributed to the variation in component thicknesses between the Variflex model and the virtual prototype, as particularly evident in the 0° loading configuration.

Future developments aim to enhance the durability and performance of the prosthetic foot through optimization of both the design and manufacturing parameters. Therefore, it can be drawn that the proposed prosthetic foot design method using bamboo laminate material is effective, but further work to validate the method against fatigue loading is still

necessary. Particular attention should be paid to the interlaminar region of the composite, using CZM analyses to identify and assess potential failure mechanisms [42]. In parallel, further studies could focus on the resin, comparing different types to identify the optimal formulation for bonding the bamboo laminates. Regarding durability, in addition to fatigue cycling, it will be valuable to investigate material behavior under varying environmental conditions, evaluating the effects of increased temperature and humidity on mechanical performance and the degradation of the laminated structure.

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