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Processing–Structure–Properties Relationship of Bamboo Z-Pinned Sandwich Composites: Comparison of Hand Lay-Up and VARI Techniques

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***Abstract*—This study investigates the processing-structure-property relationships of polyurethane foam core sandwich composites reinforced with bamboo Z-pins, focusing on the influence of manufacturing techniques on their mechanical performance. The sandwich panels were fabricated using the hand lay-up and vacuum-assisted resin infusion (VARI) method, and their bending behavior were systematically evaluated. The insertion of bamboo Z pins aims to increase reinforcement through thickness and reduce delamination, a critical failure mode in sandwich structures.**

The results show that the manufacturing route significantly influences the quality of resin impregnation, interfacial bonding, and overall structural integrity. Composites produced via VARI show improved mechanical performance compared to those manufactured by the hand lay-up method, mainly due to reduced void content and increased fiber-matrix adhesion. The presence of bamboo Z pins contributes to improved load transfer and damage tolerance; however, its effectiveness is highly dependent on the quality of interfacial bonding and resin infiltration. The bending performance shows obvious improvement indicating the important role of Z-pin in suppressing delamination and improving core-surface interaction under bending load. Failure analysis further confirmed the transition from interfacial debonding in specimens fabricated by the hand lay-up method to a more cohesive and progressive failure mode in composites fabricated by the VARI method.

***Keywords*—Bamboo Z-pin; Sandwich composites; Polyurethane foam core; Vacuum-assisted resin infusion; Flexural behavior; Fracture mechanisms**

I. Introduction

Sandwich composite structures have been used in various engineering applications, such as maritime, aerospace and light transportation industries, because they have a high stiffness to weight ratio and good energy absorption capabilities. This structure generally consists of two layers of skin [face sheets] that are stiff and strong, which are bound by a light core, such as polyurethane (PU) foam, which plays an important role in resisting shear loads and maintaining structural stability [1]. Despite their significant mechanical advantages, sandwich structures are susceptible to interfacial failure, especially delamination between the skin and core layers, which can reduce the structural reliability and overall service life of the component [2].

Various strategies have been developed to overcome this weakness, one of which is strengthening the thickness direction using the Z-pinning technique [3]. This technique involves the vertical insertion of reinforcing elements that penetrate the composite layer to increase interlayer strength and inhibit crack propagation. Previous studies have shown that the use of Z-pins made from synthetic materials, such as carbon fiber and glass, can increase resistance to delamination and damage. However, these synthetic materials generally have high costs and raise environmental sustainability issues, thus encouraging the development of alternatives based on natural materials [4].

In this context, bamboo fiber emerges as a promising candidate because it is renewable, light, and has relatively good mechanical strength. Bamboo fiber is known to have quite high tensile strength and stiffness, so it has the potential to be used as a reinforcing element in composite structures [5]. However, the use of bamboo as a Z-pin in sandwich structures, especially those using polyurethane foam cores, is still very limited and has not been studied systematically.

Although research related to natural fiber-based composites continues to develop, there are several important problems that have not been answered. First, the effectiveness of bamboo Z-pins in improving the mechanical performance of sandwich structures is not fully understood, especially in terms of load transfer mechanisms and failure behavior under tensile and bending loading. Second, the performance of the composite is greatly influenced by the quality of the interfacial bond between the bamboo fiber and the polymer matrix, which is highly dependent on the fabrication method used. Conventional fabrication methods such as hand lay-up tend to produce defects in the form of voids and uneven resin distribution, which can reduce the structural integrity of the composite. In contrast, the vacuum-assisted resin infusion method is known to improve the quality of resin impregnation and reduce void content, thereby potentially producing better mechanical properties [6]. Recent research shows that natural fibers have great potential as environmentally friendly composite reinforcements [7]. In addition, the Z-pinning technique has been proven to be effective in increasing the delamination resistance of layered composites [8]. However, most research still focuses on the use of synthetic Z-pins, not yet on the use of natural fibers. On the other hand, the influence of fabrication methods such as VARI on the quality and mechanical properties of composites has been widely reported [9]. Until now there has been no comprehensive study comparing the two methods in the context of sandwich composites with bamboo Z-pin reinforcement and a polyurethane foam core.

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Based on these problems, this paper aims to systematically examine the relationship between process, structure and properties of sandwich composites with a polyurethane foam core reinforced with bamboo Z-pins, which are produced using the hand lay-up and VARI methods. Specifically, this research aims to: (i) evaluate the flexural properties of the resulting composite, (ii) analyze the effect of fabrication methods on resin distribution, interfacial bond quality, and structural integrity, and (iii) identify the dominant failure mechanisms that occur in each fabrication method. Through this approach, it is hoped that a deeper understanding will be obtained regarding the influence of the manufacturing process on the mechanical behavior of natural fiber-based composites.

This research offers several significant new contributions. First, this research introduces the use of bamboo fiber as a Z-pinning element in sandwich structures as a sustainable alternative to synthetic Z-pins. Second, this research presents a comprehensive comparison between the hand lay-up and VARI methods in influencing the mechanical performance of composites. Third, this research develops an understanding of the relationship between manufacturing processes, material structure, and mechanical properties. The urgency of this research lies in efforts to bridge the need for environmentally friendly materials with high mechanical performance. By examining the potential and limitations of bamboo Z-pins in various fabrication conditions, this research is expected to make an important contribution both in the development of composite materials science and in practical applications in high-performance lightweight structures.

II. RESEARCH METHODOLOGY

The main materials used in this research consisted of polyester resin and glass fiber as face sheets, polyurethane foam as the sandwich core, and bamboo as the Z-pin material. Unsaturated polyester resin was chosen because it has good impregnation ability, relatively short curing time, and is commonly used in composite sandwich structures [10]. Methyl ethyl ketone peroxide (MEKP) catalyst was used as a curing initiator according to the manufacturer's recommendations. PU foam is used as a sandwich core because it has low density and good ability to absorb shear loads [11]. The composite skin layer uses 200 gr/m2 fiberglass woven roving to produce adequate surface stiffness and strength. Meanwhile, apus bamboo was chosen as the Z-pin material because it is renewable, light, and has a fairly high specific strength compared to several other natural fibers [12]. The apus bamboo used is cut and then shaped into cylindrical sticks with a diameter of 2 mm and dried at room temperature for several days to reduce the water content before use. The drying process is carried out to minimize weaknesses in interfacial bonds due to the natural moisture content of bamboo.

Two variations of fabrication methods were applied, namely: hand lay-up and VARI (figure 1) to evaluate the effect of the manufacturing process on the structural quality and mechanical properties of the composite. In each method, the sandwich structure is made with the same material configuration and dimensions so that the influence of the fabrication method on the mechanical properties can be analyzed objectively. The top and bottom face sheets are fiberglass-reinforced polyester composites which have the same thickness, namely 2.5 mm, while the core that binds them together is polyurethane foam with a thickness of 19 mm so the total thickness of the sandwich composite is 24 mm. The distribution and number of bamboo Z-pins were kept constant in all specimens to avoid the influence of other variables on the test results. Bamboo pins are inserted through the core perpendicular to the face sheet with a distance between the pins of 15 mm.

In the hand lay-up method, layers of fiberglass are arranged on a flat glass mold that has been coated with a release agent. Polyester resin that has been mixed with a catalyst is then applied using a brush and roller until all layers of fiberglass are evenly impregnated. After the bottom layer is formed, PU foam is placed in the middle of the sandwich structure. The PU foam has been inserted with bamboo Z-pins by inserting them perpendicularly through the foam core with a distribution pattern of 15 mm between the pins. After the Z-pin installation process is complete, the top fiberglass layer is assembled and reinsinated again to form a complete sandwich structure. The curing process was carried out at room temperature for 24 hours before the specimen was removed from the mold [13].

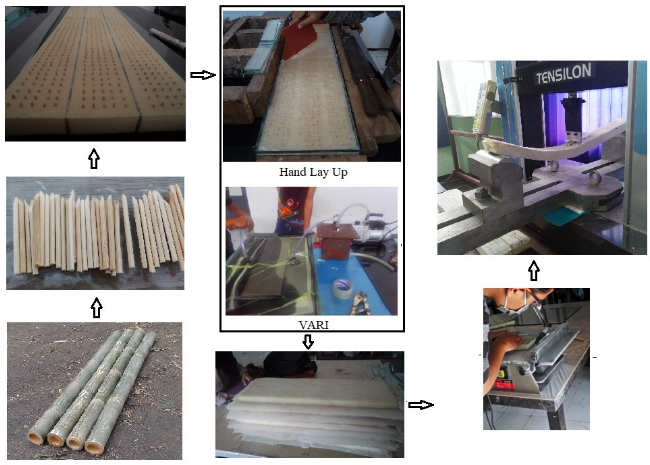

Figure 1 Two methods for making sandwich composites

In the VARI method, all layers of fiberglass, PU foam core, and bamboo Z-pin are first arranged dryly on the mold. After the arrangement is complete, peel ply, flow media, and vacuum bags are installed to form a closed system. Vacuum is applied using a vacuum pump until it reaches a pressure of -60 mmHg, to remove air from the system and minimize void formation. The polyester resin is then infused into the system through the inlet channel due to the pressure difference [14]. This process allows the resin to flow and impregnate the entire structure more evenly. After all layers are completely impregnated, the resin flow is stopped and the curing process is carried out under vacuum conditions for 24 hours at room temperature. The hardened composite panel is then cut to the dimensions of the test specimen.

The bending characteristics of the sandwich composite were evaluated using the three-point bending method according to the ASTM C393 standard [15]. Testing was carried out using a universal testing machine TENSILON type RTG 1310 with a support distance of 550 mm. During the test, a load is applied to the center of the specimen with a deflection speed of 0.5 mm/min until failure occurs. Load and deflection data are recorded continuously to determine the flexural strength and stiffness of the sandwich structure. Visual observations of failure modes were carried out to identify the possibility of delamination, core shear failure, face wrinkling, or pull-out in Z-pin bamboo.

The failure surface of the bending test results was analyzed using macro observations to evaluate the quality of the interfacial bond, resin distribution, the presence of voids, and the dominant failure mechanism. This analysis focuses on the differences in structural characteristics produced by the hand lay-up and VARI methods, especially in the face sheet area around the Z-pin bamboo and the face-core interface. Morphological observations are used to explain the relationship between fabrication quality and mechanical behavior of composites.

Data from mechanical testing results were analyzed comparatively to evaluate the effect of fabrication methods on the performance of sandwich composites. Mean values and standard deviations were calculated from several repetitions of testing to ensure data reliability. The relationship between fabrication methods, structural quality, and mechanical properties is analyzed using a processing–structure–property relationship approach. This approach was used to understand how resin impregnation quality, void content, and interfacial bonding influence the load transfer and failure mechanisms of sandwich structures [16].

III. Results and Discussion

A. Visual Characteristics and Fabrication Quality of Sandwich Composites

The results of visual observations of the sandwich composite structure show that there are differences in surface characteristics and resin impregnation quality between the hand lay-up and vacuum-assisted resin infusion methods, as shown in Figure 2. In general, both methods succeeded in producing a sandwich structure consisting of a fiberglass-polyester composite layer as the face sheet, polyurethane foam as the core, and bamboo Z-pins arranged perpendicularly through the thickness of the structure. However, the quality of the fabrication produced by the two methods shows quite significant differences.

In composites produced using the hand lay-up method, the panel surface looks less homogeneous with uneven resin distribution in several areas. Apart from that, the results of cross-sectional observations show that there are voids in the face sheet around the Z-pin bamboo and at the interface. The existence of these voids is thought to be caused by the manual impregnation process which is unable to remove trapped air during the fabrication process [17]. This condition indicates that the resin flow in the hand lay-up method tends to be non-uniform, especially in the interface area between the face sheet, foam core and bamboo Z-pin. In contrast, composite panels fabricated using the VARI method show better surface quality with a more homogeneous resin distribution. The composite cross section shows that the resin is able to impregnate the structure more evenly, including in the area around the bamboo Z-pin and the face-core interface. In addition, the number of voids observed is relatively less than the hand lay-up method. This condition shows that the application of vacuum pressure during the resin infusion process is effective in assisting resin flow while minimizing trapped air in the composite structure.

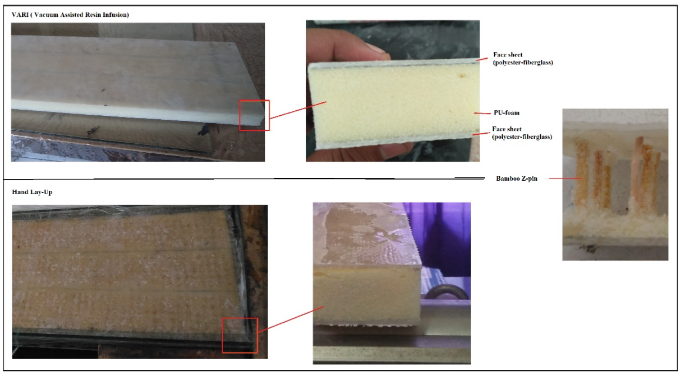

Figure 2 Sandwich composite molded using the hand lay up and VARI methods

In the hand lay-up method, the resin is applied manually using a brush and roller so that its distribution is very dependent on the skill of the operator and the pressure applied during the lamination process. As a result, several areas, especially around the bamboo Z-pin and PU foam pores in the interface area, experienced less than optimal impregnation. This condition causes the formation of voids. The presence of voids in composite structures is known to reduce the effectiveness of load transfer between the matrix, fiberglass fiber, bamboo Z-pin, PU-foam. Voids can also act as crack initiators that accelerate damage propagation. In addition, non-homogeneous resin distribution can cause the interfacial bonding quality to be non-uniform, thereby reducing the overall structural integrity of the sandwich composite [18]. Meanwhile, the VARI method produces better impregnation quality because the resin flows throughout the structure due to the pressure difference generated by the vacuum system. Vacuum pressure not only helps distribute the resin more evenly, but also reduces the air content trapped in the facesheet and interface [19]. Thus, the resulting composite structure has a better interface between the face sheet, PU foam, and bamboo Z-pin. Improving the quality of this interface is very important because it determines the effectiveness of load transfer and resistance to delamination in sandwich structures.

B. Flexural Properties

The load–deflection relationship curve from the bending test results shows differences in deformation behavior between the hand lay-up and VARI specimens (figure 3). The VARI fabricated specimens show the ability to withstand higher loads with deformation occurring more progressively before final failure occurs. This condition indicates that the VARI composite structure has better stiffness and interface integrity than the hand lay-up structure. The increase in stiffness in VARI specimens is closely related to the lower void content and better resin impregnation quality [20, 21]. Homogeneous resin distribution results in more effective stress transfer between the fiberglass layers, polyester matrix, foam core, and bamboo Z-pin. Thus, the structure is able to maintain its stiffness during the bending loading process. Vacuum molded specimens had a higher maximum load, while hand lay-up specimens showed faster deformation accompanied by a sudden decrease in load after reaching the maximum load. This

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phenomenon indicates a more brittle failure due to weak interfacial bonds and the presence of internal defects in the composite structure. In some specimens, failure was initiated by delamination at the face-core interface which was then followed by shear cracking at the polyurethane foam core.

The presence of bamboo Z-pins has been proven to help increase the structure's resistance to delamination during bending loading. Z-pins function as barriers to crack propagation between layers so that the failure process takes place more gradually [22, 23]. However, the effectiveness of this mechanism is greatly influenced by the quality of the bond between the bamboo pin and the resin matrix. In specimens with less than perfect impregnation, some Z-pins experience pull-out due to weak interface adhesion [24].

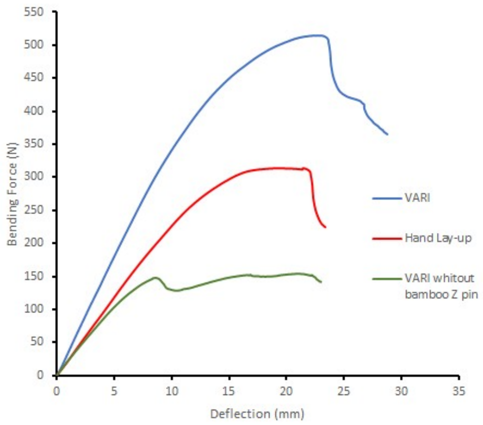

Figure 3. Load–deflection relationship curve for sandwich composites fabricated by hand lay-up and VARI.

The bending strength of sandwich composites is the average stress that occurs in the composite shell with the equation as in equation 1,

$$\sigma b = \frac{P.L}{2t(d+c)b} \quad ....[1]$$

while the shear stress in the sandwich composite core is formulated as in equation 2 [15].

$$\tau = \frac{P}{(d+c)b} \quad ....[2]$$

with:

σb= Bending strength of sandwich composite, MPa
P = Maximum bending load, N
L = Span length, mm
t = Skin thickness, mm
d = Sandwich composite thickness, mm
c = Core thickness, mm
b = Width of sandwich composite, mm

The bending test results show that the fabrication method has a significant influence on the ability of the sandwich structure to withstand bending loads. The flexural strength, shear stress and maximum deflection values of each specimen are shown in Table 1. In general, specimens produced using the vacuum-assisted resin infusion [VARI] method show better flexural performance compared to specimens produced by hand lay-up fabrication.

Under bending loading, the top layer of the composite experiences compressive stress while the bottom layer experiences tensile stress. In these conditions, the integrity of the interface between the face sheet and the core is a very determining factor in the resistance of the sandwich structure to delamination and shear failure of the core [25], the stress that occurs in the composite core is 0.201 MPa. Hand lay-up specimens show lower flexural strength values due to the presence of voids and uneven resin distribution, especially in the area around the bamboo Z-pin – face sheet and face-core interface. Voids formed during the manual fabrication process can act as stress concentration points that accelerate crack initiation when the structure is subjected to bending loading. In addition, imperfect resin impregnation causes stress transfer between layers to be less than optimal, thereby reducing the stiffness and strength of the sandwich structure [26].

The existence of Z-pin bamboo makes a positive contribution to increasing bending performance through a delamination suppression mechanism. The Z-pin works as a thickness direction connector which helps increase the interaction between the face sheet and the foam core, so that crack propagation between layers can be slowed [27]. This effect is seen to be more dominant in the VARI specimens, where the better interfacial bond quality allows the Z-pin to work more effectively in distributing the load during the bending process. It can be seen in table 1 that the shear stress that can be withstood by the sandwich composite core reinforced by bamboo z-pins is greater, namely 0.201 MPa compared to 0.061 MPa without reinforcement. The results of this research indicate that improving fabrication quality through the VARI method has a more significant influence on the flexural performance of sandwich composites. This indicates that the flexural properties of the sandwich structure are very sensitive to the quality of the interface and the homogeneity of resin distribution within the composite structure.

Table 1. Flexural Test Results of Sandwich Composites

Specimen variations	Flexural Strength [MPa]	Deflection at maximum force [mm]	Core shear stress [MPa]
Hand Lay-Up	14.41 ± 0.96	19.14 ± 0.46	0.123 ± 0.003
VARI	22.96 ± 0.76	21.26 ± 0.59	0.201 ± 0.006
VARI without bamboo z-pin	6.72 ± 0.28	20.03 ± 0.42	0.061 ± 0.002

Overall, the VARI method produces better bending performance than hand lay-up. This increase indicates that the effectiveness of bamboo Z-pin is greatly influenced by the quality of impregnation and interfacial adhesion formed during fabrication.

C. Failure Mechanism Analysis

Observation results after flexural testing show that the sandwich structure experiences several typical failure modes, namely core shear failure, face wrinkling, delamination between layers, and cracking (figure 4). The failure mechanism is influenced by the quality of the resin impregnation, interface integrity, and the ability of the Z-pin to resist crack propagation during bending loading. In hand lay-up specimens, failure generally begins with delamination at the interface between the face sheet and the polyurethane foam core in the area below the loading point. Delamination then develops into shear cracks in the foam core due to uneven stress distribution. In addition, some specimens showed face wrinkling in the upper layer due to low local stiffness and weak support from the foam core. The presence of voids and resin-poor areas in hand lay-up specimens causes stress transfer between layers to be less than optimal. This condition accelerates local buckling and crack propagation in the interface area [28]. In several locations, Z-pin bamboo experienced partial pull-out due to weak adhesion between the bamboo surface and the polyester matrix.

Meanwhile, the VARI specimens show a more stable failure behavior. The cracks and delamination that occur tend to be more limited and spread more gradually. This shows that better quality resin impregnation can improve the structural integrity of the sandwich and slow down the propagation of damage. In addition, the Z-pin bamboo in the VARI specimen appears to be more effective in resisting separation between layers so that the structure is able to maintain its load capacity for longer before experiencing final failure.

The differences in failure patterns between the two fabrication methods indicate that the damage mechanism in the sandwich structure is strongly influenced by the quality of the interface and the homogeneity of the microstructure. The VARI method produces a more homogeneous structure with better load transfer capabilities thereby increasing resistance to delamination and core shear failure.

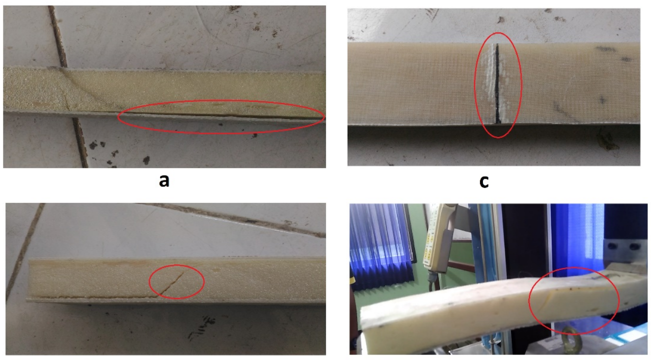

Figure 3. Failure mechanisms in sandwich composite bending tests: (a) delamination at the face-core interface, (b) core shear failure at the polyurethane foam, (c) face wrinkling at the top layer, and (d) effectiveness of bamboo Z-pin in resisting crack propagation in VARI specimens.

Overall, the results of failure mechanism analysis show that fabrication quality has a dominant influence on the damage behavior of sandwich composites. The hand lay-up method tends to produce structures where failure occurs more quickly and locally, this is due to the higher void content and poor interface quality. This condition shows that the manual resin impregnation process has not been able to produce optimal resin penetration throughout all parts of the sandwich structure. In addition, several fracture surfaces on the hand lay-up specimens showed a debonding phenomenon between the bamboo Z-pin and the resin matrix, which indicated weak interface adhesion due to incomplete wetting.

On the other hand, the VARI method produces a more homogeneous structure with a more even resin distribution so that crack propagation can be slowed down. The presence of Z-pin bamboo is proven to contribute to increasing delamination resistance through crack bridging and through-thickness reinforcement mechanisms. However, the effectiveness of this mechanism is greatly influenced by the quality of adhesion between the bamboo and the resin matrix. Therefore, optimization of the fabrication process is an important factor in improving the performance and reliability of natural fiber-based sandwich structures. The research results show that the fabrication method has a very significant influence on the quality of the structure which in turn determines the mechanical performance of the material.

D. Comparison with Previous Research

The results of this research show that the use of bamboo as a Z-pin in a sandwich structure with a polyurethane foam core makes a positive contribution to improving mechanical performance, especially under bending loading. In addition, the fabrication method was shown to have a significant influence on the effectiveness of the Z-pin reinforcement mechanism and the overall quality of the composite structure.

In general, previous research shows that the Z-pinning technique is effective in increasing delamination resistance and damage tolerance in sandwich composites and composite laminates. However, most research still uses Z-pins based on synthetic materials such as carbon or fiberglass. The use of bamboo as the Z-pin material in this research offers a more environmentally friendly approach with a relatively low density and better sustainability potential.

Compared to the research of Selver, E. and Rich,G. [29], who used carbon fiber and Z-pin glass fiber in composite laminates, the increase in flexural strength obtained in this study was relatively lower. However, this research shows that natural materials such as bamboo still have potential as reinforcements in the thickness direction if supported by good quality resin impregnation. In addition, the use of the VARI method in this research produces a structure with a lower void content, thereby increasing the effectiveness of load transfer and improving resistance to delamination.

Santana, E. et al [30] reported that the quality of the interface between the Z-pin and the matrix was the dominant factor in determining the mechanical performance of Z-pinned composites. These findings are in line with the results of this study, where the VARI specimens showed better performance due to more optimal wetting quality and interface adhesion compared to the hand lay-up method.

Oosterom Research, S.V. et al. [31] stated that the vacuum infusion method was able to increase the homogeneity of resin distribution and reduce the void content in the composite structure. The results of this research strengthen these findings through morphological observations and mechanical tests which show that the VARI method produces a sandwich structure that is more homogeneous and has higher mechanical resistance than the manual fabrication method.

Overall, this research makes a new contribution to the development of natural material-based sandwich composites by showing that the combination of Z-pin bamboo and the VARI method can be a potential alternative to produce lightweight structures that are more environmentally friendly and have competitive mechanical performance.

E. Research Implications and Limitations

The success of Z-pin bamboo in improving the integrity of sandwich structures, especially under flexural loading, shows that natural materials can be used as an alternative to synthetic reinforcement in certain applications. In addition, this research confirms the importance of fabrication methods in determining the quality of composite structures. The vacuum-assisted resin infusion method has been proven to produce better mechanical properties than the hand lay-up method. These findings provide important information for the development of natural fiber-based composite manufacturing processes to produce structures with more consistent and reliable performance.

In terms of applications, Z-pin bamboo-based sandwich composites have the potential to be used in various light structures such as vehicle interior panels, maritime components, light building structures, as well as non-structural applications that require a combination of low weight and adequate mechanical resistance. Apart from that, the use of natural materials also supports the development of more sustainable and environmentally friendly material technology. The processing–structure–property relationship approach used in this research also provides an important scientific contribution in understanding the relationship between fabrication process quality, structural characteristics, and mechanical behavior of sandwich composites. This understanding can be the basis for optimizing the design and manufacturing of natural fiber-based composites in future research.

Although this research succeeded in showing the influence of the fabrication method on the mechanical performance of Z-pin bamboo-based sandwich composites, there are several limitations that need to be considered. First, this study only used one variation in diameter and distribution of Z-pin bamboo. Second, the characterization carried out is still limited to flexural testing, so the behavior of the composite against other loads such as impact, fatigue and creep is not yet known. Third, this research has not evaluated the effect of surface treatment on bamboo on the quality of interface adhesion with the resin matrix. Considering the hydrophobic nature of the polyester matrix and the hygroscopic nature of bamboo, interface optimization through chemical treatment has the potential to provide a more significant performance improvement. Therefore, further research is recommended to explore variations in Z-pin parameters, bamboo surface treatment, multi-load testing so that the development of natural fiber-based sandwich composites can be carried out in a more comprehensive and applicable manner.

IV. CONCLUSION

This research shows that the fabrication method has a significant influence on the structural quality and flexural performance of Z-pin bamboo reinforced polyurethane [PU] foam core sandwich composites. Composites produced using the vacuum-assisted resin infusion method show better flexural performance compared to the hand lay-up method, indicated by higher values of flexural strength and core shear stress as well as more progressive deformation behavior before failure. This increase in performance is related to the quality of the resin impregnation which is more homogeneous, lower void content, and better quality of interfacial adhesion in the resulting VARI structure.

The existence of Z-pin bamboo is proven to make a positive contribution to increasing the integrity of the sandwich structure through a through-thickness reinforcement mechanism, especially in inhibiting delamination propagation and increasing load transfer between the face sheet and the sandwich core. However, the effectiveness of this mechanism is greatly influenced by the quality of wetting and adhesion between bamboo and the resin matrix. In specimens with poor impregnation quality, such as hand lay-up results, pull-out and debonding mechanisms occur more easily, thereby reducing the effectiveness of reinforcement.

Overall, the research results confirm that the success of developing sandwich composites based on natural materials is not only determined by the selection of reinforcing materials, but also by optimizing the manufacturing process which is capable of producing a homogeneous structure and a strong interface. The combination of bamboo Z-pin and VARI method shows promising potential as a sustainable approach to produce lightweight sandwich structures with better mechanical performance.

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