Journal of Creativity Student
http://journal.unnes.ac.id/journals/jcs

Experimental Analysis of Bamboo Strip Perforation Geometry on the Impact Response and Water Absorption of Epoxy Composites

Muhammad Abiyyu Hafizh Harahap[1]*, Kriswanto[2], Muhammad Irfan Nuryanta[3]

[1,2]*Department of Mechanical Engineering, Universitas Negeri Semarang, Indonesia*

*Corresponding Author: muhammadabiyyu0098@students.unnes.ac.id

Abstract
Local geometric modification of natural fiber reinforcement offers a non-chemical route for tailoring composite behavior, but the effect of perforating bamboo strips on mechanical response and moisture uptake remains insufficiently resolved. This study experimentally evaluated the influence of bamboo-strip perforation geometry on the impact response and short-term water absorption of epoxy composites. Three-layer cotton fiber, bamboo strip, and cotton fiber laminates were fabricated by hand lay-up. Charpy impact testing, adapted from ASTM D6110, compared perforation diameters of 0, 3.2, 4, and 6 mm, while water absorption testing, adapted from ASTM D570, compared 0, 1, 2, and 3 perforations of 3.2 mm diameter after 1, 2, and 3 h of immersion five specimens were tested for each variation. Impact strength showed a non-monotonic response, reaching 200.1 kJ/m² at 6 mm and 157.71 kJ/m² at 4 mm. Water absorption increased with immersion time in all configurations, while the one and three perforation configurations generally produced lower mean values than the unperforated control. The results show that perforation geometry should be treated as a configuration dependent, multi response design variable rather than a uniformly beneficial interfacial modification. Microstructural characterization and inferential analysis are required to verify the mechanisms underlying these trends and their statistical robustness.

Keywords: bamboo composite, epoxy matrix, impact strength, perforation geometry, water absorption

INTRODUCTION

Natural fiber-reinforced composites continue to be developed as an alternative to conventional materials because they offer a combination of relatively low density, the availability of renewable resources, and the opportunity to reduce dependence on synthetic reinforcements (Andrianto et al., 2025). In polymer composites, the final performance is not solely determined by the individual properties of the matrix or the reinforcement, but rather by their combined ability to form a system capable of transferring loads effectively (Goda et al., 2024). Therefore, the selection of fiber type, reinforcement geometry, material fraction, and interface quality become interrelated aspects in composite design (Purwanto et al., 2023; Zulkifli & Dharmawan, 2019). The demand for lightweight materials with adequate mechanical performance makes natural fiber composites relevant for various engineering applications, including construction and automotive components, while simultaneously establishing sustainability as a design consideration (Djamil & Irawan, 2017). Among natural reinforcements, bamboo is attractive due to its specific strength and stiffness, which support its utilization as a structural reinforcing element (Widiastuti et al., 2020; Firdausi et al., 2025). This potential is also supported by the widespread availability of bamboo in the Asian region, including Indonesia (Setyawan et al., 2023), as well as its cellulose characteristics that contribute to the tensile properties and stiffness of the reinforcement (Chin et al., 2020). Nevertheless, the utilization of bamboo in a polymer matrix cannot be evaluated solely based on its intrinsic strength. The shape of the reinforcement, material continuity, orientation, resin distribution, and the condition of the interfacial region can alter the manner in which the load is transferred from the matrix to the bamboo. Therefore, engineering bamboo composites requires an approach that evaluates the reinforcement as a geometric and interfacial element, rather than merely as a substitute for synthetic fibers. This perspective becomes crucial when strip-shaped reinforcements are used, as local modifications to the strips can yield both advantages and drawbacks: geometric changes have the potential to expand contact with the matrix, but simultaneously, they can reduce the effective area of the reinforcement and create local discontinuities.

Studies on bamboo composites over the past decade have demonstrated that bamboo-based reinforcements can provide competitive mechanical responses when the material configuration and fabrication process are well-controlled (Chen et al., 2022; Talango, 2023). However, mechanical performance is not the only relevant criterion. Bamboo is a lignocellulosic material that exhibits an affinity for moisture; thus, water transport, dimensional stability, and interfacial integrity must be considered alongside mechanical strength (Fachrudin et al., 2026; Hasan et al., 2023; Muhamad et al., 2025). Water entering the composite can interact with fiber-rich regions, pores, crevices, or imperfectly impregnated interfaces. Consequently, altering the geometry of the reinforcement potentially yields two consequences that need to be tested simultaneously: changes in the load transfer pathway during mechanical testing and changes in the water intrusion pathway during absorption testing. Findings regarding bamboo strips also indicate that geometric configuration plays a tangible role. Changing the strip orientation has been reported to produce different impact responses (Kamarudin et al., 2016), signifying that the composite's ability to absorb energy does not solely rely on the properties of the raw bamboo material. For material design, the implication is significant: geometry can be treated as a design variable that can be modified without altering the system's chemical composition. Nevertheless, the response to geometric changes is not necessarily monotonic. The addition of openings, changes in orientation, or material redistribution can improve one mechanism while simultaneously deteriorating another. Therefore, the evaluation of a new configuration should not stop at a single performance indicator; rather, it should consider at least the mechanical response and the environmental durability relevant to the composite's application.

Previous research on bamboo strip-based composites has explored several strategies for performance enhancement, but the focus has not fully addressed the consequences of local geometric modifications. Strip orientation is known to influence the ability to absorb impact energy (Kamarudin et al., 2016), whereas chemical approaches are predominantly directed toward alkaline treatments to improve surface conditions and reinforcement-matrix interactions (Hasyim et al., 2018; Fadlurrahman et al., 2023). Studies on water absorption also emphasize the importance of interface quality, porosity, and processing conditions in determining the response of bamboo composites to moisture (Hasan et al., 2023). On a larger geometric scale, node distribution and strip joint configurations have been reported to affect the mechanical characteristics of continuous composites (Lin et al., 2026). This series of findings indicates that both the interface and geometry are equally important, yet it leaves unanswered questions regarding how local perforations on bamboo strips affect composite responses. Perforation is appealing as an engineering approach because the cavities can serve as matrix penetration spaces and theoretically support mechanical interlocking; however, hole formation also reduces the continuity and effective area of the reinforcement and can increase local stress concentrations. On the environmental durability front, perforations can alter the resin distribution around the strip, but they also have the potential to become sites for water penetration pathways if impregnation is imperfect. Thus, the assumption that perforation consistently improves interfacial bonding is overly simplistic. A more relevant gap is the lack of clarity regarding the pattern of composite responses when perforation parameters are altered and evaluated through more than one outcome, specifically impact response and water absorption. The literature reviewed in this study demonstrates that investigations into orientation, surface treatment, hygroscopic properties, and strip configuration have advanced, whereas the evaluation of perforation diameter and quantity as local design variables remains relatively limited. Therefore, experimental evidence is required to separate direct observations from mechanistic interpretations, ensuring that performance changes are not automatically attributed to mechanical interlocking without verification of the interfacial structure.

This study positions perforation as a reinforcement geometric variable and evaluates it through two sets of experiments with distinct objectives. In the impact testing, three perforations were maintained on the perforated specimens, while the hole diameter was varied at 3.2, 4, and 6 mm to assess changes in absorbed energy and impact strength relative to the non-perforated control. In the water absorption testing, the perforation diameter was maintained at 3.2 mm, while the number of holes was varied from one to three and compared against a non-perforated control at immersion times of 1, 2, and 3 hours. The separation of these factors allows each response to be analyzed clearly, but it also limits cross-response optimization claims since the diameter and quantity of perforations were not tested in a single factorial design. The objective of this study is to analyze the relationship between the perforation geometry of bamboo strips and the impact response and short-term water absorption of epoxy matrix composites. The contribution of this research is directed at two aspects. First, the study provides experimental evidence that the response to perforation cannot be assumed to be linear or universally beneficial. Second, the research identifies a single configuration that can be directly compared across both tests, namely three perforations with a diameter of 3.2 mm, allowing the relationship between mechanical response and water absorption to be discussed in a more integrated manner. Mechanistic interpretations remain limited as plausible explanations because the microstructure, void fraction, and interface quality were not measured directly.

METHOD

This study employed a laboratory experimental approach to evaluate changes in composite responses due to geometric modifications of perforations on bamboo strips. The composites were fabricated using the hand lay-up method at the Mechanical Engineering Department Laboratory, Universitas Negeri Semarang. The treatment variables were designed differently for each type of testing because the observed responses possessed different characteristics. The impact testing utilized perforation diameter as the independent variable, while the water absorption testing used the number of perforations and immersion time as the treatment variables. The response variables included absorbed energy, impact strength, and water absorption percentage. All results were analyzed as comparisons among variations under identical experimental conditions, not as the establishment of standard material property values that can be generalized indefinitely.

The experimental design was divided into two testing matrices. In the impact testing, the control specimens possessed no perforations, whereas the treatment specimens had three perforations with diameters of 3.2, 4, or 6 mm, respectively. Absorbed energy and impact strength were used as responses. In the water absorption testing, the diameter of each perforation was maintained at 3.2 mm, and the number of perforations was varied to 0, 1, 2, and 3 holes. Each configuration was observed after immersion times of 1, 2, and 3 hours. Five specimens were used for each variation in each type of testing. The separation of these designs is crucial for interpretation: the impact testing results answer the effect of diameter changes on a three-hole configuration, while the water absorption results answer the effect of the number of holes at a fixed diameter of 3.2 mm. Therefore, the data were not treated as a full factorial design between diameter and the number of perforations. Cross-testing comparisons were only conducted on configurations that were entirely identical and available in both matrices, namely the control without perforations and the configuration with three 3.2 mm diameter perforations.

The type of matrix, type of reinforcement, alkaline treatment, resin-to-hardener ratio, fabrication method, curing time, and basic specimen geometry were maintained according to the respective testing procedures. This control aimed to ensure that the variations compared within a single testing series had a consistent fabrication process. Because the impact and water absorption tests utilized different specimen dimensions and treatment factors, interpretations were conducted within each respective series prior to performing cross-synthesis and response analysis. This approach mitigates the risk of concluding one configuration as universally optimal when the experimental matrix has not tested all combinations of diameter and number of perforations.

The composite constituent materials consisted of bamboo strips as the primary reinforcement, cotton fiber as an additional reinforcing layer, CHEMPOXY A epoxy resin as the matrix, and CHEMPOXY B as the hardener. The resin and hardener were used at a mass ratio of 3:1. The laminate arrangement was designed with cotton fiber at the bottom layer, bamboo strips in the core, and cotton fiber at the top layer. The bamboo strips were cut according to the specimen dimensions of each test prior to perforation. The use of a single material system and one fabrication method for all variations was intended so that the comparison focused on the geometric changes of the perforations, rather than changes in the composite composition. For the impact testing, the specimens were fabricated in four perforation diameter variations, namely 0, 3.2, 4, and 6 mm. Across all perforated specimens, three holes were used, making the primary difference among treatments the size of the perforation diameter.

For the water absorption testing, configurations of 0, 1, 2, and 3 holes with a fixed diameter of 3.2 mm were used. Each variation consisted of five specimens. Prior to the lamination process, the bamboo strips and cotton fibers were soaked in a 5% NaOH solution for one hour, rinsed with distilled water, and then dried before use. The same treatment was applied to all reinforcements to ensure consistent material preparation conditions. In the context of this study, alkaline treatment was treated as part of the standard fabrication procedure, not as an experimental variable. Thus, the discussed differences in responses were not used to assess the alkalinization effect but rather to compare perforation configurations on materials that received the same initial treatment.

The composite matrix was prepared from CHEMPOXY A and CHEMPOXY B at a mass ratio of 3:1. Both components were mixed for two minutes until homogeneous. The mixture then underwent degassing for five minutes using a vacuum chamber to reduce air bubbles formed during mixing. The degassing stage was maintained for all variations because the presence of voids can affect matrix continuity and the mechanical response of the composite (Fadlurrahman et al., 2023). Consistent procedures are particularly important in perforation research, as the intentionally designed cavities on the strips need to be conceptually distinguished from undesired process voids. This study did not measure the void fraction after fabrication; therefore, the potentially remaining porosity variations were treated as one of the sources of uncertainty in result interpretation, rather than being assumed to be perfectly identical in every specimen.

The composites were fabricated using the hand lay-up method, which is the manual application of resin onto the reinforcement layers until a laminate is formed (Siregar et al., 2022). The composite arrangement consisted of cotton fiber at the bottom layer, parallel-arranged bamboo strips at the core layer, and cotton fiber at the top layer. Resin was applied to each layer to impregnate the reinforcements and fill the spaces around the strips, including the perforation areas in the treatment specimens. Following the lamination process, the composites underwent curing for 24 hours at room temperature. All variations followed the same fabrication sequence. Because the hand lay-up process relies on manual resin distribution, the possibility of local impregnation variations remains an experimental limitation that must be considered when explaining non-monotonic patterns. Consequently, the research findings are discussed based on measured responses and do not use impregnation quality as a verified fact.

The impact testing was conducted using the Charpy method with a procedure adapted from ASTM D6110. The specimens possessed dimensions of 64 mm × 12.7 mm × 4 mm and were placed horizontally on two supports with a support span of 51 mm. The specimen dimensions and support span were adjusted to the composite geometry used in the study, thus not fully replicating the standard configuration, as shown in Figure 1. These adjustments were applied identically across all variations so that the results could still be compared internally. Consequently, the absorbed energy and impact strength values in this study are primarily used to evaluate relative differences among variations, rather than being claimed as material certification values according to ASTM D6110.

Each specimen possessed a V-notch in the center with a 45° angle and a root radius of 0.25 mm. The control specimens had no perforations. In the treatment specimens, three holes were positioned along the longitudinal centerline of the bamboo strip with a distance of 12 mm from the specimen edge to the center of the outermost perforation and a distance of 20 mm between perforation centers. The hole diameters were varied at 3.2, 4, and 6 mm. The three-point placement was maintained for all diameters so that changes in response could be interpreted primarily as a consequence of perforation size changes within the same spatial configuration. This geometry simultaneously created two inseparable changes from the impact data alone: larger perforations reduced the remaining portion of the bamboo material, but also enlarged the local space that could be occupied by the matrix. Both of these consequences form the basis of the mechanistic interpretation in the discussion section.

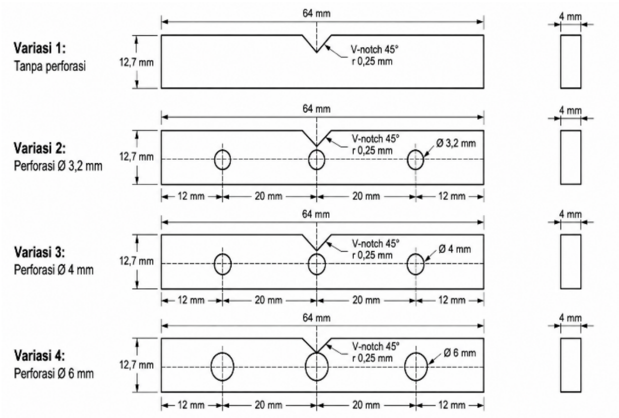

Figure 1. Dimensions of the Impact Test Specimen

The testing utilized a GOTECH Charpy impact machine, as shown in Figure 2. The specimens were placed on the supports with the V-notch orientation corresponding to the Charpy testing configuration and were subsequently subjected to an impact until failure. The energy absorbed during the fracture process was recorded in joules and used to calculate the impact strength based on the effective cross-sectional area at the fracture region. Each variation was tested on five specimens. Average values were used to depict response trends. Absorbed energy and impact strength are reported separately because they provide different information: absorbed energy describes the absolute energy required to fracture, whereas impact strength is a value normalized against the geometric parameters used in the calculation. Discrepancies in performance ranking between the two indicators, if any, are therefore not treated as contradictions, but rather as reasons to read both simultaneously. Because the specimen dimensions and support span were adapted from the standard, the interpretation is directed toward internal comparisons among variations under the same testing conditions. The impact strength value was calculated using Equation 1.

$$HI = \frac{E}{A} \times 1000 \quad \ldots\ldots\ldots (1)$$

Where:

- HI : Impact strength (kJ/m^2)
- E : Absorbed energy at fracture (J)
- A : Effective cross-sectional area at the fracture region (mm^2)

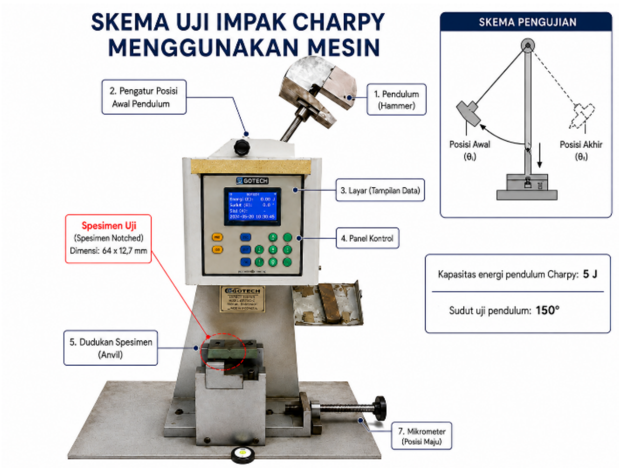

Figure 2. Schematic of the Charpy impact testing

The water absorption testing was conducted using the gravimetric method adapted from ASTM D570 to evaluate the increase in composite mass during short-term immersion. The specimens measured 30 mm × 6 mm × 3 mm and were divided into four configurations, namely without perforations, one perforation, two perforations, and three perforations, as presented in Figure 3. All holes on the treatment specimens had a diameter of 3.2 mm and were positioned along the centerline of the bamboo strip. With the diameter maintained constant, this series was used to investigate whether the addition of perforation points corresponded with changes in the water absorption response. The testing was not designed to determine diffusivity or saturation conditions; thus, the results are limited to water absorption characteristics at intervals of 1 to 3 hours, in accordance with the applied experimental procedure.

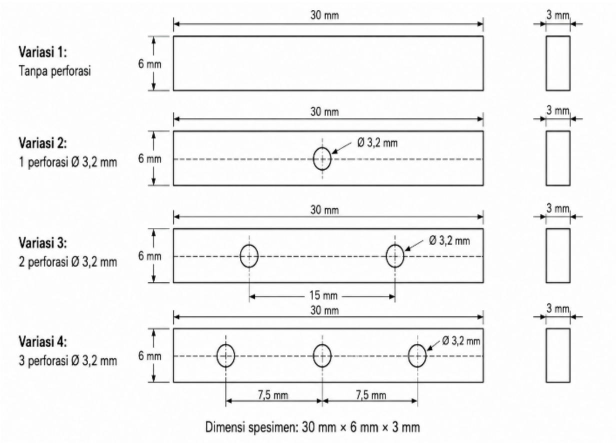

Figure 3. Dimensions of the Water Absorption Test Specimen

Prior to immersion, each specimen was weighed to obtain its initial mass (m_0). The specimens were then immersed in distilled water and evaluated after 1, 2, and 3 hours. At each interval, the specimens were removed from the immersion medium, free water on the surfaces was removed using a lint-free cloth, and the specimens were immediately weighed to obtain their mass after immersion (m_1). The same procedure was applied to all configurations, as illustrated in Figure 4. The water absorption percentage was calculated as the mass increase relative to the initial mass. Using the initial mass of each specimen as the denominator helps reduce the influence of initial mass differences among specimens on the percentage comparison. However, because the test relied solely on mass changes, this method does not identify the location of water entry, the type of transport pathway, or the interfacial conditions acting as the source of absorption. The water absorption percentage was calculated using Equation 2.

$$M = \frac{m_1 - m_0}{m_0} \times 100\% \quad \dots \dots \dots (2)$$

Where:

- M : Water Absorption Rate Percentage (%)
- m_0 : Initial Mass (g)
- m_1 : Final Mass (g) (Ibrahim et al., 2021)

Figure 4. Schematic of the water absorption testing

Data analysis was conducted descriptively using the average values from five specimens for each variation. The impact data are presented as absorbed energy and impact strength, while the water absorption data are presented as the mass increase percentage at each immersion interval. Primary comparisons were made against the non-perforated control and among variations within the same testing series. In addition to absolute values, differences relative to the control are used in the discussion section to clarify the magnitude of trends, with all calculations derived directly from the reported average values. No inferential testing was performed to establish statistical significance. Therefore, terms such as *significantly different*, *significant effect*, or statistical causal claims are not utilized. The mechanistic interpretations are constructed by connecting the experimental patterns to concepts of effective reinforcement area, stress concentration, mechanical interlocking, matrix impregnation, and water transport previously discussed in the literature. These mechanisms are treated as plausible explanations, rather than as direct measurement results, because the study does not encompass microstructural characterization, void fraction, or fracture surface analysis.

RESULTS AND DISCUSSION

Impact testing was utilized to assess how local geometric changes on bamboo strips correspond to the composite's ability to withstand impact loads. Two parameters were evaluated concurrently: absorbed energy as a measure of absolute energy until fracture, and impact strength as the energy value normalized against the effective cross-sectional area. The separation of these two indicators is crucial because perforation configurations alter the specimen geometry; consequently, the configuration absorbing the highest absolute energy does not necessarily yield the highest impact strength value. The analysis begins with the absorbed energy pattern, followed by the impact strength and mechanistic interpretations that can explain the non-monotonic responses.

The Charpy testing yielded different absorbed energies for each perforation diameter. The average values from five specimens were used to observe the trend in changes in energy absorption capacity. The focus of the analysis was not on establishing statistical significance, but rather on the direction and magnitude of changes among variations under identical testing conditions. The absorbed energy values are presented in Table 1 and subsequently compared with the impact strength to determine whether both indicators provided the same performance ranking.

Table 1. Average absorbed energy of composites based on perforation diameter variations

Perforation Diameter (mm)	Average Absorbed Energy (J)
0.0	11.990
3.2	13.228
4.0	10.020
6.0	12.914

Note: Values represent the average of five specimens (n = 5).

Table 1 demonstrates a non-monotonic pattern for absorbed energy. The control without perforations produced an average absorbed energy of 11.990 J. At a 3.2 mm diameter, the value increased to 13.228 J, approximately 10.3% above the control. When the diameter was enlarged to 4 mm, the absorbed energy decreased to 10.020 J, approximately 16.4% lower than the control. At a 6 mm diameter, the absorbed energy increased again to 12.914 J, roughly 7.7% above the control. Thus, the 3.2 mm diameter yielded the highest absolute absorbed energy, whereas the 4 mm diameter produced the lowest value. This pattern refutes the simplistic interpretation that enlarging perforations will sequentially increase or decrease the energy absorption capacity. The absorbed energy values were then used to determine the impact strength. Because impact strength accounts for the effective area parameter in its calculation, the ranking of its values needs to be analyzed separately from the absorbed energy.

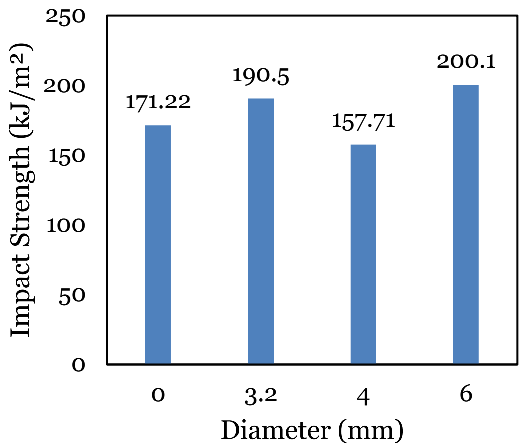

Figure 5. Graph of Impact Strength

Figure 5 illustrates that the impact strength also changed in a non-monotonic manner, but the ranking of its highest values differed from that of the absorbed energy. The non-perforated control produced 171.22 kJ/m². The 3.2 mm diameter increased the value to 190.5 kJ/m², approximately 11.3% above the control. The 4 mm diameter decreased the value to 157.71 kJ/m², about 7.9% below the control. The highest value, 200.1 kJ/m², was obtained at a 6 mm diameter, approximately 16.9% above the control. A crucial distinction emerges when these results are compared to Table 1: the highest absorbed energy was found at a 3.2 mm diameter, whereas the highest impact strength was found at a 6 mm diameter. These findings indicate that absorbed energy and impact strength must not be treated as interchangeable terms. Absorbed energy describes the total energy received by the specimen prior to fracture, whereas impact strength is the result of normalization against the effective geometry. The intellectual payoff from these results is that evaluating perforations based solely on a single indicator can lead to differing design recommendations because both measures need to be analyzed simultaneously when the reinforcement geometry also changes.

The non-monotonic responses can be explained as a possible consequence of competing geometric effects. The formation of perforations removes a portion of the bamboo material, thereby reducing continuity and the effective area of the reinforcement. Concurrently, the perforation cavities provide space for the resin and can theoretically increase the local mechanical contact between the matrix and the strip. Mechanical interlocking is recognized as a mechanism that can contribute to the interfacial bonding of natural fiber composites (Mohammed et al., 2022), while the quality of interfacial adhesion plays a role in stress transfer efficiency and load distribution (Goda et al., 2024). However, the data in this study did not measure interfacial bond strength, void fraction, or fracture morphology. Therefore, the increases at 3.2 and 6 mm diameters cannot be directly declared as evidence of enhanced mechanical interlocking. Similarly, the decrease at a 4 mm diameter is insufficient to conclude that such perforations intrinsically damage the interface. A more defensible interpretation is that each diameter yields a different equilibrium among the remaining reinforcement material, local stress concentrations, resin distribution, and interfacial conditions. The lower pattern at 4 mm compared to the control also indicates that the mere presence of perforations does not guarantee an enhancement in impact response. SEM observations or fracture surface analyses are required to determine whether failure is dominated by pull-out, debonding, strip fracture, matrix cracking, or a combination of these mechanisms.

These findings expand the discussion regarding the role of bamboo strip geometric configurations on impact response. Previous research demonstrated that altering strip orientation could change the composite's ability to absorb energy (Kamarudin et al., 2016). The results of this study reveal another dimension to the same issue: even when the orientation and basic arrangement are maintained, local geometric changes via perforations correspond to different responses. Distinctively, this study found no unidirectional pattern with respect to diameter. This is conceptually significant as it shifts the question from whether perforations improve impact strength to what combination of effects emerges at a specific perforation geometry. In other words, perforation is more appropriately viewed as a design parameter with a configuration-dependent working point, rather than as an unconditionally positive interfacial enhancement treatment. The boundaries of interpretation remain clear, as the available data are descriptive and unaccompanied by microstructural characterization; the results support a configuration-response relationship but have yet to prove the underlying causal mechanisms at the interfacial level.

The second series evaluated water absorption as a response to the number of perforations and immersion time. Unlike the impact testing, which varied the diameter on three holes, this testing maintained the diameter at 3.2 mm and varied the number of holes. This separation allowed the effect of the number of perforation points to be observed at a fixed diameter. The focus of the discussion is on two patterns: the increase in water absorption over time for all configurations, and the absence of a linear relationship between the number of perforations and the magnitude of absorption. Water absorption was calculated as the percentage of specimen mass increase relative to the initial mass at immersions of 1, 2, and 3 hours. The data for each configuration represents the average value of five specimens. Because the testing duration was relatively brief, the results are interpreted as short-term water absorption responses, not as saturation conditions or diffusion parameters. Comparisons against the control were utilized to assess whether a specific perforation configuration exhibited a tendency to increase or decrease the mass gain over the same interval.

Table 2. Average water absorption values of composites based on perforation configurations and immersion time

Perforation Variation	Water Absorption, WA (%)		
	1 hour	2 hours	3 hours
Without perforations	10.90	16.72	20.79
1 perforation	6.59	8.36	11.52
2 perforations	12.77	15.11	17.91
3 perforations	6.56	8.41	11.96

Table 2 illustrates a consistent pattern across all configurations: water absorption increased as immersion time augmented. The non-perforated control increased from 10.90% at 1 hour to 16.72% at 2 hours and 20.79% at 3 hours. The one-perforation configuration increased from 6.59% to 8.36% and 11.52%; two perforations from 12.77% to 15.11% and 17.91%; while three perforations went from 6.56% to 8.41% and 11.96%. This increase over time indicates that the water intrusion process was still ongoing throughout the observation period. However, the relative positions among variations did not adhere to the sequence of the number of perforations. This fact is critical because if the number of holes were the sole governing factor, a more orderly response across 0, 1, 2, and 3 perforations should be expected. The data, instead, demonstrate that the configuration effects are more complex.

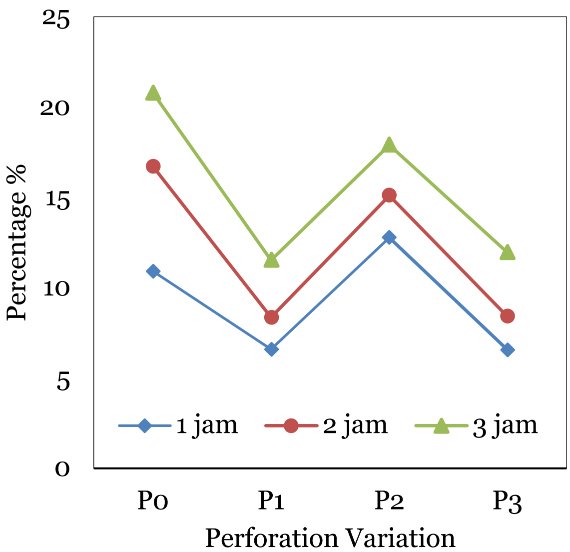

Figure 6. Graph of Changes in Composite Water Absorption

At 1 hour, the lowest value was found in three perforations at 6.56%, nearly identical to one perforation at 6.59%. Both values were approximately 39.8% and 39.5% lower than the control of 10.90%. The two-perforation configuration, conversely, reached 12.77%, approximately 17.2% higher than the control at the same interval. After 2 hours, one and three perforations again formed the group with the lowest average values, at 8.36% and 8.41%, respectively, or roughly 50.0% and 49.7% below the control of 16.72%. At 3 hours, the same pattern persisted: one perforation at 11.52% and three perforations at 11.96%, compared to the control's 20.79%. These substantial average differences denote a configuration-specific tendency but cannot be termed statistically significant as inferential analysis was not performed. Therefore, relative percentage figures are used to clarify the magnitude of trends, rather than to establish population effects.

Two deductions can be drawn from these patterns. First, the addition of perforations is not synonymous with an increase in water intrusion pathways. One and three perforations actually demonstrated lower average values than the control across all intervals, whereas two perforations exhibited different behavior. Second, there is no basis for selecting an optimal number of perforations solely based on the sequence of 0 to 3 holes, as the formed relationship is not monotonic. This finding shifts the focus of interpretation from the number of holes as a singular variable to the quality of local configurations. In a hand lay-up system, perforation position, resin distribution around the holes, contact between bamboo and matrix, as well as the natural heterogeneity of the reinforcement can yield different conditions for each configuration. All these factors are mechanistically plausible but were not directly measured in this study.

The intellectual payoff from the water absorption results is that perforations cannot be treated merely as an addition of open areas that automatically increases absorption. The actual responses are more consistent with the notion that geometry modifies the local environment around the interface; consequently, the outcomes depend on how the cavities are filled by the matrix and how the water transport pathways are formed. The two-perforation configuration, which is higher than the one and three perforations, serves as a pivotal case because it indicates potential interactions with process factors or specimen heterogeneity. Without microstructural data and void distribution, such anomalies should be preserved as findings requiring explanation, rather than being smoothed over with a linear narrative. This stance also restricts overclaims, asserting that the study demonstrates descriptive patterns capable of shaping design hypotheses, but has not yet established a cause-and-effect relationship between the number of perforations and the water transport mechanism.

In general, mass increase during immersion can be associated with water penetration through the matrix, the interfacial region, and micro-voids, while the hygroscopic nature of the bamboo lignocellulosic components heightens the reinforcement's affinity for moisture. Studies on bamboo-polymer composites position interface quality and processing conditions as critical factors in the response to water (Hasan et al., 2023). In hybrid composites of cotton, bamboo, and epoxy, water absorption is also linked to the hydrophilic properties of natural fibers, the presence of micro-voids, and interfacial debonding (Karthik et al., 2023). This literature provides comparative mechanisms but does not prove that the same mechanisms were dominant in every specimen of this study. The connection to the research data is more appropriately used to formulate plausible explanatory pathways: configurations with more continuous impregnation may restrict penetration pathways, whereas regions leaving voids or gaps may enhance water accessibility. Because there were no SEM observations or void fraction measurements, these statements remain at the level of interpretation.

The differences among variations reinforce the need to separate measurement results from proposed mechanisms. The data directly demonstrate that all configurations absorbed more water as time progressed, and that the number of perforations did not produce a linear sequence of responses. The data do not directly indicate the location of water penetration or the quality of impregnation in the perforation areas. Therefore, the strongest conclusion is not that a specific perforation seals water pathways, but rather that perforation configurations are associated with different water transport conditions in the tested composite systems. This limitation is essential for the transferability of the results. The obtained values apply to the composition, hand lay-up method, alkaline treatment, specimen dimensions, hole diameter, and immersion duration utilized. Application to other resin systems, bamboo species, strip thicknesses, or environmental conditions would necessitate retesting.

When both series of experiments are interpreted together, the most crucial finding is not the identification of a single perforation size that is universally optimal, but rather the evidence that perforation geometry functions as a multi-response design variable. The impact testing altered the diameter on a three-hole configuration, while the water absorption testing altered the number of holes at a fixed diameter of 3.2 mm. This design structure implies that the 6 mm diameter, which yielded the highest impact strength, cannot be immediately declared the best configuration for water absorption, because that diameter was not tested in the water absorption series. Similarly, one perforation, which yielded the lowest water absorption at 2 and 3 hours, had no direct counterpart in the impact testing matrix. Consequently, claims of universal optimums would overextend the data. There is one cross-response comparison that is configurationally valid, namely the specimens with three 3.2 mm diameter perforations against the non-perforated control. In impact testing, this configuration produced an impact strength of 190.5 kJ/m² compared to 171.22 kJ/m² for the control, or a descriptive increase of approximately 11.3%. In water absorption testing, the identical configuration yielded 6.56%, 8.41%, and 11.96% after 1, 2, and 3 hours, while the control yielded 10.90%, 16.72%, and 20.79%. Relatively, the average values of the three-perforation configuration were about 39.8% to 49.7% lower than the control throughout the observation intervals. Because no inferential testing was performed, this comparison is not used as proof of significance, but it demonstrates that the 3 × 3.2 mm configuration is a viable candidate for further testing with a more robust design.

This synthesis also highlights a significant methodological trade-off. An increase in impact strength for a given geometry does not automatically equate to an increase in absolute absorbed energy, as evidenced by the differences in the best configurations for absorbed energy and impact strength. Concurrently, low water absorption values cannot be directly attributed to stronger interfacial bonds without microstructural evidence. Therefore, perforation designs should be evaluated through a set of responses, not a single metric. The framework emerging from this study is the relationship among geometry, interface, and response. Geometry alters the amount of reinforcement material and local spatial conditions; these conditions potentially affect the interface, and the consequences are observable in both mechanical and water transport responses. The *interface* component within this framework remains a mechanistic hypothesis that requires verification.

The scientific value of these findings lies in the design boundaries that can be more sharply formulated. Perforation is not a treatment that inherently enhances or degrades composite performance. Its effects are configuration-dependent and can vary according to the indicators employed. Thus, subsequent research should not merely seek the largest diameter or the highest number of holes, but rather test combinations of diameter, quantity, position, and impregnation quality within a factorial design, and then correlate the mechanical results with the characterization of the interfacial structure. Such an approach will transform perforations from empirical geometric modifications into design variables that can be optimized in a more measurable manner.

CONCLUSION

This study demonstrates that perforation geometry correlates with the impact response and short-term water absorption of epoxy matrix bamboo strip composites, but the relationship is not linear. In impact testing, the 3.2 mm diameter produced the highest average absorbed energy of 13.228 J, while the highest impact strength of 200.1 kJ/m² was obtained at the 6 mm diameter; the 4 mm diameter produced the lowest response, meaning that enlarging the perforation cannot be treated as a unidirectional performance enhancement strategy. In water absorption testing, all configurations exhibited an increase in values over time, whereas the one- and three-perforation configurations tended to produce lower average values than the control, and the two-perforation configuration did not follow the same downward pattern. The configuration of three 3.2 mm diameter perforations was the only treatment that could be directly compared across both series, exhibiting a tendency for increased impact strength simultaneously with decreased water absorption relative to the control. The primary contribution of this research is demonstrating that bamboo strip perforation is more appropriately treated as a multi-response design variable with configuration-dependent effects, rather than as a mechanical interlocking mechanism assumed to be universally beneficial. Because the analysis was descriptive and the interfacial mechanisms were not measured directly, these findings support the formulation of design hypotheses and the selection of configurations for further validation, rather than universal optimization claims. Theoretically, the resulting patterns support a conceptual model of competing effects in reinforcement geometry modification. Perforation simultaneously reduces the continuity of the bamboo material, alters local geometry, and provides additional space for the matrix. This combination can produce varying responses according to the hole size and the evaluated indicators. Because mechanical interlocking was not measured, this study does not confirm the mechanism; its contribution lies in narrowing the hypothesis that the perforation response arises from a balance between the loss of effective reinforcement area and changes in local interfacial conditions. This model can be tested directly in future studies through measurements of fracture morphology, void fraction, and interfacial adhesion quality. For the design of bamboo strip composites, the results indicate that perforation decisions should not be based on the assumption that larger or more numerous holes will improve performance. The diameter and number of perforations need to be treated as separate parameters and evaluated against more than one response. The configuration with three 3.2 mm diameter perforations deserves to be prioritized as a candidate for validation because it exhibited favorable tendencies in the two tested responses, though it cannot yet be termed optimal. In the hand lay-up process, impregnation consistency around the holes also needs to be controlled because local variations have the potential to obscure the true geometric effects. This study has several limitations that define the validity scope of its conclusions. The statistical analysis remains descriptive despite each variation using five specimens; thus, the uncertainty and significance among variations have not been established inferentially. The dimensions and support span in the Charpy testing were adapted from ASTM D6110, meaning the values are primarily used for internal comparison. The water absorption testing only covered 1 to 3 hours and does not depict saturation conditions or long-term kinetics. Furthermore, the diameter and number of perforations were not tested in a full factorial design. Additionally, the study did not measure void fraction, resin distribution, interfacial bond strength, or fracture morphology. Consequently, the mechanisms explaining the outcome patterns could not be directly verified. Future research needs to address these limitations through a factorial design combining the diameter and number of perforations, so that the interaction of both parameters can be tested on impact response and water absorption with truly comparable configurations. Adequate replications need to be analyzed using inferential methods and supplemented with measures of variance to distinguish experimental tendencies from statistically consistent differences. Characterization of fracture surfaces and perforation regions using microscopy techniques, accompanied by measurements of void fraction or impregnation quality, is required to test the mechanical interlocking and stress concentration hypotheses. Water absorption testing also needs to be extended to approach equilibrium conditions so that the geometric effect on water transport can be separated from the initial immersion response. With such a design, the candidate configurations from this study can be tested to determine whether they continue to provide advantages when mechanical criteria and moisture resistance are evaluated simultaneously.

REFERENCES

Andrianto, S. N. K., Maulana, J., Riyanto, O. E. S., Tsamroh, D. I., Sasongko, M. I. N., Andromeda, T., ... Fahrozy, M. M. (2025). Analisis Sifat Mekanik dan Penyerapan Air Komposit Polyester Berbasis Serat Alami. *Jurnal Mekanik Terapan, 6*(3), 172–180.

Chen, C., Li, H., Dauletbek, A., Shen, F., Hui, D., Gaff, M., ... Ashraf, M. (2022). Properties and Applications of Bamboo Fiber-A Current-State-of-the Art. *Journal of Renewable Materials, 10*(3), 605–624.

Chin, S. C., Tee, K. F., Tong, F. S., Ong, H. R., & Gimbun, J. (2020). Thermal and Mechanical Properties of Bamboo Fiber Reinforced Composites. *Materials Today Communications, 23*, 100876.

Djamil, S., & Irawan, A. P. (2017). Karakteristik Mekanik Komposit Serat Bambu Kontinyu dengan Perlakuan Alkali. *POROS, 15*(1), 69–75.

Fachrudin, A. R., Astuti, F. A. F., Martawati, M. E., & Walid, A. (2026). Pengaruh Rasio Serat dan Fraksi Volume terhadap Kinerja Komposit Serat Bambu–Kapas. *Pendas: Jurnal Ilmiah Pendidikan Dasar, 11*(2), 291–303.

Fadlurrahman, Z., Alandro, D., Santos, G. N. C., & Muflikhun, M. A. (2023). Mechanical and Chemical Properties of Matrix Composite: Curing Agent Ratio, Degassing Process, and Filler Effect Perspectives. *Journal of Engineering Research, 11*(4), 488–497.

Firdausi, F., Dese, N. O., & Putra, H. A. (2025). Tinjauan Potensi dan Tantangan pada Penggunaan Bambu sebagai Bahan Komposit dengan Struktur Berlapis. *LingKAr Journal, 4*(1), 50–57.

Goda, I., Padayodi, E., & Raoelison, R. N. (2024). Enhancing Fiber/Matrix Interface Adhesion in Polymer Composites: Mechanical Characterization Methods and Progress in Interface Modification. *Journal of Composite Materials, 58*(29), 3077–3110.

Hasan, K. F., Al Hasan, K. N., Ahmed, T., György, S. T., Pervez, M. N., Bejó, L., ... Alpár, T. (2023). Sustainable Bamboo Fiber Reinforced Polymeric Composites for Structural Applications: A Mini Review of Recent Advances and Future Prospects. *Case Studies in Chemical and Environmental Engineering, 8*, 100362.

Hasyim, U. H., Yansah, N. A., & Nuris, M. F. (2018). Modifikasi Sifat Kimia Serbuk Tempurung Kelapa (STK) sebagai Matriks Komposit Serat Alam dengan Perbandingan Alkalisasi NaOH dan KOH. *Prosiding Semnastek.*

Ibrahim, M. M., Desiasni, R., & Widyawati, F. (2021). Pengaruh Volume Serbuk terhadap Laju Penyerapan Air pada Komposit Partikel Tongkol Jagung (Corn Cob) dengan Matriks Epoksi. *Hexagon: Jurnal Teknik dan Sains, 2*(1), 52–56.

Kamarudin, M. H., Saringat, M. S., & Sulaiman, N. H. (2016). The Study of Mechanical Properties of Laminated Bamboo Strip (LBS) From *Gigantochloa levis* Type Mixed With Epoxy. *Jurnal Teknologi, 78*, 59–64.

Karthik, A. D. J. D. J., Vijayan, V., Ahmad, Z., Rajkumar, S., Sharma, S., Sharma, K. P., ... Eldin, S. M. (2023). Study on the Physicomechanical, Fracture-Deformation, Interface-Adhesion, and Water-Absorption Properties of Twill Fabric Cotton-Bamboo/Epoxy Composites. *Journal of Materials Research and Technology, 24*, 8429–8442.

Lin, Z., Hao, X., Fan, Q., Xu, J., Ou, R., & Wang, Q. (2026). Effect of Distribution Patterns of Bamboo Nodes and Scarf Joints on the Mechanical Properties of Continuous Bamboo Strip Composites. *Acta Materiae Compositae Sinica, 43*(4), 2133–2142.

Mohammed, M., Rasidi, M. S. M., Mohammed, A. M., Rahman, R., Osman, A. F., Adam, T., ... Dahham, O. S. (2022). Interfacial Bonding Mechanisms of Natural Fibre-Matrix Composites: An Overview. *BioResources, 17*(4), 1.

Muhamad, S., Wijayanto, A., Nurhanifah, N., Mulyosari, D., & Anggiriani, S. (2025). Effect of Steam and Layer Variation on the Physical and Mechanical Properties of Jabon Wood and Betung Bamboo Hybrid Particleboard. *Jurnal Silva Tropika, 9*(1), 140–152.

Purwanto, H., Andary, S. R., & Hartono, H. (2023). Kekuatan Tarik terhadap Beberapa Sudut Serat pada Polimer Matrik Komposit yang Berpenguat Serat Bambu dengan Perlakuan di Alkali untuk Pengembangan Bodi dan Rangka Kendaraan Elektrik. *Jurnal Pengembangan Potensi Laboratorium, 2*(2), 72–78.

Setyawan, P. D., Sugiman, S., Sinarep, S., & Hilwan, H. (2023). Karakteristik Komposit Sandwich dengan Inti (Core) *Open Cell Foam* Bambu Berlubang. *Dinamika Teknik Mesin, 13*(2), 157–164.

Siregar, I. R., Alfatih, M. F. I., & Alimi, S. (2022). Eksperimen Uji Kekuatan Tarik Komposit dengan Resin Epoxy dan Penguat Serat Kulit Singkong Menggunakan Metode *Hand Lay Up*. *Teknika STTKD: Jurnal Teknik, Elektronik, Engine, 8*(2), 220–226.

Talango, N. (2023). Analisis Kekuatan Tarik Material Komposit Berbahan Serat Bambu Mayam. *Jurnal Simetrik, 13*(2), 729–733.

Widiastuti, I., Pratiwi, Y. R., & Cahyo, D. N. (2020). A Study on Water Absorption and Mechanical Properties in Epoxy-Bamboo Laminate Composite with Varying Immersion Temperatures. *Open Engineering, 10*(1), 814–819.

Zulkifli, Z., & Dharmawan, I. B. (2019). Analisa Pengaruh Perlakuan Alkalisasi dan Hydrogen Peroksida terhadap Kekuatan Mekanik Komposit Serat Sabut Kelapa Bermatriks Epoxy. *Jurnal Polimesin, 17*(1), 41–46.