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Performance of the Pivot Hooks to Enhance the Flexural Capacity of Bamboo Reinforced Concrete Beams

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Abstract

Some researchers overlooked the role of hooks in their bamboo reinforcement. Consequently, the bamboo reinforcement and concrete used had slip issues, leading to a failure in composite action. This caused the concrete and bamboo to work independently to sustain the given load, making bond failure the main issue rather than beam failure. This research focuses on the role of pivot hooks, which have the capability to enhance loading capacity more effectively than beams without pivot hooks. Experimental tests were performed to identify the impact of the presence of pivot hooks in the flexural reinforcement made of bamboo materials. The aim was to prevent bond slip failure, which commonly occurs in bamboo-reinforced concrete beams. A numerical analysis using FEA NX was conducted to validate the experimental test results and demonstrate that pivot hooks can increase the loading capacity of a concrete beam by 33% to 40% compared to bamboo reinforcement without pivot hooks. Due to factors such as architectural façade and budget efficiency, bamboo has become an unavoidable material in construction. By incorporating structural modifications, such as pivot hooks for bamboo reinforcement, failures can be reduced, making bamboo more functional in construction applications.

Keywords: *Pivot hooks, bamboo, reinforced concrete, beam, static loading*

Abstrak

Peran dari kait pada ujung-ujung tulangan bambu sebagai tulangan utama seringkali diabaikan. Mempertimbangkan material bambu dan beton yang dikombinasikan bersama menjadi struktur komposit sangat rentan terhadap selip akibat susut yang dialami bambu dan beton seiring bertambahnya usia material. Penelitian ini mempelajari peran dari pivot hooks, yang merupakan kait berbentuk pasak yang terpasang di setiap tulangan lentur bermaterial bamboo. Dalam penelitian ini membuktikan bahwa penambahan pivot hooks dapat meningkatkan kapasitas beban yang dapat diterima oleh balok jika dibandingkan dengan tulangan bambu tanpa adanya pivot hooks. Pada dasarnya pivot hooks ditambahkan sebagai tindakan preventif terhadap selip tulangan dengan beton yang menyebabkan kedua material tidak dapat bekerja bersama secara komposit. Analisis numerik dengan menggunakan software FEA NX dilakukan untuk memvalidasi hasil pengujian eksperimental yang membuktikan bahwa peran pivot hooks dalam tulangan bambu dapat meningkatkan kapasitas beban yang dapat diterima sebesar 33% - 40% dari tulangan tanpa pivot hooks. Saat ini dalam sisi arsitektural dan efisiensi biaya, bamboo menjadi material alternatif pengganti tulangan baja yang keberadaannya-pun juga melimpah untuk pembangunan berkelanjutan, pivot hooks merupakan upaya peningkatan kekuatan struktur pada bambu untuk meningkatkan fungsi bambu dalam konstruksi bangunan.

Kata kunci: *Pivot hooks, bambu, beton bertulang, balok, beban statik*

Introduction

As a developing country, Indonesia has a significant responsibility to maintain economic stability and support the needs of its population through massive infrastructure development. The development largely still relies on conventional concrete and its reinforcement, although there have been several innovations applied in construction. Nevertheless, steel reinforcement is commonly used. According to the Indonesian Iron and Steel Industry Association (IISIA), the demand for rebar in Indonesia has been increasing annually, reaching more than 3 million tons every year since 2018. This phenomenon indicates that the production of rebar is becoming massive each year, along with its associated emissions, namely carbon dioxide, Sulphur oxide, nitrogen oxide, and other particulates. Due to the escalating environmental impact of cement and rebar production, alternative materials need to be discussed (Dixit, et al., 2019) (Riofrio, et al., 2022), such as the utilization of ground glass and coal bottom ashes (Kasaniya, et al., 2021), fly ashes (Pangestuti, et al., 2018), and bamboo leaf (Odeyemi, et al., 2022).

Specifically discussing about bamboo, as a species of flora that massively grow in Indonesia (Putra, et al., 2020), this kind of plant is often be used in traditionally architectural component of custom houses in every part of Indonesia. Some people in specific regions use bamboo as structural components of the houses, such as its beam and columns. The trend using bamboo can be considered that bamboo can be easily shaped (Fahim, et al., 2022) and affordable (Putra, et al., 2007). In the perspective of the material strength, bamboo culms have a quite good mechanical properties, such as tensile strength up to 210 MPa and the elastic modulus up to 17500 MPa depends on its species. This fact shows that bamboo can be considered to replace steel as concrete reinforcement (Fahim, et al., 2022) (Javadian, et al., 2019) (Qaiser, et al., 2020).

Bamboo reinforced concrete performance depends on the species of bamboo used, because of its natural characteristics that every species has its own morphology. The studies, that conducted to beam structures, show a trend that bamboo reinforced concrete is able to improve the flexural strength of structures (Qaiser, et al., 2020) (Sutharsan, et al., 2019) (Awoyera, et al., 2019) (Dey, et al., 2018) (Rahman, et al., 2011). The strength is in line to the number of days of curing and the dimension of the rebars (Dey, et al., 2018). The use of bamboo as rebar contributes the minimum deformation and crack propagation, but low elastic modulus (Awoyera, et al., 2019). The strength of bamboo reinforced concrete can be improved by adjusting the shape of the bamboo rebar, such as the present of bark and node contribute the higher tensile strength up to 50% (Muhtar, 2021). Another study also shows the presence of notches and clamps can increase the bond-stress and flexural capacity, as well as reducing slip between the bamboo and concrete (Al-Fasih, et al., 2021) (Budi, et al., 2019) (Muhtar, et al., 2019). However, the utilization of bamboo as rebar is still under study, thus some scholars still oppose this trend because bamboo reinforced concrete still has low strength compared to steel reinforced (Nuraeni, et al., 2018) (Archila, et al., 2018) (Mali, et al., 2020), while some innovation brings to an improvement to the bamboo reinforced concrete (Karthik, et al., 2017) (Wei, et al., 2021). Hence, this paper will discuss bamboo reinforced concrete with pivot hooks at the end of the bamboo rebar, initiated by the preliminary explanation of the experimental test to identify the behavior of the beam with the pivot hooks (Ummati, et al., 2023).

Research Method

The experimental test was conducted to identify the effect of applying pivots, representative of hooks, on both ends of embedded bamboo reinforcement as flexural reinforcements to improve the flexural capacity of bamboo-reinforced concrete beams. Material preparation was carried out to investigate the quality of materials, including aggregates gradation, cement, concrete mix proportions, and reinforcement preparation.

Concrete

Normal concrete is composed of fine aggregate, coarse aggregate, and cement. The fine aggregate used in the mixing process is ordinary sand with a fineness modulus of 2.9, within the accepted value range of the standard fineness modulus as per SNI 7656-2012, which proposes a value between 1.5 and 3.8. The water content was evaluated in a 1500-gram fine aggregate sample used in this research, revealing a water content of 5.933% after reducing the weight to 1411 grams, with a mud content of 4.9%. The specific gravity of the fine aggregate is 2.53 in the SSD (Saturated Surface Dry) condition, with water absorption at 0.5%. The density of the fine aggregate used in this research is 486.9 kg/m³. The coarse aggregate is crushed gravel with a fineness modulus of 4.1 and a maximum size of 25 mm. The water content, evaluated from a 3000-gram coarse aggregate sample reduced to 2876.5 grams, is 4.117%, with a mud content of 1.7%. The specific gravity in SSD (Saturated Surface Dry) condition is 2.473, with an absorption capability of 2.58%.

Table 1. Parameters of the job mixed formula

No	Parameters	Qty	Unit
1	Targeted compressive strength	30.00	MPa
2	Targeted slump	100.00	mm
3	Maximum aggregates size	25.00	mm
4	Free water	193.00	kg/m^3
5	Water cement ratio	0.54	
6	Cement	357.41	kg/m^3
7	Fineness modulus of fine aggregate	2.90	
8	Weight of coarse aggregate (Dry)	1506.00	kg/m^3
9	Coarse aggregate volume (Dry)	0.66	m^3
10	Coarse aggregate weight	993.97	kg
11	Fresh concrete weight	2380.00	kg/m^3
12	Weight of fine aggregate	835.62	kg/m^3

The density of the coarse aggregate used in this experiment is 1753.2 kg/m³. A physical identification to evaluate the cement properties revealed that the cement used for the specimens is ordinary Portland cement with a setting time of 120 minutes and 26 mm of penetration. The density of the cement used in the experiment is 3.048 grams/cm³. The material preparation, as mentioned before, was carried out to design the mix proportion in accordance with the Job Mix Formula (JMF) based on SNI 7656-2021, with a targeted compressive strength and slump of concrete set at 30 MPa and 100 mm, respectively. The parameters used for JMF calculation are based on the entities listed in Table 1. Regarding the JMF parameters on Table 1, for 1 m³ of concrete, the requirements are as follows: 357.41 kg of cement, 204.54 kg of water, 821.5 kg of fine aggregate, and 996.55 kg of coarse aggregate.

The compressive test was conducted on the concrete at the age of 28 days using a Compression Testing Machine within the cylinder model list in Table 2 and Figure 1. Three concrete cylinder samples were taken during the mixing process of the beam specimens. The mix proportion was designed for f'_c 30 MPa, and the compressive strength of the cylinder identified the actual f'_c as 25.57 MPa, with an average concrete density of 2228 kg/m³.

Table 2. Cylinder testing result

No	Weight (kg)	f'c (MPa)
1	12.04	27.74
2	11.36	22.65
3	12.02	26.33
Mean	11.81	25.57

Reinforcement

Bamboo was used as the longitudinal reinforcement to assess its capacity to combine with concrete as flexural reinforcement. Since bamboo is an anisotropic material with strength varying depending on the fiber direction, it demonstrates strong capacity in the axial fiber direction. Five specimens were used to evaluate the bamboo's tensile capacity within a Universal Tensile Machine (UTM) with a loading rate of 10 MPa/second, as shown on Figure 2. Local bamboo materials, tested in dry condition and with dimensions of 5 x 10 x 300 mm, were clamped at both ends. Regarding the tensile test conducted on the five specimens, the local bamboo used as the longitudinal reinforcement exhibited an average yield strength of 192.734 MPa (Table 3). This value falls within the range of 100 – 260.68 MPa for yield strength, as proposed by previous studies. Steel reinforcement was used as confinement, with dimensions of Ø8-100 mm, to prevent shear failure.

Figure 1. Cylinder testing

Table 3. Tensile test result

No	Specimen ID	fy (MPa)
1	B1	259.177
2	B2	200.656
3	B3	183.549
4	B4	153.018
5	B5	167.271
Mean		192.734

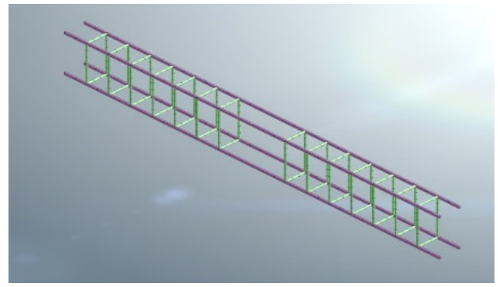
Figure 2. Tensile testing

Results and Discussion

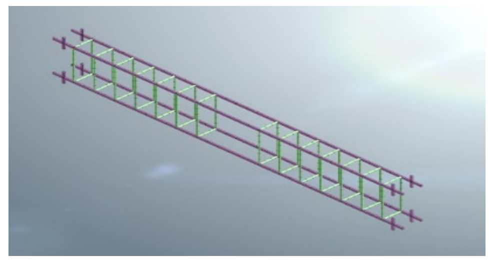
Numerical Analysis

Numerical analysis was performed to validate the experimental test, with the beam modeled as a 3D solid finite element within the Midas FEA NX commercial software. Concrete was modeled as a solid element, while bamboo and confinement were modeled as truss elements embedded inside the concrete. Material properties of the specimens are listed in Table 4 based on actual material laboratory testing, and the geometry modeling of the reinforcement assembly is shown in Figure 3. A three-point bending loading protocol was applied to the beam, as illustrated in Figure 4. Material and section properties in the numerical modeling were analyzed using the Von Mises failure criteria to define nonlinearity. The result of this specific test is shown on Figure 5, which shows the distinctive trend of load-displacement relation. The pivot-hook-beam resulted a higher load-resistance than normal reinforced concrete beam.

A displacement loading was applied with a designed loading of 60 mm, and load-displacement curves were plotted to evaluate the beam's behavior under static loading. The control beam is the beam with ordinary flexural reinforcement made from bamboo materials. In contrast, the Pivot Hooks beam is the model that added a pivot hook at both ends of the flexural reinforcement, also made from the same material. The pivots serve a similar role as hooks in traditional rebar.



(a)



(b)

Figure 3. Reinforcement assembling of: (Top) Control beam, (Bottom) Pivot hooks beam

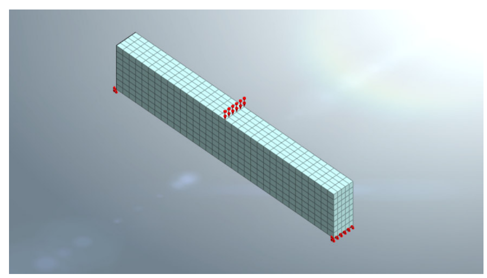


Figure 4. Loading protocol and boundary conditions of the numerical analysis.

By adding these pivots to the bamboo bar, the failure due to bond slip between the bamboo and concrete can be reduced, as this is a crucial issue with a high likelihood of occurring in practical situations. Comparing the load and displacement relationship between the control beam and the pivot hooks beam, both subjected to a designed load control of 60 mm, the red line with a small dashed line represents the load-displacement relation of the control beam, failing under 2026.004 kgf.

Table 4. Material properties

No	Material	Size (mm)	E (MPa)	υ	f'c (MPa)	fy (Mpa)
1	Concrete	150 x 250 x 1700	23766	0.2	25.57	-
2	Bamboo	5 x 10	14279	0.16	-	192.73
4	Con-fine-ment	Ø8 - 100	210000	0.3	-	556

Meanwhile, the blue line with a large dashed line represents the load-displacement relation of the pivot hooks beam, failing under 2839.147 kgf. Based on numerical analysis, the bamboo RC beam with pivot hooks could bear 40% more load than what the control beams could sustain, serving as an estimate for the experimental test outcome.

The evaluation of stress (S_{xx}) under the given loading is closely related to the location of cracks. The numerical modeling resulted in the stress of control beams, as described in Figure 6, with the maximum stress being 27.903 MPa in tension and 41.769 MPa in compression. Meanwhile, for the pivot hooks beam, the stress is described in Figure 7, with the maximum stress being 27.914 MPa in tension and 42.156 MPa in compression.

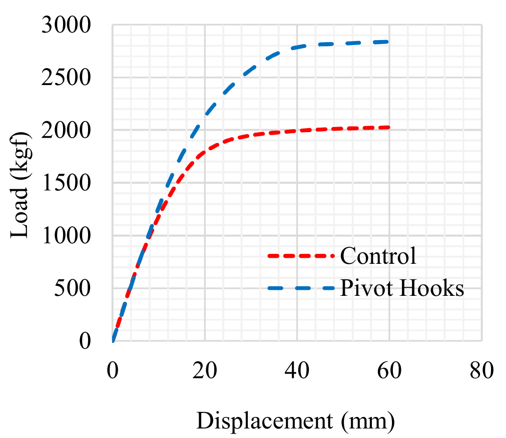


Figure 5. Load and displacement curve comparison by numerical analysis

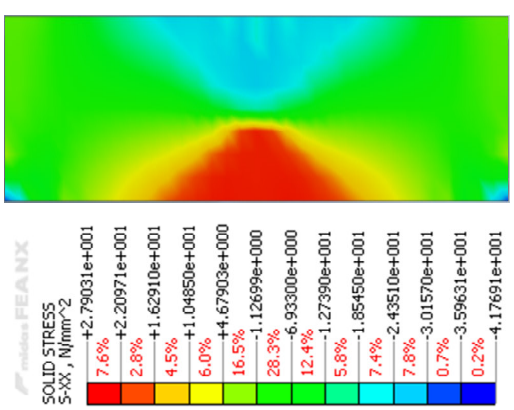


Figure 6. S_{xx} of the control beam

Cracks will develop in locations where the internal stress exceeds the allowable tensile stress. For both cases, the initial crack is predicted to occur on the middle bottom span due to tensile stress and continue to propagate on the middle top due to compression.

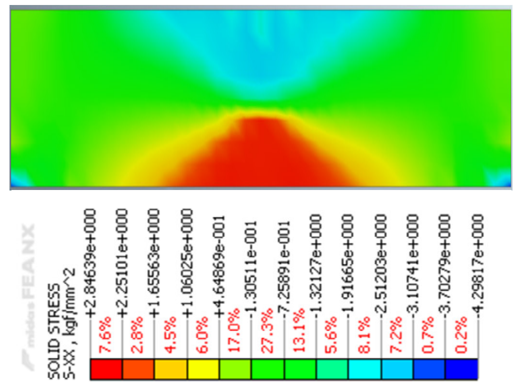


Figure 7. S_{xx} of the Pivot hooks beam

Experimental Test

There are two variants of beams, one with and one without the pivot hook applied to the flexural reinforcements, aiming to identify the effect of pivot hooks in enhancing the flexural capacity of beams with dimensions of 15 x 25 x 170 cm. The clear area from the outer surface of the beam to the reinforcement is 3 cm. The beams are designed to have four longitudinal reinforcements made from 5 x 10 mm square-section bamboo. The confinement is made from steel bars with a diameter of Ø8 - 100 mm, with a total of 14 confinements located in the shear zone. The experimental design of the specimens is shown in Figure 8.

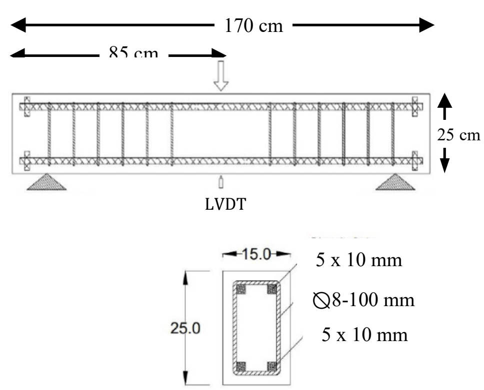


Figure 8. Details of pivot hooks beam

There are four specimens, consisting of two beams with ordinary flexural reinforcement made from bamboo materials, further named control beams (Figure 3 - left), and two beams with pivot hooks at both ends of the flexural reinforcement made from the same materials (Figure 8 and Figure 3 - right). The beams are loaded by a concentrated force in the middle span at the position of the load cell, and the displacement is measured by an LVDT placed at the middle bottom of the beams. Tables 5 and 6 show the load capacity and displacement of all specimens tested in the laboratory.

Table 5. Load capacity based on the experimental test

Specimen	Maximum Load (kgf)	Average (kgf)	Diffe- (Ummati, et al., 2023)
Control 1	1777.92	2105.510	33%
Control 2	2433.1		
Pivot Hooks 1	2980.97	2806.225	
Pivot Hooks 2	2631.48		

Table 6. Displacement of all beams by the experimental test

Specimen	Maximum Disp (mm)	Average (mm)	Difference
Control 1	31.63	45.850	25%
Control 2	60.07		
Pivot Hooks 1	43.98	34.590	
Pivot Hooks 2	25.2		

Based on the experimental tests conducted on two beams in each category, which is shown on Table 5 dan Table 6, the average flexural capacity of control beams is 2105.510 kgf and the pivot hook one is 2806.225 kgf. These are in line t the decrease of average displacement of pivot hook beams compared to the normal one. The facts shows that the addition of pivot hooks was found to increase the load capacity by up to 33% (Table 5), while reducing the displacement by 25% compared to normal beams without pivot hooks (Table 6).

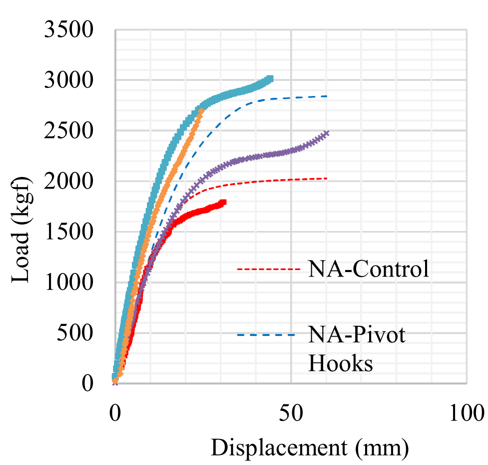


Figure 9. Load and Displacement Curve Comparison of The Numerical Analysis and Experimental Test

Figure 9 illustrates the load and displacement relationship of the control beams and pivot hooks beams obtained through experimental testing (ET), along with a comparison to the dashed line of the numerical analysis (NA). The results from both the numerical analysis and experimental test indicate that the addition of pivot hooks enhances the beams' flexural capacity compared to beams without pivot hooks.

These were proved by the specimens of ET-Pivot Hook 1's flexural capacity is up to 3000 kgf. The trend is also quite similar to the numerical analysis. As well as the pivot hook specimens, the control specimens shows the similar trend, which the flexural capacity is significantly lower than the pivot hook ones.

Cracks developed under the given loading are depicted in Figure 10 for the control beams and Figure 11 for the pivot hooks beams. The crack depth and width are shown in the pictures with units in millimeters (mm). Figure 10 explains that the depth of crack appears on control beams (which is without pivot hook bamboo inforcement) are 22 and 20,9 cm for both Beam 1 and Beam 2, respectively.

However, the width of the crack is significantly different. The first beam crack width is 4,2 cm and the crack width of the second one is only 2,2 cm. As well as the control beams, the pivot hook beams show the similar patterns of crack in the middle of the span. The depth and width of crack that happens on the pivot hook beams also share the insignificantly different rate.

The cracks that appear as a consequence of the given loading indicate that the failure is predominantly due to flexure. It initiates from the tension part in the middle span and then progresses into the compression zone, consistent with the predictions from the numerical analysis.

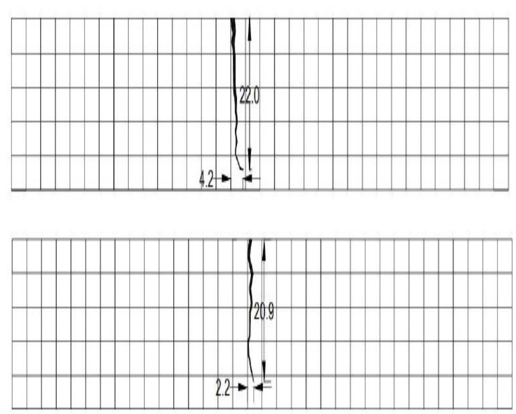


Figure 10. Crack pattern for the: (Top) Control beam 1, (Bottom) Control beam 2

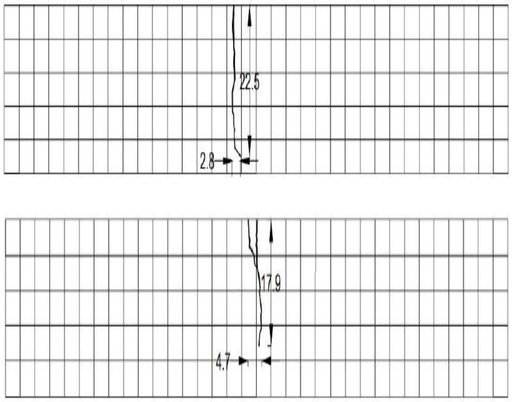


Figure 11. Crack pattern for the:(Top) Pivot hooks beam 1, (Bottom) Pivot hooks beam 2

Conclusion

The experimental test, validated by numerical analysis, was conducted to identify the effect of the presence of pivot hooks on bamboo reinforcement in enhancing the flexural capacity of bamboo RC beams. Bamboo has been widely embraced as a construction material due to its anisotropic characteristics, providing an advantage in its strong fiber direction to complement concrete and substitute tension strength. Previous studies, verified by the experimental test in this research, identified that the tension capacity of bamboo is half that of steel, with a yield strength of bamboo at 192.734 MPa.

The added pivot hooks on both ends of the reinforcement assist the bar in enhancing the bonding capability between bamboo rebar and concrete. This was evidenced by the experimental test, which showed that the loading capacity sustained by beams with pivot hooks is 33% higher than beams without pivots. This result aligns with the numerical analysis, predicting that pivot hooks can improve the loading capacity by up to 40% in perfect modeling. This outcome is satisfactory for enhancing the capacity of concrete beams reinforced by bamboo material, which inherently has lower capacity than steel RC beams. The role of bamboo in construction is unavoidable, particularly for architectural and financial efficiency, especially in rural areas. Thus, the presence of pivot hooks becomes a solution to reduce bonding slip failure between concrete and reinforcement, ultimately enhancing the capacity of bamboo-reinforced concrete beams.

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