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Finite Element Analysis of Beams Reinforced with Banana Fiber Bars (BFB)

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Abstract: One of the challenges of the century is to reach compatibility between the required resistance and the usage of lightweight building materials that may negatively affect the mechanical properties. Natural fibers nowadays are used as enhancers in the industrial field. Hence, the fibers contribute by giving an ideal solution to improve mechanical proprieties of the structural elements such as tensile and impact strength. In previous studies, the use of natural fibers as reinforcement in construction materials has increased. Natural fibers have a lot of characteristics such as being strong, lightweight, inexpensive, and eco-friendly. This paper aims to investigate the performance of banana fiber bars (BFB) as reinforced material. Through this study, the development and characterization of natural fibers-based composite beams were observed. After the beams were designed, several types of finite element analysis were conducted using 'ANSYS' nonlinear finite element program under one-point loading. Results show good correlations between experimental and predicted results.

Keywords: banana fiber bars; BFB; bond strength; flexure behavior; cracking; finite element analysis; ANSYS

1. Introduction

Natural fibers are distinguished by many properties, as they are renewable with good mechanical proprieties, and low cost compared to other materials, where their low cost can contribute to the availability of papers, weaves, construction materials, and cars [1,2]. Some studies have been done on merging the fibers with each other and obtaining composite materials, which are a mixture of synthetic and natural fibers, in order to enhance the tensile strength, flexural strength, and many other mechanical properties [3,4]. Banana fibers are considered one of the most common materials studied recently, as they are extracted from banana cultivation waste, due to its low cost [5,6].

Pothan et al. [7] showed that the size of banana fibers has a clear effect on the mechanical properties of the composite. Studies have shown that composites that contain 40% of the fibers are characterized by a clear increase in the mechanical properties. Idicula et al. [8] conducted a study on both banana and sisal fibers, and the results showed a significant improvement in properties when three banana fibers were used with each sisal fiber. Numerous tests have shown that treated banana fibers has a big effect on improving many of the mechanical properties compared with untreated fibers [9,10]. It has been found that the main controller in improving properties of fibers is the cellulose content found in fibers, as it plays an important role in improving the mechanical properties [10].

The finite element analysis is widely applied in engineering purposes through different software programs, giving a huge probability for solving issues of structural analysis. ANSYS software can be utilized to achieve numerical simulations close to the real behavior.

In this paper, a finite element analysis was done using the ANSYS R14.0 software [11]. Nonlinear finite element analysis was used to study the flexure strength of the concrete beams using BFB as a main reinforcement with different diameter values. The main purpose of completing the finite element analysis was to develop the response of the beams with bananas to validate the experimental work.

2. Process and Geometrical Property for Banana Fiber

2.1. Banana Fibers Types

Poovan type represents a type of banana fibers that has been utilized in this research for the constructional purpose. In order to show its mechanical properties, Table 1 has been added. This product was obtained from India. Figure 1 shows the shape of the fibers after extracting it from the stem of the banana plant. The fibers were extracted with a length of 1.5 m, and these fibers were converted into bars by manual process in the lab in an attempt to use it as an alternative to traditional steel bars [12].

Table 1. Mechanical properties of banana fibers.

Single Fiber Properties	Banana Fiber
Mean breaking strength f_{max} (gf)	465
Mean breaking elongation (%)	1.8
Tensile strength, MPa	267
Young's modulus, MPa	30,000
Passion ratio	0.3
Density, Kg/m^3	710
Fiber diameter in mm, Max	0.1663
Fiber diameter in mm, Min	0.1243
Average fiber diameter in mm	0.1474

Figure 1. Poovan banana fiber type.

2.2. Alkali Treatment of Banana Fibers

In order to obtain high quality fibers, treatment of these fibers is performed by adding sodium hydroxide to these fibers. This alkaline treatment helps to remove all suspended impurities on the surface, which improves the cohesion strength between them and other elements and makes them work better, and increases their mechanical properties [1]. Alkali treatment also increases the percentage of cellulose exposed on the fiber surface, increasing accessibility to possible reaction sites and allowing for better fiber wetting [1]. The equation reaction of the banana fiber to sodium hydroxide (NaOH) [13] is indicated as follows.

$$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{Fiber-O-Na}^+ + H_2O \quad (1)$$

The chemical components of natural banana fibers include lignin and cellulose. The treatment by using NaOH was used for releasing fibers as it is utilized in the paper industries and pulp for the removal of lignin (as shown in Figure 2).

Figure 2. Sodium hydroxide alkali treatment.

According to the previous experiments and studies in chemically treating fibers [1,2], banana fibers are carefully cleaned and submerged in sodium hydroxide with a concentration of 6% for two hours at room temperature, as shown in Figure 3. Next, they are completely washed by immersion in a water tank to remove the inactive reactions until the fibers become free from alkali. Finally they are left to dry at 80 °C for 24 h.

Figure 3. Submerging banana fibers in NaOH solution.

The cohesion between banana fiber bars and the surrounding concrete was conducted. The geometrical proprieties of banana fibers were analyzed to observe the homogeneity between banana fibers and concrete. As the concrete is alkaline with a pH more than seven and banana fiber is acidic with a pH less than seven, (in order to ensure homogeneity), banana fibers are treated with sodium hydroxide (NAOH) for two hours at room temperature.

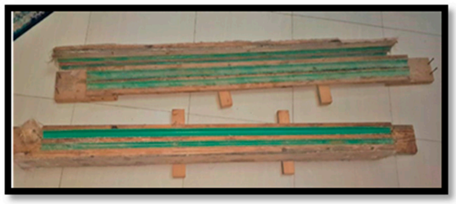
2.3. Banana Fiber Bars as Main Reinforcement

The utilized single fibers were imported from India and manually manufactured at the lab by adding about 8% of elastic polyester with physical and chemical properties as shown in Table 2 to produce (BFB), as shown in Figure 4.

Table 2. Phytochemical properties of polyester.

Tenacity: 5–7 gm/den
Elongation at break: 15–30%
Elastic modulus: 90
Elasticity: Good
Moisture regain (MR%): 0.40%
Specific gravity: 1.38
Melting point: 2500 °C
Volumetric swelling: None

(**a**) BFB



(**b**) The manual manufacturing process

(**c**) Bundle of rebars

Figure 4. Shapes and manufacturing process of banana fiber bars.

FRP is generally characterized by a linear behavior up to failure and all fibers fail in a brittle manner without any yielding Plato. BFRP banana fiber reinforced polymer (BFRP) were fabricated using banana fibers and thermosetting polyester resin. The BFRP reinforcements used in this study include several diameters that ranges from 12 to 18 mm as shown in Figure 5 and Table 4.

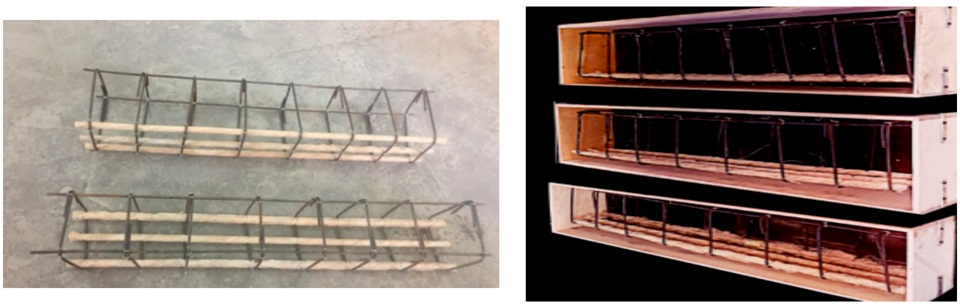


Figure 5. BFRP bars as reinforcement of the tested beams.

2.4. Preparation of the Models

Several models of beams were tested under one-point loading at the mid span to study the bond strength and cohesion between concrete and banana fiber bars. The overall dimensions of the beams were (1050 × 250 × 200) mm. The first beam B1 which has no reinforcement considered as reference model, model A that include four beams contain banana fiber bars with different diameters (Φ12, Φ14, Φ16, Φ18) and model B has two beams that contain banana fiber bars with diameter (Φ16) and with different concrete strengths (35 and 45 MPa). The experimental program for the seven beams is shown in Table 3. All beams have the same length of 1050 mm, loading span of 1000 mm, and concrete effective depth of 225 mm (total depth of 250 mm and concrete cover of 25 mm). Table 4 shows the properties of the tested.

Table 3. Studied parameters.

Group	Reference Model	Model (A)				Model (B)	
Beam symbol	Beam B1	Beam B2	Beam B3	Beam B4	Beam B5	Beam B6	Beam B7
Studied parameter		Ratio of banana fiber bars				Concrete strength	

Table 4. Details of the tested beams.

Beam	Volumetric Ratio of BFB	Longitudinal Main RFT	Type of RFT	Top RFT	Type of RFT	Steel Stirrups	Concrete Strength (MPa)
B1 (Plain concrete)	-	-		-		-	25
B2	0.67	3Φ12	Banana fiber bars	2ϕ6	Steel	ϕ6 @125 mm	25
B3	0.92	3Φ14	Banana fiber bars	2ϕ6	Steel	ϕ6 @125 mm	25
B4	1.2	3Φ16	Banana fiber bars	2ϕ6	Steel	ϕ6 @125 mm	25
B5	1.52	3Φ18	Banana fiber bars	2ϕ6	Steel	ϕ6 @125 mm	25
B6	1.2	3Φ16	Banana fiber bars	2ϕ6	Steel	ϕ6 @125 mm	35
B-7	1.2	3Φ16	Banana fibers	2ϕ6	Steel	ϕ6 @125 mm	45

3. Finite Element Model of Beams

Seven simply supported reinforced concrete beams were analyzed with different flexural parameters. All analyzed beams have the dimensions (1050 × 250 × 200) mm as shown in Figures 6 and 7. Different banana fiber bars ratios and various grades of concrete were considered to study the effect of banana fiber bars on the flexure strength [12].

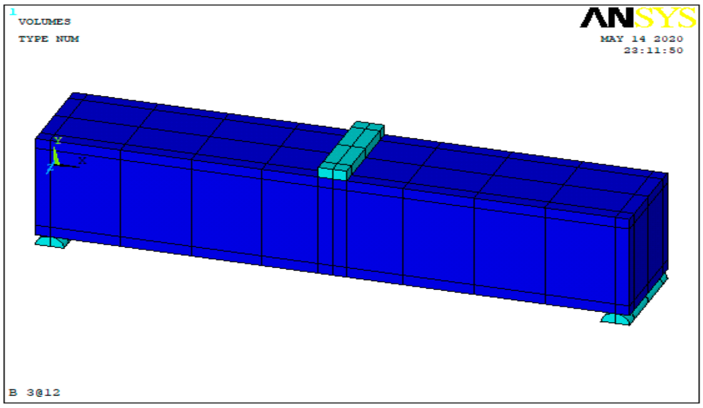


Figure 6. Typical idealization of the volume.

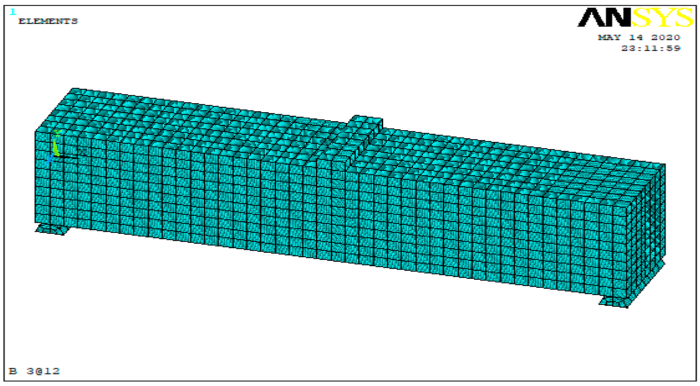


Figure 7. Typical idealization of the beam element.

The area of the top and bottom longitudinal reinforcement was assigned for Link 180 element. Concrete compressive strength was assigned as 25 MPa, and banana fiber bars strength was taken as 265 MPa while the yield strength is taken 240 MPa for shear and top reinforcement as shown in Figure 8. The load is exposed in the top face of the beam as concentrated load with consistent position from the support at the mid span as shown in Figure 8.

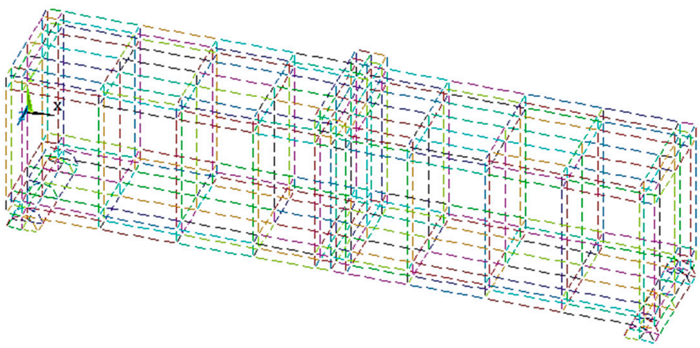


Figure 8. Typical idealization of the steel stirrups, top, and bottom bars.

The details of the seven beams are shown in Table 5. The mesh used in the numerical analysis is shown in Figure 9, where concrete and steel loading and bearing plates are represented using solid 65 and 185 elements, respectively. The size of the mesh was taken (25 × 25). The extent sweep command was once used to mesh the steel plate and supports.

Table 5. Properties of the tested beams.

Beams Group	Symbol	Dimensions (mm)			Shear-Span-to-Depth Ratio	f_{cu} (MPa)	Longitudinal RFT		
		b	t	d	(a/d)		A_s	A_s'	Stirrups
Reference beam	B1	200	250	225	2.2	25	-	-	-
Group (1)	B2	200	250	225	2.2	25	3Ø12	2Ø6	Ø6@125
	B3	200	250	225	2.2	25	3Ø14	2Ø6	Ø6@125
	B4	200	250	225	2.2	25	3Ø16	2Ø6	Ø6@125
	B5	200	250	225	2.2	25	3Ø18	2Ø6	Ø6@125
Group (2)	B6	200	250	225	2.2	35	3Ø16	2Ø6	Ø6@125
	B7	200	250	225	2.2	45	3Ø16	2Ø6	Ø6@125

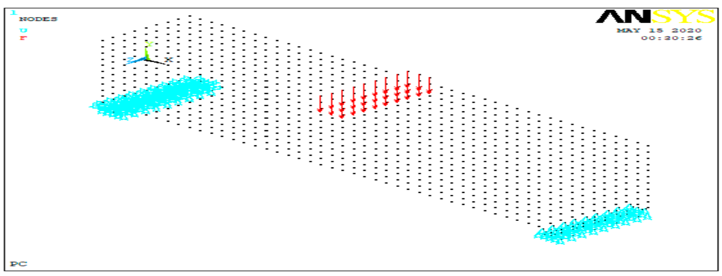


Figure 9. Loading and supports simulation.

Beam B1 is the reference beam with a cross section (200 × 250) without reinforcement (plain concrete). Concrete compressive strength is assigned as 25 MPa as shown in Figures 10 and 11.

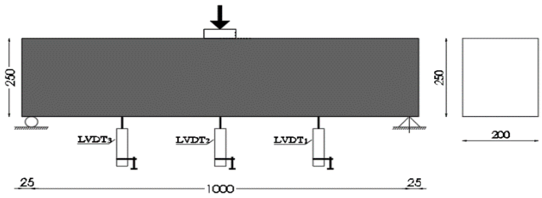


Figure 10. Details of the tested beam (B1).

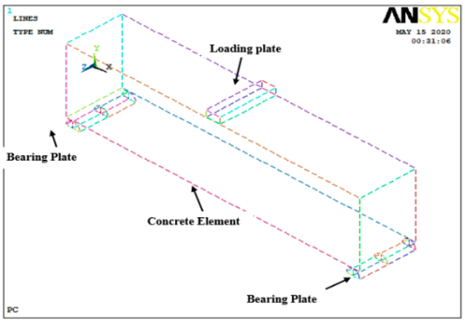


Figure 11. Modeling of beam (B1).

Group 1: This group consists of four beams (B2, B3, B4 and B5). These beams have the same dimensions with variable reinforcement to study the influence of banana fibers ratio on the ultimate flexure strength compared to the reference beam (B1) as shown in Table 1 and Figure 12. Details of beams (B2, B3, B4, and B5) are shown in Figure 13.

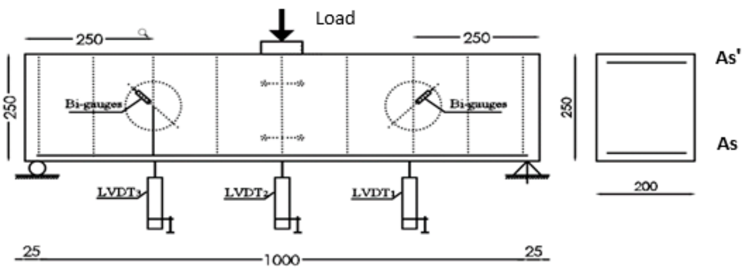


Figure 12. Details of the tested beams and instrumentations.

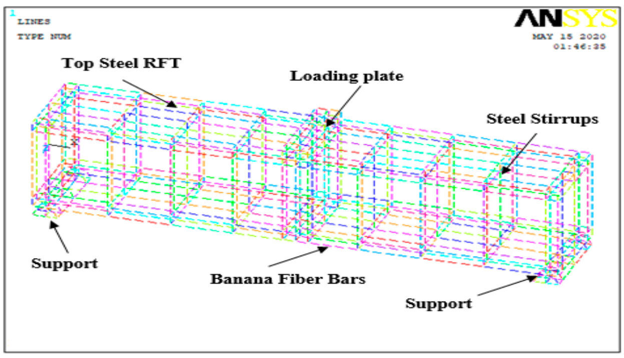


Figure 13. Model of reinforcement of beams (B2 to B5).

Group 2: This group consists of two beams (B6 and B7). These beams have the same longitudinal reinforcement details (3Φ16) with a different concrete grade 35 and 45 MPa to study the effect of concrete strength on in the flexure strength compared to beam B4 as shown in Figure 14.

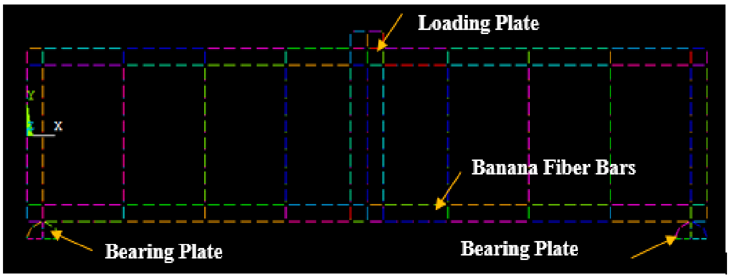


Figure 14. Reinforcement modeling for beams (B4, B6, and B7).

4. Analysis and Discussion of Numerical Results

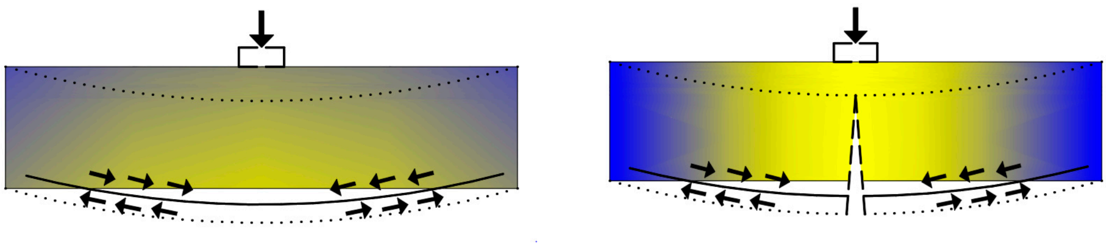
Table 6 shows the experimental and the numerical results of the seven tested beams. The results illustrated good agreement between the experimental and the numerical analysis.

Table 6. Comparison between experimental and numerical results.

Model	Main RFT	Φ (mm)	First CRACK LOAD Exp.	Ultimate Load (kN) Exp.	Ultimate Load (kN) ANSYS	$P_{ANSYS}/P_{Exp.}$	Type of Failure	Rapture
B1	Plain concrete	—		20	23	1.15	Brittle failure	—
B2	Banana fiber bars	12	11	26	30	1.15	Flexure failure	Rapture of bars
B3	Banana fiber bars	14	12.5	26.8	30.5	1.14	Flexure failure	Rapture of bars
B4	Banana fiber bars	16	12	27.3	30.9	1.13	Flexure failure	Rapture of bars
B5	Banana fiber bars	16	10	28	32	1.14	Flexure failure	Rapture of bars
B6	Banana fiber bars	16	14	27	29	1.07	Flexure failure	Rapture of bars
B7	Banana fiber bars	16	13.8	27	29.2	1.08	Flexure failure	Rapture of bars
Average	-	-	-	-	-	1.12	-	-

5. Crack Patterns

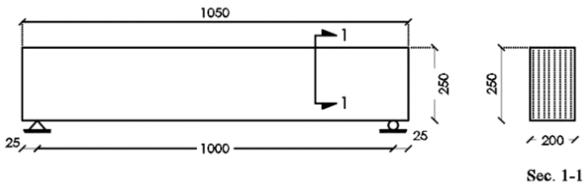
Figure 15 shows a typical crack pattern at ultimate load.



(**a**) Concrete Elongation (**b**) Vertical Cracks

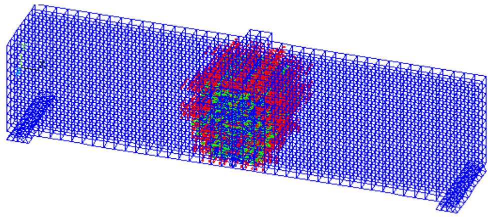
Figure 15. Cracks pattern at ultimate load.

During testing and at the start of loading, a few vertical flexure cracks bending. Cracks begin to start at the bottom of the beams near mid span and propagated to reach the top at a load approximately from 15% to 30% of the ultimate load. As the load increased approximately from 60% to 80% of the ultimate load, the cracks began to propagate as shown in Figures 16–22. The numerical analysis cannot consider the descending branch after reaching the ultimate load due to the numerical failure.



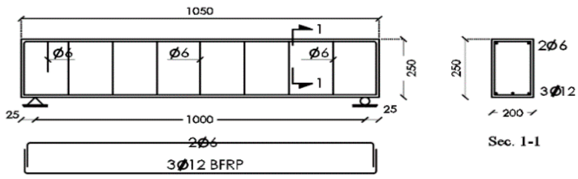
(**a**) Dimensions

(**b**) Experimental crack pattern



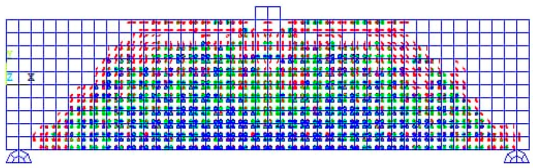
(**c**) Numerical crack pattern

Figure 16. Beam B1 modeling.



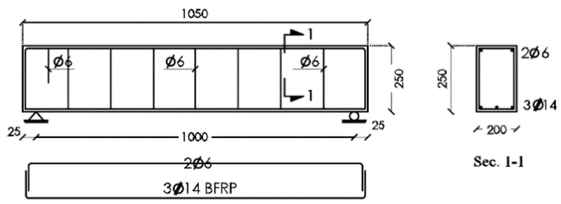
(**a**) Details of reinforcement

(**b**) Experimental crack pattern

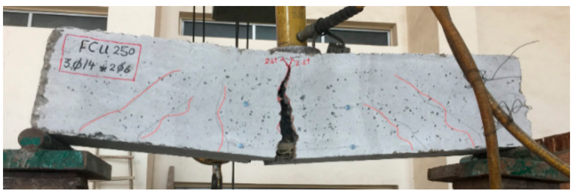


(**c**) Numerical crack pattern

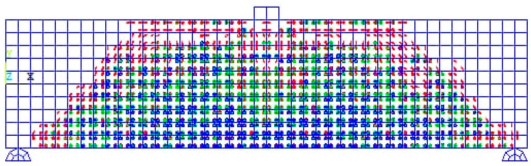
Figure 17. Beam B2 modeling.



(**a**) Details of reinforcement

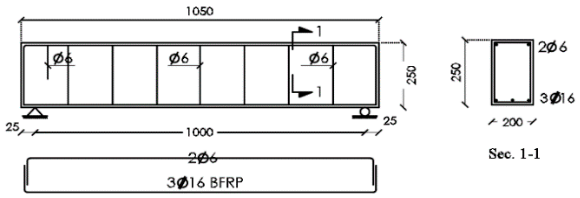


(**b**) Experimental crack pattern

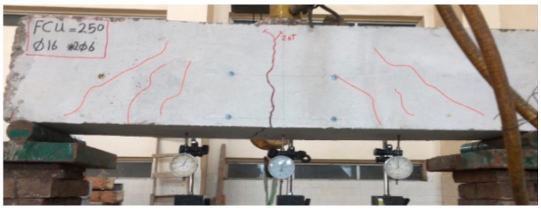


(**c**) Numerical crack pattern

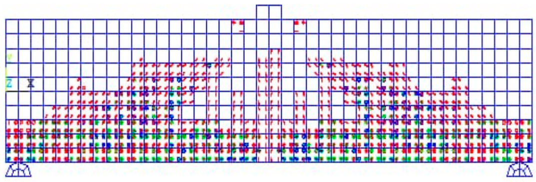
Figure 18. Beam B3 modeling.



(**a**) Details of reinforcement

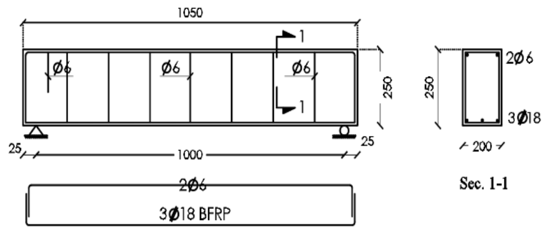


(**b**) Experimental crack pattern

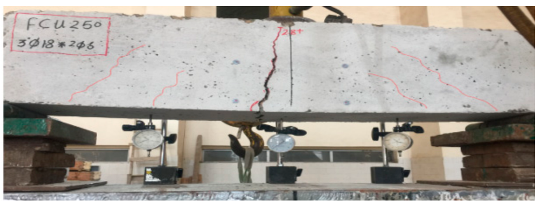


(**c**) Numerical crack pattern

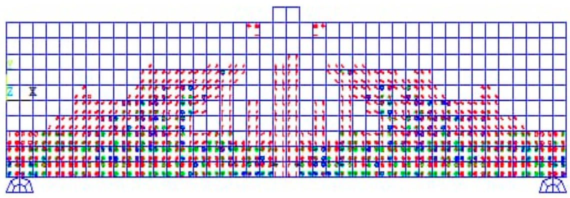
Figure 19. Beam B4 modeling.



(**a**) Details of reinforcement

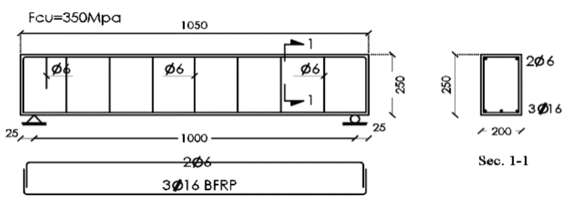


(**b**) Experimental crack pattern

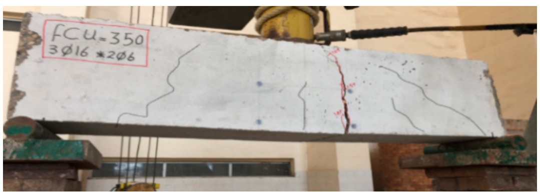


(**c**) Numerical crack pattern

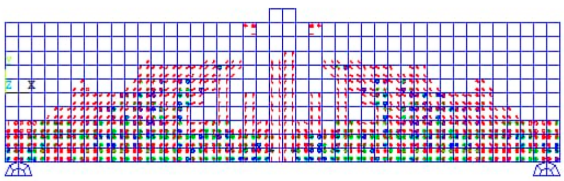
Figure 20. Beam B5 modeling.



(**a**) Details of reinforcement

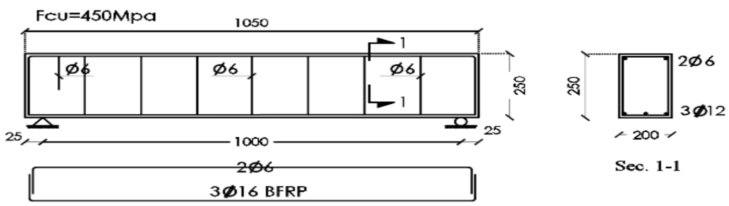


(**b**) Experimental crack pattern

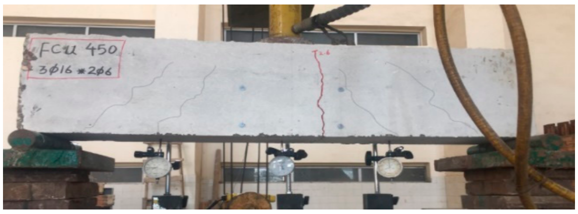


(**c**) Numerical crack pattern

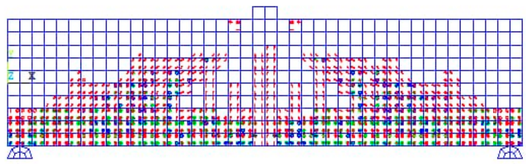
Figure 21. Beam B6 modeling.



(**a**) Details of reinforcement



(**b**) Experimental crack pattern



(**c**) Numerical crack pattern

Figure 22. Beam B7 modeling.

Beam B1 represents the reference model of simply supported beams without any type of reinforcement. Cracking which was observed when the load increased to brittle failure at a load of 20 kN is shown in Figure 16. This type of failure is called flexure failure that happened due to principle tension. As shown in this Figure, the beam failed at a load of 20 kN at the middle of the beam.

Figures 17–22 show the crack pattern of beams B2 to B7. The first crack appears at mid-span at load 11, 12.5, 12, 10, 14, and 13.8 kN for beams B2 to B7 respectively. Then fine flexural cracks formed at the mid-span. Upon increasing the load, flexure cracks increased. At higher levels of loading, the flexure cracks propagated and the width of cracks increased. Finally, the beams failed in flexure at a load of 26, 26.8, 27.3, 28, 27, and 27 kN for beams B2 to B7 respectively.

A good agreement was obtained between the experimental and the predicted results. Depending on the evaluation of the computed results of the reachable numerical and experimental data, it was confirmed that the finite element method and materials models used in the ANSYS application were responsible and truthful in predicting the behavior of nonlinear geometric and nonlinear material behavior of reinforced concrete beams reinforced with banana fiber bars.

6. Deflection and Flexure Strength

Figures 22–29 show the experimental and the predicted load-deflection curves for the tested beams. These figures and Table 6 show good agreement between the experimental and the predicted load–deflection curves. Also the results show that banana fiber bars increase the ultimate strength of beams by 25% compared to beam B1 (plain concrete). The results indicated that there is no effect of concrete grade on the first cracking load and the ultimate load, and the rupture was the same for all models.

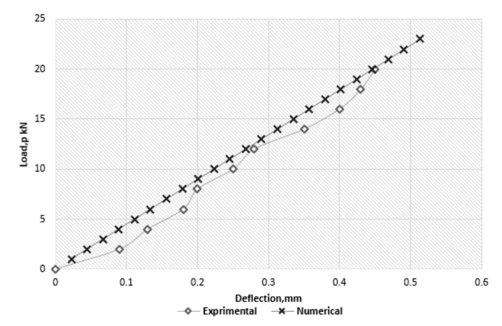


Figure 23. Load–deflection diagram of beam (B1).

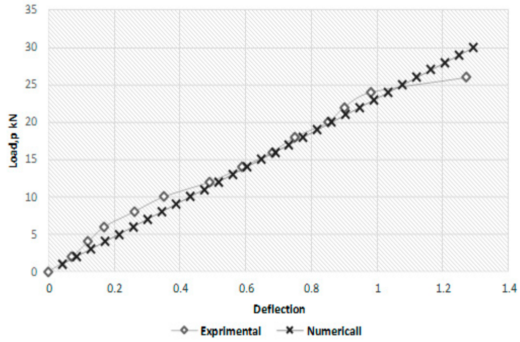


Figure 24. Load–deflection diagram of beam (B2).

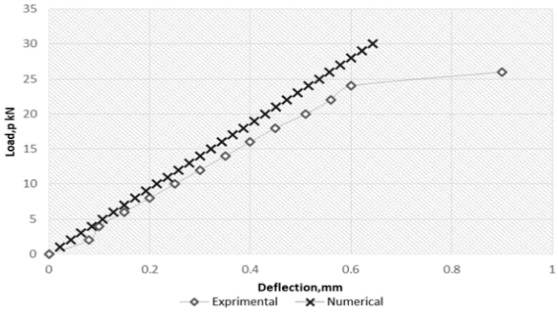


Figure 25. Load–deflection diagram of beam (B3).

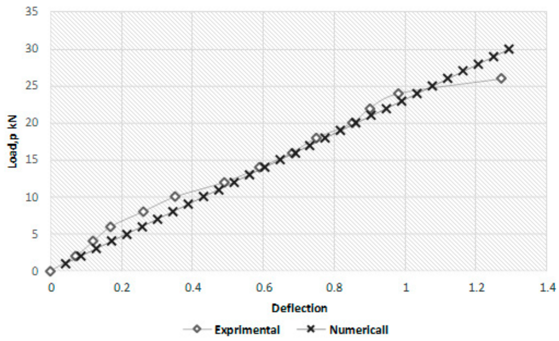


Figure 26. Load–deflection diagram of beam (B4).

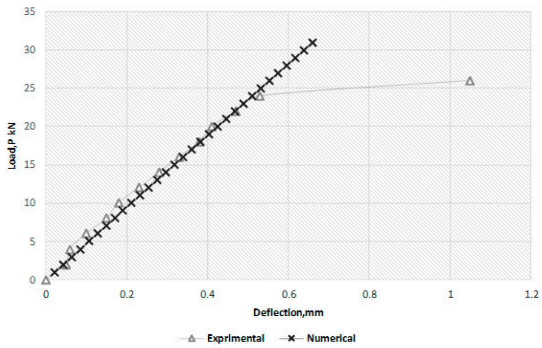


Figure 27. Load–deflection diagram of beam (B5).

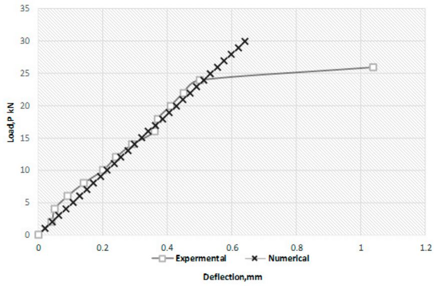


Figure 28. Load–deflection diagram of beam (B6).

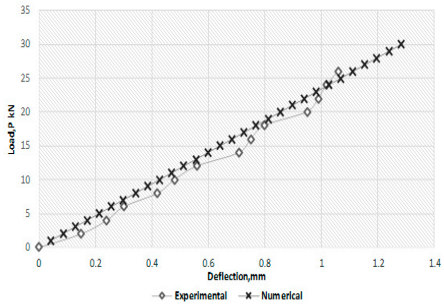


Figure 29. Load–deflection diagram of beam (B7).

7. Conclusions

Based on the experimental program and the numerical study of reinforced concrete beams reinforced with banana fiber bars, the following conclusions can be made:

1. Waste materials from banana fibers can be converted into construction elements after chemical treatments.
2. Banana fiber recycling participates in reducing the global warming that comes from pruning of this waste and also reduces the percentage of CO_2.
3. The use of banana fiber bars has good economic impact due to the low cost of banana fibers.
4. The use of banana fiber bars increases the flexural strength by 25% compared to plain concrete.
5. Banana fibers are considered a renewable resource, so they can be obtained for industrial purposes.
6. The predicted numerical results from the nonlinear analysis program ANSYS for loading and deflection at ultimate and first cracking levels show a good agreement with the experimental results. The average ratio between experimental measured load and predicted numerical load is 0.989 at ultimate level.
7. The simulated cracking patterns and failure modes are similar to those of the testing results for all beams.
8. The average ratio between the predicted and the experimental deflection at ultimate load is 0.866. This is due to the assumption of full bond between banana fiber bars and concrete.

8. Recommendations

1. The use of banana fiber bars in reinforced concrete beams is recommended due to their corrosion resistance, low cost, and ecofriendliness compared to the use of other types of synthetic fibers.
2. This kind of fiber is needed for low-cost buildings due to the fact that the urgent need to enhance suitable and cheap housing is born as an outcome of the fact that over 1 billion human beings in the world, who mostly stay in developing nations, are both homeless or stay in very poor housing.
3. Concrete has high permeability coefficient, and that allows water to enter the concrete and reach the reinforcing steel, causing corrosion, which reduces the diameter of the steel that leads to damage in the structural elements (beams), so more sustainable elements such as banana fibers bars should be sought as a substitute for traditional steel for severe atmospheric conditions.

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