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Repair and strengthening of bamboo reinforced acrylic polymer modified square concrete columns using ferrocement jackets

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ABSTRACT

This study investigated the role of acrylic polymer as concrete matrix modifier and ferrocement jacket confinement to repair and strengthen treated bamboo reinforced square concrete columns. 30 concrete columns (CC) of 150 × 150 × 600mm were produced using cement:sand:aggregate ratio of 1:3:3 and a polymer:cement ratio of 1:10 based on ACI 548.3R standard. 10 CCs' were produced from both conventional and modified concrete which were tested until failure. Another 10 CCs' from both concrete design mixes were preloaded at 25%, 50%, and 75% of ultimate load and thereafter repaired with ferrocement jacket and axially tested. The last 10 CCs' were ferrocement jacketed before axial testing. Axial and lateral deflections were evaluated during the tests. The crack pattern and failure modes of the columns were also considered. The highest average ultimate load was obtained from column with ferrocement and polymer addition at 60% increase in comparison with the control column. The least axial and lateral deflections were 93% and 72% which were from columns repaired with ferrocement material. The cracks in the interface and its propagation developed with sequential increment of load and new cracks started to form at zones closer to the upper face in contact with the machine. Bulging and peeling of mortars characterised the failure pattern of the CCs'. Acrylic polymer and ferrocement jacket repaired columns showed an improvement which came close to the strength of the unrepaired columns.

1. Introduction

Steel is a major construction material, mostly used for reinforcement in constructions involving load bearing applications. On the other hand, some variables which include huge cost, corrosion in concrete and steel's non-renewability are key issues for users. Therefore, focus has shifted to the more environment friendly and renewable material such as bamboo, which obviously has some characteristics like steel [1]. Bamboo has a huge advantage because it grows rapidly and attains

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its optimum strength in few years. It is found in abundant supply in the subtropical and tropical parts of the world [2]. These are regions that are closely associated with third world countries in which the greatest urbanization and birth rate rates can be found and they require adequate shelter to be provided for their teeming population. Bamboo has become an alternative to steel, as most developing countries will benefit from its use in construction economically [3]. The amount of energy required for the production of steel or cement which are essential materials used in construction industries is huge and it is in contrast to that of bamboo, which needs little energy [4]. Bamboo has a high tensile strength which could get to around 365MPa [5]. Many studies on the use of bamboo as a structural material to replace conventional steel have been carried out. Chow studied the use of bamboo as a low cost building material as early as 1914 [6]. Nevertheless, work on reinforced concrete by bamboo started only after the 1950's [7]. Earlier studies include [8–11]. More recent studies on use of bamboo as reinforcement include [12-14]. In some of the foregoing researches, problems such as concrete debonding, water absorption, fungal attacks and thermal expansion coefficient were prevalent. More innovative ways of utilising bamboo in cement were similarly conducted by some contemporary researchers. An experimental study to increase bamboo's load carrying capacity by filling the bamboo cavity with concrete mortar was carried out by Li *et. al.*, [15]. Another important study was carried out by Puri [16] in which prefabricated bamboo reinforced walls were built to promote low-cost housing. In the same vein, Moroz *et. al.*, [17] analysed and compared the performance of bamboo reinforced shear walls with steel reinforced walls. Others include Zhao *et. al.*, [18], Karthik *et. al.*, [1]. Researchers have analyzed the behaviour of bamboo bond strength with concrete under various epoxy forms such as Sand Negrolin, Sand and wire Negrolin, Araldite, Tapecrete P-151, Sikadur 32 Gel, Negrolin [19]. Nevertheless, such epoxy treatment is costly and alternative methods which can render bamboo impermeable involve using cheaper treatments such as asphalt paints, tar-based paints, bituminous materials for treatment of the surface [2]. Bamboo strips as reinforcement in concrete columns hold a huge prospect most especially for developing countries. Columns are important structural components designed to support the buildings' vertical loads and hence need adequate lateral confinement to effectively bear axial loads. Lateral confinement however is necessary to support major deformation while loading. In the situation of a major earthquake, an adequately confined concrete core will disperse high quantities of energy. Therefore, when exposed to such intense loading activities, the strength of this core increases. Existing below-standard or weakened columns should therefore be retrofitted or strengthened by external confinement to improve load carrying capacity and ductility. Different materials and methods for repairing substandard or damaged columns from reinforced concrete have been identified. Ferrocement is a long-established and potential material used to strengthen concrete structural elements due to its inherent crack-resistant capability and strength [20]. Ferrocement in developing countries is a cost-effective technique as its raw materials are readily accessible. However, its installation requires no skilled labour for the structure to be put in place. There are already concluded researches on the analysis of the nature of confined reinforced concrete columns when cracked or preloaded using square and rectangular ferrocement columns. These studies include; Mansur and Paramasivam [21], Ganesan and Anil [22], Seshu and Rao [23], Rajesh [24], Mourad and Shannag [25]. For ferrocement to be effective it is important to maintain the component materials' strength over time when exposed to any environment. These components include mortar, wire mesh reinforcement, and the bond between these materials. One way to improve the matrix material to achieve high efficiency is by modifying the mortar in the ferrocement mixture with polymer [26]. Concrete mix based on polymer modification is defined as combination of compounds composed of polymer material as a key ingredient which are effective in modifying or enhancing properties such as strength, adhesion, deformability, waterproofing of the cement mortar in order to enhance concrete durability. The product of blending polymers based admixtures with cement mortar and concrete are known as polymer-modified mortar and concrete. The inclusion of polymer has been shown to improve the mechanical and other engineering properties of cement based composites [27]. All the researches described centered on structural bamboo's mechanical properties or bamboo's behaviour as concrete reinforcement. Additionally, ferrocement experiments focused mainly on its use as a constituent of conventional or unmodified cement mortar/concrete. However, to the best knowledge of the authors, limited studies exist on the effect of polymer modified mortar on treated bamboo reinforced concrete columns. Secondly, there seems to be dearth of information on the axial strength behaviour of polymer modified ferrocement material used in retrofitting bamboo reinforced columns. Therefore this paper reports a novel experimental investigation on the suitability of treated bamboo strips as reinforcement in both normal and modified concrete columns, as well as the prospect of repairing damaged columns with modified mortar in the ferrocement material.

2. Experimental Programme

2.1. Selection and preparation of bamboo strips

Bamboo culms from *Bambusa vulgaris* species were obtained from Landmark University with their ages ranging from 4 to 5 years. They were held in a bench vice and subsequently pre-cut into 5×50×450mm. Subsequently, four of these strips were connected together using short steel stirrups to form a column of bamboo reinforcement. The nodes of the bamboo splits were positioned upwards to improve bonding with cement matrix because the bending strength of bamboo is greatly dependent on the position of nodes, which stiffens the culms (stem) at intervals thereby preventing buckling or collapse of the columns. These pieces were approximately 100mm apart from each other with an average thickness of 0.4 - 0.6 cm. OCI 934H Super bond adhesive which is a bitumen based thermosetting adhesive was applied on the surface on the bamboo columns. Thereafter, for good bond with the concrete, fine sand was applied on the adhesive coated surface to produce a

(a) bamboo strips within moulds (b) Demoulded columns

Figure 1. Treated bamboo strips columns.

simulated ribbed surface similar to that of steel bars which would improve the bond to the concrete. The bamboo columns were then stacked on top of each other and placed on a flat surface for air drying in the laboratory at 23 °C for 14 days.

2.2. Mortar preparation

The materials used in the preparation of the mix were Type 1 Portland cement while the acrylic latex polymer used has a viscosity at 30°C of 10.30(mPa.S), density of 2.15g/cm^3 and refractive index of 1.4210 respectively. Fine sand passing through 2.0mm sieve from river sand was also used. It has been established from a previous study [28] that the optimum latex polymer constituent necessary for modifying mortar to produce the desired high strength is 10% of cement content. The cement:sand:aggregate mix ratio of 1:3:3, water/cement ratio of 0.58 and the acrylic polymer:cement ratio of 1:10 (ACI 548.3R standard) were maintained for good workability of the mix. The concrete mix achieved a compressive strength of 42 MPa after 28 days. Chicken wire mesh used had small openings of 7×7mm and average yield strength of 547MPa at a yield strain of 0.0012.

2.3. Preparation of column specimens

Ten numbers of 5 × 150 × 600mm (Figure 2) wooden columns were utilised for the experiment while a total of 30 columns were produced for the tests. Table 1 was used to produce the two different types of mortar reinforced columns. The first has conventional cement mortars (without acrylic polymer modification) while the second group were for acrylic polymer modified concrete. Subsequently, small portions of the matrix were poured into all the 10 moulds and the already treated bamboo columns were placed inside them (Figure 1a). The reinforcements were vibrated manually for some seconds to allow the concrete to encapsulate them and also to eliminate voids at the edges and the nodal region. The remaining empty part of the columns were later filled up with concrete and allowed to cure in the air for 24 hours before they were demoulded (Figure 1b).

For column groups $P_{11\ -15}$ and $C_{11\text{-}15}$ which required ferrocement jacket before the tests, the edges were chipped off to a radius of 20 mm from one side to the other. This was done for the entire 4 edges of the square column to give a round edge and for proper adhesion between the applied mortar layer and concrete surface. Thereafter, the bundle of the wire mesh was placed around the columns with an allowance of 15mm at the top and bottom of the columns. The mortar was applied on the surface layers of the columns through the mesh until they were completely covered. This was done for the already cured samples that needed to be ferrocement jacketed before the test in order to improve the uniform lateral confinement [29].

2.4. Testing procedure

Three phases of testing were performed:

Phase 1: control column samples without preloading and without jacket were tested until failure and the ultimate loads were noted. Phase 2: Preloaded at 25%, 50% and 75% of ultimate load and thereafter repaired with ferrocement jackets while Phase 3 involves ferrocement jacketing before the preloading at 25%, 50% and 75% of failure load. The control and preloaded column samples were prepared for axial testing after 28 days of curing.

Table 1
Design for bamboo reinforced acrylic polymer modified ferrocement columns.

Specimen Designation	Production details	Process involved	Jacket Status	Status	Replicates
P_{1-5}	Acrylic polymer mortar and bamboo column reinforcement	Tested until ultimate failure and the load was noted	None	Control	5
C_{1-5}	Conventional mortar without polymer and bamboo column reinforcement	Tested until ultimate failure and the load was noted	None	Control	5
P_{6-10}	Acrylic polymer mortar and bamboo column reinforcement	Preloaded at 25%, 50% and 75% of ultimate load	Ferrocement jacketed after preloading was concluded	Repaired	5
C_{6-10}	Conventional mortar without polymer and bamboo column reinforcement	Preloaded at 25%, 50% and 75% of ultimate load	Ferrocement jacketed after preloading was concluded	Repaired	5
P_{11-15}	Acrylic polymer mortar and bamboo column reinforcement	Ferrocement jacketing was done before the preloading at 25%, 50% and 75% of failure load	Ferrocement jacketed before preloading.	Not repaired	5
C_{11-15}	Conventional mortar and bamboo column reinforcement without polymer	Ferrocement jacketing was done before the preloading at 25%, 50% and 75% of failure load	Ferrocement jacketed before preloading.	Not repaired	5

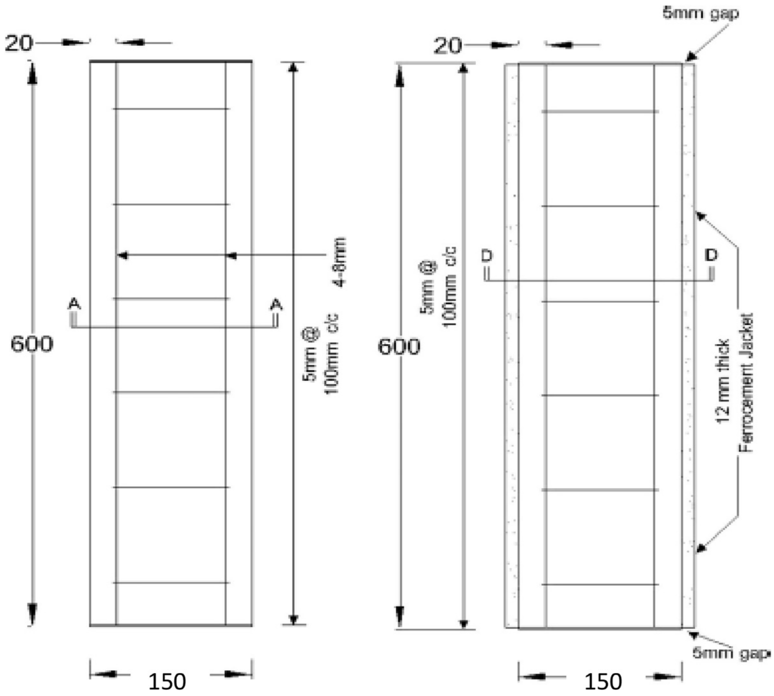

Figure 2. Schematic diagram of ferrocement jacketed bamboo column [33].

Figure 3. Test set up.

2.5. Instrumentation and test setup

Two sets of metal stand were used to hold dial gauges during the test without any form of contact with the specimens and the machine in order to give an accurate reading of the dials. The axial deflection at the top plate and the lateral deflections at the mid-point of the column specimens were measured with dials gauges. The load was applied at the top of the column and the failure was observed while the corresponding ultimate load was recorded (Figure 3).

Table 2
Comparison between ultimate loads of ferrojacketed and non-ferrojacketed samples.

S/N	Specimen Type	Status	Ultimate Load (kN)	Difference of loading
1	C_{1-5}	No Ferrocement	130(11)	-
2	P_{1-5}	No Ferrocement	143(9)	10%
3	C_{11-15}	Ferrocement	190(10)	46.2%
4	P_{11-15}	Ferrocement	210(14)	60%

*Values in parenthesis show standard deviation.

Table 3
Comparison between ultimate loads of ferrojacketed and non-ferrojacketed.

S/N	Specimen Type	Status	Ultimate Axial Deflection (mm)	Difference in Axial Deflection (%)
1	C_{6-10}	No Ferrocement	3.64(0.08)	-
2	P_{6-10}	No Ferrocement	2.09(0.03)	42 % decrease
3	C_{11-15}	Ferrocement Jacketed	1.66(0.01)	54 % decrease
4	P_{11-15}	Ferrocement Jacketed	1.61(0.02)	56 % decrease
5	C_{6-10}	Repaired with Ferrocement Jacket	0.25(0.004)	93 % decrease
6	P_{6-10}	Repaired with Ferrocement Jacket	0.65(0.007)	82 % decrease

*Values in parenthesis show standard deviation.

Table 4
Difference in lateral deflections.

S/N	Specimen Type	Status	Ultimate Lateral Deflection (mm)	Difference in Lateral Deflection (%)
1	C_{1-5}	No Ferrocement	1.26(0.04)	-
2	P_{1-5}	No Ferrocement	0.90(0.003)	29 % decrease
3	C_{11-15}	Ferrocement Jacketed	0.52(0.005)	59 % decrease
4	P_{11-15}	Ferrocement Jacketed	0.64(0.008)	49 % decrease
5	C_{6-10}	Repaired with Ferrocement Jacket	0.46(0.002)	63 % decrease
6	P_{6-10}	Repaired with Ferrocement Jacket	0.35(0.006)	72 % decrease

*Values in parenthesis show standard deviation

3. Results and discussions

3.1. Axial and lateral strength behaviour of samples

A higher ultimate axial load was observed with ferrocement jacketed specimens than control specimens. Table 2 shows the ultimate load carrying capacity of all tested specimens. Addition of acrylic polymer and ferrocement jacket definitely led to an increase in the ultimate load of P_{11-15} which had the highest axial load when compared with the control specimen. The improved ferrocement jacket technique was able to rehabilitate the cracked and damaged columns with the ultimate load and deflection comparable to that of control specimens as seen in Table 3. This possibly meant that the original load-deflection behaviour of the damaged columns was almost regained because of the efficient confinement provided by the ferrocement jacketing. The enhancement of dimensional stability and improved integrity of the composite material caused the increase in strength which was aided by the presence of a large volume fraction of mesh which provided confinement to the concrete core [30]. Huge confinement pressure is also applied on the core components and the redistribution of crack propagation led to less lateral expansion of the core. Thus, the strength of the confined specimen was found to be stronger than the unconfined controlled specimens. Higher values of ultimate load and lower displacement were noted with acrylic polymer modified columns on rehabilitation in comparison with control samples. This implies that repairing partially damaged column specimens helps in regaining the initial strength and improved the load-deflection reaction. A comparable report was made by Fang *et al* [31] who explored the use of alkali-activated slag (AAS) ferrocement to strengthen corroded reinforced concrete columns. For the repaired specimens, the reinforcements and stirrups were observed to be stronger with confinement of AAS ferrocement. When force is exerted externally to a body, stress is developed within the body and the level of stress increases as the force increases until the failure of that body is reached. Therefore, stress concentration occurs at the corners in the case of the conventional square ferrocement jacketing specimen [29]. There is concentration of stress at the middle of the jacketed specimens and this caused the bulging and peeling of the mortars. Another reason was provided by Smith *et al.* [32] in a recent experiment. It was outlined that the method of confinement could be changed by the regional confined concrete which works by transferring the stress in the well-confined region to less confined region thereby making the confinement stress to be well distributed and more effective.

Table 4 showed that movement along the lateral direction perpendicular to the applied load is less than movement along the axial direction which attests to the strength of the dual improvement of both the polymer and the mesh which were incorporated into the columns.

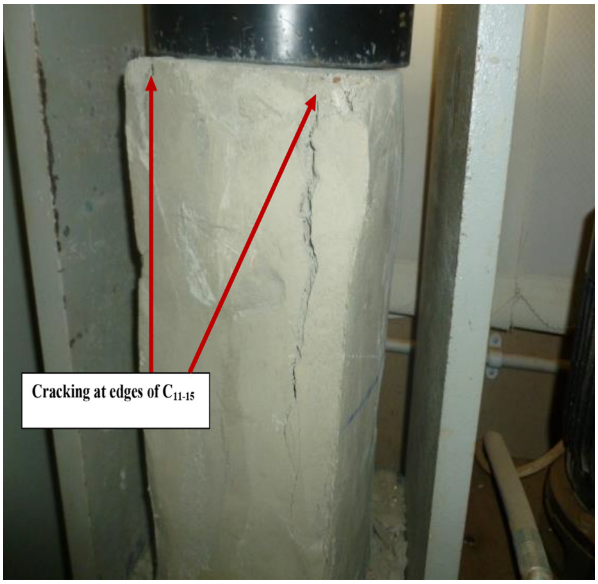

Figure 4. Cracking at edges.

3.2. Crack pattern and failure modes

3.2.1. Control columns

Formation of the first crack of the control specimen occurred at the point of contact with the top plate. The failure was caused by cracks emanating from vertical hairline at the center of the control column sample. The cracks in the interface and its propagation developed with sequential increment of load and new cracks started to form at zones closer to the upper face in contact with the test machine. The vertical cracks became noticeable around 91% to 96% of the ultimate load value. The amount and size of these cracks increased with increment in axial loading until failure of the specimens occurred. It could also be observed that these columns failed by development of cracks, little splinters and chips of mortars being broken off the interface of the columns. However for majority of these samples, the physical appearance of the columns looked okay unless a closer observation was made, but the structural integrity of the its core has already been compromised which typifies that internal cracks had developed first before it is propagated to the surface of structures and widens over time.

3.2.2. Unloaded columns (Ferrocement Jacketed Specimens)

Failure of the specimens commenced by cracking in the ferrocement jacket. The applied load resulted into stress concentrating on the ferrocement jacket which developed into initial cracking at these points of stress. Cracking occurred at the edges of the C_{11-15} samples because of stress concentration while cracking took place at the center of each face for the P_{11-15}-type columns because the stress concentration has been reduced due to the presence of rounded corners. Points of curvature change also experienced cracks as these points are known for their stress concentration areas. For the other concrete columns, occurrence of cracks took place at the center of each column face and at the corners. These were responsible for the peeling and bulging of the mortar layer from the specimen as observed in Figure 4.

3.2.3. Preloaded columns (repaired)

Repaired preloaded columns failure occurred gradually by bulging and cracking of the mortar that was worked through the mesh of the ferrocement jacket during the repair process at the upper part of the specimen. It progressed downwards (Figure 5) while failure of the C_{6-10} occurred near the corners. Progressive failure mode was observed as a result of the initial damage triggered by preloading the columns to 25%, 50% and 75% of ultimate load. All the tested concrete columns started to fail at the upper level in contact with the loading plate. This might have been due to the strong internal confinement of bamboo reinforcement within columns supplied by the metal tie bars. The crushing levels and cracking along with the height in both types of samples were almost the same because of the comparable tie bar connections in all the types of specimens.

4. Conclusion

This study looked at the possibility of developing reinforced concrete columns using treated bamboo columns and the influence of acrylic polymer as concrete modifier. Another aspect of the experiment considered the possibilities of repair and strengthening of pre-damaged columns using ferrocement. The highest axial load was observed when acrylic polymer was

Figure 5. Initial crack, bulging and peeling of mortar.

used to modify the cement mixes in addition to the influence of the ferrocement jacket when compared with the control sample without polymer modification and ferrocement confinement. Cracked and damaged columns on rehabilitation with improved ferrocement jacketing technique showed ultimate load and deflection that is close to that of control specimens. The observed failure modes of the columns include development of cracks, little splinters and chips of mortars being broken off the interface of the column. While bulging and peeling of the mortar coatings from the surface were the dominant failure patterns of the repaired specimens.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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