THE STRUCTURAL BEHAVIOUR OF CONCRETE- FILLED BAMBOO COLUMNS UNDER AXIAL COMPRESSION

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A Thesis submitted in partial fulfilment of the requirements for award of the degree of Master of Science in Structural Engineering of Masinde Muliro University of Science and Technology

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DECLARATION

This thesis is my original work prepared with no other than the indicated sources, support, and has not been presented elsewhere for a degree or other award

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance of Masinde Muliro University of Science and Technology a thesis entitled **"The Structural Behaviour of Concrete Filled Bamboo Columns under Axial Compression."**

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DEDICATION

This thesis is dedicated to my wife Nancy and family.......with love.

ACKNOWLEDGEMENT

First of all I thank my family for the love and support they gave to me. My brother Richard deserves my wholeheartedly thanks as well.

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ABSTRACT

Bamboo is a renewable and versatile resource, characterized by high strength to weight ratio, and has been widely used in the past to build both permanent and temporary structures. However it has a low compressive bearing capacity with culm buckling considered to be one of its critical mode of failure This limits its application to structures under light loads. This research proposes an innovative scheme to improve the load bearing capacity of bamboo by filling it with concrete to form a concrete –filled bamboo composite (CFB) column. The performance of such columns subjected to axial loads was experimentally investigated with parameters of interest being effect of concrete grade on load carrying capacity, deformation behaviour, confinement effectiveness and stress strain characteristics. Two types of concrete mix C20 and C30 were used to fill bamboo of diameters 55mm, 75mm and 100mm and heights 300mm,200mm and 150 mm for each diameter. Experimental results showed that axial load bearing capacities of bamboo filled with concrete mix C30 and C20 are much higher than the conventional bamboo regardless of the height and diameter of the column. However, bamboo filled with concrete mix C20 exhibited a more ductile behaviour and underwent large deformations before failure than when filled with concrete mix C30. In addition, capacity enhancement and confinement effectiveness were more pronounced in columns filled with concrete mix C20, attributed to low stiffness and flowability of the concrete. Stress strain response was initially linearly elastic upto about 20% of the maximum crushing stresses. Above this point, the stress increased gradually up to the maximum crushing stresses. Upon attaining maximum crushing stress, the curves descended into a softening region and eventually crushing failure occurs at an ultimate strain in tension. Finally, an equation was proposed for predicting the ultimate bearing capacity of concrete-filled bamboo columns. Results calculated from the developed model compared well to those obtained from the experiment with $R^2 = 0.723$ hence can be used in predicting the axial load capacity of concrete-filled bamboo columns.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
BRE	British Research Establishment
BS	British Standard
CFB	Concrete Filled bamboo
RB	Raw Bamboo
CFST	Concrete filled steel tube
FM	Fineness Modulus
FRP	Fiber –Reinforced Polymer
USBR	United States Bureau of Reclamation
UTM	Universal Testing Machine

LIST OF SYMBOLS

A_b	Bamboo area of crossection (mm^2)
A_{sc}	Crossectional area of confined concrete (mm^2)
Do	Outer diameter of the bamboo (mm)
E	Elastic modulus (N/mm^2)
fc	Specified characteristic strength of concrete (N/mm^2)
f'_{cc}	Confined concrete compressive strength (N/mm^2)
f'_{co}	Unconfined concrete compressive strength (N/mm2)
f'_{cu}	Cubes characteristic strength (N/mm^2)
f_m	Target mean strength (N/mm^2)
f_y	Yield stress (N/mm^2)
F_{st}	Culm stiffness (N/mm^2)
M	Margin Strength
P	Load (kN)
s	Standard deviation
t	Culm thickness (mm)
FM	Fineness Modulus

CHAPTER ONE

INTRODUCTION

1.1 Background information

Housing industry is one of the most energy consuming sectors on earth. Materials such as steel, concrete, plastics, glass, and many others, have commonly been used in the construction of houses. However due to the increasing costs of these materials their use in low cost construction is not economical.

In Kenya the rapid growth of population has resulted in the growing demand for cheaper housing solutions that are both sustainable and efficient in the long term. Bamboo being a renewable material has generated special interest as an alternative building material as evidenced by many authors and researchers who have dealt with experimental and theoretical investigations on its ultimate load carrying capacity and strength. In Kenya, Bamboo farming is fast gaining popularity as it takes little time to mature, being ready for harvesting in approximately five years unlike other trees which takes decades. Bamboo takes little time to return profits and can be harvested for up to 40 years as they are self-reproducing without the need to replant.

Yushania alpina is the indigenous specie of bamboo commonly found in Kenya and naturally occurs in the highland ranges. Bamboo in Kenya has been classified as a cash crop and the Kenyan Government has urged individuals and community farmers to take up the growing of bamboo as a commercial activity that can improve their socio economic status and livelihoods. (www.kefri.org). Many research works has been done by both scientists and engineers in different ways on the overall growth of bamboo and how its property can be improved for applications in housing industry as a structural material.

Most household utilities and building applications such as trusses, purlins, windows, fences, ceiling ,rafters etc. in Asian and African have used widely bamboo due to high market demand and advances in processing technology. A Concrete filled bamboo is a composite and homogenous consisting of two distinct components physically assembled without physical blending. The resulting material is a constituent of the different materials which forms matrix and reinforcement thus combining the good characteristics of each of the material. Bamboo supports by surrounding concrete thus acting as as a reinforcing and maintaining their relative positions. Matrix properties of bamboo are enhanced by the imparted special mechanical and physical properties concrete infill. In the modern society, concrete importance cannot be ignored. Most of the structures such as dams, roads, bridges everywhere are made of concrete which is a composite material made of binder and filler. A synthetic conglomerate is made by the binder which glues together the filler. Water and cement are the constituents used for binder while coarse or fine aggregate are the materials that form the filler.

Theres significant use of bamboo as a construction material In Kenya,though on a small scale. Some demo houses were put up at Maseno University to showcase local population on how to use bamboo, in 2009. The houses include non-engineered and engineered bamboo with various techniques of construction. Bamboo was engineered to function as conventional timber. It was harvested from Kakamega forest to build the non-engineered house while the engineered bamboo house comprised of an engineered bamboo frame that was plastered. Bamboo was treated using a Boron-borax solution, seasoned and used in construction of both houses. The columns and roof were made of whole bamboo culms while the ceiling utilized flattened bamboo (www.builddesign.co.ke)

The most dominant factors in concrete making are workability and strength. By increasing the content of cement, strength can be increased though this reduces workability. For better workability, the content of water can be increased but this affects the strength. Thus there should be maintenance of perfect balance between workability and strength. While the concrete tensile strength is relatively weak, its compressive strength is generally high. Iron mesh, fibre or steel bars are generally used to reinforce concrete since it can crack under its own weight hence the need for reinforcement. Cement and water ratio, aggregate strength used, type of cement are the factors determining the strength of concrete. Good quality concrete can be obtained through correct proportion of ingredients, curing and proper placement.

Materials from the two components are produced through synergism while an optimum combination can be chosen by the product designer as a result of strengthening materials and matrix which is in wide variety. Therefore for the reliability and design purposes, the study of bamboo filled with concrete under axial loading is imperative so as to understand their behaviour and performance. In this research, emphasis is placed on concrete filled bamboo (composite material) and raw bamboo under uniaxial loads using compression machine (UTM) It is expected that filling bamboo with plain concrete, its energy absorption capacity strength and ductility can be greatly enhanced.

A concrete- filled bamboo (CFB) member consisting of a bamboo culm filled with concrete material realizes the importance of bamboo to provide confinement for the concrete and thereby increases its load bearing capacity. From the structural point of view, concrete in the hollow section of bamboo enhances ductility and prevents local buckling up to the ultimate load .Both the materials in composite member would resist the external loading by interacting together in bond and friction. Through this combination the advantages of both bamboo and concrete are utilized effectively in composite column.

1.2 Statement of the problem

Materials such as reinforced concrete, structural steel, and timber are used as a tradition in most buildings. Their global increase in prices coupled with bludgeoning population in most developing countries has provided numerous challenges in provision of decent housing to many people with low income values hence search of alternative materials which are cheap to obtain. The use of bamboo as a construction material has recently regained special interest. Bamboo growing in Kenya is currently estimated to cover about 150,000 ha. and grows in Mt Elgon, Cherangany hills, Aberdare's ranges, Mau escarpments and Mt Kenya (www.kefri.org). Bamboo properties include high strength to weight ratio, low cost, easy availability and harmless to the environment (Ashok Gupta et.al, 2015). There is potential that bamboo can be used more extensively in all parts of a building, as both architectural and structural elements. However some of the critical issues of bamboo being used in a building system are their inherent insufficient material strength, buckling and durability. In most cases, bamboo may be more suitable for use in temporary structures, rather than permanent structure. To address these problems there's need to seek out new material to form a hybrid system with bamboo to complement the inherent properties. In this research, concrete is considered due to its durability and has a high level of compressive strength. From the structural point of view, this necessitates examining this composite material in detail by carrying out more natural and numerical experiments to study their behavior when subjected to axial compressive loading. This will determine its suitability as viable alternate building material for low cost dwellings and other structures with light loads.

1.3 Justification

Whereas the behaviour and mechanical properties of several composite materials such as plastic, fibre and steel have been thoroughly studied and well documented, there's limited literature on concrete filled bamboo hence there is less comprehensive data on the same. The study thus aims in bridging this gap in providing preliminary data on the mechanical properties and behaviour of bamboo when filled with concrete.

Bamboo will be used as a confinement medium of concrete and hence act as permanent formwork thereby eliminating the necessity of providing temporary formwork. This can significantly reduce the overall cost of construction, This is an advantage where the resources are limited. Furthermore bamboo unlike steel or plastic requires no expensive technology in manufacturing and once planted it can regenerate itself over a period of time hence its cost saving. It is also less prone to corrosion, weathering and chemical attacks.

Yield strength of bamboo was determined to be between 204 N/mm^2 and 250 N/mm^2 (Alade and Olutoge, 2014) which compares well to mild steel (280 N/mm^2). On the other hand concrete fails by developing shear planes when subjected to compression loads which is a sign of brittleness hence little warning of impending failure. Combination of these materials with more less similar characteristics is thought to produce sections with better engineering properties such as more ductility.

1.4 Objectives

1.4.1 Overall objective

The general objective is to study the structural behaviour of concrete- filled bamboo columns under axial loads.

1.4.2 Specific Objectives

1) To investigate the effect of concrete grade, column diameter and column height on the load carrying capacity of the concrete filled bamboo columns

2) To determine the effectiveness of bamboo in confining the concrete

3) To investigate the axial strain, stress and deformation characteristics of the concrete filled bamboo column

4) To develop a model for predicting the carrying capacity of concrete filled bamboo column and compare it with experimental results and commonly used code formulae.

1.5 Significance of research

The out-come of this research will create knowledge and awareness in society on the potential of using concrete-filled bamboo as construction materials substitute to already limited and strained traditional building materials such as concrete, steel and timber.

Bamboo filled concrete is relatively a new material and therefore its adoption is limited due to lack of adequate information on its performance. No standards for design are available since its application in structural engineering are still in early stages. This research provides further input to literature by studying some behavioural and structural performance of this composite column system. It extends the knowledge by addressing new parameters which have not been tackled by previous researchers such as varying culm diameters, slenderness ratios and concrete characteristic strength which is necessary to provide a comprehensive database for design of this composite system.

To this moment Bamboo is mostly used exclusively as a linear element e.g. in frame works for residential projects and in formworks. In the present research, a very intuitive process of combining a highly compressive strength concrete with bamboo to form a composite column is investigated experimentally and analytically offering a better insight into the load bearing mechanisms of such system which can help the bamboo industry to increase the supply of potential commercialized bamboo for worldwide products and extend its industrial application

1.6 Scope and limitations

This research evaluates the performance of bamboo columns when filled with concrete grade C20 and C30 under concentric axial loads. Although various species of bamboo are available in the country such as Guadua angustifolia, Bambusa vulgaris,Dentrocalamus asper,Moso bamboo,Gigantochloa apus, the study was limited to the use of Bambusa vulgaris. Also due to height limit of the machine, no specimens greater than 300mm heights could be tested thus limiting the bamboo of diameter 100 to slenderness ratio of 3

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review spanning the range of the complex biology of bamboo. Prior research conducted on physical and mechanical characteristics are highlighted and compared for understanding its behaviour when used in applications as a construction material.

2.2 Physical characteristics of Bamboo

Bamboos are natural perennial giant grasses as shown in plate 2.1 that belongs to the family *Poaceae*, and tribe *Bambuseae.* There are approximately 60-90 bamboo genres with close to 1100-1500 botanical species in the world (Yan Xiao, 2008). They grow in calm and sub-tropical areas primarily on mud loamy to sandy topsoil. They have a short development cycle and adaptable to most environments (Gupta, 2015). to mature which varies according to the specie (American Bamboo Society, 2014).

Plate 2.1 Bamboo grass

Bamboo is used in many forms of construction especially in rural areas. Although not enough attention has been paid toward research and development as is the case of other building materials such as timber (Mehra 2010), due to rising demand for building materials which are not only friendly to environment but also sustainable, this concept is fast changing. Bamboo makes a good building material due to its efficient natural design. Researchers believe due to its excellent engineering properties in the near future, it would be a prominent material and the world would witness more and more uses in construction of a cheap, simple and structures which are environmentally friendly.

Due to extensive varieties of bamboo species and families, their properties change accordingly. When it loses water, bamboo shrinks more than wood with 10–16% in the cross section, and its elasticity which is enormous makes it a better construction building. It can be moved around easily as it has a relatively low weight (Klaus, 2002)

Nodes segment the bamboo culm, or stem at regular intervals. The node helps in walls buckling prevention as they manifests as a diaphragm to the inside of the stem. The internode is the space between nodes (Figure 2.1); the internodal spacing varies along the culm and between species.

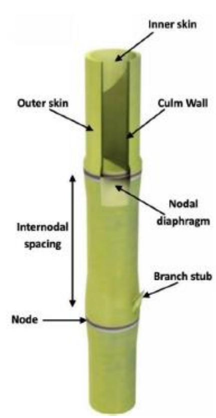


Figure 2.1 Structure of Bamboo Culmns (Kaminski et al., 2016)

Some species commonly used in structures around the world are listed in Table 2.1

Table 2.1 List of commonly used structural Bamboo species around the world (Clayton,2015)

Scientific name	Areas found	Diameter (mm)	Solid/Hollow
Guadua angustifolia	South America	120-160	hollow
Dentrocalamus strictus (calcutas)	Asia	25-80	hollow
Bambusa vulgaris	Africa Asia,South America	80-150	hollow
Dentrocalamus asper	Asia	120-180	hollow
Bambusa blumena	Asia South America	50-200	hollow
Gigantochloa apus	Asia	60-150	hollow

Table 2.2 provides various bamboo species typical design capacities and diameters with different modes of failure based on limit state approach using Technical Note 3 and 4, for Service Class 2 and permanent loading. (Kaminski et al 2016).

Table 2.2 Design capacities of different bamboo culm diameters (Kaminski et al, 2016)

Failure Mechanism	50mm wall thickness	100 mm wall thickness	150mm wall thickness
Flexure (kNm)	0.1	0.7	2.4
Shear (kN)	0.3	1.0	2.4
Axial (kN)	10	45	100

2.3 Bamboo applications in construction.

As shown in Plate 2.2, bamboo culms can be used to provide decking support as supporting pillars and skeleton frames. By treating bamboo poles against rots and fungi, they can be used in foundations by driving directly into the soil. Bamboo can also be used in flooring as shown in plate 2.3 due to its exceptional aesthetic qualities. It is a natural resource, high yielding renewable and possess an environment advantage over finite raw materials. It can help in preventing deforestation and reduce forest hardwood demand when used as flooring (Sharma P and Mehta S, 2014)

Plate 2.2 bamboo used for scaffolding in Nigeria (Anon.2015)

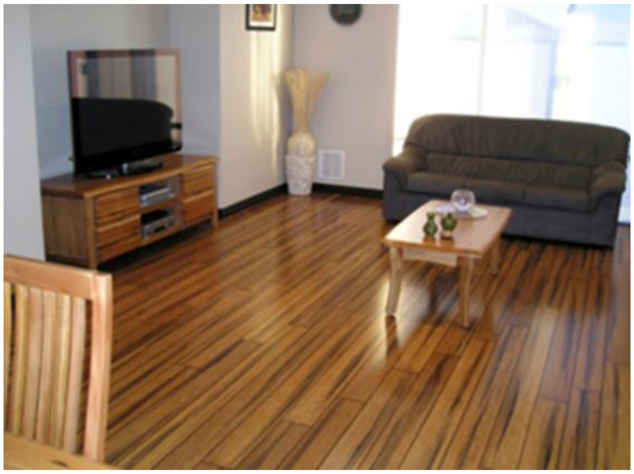


Plate 2.3 Bamboo flooring system in Nigeria (Anon 2015)

Bamboo is an excellent material to be used in trusses and for roofs and thus can substitute or form an alternative for roofing frames with large distance in span. (Oyejobi and Jimoh, 2019).

Studies conducted by Gupta et al., (2015) state that steel in reinforced concrete can be substituted by bamboo due to its strength which is greater than most timber products but is almost half that of steel tensile strength.

2.4 Bamboo structural characteristics.

One of the earliest attempted researches on bamboo structural behaviour was made by Gyansah et al., (1995) by conducting a test programme on fracture behaviour and crushing strength on fresh bamboo under compressive uniaxial loads. They found that 85.2, 79.5, 74.5, 71.2, and 51.3 N/mm^2 were the crushing stresses for the fresh bamboos of height 90, 130, 170, 210 and 250 mm respectively. This revealed that the strength of bamboo is much higher compared to concrete and other wooden structures. They also concluded that even though the compressive strength increases as the bamboo grows older; its tensile strength remains the same throughout its lifetime.

Alade and Olutoge (2014) determined the bamboo tensional strength to be between 250 and 204 N/mm^2, a result comparing favourably with those of mild steel. While the diameter of bamboo influences tensional strength, this doesn’t exist in the case of steel conventional reinforcement.

Bamboo of six different species was studied by Ghavami (2004) in terms of methods to be employed when using bamboo reinforcing concrete, application of treatments and the mechanical properties. The positive attributes were listed supporting the environment-friendly nature while its tendency to absorb water was listed as a negative attribute. The properties of bamboo were found to be based upon a functionally graded construction, with the ratio of specific weight to strength being five times that of steel. The study further concluded that for design purposes there's need to establish bamboo characteristic strength and that steel can be substituted by bamboo satisfactorily.

Dinie A. et al., (2017) conducted an experimental study on four species of treated bamboos which included *Gingantochloa Scortechnii,dentocalamus asper, Bambusa vulgaris and Schizostachyum Grande* to determine their mechanical properties.The difference in their tensile strength and mechanical strength was examined by ccarrying out a mechanical testing in various parts along these species culm. A five month interval monitoring of moisture content and strength development of these bamboo species was also carried out. From the results, excellent mechanical properties in tensile and compressive strength were found in *Gigantochloa Scortechinii Dentrocalamus asper and Bambusa vulgaris* an indication of good quality to be used as a material for housing construction. They concluded that promising advantages can be offered by bamboo hence its suitability as a structural timber substitute in various construction, facilitating an indirect environment preservation globally.

Wakachure et al (2012) presented results of experimental investigations made on Dendrocalamus strictus species of bamboo to evaluate both mechanical and physical properties and its potential to be utilized in buildings either in split form or in whole. Their study included working out on compressive strength, dimensional changes, water absorption and moisture content at different height locations. There conclusion was that after harvesting there was variation of moisture content along the height at any time. Top sections had considerably lower content of moisture at all stages of seasons than the basal or middle portions. There was decrease from top to bottom the oven dry mass specific gravity which was independent from the content of moisture. Compressive strength, tensile and dimensional changes were directly proportional to the content of moisture while water absorption was inversely proportionate.

Meng & Sun (2018) experimentally studied the distribution of bamboo nodes and their effects on outer diameter compression. A formulae for calculating compression was deduced from a model of one loaded bamboo. Compression values were measured from one loaded bamboo (Phyllostachys pubescens) with 0,11 and 42 node. Bamboo with 11 nodes had a higher value of both measured and calculated outer diameter compressions compared to bamboo with 42 nodes. In addition, bamboo with 0 nodes registered a very high value of outer diameter compression value compared to the rest.

Janseen (2018) provided details in his book on using bamboo as a building material. He dealt with various aspects of bamboo going far as its natural habitat and plant structure. Details in mechanical properties, preservation methods ,calculations showing why bamboo is economical and building with bamboo are also discussed. Bonding is one of the greatest problem as listed in her book between the two due to bamboo smooth wall in addition to water absorption which is more of a problem than steel. There's a strong bond formed around steel reinforcement when concrete shrinks which is different from bamboo during hardening process as bamboo absorbs water immediately. This breaks down the bond between the two components affecting the overall performance of the composite structure to a lower level of yield strength of each individual element. By using waterproofing agent, bamboo swelling can be effectively reduced as suggested by Ghavami (2005)

Akinlabi et al., (2020) reviewed *Bambusa arundinacea* mechanical properties. With nodes, modulus of elasticity and tensile strength were concluded to be 126.2 and 114

MPa respectively. For Bambusa vulgaris, strength of compression without nodes was 98.80 MPa and with nodes was revealed to be 113.54 MPa and concluded that using brine to treat Bamboo showed better tensile strength than samples treated using acid or pure water.

Qingfeng Xu et al., (2019) presented a detailed investigation in quantifying bamboo mechanical properties degradation when immersed in water for 1 to 7 days, simulating significant rain events effects when bamboo is used as scaffolds. To obtain modulus of elasticity and strengths, splitting, longiturdinal shear and compression tests were conducted. An increase in content of moisture to about 30% was observed to significantly degrade bamboo mechanical properties to a value close to the expected fiber saturation point (FSP).

Alireza J et al., (2019) conducted a study to evaluate the relationship between thickness of the wall, content of moisture, diameter of culm and their dependence on *Dendrocalamus bamboo* mechanical properties. Results revealed direct correlation between these mechanical properties and specific density of bamboo while rupture modulus only correlated with content of moisture. While all mechanical properties were found to correlate with thickness of the culm,diameter of culm was in correlation only with elasticity and rupture modulus. Hence specific density and geometry of culm measurements can potentially affect bamboo strength when used as a material in construction.

Zou Meng et al (2015) studied the material properties and characteristics of the *Phyllostachys pubescens* species of bamboo using dynamic tensile and drop-weight tests. In dynamic tensile test, there was a higher tensile strength in bamboo of one -yearold (251 MPa), There was a greater nodal samples absorption of energy absorption compared to internode samples in drop-weight tests, specific energy absorption (SEA) values of internode and nodal were 9.78 kJ/kg and 11.85 kJ/kg, respectively.

2.5 Concrete.

Concrete is a vital material in all construction activities. Different structural members such as beams, columns, slabs, foundation and other load bearing elements are made using concrete as it can be cast in any shape. Cement, water and aggregates (fine and coarse) which are in unlimited quantities and readily available are the main components of concrete. Other biding materials can be used as a binder instead of cement such as bitumen for asphalt concrete and lime for lime concrete. To harden the mixture, concrete is placed in forms and allowed to cure. Reaction between the cement and water results in hardening which increases the concrete strength with age. (Neville 2011). Compaction and curing mix proportion and ingredient properties are the factors that determine the strength and durability of concrete.

2.5.1 Constituents of concrete

2.5.1.1 Water

Water is needed during hydration process to produce concrete by reacting with cement. For the full course of reaction to take place there must be sufficient amount of water available but strength depends on the amount of water added . (Neville 2011). Provided concrete is placed properly and cured, high quality of concrete can be provided when water is used in less quantity. Compressive strength and split tensile strength of cement concrete decreases with an increase in the *w*/*c* ratio and minimum *w*/*c* ratio required to make the cement concrete workable is 0.5 (Singh,S. et al.,2015)

2.5.1.2 Portland cement

The strength of concrete is derived from the cement hence it is important part of concrete. Concrete mix is composed of 10 to 15 percent of cement by volume. Water and cements reacts together during hydration and a rocklike mass is formed by binding to aggregates. As concrete gets older it gets stronger as the process continues over the years. In the chemical reaction, heat is released as a result making the reaction exothermic (Shirke A.H.and Bhandari P.K. 2014).

2.5.1.3 Aggregates

Aggregates have an influence on the properties of concrete since it occupies about 65 to 75% of the concrete volume. (Neville,2011). Aggregates passing through number 4 sieve can be defined as fine aggregates and include clay silt and sand. This category can also include crushed gravel and stone. Concrete mix typically can be improved by using fine aggregates. Coarse aggregates measure above the 4.75mm limit. These include gravel or natural stone which is not processed or crushed. They reduce amount of water needed for a concrete mix and but improve overall strength of concrete. (Ali S.A. and Abdullah S. 2014).

2.5.2 Design mix for concrete

Suitable ingredients selection (Water, coarse and fine aggregates, cement with admixtures if any) and calculating their relative proportions to give a desired strength, durability and workability is the main task involved in concrete design mix. Concrete quality in fresh state is determined by workability while in hardened state is determined by durability and compressive strength. Some of the factors considered in the design of concrete mix include type of cement, concrete characteristic strength requirements, the grading and type of aggregate minimum cement water ratio and workability.

Extensive experimental investigations have been done in different countries to produce empirical relationships, graphs and charts which constitute mix design methods. American Concrete Institute (ACI) and British Research Establishment (BRE) are the two methods commonly used in designing mix for concrete. The following is a description of the above mentioned methods.

2.5.2.1. ACI Method of design

In this method coarse aggregate content is determined based on Fineness Modulus (FM) of sand and bulk density of dry-rodded coarse aggregate.

Actual voids in compacted coarse aggregates to be filled by water fine aggregates and cement is taken into account by this method. The method is more suitable for air entrained since tables for both non air entrained and air entrained are given separately. Sand content values and water quantity for maximum aggregate sizes of up to 150 mm are given hence a preferred method of design for plum concrete.

2.5.2.2. BRE Method of design

Concrete mixes in this method are restrictedly designed to meet workability, durability and compressive strength requirements using cement complying with BS 4027 or BS 12 and natural aggregates meeting requirements of BS 882 or coarse and air cooled slag complying to BS 1047. Pumped or flowing concrete, lightweight concrete and other special material or special concretes are not dealt with in this method. The method is based on results based at building research Establishment, British Cement association and the Transport research Laboratory.

The method adopted in this research is the British mix design and BRE manual was used as a guide in all the design process and some figures and tables used in design extracted from the manual and referenced in the appendices.

2.5.3 Concrete- filled bamboo

Little research has ventured into the area of concrete- filled bamboo thus limited literature and data are available pertaining to the use of this type of composite column. Preliminary tests by Muhamad et al (2017) suggested using foamcrete to fill conventional bamboo as a modification on raw bamboo to reduce timber usage in construction. The study included tensile strength, compression strength, flexural strength, and splitting strength on the foamcrete filled bamboo (FCIB) and raw bamboo as the control sample. For compression strength and tensile splitting test, the height of culms was 300 mm while for bending strength test the length of the culm was 500 mm and for nailing test the height of culms was 200 mm. A total of 16 samples was used in the research. The results obtained from this research are summarized in Table 2.3

Table 2 3 Specimens strength of Bamboo filled with foamcrete (Muhammad et al.,2017)

SAMPLE	FCIB 1	FCIB 2	FCIB 3	AVERAGE
Compression (N/mm^2)	6.5	9.7	10.0	8.8
Flexural (N/mm^2)	4.5	4.2	3.8	4.2
Tensile (N/mm^2)	0.5	0.4	0.4	0.4

The results showed that there is an improvement of mechanical properties when bamboo is filled with foamcrete compared to original bamboo.

Gyansah and Abd (2015) studied the mechanical properties and deformation behaviour of concrete filled bamboo by filling bamboo specimens of different height with cement paste ratio of 1:3:6. The specimens were subjected through a series of axial compression tests The results from the research are summarized in Table 2.4

Table 2.4 Results of fresh Bamboo filled with concrete (L Gynsah and Abd 2015)

Height	Diameter	Concrete	Area	Failure	Stress	Strength
mm	mm	Mm^2	Mm^2	(kn)	Mpa	(kn/M)
250	86	74	4300	1507	26.09	13.717
210	85	74	4300	13.73	25.52	13.602
170	84	72	4071	1470	24.85	13.342
130	84	72	4071	1470	21.97	11.977
90	82	71	3959	1193	21.86	11.3

The following conclusions were made from the results.

- Reinforced bamboo crushing stresses of 21.86,21.97,24.85,25.52 and 26.09 MPa were of heights 90,130,170,210,and 250 mm respectively. It was thus concluded that filled concrete added strength in bamboo.
- Fresh bamboo strength was reduced by 21.8 % due to moisture content, a significant percentage since it can cause severe structural failures during analysis of structures.

However the research did not investigate on the effect of varying the concrete grade since all columns had similar concrete mix.

Li-Mian et al., (2019) conducted experimental studies on the Axial compressive behavior of sprayed composite mortar–original bamboo composite columns**.** Eight bamboo composite columns made of sprayed mortar and eight raw were investigated to determine their stability and bearing capacity through axial compression testing. Buckling was the main failure mode in slender columns while strength failure was the main failure mode in short columns at the ends of the columns. Short composite column supported by the total cross section experimentally ductility and ultimate load were 1.5 and 2.6 times higher than those of the short original bamboo column, respectively

Li. W. et al (2017) investigated the Axial load behavior of structural bamboo filled with concrete and cement mortar. A total of 19 specimens were subjected to compressive test. Results indicated that filling bamboo with cement mortar and concrete increased the intiall stiffness and axial load capacities, verifying the use of stiffening scheme proposed. Better ductility was seen in bamboo filled with concrete specimens than bamboo columns filled with cement mortar. The node effect on bearing capacity was found in bamboo specimns when filled with materials, hence bamboo nodes integrity is essential for the load carrying capacities of bamboo columns filled with materials.

Gan et al (2018) studied bamboo concrete filled steel tube columns under axial loading. In this type of column, concrete was used to fill the space between the inner raw moso bamboo and the external steel tube. Additionally, testing of both concrete-filled double skin and hollow concrete filled steel were done for comparison. The D/t of the steel tube (Diameter to thickness ratio) was the main experimental parameter in consideration. Results of the test showed ductility was better in composite columns with moso bamboo pipe as inner core than hollow concrete-filled steel tubular stub columns. Increase in D/t ratio increased ductility and bearing capacity in all the specimens tested.

Terai M et al., (2019) conducted a study in using cement paste to fill bamboo joints. Very limited results were produced when cement paste was used in reinforcing the joints in bamboo poles. The problem arises from the water present in cement mixture such that bamboo sucks part of the water when injected in the cavity resulting in the swell up of bamboo fiber.

Dulai et al., (2019) conducted an experimental study of the capacity of cement stabilised rammed earth Bamboo filled columns (CSRE) under concentric axial loading. Load lateral deformation, failure pattern due to reinforcement effects, and columns load –axial deformation were studied. It was shown from the results that columns load-capacity was significantly increased due to reinforcement i.e high ratio of reinforcement led to higher load-capacity.

2.6 Concrete confinement modelling.

Concrete confined composite elements are increasingly used in composite construction such as Concrete filled steel columns. When axially compressed, the confining element will not only provide confinement to the concrete infill, but also partially sustain the axial force. The composite element has a high axial strength as a result of confinement produced by the confinement medium. Medium of confinement such as plastic tubes, steel, composite wraps and steel have been studied extensively. However, to quantify confinement efficiency of bamboo is still missing. In this case passive confinement is considered as there is variation in confining pressure. To develop relevant models therefore careful investigation should be done on axial strength and stress state of bamboo.

2.6.1 Stress State of concrete and bamboo in confinement

In concrete-filled bamboo, the compression force (P) is sustained by both concrete and bamboo. The bamboo exerts a lateral confining pressure on the filled concrete and is therefore under triaxial stress state. Equation 2.1 as developed by Mander and Priestly (1988) can be used to estimate the compressive strength f_{cc} of the concrete when confined actively i.e. when confining pressure is constant.

$$fcc=fc+k\sigma r \qquad \text{2.1}$$

The confining element cross section geometry and state of loading are the limiting factors to the applicability of this model. To predict the confined concrete compressive strength, the following relationship was proposed from the results (Equation 2.2)

$$f_{cc}= 4.8\ f+klf_{co} \qquad \text{2.2}$$

where

f_{co} is unconfined concrete ultimate stress

f_{cc} is the confined concrete ultimate stress

k is a varying constant between 1.5 and 1

f is the applied confining pressure which is lateral.

Richart et al., (1986) investigated further those findings by subjecting normal weight cylinders of sizes 200mm x100mm to axial loading while applying hydraulic pressure constantly until failure. Concrete strength of confinement was defined as

$$f_{cc}=k_c f_r +f_{co} \qquad \text{2.3}$$

Confinement effectiveness is the measure of how well concrete is confined by a certain material and can be defined as equation 2.4

$$f_{cc}/f_{co} \qquad \text{2.4}$$

where

f_{co} is the unconfined concrete ultimate strength of compression

f_{cc} is the confined concrete ultimate strength of compression.

2.7 Summary

Much work has been done by various researchers on investigating both physical and mechanical properties of bamboo and its use as reinforcement strips in concrete. There is however limited studies on the behaviour of bamboo when filled with concrete of various grades to the best knowledge of the author. There is also lack of adequate information in regard to the use of concrete-filled bamboo from the review of previous researchers who have ventured into this composite material. This is even with the fact that bamboo has been found to be of great potential as an alternative to traditional building materials such as steel and concrete e.g. in low cost houses where their use would be uneconomical and other structures that needs nominal reinforcement as suggested in their recommendations and conclusions.

It is therefore imperative to understand through comprehensive study, behaviour of bamboo when filled with plain concrete for the purpose of reliability and design when subjected to monotonic axial loads. The current research focused on parameters such as CFB columns compressive strength variation when filled with concrete of varying grade, deformation behaviour, effect of varying slenderness ratio, and stress strain characteristics of this composite column. Finally a model is proposed for predicting the axial load carrying capacity that would provide a source reference for future design of similar materials. This aims in expanding and generating more knowledge to form a basis for suitability of using such material in housing construction.

2.8 Conceptual framework

This study involved the combination of mechanical and physical characteristics of both bamboo and concrete to form a homogeneous composite element. The independent variables include Bamboo column height, diameter and concrete grade. The Dependent variables are the compressive strength and ductility of the concrete-filled Bamboo columns and were obtained through compressive tests of the composite specimens. Figure 2.2 shows the conceptual framework of this research.

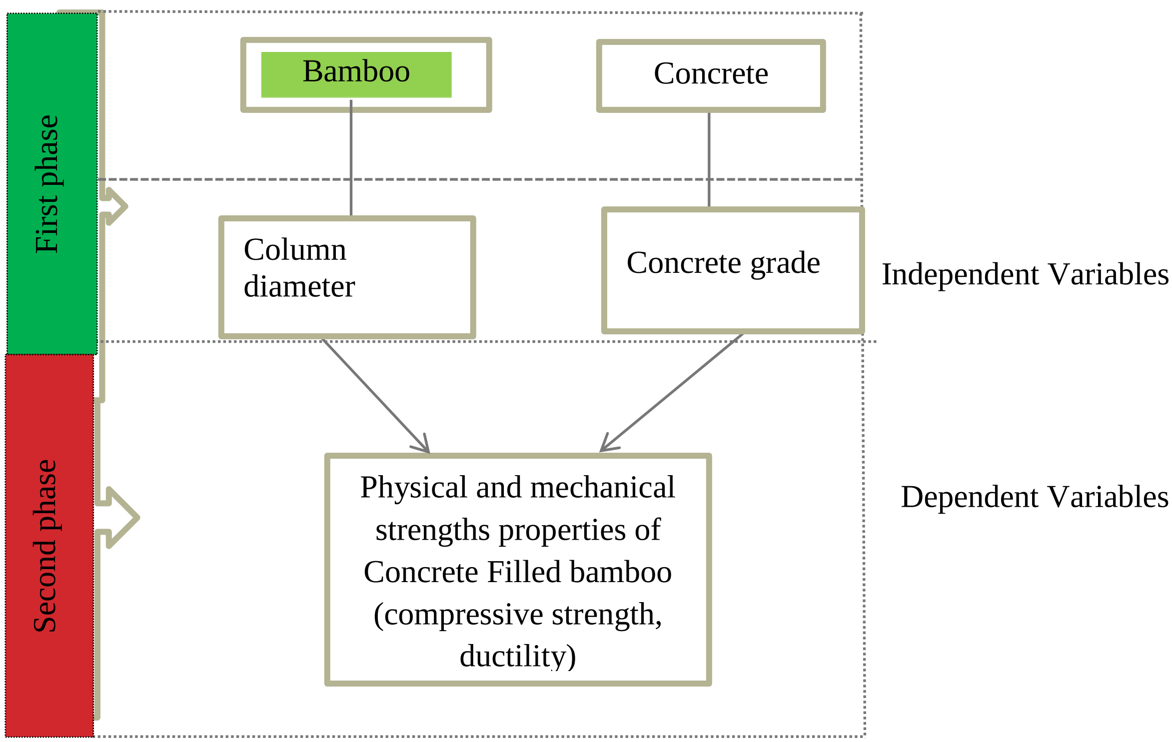


Figure 2.2 The Conceptual famework of the research

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter presents the experimental program of this research consisting of sample preparation, determination of general properties including sieve analysis and cube test for concrete .To study the interaction between bamboo and concrete in compression, several concrete reinforced bamboo specimens with different diameters and slenderness ratio were tested. The test setups and procedure are discussed below.

3.2 Site of study

This research was done in Civil Engineering laboratory of Masinde Muliro University of Science and Technology.

3.3 Research design

Through laboratory experiments all materials physical properties were determined. Then several specimens of bamboo filled - concrete, raw bamboo and plain concrete columns were subjected to axial compression.

3.4 Material properties

3.4.1 Fine aggregates

About 2kg of sand of the batch was taken and sieved through a set of sieves. The sieves comprised of 0.15,0.3,0.6,1.18,2.36,5.00 and 10 mm. After handshaking for two minutes, retained mass on each sieve was weighed and recorded. Weighted average of material as retained on each sieve i.e Fineness modulus (FM) was calculated from equation 3.1.

$$FM= \quad \Sigma \frac{(cummulative\%\ retained)}{100} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (3.1)$$

3.4.2 Coarse aggregate

Crushed granite materials of 12mm as maximum size was sourced from a local hardware to be used as coarse aggregate. To remove granitic dust, grains less than 9mm, mud particles and silt, the aggregates were sieved through a series of sieves and graded to conform to limits as defined by BS882 (1992)

3.4.3 Cement

The cement used was cement of grade 32.5N (Mombasa cement) conforming to BS12 (1996). It was sourced from a local hardware based in Kakamega. Same grade of cement from same company was used throughout the experiments.

3.4.4 Water

Fresh water free from impurities and organic matter was used in mixing of concrete. It was readily available in the Laboratory.

3.4.5 Bamboo

Bambusa Vulgaris, a species commonly found in western Kenya was used for this research. and has a maximum of 12 cm thickness when fully grown to a height of 13m. Ashok (2007) In preparation of the sample, a guide from ISO 2215-1 and 2 was used (Determination of mechanical properties of bamboo part 1 and 2)

Plate 3.1 Cutting of Bamboo Specimens

Ten straight Bamboo culms each five meters long and free from any form of deformation were sourced from a local farmer in Kakamega and brought to the outside of Laboratory. They were air dried for two weeks and cut into the specified geometrical properties shown in table 3.1 with cross-cut saw.

Table 3.1 Geometrical properties of Bamboo Test Specimens

No	Sample	Outer Diameter	Culm Thickness	Length	Loading
		(mm)	(mm)	(mm)	(kN/m^2)
1	S1	100	10	200	31
2	S2	100	10	300	31
3	S3	75	8	150	31
4	S4	75	8	225	31
5	S5	75	8	300	31
6	S6	55	6	110	31
7	S7	55	6	165	31
8	S8	55	6	220	31

The specimens were carefully cut such that, most nodes lie at the center of culm. The external D_o was measured at three locations to conform with the prescribed diameters. Nodes inside the culms of the raw bamboo were opened by chisel to make them hollow for concrete materials to pass through.

3.5 Selection of concrete mix proportions and trial mix

3.5.1 Concrete mix design

Table 3.2 shows the summary of the values computed for the two concrete mixes following the criteria outlined in BRE (1997) manual for concrete mix design as shown in Appendix A3. Materials used in preparing concrete mixes for trial were the constituent materials from the resultant proportion

3.5.2 Production of trial mix

Before commencing the casting of composite specimens, the required proportions to prepare ten cubes of 150 mm sizes and enough to carry out workability test were calculated. By multiplying the three constituent materials with the volume of the mix, trial mix batch weight was obtained. Concrete mixing followed procedures provided by BS and ASTM. The coarse and fine aggregates were mixed first with small amounts of water added to allow absorption. Cement was then added to the aggregates in correct proportion and then thoroughly mixed while as the remaining water was added according to water cement ratio. The consistency was such that the concrete could be placed and finished sufficiently without segregation

Table 3.2 Values for concrete design mixes

Parameter	C20	C30
28 days strength fc (N/mm^2)	20	30
Margin (N/mm2)	5	5
Target mean strength (N/mm^2)	25	35
Free W/C ratio	0.65	0.55
Free water content (Kg/m^3)	180	180
Cement content (Kg/m^3)	230	325
Total Aggregate (kg/m^3)	1950	1820
Fine Aggregate (Kg/m^3)	635	600
Coarse aggregate (Kg/m^3)	1315	1220

3.5.3.1 Workability Test

Workability of casted concrete was measured with the objective of determining the slump of the mix. Mould was placed on base and held and the filled with fresh concrete in three equal layers. The steel tamping rod was used to tamp each layer 25 times. The initial height of the cone was measured by the slump measure and the cone was removed carefully to leave the moulded concrete.

Plate 3.2 is the pictorial view of the slump after the removal of the cone.

Plate 3.2 Slump test

3.5.3.2 Concrete cube strength

The ultimate compressive strength of the hardened concrete was obtained by preparing cubes of 150mm × 150mm × 150mm for each concrete mix designed. The procedure for making and curing the cubes was as follows; To prevent adhesion of concrete, lubricating oil was thinly coated in the interior surface of the moulds. Concrete was filled in three layers in each mould with each layer compacted with 35 strokes. They were cured for 28 days by immersing them in a water tank. Compression tests were done after 28 days to determine the ultimate compressive strength of the mix designed

Plate 3.3 Concrete cube strength

3.5.4 Theoretical Nomenclature

The specimens were organized in groups for easier referencing during analysis of results. Typical nomenclatures for the specimen were used in designation.

For instance, Y/C30/100/3 represent a Bamboo (Y) concrete column cast with concrete grade C30, having a diameter of 100 mm and a slenderness ratio of 3.Each specimen was marked for easier identification.

Table 3.3 Specimens classification

Test	**Test 1**						**Test 2**						**Test 3**		
Specimen	Concrete Filled bamboo						Unconfined Concrete column						Raw Bamboo		
Grade of Concrete	C20			C30			C20			C30					
External Diameter d (mm)	10 0	7 5	5 5	10 0	7 5	5 5	10 0	7 5	5 5	10 0	7 5	5 5	10 0	7 5	5 5
Slenderness Ratio(h/d)	2 3	2 3 4	2 3 4	2 3	2 3	2 3 4	2 3 4	2 3 4	2 3 4	2 3	2 3 4	2 3	2 3 4	2 3 4	2 3 4

3.5.5 Compression Test for raw Bamboo

Raw Bamboo specimens were tested in a similar manner to bamboo-filled concrete specimens as shown in plate 3.4

To designate them typical nomenclatures were used. Y/100/2 represent an empty bamboo (Y) with a diameter of 100 mm and a slenderness ratio of 2. All tested specimens details are summarized in the appendix.

3.5.6 Concrete filled bamboo specimens

Forty eight concrete- filled bamboo specimens with prescribed sizes were tested in this study. The prepared bamboo were used to make the CFB specimens. Twenty four specimens were filled with concrete mix C30 and the remaining twenty four were filled with concrete mix C20. Table 3.3 shows the specimens classification. Bamboo inner surfaces were moisture to prevent it from absorbing some of the water in concrete mix. Concrete was eventually poured inside in three layers with each layer compacted by a tamping rod with at least twenty strokes. The specimens were later cured for 28days by wetting daily with water. The same process was repeated for the second batch of concrete mix C30 the next day. After 28 day specimens were cleaned and dried in the open air.

Plate 3.4 Specimens casting

3.5.7 Plain concrete column specimens.

Empty UPVC tubes were used as moulds for casting plain concrete column specimens. They were made to be of identical geometrical sizes as the bamboo filled concrete specimens. This was to obtain unconfined conditions for a concrete column of a similar diameter and height as a confined column.

3.6 Experimental Setup.

The UTM machine was utilized and its general setup is as shown in Plate 3.5 below.

The specimens after cleaning and drying were placed in between the plates of the compressive machine and loading rate of 31kN/s applied. Tests were stopped when there was a total failure of the sample or when the applied load had dropped to 60%. All the specimens load at failure, stress and strains were automatically recorded by the machine which were later retrieved for further analyses as shown in the Tables of appendices. Both the strains and stress graphs as well as load-deformations graphs presented in chapter four, data was obtained from machines in built gages.

Plate 3.5 Compression test

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the tests conducted in this research and there analysis. From the concrete cube test, the characteristic strength of concrete after 28 days was determined. Next, the compression tests of both raw and bamboo filled concrete specimens provided the load carrying capacity, deformation and stress-strain characteristics of raw bamboo and concrete filled bamboo which are very important properties in concrete filled bamboo interaction.

4.2 Material Properties

4.2.1 Grading and Fineness modulus

Using the results from sieve analysis, the findings were computed as in Appendix A1 and the grading curve graphically presented in Figure 4.1 i.e. percentage (%) of sand material against the size of the sieve.

The sand was found fit to be used in the design of the concrete mix as per the recommendations of the BRE method of concrete design.

The Fineness of Modulus (FM) for the sand used was calculated as per equation 3.1

Fineness Modulus = 243/100 =2.41. The lower the FM the finer the aggregates. The proportion value of fines was necessary in designing the mixes by first determining the percentage of fine aggregates passing through the sieve of 600µm

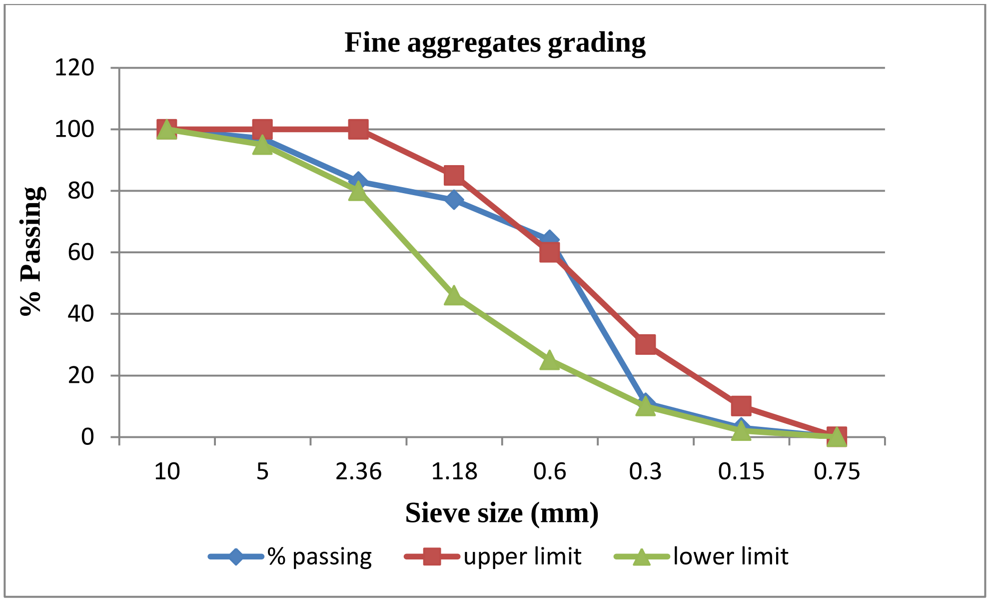


Figure 4.1 Results of sieve analysis for fine aggregates

Mass passing through the 600μm sieve=579.2 +79.4+24.7=683.3

Hence % passing through 600μm sieve $=\frac{Mass\ passing}{Total\ mass}\ \times 100 = \frac{683.3}{999.5} \times 100 = 68$

Using the above value and the semi log graph, the proportion of fines was determined to be 35 %

4.2.2 Coarse aggregate

The sieve analysis findings were computed as in Appendix A2, Table B2 and graphically presented in Figure 4.2. From the figures, the natural aggregates used for this research showed uniform-grading pattern

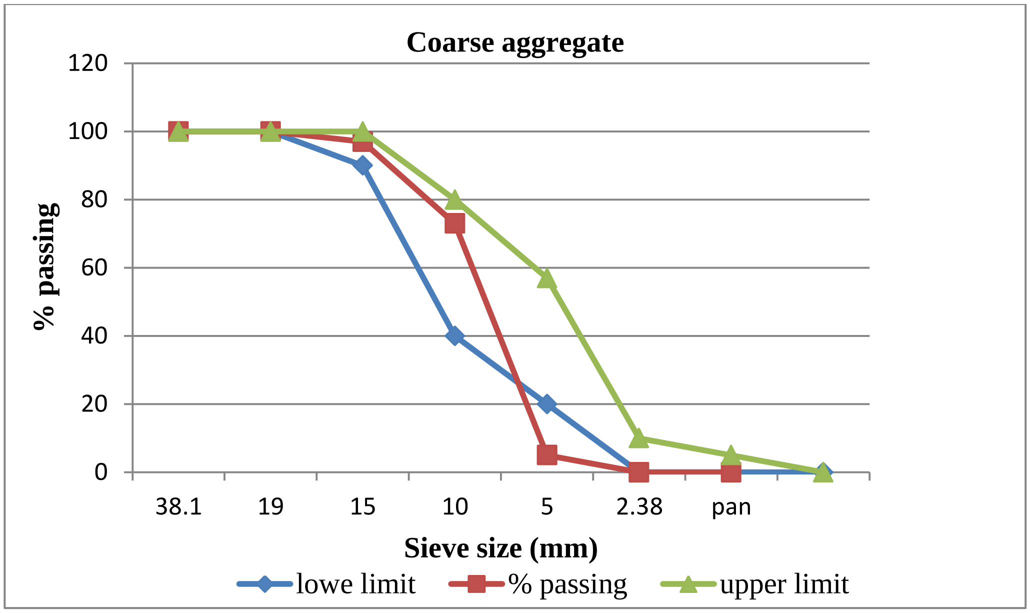


Figure 4.2 Results of sieve analysis for coarse aggregates

4.2.3 Slump test

The slump test was conducted to determine the workability of fresh concrete. On the removal of the cone, the difference in height between the uppermost part of the slumped concrete and the upturned cone which was recorded in mm. The slump was recorded as 20 mm which was well within the targeted slump of 15 to 25 mm

4.2.4 Concrete cube test

Concrete cubes cast from the same batches used to fill the bamboo culms were subjected to standard compressive test after 28 days to determine the two concrete batches' concrete characteristic strength. The characteristic strength for each concrete mix after 28 days was close to the targeted compressive strength hence the calculated proportions have achieved the design mix proposed (Table 4.1). Because of the levelled cube sides, there was no stress concentration that took place during testing hence slight difference in the test results.

Table 4. 1 Concrete cube strengths after 28 days

Grade	W/C Ratio	Water	Cement	Sand	Aggregate	Strength
C20	0.85	220	263	624	1250	29.8
C30	0.65	209	312	602	1210	20.1

The dominant failure in the cubes was a double cone failure an indication of homogeneous and good distribution of particles in the mix.

4.2.5 Raw bamboo

Compressive tests data of the bamboo is summarized in the appendix A5 Table A5.3. It was used in capacity enhancement and confinement effectiveness determination as discussed in section 4.5.

4.3 General Observation

In the early loading stages, sounds were heard which may be due to concrete micro cracking, an indication of the start of stress transfer to the bamboo from the dilated concrete

Specimens filled with concrete mix C30 (Plate 4.1b) showed better behaviour in post cracking stage and exhibited clear sign of concrete crushing at the mid-height, which indicated the brittle characteristic of concrete with a higher strength compared to C20.

Highest stiffness can be seen in bamboo filled with concrete of mix C30 in comparison to specimens filled with concrete mix C20 and raw bamboo due to higher characteristic strength as obtained from concrete cube tests which gave more strength and ductility for specimen.

a) Bamboo filled with C20

b) Bamboo filled with C30

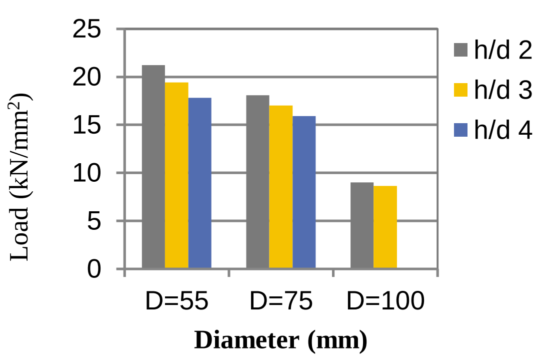
c) Raw Bamboo

Plate 4.1 Final failure mode of each specimen

Several failure modes were observed depending on the specimens' properties. The infill concrete present in the empty space of bamboo delayed buckling and also prevented bamboo from buckling inward as shown in plated 4.1a and 4.1b. The delay in buckling and the presence of nodes in bamboo keeps infill concrete in the elastic range longer thus increasing the ultimate strength of the composite elements as shown in plate 4.1(c)

4.4 Slenderness ratio influence on the failure loads of the composite column

Figures 4.3 to 4.5 show results of varying concrete mix, slenderness ratio (h/d) and diameter (D) effect on load capacity and crushing stresses.



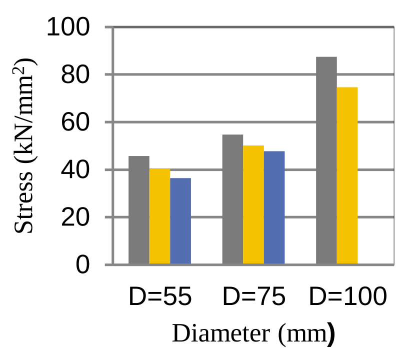


Figure 4 3 Load and crushing stresses vs change in Diameter for concrete mix C20

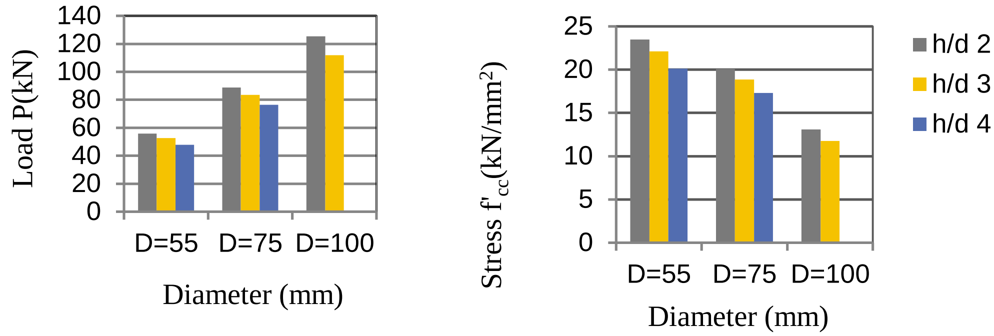


Figure 4.4 Load and crushing stresse with change in Diameter for concrete mix C30

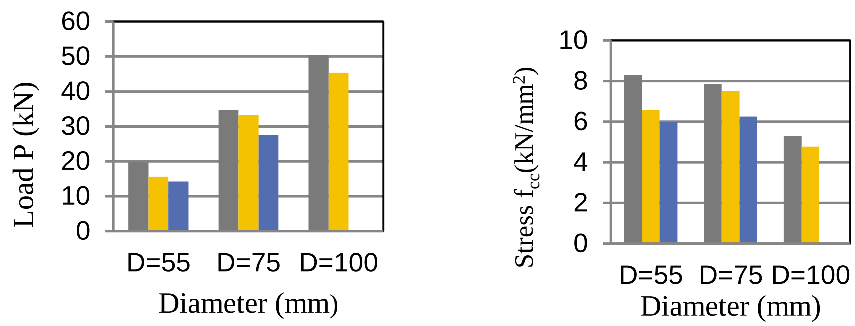


Figure 4.5 Load and crushing stresses with change in Diameter for Raw Bamboo

It can be seen from the figures that bamboo composite sample filled with concrete shows higher higher load carrying capacity than the raw bamboo. The compressive strength and carrying capacity of the composite column depends on the concrete characteristic strength. The load capacity of bamboo filled with concrete mix C30 is on average 50% higher than that of concrete mix C20. It means that composite columns provide better strength with high concrete characteristic strength than when filled with concrete of low grade. The results further indicate that as the diameter of the column increases the load capacity is increased for composite column cast with the same concrete mix due to increased carrying area. Increase in slenderness ratio for specimens of the same diameter decreases the crushing stresses and the load capacity of the column as slender columns tends to buckle easily than short columns due to reduced column stiffness. This explains why when the diameter of the column is reduced from 100mm to 55mm the bamboo and composite column compressive strength increases in all specimens

4.4 Loads-deformation characteristics

The figures 4.6 to 4.11 shows the measured axial load vs. compressive deformation for all specimens

From Figures 4.6 and 4.7 the column has been cast with the same concrete mix but vary in slenderness ratios and culm diameters. Figure 4.8 is for raw bamboo and figures 4.9 to 4.11 the columns are of the same diameter but cast with different concrete mix

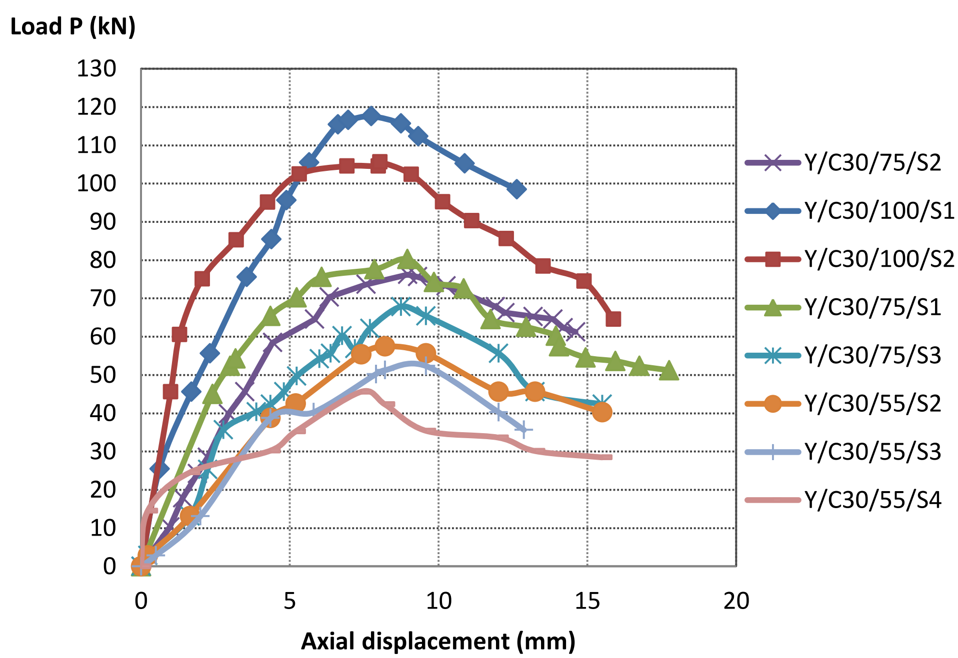


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Figure 4.6 Deformation characteristics for concrete class 30

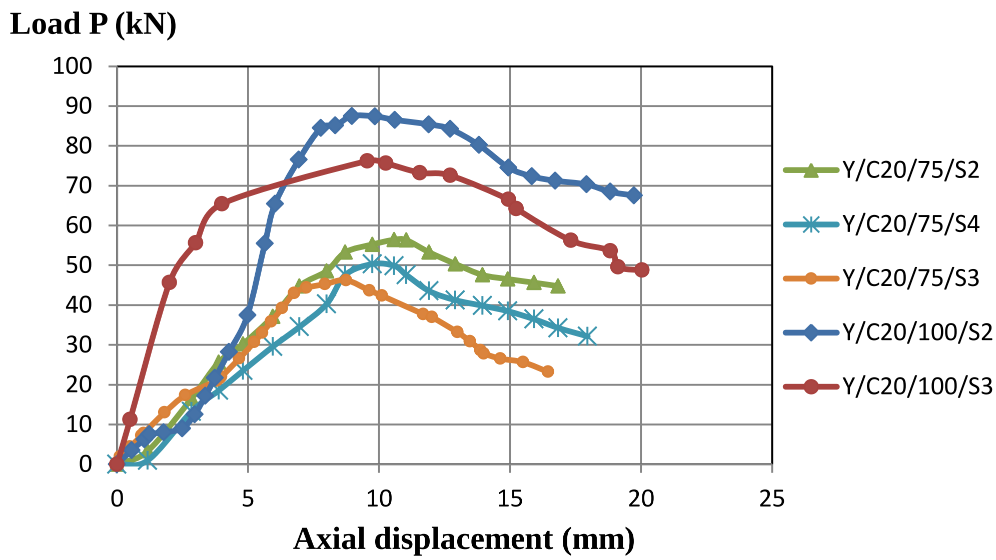

Figure 4.7 Deformation characteristics for concrete class 20

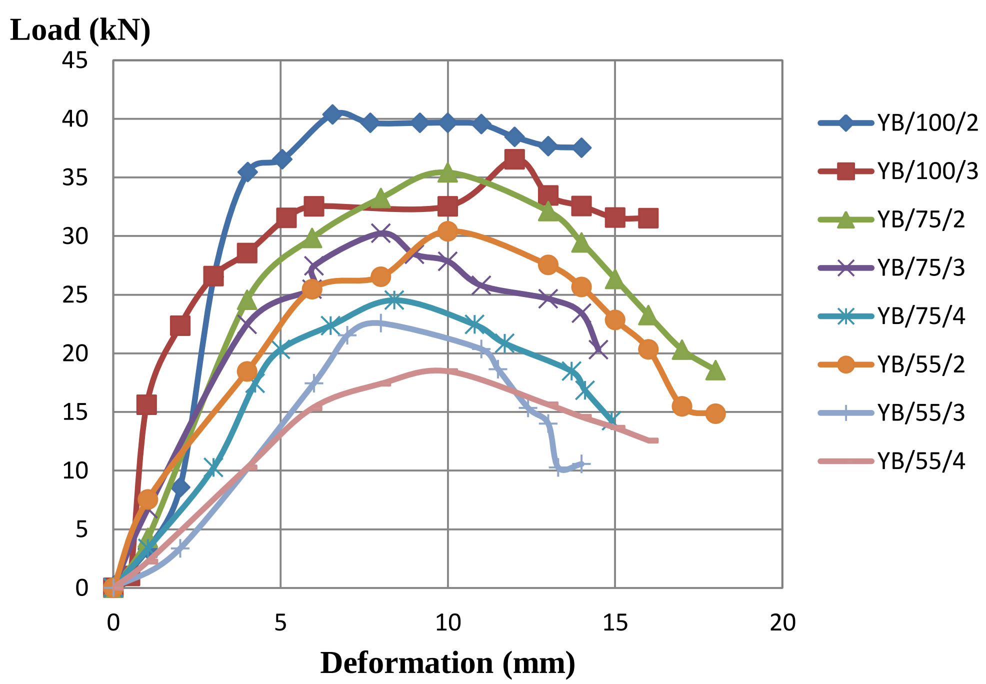

Figure 4.8 Deformation characteristics for raw bamboo

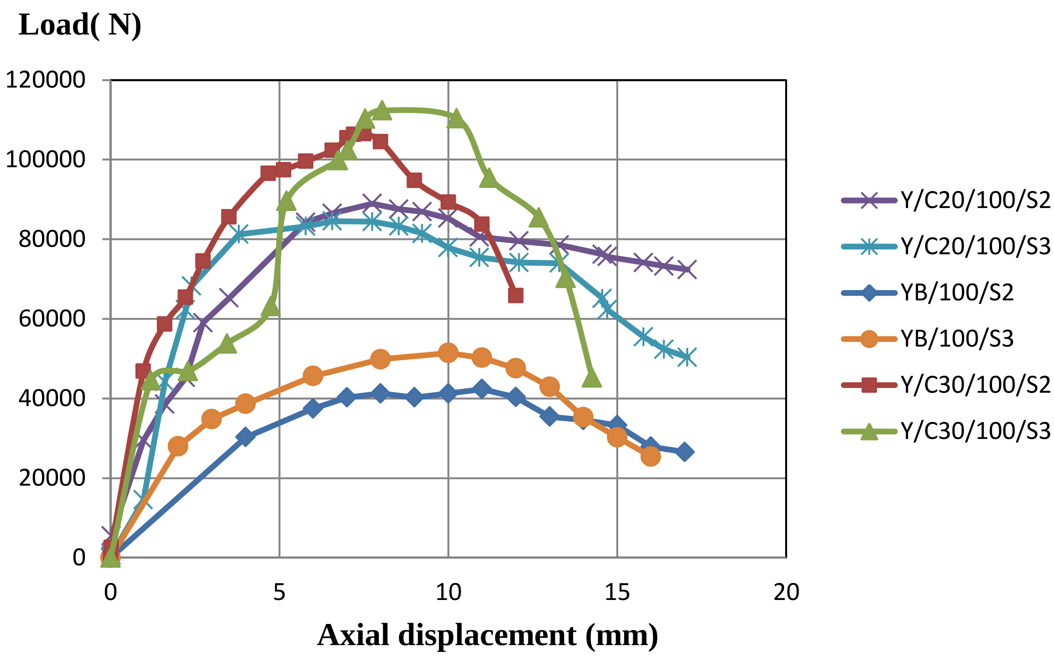

Figure 4.9 Deformation characteristics for 100mm culm Diameter

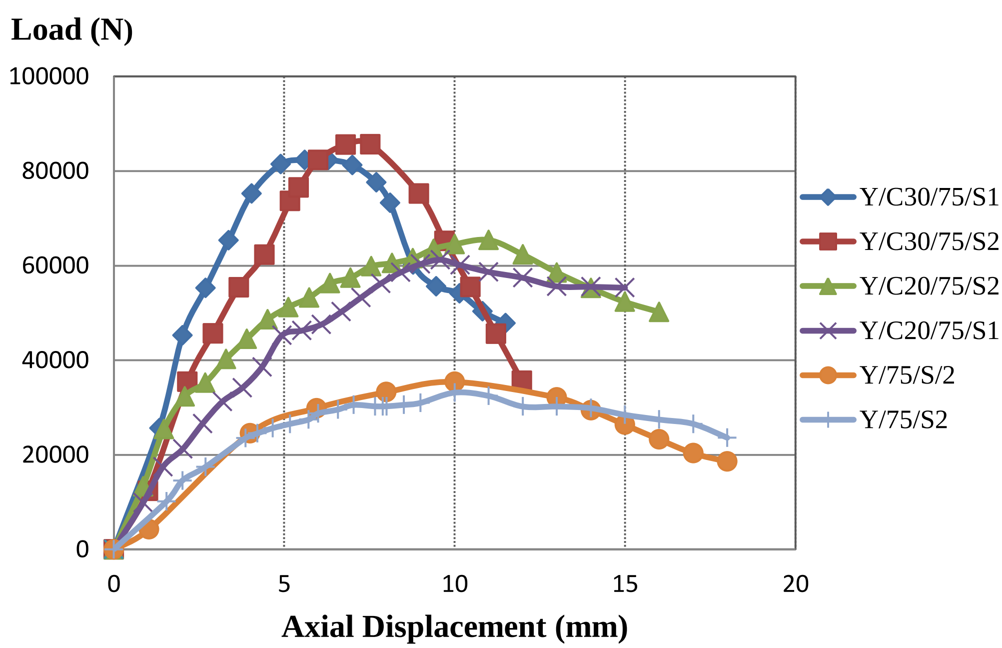

Figure 4.10 Deformation characteristics for 75mm culm Diameter

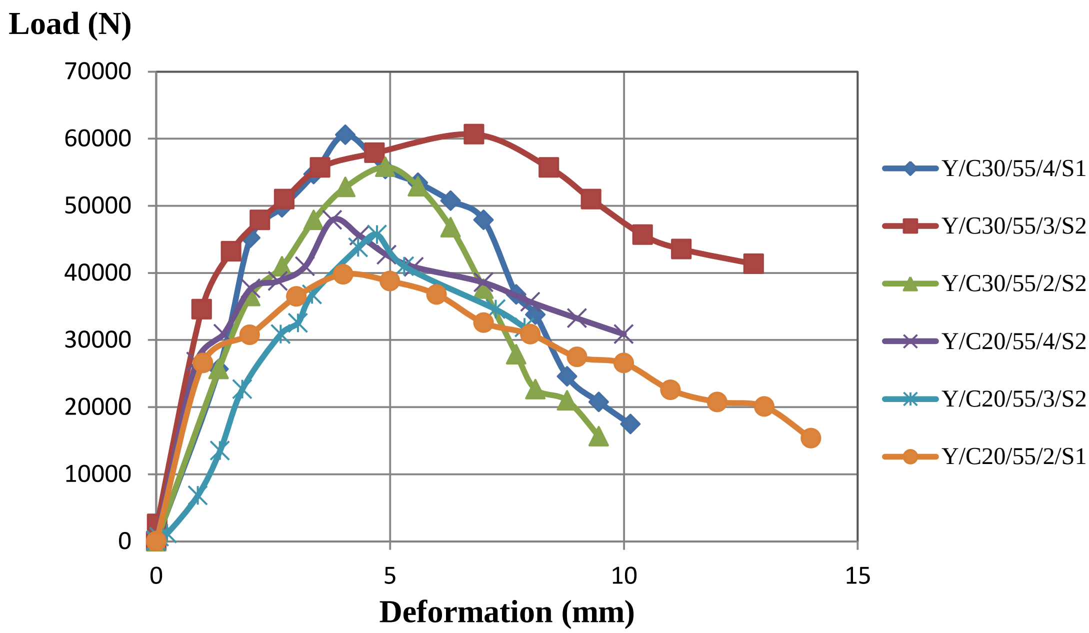

Figure 4.11 Deformation characteristics for 55mm culm Diameter

Observations made from the figures shows that the most obvious difference in the load deformation curves can be seen in post peak behaviour. Concrete filled bamboo with mix C30 has the sharpest decrease of strength after attaining the peak load with the maximum displacement being only 1% of the column height. Just after reaching the peak strength the axial strength dropped to less than half of the ultimate load. In view of resistance capacity collapse of the building, such a sudden decrease of axial strength needs to be avoided. Concrete mix C20 undergoes large deformation before reaching peak compression strength. This can be attributed to its low stiffness as a result of its low elastic modulus hence its able to interact more effectively with the bamboo with consequent increase in composite action. Concrete of low strength in confined state resist higher loads due to confining medium unlike in unconfined state where it will disintegrate when subjected to low loads. Generation of concrete cracks is delayed by the nodes present in bamboo in the elastic stress stage, thus increasing the axial load capacity proportional limit. This improves the ultimate deformability and ductility of the columns. The shape of axial deformation curves exhibits no clear difference hence column diameter does not influence the post peak behaviour as observed from figures 4.9 to 4.11. However strength of concrete affect significantly the post peak behaviour as seen from figure 4.6 and 4.7. With the increase in concrete grade, sloping curves becomes steeper, a sign of concrete becoming more brittle. Filled columns failure can thus be characterised as brittle failure with semi ductility. The relationship between slenderness ratio and deformations shows that large diameter specimens with small slenderness ratio specimens resist high loads due to great energy dissipating behaviour than those with small diameter.

4.5 Load capacity enhancement

It's believed that a composite structural element when used in construction has properties improved than those of the constituent elements. To determine the benefits of using this composite column, a comparative study was made in this research. Capacity enhancement ratio, B_{cc}/B_{sum} for purposes of comparison is used as expressed below. B_{cc} is the bamboo filled concrete column carrying capacity while B_{sum} is the sum total of the load capacity of the unconfined column and the raw bamboo

$$B_{sum} = B_{co} + B_{raw}$$

B_{co} ....Unconfined concrete column load capacity

B_{raw}.........Raw Bamboo (empty) load carrying capacity

The calculations are presented in the appendix A6 Table A6.1. Figure 4.11 is the graph of the results computed.

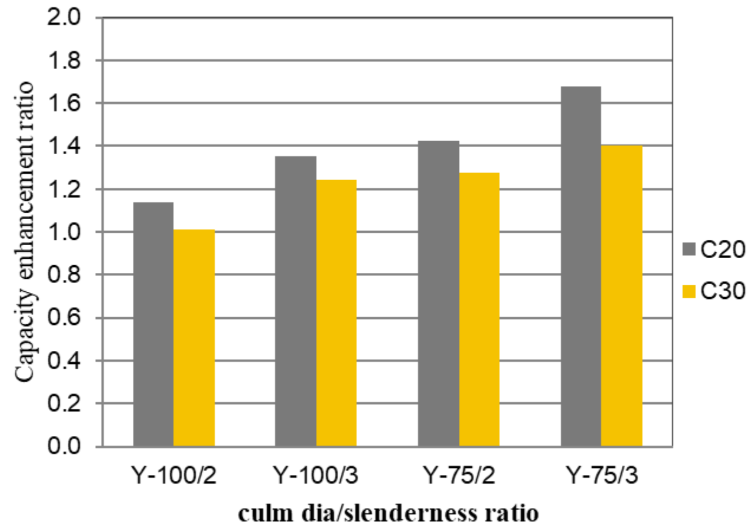

Figure 4.12 Capacity Enhancement for composite culm sections

Compared to raw bamboo improved structural properties are found in bamboo filled concrete due to composite action of concrete core and bamboo. Obsevations from figure 4.12 shows that B_{cc}/B_{sum} is greater than one in all specimens. The failure load of the composite column relatively large compared to the sum of individual failure loads of both bamboo and unconfined concrete columns. Factors such as diameter to length ratio, area of the cross section, strength of the concrete core and bamboo determines the level of confining effect and failure load of the composite column.

Strength and stability of concrete filled bamboo is increased due to triaxial state of stress of concrete core as a result of confinement effect. It can be seen that capacity enhancement in bamboo columns filled with concrete mix C20 is more pronounced which can be attributed to low stiffness than in column specimens with concrete mix C30. Also as the slenderness ratio of the columns is increased capacity enhancement increases. With increase in the height of columns rate of reduction in axial load capacity is more pronounced in unconfined columns than in confined columns.

4.6 Effect of bamboo confinement

Table 4.2 shows the effect of Bamboo confinement in relation to slenderness ratio and concrete strength**.** Confinement effect is usually quantified by the factor (f'_{cc}/f'_{co}) where f_{cc} and f_{co} are the strength of confined and unconfined columns respectively

Table 4. 2Bamboo Confinement Effectiveness Results

Culm Dia/slenderness	Concrete Strength f_{cu}	Compressive strength		Confinement Effectiveness
		Confined	Unconfined	
ratio	Mpa	f_{cc}	f_{co}	f_{cc}/f_{sum}
Y-100/2	C30	15.97	9.35	1.71
	C20	11.15	3.38	3.30
Y-100/3	C30	14.24	5.89	2.42
	C20	11.53	2.94	3.92
Y-75/2	C30	18.43	7.34	2.51
	C20	15.56	3.80	4.09
Y-75/3	C30	18.89	7.93	2.38
	C20	14.41	3.28	4.51
Y-75/4	C30	10.85	5.47	2.03
	C20	8.34	3.11	1.98

The improved concrete filled bamboo specimens compressive strength is attributed to the confinement provided by the bamboo to the concrete infill. From Table 4.2 in all cases f'_{cc}/f'_{co}>1, an indication of effectiveness of bamboo in confining concrete.

Confined concrete is considered to be under triaxial compression which has an effect in increasing the carrying capacity of the composite column

There is increase in strength to between 1.6 and 4.5 times the unconfined strength depending on the level of confinement. The table also shows a general trend where for low grade concrete strength effect of confinement is high. It is worth noting that concrete compressive strength is directly related to elastic modulus. This is the reason why composite action is increased and hence high f'_{cc}/f'_{co} ratio for columns cast with low strength, a similar observation made by Gathimba et al (2016).

4.7 Axial strain - stress characteristics

Figures 4.13 to 4.15 show the raw bamboo and composite columns longitudinal strain and stress curves. Calculation of stress was done by getting the quotient of applied axial load and the cross sectional area of the specimens measured

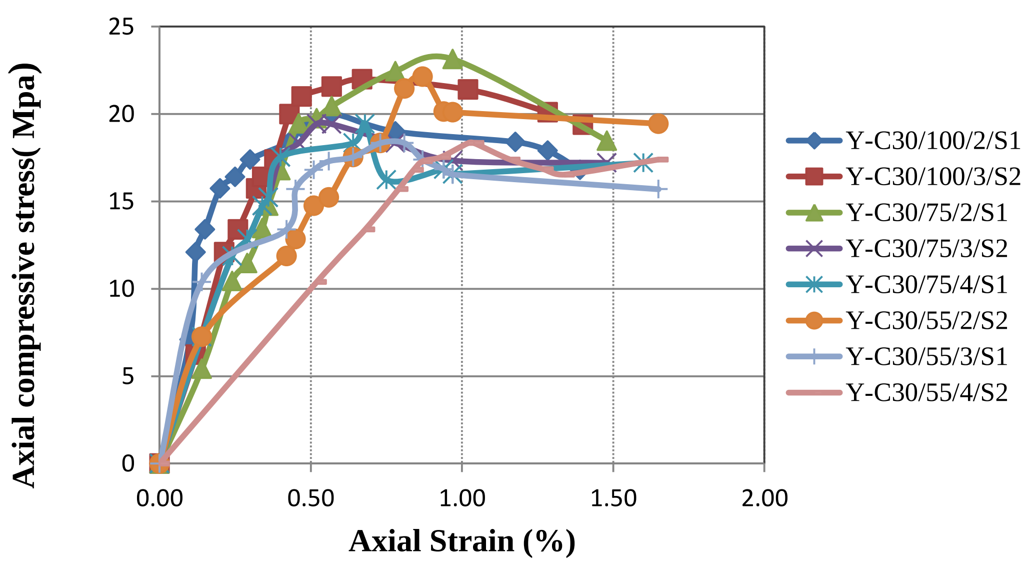

Figure 4.13 stress strain curves for concrete class 30 composite columns.

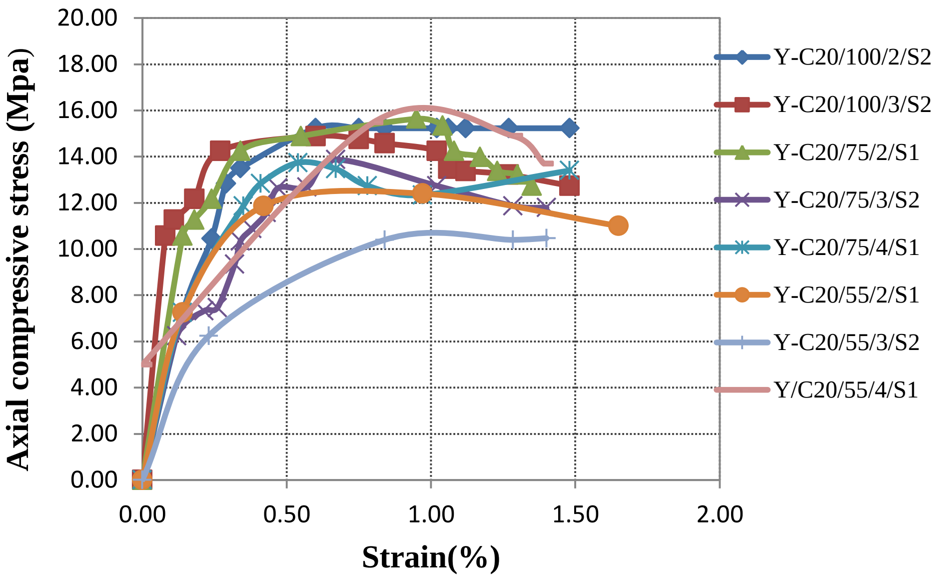

Figure 4.14 Stress strain curves for concrete class 20 composite columns

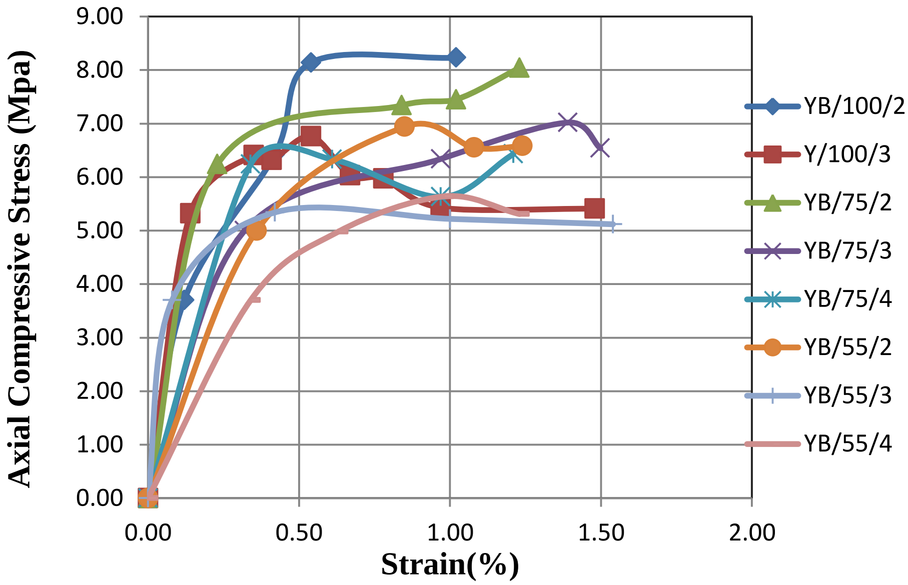

Figure 4.15 Stress strain curves for Raw Bamboo columns

Stress strain behaviour of plain bamboo as shown in Figure 4.15 exhibits certain variation due to variation in bamboo physical properties it being a natural material.

Based on comparison with test results of bamboo confined concrete it can be seen that the use of concrete apparently depending on the characteristic strength affect the maximum stress and the corresponding strain as well as the slope of the descending curves. This finding is in conformance with the results obtained by other researchers (Davalos et.al 1999, Najm et.al 2007). However, the results about the initial stiffness show a different trend and this is due to the presence and position of nodes as well as load eccentricity at some point. The initial part of the region exhibits a linearly elastic behaviour up to a stress of about 4MPa and compression strain of about 0.5% .is largely an elastic response of the bamboo to compressive stress. The onset of plastic region is characterised with slow rate of stress increase up to a compressive strain of about 0.5% in strain culminating into plateau region in which strain increased sharply with little change in stress . Prior to collapse the curves are near horizontal which signifies the buckling of bamboo cellular structure with the culm bending elastically due to increased loading which primarily depends on the crossectional area and slenderness ratio. It should be noted that although the response are similar in the elastic region, the curves differ significantly in the post- peak region

4.8 Load-carrying capacity prediction

Many standards and codes are available to address the design of Steel filled concrete columns such as Eurocode 4, AISC, AS 5100 etc. However in the design of concrete-filled columns, no standards are available. Based on the results presented a model is developed to predict the carrying capacity of concrete filled bamboo and compared to some of this codes to evaluate their applicability.

4.8.1 Theoretical formulae

This formulae simply combines the bamboo load capacity and the concrete infill capacity as shown

$$N_{the} = f_c' A_c + f_b A_b \qquad 4.1$$

Where f_c is the concrete characteristic strength

N_{the} Is the theoretical Load according to theoretical formulae

A_c is the cross-sectional area of concrete infill, F_b is the load carrying capacity of bamboo, A_b is the area of bamboo

The formula does not take into account increase of concrete strength capacity when under triaxial loading. It assumes yielding of bamboo and concrete occurs at the same time. Predicted load capacities of specimens using this formulae in this research are shown in Table 4.3. The computation of the results are shown in Appendix A8

Table 4.3 Theoretical formulae results

f'c	Specimen identifier	P_{Theor} (kN)	P_{Exp} (kN)	% diff
30	Y-100/2	109.7	125.4	13
30	Y-100/3	90.8	111.8	18
30	Y-75/2	80.4	88.7	9
30	Y-75/3	64.2	83.4	23
20	Y-100/2	72.1	87.5	17
20	Y-100/3	60.7	74.7	18
20	Y/75/2	42.1	54.7	23
20	Y/75/3	37.8	50.2	24

To evaluate the predicted capacities effectiveness, a comparison with the experimental output is performed and summarized in Figures 4.17 and 4.18

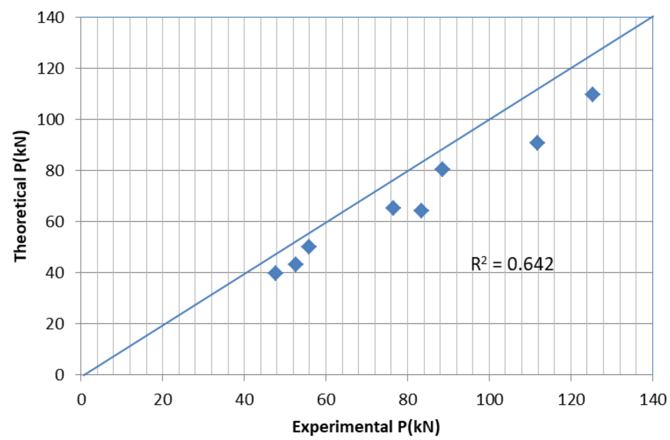

Figure 4.16 Experimental and calculated load carrying capacity for Mix C30

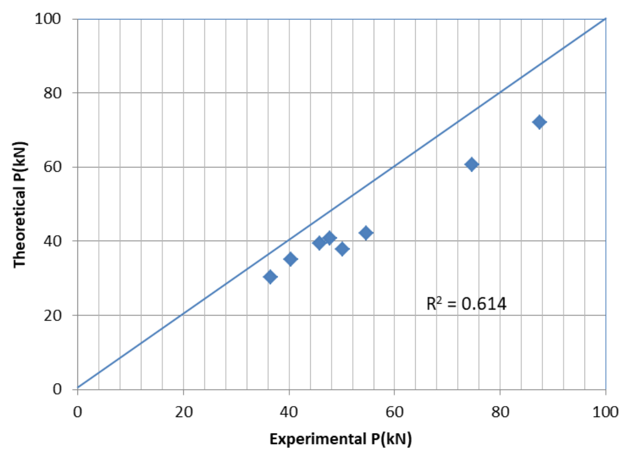

Figure 4.17 Experimental and calculated load carrying capacity for C20

It can be observed that load capacity of all tested column specimens have been underestimated when theoretical formulae is used with the factors ranging from 1.9 to 1.23. Concrete grade C30 predicted load capacity values are closer to actual capacities an indication that such columns have a pronounced confinement effects. Moreover the predicted values for concrete mix C30 are closer to the actual capacities than the concrete mix C20 which implies that confinement effect is not pronounced in such columns. Hence the lower the grade of cement, the higher the confinement effectiveness of confining medium thus the large variation in the predicted and experimental values in specimens

4.8.2 Mander et al., (1988) formulae

The multi-axial compressive stresses contributing to the ultimate strength are considered in this model to determine the confined compressive strength of the composite element. The formulae is avariation of theoretical one to take into account confinement effects.

$$N_{Man} = f'_{cc}A_c + f_bA_{sb} \qquad 4.2$$

The core of the concrete is triaxially compressed by the confining medium in the concrete filled composite with equivalent lateral confining stresses .The compressive strength due to confinement can is given as

$$f'_{cc} = f'_c(-1.254+2.254\sqrt{1+\frac{7.94f1}{f'c}} - 2\frac{f1}{f'c} \qquad 4.3$$

Where:

f_1 = Concrete lateral confining stress

$f1 = \frac{2\sigma\theta t}{D}$ and $\sigma\theta = 0.1\ f_b$

t = Thickness of bamboo culm

f'_c = Concrete characteristic strength

f_{cc} = Compressive strength of concrete due to confinement

Results of calculation as proposed by the Mander, et al., (1988) are presented in Table 4.5 for the specimens tested in this research

Table 4.4 Mander et al., (1988) calculation results

f'c	Specimen identifier	$P_{Man.}$ (kN)	P_{Exp} (kN)	% diff
30	Y-100/2	118.7	125.4	6.7
30	Y-100/3	104.3	111.8	7.5
30	Y-75/2	83.4	88.7	5.3
30	Y-75/3	87.24	83.4	-3.84
20	Y-100/2	93.14	87.5	-5.64
20	Y-100/3	64.1	74.7	10.6
20	Y/75/2	47.21	54.7	7.49
20	Y/75/3	56.31	50.2	-6.11

To evaluate the predicted capacities effectiveness, a comparison with the experimental output is performed and summarized in Figures 4.18 and 4.19

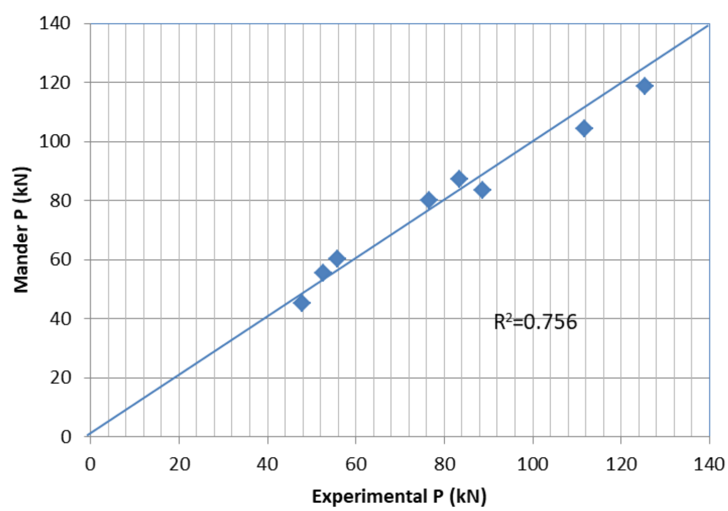

Figure 4.18 Experimental and calculated load carrying capacity for C30

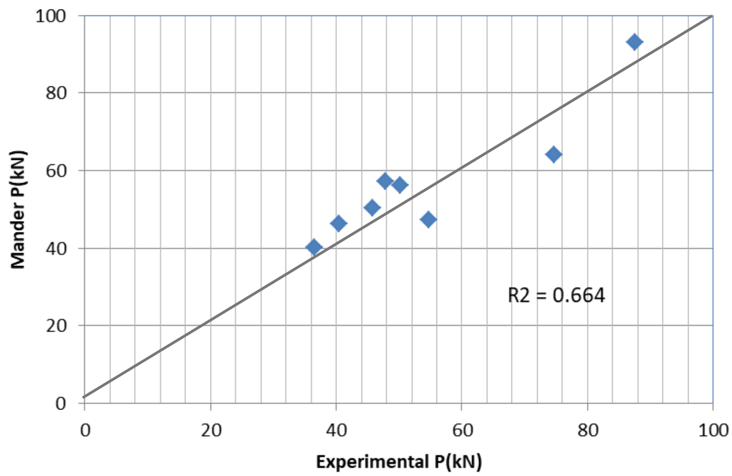

Figure 4.19 Experimental and calculated load carrying capacity for C20

In using Mander et al. (Pman) formulae that includes effects of confinement to estimate the axial load carrying capacity of concrete-filled bamboo columns, confined concrete compressive strength values are replaced by compressive strength of unconfined specimens values in the estimation to calculate concrete contribution. Section capacities are overestimated in some cases hence its use may generate unconservative design.

4.8.3 Model Development

To predict the behaviour of CFB columns, a model is developed through modification of both Richart, et al (1928) and Mander, et al (1988) as written in equations (10) and (11) respectively.

$$\frac{fcc - fc}{fc} = 4.1\,\frac{f1}{fc} \qquad 4.4$$

$$\frac{fcc - fc}{fc} = 2.254\sqrt{1 + \frac{7.94f1}{fc}} - 2\frac{f1}{fc} \qquad 4.5$$

Where f_{cc} confined compressive strength

f_c unconfined compressive strength

f_1 lateral confining pressure

f_1/f_c confinement ratio (C_r)

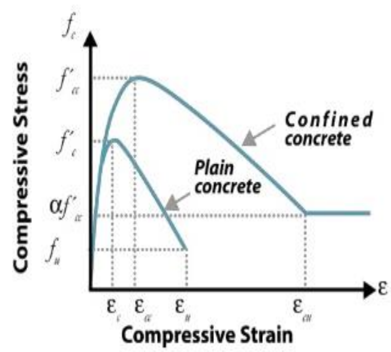

Figure 4.20 Compressive stress- strain relationship

Confining pressure *(f_1)* applied to the concrete core which corresponds to compressive strength of passively-confined specimens.

$$f_1=\frac{2tfy}{D-2t} \qquad 4.6$$

where, t is bamboo culm thickness, D is Outer diameter of bamboo and f_y is Bamboo stress at yield point

Circumferential stress of the bamboo (σ_θ) according to von-misses can be calculated in terms of its circumferential to longitudinal stress ratio (α) as shown below.

$$\sigma_\theta = \frac{f_y}{\sqrt{1+\alpha+\alpha^2}} \qquad 4.7$$

This can be obtained when elastic-plastic theory is used. In biaxial state of bamboo, confining pressure can be determined by substituting f_y from equation (15) for that in equation (14) giving,

$$f_l = \frac{2tf_y}{(D-2t)\sqrt{1+\alpha+\alpha^2}} \qquad 4.8$$

Thus f_l and C_r can be obtained as equation (16)

$$f_l = \frac{2tf_y}{(D-2t)\sqrt{3}} \qquad C_r = \frac{2tf_y}{f_c(D-2t)\sqrt{3}} \qquad 4.9$$

Confinement relationships are obtained by using bamboo circumferential strength contribution. This is confined concrete total capacity minus bamboo longitudinal strength contribution defined as confinement strength in this stud

Table 4.5 Compressive strength results of Bamboo confined concrete

Specimen Identifier	Comp. strength (MPa)	load . (kN)	Compr. strength Uncon. (MPa)	Relative increase in comp. strength%	Conf. pressure (MPa)	Conf. ratio (C_r)	Conf. strength (MPa)	Relat. inc Confin. strength %
Y-C30-100/2	15.97	125.4	11.26	42	8.3	0.7371	13.2	23.4
Y-C30-100/3	14.24	111.8	8.67	64	8.3	0.9573	11.43	31.8
Y-C20-100/2	11.52	90.4	6.42	79	8.3	1.2928	8.21	84.2
Y-C20-100/3	11.53	90.5	6.44	63	8.3	1.2888	7.94	61.4
Y-C30-75/2	18.43	81.4	11.31	63	6.7	0.5924	14.32	26.6
Y-C30-75/3	18.89	83.4	9.34	102	6.7	0.7173	15.1	61.4
Y-C30-75/4	18.97	76.2	11.03	72	6.7	0.6074	13.14	19.1
Y-C20-75/2	15.56	68.7	7.86	98	6.7	0.8524	13.54	72.2
Y-C20-75/3	14.81	65.4	5.41	74	6.7	1.2384	10.41	57.4
Y-C20-75/4	16.57	62.1	4.36	80	6.7	1.5367	11.23	67.1

Table 4.6 is the relationship between compressive strength and the confinement strength of the bamboo and corresponding unconfined concrete while Figure 4.21 is the graphical relationship.

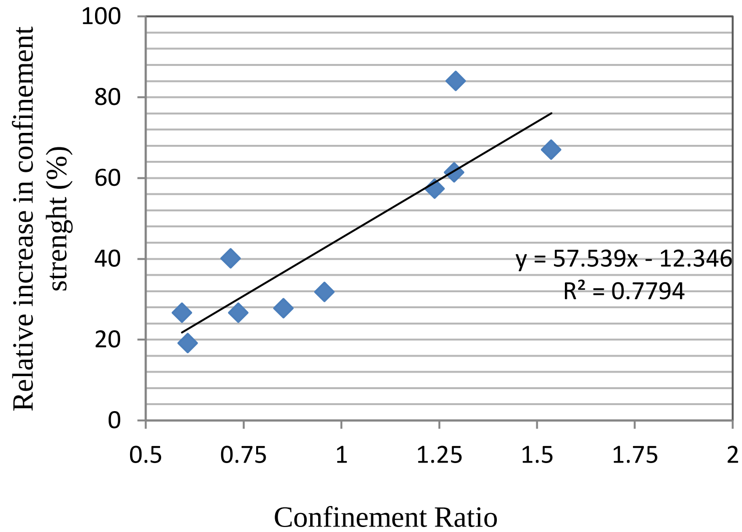

Figure 4.21 Relationship of Confining ratios with relative increase in confinement strength.

A linear equation is proposed based on regression analysis, to predict relative confinement strength vs. confinement ratio. This can be written as

$$\frac{fpc - fc}{fc} = 2.17\frac{f1}{fc} \qquad 4.10$$

f_{pc} confined concrete confinement strength

Confinement effectiveness coefficient (k) can be defined as the ratio of relative increase in confinement strength to the confinement ratio. Confinement effectiveness coefficient from this research is almost constant and equal to 57.539.

By combining strength values of the individual components, concrete-filled bamboo load carrying capacity can be calculate as follows in equation 4.15

$$Ppc = A_b f_y \frac{\alpha}{\sqrt{1+\alpha+\alpha^2}} + A_c(f_c + k \frac{2tf_y}{(D-2t)\sqrt{1+\alpha+\alpha^2}}) \qquad 4.11$$

Table 4.6 Model equation calculation results

f'c	Specimen identifier	$P_{Mod.}$ (kN)	P_{Exp} (kN)	% diff
30	Y-100/2	133.8	125.4	6.7
30	Y-100/3	96.24	111.8	7.5
30	Y-75/2	80.11	88.7	5.3
30	Y-75/3	74.28	83.4	-3.84
20	Y-100/2	88.21	87.5	-5.64
20	Y-100/3	72.37	74.7	10.6
20	Y/75/2	57.21	54.7	7.49
20	Y/75/3	56.14	50.2	-6.11

In this study, k and α were equal to 57.53 and 1, respectively. Therefore, the load-carrying capacity of the bamboo takes the following form:

$$Ppc = 0.58 A_b f_y + (1+57.53 \frac{tf_y}{(D-2t)fc} A_c f_c) \qquad 4.12$$

Table 4.6 gives the calculated results based on the model for the tested bamboo specimens.

Figure 4.20 is plotted to examine proposed model effectiveness in relation to the experimental values. In the figure, the scatter of the experimental vs. predicted data about bisector line (y=x) was observed. A point stands on the bisector for the perfect estimation.

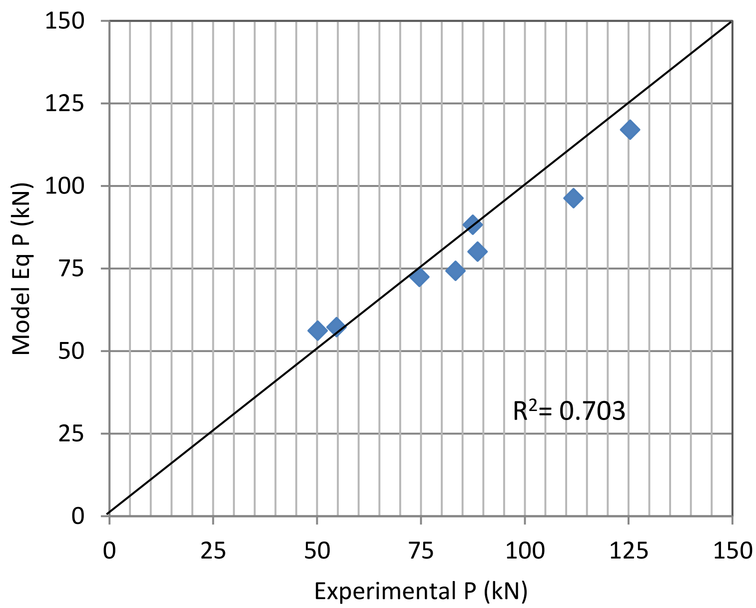

Figure 4.22 Experimental and Calculated load carrying capacity of specimens

The proposed model revealed almost fairly estimation capability for all of the data samples According to the results observed from the codes, it was found out that for the high experimental values of axial loads (Nu), the codes underestimated the axial load capacity. The little disparity between the experimental and predicted results may be due to imperfections in the assumption made in the model development.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The study focused on the structural behaviour of concrete-filled bamboo (CFB) column by studying their behaviour under compressive loading. The following were the conclusions and recommendations from the research.

5.1 CONCLUSIONS

In general there is a considerable improvement in terms of strength and ductility when the bamboo columns are strengthened with plain concrete. The following conclusions were drawn from the parameters studied

- The axial load capacity was found to be increasing with the increase in concrete grade. Concrete mix of C20 led to a load carrying capacity increment of 55 % compared to raw bamboo and concrete mix C30 led to an increment of 90 % of the load carrying capacity relative to that of the raw bamboo column. Concrete filling enhances the axial load capacity of identical bamboo columns up to two times based on height to thickness ratio.
- It was concluded that bamboo is effective in confining concrete, since in all cases $f'cc/f'co>1$. Confined strength values increased between 1.12 to 2.02 times the unconfined strength values thus revealing a good performance.
- Stress strain response consisted of three distinct regions for all the columns. In the first region, the response was almost linearly elastic up to about 40% of the ultimate compressive strength, behaviour similar to plain concrete. A softer descending branch on the stress–strain curve for the bamboo columns filled with

concrete mix C30 is shown for the columns with small slenderness ratio. The curves however differ significantly in the post peak region depending on the concrete grade.

- The results from the proposed model followed closely results experimentally obtained, in the estimation of the maximum axial load of the composite column. Overall the deviation of estimated axial load capacity values from experimental values is high for CFB columns of concrete mix C20 and larger slenderness ratio. Hence it can be concluded that confinement is more effective in slender columns when filled with concrete of lower strength. This needs further investigation

5.2 RECOMMENDATIONS

There is an enormous potential for bamboo concrete composite columns to be adopted in the construction industry as illustrated by findings of this study. Nevertheless, there is need for more research in the use of this kind of material in composite construction. Therefore a list of other related issues are recommended for further research.

- Major work done on concrete filled bamboo is experimental, further numerical study is needed to check the parameters which affect the ultimate strength of the composite column.
- More research should be done on interface friction characteristics, expansion and contraction in relation to concrete and bamboo.
- There’s need to investigate the effect of moisture content in the bamboo to the ultimate carrying capacity of CFB columns

- There is also need for innovative techniques for dealing with fire resistance and the exposure of this composite material to harsh conditions
- There is need to test the CFB samples at higher loading rates to study the behaviour of the element when impacted
- Reinforced bamboo with concrete has significant strength and is hence, recommended for building under light loads such as low rise houses

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APPENDICES

Appendix A 1 Sieve analysis for Fine aggregates

Sieve Aperture	Retained (g)	Retained (%)	Cumulative retained (%)	Cummulative Passing
10mm	0	0	0	100
5mm	22.5	3	3	97
2.36mm	117.3	11	14	83
1.18mm	65.4	6	20	77
600µm	121.4	13	33	64
300µm	579.2	56	89	11
150µm	79.4	8	97	3
75µm	24.7	3	100	0

Appendix A 2 Sieve analysis for Coarse aggregates

Sieve Size (mm)	Retained (g)	Retained (%)	Cumulative retained (%)	Cummulative Passing
38.1	0	0	0	100
19	4	0	0	100
15	450.5	23	23	77
10	1449	72	95	5
5	97	5	100	0
2.38	1	0	100	0
pan	0	0	100	0

Appendix A 3 Concrete Mix Design values

Stage	Item	Reference	Value	
1.0	**Selection of target w/c ratio**			
1.1	Characteristic strength	**specified**	20N/mm2 at 28 days Proportion defective 5 %	
1.2	Stardard deviation		8N/mm 2	
1.3	Margin		K=1.64 13.12N/mm2	
1.4	Target mean strength		20 13.12 33.12N/mm2	
1.5	Cement Type	specified		
1.6	Aggregate type		Sand Coarse	
1.7	Water/Cement ratio	specified	0.59	
1.8	Max free water/cement ratio	specified	0.55	
2.0	**Water content selection**			
2.1	slump	specified	10-30 mm	
2.2	Max agg size	specified	20mm	
2.3	Free water content		170.0	
3.0	**Determination of cement content**			
3.1	Cement content	[water	309	
3.2	Max cement content			
3.4	Modified W/C		0.55	
3.4	Minimum cement content		290	
4.0	**Determination of total aggregate**			
4.1	Concrete density		2830	
4.2	Total aggregate content	=concrete density-water content-cement content 1901		
5.0	**Selection of fine and coarse aggregate content**			
5.1	Grading of fine aggregate	BS882	%passing 0.6 mm	
5.2	Proportion of fine aggregate	30-37%		34 %
5.3	Fine aggregate content	=aggregate content x 34%		646
5.4	Coarse aggregate content	=aggregate content-fine aggregate content		1255

Appendix A 4 Details of Test Specimens

Table A4.1) Column specimen specifications for Bamboo

Concrete Grade	Sample no	Column designation	Outer Diameter (mm)	Height h(mm)	Culm thickness (mm)	Slenderness
C20	1	Y/C20/100/2/S1	100	200	10	2
	2	Y/C20/100/2/S2	100	200	10	2
	3	Y/C20/100/3/S1	100	300	10	3
	4	Y/C20/100/3/S2	100	300	10	3
	5	Y/C20/75/2/S1	75	150	8	2
	6	Y/C20/75/2/S2	75	150	8	2
	7	Y/C20/75/3/S1	75	225	8	3
	8	Y/C20/75/3/S2	75	225	8	3
	9	Y/C20/75/4/S3	75	300	8	4
	10	Y/C20/75/4/S4	75	300	8	4
	11	Y/C20/55/2/S1	55	110	6	2
	12	Y/C20/55/2/S2	55	110	6	2
	13	Y/C20/55/3/S1	55	165	6	3
	14	Y/C20/55/3/S2	55	165	6	3
	15	Y/C20/55/3/S1	55	220	6	4
	16	Y/C20/55/3/S2	55	220	6	4
Concrete Grade	Sample no	Column designation	Outer Diameter (mm)	Height h(mm)	Culm thickness (mm)	Slenderness
C30	1	Y/C30/100/2/S1	100	200	10	2
	2	Y/C30/100/2/S2	100	200	10	2
	3	Y/C30/100/3/S1	100	300	10	3
	4	Y/C30/100/3/S2	100	300	10	3
	5	Y/C30/75/2/S1	75	150	8	2
	6	Y/C30/75/2/S2	75	150	8	2
	7	Y/C30/75/3/S1	75	225	8	3
	8	Y/C30/75/3/S2	75	225	8	3
	9	Y/C30/75/4/S3	75	300	8	4
	10	Y/C30/75/4/S4	75	300	8	4
	11	Y/C30/55/2/S1	55	110	6	2
	12	Y/C30/55/2/S2	55	110	6	2
	13	Y/C30/55/3/S1	55	165	6	3
	14	Y/C30/55/3/S2	55	165	6	3
	15	Y/C30/55/3/S1	55	220	6	4
	16	Y/C30/55/3/S2	55	220	6	4

Appendix A 5 Test results of column specimens

Table A5.1 Test results of yellow bamboo columns filled with concrete class 20

S no	Column Series Designation	Outer Diameter D	Height h	Culm thickness	Slenderness ratio (h/d)	Average Load (kN)	Average Strength (N/mm^2)
1	Y/C20/100/2	100	200	10	2	87.5	9.21
2	Y/C20/100/3	100	300	10	3	74.7	7.86
3	Y/C20/75/2	75	150	8	2	54.7	12.38
4	Y/C20/75/3	75	225	8	3	50.2	11.36
5	Y/C20/75/4	75	300	8	4	47.8	10.82
6	Y/C20/55/2	55	110	6	2	45.8	19.28
7	Y/C20/55/3	55	165	6	3	40.4	17.07
8	Y/C20/55/4	55	220	6	4	36.5	15.37

Table A5.2 Test results of yellow bamboo columns filled with concrete class 30

S no	Column Series Designation	Outer Diameter D	Height h	Culm thickness	Slenderness ratio (h/d)	Average Load (kN)	Average Strength (N/mm^2)
1	Y/C30/100/2	100	200	10	2	125.4	13.1
2	Y/C30/100/3	100	300	10	3	111.8	11.75
3	Y/C30/75/2	75	150	8	2	88.7	20.07
4	Y/C30/75/3	75	225	8	3	83.4	18.87
5	Y/C30/75/4	75	300	8	4	76.5	17.31
6	Y/C30/55/2	55	110	6	2	55.8	23.48
6	Y/C30/55/3	55	165	6	3	52.7	22.1
7	Y/C30/55/4	55	220	6	4	47.8	20.11

Table A5.3) Tests results of Raw bamboo culms							
S no	Column Series Designation	Outer Diameter D	Height h	Culm thickness	Slenderness ratio (h/d)	Average Load (kN)	Average Strength (N/mm^2)
1	Y/100/2	100	200	10	2	50.4	5.30
2	Y/100/3	100	300	10	3	45.4	4.77
3	Y//75/2	75	150	8	2	34.7	7.85
4	Y/75/3	75	225	8	3	33.2	7.51
5	Y/75/4	75	300	8	4	27.6	6.25
6	Y/55/2	55	110	6	2	19.7	8.30
7	Y/55/3	55	165	6	3	15.6	6.57
8	Y/55/4	55	220	6	4	14.2	5.98

Table A5.4 Test results for unconfined concrete specimens						
S no	Column Series Designation	Outer Diameter D	Height h	Slenderness ratio (h/d)	Average Load (kN)	Average Strength (N/mm^2)
1	U/C30/100/2	100	200	2	88.4	11.26
2	U/C30/100/3	100	300	3	72.7	6.43
3	U/C30/75/2	75	150	2	48.7	11.03
4	U/C30/75/3	75	225	3	45.2	7.86
5	U/C20/100/2	100	200	2	50.4	6.42
6	U/C20/100/3	100	300	3	43.9	5.98
7	U/C20/75/2	75	150	2	34.7	6.90
8	U/C20/75/3	75	225	3	20.3	4.25

Appendix A 6 Summary of calculation results for composite columns

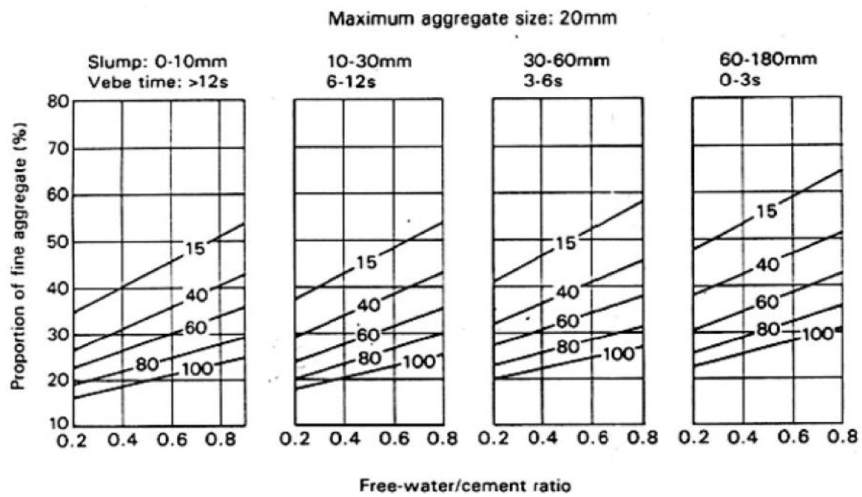
Table A6. 1 Carrying capacity calculations

Slenderness ratio	Concrete Strength	Confined strength	Load carrying capacity kN		Sum
			unconfined	confined	
Y-100/2	C30	125.4	88.4	33.4	121.8
	C20	90.4	50.4	33.4	83.8
Y-100/3	C30	111.8	72.7	29.7	102.4
	C20	90.5	50.4	29.7	80.1
Y-75/2	C30	81.4	48.7	20.1	68.8
	C20	68.7	34.7	20.1	54.8
Y-75/3	C30	83.4	45.2	15.7	60.9
	C20	65.4	15.7	15.7	44.0

Table A6.2 Capacity enhancement calculations

Slenderness ratio	Concrete strength	Confined Strength	Unconfined Strength	Capacity Enhancement
Y-100/2	30	15.97	11.26	1.42
	20	11.52	6.42	1.79
Y-100/3	30	14.24	6.43	2.21
	20	11.53	6.42	1.80
Y-75/2	30	18.43	11.03	1.67
	20	15.56	7.86	1.98
Y-75/3	30	18.89	6.90	2.74
	20	14.41	4.25	3.48

Appendix A 7 Extracts from BRE Manual



Recommended proportions of fine aggregate for various levels of free water cement ratio according to % passing a 600µm

Appendix A 8 sample calculations for code formulaes

a) Theoretical formula

$A_b = \frac{\pi}{4}\,[D^2 - (D - 2 \times t)^2]$

$= A_b = \frac{\pi}{4}\,[100^2 - (100 - 2 \times 10)^2] \quad = 2862\text{mm}^2$

$A_c = \frac{\pi}{4}\,(D - 2 \times t)^2 = \frac{\pi}{4}\,(100 - 2 \times 10)^2 \quad = 5024\text{mm}^2$

$N_{the} = f_c' A_c + f_b A_b \qquad N_{the} = 20 \times 5024 + 5.30 \times 2862 \quad = 115.64\ \text{kN}$

b) Mander, et al (1988). Repeated values are taken from previous examples.

$\sigma\theta = 0.1 f_y = 0.1 \times 5.30$

$= 0.53\text{MPa}$

$f_1 = \frac{2\sigma\theta t}{D} \quad = \frac{2\times0.53\times10}{100} = 0.1$

$f'_{cc} = f'_c(-1.254+2.254\sqrt{1+\frac{7.94f1}{f'c}} - 2\frac{f1}{f'c}$ $\quad f'_{cc} = 20(-1.254+2.254\sqrt{1+\frac{7.94\times0.106}{20}} - 2\times\frac{0.106}{20}$

$=21.684$

$N_{Man} = f'_{cc}A_c + f_bA_{sb} = N_{Man} = 21.684 \times 5024 + 5.30\times2 \quad =124.109$Kn

c) Proposed Model Equation. Repeated values are taken from previous examples.

$$Ppc = 0.58\, A_b f_b + (1+2.51\, \frac{tf_b}{(D-2t)fc} A_c f_c)$$

$$= \quad Ppc = 0.58 \times 2862 \times 5.30 + (1+2.51\, \frac{10\times5.30}{(100-20)20} \times 5024\times20)$$

$= 114\text{kN/m}^2$