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Reliability Assessment of the Strength Capacity of Solid Timber Columns in FRP Laminates and Sprays

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Abstract: Carbon Fiber-Reinforced Polymer (CFRP) composite materials have proven valuable properties and suitability to be used in the construction of new buildings and in upgrading the existing ones. This research therefore showcases the improvement of solid timber columns with varying thickness of CFRP laminates while checking the stress patterns, displacements and reactions of the solid timber columns. The reliability assessment of compositewith length of 3700 mm, width of 150 mm, depth of 200 mm and varying thicknesses of 0.2 mm, 0.4 mm, 0.6 mm, 0.8mm and 1 mm with coded specified axial applied load for three different timber species was executed using the MATLA programming. Adequate safety indices were obtained for different load ratio, MOE of CFRP, thickness of CFRP, thickness of CFRP and strength classes of the timber species.
Keywords: Column, Timber, CFRP, Reliability

1.0 Introduction

Timber have for ages remained among the major structural materials for building construction worldwide due to their renewable nature, availability in various sizes, shapes and colours, affordability, relatively high fatigue resistance and specific strength, ease of joining, durability, and aesthetic appeal. In Europe, timber, have been successfully utilized in both simple and complex structures (Ratief and Holicky, 2005). In Nigeria however, the only area where timber received wide acceptance is in roof framings. The utilization of the material in the engineered design of residential and commercial building receives little or no attention.

The use of limit state design, instead of permissible stresses, enables differentiation of partial safety factors for permanent and variable loads, and makes it possible to reach a more even nominal safety level in all structures (Alpo, 2004). As a recently developed and formulated structural design standard, EC5 (2004) provides a wide range of consistent and up to date models and procedures that can be considered for the development of a local code. Revision of the EC5 (2004) design requirements based on the data on the properties of Nigerian timber species will go a long way in providing a background for the adaptation of advances in technology in the developed countries of Europe to local design practice of timber structures in Nigeria, just as it is being done in other developing countries like South Africa (Ratief and Holicky, 2005).

The benefits of confining timber have mostly been documented from experimental research. North American and European standards establish that CFRP confinement of steel and reinforced concrete has structural benefits such as increased strength and ductility, comparable to the limited timber research conducted. The advantages of using CFRP confinement for reinforcement are that it is durable, corrosion resistant, easy to use and transport due to its high strength to weight ratio and is more flexible than steel (Micheal, 2006). In a circular or rectangular timber column, the axial capacity may be increased, enhancing the compressive strength. Comparably to steel plate bonding, an alternative strengthening system in CFRP confinement, requires less manpower and scaffolding as it is a light material, saving time and money (Heslehurst, 2008).

1.1 Background of The Study

CFRP confinement as a strengthening system has been found to increase the load capacity of structures. The uncertainty of the mechanical properties of timber can be dissipated through the use of CFRP wraps. The laminates are carbon fibre reinforced polymers. The fibres, which are highly anisotropic (Pearce, 1970) provide the stiffness and strength of the system, while the polymer matrix holds the fibres in place. As timber does not have equal properties in all directions, confinement with CFRP can help to mitigate the random character of wood (Kasal and Heiduschke, 2010). Fibres are used from a mass of materials, a significant increase in strength and decrease in brittleness occurring when the materials undergo an extrusion-like process (Heslehurst, 2008). The bond of the confinement of timber with CFRP is of great significance. The epoxy matrix displays excellent adhesion and strength, forcing the individual and flexible fibres to cooperate in the same direction, transfer loads between the fibres and protect the fibres from environmental factors (Pearce, 1970). The epoxy matrix is cured by the addition of a hardener, the mix forming a chemical bond. When cured, the once flexible and workable fibres become very stiff. This is important for compressive loads and the avoidance of buckling. Strengthening of structures is a requirement for rehabilitation of structures in order to increase its structural capacity.

Compressive strength, ductility and environmental protection are three of the factors considered to be benefited from confinement. The benefits vary depending on wrap number and orientation, and produce differing failure mode from the reference samples (Zhang *et al*., 2012; Heiduschke and Haller 2012; Kasal and Heiduschke 2010). Compressive forces are jointly transferred to the timber and the carbon fibre reinforcement polymers, thereby increasing the strength of the columns. Tests have shown that with the combination of different orientations and types of wraps, as well as number of layers, different benefits can be found including increase in strength, ductility and stiffness (Zhang *et al*, 2012; Heiduschke and Haller, 2012). Dissimilar failure modes were also observed in comparison to the reference specimens. The notion of CFRP for rehabilitation of timber structures has not been examined to satisfied extent. The benefit of confining timber has mostly been documented from experimental research.

There are so many advantages derived from wrapping timber with CFRP. Some of the main advantages of CFRP wrapping of timber are (Najm*et al*, 2007; Heiduschke and Haller, 2012; Zhang et al., 2012 Jimenez et al., 2011; Tsakania and Mouzakis, 2010; Webber and Yao, 2001): (i) Increase in compressive strength; (ii) Protection from environmental degradation; (iii) Restoration of historical building or structures; (v) Can be designed or manufactured to meet specific mechanical properties. Emerson (2004) found that transverse reinforcement increased the strength of the column so that it exceeded that of the design value of the column. Additional compressive and bending strength was provided by longitudinal reinforcement. In both of these cases, full wraps were utilized, which has shown to produce the most promising results. Longitudinal cracks in timber are a common concern and reduce compressive strength in columns. Cai*et al*,(2012) found that with wraps 50 mm wide and 115 mm apart that eccentric load capacity could be increased, and that the CFRP could contain further crack opening and confine local ruptures. Najm*et al*, (2007) compared the behavior of full wraps and spirals, finding that the full wrapping had greater benefits than those with spiral reinforcement. This coincides with research conducted by Zhang *et al*, (2012), a main variable being CFRP spacing and width along the length of the timber columns. The benefits increased with smaller spacing between wraps and an increase in the width of the sheets. The number of layers also had an effect with Zhang et al, (2012) finding that results became stable after three layers of CFRP were applied. The use of three layers produced the best results Najm*et al*, (2007), they found that tests fully confined with CFRP showed an increase in load capacity as more layers were added. A favorable failure mode occurs when deformation is observed before failure. A sudden failure can cause sudden collapse without warning, potentially resulting in the loss of lives. The failure modes observed by Heidushke and Haller (2012) of reinforced tubes demonstrated ductile behavior, the wood fibres crushing parallel to the grain, in conjunction with local buckling. Song *et al*, (2010) found that two types of failure modes were prevalent, significant changes in the columns occurring in both types around 70% of the maximum loads. For the first types of failure, compression wrinkles become apparent at mid-height of the specimens which then propagated until maximum load, while in the second type, significant crushing deformation occurred near the ends of the cylinders, the deformations propagating until maximum load.

This study therefore evaluates the data as obtained from laboratory experiment to develop the strength classes for the three (3) selected Nigerian timber species based on the recommendations of EN 338 (2009), which are: *Mitragynaciliata* (Abura), *Afromosiaelata* (Afromosia) and *Berlinia/confusa grandiflora* (Berlinia). Finite Element Analysis (FEA) as coded in ABAQUS software is employed to evaluate the strength effectiveness of the CFRP laminated timber columns under axial loads.

2.0 Structural Behaviour of Timber

Timber is a unique engineering material because it is a defect-filled natural composite. A distinction must be made between timber and wood. Madsen (1992) defines timber as a useful construction material produce from logs of trees and wood as defect free wood.

Timber and wood, in the sense of clear wood, are two very different materials. Failure in clear wood beams in bending is initiated by wrinkles in the compression zone, while failure in timber is initiated by cracking in the tension zone. The cracking in the tension zone is created by tension perpendicular to the grain stresses where the fibres have been disturbed in the vicinity of defects such as knots or other localized slope of grain. The presence of defects in timber causes different behavior in bending and tension than in compression (Christopher, 2000).

2.1 Fibre Reinforced Polymers (FRP)

Fiber reinforced plastic (FRP) (also *fiber-reinforced polymer*) is a composite material made of a polymer matrix reinforced with fibers. The fibers are usually fiber glass, carbon, or aramid, while the polymer is usually an epoxy, vinylester or polyester thermosetting plastic. FRPs are commonly used in the aerospace, automotive, marine, and construction industries (Lofgren, 2005).

In recent years, the fiber reinforced polymer (FRP) composites are becoming a popular material for a wide range of structural rehabilitation due to their superior material properties including; corrosion and weather resistance, high mechanical strength and low weight, ease of handling, good fatigue resistance, and versatility of size, shape and quality (Ede, 2012). Unlike most of the traditional building materials, the FRP composites can be specifically designed by blending the best combination of material properties in response to specific necessities (Ede, 2012). The use of fiber reinforced polymer (FRP) composites in various engineering fields, for example, aerospace, automotive, and marine engineering applications has attained an advanced level, while the use in civil structural applications is constantly increasing (Bakis et. al., 2002). The fiber reinforced polymer (FRP) is gradually taking the place of steel in some field of structural rehabilitation. In fact, FRP sheets may be wrapped around structural elements, resulting in considerable increases in strength and ductility without excessive stiffness change (Ede, 2012). The most common FRP products for civil structural applications are internal reinforcing bars, pre-stressing tendons/anchor systems, and externally bonded plates, sheets, shells and tapes.

FRP composites for structural strengthening are produced by embedding continuous fibers in a resin matrix which binds them together. The fibers are the load carrying elements and have highly oriented-defect free micro structures. The resin matrix binds the fibers together, protects fibers from the environment, provides stability to the fibers and acts as a medium to transfer stresses between adjacent fibers (Karbhari and Zhao, 2000). The main material properties include anisotropy, linear elasticity to failure, high tensile strength/modulus in the direction of the fibers, and generally limited compressive properties (Nanni, 1993).

3.0 Materials and Methods

3.1 Timber

Three timber species will be used in this work, namely, *Mitragynaciliata* (Abura), *Afromosiaelata* (Afromosia) and *Berlinia/confusa grandiflora* (Berlinia).

3.2 Finite Element Method

This approach discretizes the structure into small divisions (or elements) where each element is defined by a specified number of nodes. The behaviour of each element (ultimately the structure) is assumed to be a function of its nodal quantities (displacements and/or stresses), that serve as the primary unknowns in this formulation. This is one of the most general and accurate methods to use, because it does not put any limitations on the geometry, loads, or boundary conditions, and can be applied to open/closed girders and static/dynamic analysis. Additionally, the structure’s response can always be improved by refining the mesh and increasing the number of nodes (or degrees of freedom) for each element. However, the rather involved modeling and analysis efforts required by this method may in some cases make it impractical for preliminary analysis (Beneditti and Tralli, 1989).

In order to apply the finite element technique, the region of interest is discretized by a finite element mesh. The basic idea of the mean-based, second- moment analysis as used in stochastic finite element analysis is to expand via Taylor series, the entire vector and the matrix stochastic field variables, to retain only the second order methods terms and to use it in the analysis, only in the first tier statistical moments. (Stefanou, 2003).

3.3 Finite Element Modelling

The Finite Element Method (FEM) (and its practical application often known as finite element analysis (FEA) is a numerical technique for finding approximate solutions of Partial Differential Equations (PDE) as well as integral equations. In a structural simulation, FEM helps tremendously in producing stiffness and strength visualizations and also in minimizing weight, materials, and costs.

The FEM allows detailed visualization of where structures bend or twist, and indicates the distribution of stresses and displacements. FEM software provides a wide range of simulation options for controlling the complexity of both modeling and analysis of a system. Similarly, the desired level of accuracy required and associated computational time requirements can be managed simultaneously to address most engineering applications. The FEM allows entire designs to be constructed, refined, and optimized before the design is manufactured.

Tables 3.1 to 3.6; show the material properties of CFRP and stochastic parameters obtained from the literature (Abubakar Mamman Msc thesis Civil engineering Ahmadu Bello University Zaria).

Table 1: Material properties used for CFRP.

Material	Young Modulus	Poison Ratio	Density(kN/m^3)	Yield Stress	Strain
CFRP	310000Mpa	0.34	1400	2250Mpa	0.019

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Table 2: Characteristic Values of Other Material Properties

Other Material Properties	Timber species		
	Mitragynaciliata (Abura)	*Afromosiaelata* (Afromosia)	*Confusa grandiflora* (Berlinia)
Tension Parallel $f_{t,k,0}$ (N/mm²)	48.12	78.72	53.52
Tension Perpendicular $f_{t,k,90}$ (N/mm²)	0.6	0.6	0.6
Compression Parallel $f_{c,k,0}$ (N/mm²)	35.96	57.27	47.22
Compression Perpendicular $f_{c,k,0}$ (N/mm²)	3.30	3.36	3.2
Shear Strength $f_{v,k}$ (N/mm²)	3.8	3.8	3.8
5% MOE Parallel $E_{0.05}$(KN/mm²)	5.3	6.5	6.7
Mean MOE Perpendicular $E_{0.90}$ (kN/mm²)	0.27	0.32	0.33
Mean Shear Modulus G_{mean} (kN/mm²)	0.5	0.61	0.62
Mean Density ρ_{mean} (kg /m)	545	544	526

4.0 Discussion of Results

The analytical result obtained from the structural models of the Abura, Afromosia and Confusa timber species in the finite element method using ABAQUS CAE software are presented in the plates 1-9 (see appendix). In their design, the strength limit state functions are considered.

The column prototype is modelled for performance in service loads. The column is bonded with 0.2 mm, 0.4 mm, 0.6 mm, 0.8 and 1.0 mm thickness of CFRP-laminates, which improved strength capacity of the timber columns. The lengths of the columns are 3700 mm; width is 150 mm and the depth 200 mm.

Results in Table 3 show variation in stresses, deformations, and reactions with varying thicknesses of CFRP laminates for strengthened timber columns and it has been found that there are changes in the parameters with changes in applied loads and thicknesses.

Parameters	**Thickness of CFRP (mm)**				
	0.2	0.4	0.6	0.8	1.0
***Mitragyna ciliate* (Abura) Timber Column Species Laminated with Various Thicknesses of CFRP Laminate with Axial load of 36 kN (Fixed-Free)**					
Stress (N/mm^2)	1.833E+03	1.506E+03	1.278E+03	1.109E+03	9.782E+02
Displacement (mm)	1.997E+01	1.663E+01	1.429E+01	1.256E+01	1.123E+01
Reaction (kN)	1.257E+05	1.026E+05	1.033E+05	1.044E+05	1.052E+05
***Afromosiaelata* (Afromosia) Timber Species for Various Thicknesses of CFRP with Axial load of 58kN (Fixed-Free)**					

Stress (N/mm^2)	2.509E+03	2.114E+03	1.828E+03	1.609E+03	1.435E+03
Displacement (mm)	2.721E+01	2.323E+01	2.032E+01	1.809E+01	1.632E+01
Reaction (kN)	2.115E+05	1.771E+05	1.653E+05	1.670E+05	1.683E+05
Confusa grandiflora **(Berliania) Timber Species for Various Thicknesses of CFRP with Axial load of 49kN (Fixed-Free)**					
Stress (N/mm^2)	2.027E+03	1.715E+03	1.487E+03	1.312E+03	1.173E+03
Displacement (mm)	2.199E+01	1.884E+01	1.652E+01	1.473E+01	1.332E+01
Reaction (kN)	1.761E+05	1.481E+05	1.367E+05	1.381E+05	1.392E+05

The test results from Table 4.4 on *Mitragyna ciliate* species of timber columns with axial load of 36kN (fixed-free) was modelled with varying thicknesses of CFRP laminates. From the result obtained there are decreases in displacement as thicknesses of CFRP laminates increase which makes it a good retrofitting material as it accommodates more carrying capacity and reduces deformation on timber columns. The displacements obtained for 0.2mm CFRP laminates are 1.997E+01 mm while for 1mm CFRP laminates are 1.123E+1 mm. The differences in displacement are 0.251E+01 mm which is about 43% reduction from 0.2 mm thick laminate. The reaction obtained for 0.2mm CFRP laminates are 1.257E+05kN while for 1mm CFRP laminates are 1.052E+05kN. The differences in reactions are 0.205E+05kN or 20500N which is about 16% decreases from the 0.2 mm thick CFRP laminate.

The *Afromosiaelata*specie test results shows a consistent trend when an axial load of 58kN (fixed-free) was modeled with varying thickness of CFRP laminates. In addition, the result also shows a decrease in stress b 42% as the thickness of the laminate increases from 0.2 – 1.0mm. The displacement and reactions were also reduced by 40% and 20% respectively. The *Confusa grandiflora* (Berliania) specie of timber column fixed with an axial load of 49kN also showed a decrease in stresses as the thickness of CFRP laminate increases. The decrease in displacement was relatively small which indicates that increase in thickness of the laminate has little effect in as compared to the stress distribution. The differences in displacement are 0.867E+01 mm or about 39% reduction of displacements from 0.2 mm thick CFRP laminate to 1.0mm thick laminate. The reaction is in a similar manner with *Afromasiaelata*with a decrease of about 20% from 0.2mm to 1.0mm thickness of CFRP laminate.

In general, the strength capacity of the timber column has been increased, because the CFRP reinforcement offered some degree of resistance to the timber column, thus making it to accommodate more loadings prior to its failure. The stability is also enhanced as the timber column reacts less to the axial loadings. The distributions patterns and plots of stress, displacement and reaction are showed in Figures 1 to Figure 9, and Plates 1 to Plate 9 respectively. (see appendix).

5.0 Conclusion

From the results obtained, the following conclusions are drawn.

a) There was decrease in stresses as CFRP laminates and sprays are increasing in thickness with the same axial applied load acting on the timber columns.
b) Bond characters are studied and empirical load-carrying capacity based on stress-based approach for solid timber column strengthened with CFRP is found to be in good agreement with the test results reviewed from literature.
c) External strengthening of timber columns using normal modulus CFRP strips is quite an effective technique in increasing the load carrying capacity and stiffness of the solid timber columns sections.

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