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Research Paper

Performance Analysis of Solid Timber Columns Laminated or Sprayed With Carbon Fibre Reinforced Polymer (CFRP) Using Finite Element Method (FEM)

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ABSTRACT
The performance analysis of solid timber columns laminated or sprayed with carbon fibre reinforced polymer (CFRP) using FEM is discussed. Selected timber specie columns are laminated and sprayed to check the pattern of stresses developed, displacements and reactions of the specimen when loaded using Abaqus. An analytical model for CFRP strengthened timber columns with 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 different end conditions and specified axial applied load for three different timber species of Abura, Afromosia and Confusa. This paper findings have shown that CFRP laminates and sprays are not only effective in restoring the lost capacity of damaged timber columns sections, but are also quite effective in strengthening of timber columns sections to sustain higher loads, extend their fatigue life and reduce crack propagation.

***KEYWORDS**: Carbon Fibre Reinforced Polymer, Solid Timber Liminates, Finite Element Analysis, CFRP Laminates and sprays*

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I. INTRODUCTION

Timber has 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[1]. 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 concept of rehabilitation to increase structures stability should be considered as an alternative to complete reconstruction which can be uneconomical and timely due to jacking up of the structure, while repairs occur. The replacement of structural components would normally require the use of hardwood which is generally stronger than softwood, due to its superior density. This is typically an expensive process [2], also creating sustainability issues due to the difficulty of obtaining old growth mature forest sawn timber[3]. For softwood to be used in an outside environment, it generally has to be treated with toxic preservatives to protect it against fungi and insect pests. Although considered weaker, softwood timber forests are sustainable due to the speed at which the trees grow. If the softwood timber were able to be sufficiently protected, it could make for a viable option environmentally. Due to these concerns, column strengthening using alternative construction methods must be considered. Carbon Fibre Reinforced Polymers (CFRP) can strengthen timber components in compression. Limited research has been conducted on layers of CFRP as a protective method from environmental degradation, but some promising results have been demonstrated.

There are severally advantages in the use CFRP confinement material. They include include durability, corrosion resistance, ease of use and transport as a result of its high strength to weight ratio. In a circular or rectangular timber column, the axial capacity may be increased, enhancing the compressive strength. An alternate strengthening system in CFRP confinement, compared to steel plate bonding, requires less labor and scaffolding because it is a light material, saving time and money. Therefore, this paper aims to study the performance of three selected Nigerian timber species strengthened with CFRP laminatesbased on the recommendations of EN 338 (2003) using a finite element modelling tool, Abaqus/CAE. The timber species are *Mitragynaciliata*(Abura), *Afromosiaelata*(Afromosia) and *Berlinia/confusa grandiflora* (Berlinia).

II. BACKGROUND OF STUDY

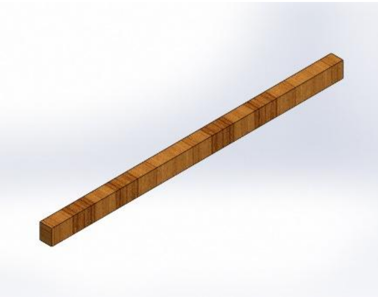
CFRP confinement as a structural strengthening technology has been demonstrated to boost structure load capacity while also reducing column strains. The highly anisotropic fibres[4] provide the stiffness and strength of the system, while the polymer matrix holds the fibres in place. As timber does not have equal properties in all directions, confinement with CFRP can help to mitigate the random character of wood[5].Fibres are made from a mass of materials that undergo an extrusion-like process, which results in a large increase in strength and decrease in brittleness. 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 [4]. The epoxy matrix is cured by the addition of 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 the rehabilitation of structures 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 [6][5]. Compressive forces are jointly transferred to the timber and the carbon fibre reinforced 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 several layers, different benefits can be found including an increase in strength, ductility and stiffness [6]. Dissimilar failure modes were also observed in comparison to the reference specimens. The notion of CFRP for the rehabilitation of timber structures has not been examined to a 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 [7]: (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 [2] 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. Najm et al.[7] compared the behaviour of full wraps and spirals, finding that the full wrapping had greater benefits than those with spiral reinforcement. A favourable 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 of reinforced tubes observed by [6] demonstrated ductile behaviour, the wood fibres crushing parallel to the grain, in conjunction with local buckling.

III. METHODOLOGY

The materials used for this paper are; Abura (*Mitragyna ciliate*), Afromosia (*Afromosiaelata*), Berlinia (*Confusa grandiflora*), and Carbon fibre reinforced plastics (CFRP). The material properties of each are shown in Tables 1 to6. The material properties were obtained from literature. The column prototype is modelled for performance in service using finite element method using ABAQUS (a finite element software) for a fixed-free end and fixed-fixed end column (short column). The column is bonded with varying thickness 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.

To understand the effect of CFRP laminates on timber, a 3D model using Solidworks of the various timber species are as shown in Plates I to III.These models were assigned the various materials properties as shown in table 1-6, then exported using .DXF file format. This is because it is the file format, which can be read by ABAQUS when the model is exported to it.



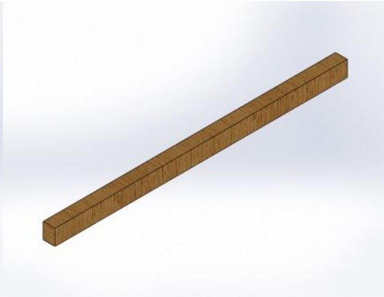


Plate I:Model of Abura Plate II:Model of AfromosiaPlate III:Model of Confusa

In ABAQUS, a finite element analysis software, the various models were imported. The load and restraint constraints were applied. For this paper, a fixed-free (cantilever beam) and fixed-fixed column were used. The dimension of the timber column are; length = 3700 mm; width = 150 mm and depth = 200 mm**.**

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

Table 2: Characteristic values of timberspecies

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

Table 3: Stochastic parameters for *Mitragynaciliata*timber species

S/No	Variable	Meaning	Distribution	Mean E(X)	Coefficient of Variation (COV)	Standard Deviation S(X)
1	E	Modulus of elasticity *Mitragynaciliata* (Abura)	Log-Normal	7973kPa	0.0126	104.54
2	E_{CFRP}	Modulus of elasticity of CFRP	Log-Normal	120kPa	0.0833	10000
3	B	Breadth	Deterministic	150mm	-	-
4	H	Depth	Deterministic	200mm	-	-
5	T	Thickness of CFRP	Normal	0.2mm	0.0052	1.93
6	L	Length	Deterministic	3700mm	-	-
7	Q_k	Live Load	Deterministic	1.5	-	-
8	G_k	-	Deterministic	1.35		
9	K_{mod}	-	Log-Normal	0.8	0.16	0.105
10	ρ_{mean}	Mean Density	Deterministic	544.73	0.062	33.68

Table 4: Stochastic parameters for *Afromosiaelata*timber species

S/No	Variable	Meaning	Distribution	Mean E(X)	Coefficient of Variation (COV)	Standard Deviation S(X)
1	E	Modulus of elasticity *Afromosiaelata*	Log-Normal	9695kPa	0.00672	64.06
2	E_{CFRP}	Modulus of elasticity of CFRP	Log-Normal	120kPa	0.0833	10000
3	B	Breadth	Deterministic	150mm	-	-
4	H	Depth	Deterministic	200mm	-	-
5	T	Thickness of CFRP	Normal	0.2mm	0.0052	1.93
6	L	Length	Deterministic	3700mm	-	-
7	Q_k	Live Load	Deterministic	1.5	-	-
8	G_k	-	Deterministic	1.35		
9	K_{mod}	-	Log-Normal	0.8	0.16	0.105
	ρ_{mean}	Mean Density		544.27	0.047	24.84

Table 5: Stochastic parameters for *Confusa grandiflora* timber species

S/No	Variable	Meaning	Distribution	Mean E(X)	Coefficient of Variation (COV)	Standard Deviation S(X)
1	E	Modulus of elasticity *Confusa grandiflora*	Log-Normal	9958kPa	0.00561	54.63
2	E_{CFRP}	Modulus of elasticity of CFRP	Log-Normal	120kPa	0.0833	10000
3	B	Breadth	Deterministic	150mm	-	-
4	H	Depth	Deterministic	200mm	-	-
5	T	Thickness of CFRP	Normal	0.2mm	0.0052	1.93
6	L	Length	Deterministic	3700mm	-	-
7	Q_k	Live Load	Deterministic	1.5	-	-
8	G_k	-	Deterministic	1.35		
9	K_{mod}	-	Log-Normal	0.7	0.15	0.105
10	ρ_{mean}	Mean Density		525.71	0.029	15.28

Table 6: Properties of timber in strength Classes

Strength Properties (N/mm^2)	Strength classes and timber species		
	Mitragynaciliata (Abura)	*Afromosiaelata* (Afromosia)	*Confusa grandiflora* (Berlinia)
	C18	D30	D30
Bending Strength, $f_{m,k}$	18	30	30
Tension Strength Parallel to grain, $f_{c,0,k}$	11	18	18
Tension Strength Perpendicular to grain, $f_{t,90,k}$	0.5	0.6	0.6
Compression Strength Parallel to grain, $f_{c,0,k}$	18	23	25
Compression Strength Perpendicular to grain, $f_{c,90,k}$	2.2	8	8
Shear Strength. $f_{v,k}$	2.0	3	3
Stiffness Properties (kN/mm^2)			
Mean Modulus of Elasticity Parallel to grain, $E_{0,mean}$	9	10	10
5% Fractile value of Modulus of Elasticity in bending, $E_{o,05}$	6.0	8	8.0
Mean Modulus of Elasticity Perpendicular to grain, $E_{90,mean}$	0.30	0.64	0.64
Mean Shear Modulus, G_{mean}	0.56	0.6	0.6
Density (kg/m^3)			
Characteristic Density, ρ_k	320	530	530
Mean density, ρ_{mean}	380	640	640

IV. RESULTS AND DISCUSSION

(a) The experimental result of maximum axial failure load acting on unstrengthened timber columns for Abura, Afromosia and Confusa timber species are shown in Table 7. This maximum failure loads will be used for the modelling of the strengthen timber column with CFRP laminates of varying thickness.

Table 7: Axial load for timber species for unstrengthened timber columns

Parameters	Abura	Afromosia	Confusa
Stress (N/mm^2)	4.002E+01	6.448E+01	5.336E+01
Displacement (mm)	2.502E+01	3.284E+01	2.639E+01
Reactions (kN)	1.688E+05	2.723E+05	2.252E+05

(a) Performance Model of Abura (*Mitragynaciliate*)Bonded CFRP laminate

The column is modelled for performance in service loads using ABAQUS and the results of variation in stress, deformation and reactions when bonded with 0.2 mm, 0.4 mm, 0.6 mm, 0.8 and 1.0 mm thickness of CFRP laminatesor sprays are shown in Tables 8and9. The dimensions of the column are; lengths = 3700 mm; width = 150 mm and depth = 200 mm.

Table 8:*Mitragyna ciliate* (Abura) timber column specie laminated or sprayed with CFRP (Fixed-Free) at 36kN

Parameters	The thickness of CFRP (mm)				
	0.2	0.4	0.6	0.8	1.0
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

Table 9: Abura timber species laminated or sprayed with CFRP (fixed- fixed) at 36kN.

Parameters	Thickness of CFRP (mm)				
	0.2	0.4	0.6	0.8	1.0
Stress (N/mm^2)	1.131E-16	2.997E-16	4.984E-16	6.714E-16	8.635E-16
Displacement (mm)	4.002E-17	1.040E-16	1.705E-16	2.388E-16	2.979E-16
Reaction (kN)	1.800E+05	1.800E+05	1.800E+05	1.800E+05	1.800E+05

The results from Tables 8 and 9 for the cantilevered timber column and fixed-fixed end column respectively, showed that the stresses and deformation developed within Abura species decreases with increases in the thickness of CFRP laminates. As compared to the unstrengthened Abura timber column, there is a significant increase in the stresses developed within the timber column (fixed-free end) strengthened with 0.2mm thick CFRP laminates or sprays, after which it reduces. . Plate IV shows the results and stress pattern for Abura timber species strengthened with 0.2mm thickness of CFRP laminates or sprays.

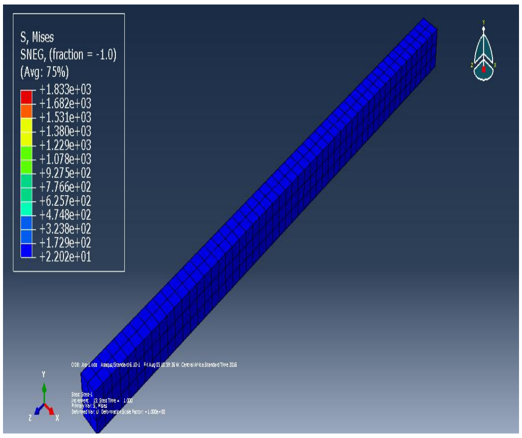


Plate IV: Stress Distribution Model for Abura Timber Species (Fixed-Fixed Ends) Strengthened with 0.2mm CFRP Laminates or sprays usingFEM coded in ABAQUS

Evaluatingstructural performance between fixed-free end and fixed-fixed end, the fixed-free end (cantilever column) showed a significant stress level, while the fixed-fixed end Abura timber column developed little stress. This shows that 0.2mm CFRP laminate thickness is the optimum for maximum result when used to strengthen Abura, especially for fixed-fixed end as it will take a higher loads than 36kN which is the failure load for the unstrengthened and fixed-free end Abura timber columns for failure to occur

Where deformation or displacement is unavoidable, the fixed-free end Abura timber species strengthened with CFRP laminates or sprays, shows that the deformation decreases with increases in the thicknesses of the laminates or sprays. Comparing with the unstrengthened Abura timber species, which had a deformation of about 25.02mm, the fixed-free end specimen shows a lower deformation at 19.97mm. The fixed-fixed end Abura timber column showed the least deformation of 4.0×10^{-17}mm, which is practically zero. Therefore, the deformation of fixed-fixed endsAbura timber species strengthened with 0.2mm thickness of CFRP is shown inPlate V

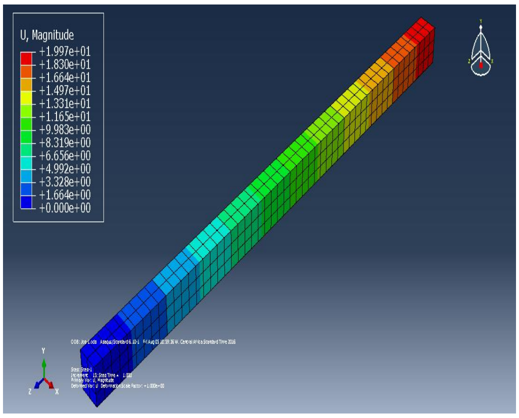


Plate V: Deformation Model for Abura TimberSpecies (Fixed-Fixed Ends) for Strengthened Timber with 0.2mm thick CFRP laminates or sprays using FEM coded in ABAQUS

Similarly, the reaction at the ends of the timber columns decreases when the CFRP laminate or spray thickness is 0.2mm to 0.4mm for fixed-fixed ends, and then increases when the thickness is from 0.6mm to 1.0mm for Abura timber specimens with fixed-free ends.
Plate VI shows the reaction model for fixed-fixed ends Abura timber strengthened with 0.2mm CFRP thickness.

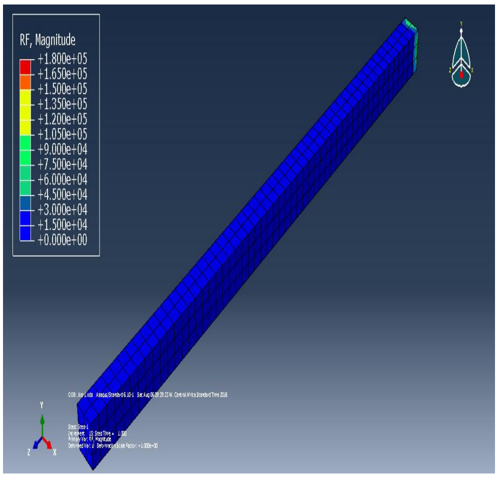


Plate VI: Reactions Model for Abura Timber SpeciesStrengthened with 0.2 mm thick CFRP Laminates or sprays using FEM coded in ABAQUS

As compared to the unstrengthened Abura timber with end reaction of 1.688×10^5kN, the fixed-free ends had smaller value of reactions which shows that Abura strengthened with CFRP laminates or sprays has a reduced structural capacity performance in terms of reaction. When compared to Abura with a fixed-fixed end, the reactions are higher when strengthened with 0.2mm CFRP laminates or sprays.

(b) Performance model of Afromosia (*Afromosiaelata*)with CFRP laminates or sprays

The column is modelled for performance in service loads using ABAQUS and the results of variation in stresses, deformations and reactions when bonded with 0.2 mm, 0.4 mm, 0.6 mm, 0.8 and 1.0 mm thickness of CFRP-laminates or sprays are shown in Tables 10and11. The dimensions of the column are; lengths = 3700 mm; width = 150 mm and depth = 200 mm.

Table 10:Afromosia Timber Species for varyingthicknesses of CFRP laminates or Sprays (Fixed-Free end)

Parameters	Thickness of CFRP (mm)				
	0.2	0.4	0.6	0.8	1.0
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
Reactions (kN)	2.115E+05	1.771E+05	1.653E+05	1.670E+05	1.683E+05

Table 11:Afromosia Timber Species for varyingthicknesses of CFRP laminates or Sprays (Fixed-Fixed end)

Parameters	Thickness of CFRP (mm)				
	0.2	0.4	0.6	0.8	1.0
Stress (N/mm^2)	1.081E-16	2.823E-16	4.788E-16	6.672E-16	8.390E-16
Displacement (mm)	2.758E-17	8.040E-17	1.319E-16	1.920E-16	2.451E-16
Reaction (kN)	2.900E+05	2.900E+05	2.900E+05	2.900E+05	2.900E+05

The results from Tables 10 and 11 for the cantilevered timber column and fixed-fixed end column respectively, showed that the stresses and deformation developed within Afromosia species decreases with increases in the thickness of CFRP laminates or sprays.

Plate VII shows the results and stress pattern for Afromosia timber species strengthened with 0.2mm thickness of CFRP laminates or sprays.

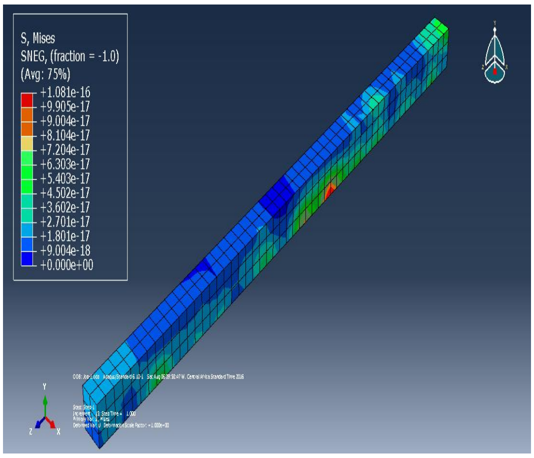


Plate VII: Stress Distribution Model for Abura Timber Species Strengthened with 0.2mm CFRP thicknessusing FEM coded in ABAQUS

When compared to the unstrengthenedAfromosia timber column which had maximum stress of 64.48kN before failure, the model indicates that there is a significant increase in the stresses developed within the timber column (fixed-free end) strengthenedAfromosia with the maximum stresses ocurring where 0.2mm CFRP thicknesses were used and resulted to a stress of 2.509kN, after which it reduces as the thickness increases from 0.4mm to 1.0mm. Evaluating structural performance between fixed-free end and fixed-fixed end, the fixed-free end (cantilever column) showed a significantly higher stress level than the fixed-fixed end Afromosia timber columns at 1.081 x 10^{-16}kN. This indicates that 0.2mm CFRP laminates or sprays thickness is the optimum for maximum structural capacity when used to strengthen Afromosia, especially for fixed-fixed end as it will take a higher load 36kN, which is the failure load for the unstrengthened and fixed-free endsAfromosia timber columns for failure to occur.

Where deformationordisplacement is unavoidable, the fixed-free end Afromosia timber species strengthened with CFRP shows that deformation decreases with increases in the thickness of the laminates or sprays. Comparing with the unstrengthenedAfromosia timber species, which had a deformation of 32.84mm, the fixed-free end specimen shows a lower deformation at 27.21mm. The fixed-fixed end Afromosia timber column showed the least deformation of 2.75×10^{-17}mm, which is practically zero.

The deformation of fixed-fixed end Afromosia timber species strengthened with 0.2mm thickness of CFRP laminates or sprays is shown inPlate VIII.

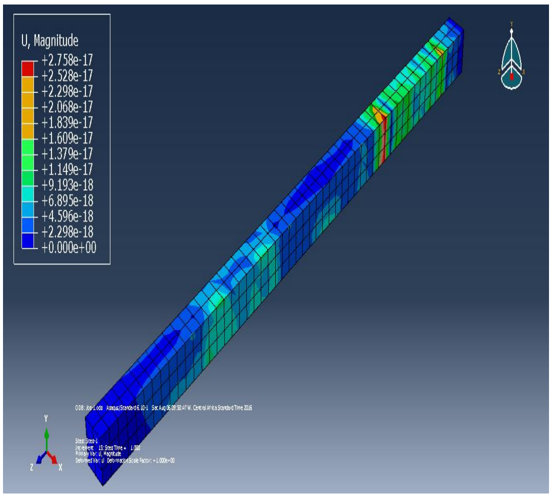


Plate VIII: Distribution Model for Afromosia Timber Species Strengthened Column (Fixed-Fixed) with 0.2 mm CFRP Laminates and Sprays using FEM in ABAQUS.

Similarly, the reaction at the ends of the timber column decreases when the CFRP laminates or sprays thickness for Afromosia timber specimens with a fixed-free end. As compared to the unstrengthened Abura timber with end reaction of 2.723×10^{5}kN, the fixed-free ends had smaller value of reactions, which shows that Afromosia strengthened with CFRP laminates or sprays performs structurally lower in terms of reaction. When compared to Aformosia with a fixed-fixed end, the reactions are higher when strengthenen with 0.2mm thick CFRP laminate or spray at 2.9×10^{5}kN.

Plate IX shows the reaction model for fixed-fixed end Afromosia timber strengthened with 0.2mm CFRP thickness.

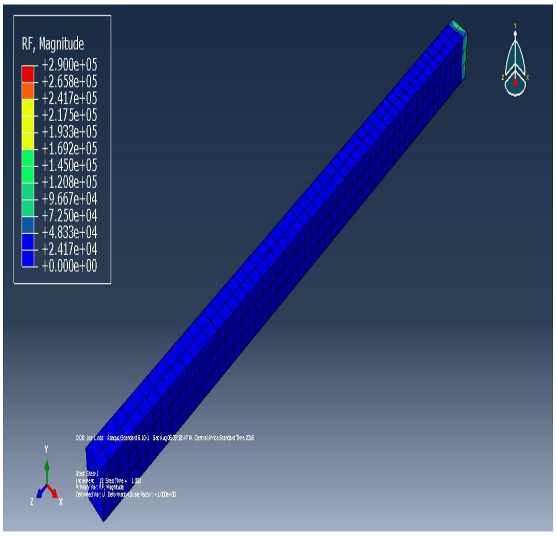


Plate IX: Reactions Distribution Model for Afromosia Timber Species Strengthened Column (Fixed-Fixed) with 0.2 mm CFRP Laminates or sprays using FEM inABAQUS.

(c) Performance model of Berliania (*Confusa grandiflora*)inCFRP laminates or Sprays

The column is modelled for performance in service loads using ABAQUS and the results of variation in stresses, deformations and reactions when bonded with 0.2 mm, 0.4 mm, 0.6 mm, 0.8 and 1.0 mm thickness of CFRP-laminatesor sprays are shown in Tables 12and13. The dimension of the column are; lengths = 3700 mm; width = 150 mm and depth = 200 mm.

Table 12:*Confusa grandiflora* (Berliania) Timber Species for Various Thicknesses of CFRP (Fixed-Free)

Parameters	The thickness of CFRP (mm)				
	0.2	0.4	0.6	0.8	1.0
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

Table 13: Confusa Timber Species for Various Thicknesses of CFRP (Fixed-Fixed)

Parameters	The thickness of CFRP (mm)				
	0.2	0.4	0.6	0.8	1.0
Stress (N/mm^2)	1.077E-16	2.797E-16	4.753E-16	6.654E-16	8.388E-16
Displacement (mm)	2.600E-17	7.756E-17	1.270E-16	1.270E-16	2.378E-16
Reaction (kN)	2.400E+05	2.400E+05	2.400E+05	2.400E+05	2.400E+05

The results from Tables 12 and 13 for the cantilevered timber column and fixed-fixed end column respectively, showed that the stresses and deformations developed within *confusa* species decreases with increases in the thickness of CFRP laminates or sprays. As compared to the unstrengthened*confusa* timber column, which had maximum stress of 53.36kN before failure, there is a significant increase in the stresses developed within the timber column (fixed-free end) strengthened*confusa* with the maximum stresses where 0.2mm thickness of CFRP laminate or sprays are used and resulted to a stress of 2.027kN, after which it reduces as the thickness increases from 0.4mm to 1.0mm. Comparing between fixed-free end and fixed-fixed ends, the fixed-free end (cantilever column) showed a significantly higher stress level capacity than the fixed-fixed end Confusa timber column at 1.077 x 10^{-16}kN. This shows that 0.2mm CFRP laminate thickness is the optimum for maximum result when used to strengthen Confusa, especially for fixed-fixed end as it will take a higher load of 58kN, which is the failure load for the unstrengthened and fixed-free end c*onfusa* timber columns for failure to occur. Plate X shows the results and stress pattern for *confusa* timber species strengthened with 0.2mm thickness of CFRP laminates or sprays.

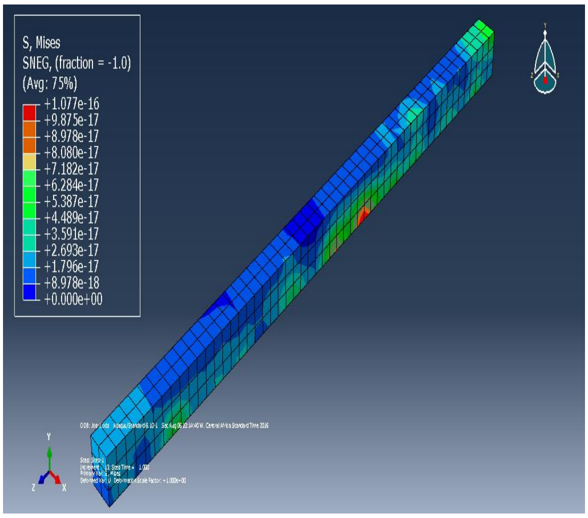


Plate X: Stress Distribution Model for Confusa Timber Species Strengthened with 0.2mm CFRP Laminates or Spraysusing FEM coded in ABAQUS

Where deformation or displacement is unavoidable or expected, the fixed-free end *confusa* timber species strengthened with CFRP laminates or sprays shows that deformation decreases with increases in the thickness of the CFRP. Comparing with the unstrengthened*confusa* timber species,which had a deformation of 26.39mm, the fixed-free end specimen shows a lower deformation at 21.99mm. The fixed-fixed end *confusa* timber column showed the least deformation of 2.6 x 10^{-17}mm, which is practically zero.

The deformation of fixed-fixed end confusa timber species strengthened with 0.2mm thickness of CFRP is shown in Plate IX.

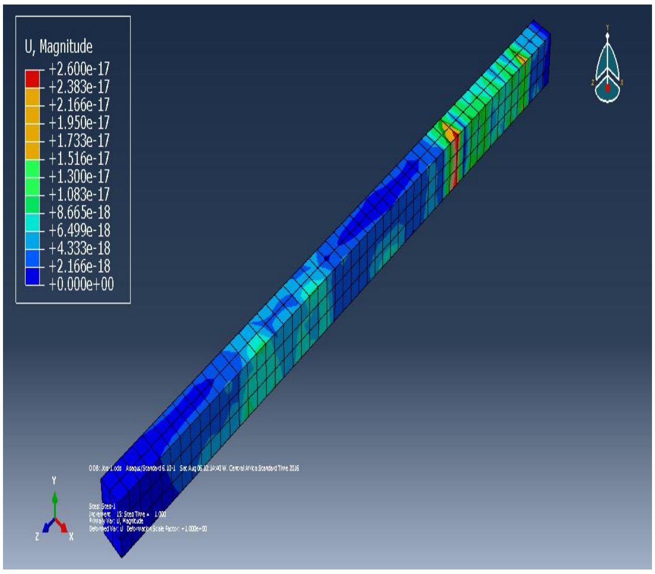


Plate IX: Distribution Model for confusa Timber Species Strengthened Column (Fixed-Fixed) with 0.2 mm CFRP Laminates or Sprays using FEM coded in ABAQUS.

Similarly, the reaction at the ends of the timber column decreases when the CFRP laminate or spray thickness for *confusa* timber specimen with a fixed-free end. As compared to the unstrengthened*confusa* timber with end reaction of 2.252 x 10^5kN, the fixed-free end had lower value of reactions which, show that c*onfusa* strengthened with CFRP laminates or sprays performs structurally lower in terms of reactions. When compared to *confusa* with a fixed-fixed end, the reactions are higher when strengthened with 0.2mm CFRP laminate or sprays at 2.4 x 10^5kN.
Plate XII shows the reaction model for fixed-fixed end Abura timber strengthened with 0.2mm CFRP thickness of laminates and sprays.

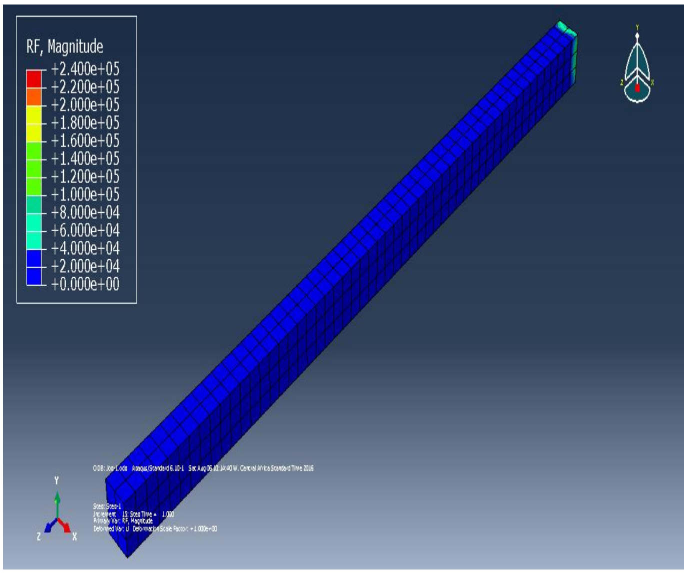


Plate XII: Reactions Distribution Model for Afromosia Timber Species Strengthened Timber Column (Fixed-Fixed) with 0.2 mm CFRP Laminates or sprays using FEM in ABAQUS.

V. Conclusion

From the finite element evaluation of structural performance of the solid timber column sections laminated or sprayed with CFRP in various thicknesses, the following conclusions are obtained.

(a) There were decreases in stresses as CFRP laminates and sprays are increasing in thicknesses with the same axially applied load acting on the timber columns.

(b) External strengthening of timber columns using normal modulus CFRP strips or sprays are quite effective techniques in increasing the structural load carrying capacity and stiffness of the solid timber columns sections.

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