

Optimization and Stress Modelling of Carbon Fibre Reinforced Plastic (CFRP) Hollow Section for Civil Engineering Applications

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ABSTRACT:Mathematical optimization and numerical modelling were used to assess the suitability of the CFRP hollow sections for structural applications. A Genetic Algorithm program incorporating MATLAB was used to obtain an optimal section. FE analysis using ANSYS was also used to simulate the effect of a column axial load of 10,000(representing loads from offshore platforms, bridges, etc) on the CFRP section with Young modulus, 420GPa, length, 5m, and the results compared to that of steel hollow section (SHS) using the same optimal values. The results show that the optimal mass of CFRP required is 90.168kg while the thickness, inner radius and external radius were obtained as 28.8mm, 79.2mm, and 50.4mm respectively. A comparative FE analysis performed using ANSYS workbench shows that the strain intensity of CFRP was 63.67MPa against SHS at 67.26MPa. The shear stress was also higher in SHS against CFRP Hollow section. The comparative study shows that CFRP hollow sections can be much more stable and will be able to sustain heavy loadings with consequent deformations over a longer period of time before failure than steel hollow sections.

KEYWORDS:Optimization, Genetic Algorithm, ANSYS Workbench, Hollow Section, Stress Modelling.

I. INTRODUCTION

Fibre Reinforced Polymers (FRPs) are have gained ground in civil engineering construction works over the last decades due to its enormous performance which is attractive to the engineering community [8]. Several countries have used fibre composite members for large scale structures construction like traffic lights and pedestrian bridges [1]. Concrete reinforcing bars have been produced using FRPs as source material [10], this is due to their corrosion resistance nature. Its structural suitability is due to the excellent material properties like strength and weight characteristics as well as the ability to be tailored into very complex structures [6]. This paper considers the optimization and modelling of carbon fibre reinforced plastic (CFRP) circular hollow section for civil engineering applications, especially when used in a marine environment for the construction of concrete offshore platforms. Song et al [9] explained that using FRPs with the aid of retrofitting techniques that corresponds to the requirements for increasing loads deterioration of the structure, the performance of the structure can be recovered.

II. LITERATURE SURVEY

The increase in the deterioration of infrastructures is a large-scale problem in any country and especially Nigeria, especially in the marine environment where chemical attacks are common which causes concrete cracking followed by ingress chemicals leading to corrosion and deterioration, limiting the lifespan of a structure and therefore maintenance is required as an additional cost [10]. Therefore, intervening on the structure with most feasible, economical, requires

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little maintenance and will sustain the designed loads during its service time. The challenges associated with upgrading, repairs and maintenance are greater than the ones required to design and build a new structure. Fiber Reinforced Polymer (FRP) now presents a new and promising solution to the shortcomings of several traditional materials and upgrading techniques and has a great potential to integrate into a structure as an integral part of it [8]. Li [11] researched the structural design optimization for civil engineering infrastructures. He explained that profits if not the only way in which optimization can be of advantage to civil engineering structural design, it can ensure the quality of civil engineering to a certain extent and prolong its service life. Dede et al [12] explained the usage of optimization techniques in civil engineering during the last two decades and they reported that single and multi-objective optimization problems are nature-inspired and are proving to be better than the classical deterministic methods.

III. METHODOLOGY

In this paper, MATLAB and ANSYS packages were combined to assess the optimization and modelling of carbon fibre reinforced plastic (CFRP) structural circular members for civil construction applications. Specifically, the optimization algorithm will be written using MATLAB where genetic algorithm (GA) will be employed, whereas structural strength will be computed in ANSYS 15.0 [2] which is an FEA based software.

a) Genetic Algorithms

The GA optimization algorithm is the algorithm that is employed for the optimization design algorithm.

b) Formulation of the Objective function

The goal of the optimization is to design an optimized CFRP structural member (hollow section) with the following dimensions: l = length, which supports an axial load, P successfully without failure and buckling. The section is designed as a cantilever column, which means it has a fixed-free end.

According to Arora [3] and Dugguh [5], for a cantilever column, the critical and buckling load is given as

$$P_{cr} = \frac{\pi^2 EI}{4l^2} \tag{1}$$

Where the moment of inertia = I

Modulus of elasticity = E (Young's modulus).

Variables for the design optimization are: mean radius = R ; thickness of the column wall = t .

For the CFRP section, the wall is taken to be a thin wall. Which means $R \gg t$ (average radius is greater than the thickness), and also the sectional area (cross) and moment of inertia are:

$$A = 2\pi Rt; I = \pi R^3 t \tag{2}$$

The mass of the CFRP structural member to be optimized is given as

$$Mass = \rho(lA) = 2\rho l\pi Rt \tag{3}$$

c) Formulation of Constraints

There are two major constraints that govern the optimization of the hollow section. They are stress and buckling constraints. The stress (P/A) developed within the CFRP structural member should not exceed the allowable stress σ_a , this is to avoid failure by crushing the material and it can be expressed as the inequality $\sigma \ll \sigma_a$. Substituting σ with P/A and solving for A , we obtain

$$\frac{P}{2\pi Rt} \leq \sigma_a \tag{4}$$

$$\frac{P}{2\pi Rt} - \sigma_a \leq 0 \tag{5}$$

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The second constraint, under the action of applied load, the CFRP column should not buckle. This means that the buckling load should be more than applied load and it is given by, $P \leq P_{cr}$. Substituting for I in the expression for buckling, we have

$$P \leq \frac{\pi^3 ER^3 t}{4l^2} \tag{6}$$

$$P - \frac{\pi^3 ER^3 t}{4l^2} \leq 0 \tag{7}$$

After the stress and buckling constraints have been fulfilled, the optimization variables (R and t) should not the minimum and maximum values specified:

$$R_{min} \leq R \leq R_{max}; t_{min} \leq t \leq t_{max} \tag{8}$$

d) Numerical Modeling (Finite Element Analysis)

A modern and powerful computational tool used for analysis in recent years is the Finite Element Method (FEM) of analysis [4,5]. A 3-D model of the CFRP structural member with properties as shown in Table 1 and 2 was modelled using ANSYS Workbench [2] which is a finite element package.

Table 1: Material Properties of CFRP [10]

Materials Properties	Density (kg/m ³)	E _x (GPa)	E _y (GPa)	E _z (GPa)	G _{xy} (GPa)	G _{yz} (GPa)	G _{zx} (GPa)	V _{xy} (GPa)	V _{yz} (GPa)	V _{zx} (GPa)
CFRP	1570	420	10.5	10.5	8.0	5.0	5.0	0.27	0.40	0.27

Table 2: Dimension of Optimized Hollow Section

Materials Properties	Outer Radius (R ₁)	Inner Radius (R ₂)	Thickness (t)	Height (h)
Dimensions (mm)	79.2	50.4	28.8	5000

IV. RESULTS AND DISCUSSIONS

a) Design optimization input parameters

The parameters used for the optimization algorithm are:

Load, $P = 1\text{MN} = 1000\text{kN}$,

Length, $L = 5\text{m} = 5000\text{mm}$

Mass Density, $\rho = 1570\text{kg/m}^3$,

Allowable Stress $\sigma_a = 248\text{MPa}$,

Young Modulus, $E = 420\text{GPa}$

Area, $A = 2\pi R t$

Moment of Inertia, $I = \pi R^3 t$

For the optimization algorithm to run successfully, the constraints variables are redesign in MATLAB variables. The standard optimization problem is stated as follows

$$f(x) = 2 * \pi * \rho * l * x_1 * x_2 \equiv 2 * \pi * 1570 * 5 * x_1 * x_2 \tag{9}$$

Subject to

$$g_1(x) = \left[\frac{P}{2 * \pi * x_1 * x_2} \right] - \sigma_a \leq 0 \equiv \left[\frac{1(1.0 \times 10^6)}{2 * \pi * x_1 * x_2} \right] - [248(1.0 \times 10^6)] \leq 0 \tag{10}$$

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$$g_2(x) = P - \left[\frac{\pi^3 * E * x_1^3 * x_2}{4 * L^2} \right] \leq 0 \equiv 1(1.0 \times 10^6) - \left[\frac{\pi^3 * (230 \times 10^9) * x_1^3 * x_2}{4 * (5)^2 * (5)} \right] \leq 0 \quad 11$$

$$g_3(x) = -x_1 \leq 0; \quad 12$$

$$g_4(x) = -x_2 \leq 0; \quad 13$$

$$0.001 \leq x_1 \leq 1; 0.005 \leq x_2 \leq 0.2 \quad 14$$

The optimization algorithm using GA in MATLAB, read the data of the objective function and applied the necessary constraints, it then iterates between the constraints variables and subjects them to the objective functions to adequately evaluate the combination of variables that will carry the given applied load on the CFRP columns at minimum design variables.

b) Results of Finite Element Analysis

In order to get accurate stress when a load is applied, the static structural analysis is conducted in ANSYS Workbench. The finite element model is the hollow section as shown in Plate 2. The dimensions of the cross-sections which were used for the modelling are shown in Plate 1.

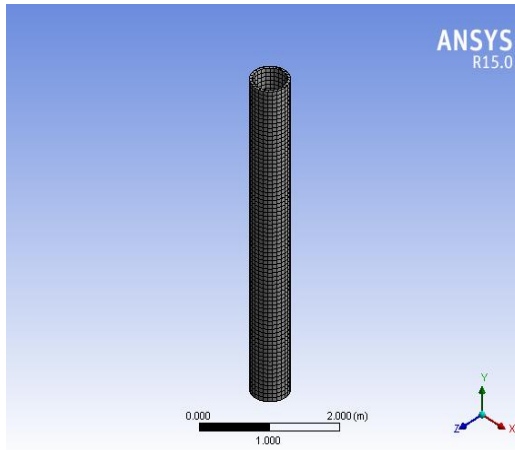


Plate 1: Hollow Section used for Modeling



Plate 2: Results from the Optimization Process

c) Stress Intensity of Hollow Section

The stress intensity of CFRP and steel obtained after the analysis can be seen in the deformed model as shown in Plate 3 and 4. The applied load of 1000kN was used for the analysis. The analysis shows that CFRP can sustain the load applied without much deformation. However, steel will not be able to sustain the applied load.

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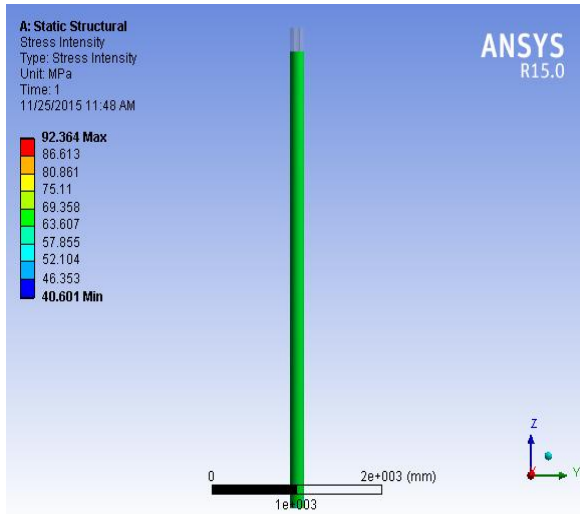


Plate 3: Stress Intensity of CFRP

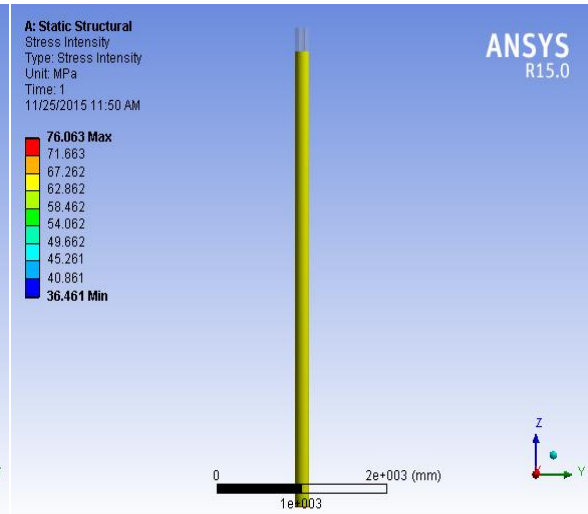


Plate 4: Stress Intensity of Steel.

d) Shear Stress Pattern in the Hollow Section

The shear stress pattern obtained after the analysis for CFRP and steel can be seen in the deformed diagram of the model shown in Plates 5 and 6 using the same applied load of 1000kN. The analysis shows that there are lower shear stresses within the CFRP Hollow Section than the Steel Hollow Section.

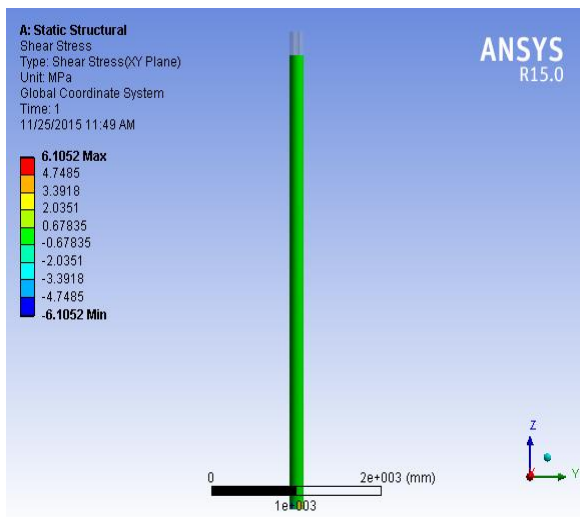


Plate 5: CFRP Shear Stress

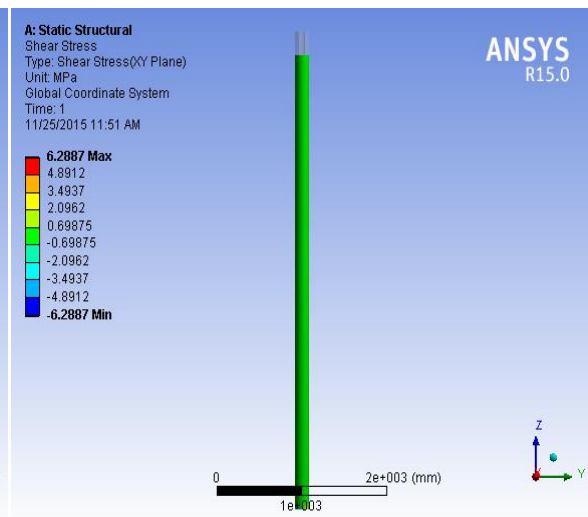


Plate 6: Steel Shear Stress

e) Strain Energy in the Hollow Section

The strain energy, which is the energy stored to resist deformation in a material when a load is applied, obtained after the analysis for the CFRP hollow section and Steel hollow section can be seen in the deformed diagram of the model shown in Plates 7 and 8 at same applied Load of 1000kN. The results showed that steel having a lower strain energy

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921.23mJ, will not be able to sustain the load. CFRP having strain energy of 17407mJ is an indication that CFRP hollow columns are much more stable than steel hollow columns under deformation caused by the applied loads and will sustain the loads.

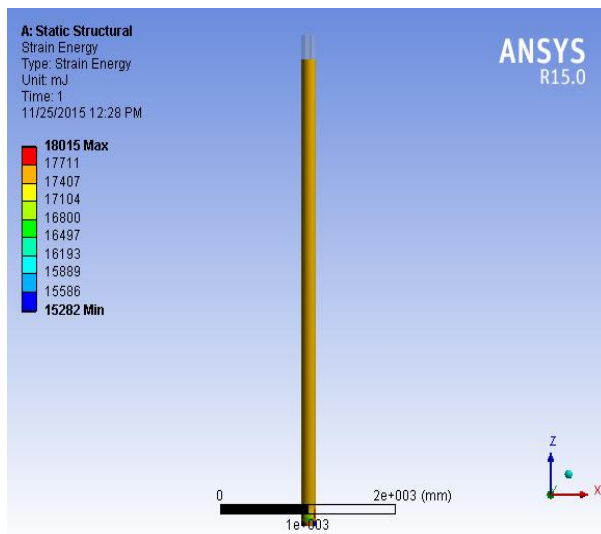


Plate 7: CFRP Strain Energy

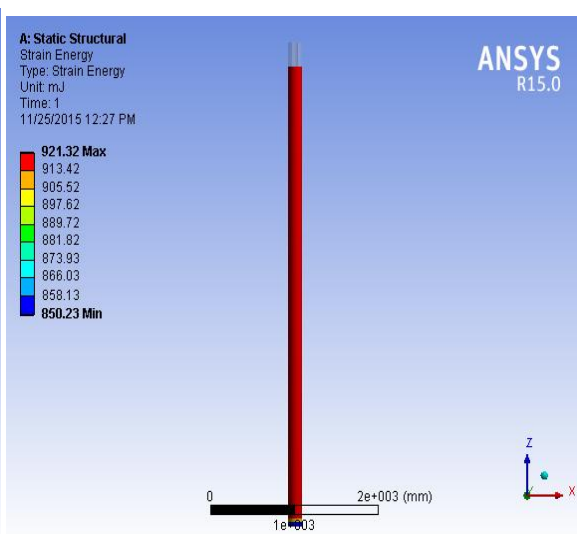


Plate 8: Steel Strain Energy

V. CONCLUSION

From the material optimization and finite element analysis of the CFRP hollow section in accordance with the identification of the objective function, constraints and design variables, the following conclusions are made.

- (1) The study resulted in optimal values of 90.168kg, 28.8mm and 64.2mm for mass, thickness and mean radius respectively for a CFRP Hollow section.
- (2) The same results from the study were also used to simulate the stress intensity and shear stresses and showed that the CFRP hollow section is more stable than steel hollow section after the deformation is caused by the load.
- (3) The results also showed steel having a lower strain energy value of 921.23mJ against CFRP hollow column having strain energy of 17407mJ and hence it is an indication that CFRP hollow columns are more stable than steel hollow columns under deformation caused by the applied loads.

These results indicate that CFRP hollow sections can be safely used as structural hollow columns in civil engineering infrastructure and may successfully replace steel hollow columns. The advantages of CFRP over steel can be adequately harnessed in these applications.

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