STOCHASTIC OPTIMIZATION OF HOLLOW CFRP CONCRETE FILLED COLUMNS

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ABSTRACT

Columns have always been made of steel, timber or reinforced concrete which have been used in residential and industrial buildings. This study aims at obtaining effectiveness which can be attained when Carbon Fibre Reinforced Plastic (CFRP) is used as the structural sections of columns. CFRP hollow and concrete filled columns are loaded using Euler's buckling loading conditions. Finite Element Analysis modes were performed on various columns sections with end conditions using ABAQUS software. Results indicate that there were deformations on the column sections due to loading according to the restraint conditions at the column ends. This failure condition in CFRP is similar to that of steel hollow concrete filled columns. Thus it is suggested that CFRP pultruded sections can be safely adopted as a substitute for steel columns in structure. The load carrying capacity of these columns is about 75% of their steel hollow filled counterpart.
Keywords: FEM, concrete filled, hollow CRFP sections, optimized load capacity, columns.

1.0 INTRODUCTION

Carbon fiber reinforced polymer or Carbon fiber reinforced plastic is an extremely strong and light fiber reinforced polymer which contains carbon fibers. The polymer is often epoxy, but other polymers, such as polyester, vinyl ester, or nylon, are sometimes used. The composite may contain other fibers, such as Kevlar, aluminium, or glass fibres, as well as carbon fibre.

During the last decade, the use of fiber reinforced polymer (FRP) composites has been successfully promoted for external confinement of reinforced concrete (RC) columns all over the world. This technique is considered superior to conventional concrete and steel jacketing methods in terms of confinement strength, post retrofit ductility, sectional areas, weight, corrosion resistance, application ease, and overall project costs. Strengthening and/or upgrading reinforced concrete columns through utilization of composite sheets is now receiving wide acceptance worldwide. The technique is simple to use and has many advantages over other available methods. However limited data is available about its efficiency in confining non-cylindrical shape columns.

Shape of cross sections of columns can directly affect the confinement effectiveness of externally bonded FRP jackets. Benefit of strength is higher for circular than for square or rectangular sections. Poor confinement may be due to low FRP jacket stiffness (dependent on type of FRP and number of plies) or to sharp edges in cross-section. Fibre Reinforced Polymer (FRP) composites can provide effective confinement to circular concrete columns for the purpose of seismic retrofit of bridges. However, the retrofit effectiveness of FRP confinement for square and rectangular columns is greatly reduced due to the flat sides and sharp corners.

CFRP are used to construct various types of structures such as off-shore platforms, buildings and bridges, either to build new structures or upgrade existing ones. Off-shore platforms and bridge engineering are among the fields in civil engineering benefiting from the introduction of CFRP composite. In the past 10 years, experiments have been conducted to investigate the application of CFRP in civil engineering structures, including the applications of CFRP composites on girder and bridge decks, columns and beam strengthening, etc. This work presents some basic information of CFRP composite, including its mechanical behaviors and manufacturing processes relevant to civil engineering applications.

The aim of this work is to examine the safety of concrete filled FRP of hollow section in compression. This work is considered because irrespective of the characteristic advantages CFRP has got over steel, safety of the structure is required. CFRP are new materials and not so widely used, therefore there be some doubts in using it. This work thus suggests adequate, effective and safe concrete filled FRP hollow sections in compression. The objectives of the work include: (i) investigate the safety of using CFRP hollow sections in compression; (ii) examine the efficiency of CFRP sheets in upgrading concrete structures; and (iii) effectiveness of CFRP materials in hollow sections subjected to compression. The scope adopted is to enhance the safety of concrete filled FRP for hollow sections when subjected to compressive forces, having noted the following limitations: (i) CFRP bars when loaded in tension, exhibit linear stress-strain behaviour up to rupture; (ii) much research continues to be done on using CFRP both for retrofitting and as an alternative to steel as a reinforcing or prestressing material. Cost remains an issue and long term durability questions still remain. Some are concerned about the brittle nature of CFRP, in contrast to the ductility of steel; (iii) structural limitation of CFRP is that it lacks fatigue endurance limit and (iv) there have been attempts to improve the ductility of CFRP with little or no success (Michael, 2006).

2.0 BACKGROUND OF CRFP PULTRUDED SECTIONS

Carbon Fiber-Reinforced Polymer (CFRP) is increasingly being used in civil engineering applications to retrofit and strengthen deficient and ageing concrete members in existing buildings and bridges. CFRP application in civil engineering composites are heterogeneous materials composed of fibre reinforcement and matrix. Glass, aramid and carbon fibre polymers are three common fibrous materials to fabricate composites. In structural applications, these composites are called advanced composites due to their high-specific stiffness (stiffness divided by density) and high-specific strength (strength divided by density). Compared to glass and aramid fibre polymers, carbon fibre polymers exhibit improved resistance to harsher environmental exposure and greater toughness to fatigue loading (Benmokrane, 2006). When a concrete column section is wrapped with CFRP, its axial load capacity is expected to enhance due to two factors, firstly the confinement effect of externally bonded transverse fibres, and secondly the direct contribution of longitudinal aligned fibres. Fiber-reinforced polymer FRP composite materials have recently been used as internal and external reinforcements in the field of civil engineering constructions. It has been used as internal reinforcement for beams, slabs, and pavements (Masmoudi et al, 1998; Benmokrane et al., 2006) and also as external reinforcement for rehabilitation and strengthening different structures (Demers and Neale, 1999). In addition, the concrete-filled FRP tubes CFFTs technique has been used successfully for different concrete structures (Fam and Rizkalla, 2001; Yuan and Mirmiran, 2001). Durability and structural integrity of concrete bridge pier, columns and piles are adversely affected in aggressive environments through permeability of concrete and corrosion of the embedded reinforcing steel. CFFT members can increase both durability and strength of the structure. Previous studies have shown that lateral confinement with a FRP tube not only increases the ultimate compressive strain of concrete (Samaan et al., 1998) but also results in an axial compressive strength much greater than the sum of the individual strengths of concrete core and the FRP tube (Fam and Rizkalla, 2001) Engineers throughout the world have used FRP to solve their structural problems in an efficient and economical manner. In the field of civil engineering, most of the use of FRP is confined to repairing and strengthening of structures. CFRPs offer an added advantage over conventional materials and methods of retrofitting. Like other materials, CFRP also has its limitations (Micheal, 2006).

2.1 Properties of CFRP Pultruded Columns

The mechanical properties of FRP bars are typically quite different from those of steel bars and depend mainly on both matrix and fibres type, as well as on their volume fraction, but generally FRP bars have lower weight, lower Young's modulus but higher strength than steel. The most commonly available fibre types are the carbon (CFRP), glass (GFRP) and aramid (AFRP) fibres.

2.2 Advantages of CFRP and Hollow Columns sections

CFRP exhibits some specific advantages such as corrosion resistance, high longitudinal strength, high fatigue endurance and reduced weight. Due to these advantages, carbon fiber-reinforced polymer (CFRP) composites have been increasingly used in various fields such as aerospace, automotive, athletic and recreational equipment, military and infrastructure applications. In civil engineering, CFRP composites are being used as reinforcing bars and externally bonded reinforcement for the retrofitting and repair of deficient and ageing bridges and buildings. The CFRP tube provides lightweight structural component, permanent formwork, non-corrosive characteristics, and saving of construction time and effort. The fibres in the circumferential direction are utilized to provide confinement of the concrete, while the fibres in the axial direction provide the flexural strength and stiffness. For quite a long time, concrete-filled steel tubes are used as structural members and have been extensively studied. Steel tubes are, however, susceptible to corrosion and could be less efficient in confinement at low load levels due to the higher Poisson's ratio of steel, compared to that of concrete. On the other hand, the laminate structure of FRP tubes could be optimized by controlling the proportions of fibres in the axial and hoop directions to suit the application. For flexural members, larger stiffness would be required in the axial direction while for axial members; larger stiffness is required in the hoop direction as well as a minimum Poisson's ratio in order to produce the maximum confinement of concrete.

The radius of gyration, especially about the minor axis, of a structural hollow section is significantly higher than that of an open section of a similar size and area. This results in lower slenderness ratio for the same effective length, and hence higher compression capacity. Any residual stresses that may be in the section due to the method of manufacture are generally also distributed in a much more favorable way than those in open sections because of the different shape characteristics and this can also result in an increase in the compression capacity. Structural hollow sections are generally available in lengths up to 12 or 15 m, but in some circumstances longer lengths, up to 20 m, may be available. This means that for buildings of up to about 4 storeys only one length per column is required. An additional benefit of structural hollow sections is that for any given section size the outside dimensions remain the same irrespective of the thickness, unlike H-section columns, where the inside dimensions remain the same and the external dimensions change. This means that even if the column cross sectional area is reduced in higher storeys, the beam lengths can remain the same for the full height of the building, which should result in reduced beam fabrication and erection times and therefore reduced overall costs.

2.3 CFRP Concrete Filled Hollow Columns

The concept of concrete filled fibre reinforced polymer tubes (CFFT) piles and pile splices were initially introduced to address corrosion problems in Florida. Mirmiran and Shahawy (1995) and, Carbrera (1996) carried out a hysteretic moment–curvature analysis of CFFT columns. The analysis utilized a cyclic stress–strain model of FRP-confined concrete, which was developed based on a limited number of loading and unloading tests of FRP-confined concrete cylinders in axial compression. Her studies indicated little ductility and significant pinching for both carbon and glass FRP (GFRP) tubes. She concluded that internal steel reinforcement may be required in the plastic hinges of CFFT columns. Seible et al. (1996) conducted an experimental feasibility study of carbon CFFT columns under simulated seismic actions. Three 40% scale models of a prototype circular bridge column were tested as 3.7 m high cantilever columns with a core diameter of 0.6m, supported on 1.7 m square footings. The as-built specimen was a control reinforced concrete column with 2.66% longitudinal steel reinforcement, but no FRP tube. Specimen CSS-1 had a carbon- FRP (CFRP) tube with the same internal steel reinforcement, but only as starter bars for a length of 0.9 m. The tube for this specimen was only 4.6 mm thick, except for the plastic hinge region where it was thickened to 9.5 mm. The tube was set 24 mm above the footing. On the other hand, Specimen CSS-2 had a tube with 9.5 mm thickness throughout, which was embedded into the footing for about 0.8 m. Specimen CSS-1 with starter bars but no embedment of FRP tube showed a stable hysteretic response up to a displacement ductility of 8, essentially mirroring the response of the as-built reinforced concrete specimen. Specimen CSS-2 with embedded FRP tube but no starter bars matched the initial stiffness of the other two specimens. However, premature failure of the tube due to a combined state of compressive inter laminar shear stresses prevented the specimen from absorbing an equal amount of energy as the ductile columns. Due to the high shear and moment at the column-footing connection, cantilever tests tend to focus on the behaviour of the connection rather than the member itself; Davol et al. (2001) extended the work to include different laminate structures, and showed the effect of fibre architecture on attaining a high compressive strain in the tube. Fan et al. (2000) studied the seismic performance of reinforced concrete columns confined by glass or carbon FRP tubes under pseudo-static reverse cyclic loading as cantilever columns. A 50 mm gap was placed between the tube end and the footing surface. Test results indicated that the tube did not increase column strength, but greatly enhanced its hysteretic response up to a displacement ductility of 10. Most recently, Yuan et al. (2002) reported on a novel hybrid GFRP/CFRP tube with ±45° fibre orientation, where the strength of concrete was enhanced by 21 2 times. Coupon tests indicated a bilinear response with a distinct yield point for the FRP tube. Findings of a similar yield phenomenon and a stable hysteretic response for FRP materials in the off-axis direction have been reported in the aerospace and materials engineering literature (Zhang et al, 1993).

2.4 Stress-axial and Hoop Strains Behaviour of Concrete Filled Fibre Tubes (CFFT) Cylinder

The stress-axial and hoop strains behaviour for the CFFT cylinders are practically bilinear. The stress-strain curve at the first stages of loading is similar to the unconfined concrete. Stress-strain hardening behaviour occurred after achieving the approximate unconfined concrete strength and eventually exhibit linear behaviour until sudden failure due to the rupture of the tube. It is clear that a significant enhancement of the strength as well as the ductility for the CFFT cylinders was achieved ( ) by increasing the thickness of FRP tubes. The f_{cc} values were obtained using Equations

(2.5) and (2.6) for unreinforced and reinforced specimens, respectively. Also, Equation (2.7) was used to present the confined compressive strength at yielding level.

$f'_{cc} = P_{max} / A_g$ (1)

$f'_{cc} = P_{max} - f_y A_s / A_g - A_s$ (2)

$f'_{ccy} = P_y - f_y A_s / A_g - A_s$ (3)

where, f'_{cc} is the confined concrete compressive strength, P_{max} is the maximum axial load, P_y is the yield load, f_y is the yield strength of steel reinforcement, A_s is the area of steel, f'_{ccy} is the confined compressive strength of concrete at yield level and A_g is the gross area of the concrete section.

Depending on the level of the confinement, the ACI 440.2R (2008) supported by Rocca et al (2008), classified the stress-strain behaviour of the reinforced concrete column to unconfined, lightly confined, heavily confined with softening, and heavily confined with hardening.

2.5. Relevant Codes and Design Guidelines.

The Canadian codes represent the nominal axial load capacity, P_o, of the conventional reinforced concrete column under concentric loading by the following rational equation:

$P_o = k_c f'_c (A_g - A_s) + f_y A_s$

(4)

The concrete and steel strengths at ultimate and yielding, respectively, are added together to compute the theoretical nominal strength or yield point of short loaded RC columns under pure axial load. It was possible to express the column capacity in this simple form because both the concrete and steel reached their plastic states at approximately the same strain level (Ozbakkaloglu and Saatcioglu, 2004). The parameter k_c is defined as the ratio between the in-place-strength of concrete to concrete cylinder strength, (f_{co} / f'_c). The difference is usually attributed to the size effect, shape, and concrete cast practice between columns and concrete cylinders. An extensive experimental program was conducted on reinforced concrete columns; as a result, a value of 0.85 was suggested for k_c (Lyse and Kreidler, 1930). In fact, a perfect axially loaded column does not exist, unintentional eccentricity occurs on the column section due to the end condition, inaccuracy of construction, and normal variation in material properties. To take these factors into consideration, the ACI 318 (2008) specifies a reduction factor of 20% and 15% in the maximum nominal load *Po*, for tied and spiral columns, respectively. Introducing the strength reduction factor, φ, the axial load capacity of the reinforced concrete columns according to the ACI 318 (2008) code is as follows:

For spiral columns φ = 0.75.

$P_r = \varphi P_n = 0.85\varphi [0.85 f'_c (A_g - A_s)] + f_y A_s$

(5)

For tied columns φ =0.65

$P_r = \varphi P_n = 0.80 [0.85 f'_c (A_g - A_s)] + f_y A_s$ (6)

2.6 Flexure in Hollow Sections

In general, I and H sections are more economical under bending about the major axis (I_{max} larger than for hollow sections). Only in those cases in which the design stress in open sections is largely reduced by lateral buckling do hollow sections offer an advantage (Shurlle, 2006). It can be shown by calculations that lateral instability is not critical for circular hollow sections and for rectangular hollow sections with b/h > 0.25 (with bending about the strong axis), which are normally used (Fem, 2006). It is apparent that hollow sections are especially favourable compared to other sections if bending about both axes is present. Hollow sections used for elements subjected to bending can be more economically calculated using plastic design. However, then the sections have to satisfy more restricted conditions to avoid premature local buckling. Like other steel sections loaded in bending, different moment-rotation behaviours can be observed.

2.14 Concrete Filled Carbon Filled Carbon Fibre Reinforced Plastic (CFRP) Composite Piles.

For the past decade, CFRP composites have found increasingly wide applications in civil engineering, both in retrofit of existing structures and in new construction. CFRPs offer advantages compared to traditional construction materials for being lightweight, high strength and corrosion resistant. As a result, application of composite piles started to gain acceptance in pile rehabilitation and replacement. Indeed, several studies around the world are currently underway examining its behaviour and its extent of relevance in waterfront and highway structures.

Pile materials such as steel, concrete and timber have limited service life when used in harsh marine environment due to corrosion, degradation and marine borer attack. These problems coupled to traditional materials led researchers to investigate the feasibility of adopting CFRP composite piles as an alternative in piling system. Currently there are five common types of composite piles which are considered as potential substitutes. These include plastic encased steel pipe core piles, structurally reinforced plastic matrix piles, concrete-filled CFRP tubular piles, fibre-glass pultruded piles and plastic lumber piles (Ni-roumand, 2009). Among these five pile types, the first three are considered to be better suited for load–bearing applications (Lampo et al., 1998). Concrete-filled CFRP piles, which somehow have a relation to the present study, may be made from filament winding, pultrusion, and resin transfer moulding processes (Iskander and Hassan, 1998). The CFRP shell provides, among other things, a stay-in-place concrete form, confinement to the concrete, tensile reinforcement, and corrosion protection (Fam and Rizkalla, 2001) while the concrete infill provides compressive load capacity. Basic among the in-need for assessment in CFRP composite piles is its behaviour when subjected to axial compression. The response of the pile under axial loading is considered to be among the factors that most affect the superstructure's behaviour especially for gravity loading (Comodromos et al., 2009), thus this necessitates attention.

Studies on hollow CFRP concrete filled composite piles are very rare due mainly to some issues particularly on its performance when driven on the ground. Mirmiran (2002) found out that empty tubes are susceptible to buckling and damage during driving due to lower impedance and can only sustain driving stresses up to 40-50% of the refusal rate of the concrete piles, unless driven to shallow depths or in soft soils. However, this driving issue is not considered as significant if hollow CFRP composite piles are used in partial replacement of a damaged traditional pile where driving force is not required. Outcome of the previous study conducted by Pan-do et. al (2002) on concrete-filled tubular pile revealed that both of the components responded significantly until failure with unique responses at on plies was developed at increasing applied load. Furthermore, the load-strain curves of the finite element model as produced by them are in close agreement with the experimental results.

3.0 METHODOLOGY

3.1 Design of Hollow Column Using ABAQUS/CAE 6.10.1

The columns were designed using ABAQUS through the following procedures

(a) Creating a Part

The column to be designed was created using a three-dimensional, deformable solid part. This is done by sketching the geometry of the column. When this is done, ABAQUS automatically enters the Sketcher when one creates a part. The Sketcher contains a set of basic tools that permits the sketching of the three dimensional profile of the created part or element.

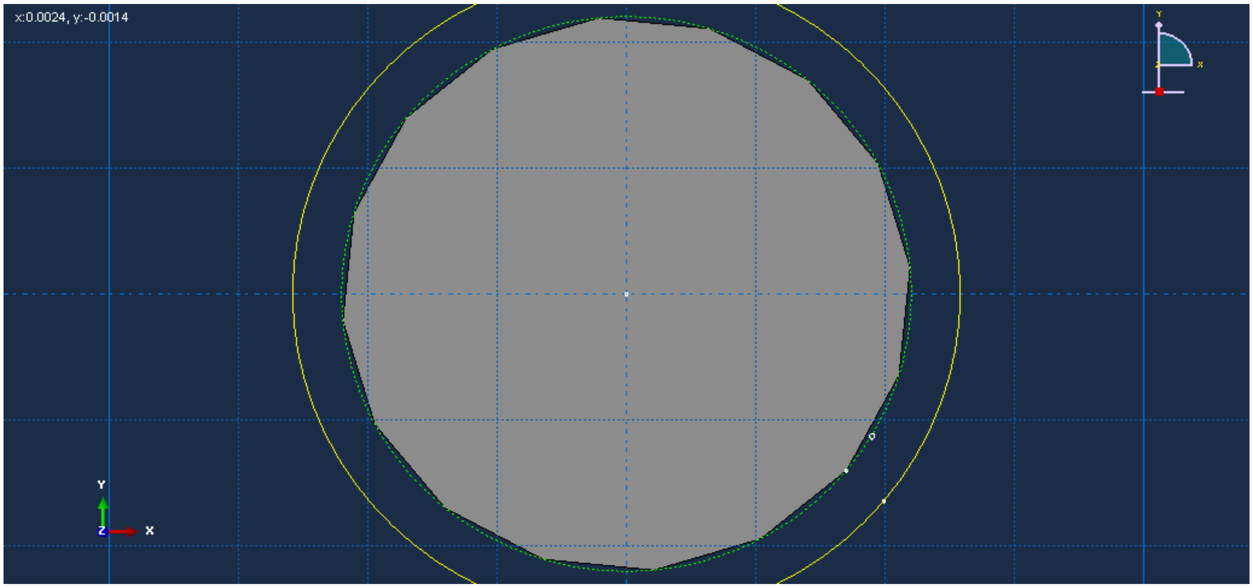

Plate 1: Created part of a reinforced concrete filled hollow column.

In this study all the members of the column are made of Carbon Fibre Reinforced Polymer and assumed to be linear elastic with Young's modulus of 150 x 10^9 N/m^2 and Poisson's ratio of 0.74. Thus, one creates a single linear elastic material with these properties; and after which the section is defined and assigned the corresponding section properties.

Now that the sections have been created, only the analysis step is needed for the simulation. This analysis will consist of two swift steps overall: initial step, in which one applies boundary conditions that constrain the ends of the column; and an analysis step, in which a concentrated load is applied at the top of the column. However, ABAQUS generates the initial step automatically, but the user must create the analysis step. The user may also request output for any steps in the analysis. There are two kinds of analysis steps in ABAQUS: general analysis steps, which can be used to solve linear or nonlinear response, and linear perturbation steps, which can be used only to analyze linear problems. Only general analysis steps are available in ABAQUS/Explicit. For this simulation we have considered or defined a static linear perturbation step.

(b) Applying Boundary Conditions and Loads

In this work the various columns were fixed at the bottom and uniformly loaded at the top, the loading was based on the Euler's critical buckling load given as:

$$p_{cr} = \frac{\pi^2 EI}{L^2} \tag{1}$$

where, E = modulus of elasticity; I =Moment of inertia and Pcr = critical maximum axial load on the column just before it starts to buckle.

(c) Requesting Data Output

Finite element analysis creates very large amount of output. ABAQUS allows the user to control and manage this output so that only data required to interpret the results of the simulation are produced. Four types of output are available from an ABAQUS analysis namely: (i) results stored in a neutral binary file used by ABAQUS/CAE for post-processing. This file is called the ABAQUS output database file and has the extension *.odb. (ii) printed tables of results, written to the ABAQUS data (*.dat) file. Output to the data file is available only in ABAQUS/Standard. (iii) Restart data used to continue the analysis, written to the ABAQUS restart (*.res) file. (iv) results stored in binary files for subsequent post-processing with third-party software, written to the ABAQUS results (*.fil) file.

The output is the requested from the Manager and from which the relevant information is obtained for the work.

4.0 RESULTS

The hollow CFRP and steel columns were analysed using Simulia ABACUS CAE 6.10.1 the columns were loaded using Euler's critical buckling load. Finite element analysis were carried out on the columns of various cross sections at depths of 3m,4.5m and 6m using the critical buckling load of columns and the various results are shown below.

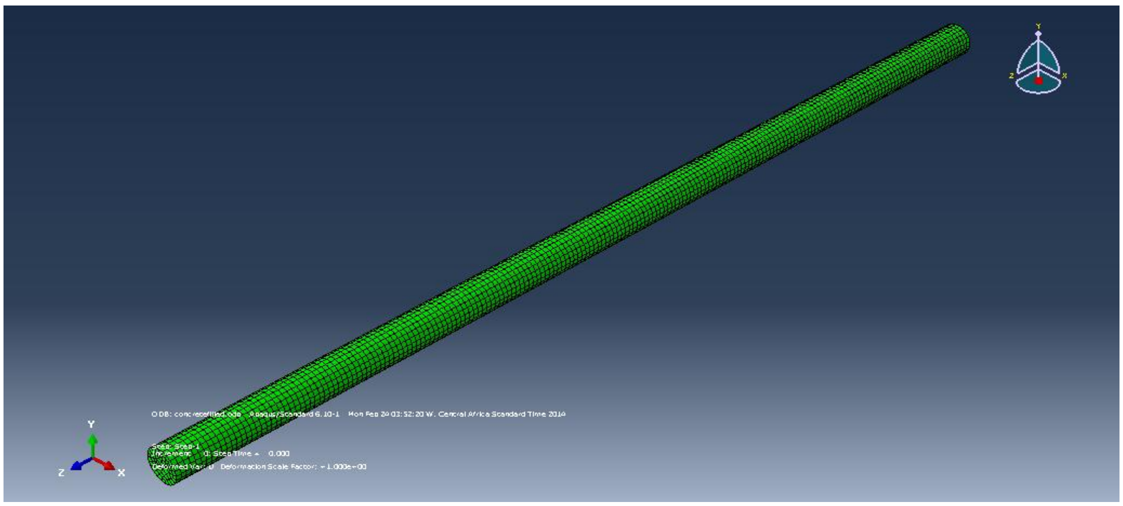

Plate 2: A circular concrete filled hollow column of CFRP confinement 3.5*0.33 inches

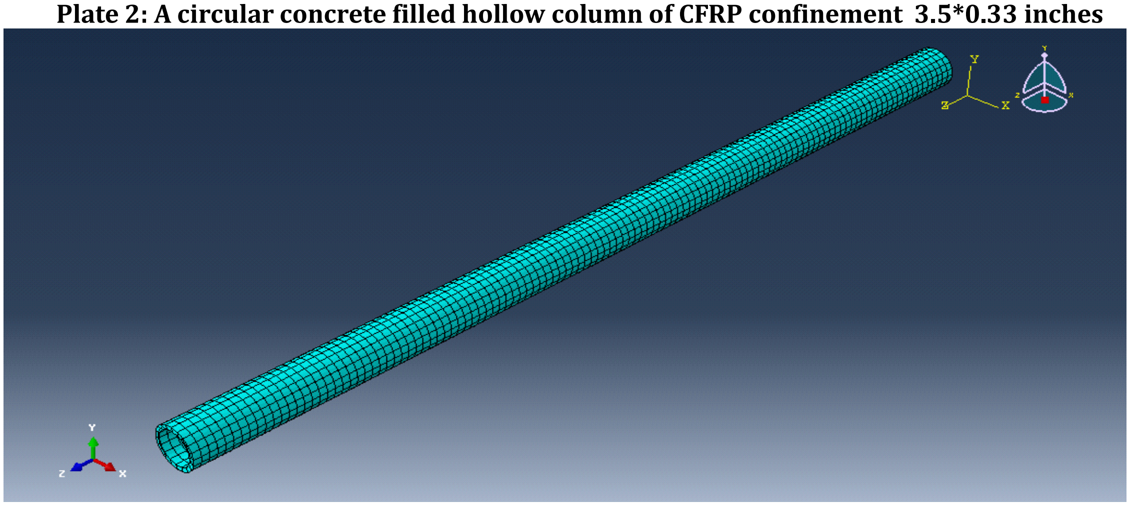

Plate 3: A cross section of the CFRP confinement.

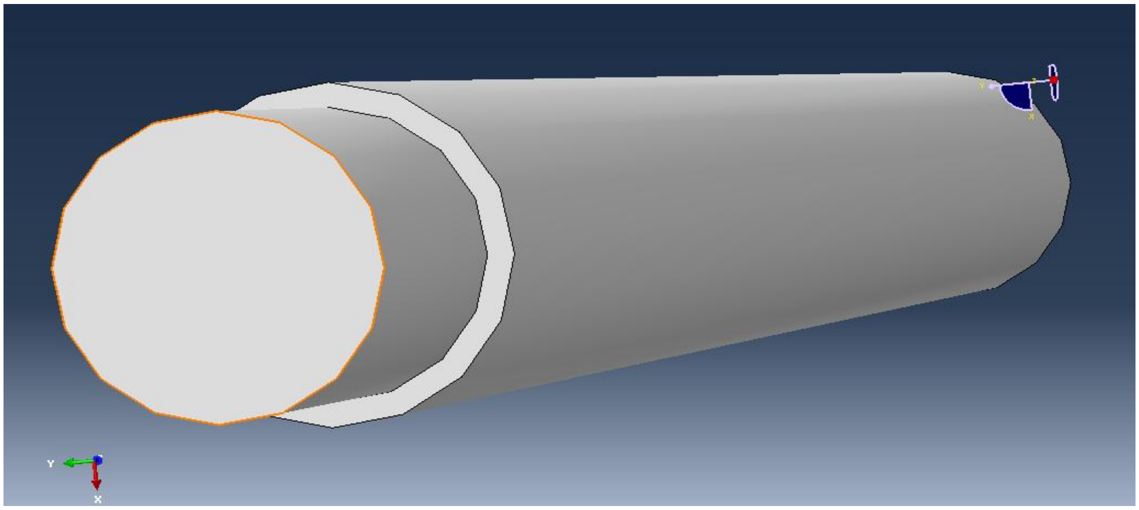

Plate 4: A 6m circular CFRP hollow column filled with concrete and carrying axial load of 40146kN.

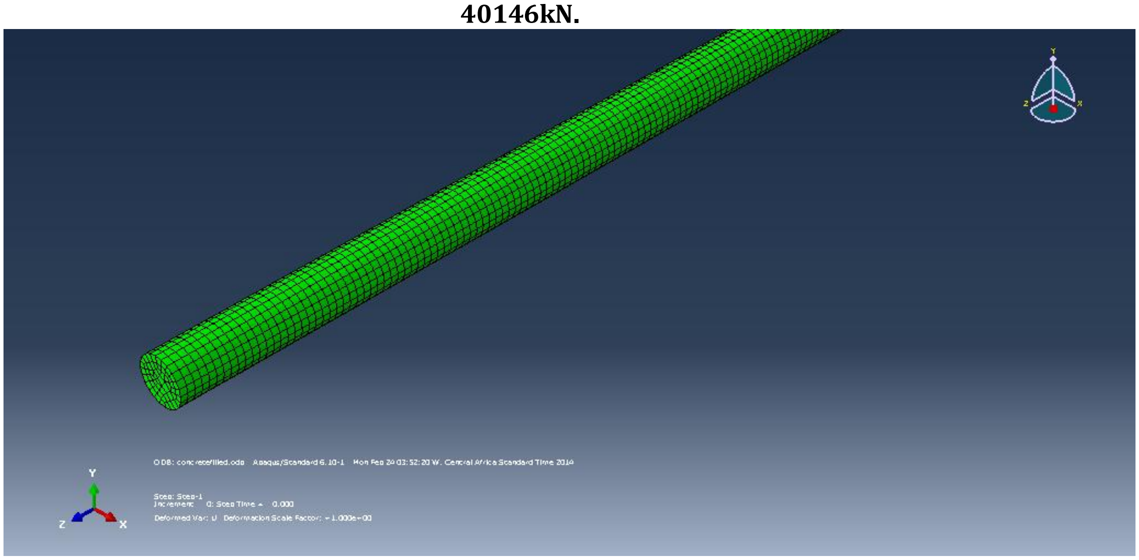

Plate 5: The 6m column showing no compression or deformation due to loading

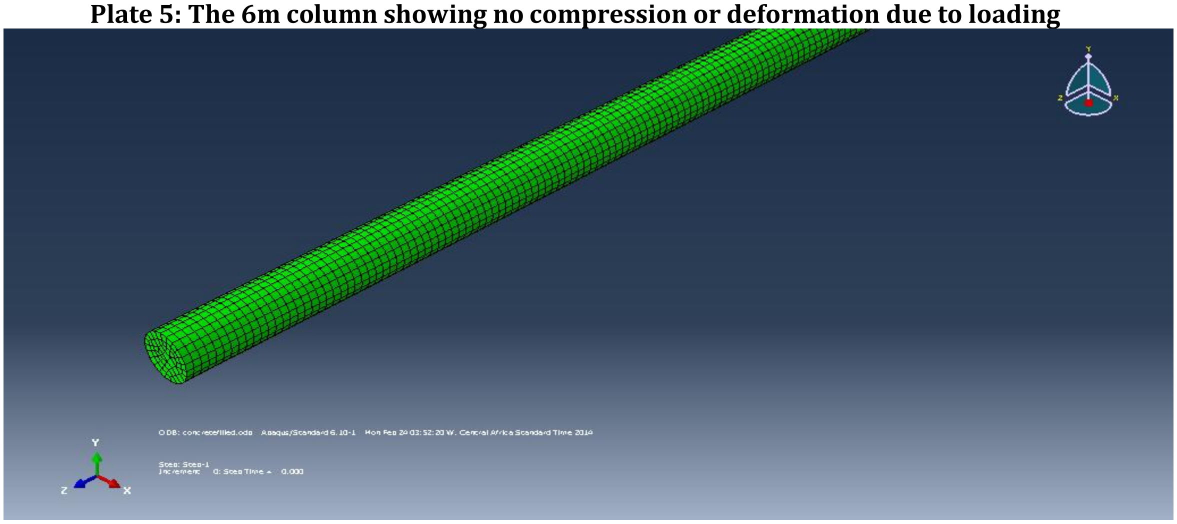

Plate 6: A 6m hollow steel concrete filled column showing no buckling due to critical bucking load of 29118kN

4.1 Calculations

The calculation of moment of inertia of circular confinement of external diameter 89.9mm and internal diameter of 81.6mm and thickness 8.3mm.

$$I = \frac{\pi^2(D-d)^4}{64} \tag{2}$$

$$I = \frac{3.142^2(89.9-81.6)^4}{64}$$

$$I = 732mm^4$$

Calculation of buckling load for CFRP hollow column, using E = $150 * 10^9 Pa$

$$p_{cr} = \frac{\pi^2 EI}{L^2} \tag{3}$$

$$P_{cr} = \frac{3.142^2 * 150 * 10^9 * 732}{6000 * 6000}$$

$$p_{cr} = 30112kN$$

Calculation of buckling load for same steel section as above, using E = $200 * 10^9 Pa$

$$P_{cr} = \frac{3.142^2 * 200 * 10^9 * 732}{6000 * 6000}$$

$$p_{cr} = 40146kN$$

Where I=moment of inertia; P_{cr} =Euler's critical buckling load; L = length of column; E = Modulus of elasticity; D = Outer diameter; and d = Internal diameter.

Comparing the load of CFRP with that of steel, gives;

$$\frac{30112}{40146} * 100 = 75\%$$

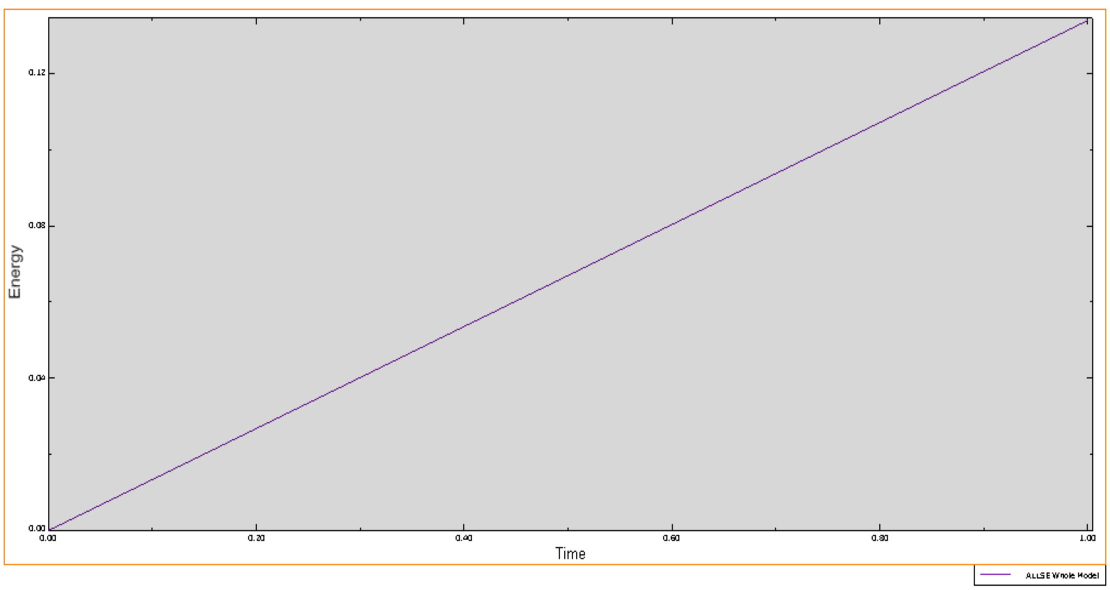

Figure1: Relationship of strain energy with time for a hollow CFRP confinement of length 6m.

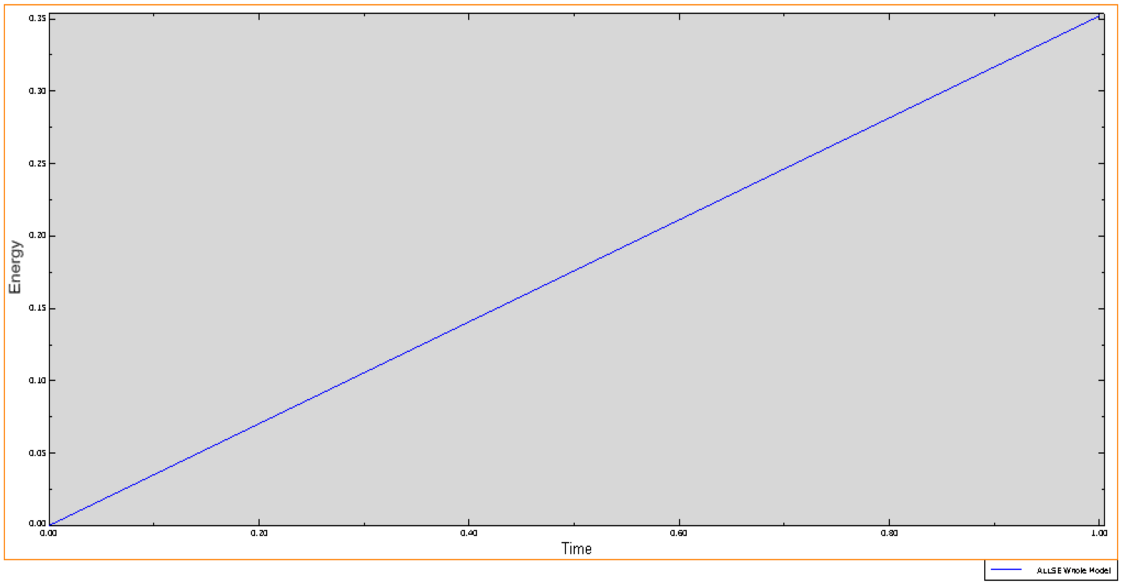

Figure 2: Relationship of strain energy with time for a hollow steel confinement of length 6m.

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

It can be observed that the various hollow columns were deformed mostly at the base of the column.

The results show in Plates 1 to 5 that there is no buckling due to the confinement of concrete with CFRP and steel respectively.Also, Figures 1 and 2 show the same results which means that both steel and CFRP behave in a similar manner. CFRP can sustain up to 75% of the load concrete filled steel columns can sustain.

5.2 Recommendation

From the results obtained it is observed that both CFRP and steel behave in the same manner, so CFRP hollow columns is a good substitute for steel hollow columns as it has been shown to be structurally strong, effective for concrete confinement and environmentally friendly.

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